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Impact of Architectural Styles on Acoustic Characteristics in Selected European Churches

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Abstract: This study explores the acoustic properties of European Churches, influenced by architectural design, historical context, and spatial configurations. A comparative analysis of 83 Churches from different regions and periods combines literature reviews and empirical data to understand the interplay between architecture and acoustics. Key geometric parameters—volume, surface area, length, height, and aisle count—were compared with acoustic metrics to provide a comprehensive view of these sacred spaces. The study identified the key factors influencing acoustic characteristics, uncovering significant variability within the same architectural style. Linear Discriminant Analysis (LDA) further highlighted distinct patterns and outliers, showing that Gothic, Neoclassical, and modern architectural styles possess unique acoustic signatures. These findings challenge the assumption of uniform acoustics within similar styles, revealing that even minor architectural differences can substantially impact sound behavior. Outliers were particularly informative, representing Churches with unique acoustic properties, which shed light on how specific design elements affect sound propagation. The study underscores the complexity of the relationship between architecture and acoustics in Churches and suggests that further research should consider both quantitative measures and subjective experiences to fully capture the acoustic environment of these historic spaces.

Keywords: historical building; architectural technology; analytical and numerical approaches; acoustic heritage building

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1. Introduction

Since ancient times, humans have practised religious rituals and identified sacred places as sites where these venerations have been and can be performed.

The acoustic design of cathedrals and other religious spaces has historically been shaped by multiple social, cultural, and technological factors. Throughout different periods, changes in societal needs, liturgical practices, and advancements in construction methods influenced how churches and cathedrals were designed with acoustics in mind [1]. For example, during the Medieval period, the church served as a center of community life, and its acoustic design was crucial in facilitating both communal worship and the participation of the congregation [2]. With the evolution of liturgical practices, such as the introduction of polyphonic music and the organ, acoustics had to adapt to accommodate new forms of worship and musical expression. Similarly, advancements in construction technology, such as the development of vaulted ceilings and the use of new materials, allowed for more sophisticated acoustic environments. Architectural elements like the shape of the nave, the use of reflective surfaces, and the integration of sound-reflecting structures were employed to enhance sound propagation, contributing to the solemnity and grandeur of religious services [3,4].

Numerous researchers have studied the acoustic properties of places of worship over the years, such as Italy [5–9], Poland [10–13], Spain [14,15].

Although the concept of acoustic design is a relatively modern development, it is important to acknowledge that acoustics played a significant role in the historical design of liturgical spaces, even if implicitly. The design of liturgical spaces historically took into account specific acoustic considerations, such as enhancing the clarity of spoken words and the richness of musical performances, with the architecture often tailored around the needs of the liturgy [16]. However, it is also crucial to recognize that acoustic requirements were balanced with other priorities, including aesthetic symbolism, structural integrity, and spatial arrangements necessary for the liturgical rituals of the time. This approach ensured that sound perception and speech intelligibility were prioritized, facilitating the active participation of the congregation during religious services [17].

Brenzina et al. [18] emphasizes that the acoustics of historic spaces constitute a significant aspect of intangible cultural heritage. Additionally, Murphy et al. [19] explore the role of acoustic heritage in understanding and experiencing past environments, further highlighting the importance of sound in the design of sacred spaces. A recent literature review by Navas-Reascos et al. [20] also underscores the global significance of archaeoacoustics in understanding historical soundscapes.

In order to make the most of these areas, it is necessary to establish a balance between the acoustic parameters. This means that the reverberation time should be short enough to ensure that the spoken word is clearly understood, but long enough to allow for a pleasant listening experience of the music and to give the message a certain solemnity, which is typical of religious ceremonies.

Most investigations of the properties of liturgical places are based on the determination of the individual acoustic parameters defined in ISO 3382 [21].

Lidia Álvarez-Morales et al. [22] explores the relatively unexplored topic of sound propagation in large reverberant religious spaces, focusing specifically on the acoustic environment of the Catholic Churches in southern Spain, with the Churchesof Malaga as a case study. The study examines the monaural and binaural impulse responses of various receivers positioned at the main altar, pulpit, choir, organ, and retrochoir.

Suarez et al. [23] focusses on the examination of the sonic characteristics of the space and the analysis of how its acoustics have evolved and adapted to the various liturgical needs of each historical period.

Throughout history, sacred spaces have been treated with the aim of restoring their spiritual significance rather than focusing solely on architectural aesthetics. A notable example is the Christianization of the Córdoba Mosque [24], where two Churches were integrated into the original Muslim site: the Gothic Churchesin the chapel of Villaviciosa and the later 16th-century construction of the Churchestransept, which includes the main chapel and choir. These architectural interventions blend harmoniously with the existing Islamic mosque, creating a unique interplay between Christian and Muslim elements. This interrelation significantly influences the acoustic performance of these spaces. This study conducts a comparative analysis of acoustics in these liturgical and cultural environments and proposes architectural interventions to optimise their acoustic qualities [25].

Tronchin et al. [26] investigate two acoustic projects implemented in the churches of Foligno and Imola, both dedicated to S. Dominic. These initiatives involve both permanent and temporary alterations of the spaces, creating environments specifically tailored for the enjoyment of live music.

