The Acoustics of Ely Cathedral's Lady Chapel: a study of its changes throughout history

Lidia Alvarez-Morales
Department of Theatre, Film, Television and Interactive Media, University of York
York, UK
ORCiD: 0000-0003-2369-0537

Angel Alvarez-Corbacho
Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura Universidad de Sevilla
Seville, Spain
ORCiD: 0000-0001-5617-4673

Mariana Lopez
Department of Theatre, Film, Television and Interactive Media, University of York
York, UK
ORCiD: 0000-0003-0374-7727

Pedro Bustamante
Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura Universidad de Sevilla
Seville, Spain
ORCiD: 0000-0003-3398-4934

Abstract— **The Lady Chapel of Ely Cathedral, built in the 14th century, is considered one of the greatest architectural achievements of medieval England. The Lady Chapel is a semi-independent space connected to the north of the cathedral choir. Its interior is a great example of the Decorated Gothic style, being also the largest Lady Chapel and one of the widest stone vaulted spaces in England. This work presents the study of the acoustic behaviour of Ely Cathedral's Lady Chapel throughout history, which has been undertaken using both on-site measurements and simulation techniques. Three different acoustic models were created for the purpose of this work. The acoustic model of the Lady Chapel in its current state was adjusted and validated by taking as a reference a set of room impulse responses registered on site. Then, the model was carefully modified to recreate the acoustics of the space at different points in history: as it was in its origins, before being heavily damaged during the Reformation in the 16th century; and when it was fully furnished to be used as the parish of Holy Trinity, as it remained until the beginning of the 20th century. A comprehensive study is undertaken based on a comparative analysis of the acoustic parameters derived from the simulated room impulse responses, and the results are discussed focussing on the architectural alterations and the interior arrangement modifications undertaken to serve the great varieties of uses it has had over time.**

Keywords— Room acoustics, heritage acoustics, acoustic simulation, virtual acoustics.

I. INTRODUCTION

The acoustics of historical buildings and sites has a huge impact on how we experience and have experienced them over time. Consequently, their sound is considered part of our intangible cultural heritage, and for that reason its analysis and preservation has been a priority in recent years [1,2].

Historical acoustic research is normally based on a combination of experimental and simulation techniques [3,4]. The onsite measurements aim to gather a representative set of room impulse responses (RIR), which fulfil a double function: on the one hand, they serve to describe the current acoustic behaviour of the space, normally in terms of the acoustical parameters described in ISO3382-part 1 [5], providing new knowledge and modern documentation of the surveyed buildings. On the other hand, they can be used to adjust and validate the acoustic simulation models.

Simulation software tools are based on geometrical acoustics theories (GA) [6]. The development of simulation techniques in the last decades allows researchers to assess the acoustics of existing spaces under different conditions or at different points in history [7], and even recreate those that are in ruins or don't exist anymore [8], with a certain degree of plausibility.

Cathedrals are key to European culture, and that is why the *Cathedral Acoustics* project [9] focused on analysing and preserving the acoustics of four English cathedrals: Bristol, Ely, Ripon and York.

The present article concentrates on the analysis of the acoustic behaviour of the Lady Chapel of Ely Cathedral throughout history, which has been undertaken using both on-site measurements and simulation techniques. Three different GA models were built with the purpose of assessing how the alterations and the variety of uses of the space over time influenced the acoustic environment experienced in its interior. First, an acoustic model of the Lady Chapel in the present day was completed after a careful process of adjustment and validation. Said validation was conducted by taking as a reference a set of room impulse responses registered on site. Then, that model was carefully altered to recreate the acoustics of the space at different points in history, which resulted in two additional versions. The first aims to represent the chapel as it was in its origins, before being heavily damaged during the Reformation in the 16th century; whereas the second represents the space when it was fully furnished to be used as the parish of Holy Trinity, as it remained until the beginning of the 20th century.

II. ELY CATHEDRAL´S LADY CHAPEL: A BRIEF DESCRIPTION OF THE SPACE AND ITS EVOLUTION THROUGH HISTORY

The history of Ely Cathedral goes back to the 7th century when St Etheldreda founded the original abbey church. Three hundred years later, the church, which had been destroyed by the Danes, was re-founded as a Benedictine monastery. The reconstruction of the Norman Abbey started in 1082. In 1109, Ely was raised to cathedral status [10], and the works continued until 1174.

During the 13th century some major additions and alterations were made to the building, including a new presbytery and the Galilee porch. At this time, there was a Lady Chapel located in the south aisle of the choir [11]. The

This research was funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 797586.

14th century was an important century for the construction of the cathedral: two of the main compositional features of the building, the magnificent central octagon and the stunning Lady Chapel, were built. Ely Cathedral's Lady Chapel is the largest Lady Chapel in England, and one of the widest (stone) vaulted spaces in the country [12]. We focus now on the construction process and evolution of the Lady Chapel.

The construction of the Lady Chapel was laid by Alan de Walsingham in 1321 [13]. The Norman crossing tower collapsed a year later, so it is believed that the construction of the chapel was interrupted for a few years then. The chapel is designed as a rectangular space, partially independent of the main building (Fig. 1). It is located at the north-east of the north transepts, connected to the main building by a passage to the north choir aisle. This position is rather unusual, almost unique, only seen at Bristol and Petersburg Cathedrals [13]. Around 1330 the side walls were erected [14]. Each wall consists of 5 bays, which comprises a series of stone (*clunch*) stalls decorated with rich carved canopies that creates the dado and huge traceried windows, which were once filled by coloured stained glass [14].

