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Modeling and Designing Acoustical Conditions of the Interior – Case Study

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The primary aim of this research study was to model acoustic conditions of the Courtyard of the Gdańsk University of Technology Main Building, and then to design a sound reinforcement system for this interior. First, results of measurements of the parameters of the acoustic field are presented. Then, the comparison between measured and predicted values using the *ODEON* program is shown. Collected data indicate a long reverberation time which results in poor speech intelligibility. Then, a thorough analysis is perform to improve the acoustic properties of the model of the interior investigated. On the basis of the improved acoustic model two options of a sound reinforcement system for this interior are proposed, and then analyzed. After applying sound absorbing material it was noted that the predicted speech intelligibility increased from bad/poor rating to good category.

Keywords: acoustic field analysis and modeling; acoustic conditions measurements and analysis; sound reinforcement system design.

1. Introduction

Sound amplification in large rooms, often with irregular, non-recurring forms, creates many problems. In order to properly design a sound system, one must carefully perform a series of measurements, as well as model the interior to enable pre-evaluation of acoustic parameters and the prediction of the interior acoustical quality. The Hevelius Courtyard of the Gdańsk University of Technology Main Building is an interesting hall in the context of acoustics modeling, but difficult to manage its acoustical properties. Speech intelligibility and music perception both in quiet and noisy conditions are scored as very poor, thus an improvement of acoustical conditions is needed. It should also be noted that Hevelius Courtyard is a historic building, which greatly impedes the acoustic treatment of this place. This aspect was already discussed by Kulowski and Kamisiński (2012) and Kamisiński and Kulowski (2014) in their studies. As pointed out by Kamisiński and Kulowski (2014) rules for the historic buildings imposed by the heritage conservation authorities, also in the context of acoustics treatment, are very restrictive. However, they also showed that it is possible to introduce absorbing or wide-band sound diffusion materials that help to reduce overall reverberation without negative impact on historic qualities of such buildings (Kamisiński, Kulowski, 2014).

The assessment of sound quality in a room is directly related to the acoustic properties of the room, with primary emphasis on the natural acoustics of an interior space. In order to describe room acoustics a number of measures may be found in literature (Sabine, 1964; Beranek, 1996; Cerdá *et al.*, 2012; Gołaś, 1995; Kostek, 1999; Long, 2006; Rudno-Rudziński, Dziechciński, 2006; Vorländer, 2008). One of the first objective criteria of the acoustic quality of a room was the reverberation time RT (SABINE, 1964). During the past centuries several formulae for predicting reverberation time were developed empirically and theoretically, based on the assumption of homogeneous repartition of sound energy within the room, and consequently uniformly distributed sound absorption. Prediction of the reverberation time for non-uniform interiors, however, remains very difficult, thus for finding solutions fitted better to practical application other factors should be used, depending on the acoustical needs (Gołaś, Suder-Dębska, 2013; Neubauer, Kostek, 2001; Passero, Zannin, 2010; Zidan, Svensson, 2013). Therefore, even though, reverberation time continues to be regarded as a significant parameter, relative sound pressure level, early to late energy ratio, lateral energy fraction (Marshall, 1967; Barron, 1971) initial time delay gap (ITDG) (Beranek, 1962), background noise, speech intelligibility measured by STI (Houtgast, Steeneken, 1985), definition parameter D50 which was developed by Thiele (1953), etc., are needed for a more complete evaluation of the acoustical quality of rooms (Gimenez *et al.*, 2012; Kamisiński, 2012; Kulowski, 2011, Kamisiński, Kulowski, 2014; Niemas *et al.*, 1998; Okano, 2002; Polychronopoulos *et al.*, 2014; Rindel, 2002).

The main aim of the study was to measure the parameters of the acoustic field in the Courtyard of the Gdańsk University of Technology Main Building, then to analyze the acoustic conditions in the interior, as well as to come up with a sound reinforcement system proposal for this room. The sound system design was prepared with the use of the acoustic *CAD* software (ODEON, 2014; Rindel, 2002).

The second Section presents issues related to the measurement equipment used and the course of the measurements. The results of the measurements and their analysis are shown. The following Sections describe simulation of the acoustic conditions in the GUT Courtyard using the *ODEON* program and a suggested sound system design in two versions. Section 5 proposes the acoustic treatment of the interior, which would improve its acoustic conditions. Results of measurements are compared with results of simulations to validate analysis. The last Section contains conclusions and summary.