With the advent of the digital era, a prominent focus within acoustics research has been to measure the tangible factors that influence sound perception [27]. This collective objective is widely recognized among researchers and practitioners in the field. The resulting data is then employed during the design phase, with particular emphasis on creating architectural spaces specifically optimized for musical performances [28]. Additionally, as many of these spaces are part of our UNESCO cultural heritage, it is essential to preserve their acoustic integrity, ensuring that they continue to serve their intended functions while honoring their historical significance [29].

Giron et al. [30] examined and evaluated key advancements in the acoustics of 75 Western Christian churches, with a specific focus on ancient historical churches. Their work spans from the second half of the previous century to the present. This article presents the research conducted on church acoustics across different countries, highlighting experimental methodologies, findings, discussions, and theoretical interpretations of sound propagation within these spaces. It also covers subjective aspects of the listening experience and the use of computer simulation techniques to study and implement acoustics in these intricate architectural structures, as can be seen in the works referenced in [31–34].

In Spain, as an example of the most important buildings of Romanesque art, in their groundbreaking study, researchers from four universities collaborate to measure and analyse the acoustics of the Churches [35]. Impulse response measurements in different source-receiver configurations yield results that encompass temporal, energy, spatial, and intelligibility parameters. These parameters are categorised into distinct zones, reflecting the Cathedral's varied liturgical functions. The findings of the GAMMA research team will be compared with those of other teams and will help calibrate virtual models of the Cathedral.

Carvalho et al. [36] conducted a pioneering study on the influence of architectural features and styles on various acoustical measures in churches. His work highlighted how different design elements, such as the shape of the nave and the materials used in construction, impact parameters like reverberation time and clarity of speech. This research laid the foundation for further studies that sought to categorize churches based on their acoustic characteristics and architectural styles. In a similar vein, Desarnaulds et al. [37] analyzed reverberation time values in churches across different countries and architectural styles, demonstrating how cultural and architectural diversity shapes the acoustic environment of religious spaces. The role of architecture in enhancing or diminishing the auditory experience of worship has also been explored in more recent studies. Cirillo et al. [38] examined the intersection of worship, acoustics, and architecture, emphasizing how the acoustic design of churches can be both a functional and symbolic element of religious practice. Their work underscored the importance of acoustics in supporting the liturgical experience, from spoken word to choral music. More recent contributions, such as the study by Alberdi et al. [39], focus specifically on Baroque Catholic church spaces, providing a detailed analysis of how architectural features unique to the Baroque style influence acoustic behavior. Dianderas et al. [40] further extended this understanding by comparing the acoustical behavior of colonial churches in Peru, showing how the local context and architectural styles interact to produce distinct acoustic environments.

Contribution of This Study

This study explores the intricate relationship between architectural styles and acoustic properties within European Churches, providing valuable insights into the nuanced interplay between design elements and sound propagation. Using a data set comprising 83 churches in various European regions and historical periods, the research integrates reviews of the literature with empirical investigations to offer a comprehensive analysis of Churchesacoustics.

Furthermore, employing Linear Discriminant Analysis (LDA), the study discerns distinct patterns and relationships among architectural styles and acoustic attributes. Through LDA, it elucidates how different architectural styles manifest unique acoustic signatures, shedding light on the nuanced interrelations between design elements and sound propagation within Churchesspaces.

Moreover, the presence of outliers within the dataset offers valuable insights into anomalous acoustic behaviors that defy conventional expectations. Characterized by their deviation from expected acoustic norms associated with specific architectural styles, these outliers serve as focal points for deeper investigation. By scrutinizing these anomalies, the study aims to uncover unique architectural configurations and acoustic phenomena that contribute to a richer understanding of Churches acoustics.

Significant findings from the study include the identification of intricate relationships between architectural styles and acoustic properties, challenging conventional assumptions and highlighting the inherent variability within Churches acoustics. Furthermore, the research reveals compelling insights into the impact of specific architectural elements on acoustic performance, offering valuable guidance for architects and designers seeking to optimize acoustic environments within Churches settings.

Ultimately, the findings of this research hold significant implications for architectural design and acoustic engineering, particularly in the creation of immersive and acoustically optimized environments within Churches settings. By elucidating the complex relationship between architectural elements and acoustic properties, this study provides valuable guidance for architects and designers seeking to craft transforming spatial experiences rooted in historical and cultural contexts.

The primary contributions of this research are summarized as follows:

1. A comprehensive collection of all acoustic characteristics and geometrical properties of each Churcheswas conducted. This included factors such as volume, shape, architectural style, century, and a schematic sketch of the 83 Churches from various European nations as samples for analysis.
2. Comparative analysis of sound propagation in large reverberant religious spaces belonging to different architectural styles.
3. All collected buildings were categorized into different architectural styles, such as Gothic, Renaissance, Baroque, Neoclassical, Modern, and others, to compare their acoustic properties and identify any patterns or trends.
4. A statistical analysis was performed to uncover the hidden relationship between architectural style and the Churches'acoustic and geometrical properties. This analysis aims to provide insights into how architectural design choices impact the sound experience in these spaces.
5. Subsequently, LDA was utilized to discern the discriminative power of architectural style in predicting acoustic characteristics. This multivariate approach allowed us to uncover hidden patterns and relationships within the data, providing a comprehensive understanding of the influence of architectural style on Churchesacoustics.