The buttresses that support the ornate lierne vault have a pair of niches, decorated in the same way as the stalls, which originally contained human-size stone statues [15,16]. The chapel was considered completed in 1349, but the East window was rebuilt in 1373, and the West window just one year later [17]. In the East wall, the stalls are not as deep as in

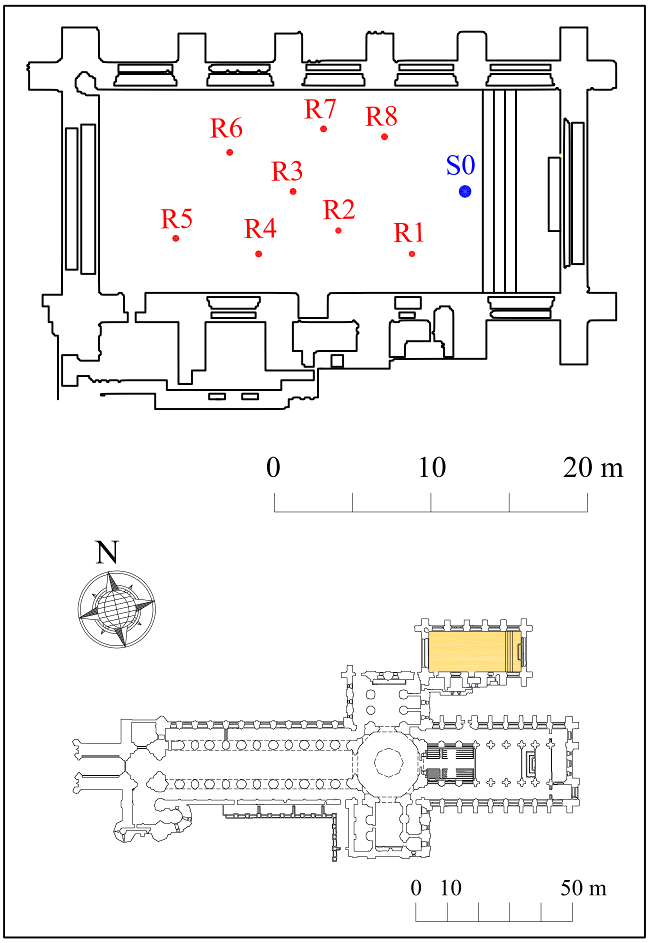

Fig. 1. Sketches of Ely Cathedral's Lady Chapel floor plan, with the sound source (S) and receiver (R) locations set for the measurement session (upper row) and the Lady Chapel's location in the cathedral floor plan (highlighted in yellow).

the rest of the room, they are actually niches [18]. In 1386 a stone reredos of about 6 meters was added in the lower part of the wall, which interrupts the dado pattern [12]. All the walls, the ceiling and the carves were richly coloured [19].

Contemplating the chapel in the late 14th century must have been awe-inspiring, but what about the aural experience? The high ceiling (about 18 m) and its hard finishing materials would have created a resonant atmosphere typical of the religious buildings constructed in those days. However, it is important to also consider whether the decoration described in this section would have significantly affected the acoustics of the space, when compared to its present acoustical features.

In 1547, and because of the Reformation, the stained glass windows were smashed and sculptures destroyed, removed or defaced, and colour ripped from the walls, partially stripping the chapel of its visual grandeur [20]. A few years later, in 1566, the use of the Lady Chapel was given to the parish of Holy Trinity [11]. During the 17th century, inscriptions on marble tablets and mural monuments started to be added to the walls below the windows [21] and Baroque furniture was installed, including closed pews. During the 18th century the roof was redone and a stone font was added to the West end of the chapel. The incorporation of these substantial pieces of furniture may have had a significant impact on the acoustics of the space by reducing its reverberation time. It is important to bear in mind, that one of the commitments of the Protestant Reformation was that the congregation needed to understand the spoken message and the vernacular language was used in the worship service [22], and therefore, it is likely that some hanging textiles and draperies helped to control the reverberant field of the chapel, even if their use had other motivations.

In the first half of the 19th century, the flooring of the old pews was removed [11] and the white/yellow-wash which thickly clogged the carving removed. In the case of being thick enough, the white/yellow-wash could have affected the acoustic behaviour of the limestone walls of the building, softening the imperfections of the flat surfaces and also obtruding the shapes of the carved canopies.

In 1847 Sir G. G. Scott was appointed architect to the cathedral [11], and the last renovation that gives the cathedral the appearance that it has today started. According to the Ely Cathedral liturgical plan published in 2016 [23], "the panelling (seven panel oak reredos) which stands against the East wall under the window of the St Etheldreda's Chapel was previously (until 1850) at the east end of the Lady Chapel". In 1865 a major renovation of the church was carried out [24]: among other things, the closed pews were replaced by lighter open-seats (oak pews designed by Sir G.G. Scott) and the organ was enlarged and located in a new position (it was then placed next to the second bay of the north wall) [24]. At the end of the century a new vestibule and vestries were constructed on the south wall of the Lady Chapel.

As a parish church, the chapel was used for all the daily and festive services, including baptisms, weddings, and funerals. The last parish funeral service was held in the Lady Chapel in 1911, and weddings were celebrated there until the chapter resumed possession of the chapel and cleared it of its modern furniture in 1938 [10].

In the following years, the Lady Chapel was restored and refurnished. It was provided with a new altar table and an altar rail, and the seating area was occupied by wooden chairs. In

Fig. 2. Photo taken during the measurement session conducted in the Lady Chapel, with the source located in the position S0 and the ambisonic microphone as receiver at R02.

1950 the cathedral was Grade I listed. In 1960, the floor was replaced by a Purbeck marble floor and the 14th century stained glass portions were restored and placed on the top part of the window of the central bay on the south wall [25].

The arrangement of the chapel has changed significantly in the last decades. In 2000 a life-size statue of the Virgin Mary by David Wynne was installed above the Lady Chapel's altar [26], which was provided with a new iron screen and altar table in 2011 [27]. In 2002 the chapel was repaved with Purbeck marble slabs with an underfloor heating system [28], and the audience area was cleared of permanent seats, and modern lightly upholstered foldable metal chairs are used when needed. There is no pulpit, and furniture is now mainly reduced to the altar table, a mirrored glass topped beech, and a chamber organ which is normally covered in a corner. Apart from the modern tapestry seat cushions which can be found in all integral stone stalls, there are no more acoustically absorbent elements in the space.

Nowadays the chapel is used for liturgical celebrations (Matins, Eucharist and Evensong) and concerts are also held on a regular basis. Having space to accommodate up to 300 seated or 400 standing guests, it is also used for banquets, receptions, presentations or exhibitions, and in recent years, it has been even used as a film and television location [29]. Of course, the variety of uses results in modern soundscapes which are completely different to the ones in the Middle Ages. Furthermore, electronic amplification is provided to improve the transmission of speech.

III. Methodology

After completing the historical study, the changes in the acoustics of the Lady Chapel of Ely Cathedral were analysed by using a combination of acoustic measurements taken on site and acoustic simulations that represent the space at different points in history.

A. *Experimental measurements*

Acoustic measurements in Ely Cathedral were carried out in July 2019, while the chapel was closed to the public and practically unfurnished.