2. Measurements

Measurements in the Hevelius Courtyard of the Gdańsk University of Technology involved several stages. First, an e-sweep measurement signal was generated by *Dirac 4.0* software, with the results recorded using *PULSE LabShop*, and then reproduced by the omnidirectional sound source (*Brüel&Kjær* 4292-*L*). The omnidirectional sound source was placed at a height of 1.8 meters. At the same time, impulse responses of two interior points were recorded simultaneously, using the *PULSE* measurement system. Measurements were performed for an empty hall without an audience (Brüel&Kjær website, 2014). The INR mean values (*Impulse Response to Noise Ratio*) calculated from all measurement points in relation to the particular frequency were determined first. Then, the measurement microphones were calibrated for 94 dB SPL to ascertain proper measurement conditions due to a high level of interference. Because of a relatively high background noise, reverberation time and EDT are shown up to 4 kHz, contrarily the simulation-based results include also results for 8 kHz.

In the Courtyard, 34 measuring points were designated at a height of 1.8 meters. For this purpose, 17 measurement series were performed, each time changing the position of the microphones. The grid with measurement points and sound sources is shown in Fig. 1. The measuring microphones were spaced in vertical and horizontal lines, 3 meters from each other. The analysis was performed using the *Dirac* software (Brüel&Kjær website, 2014; Dirac, 2014).

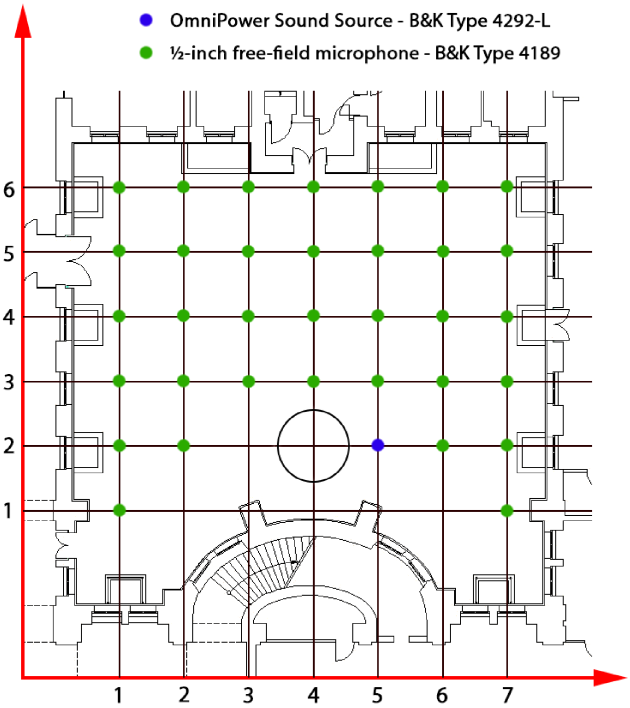

Fig. 1. The grid with measurement points and sound sources. The x- and y-axes reflect axes of STI graphic distributions shown in diagram in Fig. 4.

2.1. Analysis of results

Rooms with large cubic volume very often cause problems with overly long reverberation, echo and high noise. In such rooms, the free path average length is high, while the number of reflections per second is low (Gołaś, 1996). The measured interior has the following approximate dimensions: 23.2 m – length × 23.7 m – width × 28.4 m – height. When calculating the room volume, one should take into account the fact that the room has the geometry of a partial rectangular cuboid. Thus, the volume is approximately 14000 m^3. With such large rooms, specific resonant frequencies are not taken into account, since they occur in the band below the analyzed frequency range (Long, 2006). However, attenuation of sound in the air is greatly increased above the 8 kHz band. The Courtyard walls are made of materials that are highly sound-reflective in the range of 250 Hz to 1000 Hz, such as porous plaster, brick, glass and glazed roof. In addition, the glass roof and stone substrate enhance reflections in medium and high frequency ranges (Kulowski, Kamisiński, 2012). For low frequencies, average reverberation time fluctuates within 4 seconds; for the range of 250 Hz to 1000 Hz it is 5 seconds, while above, the reverberation time decreases with each octave by approximately 1 second.