This study, while comprehensive, is not exhaustive due to the inherent limitations tied to the availability and consistency of acoustic data in the existing literature. The dataset, which consists of 83 churches, was carefully curated with due consideration of the most relevant and rigorous research on church acoustics. The goal was to build a dataset that would provide a well-rounded representation of diverse architectural styles across Europe. However, it became evident that not all churches in the literature offered adequate or consistently reported acoustic measurements. Many sources lacked detailed or standardized data, which posed a challenge in assembling a truly exhaustive dataset. The selection of the 83 churches was, therefore, influenced by the availability of empirical measurements, with a strong emphasis on studies that adhered to recognized standards for acoustic measurement, particularly ISO 3382 [21]. This standardization is crucial for ensuring the reliability and comparability of the data, which is why studies employing ISO 3382 methods were prioritized. The choice of these specific 83 churches was not arbitrary; they were selected to reflect a broad range of architectural typologies, geographical diversity, and historical contexts across Europe. By focusing on these churches, the study aims to present a representative cross-section of church acoustics, aligning with the broader scope of architectural acoustics research. The selection process was also guided by the principle of sample size sufficiency. While a larger dataset would certainly provide a more expansive view, the 83 churches in this study were deemed sufficient to draw meaningful conclusions about the general trends and variances in church acoustics. This number strikes a balance between breadth and the availability of reliable data. Furthermore, these churches were chosen to include a variety of building types—from large, grand cathedrals to smaller, more intimate churches—thus capturing the diversity within church acoustics research and ensuring that the results could be generalized to a broader range of similar structures in Europe. In sum, the 83 churches selected for this study serve as a robust sample of the diverse acoustic environments found within religious architecture, reflecting the main architectural acoustics themes explored in the literature. Despite the challenges in data availability, this dataset provides valuable insights into the acoustical characteristics of churches across different historical and architectural contexts.

The paper is organized as follows: Section 2 presents the background of acoustic parameters in European Churches, the characteristics of the Churches analyzed and the dataset built by the authors reported in detail in supplementary materials. The results of the factor analysis and the predictive analyses are presented and discussed in Section 3. Finally, Section 4 draft the conclusion of work and comments on possible future extensions.

2. Materials and Methods

In this section, the methodology used to analyze the acoustics of European churches is presented. The research is divided into several subsections: the first Section 2.1 provides an overview of the architectural features of the churches under study, highlighting the historical and stylistic diversity of these buildings. The Section 2.2 describes the selection process for the 83 churches analyzed, and outlines the geometrical and acoustic parameters measured. These parameters, including reverberation time, clarity, and sound strength, were studied in relation to the architectural characteristics of each building. Additionally, supplementary tables offer detailed information on the architectural styles, geometrical properties, and acoustic measurements for each church included in the study. Finally, Sections 2.3 and 2.4 detail the factor analysis and linear discriminant analysis (LDA) techniques used to explore the relationships between architectural and acoustic features.

2.1. Characteristics of European Churches Architecture

The architecture of European Churches is one of the most significant expressions of art and culture in the Old Continent. Churches, which are large principal churches of a diocese or city, often represent the focal point of the community and were built during various historical periods, reflecting the dominant architectural styles of their respective eras.

The origins of large churches and Churches can be traced back to the time of the Roman Empire. As Christianity spread across the world, the construction of these religious buildings adapted to local resources and construction methods. This led to a variety of architectural styles, which were then disseminated through different channels [41].

Monastic orders played a crucial role in propagating distinct architectural styles. They constructed churches and Churches in their unique manner, and as their influence grew, these styles found their way into different regions, evolving and blending with local traditions.

The movement of bishops from one area to another also contributed to the diffusion of architectural styles. As bishops relocated, they carried with them their architectural preferences and concepts, leaving an impact on the design of churches and Churches in their new dioceses.

Moreover, skilled stonemasons and architects frequently traveled from place to place, often engaged in construction projects. They brought along their expertise, craftsmanship, and artistic vision, influencing the architectural choices of the places they visited [42,43].

As time passed, a diverse array of architectural styles emerged, becoming associated with specific regions or time periods. Notable examples include the Romanesque and Gothic styles, which spread widely across Europe, leaving an enduring imprint on Churchesand church architecture.

The dynamic exchange of architectural ideas and techniques resulted in the captivating variety of European Churchesarchitecture that we admire today. Each Churchesstands as a testament to the amalgamation of diverse cultural, artistic, and religious influences that have shaped them over the course of centuries [44–46].

To provide a thorough understanding of the dataset collected from the literature, the authors have compiled a table in the supplementary materials that presents the geometric, architectural, and acoustic information for each analyzed cathedral. This table offers a comprehensive overview of the European Churchesarchitecture under study, emphasizing the distinctive features of major styles, materials and acoustic.

2.2. Investigated Churches and Selection of the Geometrical and Acoustic Parameters

Churches are complex architectural works that arise from a collective and prolonged effort. These historic buildings, while maintaining their vitality, culturally project their grandeur within, with a notable concentration of artistic treasures, and also externally, serving as spatial landmarks that shape the urban fabric of the surrounding cities [47].