A set of RIR were registered by taking the ISO3382-1 [5] as a reference and also the specific guidelines developed for the acoustic analysis of worship buildings [30, 31]. Exponential sine-sweeps [32] of a duration of 24 seconds were emitted through the sound source, a NTi DS3 dodecahedral loudspeaker together with a NTi PA3 power amplifier. The source was placed in the central axis of the chapel, just in front of the main altar, at a height of 1.5 meters (Fig. 2). Eight receiver positions were distributed throughout the congregation area, at a height of 1.2 meters. The emission power of the sound source was set to ensure an impulse to noise ratio (INR) of at least 45 dB in all the frequency bands of interest at all the receiver locations. Fig. 1 shows a sketch of the floor plan of the Lady Chapel of Ely Cathedral with the source (S) and receiver (R) locations considered during the measurement session. Although an additional sound source location would have been advisable (for example, at the centre of the chapel), this was not possible due to time restrictions. It is worth noting that, even though the present article concentrates on the Lady Chapel, acoustic measurements included the entire cathedral, including 4 sound source locations and 38 receiver positions in total, all selected by considering the architectural features and the great variety of uses of the space.

For each source-receiver combination 1st order ambisonic RIR were captured by using a B-format microphone (Soundfield ST450) and binaural RIR were captured with an artificial head (Neumann KU 100). The digital audio workstation Pro Tools 12 and MATLAB software were used to register and process the signals respectively. Two commercial software tools, WinMLS2004 and IRIS 1.4 [33], were employed for the acoustic analysis of the RIR and the

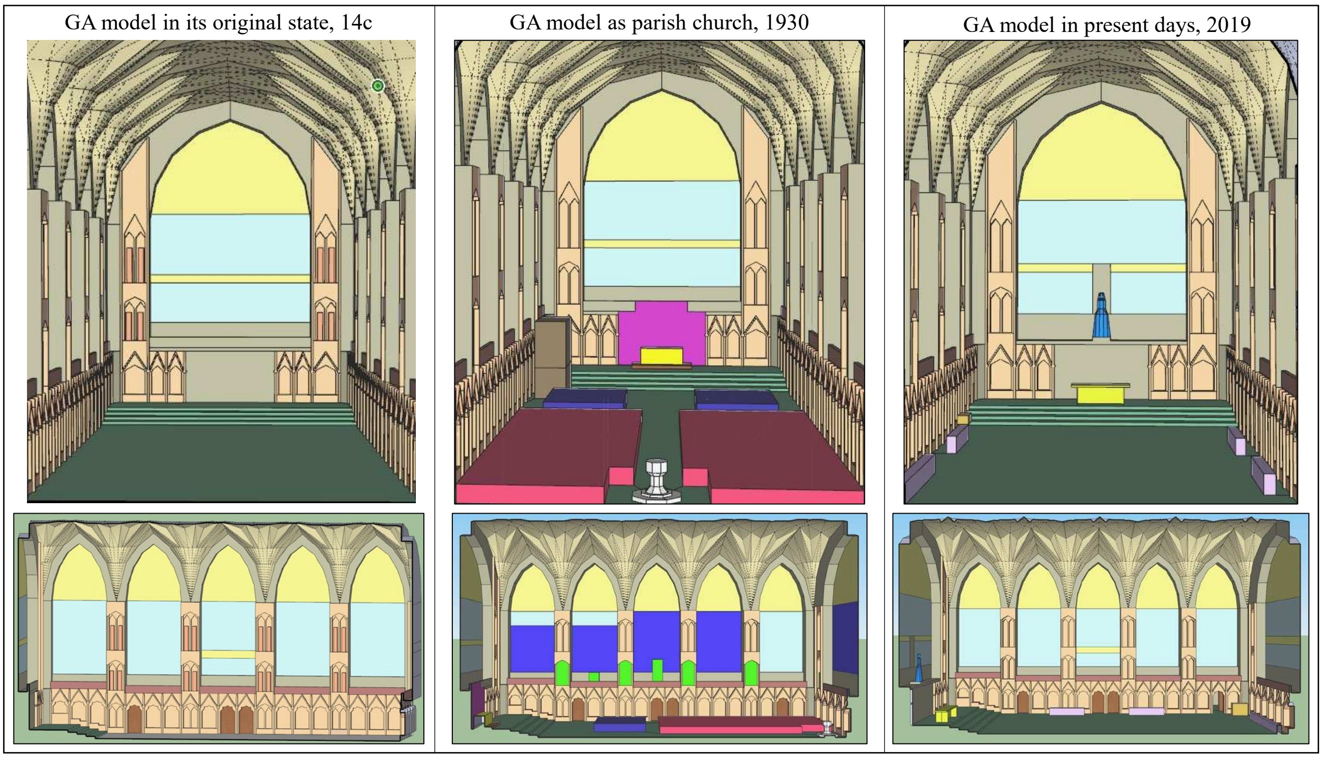

Fig. 3. GA models of Ely Cathedral's Lady Chapel at different points in history, selected for the purpose of this research, showing a view of the space looking East (upper row) and an elevation view looking south (lower row).

calculation of the acoustic parameters. All the instrumentation and data analysis methods were ISO3382-1 compliant.

The set of RIR gathered in the space serve not only to describe the acoustic behaviour of the chapel in its current state, but also to be used as a reference to validate the simulation models.

B. *Acoustic model of the Lady Chapel in the present day*

The 3D models of the Lady Chapel employed for the acoustic simulations were built by using the modelling software tool SketchUp (Fig. 3). No detailed digital plans (CAD) of the space were available, so the models were defined from architectural drawings and geometrical information found in the consulted bibliography [34-36], and also from architectural measurements taken onsite during the recording sessions. The decisions made to simplify the architectural richness of the space, avoiding overly detailed surfaces and too complex forms, aimed to build an adequate simulation model in accordance with the guidelines for the application of geometrical acoustics (GA) algorithms [37].

In a first instance, the acoustic model of the Lady Chapel in the present day was created, to be adjusted and validated with the experimental results. Major simplifications assumed in the model affected the vaulted ceiling, the carved canopies of the stone seats and the tracery of the stained glass (Fig. 3, 3rd column). The final model has 3,576 planes and an approximate interior volume of 7,930 m^3 (without considering the vestry).

The geometrical model was imported into Odeon 14 [38] by using the plugin SU2Odeon 1.09 [39]. The Schroeder frequency of the model was 43 Hz, and therefore, GA algorithm applies from the 125 Hz frequency band.