Early decay time is strongly associated with early reverberation energy. The greater the early energy in relation to the late energy, the shorter the EDT by T30. By comparing average values of the early decay time and reverberation time (see Fig. 2) in the Hevelius Courtyard, it can be seen that these values are close to each other. This is due to the fact that the acoustic measurements used the omnidirectional source set away from the reflective surfaces, and the room itself has poor absorbing properties. In this case, in the impulse response, recorded by the majority of measuring microphones, exponential acoustical energy distribution began almost immediately after the first energy arrival. Then, early decay time is numerically equal to reverberation duration. Eyring observed that energy decay functions plotted on a logarithmic scale are generally linear for spaces having uniformly distributed absorption.

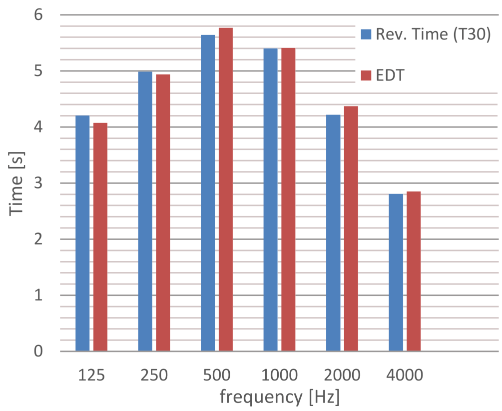

Fig. 2. Relationship of average T30 and EDT values calculated from all measurement locations in a function of frequency.

However, by analyzing EDT and T30 for each microphone separately, one can notice that for measurement points which are close to the sound source, the EDT value for each frequency is lower by up to 2.5 seconds than the reverberation time value. Kamisiński and Kulowski (2014) reported that there are discrepancies between the reverberation time and EDT, indicating a low degree of sound diffusion. They also emphasized the highly reverberant character of this interior (Kulowski, Kamisiński, 2012).

The minimum distance between the source and the measurement point for which reverberation time and early decay time have similar values is called the critical distance. For the Hevelius Courtyard it is about 7 meters. Since the noticed problem was a relatively high background noise, thus both reverberation time and EDT are shown up to 4 kHz.

In conclusion, EDT is strongly dependent on measurement location. Its value varies significantly depending on the distance between the microphone and the sound source. Thus it can be said that EDT refers to a local space in a room. In contrast, reverberation time has a global effect on the description of the acoustics.

Analysis of STI parameters showed that intelligibility of speech in the Courtyard is poor (Fig. 3). STI values are as follows: average – 0.34, minimum – 0.28, maximum – 0.47. The maximum STI value is the only point in the room which is in the fair intelligibility range. The coefficients decrease with increasing distance between the sound source and the subsequent measurement points. STI graphic presentation is shown in diagram in Fig. 4.

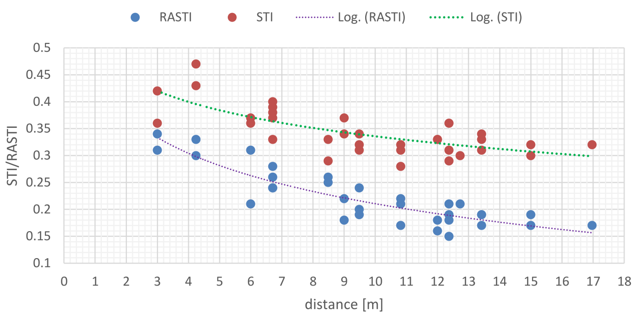

Fig. 3. Dependence of RASTI and STI values on the distance between the source and the measurement point. Speech intelligibility scale: 0–0.3 bad, 0.3–0.45 poor, 0.45–0.6 fair, 0.6–0.75 good, 0.75–1 excellent.

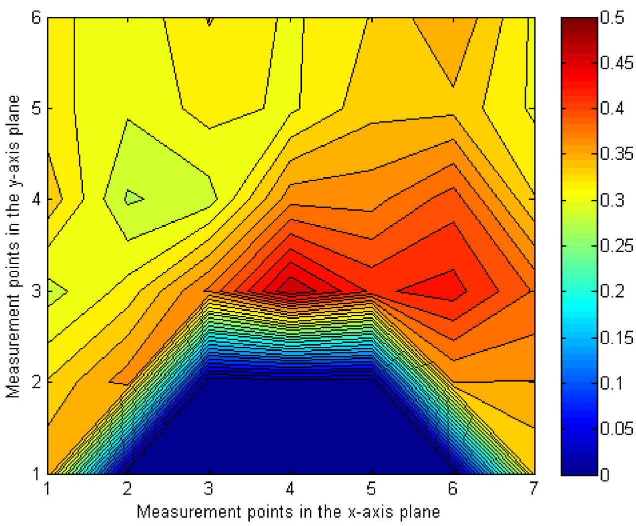

Fig. 4. STI graphic distribution.