The present study considers 83 churches belonging to different European nations and to different historical periods. Each historical period, from the Middle Ages to the modern era, has been characterized by various architectural styles, each with its own acoustic peculiarities, as a direct consequence of architectural choices.

The buildings analyzed were initially divided according to the style: Romanesque, Neoclassical, Modern, Baroque, Gothic, Byzantine, Mudejar-Gothic, Renaissance and Early Christian. For each style were then identified the main construction aspects as well as the acoustic characteristics measured.

Figure 1 shows as an example a schematic sketch of one of the Churches analyzed, highlighting its architectural features and acoustic measurements. It is the Churchesof San Petronio in Bologna, Italy. The same procedure was applied to all 83 Churches in the study.

All the information used has been collected directly by the study group through in situ surveys or obtained from the scientific literature of the last decade, particularly active in the field.

The complete details of the collected data are reported in Table S1, which is available in the supplementary materials. Table S1 summarizes the 83 Churches studied in this article in alphabetical order according to the style. Each Churcheshas been assigned a rank from 1 to 83 and for each of them has been reported the reference in literature, the place, the architectural style and the relative historic period.

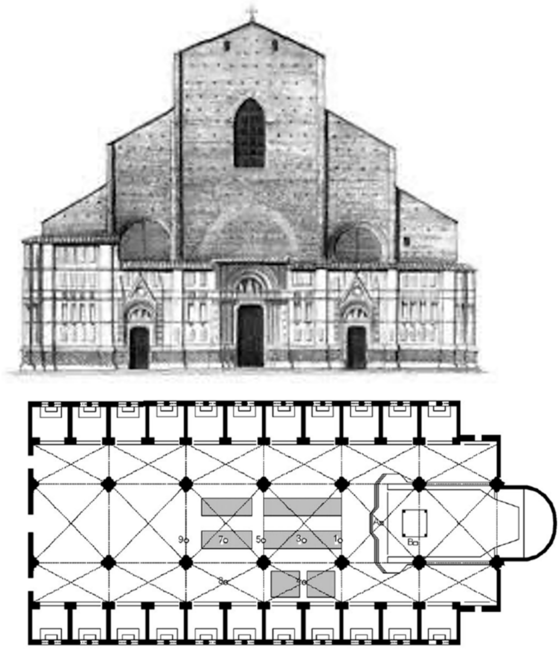

Figure 1. Chatedral of San Petronio, Italy. Note: Basilica of San Petronio (Bologna, Italy) [25,48,49], Gothic Style, 1390–1663 d.C., 170,000.00 m^3, Reverberation time 10.6 s, Clarity −11.3 dB, Definition 0.56, Sound strength 2.03 dB.

The detailed analysis of acoustic properties in 83 Churches was performed within literature investigations.

The main acoustic parameters [21] such as reverberation parameters (T30, T20, EDT), energy parameters (C50, C80, D5) and spatial (G) all in the 125 Hz–4000 Hz frequency range, were taken into account for the survey. In addition the main geometrical characteristics of the Chatedral, such as volume, surface, length, height and number of nave were also taken into account for the survey.

Table S2 summaries the main data which broadly describes the geometry and the average values from 125 Hz–4000 Hz of the acoustic parameters of each Churches. Table S2 is available in the supplementary materials.

2.3. Factor Analysis

This study employs exploratory factor analysis to explore complex interrelationships within the dataset, aiming to identify integrated concepts, such as the relationship between architectural style and acoustic properties. Given the exploratory nature of factor analysis, it does not distinguish between independent and dependent variables. Instead, it groups similar variables into the same factor in order to uncover underlying patterns. The analysis is based solely on the correlation matrix of the data. In this study, principal component extraction was used within the factor analysis to determine whether the acoustic properties of the churches are influenced by identifiable factors related to architectural style.

Factor analysis [50] is a statistical technique used to examine the relationships between observed variables and identify underlying factors that explain the patterns of correlations among these variables. Factor analysis is a statistical technique that aims to uncover the latent factors that contribute to the observed correlations between variables, providing insights into the underlying structure of a set of variables.

In the realm of Churches architecture, factor analysis can be employed to examine the connections between architectural characteristics (related to architectural style) and acoustic elements (associated with the sound qualities of the space) to determine the most significant factors. Factor analysis enables researchers to recognize which variables have the most significant effect on the variation in the dataset of Churches style features. By performing factor analysis, researchers can determine which variables and combinations of these variables explain the variation in the properties of Churches.

Let x be a vector of independent variables with:

$$x_i \in [x_i^{lb}, x_i^{ub}], i = 1, \ldots, N \quad (1)$$

and y the dependent variable.

We define

$$D_j^+ = x \in D | x_j > (\frac{x_i^{lb} - x_i^{ub}}{2}) \quad (2)$$

and

$$D_j^- = x \in D | x_j > (\frac{x_i^{ub} - x_i^{lb}}{2}) \quad (3)$$

The effect of x_j is then:

$$Eff(x_j) = \frac{\sum_{i=0}^{n} x \in D_j^+ y(x)}{card(D_j^+)} - \frac{\sum_{i=0}^{n} x \in D_j^- y(x)}{card(D_j^-)} \quad (4)$$

where "card(D_j^+)" denotes the cardinality of the set A_j.