Finishing materials and other interior details were determined by visual inspection, and based on consulted literature. Published data of the acoustic behaviour of similar materials has served as reference to assign the initial acoustic properties to the interior surfaces of the model (references detailed in Tables I to III). These initial values were carefully modified to take into consideration some simplifications made in the geometry and some details not modelled.

The model was tested considering 100% scattering and 0% scattering on all surfaces to assess the influence of scattering in the model. Results with 0% scattering were close to the Sabine values, which suggested that the model was not very sensitive to scattering, and there was no a significant difference on the results with 0% and full scattering which shows that there were no errors on the model shapes [40].

The acoustic simulation was carried out by using the precision algorithm. The IR length and the number of late rays were manually set to 7.5 ms and 300,000 rays respectively, while the early reflection settings were automatically set (15,124 of early rays with a transition order of 2).

At this point, an iterative tuning process started so that the simulated acoustic parameter values matched the measured ones. Those materials or surfaces that presented more uncertainty in their acoustic behaviour were used to adjust the model. First, the focus was on the average reverberation time (T). Once T measured and simulated values differed by no more than 1 JND (Just Noticeable Difference) (5% in this case) in all the frequency bands, other acoustic parameters are checked. The JND is the minimum variation that can be perceived by listeners for each parameter [5,41].

A thorough point–by-point comparison is made then at all frequency bands, to see if measured and simulated values are in good agreement or conversely, if any adjustment is needed. A good agreement means that measured and simulated values differ by no more than 2 JND. A margin of 2 JND is accepted due to the uncertainties associated both to the measurement and simulation processes [42]. Such adjustment may imply a modification of the acoustic properties of certain surfaces and/or a change in the geometrical model if any simplification made is affecting the results. In order to detect which surfaces need to be modified, if any, the early reflection patterns obtained from the measured and simulated RIR at the "problematic" source-receiver combination are compared in detail. The whole process is repeated until a good agreement is achieved in most of the S-R combinations.

The final comparison between measured and simulated results obtained with the adjusted version of the model of Ely Cathedral's Lady Chapel in its current state is shown in Fig. 4. At this point, the acoustic model of the chapel is considered adjusted. The comparison was done for each set of source-receiver combinations considered in the study.

Table I shows the final absorption and scattering values of the main materials present in the adjusted acoustic model, after all the iterations needed.

After the model of the chapel in the present date was validated, it was carefully modified to simulate the space under different conditions. The different models created are described in the following sections. For the selection of the different case scenarios and the historical models, the information collected as part of the historical study of the space, as well as the analysis of the current and past uses of the chapel have been taken into account.

C. *Acoustic model of Ely Cathedral's Lady Chapel as it was in its origins, late 14th century*

The validated GA model of Ely Cathedral's Lady Chapel was modified in an attempt to reconstruct the chapel in its original design, at the end of the 14th century, before being heavily damaged during the Reformation in the 16th century. The Lady Chapel's dimensions and geometrical features have remained the same since its construction date, and therefore, no significant geometrical changes are introduced in this model, except those related with small pieces of furniture and decoration details. The final GA model used for the simulation of the Lady Chapel in its original design has 3,635 faces. Table II shows the acoustic properties of the finishing materials which have been modified or introduced in this model. Those materials that remain the same as in the model of the lady chapel in the present day are not included.

The most relevant feature of the chapel was that its whole interior was smooth finished and richly coloured, and the windows were filled with colourful stained glass.

TABLE I. ACOUSTIC PROPERTIES OF THE MAIN MATERIALS USED IN THE MODEL OF THE LADY CHAPEL IN THE PRESENT DAY.

Material	Absorption coefficients						Scatt. coeff.
	125 Hz	*250 Hz*	*500 Hz*	*1k Hz*	*2k Hz*	*4k Hz*	*707 Hz*
Marble floor [43]	0.01	0.01	0.01	0.01	0.02	0.02	0.05
Limestone walls[a] [37]	0.02	0.03	0.04	0.05	0.06	0.06	0.07
Oolite niches[a]	0.02	0.03	0.04	0.05	0.07	0.07	0.10
Carved stone[a,b]	0.03	0.035	0.05	0.06	0.08	0.10	0.40
Limestonevault [a,b]	0.02	0.03	0.04	0.05	0.07	0.09	0.25
Decorated pillars[a,b]	0.03	0.035	0.05	0.06	0.08	0.10	0.25
Lead glazing [37]	0.25	0.20	0.14	0.10	0.05	0.05	0.15
Mix material (Upper part of the windows) [b,c]	0.137	0.12	0.10	0.075	0.08	0.10	0.30
Chairs, lightly upholstered [44]	0.35	0.45	0.57	0.61	0.59	0.55	0.50
Solid wooden door [45]	0.14	0.10	0.06	0.08	0.10	0.10	0.10
Seat cushions[c]	0.20	0.50	0.70	0.75	0.75	0.73	0.05

a. Material coefficients used for the adjustment of the model.
b. Modified values to compensate simplifications of the model.
c. Estimated from other coefficients found in bibliography.