3. Simulation of acoustic conditions in the GUT Courtyard

Measurements and determination of the parameters were followed by creating a virtual model that would reflect sound field properties of the actual room. The computer simulation was performed using *ODEON Room Acoustic* program (Christensen, 2003; Bork, 2000). It is based on the hybrid method, which calculates the early reflections using a combination of the image source method and ray tracing, while the late reflections are calculated by a special ray tracing process generating diffuse secondary sources. Performing simulation requires a three-dimensional model of the examined interior. For this purpose, a 3D model of the Courtyard interior using *SketchUp* software was designed. The final model as compared to the actual room is shown in Fig. 5.

In the computer model 1,949 surfaces were defined. Nine different materials were chosen with absorption and scattering coefficients taken into account (Catalog of Absorption Coeff., 2014; Ceiling Materials, 2014). They are presented in Table 1. Scattering coefficients for all surfaces were assigned a value of 0.05, because in the models comprising a large number of details the effect of scattering is calculated with the same room structure. Figure 6 shows the Courtyard model created. Next, the sound source was positioned in the model and the set-up of 34 microphones was mapped. They are placed in the model the same way as during the actual measurements. The distance between them was 3 meters vertically and horizontally, and the height was 1.8 meters.

The program was also fed with the average background noise parameters which had been estimated by measurement using *Audacity* software (Audacity, 2014).

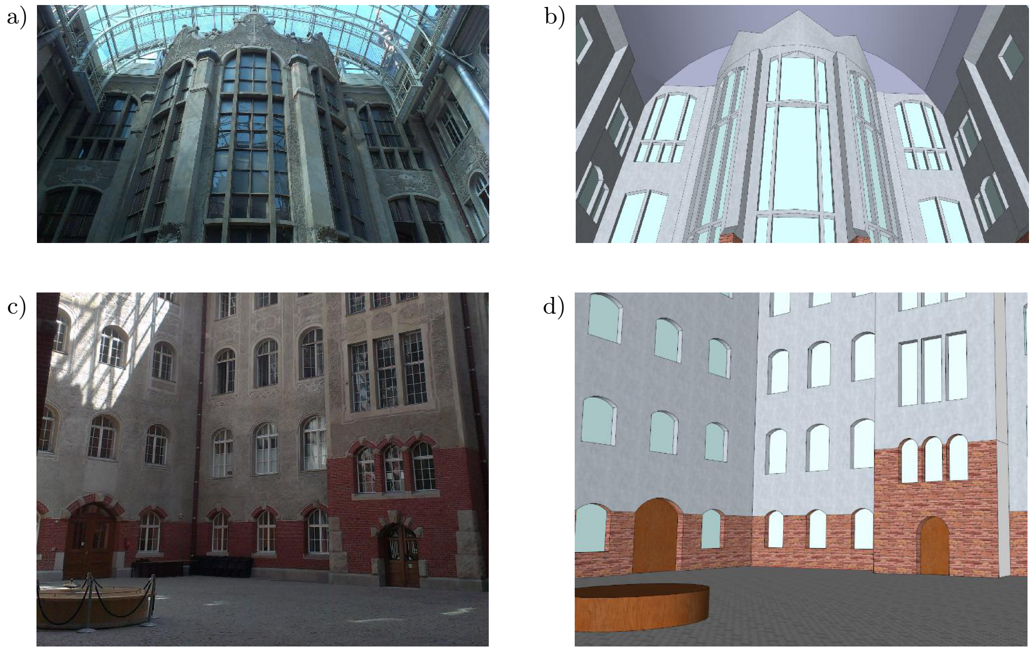

Fig. 5. a) Courtyard front (actual), b) Courtyard front (3D model), c) Courtyard back (actual), d) Courtyard back (3D model).

Table 1. Absorption coefficients of the materials used (Catalog of Absorption Coeff., 2014).