For the factor analysis on the entire dataset, we used software called ModeFRONTIER 2023R2 [9]. In this instance, we must identify the factors that are most responsive to architectural style.

In this study, we used factor analysis to analyze a dataset of 83 Churches, aiming to understand the underlying relationships between architectural characteristics and acoustic properties. Specifically, we sought to determine which acoustic parameters were most responsive to architectural style. The analysis results showed that the most influential factors were combinations of geometrical parameters (such as length and volume) and acoustic parameters like Early Decay Time (EDT), Reverberation Time (RT), and Sound Strength (G).

All the indicators on which this work is based are briefly defined and commented hereafter.

The Early Decay Time (EDT) and the Reverberation Time (T20 and T30) were estimated by the slope of the Schroeder backward-integrated decay, respectively, in the [dB] ranges: $[0, -10]$ for the EDT; $[-5, -25]$ for the T20 and $[-5, -35]$ for the T30.

The Clarity index, C80 (Equation (5)), is the ratio, in [dB], between the early energy, received in the first early time of 80 [ms], and the energy received after in the late time. The term "energy" represents the square of the instantaneous values of the pressure impulse response.

The Definition index, D50 (Equation (6)), is the dimensionless ratio between the "useful energy", received in the early 50 [ms] of the impulse response, and the total energy received.

The Sound strength, G (Equation (7)), is the measure of the room's contribution to the sound or noise level from a sound source.

$$C_{80} = 10 \cdot Log \frac{\int_{0}^{0.080} p^2(t)dt}{\int_{0.080}^{\infty} p^2(t)dt} \text{ [dB]} \quad (5)$$

$$D_{50} = \frac{\int_{0}^{0.050} p^2(t)dt}{\int_{0}^{\infty} p^2(t)dt} \tag{6}$$

$$G = 10 \cdot Log \frac{\int_{0}^{\infty} p^2(t)dt}{\int_{0}^{\infty} p^2(t)dt} = L_{pE} - L_{pE,10} \ [\text{dB}] \tag{7}$$

2.4. Linear Discriminat Analysis

Discriminant Analysis (DA) is widely used in classification problems. The traditional way of doing DA was introduced by R. Fisher, known as the linear discriminant analysis.

LDA is primarily employed for supervised classification tasks, especially when you have multiple classes. It's closely related to Principal Component Analysis (PCA) but differs in its objective and use case.

Here's the workflow of the Linear Discriminant Analysis [51]:

- Data Preparation: Start with a labeled dataset, where each data point is associated with a class label. LDA is a supervised technique, which means that it requires class labels for training.
- Compute Class Means: Calculate the mean vector for each class. These are the average feature values for each class.
- Within-Class Scatter Matrix: Calculate the scatter or variance within each class by computing the covariance matrix for each class. The within-class scatter matrix is the sum of these individual covariance matrices.
- The between-class scatter matrix is a measure of the variance between classes, which is calculated by computing the covariance between the means of each class. This matrix provides an indication of how well the classes are separated.
- Eigenvalue Decomposition: Compute the eigenvectors and eigenvalues of the matrix. These eigenvectors represent the directions (discriminants) in the feature space that maximize the separation between classes.
- Dimensionality Reduction: Select the top k eigenvectors (discriminants) corresponding to the largest eigenvalues to reduce the dimensionality of the data. Typically, you choose k based on how many dimensions you want to retain. These dimensions are classified according to their discriminative power.
- Projection: Project the original data onto the k-dimensional subspace spanned by the selected eigenvectors. This results in a reduced-dimensional representation of the data.
- Classification: After dimensionality reduction, you can use various classifiers (e.g., logistic regression, k-nearest neighbors, support vector machines) to classify the data based on the reduced feature space.

Once you have obtained the numerical vector of probabilities weighted for each class, which in this case represents the architectural style, it will be possible to determine the predictive matrix where each row represents the mean of the multivariate normal distribution of the corresponding class.

3. Results

In this study, we assumed that experimental data could be effectively represented by a linear dependence on geometrical parameters. To improve the representation of the experimental data across the diverse range of architectural styles studied, we also explored additional style-related properties that could enhance the model.

The analysis showed the following statistical results: the largest effects were obtained for the EDT × T30 (Eff = 486.87), Geometrical parameters such as lenght × volume (Eff = 476.54) and number of nave (Eff = 429.87). Complete results of the factor analysis for the full set of Churches are reported in Table 1.

Table 1. Factor analysis results. Effects were calculated according to Equation (4).

Factors	Eff(x,j)
EDT × T30	486.87
Length × Volume	476.54
Surface × Volume	431.30
Number of nave	429.87
Length	413.60
G × Number of nave	412.74
Width × Volume	398.61
Number of nave × Volume	395.28
EDT × T20	389.24
D50 × Width	372.87
D50 × Length	369.20
Surface	356.75
Width	351.43
Height × Number of nave	340.11

To assess the predictive accuracy of these factors, we evaluated the percentage of correct predictions associated with each parameter. The total number of observations in our dataset was N = 83. After applying our factor analysis model, we classified architectural styles based on the identified parameters. The number of correctly predicted styles was N correct = 62. Therefore, the percentage of correct predictions (P correct) can be calculated as follow (Equation (8)):

$$Pcorrect = \frac{62}{83} * 100\% \quad (8)$$

This indicates that approximately 74.7% of the architectural styles were accurately classified based on the parameters analyzed, providing strong evidence for the model's validity and demonstrating the relationship between acoustic properties and architectural styles in the context of Churches design.