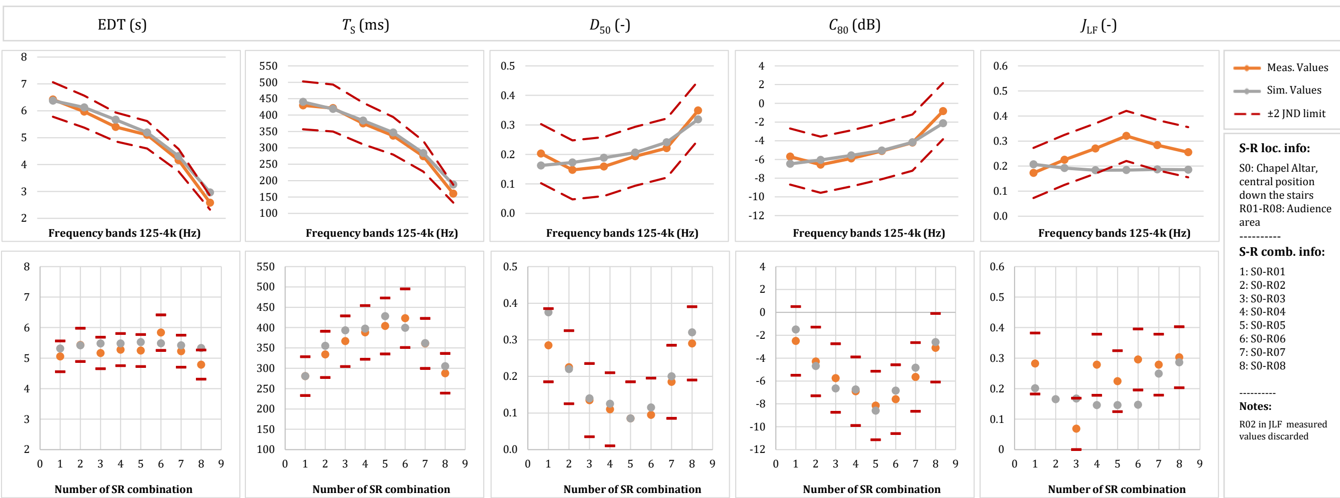

Fig. 4. Differences between spatially averaged measured and simulated values obtained for the different acoustic parameters (upper row) and point-by-point comparison of the spectrally averaged values obtained at each receiver point (lower row) with the source location S0.

TABLE II. ACOUSTIC PROPERTIES OF THE MATERIALS CHANGED IN THE MODEL OF THE LADY CHAPEL AS IT WAS IN ITS ORIGINS.

Material	Absorption coefficients						Scatt. coeff.
	125 Hz	*250 Hz*	*500 Hz*	*1k Hz*	*2k Hz*	*4k Hz*	*707 Hz*
Painted limestone walls	0.01	0.01	0.015	0.02	0.03	0.03	0.07
Painted oolite niches	0.01	0.01	0.015	0.02	0.03	0.03	0.10
Painted carved stone	0.01	0.01	0.02	0.03	0.04	0.06	0.40
Painted limestonevault	0.01	0.01	0.015	0.02	0.03	0.05	0.25
Painted decorated pillars	0.01	0.01	0.015	0.02	0.05	0.06	0.25
Stone statues	0.01	0.01	0.02	0.02	0.03	0.03	0.35

The limestone walls/pillars/canopies/seats, the balustrade, the vaulted ceiling and the stone reredos at the east end, all were coloured, and, presumably, all had a smooth finishing, so their absorption coefficients have been modified taking into consideration how the paint finishing affects the acoustic characteristics of similar materials according to the literature [46]. The windows were originally filled with stained glass, therefore, their behaviour could slightly differ from the behaviour of the lead glass that is found in the building today. Regrettably there is not enough information to estimate such change and, presumably, it wouldn't be acoustically very noticeable. Moreover, the absorption coefficients defined for lead glass are frequently used for stained glass windows in this type of buildings [40].

The chapel is considered unfurnished, so the current altar table, chairs and cushions are removed from the model, meaning a lack of acoustically absorbent materials. At that time the vestry hadn't been built yet, so there is no door to access it in the fifth southern bay. At the east wall: the central light of the lower part of the window was not walled-in; and there was no lady statue (although some texts mention that there were one at the same position originally); the stone balustrade was up as in the other walls that surround the building.

The size and the shape of the statues, as well as their position is not precise, it is just an approximation and a significant simplification of the original design of the space based on the information found in the consulted documentation. Acoustically, the shape is taken into account through the scattering coefficient (high scattering needed to compensate the lack of shape definition), and the absorption coefficient used for their finishing material is the one used for polished painted stone (used in model 01 for the Lady Statue). Maybe the number and the size/shape/position of the statues could be more accurate but, possibly not noticeable in acoustical terms, since they are far from the listener positions, and the rough approximation considered here should be enough to take them into consideration in the space for the acoustic simulation. Additionally, the niches of the dado in the East wall might have been used as tabernacles to receive statues

Even though the current tiled floor dates from the 21st century, no change in the model has been introduced for this surface, since it is known that it was a similar hard surface although presumably with a slightly more irregular and rough finishing, due to the time of construction. Therefore, it is likely that this change did not have a major impact on the acoustics, since its absorption and scattering coefficients are unlikely to have changed significantly.

D. Acoustic model of Ely Cathedral's Lady Chapel about 1930, as the parish church of Holy Trinity

In the mid-16th century, after the damage to the building as part of the Reformation, the use of the Lady Chapel was given to the parish of Holy Trinity, and it remained this way until the beginning of the 20th century. During that time, the chapel was partially restored, and its internal arrangement changed considerably.

The GA model built to assess the acoustics during this period recreate the space at about 1930, when it was fully furnished to be used as the parish of Holy Trinity. Luckily, graphic material from this period can be found in bibliography. Particularly, some illustrations by *Photochrom Co. Ltd.* have been used as a reference to build the model [13].

In this model, furniture represents the major changes from the validated model of the chapel in the present days. The audience seats filled the space and textiles were found covering some walls and windows, which no doubt would have contributed to sound absorption and dispersion.

The chapel was filled by solid oak Victorian pews (designed by Sir Gilbert Scott) in the audience area and also choir stalls were placed in the front rows. Their acoustic properties were estimated based on previous investigations on similar pews in churches [47] and they were modelled as blocks 60 cm high (about 0.5 m for pews +0.10 platform below). A similar approach was taken for choir seats, but they were 70cm high. In the case of the pews in the congregation area, they had upholstered kneelers (not clearly seen in the visual inspection of graphic material), therefore the absorption coefficients of the congregation blocks must be corrected (increased) according to the bibliography. There were no cushions covering the stone seats around the chapel, except at those seats behind the baptismal font at the West end.

There were curtains, heavy velour and draped, covering the stone reredos of the East wall and sun blinds (light curtains) were placed covering the windows of the south wall. The altar table appeared covered with cloth, and there was possibly a carpet in the altar floor, but it is difficult to be certain from the visual material and the references found in literature. Memorials were placed around the chapel, covering the lower niches on the buttresses between the windows of the south wall, and on the walls right below the windows as well. At that time there was an organ on the second bay of the north wall. A stove pipe could be seen on the right side of the chapel, and what seems to be a light pulpit located on the south side, these were not modelled, since there were too many uncertainties in their dimensions and acoustic properties. In any case they seemed very light, and presumably they have no significant impact on the overall acoustics of the space. Nevertheless, the pulpit must be considered if using it as a sound source position. The door to the vestry was considered closed in this model.

Table III includes the acoustic properties of the additional materials used in the model of the Lady Chapel in 1930.