		Frequency [Hz]						
Surface	Material	125	250	500	1000	2000	4000	8000
Windows and doors finishing	Smooth unpainted concrete	0.01	0.01	0.02	0.02	0.02	0.05	0.05
Wall plaster	30% thick concrete block, 70% hard concrete	0.12	0.15	0.11	0.11	0.14	0.12	0.12
Wall bricks	Smooth brick	0.02	0.03	0.03	0.04	0.05	0.07	0.07
Windows	90% regular window glass, 10% wood	0.32	0.26	0.24	0.2	0.14	0.09	0.09
Metal sculptures	Steel	0.05	0.1	0.1	0.1	0.07	0.02	0.01
Floor	90% hard concrete, 10% crushed stone	0.04	0.09	0.1	0.11	0.12	0.14	0.14
Roof	70% large solid glass L''', 30% steel	0.14	0.07	0.06	0.05	0.04	0.02	0.02
Doors	Solid wooden door	0.14	0.1	0.06	0.08	0.1	0.1	0.1
Pendulum	Lacquered wood	0.15	0.11	0.1	0.07	0.06	0.07	0.07

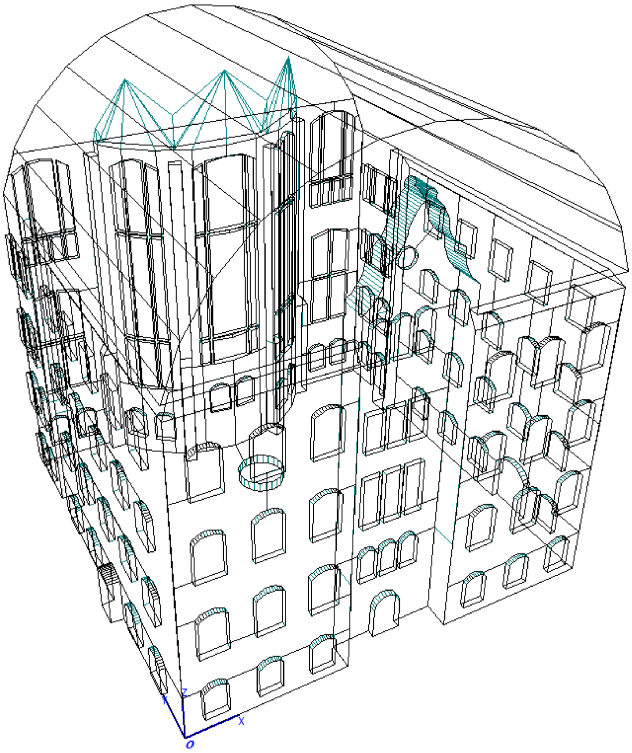

Fig. 6. Courtyard 3D model after being imported to *ODEON*.

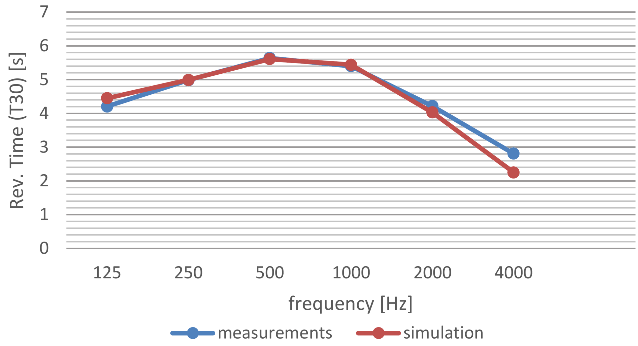

Fig. 7. Comparison of the average T30 value for measurements and simulation.

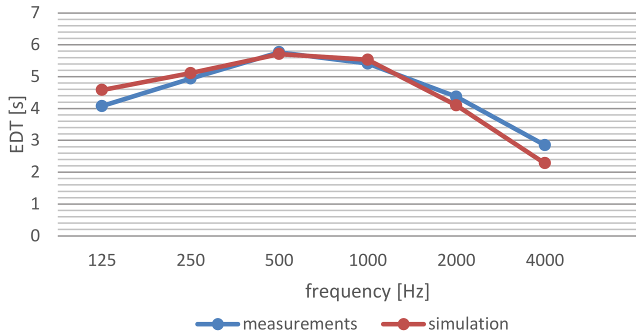

Fig. 8. Comparison of the average EDT value for measurements and simulation.