Along these lines, the statistical analysis suggested that, besides Reverberation time and Early Decay time, an important parameter with a good statistical effect might be the Number of nave.

Also, if it is expected, it is important to notice that the statistical analysis indicated that the architectural style of Churches could be predicted to some extent based on the number of architectural features present.

It is important to validate the model and investigate further the relationship between the number of naves and architectural styles in Churches. It is worthwhile to investigate this matter in order to provide a more thorough explanation of how the architectural style is related to some of the parameters that show a high statistical effect. A linear discrimination analysis (LDA) [52] of data was made. This LDA analysis aimed to further explore the relationship between architectural style and key parameters that showed a high statistical effect.

The outcomes of a Linear Discriminant Analysis (LDA) conducted on a dataset comprising architectural and acoustic parameters of Churches are reported in Table S3 in Supplementary Materials.

Each row corresponds to an observation (cathedral/churches/basil) and presents various parameters pertinent to classification.

- "Obs." denotes the observation number in the dataset.
- "Objective" represents the intended architectural style of the observation.
- "BestSoFar (obs.)" indicates the best-performing value achieved up to that point for the observation.
- "Prob. (obs.)" signifies the observed probability of the observation.
- "-Log (prob.)" displays the negative logarithm of the probability.
- "Estimated" denotes the estimated architectural style for the observation.
- "Prob. (estim.)" represents the estimated probability of the observation.

Each row in the table provides insights into the architectural characteristics of Churches, presenting the best results achieved and the probabilities associated with estimated architectural styles. This table results from a classification process that identifies distinctive patterns in the acoustic and geometric features associated with each architectural style. Through LDA, a clear separation of Churches based on their architectural styles emerges, highlighting which combinations of parameters are most influential in distinguishing styles. Thus, the table offers a comprehensive overview of the features defining and distinguishing architectural styles of Churches based on their acoustic and geometric properties.

Figure 2 shows a scatter plot of the results of the LDA analysis of the parameters, grouped by architectural styles. The scatter plot depicts the relationship between normalized geometrical and acoustic parameters of various Churches, revealing distinct clusters that indicate similarities in architectural styles and their corresponding acoustic characteristics. The ellipses surrounding each cluster illustrate the variability within styles, with tighter ellipses suggesting less variability. Churches positioned in the upper right quadrant likely exhibit larger dimensions and better acoustic performance, while those in the lower left may be smaller or less efficient.

In our analysis, outliers signify observations significantly deviating from the dataset's general trend regarding European Churches. While diverging from the norm, these observations yield crucial insights into distinct phenomena or conditions potentially impacting our overall analysis outcomes. Particularly within our study on Churches architecture and acoustics, outliers may signal Churches boasting unique acoustic or geometric traits, substantially contributing to our subject understanding. Scrutinizing these outliers may unveil novel patterns or trends, enriching our comprehension of architecture-acoustics interactions in European Churches.

Outliers identified in our study represent architectural cases that deviate significantly from the general trends observed within their respective styles. These exceptional churches exhibit unique architectural features that produce unexpected acoustic outcomes, warranting further examination. In particular:

- Basilica di S. Petronio (Gothic): Despite being Gothic, this church exhibits a unique acoustic profile due to its complex spatial configuration and tall vaults, affecting sound reflection and reverberation. This atypical geometry causes differences in acoustic behavior compared to other Gothic churches.
- S. Sebastian Church (Neoclassical): This church shows distinct acoustic properties due to its simpler nave layout and use of materials that differ from traditional Neoclassical structures, leading to deviations in reverberation time and decay.

- Santa Ana Church (Modern): As a 20th-century building, this church's modern materials and geometric forms reduce sound reflection, which contrasts with older styles, presenting an acoustically softer environment.
- Byzantine Churches (e.g., S. Vitale): Byzantine churches often feature central plans and domes. In this case, a higher dome and irregular acoustics lead to different sound propagation patterns compared to other Byzantine buildings.

These outliers highlight how unique architectural elements, such as spatial design, volume, and material choice, can significantly alter acoustic performance. Further investigation of these cases will provide deeper insights into the relationship between architectural design and acoustics. Examining these exceptional cases will strengthen our understanding of how distinctive features influence sound behavior, offering valuable knowledge for both historical and modern church acoustics.