TABLE III. ACOUSTIC PROPERTIES OF THE ADDITIONAL MATERIALS USED IN THE MODEL OF THE LADY CHAPEL IN 1930.

Material	Absorption coefficients						Scatt. coeff.
	125 Hz	*250 Hz*	*500 Hz*	*1k Hz*	*2k Hz*	*4k Hz*	*707 Hz*
Blinders [44]	0.30	0.25	0.20	0.27	0.37	0.42	0.10
Un-upholstered Pews [47]	0.025	0.079	0.105	0.102	0.10	0.14	0.70
Wooden choir seats [47]	0.066	0.151	0.209	0.253	0.286	0.29	0.60
Velvet courtains [43]	0.07	0.31	0.49	0.75	0.7	0.60	0.20
Memorials[a]	0.01	0.01	0.02	0.02	0.03	0.03	0.30
Organ pipes [48]	0.25	0.20	0.15	0.15	0.10	0.10	0.30
Organ (case) [43][a]	0.28	0.22	0.17	0.09	0.10	0.11	0.40
Wooden podium [44]	0.40	0.30	0.20	0.17	0.15	0.10	0.10
Font (marble)	0.01	0.01	0.01	0.01	0.02	0.02	0.20[b]

a. Estimated from other coefficients found in literature.

b. Scattering coefficient assigned to the surfaces of the font varies depending on the decoration.

IV. RESULTS AND DISCUSSION

For the purposes of this study, and in order to facilitate the comparison among the simulations, all the simulations were run using the same software settings, with the exception of the IR length that had to be increased up to 10 s to account for the increment in the reverberation time of the model in the 14th century. The analysis is also limited to the combinations of source and receiver positions considered during the measurement session. Moreover, the uncertainty regarding the acoustic behaviour of some of the finishing materials used in the historical models has to be considered when looking at the numerical values, always bearing in mind that they are approximate values. Further investigation into the implications of these uncertainties is needed, which may result in greater accuracy of results.

Ely Cathedral's Lady Chapel acoustic conditions have changed over time with the different configurations of the space. The simulations performed predict a reverberation time at mid frequencies of 8.7 s when totally empty in the late 14th century, in its original colourful design, 4.9 s when fully furnished in 1930 and 5.4 s when almost unfurnished in the present day, all above the values typically considered suitable for speech transmission and music reproduction in performance rooms [49], and being even slightly above the limits of preferred values for organ music and medieval plainchant (set around 2–4 s respectively) found in bibliography for this types of buildings [50]. Fig. 5 shows the simulated T_{30} values spatially averaged across all receiver positions for the late 14th century, the 1930, and present day arrangements of the space, all in unoccupied conditions.

It was found that the reverberation time significantly decreased after the chapel was damaged in the 16th century

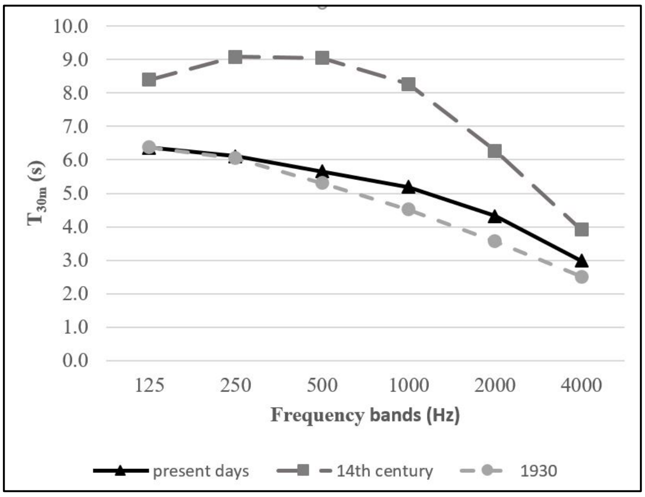

Fig. 5. Simulated T_{30} values spatially averaged across all receiver positions for the late 14th century (squares), the 1930 (dots), and present day(triagles) configurations of the space, all in unoccupied conditions.

during the Reformation, when the sculptures were destroyed and colour ripped from the walls. The cause of this significant variation was explored using the calibrated GA model. In a first instance, the simulation of the 14th century building was run only considering the changes in the geometry of the model: the space was leaved empty removing all the pieces of furniture and the stone statues were added to the upper niches, but the interior was not yet assumed painted, i.e., keeping the same acoustic coefficients (both absorption and scattering coefficients) for the stone surfaces. In such conditions, the reverberation time at mid frequencies (T_{30m}) already goes up to 6.5 s, which is 1 s higher than the T_{30m} in the present day. But in this hypothesis, a correction is also needed to be applied to the acoustic coefficients of the surfaces that were originally painted and which also had a smoother finishing that nowadays. In such conditions, the spatially averaged reverberation time obtained goes up to 8.7 s at mid frequencies (T_{30m}), revealing a clear impact of the paint finishing on the acoustics of the space. Under this condition of extreme reverberance, the intelligibility of the spoken word in the entire audience area is poor (STI<0.45 and D_{50m}<0.3) even in the closer positions to the source (in this case R1, which is a 5.26 m from the S1), which is not a surprise considering the typical recommended reverberation time to achieve favourable conditions for the transmission of speech is around 1.2 seconds [51]. Low values of music clarity are also registered at all the receiver positions, with C_{80m} values ranging from -3.5 dB in R1 to -10.4 in R5. No detailed description of the use of the Lady Chapel of Ely Cathedral during the 14th century is available, regarding the type or the location of the sound source, or the characteristics of the audience and the occupation conditions, but, in empty rooms like the Lady Chapel, with a large height and hence, volume, which predominantly used stone in its construction, with a clear lack of absorptive materials, the presence of the audience in full performance conditions must have been aurally noticeable.

The simulations of the GA model of the Lady Chapel around 1930, when it was fully furnished to be used as the parish church of Holy Trinity, show that the congregation would have experienced slightly higher clarity and definition of sound than in present days at those locations closer to the source but slightly lower at those at further distances. In contrast to what might be assumed in advance, and despite the reverberation time being reduced by half a second due to the acoustic absorption introduced by the blinders and the pews, simulations predict that the differences between the acoustic field experience in 1930 and the present day wouldn't be very noticeable (mean differences found for the energy and spatial parameters are under 1 JND), and those differences would be even less significant when considering the chapel occupied during the celebrations or events. In both cases, the values of the energy parameters denote poor clarity of the sound ($D_{50m} < 0.3$ and $C_{80m} < -2$ dB) when considering the standard values set for performance rooms.