One of the objectives when creating the Courtyard virtual model was to render its actual acoustic conditions as closely as possible. The analysis carried out in *ODEON* resulted in parameter values that were very similar to the ones measured. Diagrams in Figs. 7 and 8 compare the average values of both EDT and T30 derived from the simulation and the actual measurements. Results for 4000 Hz derived from measurements are higher. This is probably due to the fact that *ODEON* calculations take into account very high sound absorption by air in high frequency bands. The EDT parameter had slightly lower minimum values for measurements. This means that the simulated critical distance is less than the measurements would suggest. This may be caused by the difference between EDT calculation algorithms used in *ODEON* and *Dirac* (Bork, 2000; Christensen, 2003; ODEON, 2014). Another cause of this may be the cork boards lying on the floor during the measurements, located in close proximity to the speaker. They were not included in the simulation, since it was a short-term installation.

Simulated and measured STI distributions also show a strong resemblance to each other, as presented in Fig. 9. Note that the STI scale assigned for re-

a) b)

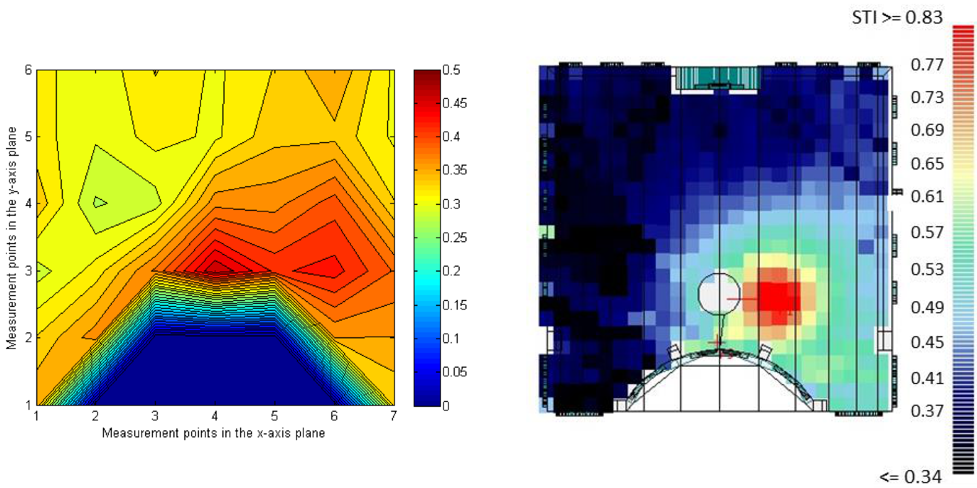

Fig. 9. STI graphic distribution for measurements (a) and simulation (b).

sults presenting differs for the measured and *Odeon*-based data (due to the specificity of the programs). The sound source is located at a point with coordinates (5,2) on diagram A. The greatest values of the parameter in the two cases differ by 0.1. The average value is 0.44, which indicates poor speech intelligibility.

4. Sound system design using acoustic CAD

The purpose of a sound amplification system is to strengthen the sound that reaches the audience. For the Main Building Courtyard, these are mostly verbal messages and music. The sound system designed for this place is intended primarily to strengthen verbal messages and music. The use of a sound system is essential for room volume in excess of about 425 m^3 and a distance between the speaker and the listener over 12 meters (Long, 2006).

The sound system is designed to provide sound level adequate to the speech message, and uniform sound coverage in a specific bandwidth, as well as to avoid acoustic effects that deteriorate the quality of sound (echo, comb filtering, unwanted reflections, acoustic shadow) (Avis *et al.*, 2005; Davis *et al.*, 2013). As demonstrated by the measurement results presented in Sec. 2, the Hevelius Courtyard has long reverberation time. Designing a sound system for this type of place is a difficult task, because the speech signal emitted by the sound source is degraded by room reverberation. This greatly reduces speech intelligibility. Intelligibility is additionally affected by a room volume, its geometry and location of sound-reflecting surfaces. The best practice used in such places in order to avoid intelligibility deterioration is to set up point sources that are precisely directed towards the area where sound is to be amplified. Section 4 discusses three sound system options that represent different approaches to the issue.