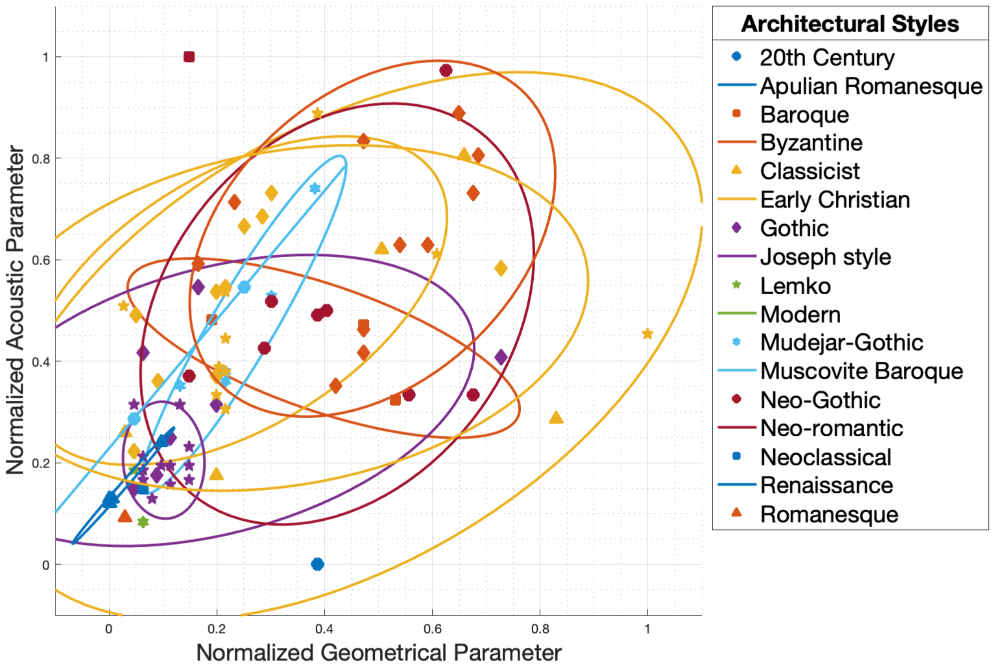

Figure 2. Scatter plot of the geometric vs acoustic parameters, grouped by styles.

Figure 3 delves deeper into the analysis by highlighting outliers, visually discernible and highlighted in red, along with their respective Church affiliations.

The study unveils compelling insights into the nuanced influence of architectural styles on acoustic properties. Contrary to conventional beliefs, significant variability in acoustic characteristics emerges even within the same architectural style, underscoring the intricate interplay between architectural elements and acoustic behavior. A significant influence of architectural style on the acoustic quality of Cathedrals is found. In particular, some styles such as Gothic ($r = 0.76$), Neoclassical ($r = 0.98$), Byzantine ($r = -0.93$), Romanesque ($r = 0.74$), Mudéjar-Gothic ($r = 0.77$), and Early Christian ($r = 0.84$) have shown a strong correlation. This indicates that the architectural features of these Cathedrals significantly impact their internal acoustics.

The high goodness-of-fit of the model, confirmed by the R^2 values, suggests that the analyses are sufficiently reliable, and the model used is capable of explaining a substantial portion of the variation in Cathedral acoustics based on architectural style.

To understand how the currently selected classifier performed for each class, the confusion matrix plot was used. The rows of the confusion matrix represent the true classes, while the columns represent the predicted classes. The diagonal cells show where the true class and the predicted class match. If these diagonal cells are blue, the classifier has correctly classified the observations of that true class. The True Positive Rate (TPR) is the proportion of correctly classified observations per true class, while the False Negative Rate (FNR) is the proportion of observations incorrectly classified per true class. The plot also shows summaries for each true class in the last two columns on the right. Figure 4 presents the confusion matrix plot for the dataset, displaying both the predicted and true classes.

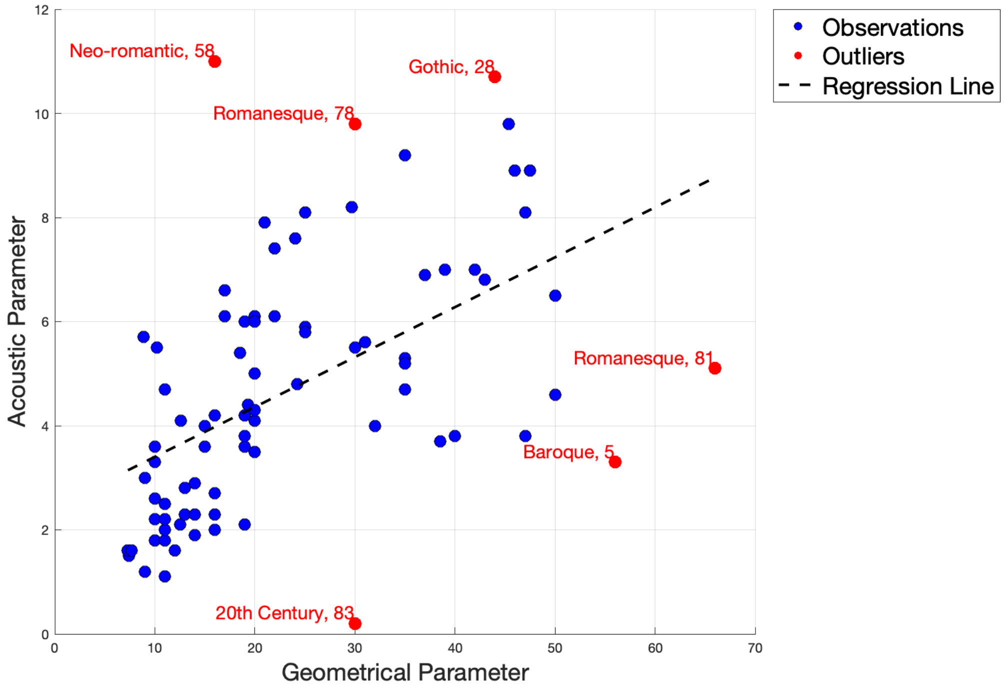

Figure 3. Geometric vs. Acoustic parameters: outlier detection in Churches data.