It must me said that, for the 3 GA models, typical values for a suitable spatial impression are found, with J_{LFm} values around 0.2 at the majority of the S-R combinations [52,53].

It is crucial to highlight that other variables such as the position and orientation of the sound source or the number of attendees and their behaviour may change the acoustic experience in the space, even when it remains unaltered in architectural terms.

V. Conclusions

This paper explores the acoustics of one of the greatest architectural achievements of medieval England: the 14th-century Lady Chapel of Ely Cathedral. The analyses presented here are based on the experimental measurements of the impulse responses registered in the space and the assessment of virtual reconstructions of the building at different points in history, which involved the creation of 3 different GA models using the acoustic simulation software Odeon.

The registered RIR, not only serve to provide modern information about the acoustics of the Chapel, which played and continues to play an important role in the religious and cultural activities of the city of Ely, but also to adjust and validate the GA model of the space in present time by comparing experimental and simulated results, and which was then used as a reference for the creation of the historical models. The Lady Chapel's dimensions and geometrical features have remained the same since its construction date, and therefore, no significant geometrical changes are introduced in the validated model, except those related with the interior arrangement and decoration of the space. Despite the unavoidable uncertainty on the acoustic behaviour of the finishing materials used in the historical models, the acoustic simulation of the original design of the building, as it might have been until being heavily damaged during the Reformation in the 16th century, reveals a clear impact of the paint finishing on the acoustics of the space, showing a considerably more reverberant space than it is in the present day. The simulation of the use of the Chapel as the parish church of Holy Trinity, about 1930 when it was fully furnished, helped to decrease the reverberation time by about half a second at mid-high frequencies while increasing acoustic diffusion.

Judging by the numerical values obtained for the reverberation and the energy parameters when simulating the 3 GA models in isolation, it could be concluded that no favourable conditions neither for the transmission of speech or music are found in the Lady Chapel at any point in history, despite offering great metrics of envelopement and spatiality. However, it is worth noting that the space cannot just be considered as a 'receptacle of sound', and the cultural expectations and other non-auditory components also influence the subjective listening experience and the perception of the acoustic functionality of the space [54,55].

Further use of these models may allow a deeper analysis of the acoustic behaviour of the space under different configurations, for instance when using different sound source positions or considering different degrees of attendance. Particular celebrations and events could also be recreated by introducing small changes to the models, adjusting them to each particular use of the space.

Supplementary Materials

Measured and simulated room impulse responses referred in this conference paper are publicly available to promote open research and facilitate their scientific or creative use. Please cite this paper in any published research or other work utilising this dataset. Dataset name: *The Acoustics of Ely Cathedral's Lady Chapel: a study of its changes throughout history,* DOI: http://doi.org/ 10.5281/zenodo.5150020

Acknowledgment

The authors are very grateful to the Dean and the personnel of Ely Cathedral for their continuous support during the project and their assistance during the measurements. Authors very much appreciate the great support from the AudioLab at the Department of Electronic Engineering (University of York), with special thanks to Prof. Damian Murphy for his overall help. Thanks to Daniel Protheroe for having made Iris software available for the analysis. Special thanks to Richard A. Carter for his time and for the photographs taken, and to Marc Girot for his help during the measurement session.

References

[1] Murphy, D., Shelley, S., Foteinou, A., Brereton, J. and Daffern, H., 2017. Acoustic heritage and audio creativity: the creative application of sound in the representation, understanding and experience of past environments.

[2] B.F. Katz, D. Murphy, and A. Farina, "The Past Has Ears (PHE): XR Explorations of Acoustic Spaces as Cultural Heritage". In International Conference on Augmented Reality, Virtual Reality and Computer Graphics (pp. 91-98). Springer, Chm, 2020.

[3] A. Alonso, R. Suarez, and J.J. Sendra, "Virtual reconstruction of indoor acoustics in cathedrals: the case of the Cathedral of Granada", Building Simulation, 10(4), pp. 431-446, 2017.

[4] U. Berardi, and G. Iannace, "The acoustic of Roman theatres in Southern Italy and some reflections for their modern uses", Applied Acoustics, 170, p.107530, 2020.

[5] ISO 3382-1. Acoustics—Measurement of Room Acoustic Parameters. Part 1: Performance Rooms; International Organization for Standardization: Geneva, Switzerland, 2009.

[6] M. Vorländer, "Computer simulations in room acoustics: Concepts and uncertainties." The Journal of the Acoustical Society of America, 133(3), pp. 1203-1213, 2013.

[7] B.B. Boren, "Acoustic simulation of JS Bach's Thomaskirche in 1723 and 1539", Acta Acustica, 5, 14, 2021.

[8] A. Planells, J. Segura, A. Barba, S. Cerdá, A. Giménez, and R.M. Cibrián, "Virtual acoustic reconstruction of the church at the lost monastery of Santa Maria de la Murta". In International Conference on Augmented and Virtual Reality, pp. 457-464, Springer, 2014.

[9] www.cathedralacoustics.com

[10] https://www.elycathedral.org/history-heritage/the-story-of-ely-cathedral

[11] D.J. Stewart, "On the Architectural History of Ely Cathedral", J. Van Voorst, London, 1868.

[12] F. Woodman. “The vault of the Ely Lady Chapel: fourteenth or fifteenth century?” Gesta, 23(2), pp. 137-144, 1984.

[13] W.D. Sweeting, The Project Gutenberg eBook, Bell's Cathedrals: The Cathedral Church of Ely, 1901, (http://www.gutenberg.org/files/21003/21003-h/21003-h.htm)

[14] J. Maddison. “Ely Cathedral: design and meaning”. Ely Cathedral Publications, Ely, UK, 2000.

[15] N. Coldstream. “The Lady chapel at Ely: its place in the English decorated style”. Reading Medieval Studies, 11, pp. 1-30, 1985.

[16] M.R. James, “The Sculptures in the Lady Chapel at Ely”, Archaeological Journal, 49(1), pp. 345-362, 1892.

[17] S. Van Rensselaer, and illustrated by J. Pennell “Handbook of English cathedrals: Canterbury, Peterborough, Durham, Salisbury, Lichfield, Lincoln, Ely, Wells, Winchester, Gloucester, York, London”; York, The century CO, 1910.