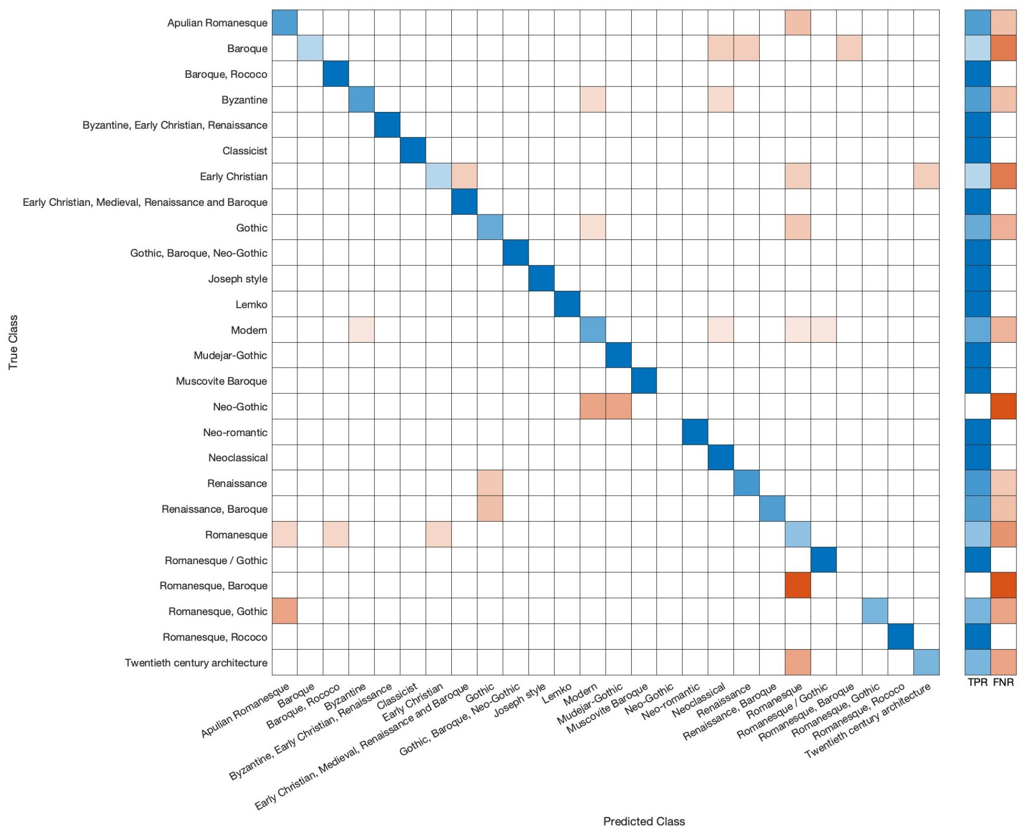

Figure 4. Confusion matrix plot of the dataset.

4. Conclusions

This study presents a significant advancement in the field of architectural acoustics by exploring the intricate relationship between architectural styles and acoustic properties in Churches. Using a combination of Principal Component Analysis (PCA) and Linear Discriminant Analysis (LDA), the research identified patterns and outliers that highlight the complex interplay between architectural elements and acoustic behavior. The findings reveal that even within the same architectural style, substantial acoustic variability exists, challenging conventional assumptions and emphasizing the influence of distinct architectural features on sound propagation.

Outliers within the dataset, such as Gothic structures like the Basilica di San Petronio, Neoclassical buildings like S. Sebastian's Church, and modern examples like the Church of Santa Ana, offer valuable insights. These deviations from typical trends highlight the importance of examining unique cases to better understand the nuanced relationship between architectural design and acoustic performance.

While the statistical approach used in this study provided robust insights, certain limitations should be noted. The dataset, comprising 83 Churches, may not fully represent the diversity of architectural styles and acoustic properties across Europe. Expanding the sample size to include a broader range of Churches would improve the generalizability of the findings. Additionally, while PCA and LDA effectively addressed linear relationships, future research could employ non-linear models or machine learning techniques to uncover more intricate interactions between architectural elements and acoustic characteristics.

Moreover, this study primarily focused on objective, measurable acoustic parameters. Future research should consider integrating subjective assessments, such as user perceptions of sound quality during liturgical services, to provide a more holistic understanding of the acoustic environment in Churches. Further investigations into specific architectural elements, including materials, spatial configurations, and geometric features, could deepen our understanding of how these factors influence acoustic properties.

Finally, longitudinal studies tracking the evolution of acoustic characteristics over time could offer valuable insights into the dynamic nature of sacred spaces, informing design practices to enhance the acoustic quality of religious buildings. By continuing to explore these dimensions, future research can contribute to a more comprehensive understanding of architectural acoustics and its implications for both historical preservation and modern design.

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