[18] C.E. Davis, “Ely Cathedral”, Journal of the British Archaeological Association, 14(3), pp. 238-256, 1858)

[19] http://penelope.uchicago.edu/Thayer/E/Gazetteer/Places/Europe/Great_Britain/England/_Topics/churches/_Texts/KINCAT*/Ely/1.html

[20] W.E. Dickson, “Ely Cathedral”, First published in 1897.

[21] https://archive.org/stream/historyantiquiti00bent_0?ref=ol#page/22/mode/2up/search/lady+chapel

[22] T. Rosendale, "Fiery toungues:" Language, Liturgy, and the Paradox of the English Reformation. Renaissance Quarterly, 54(4), pp. 1142-1164, 2001.

[23] https://www.elycathedral.org/files/pdf/surveyor/2016-ely-qi-report.pdf

[24] Anonymous, The Project Gutenberg EBook of Ely Cathedral https://www.gutenberg.org/files/20924/20924-h/20924-h.htm#LADY_CHAPEL), 1852.

[25] http://www.engineering-timelines.com/scripts/engineeringItem.asp?id=201

[26] https://ely.org.uk/cathedral/virginmarystatue.html

[27] https://www.yorkpress.co.uk/news/ryedale/8897511.chris-topp-company-of-tholthorpe-near-easingwold-creates-new-screen-for-ely-cathedral/

[28] J. Kennedy, “Reflections on 12 Years of Repairs at Ely Cathedral.” Journal of Architectural Conservation, vol. 8, no. 2, pp. 38–46, 2002.

[29] https://www.elycathedral.org/files/pdf/corporate/ec-marketing-lady_chapel.pdf

[30] F. Martellotta, E. Cirillo, A. Carbonari, and P. Ricciardi, “Guidelines for acoustical measurements in churches”. Applied Acoustics, 70, pp. 378–88, 2009.

[31] L. Álvarez-Morales, T. Zamarreño, S. Girón, and M. Galindo, “A methodology for the study of the acoustic environment of Catholic cathedrals: application to the Cathedral of Malaga”. Building & Environment, 72, pp. 102–115, 2014.

[32] A. Farina, “Simultaneous measurement of impulse response and distortion with a Swept-Sine technique”, in Proceedings of the 108th Audio Engineering Society Convention, Paris. 2000.

[33] Iris software, Iris.co.nz. Available online: http://www.iris.co.nz/ (accessed on 10 December 2019).

[34] N. Webb, and A. Buchanan, “Tracing the Past: a digital analysis of the Lady Chapel vaults at Ely cathedral”. In 3rd Digital Heritage. International Congress (DigitalHERITAGE) held jointly with 24th International Conference on Virtual Systems & Multimedia (VSMM 2018)(pp.1-4). IEEE, 2018.

[35] J. Bentham, “The history and antiquities of the conventual and cathedral church of Ely: from the foundation of the monastery, A.D. 673 to the year 1771”. Illustrated with Copper-plates. Cambridge, M.DCC.LXXI. Vol. 1 of 2 (2 vols. available) History and Geography, 1771.

[36] W. Stevenson, “A supplement to the second edition of Mr. Bentham's History & antiquities of the cathedral & conventual church of Ely” , First published in 1817.

[37] M. Vorländer, “Auralizations Fundamentals of Acoustics, Modeling, Simulation, Algorithms and Acoustic Virtual Reality”. Springer-Verlag, Berlin-Heidelberg (Germany), first edition, 2008.

[38] ODEON Room Acoustics Software User’s Manual Version 15 Published in November 2019. Available online: https://odeon.dk/download/Version15/OdeonManual.pdf (accessed on 10 December 2019).

[39] https://odeon.dk/downloads/su2odeon/

[40] B.N.J Postma, and B.F:G. Katz. “Creation and calibration method of virtual acoustic models for historic auralizations”, Virtual Reality, vol. 19 (SI: Spatial Sound), pp. 161-180, 2015.

[41] F. Martellotta, “The just noticeable difference of center time and clarity index in large reverberant spaces”. The Journal of the Acoustical Society of America, 128, pp. 654–663, 2010.

[42] I. Bork, “A comparison of room simulation software-the 2nd round robin on room acoustical computer simulation. Acta Acustica United with Acustica, 86, pp. 943–956, 2000.

[43] D. Harris, "Noise control manual." Van Nostrand Reinhold 3, 1991.

[44] B.I Dalenbäck,.CATT-A v9: User's Manual CATT-Acoustic v9. CATT, Gothenburg (Sweden), 2011.

[45] H.W. Bobran, “Handbuch der Bauphysik”, Verlag Ulstein, Berlin, 1973.

[46] T.J. Cox, and P. D’antonio, “Acoustic Absorbers and Diffusers: Theory, Design and Application”; Spon Press: London, UK, 2004.

[47] F. Martellotta, and E. Cirillo, “Experimental studies of sound absorption by church pews”. Applied Acoustics, 70(3), pp. 441-449, 2009.

[48] J.Y. Jeon, I.H. Hwang, and Y.H. Kim, “Investigation of the acoustical characteristics of organ pipes in a performing space”. Building and environment, 77, pp.50-60, 2014.

[49] M. Barron, “ Subjective study of British concert halls”, Acustica, 66, pp. 2–14, 1998.

[50] F. Martellotta, F. “Subjective study of preferred listening conditions in Italian Catholic churches”. Journal of Sound and Vibration, 317, pp. 378–99, 2008

[51] C.M. Harris, “Handbook of Noise Control”; McGraw Hill: New York, NY, USA, 1997.

[52] M. Barron, “ The subjective effects of first reflections in concert halls-The need for lateral reflections”, Journal of Sound and Vibration, 15, pp. 475–494, 1971.

[53] A. Giménez, R.M. Cibrián, S. Cerdá, S. Girón, and T. Zamarreño, “Mismatches between objective parameters and measured perception assessment in room acoustics: A holistic approach”, Building & Environment, 74, pp. 119–131, 2014.

[54] J.Y. Jeon, I.H. Hwang, and J.Y. Hong, “Soundscape evaluation in a Catholic cathedral and Buddhist temple precincts through social surveys and soundwalks”, The Journal of the Acoustical Society of America, 135, pp. 1863–1874, 2014.

[55] B. Boren, “Word and Mystery: The Acoustics of Cultural Transmission During the Protestant Reformation”, Frontiers in Psychology, 12, pp.462, 2021.