The proposed sound systems are based on speaker systems of *d&b audiotechnik Q7*. These are linear system modules. Each module has two neodymium subwoofers with a membrane diameter of 10″, and a tweeter with a diameter of 1.3″. The maximum sound pressure level which can be generated by the set, measured at 1 meter in free space, is 138 dB and its RMS power is 400 W. The frequency response (−5 dB) is in the range of 60 to 17 kHz. Sound dispersion in the horizontal plane is 75°, and in the vertical plane it is 40°.

4.1. Option I

The first proposal for the sound system is to represent a realistic approach that takes into account the fact that management of the facility is at the discretion of the heritage conservation authority, and any modifications within the facility are difficult to implement. Therefore, a system which requires the least interference in the building was used. It is a system that involves putting speaker sets on all internal walls of the courtyard. Their mounting heights and deviation angles are shown in Table 2. All speaker sets should be directed downward at an angle of 10–30° so that they emitted sound directly into the audience area to minimize additional reflections. Individual speaker sets are delayed accordingly in relation to each other. The delays were calculated for pairs of units located at the same distance from the northernmost speaker sets that were used as reference for selecting the delays. Figure 10 shows spacing of the speaker sets and the delays calculated for them.

Table 2. Speaker sets mounting height and deviation from the vertical.

Speaker	Height [m]	Downward deviation [°]
P2-P6	3	10
P11-P15	3	10
P18, P19	3	10
P16, P17	3.5	20
P8, P9	5.5	30
P7, P10	3.5	10

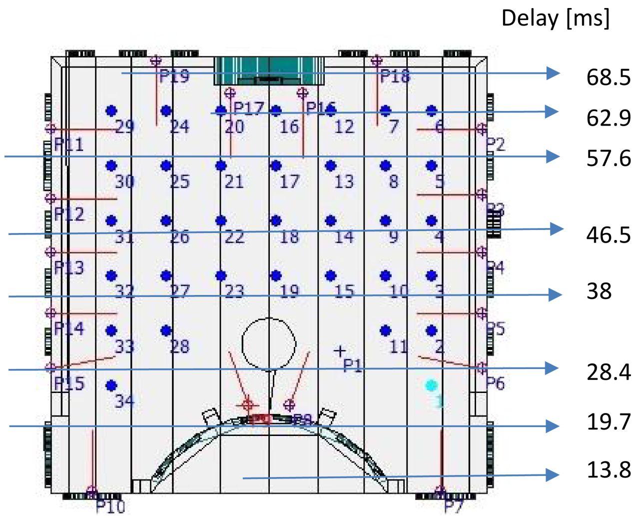

Fig. 10. Distribution of speakers and microphones in the Courtyard.

The first system simulation showed only a small improvement of the STI parameter. The average value of this parameter for the Courtyard without the sound system was 0.44, which means poor intelligibility. After introducing the sound system, this value is 0.52, which means fair speech intelligibility. This is also confirmed by values of the D50 parameter that indicate the clarity of voice communications that was improved after introducing the sound system, as shown in Fig. 11.

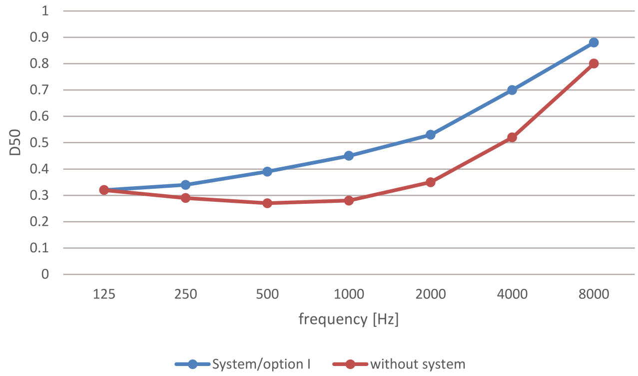

Fig. 11. Average value of D50 parameter.

4.2. Option II

Option II of the sound system shown in Fig. 12 consists of speaker sets suspended at a height of 5 meters and two sets placed on the front wall in the recesses of the facade at a height of 4 meters. The speakers make up four lines, the last of which, situated closest to the northern wall, consists of four speaker sets. The distance between the speakers in the line is 3 meters. The remaining three lines have six units each. The speaker sets are not directed at the ground at an angle of 90°, but slightly tilted from the vertical to the south by 20°. This aims at increasing the surface area that the units will be able to cover with sound. Speaker sets in different rows were delayed with respect to the units on the north wall.

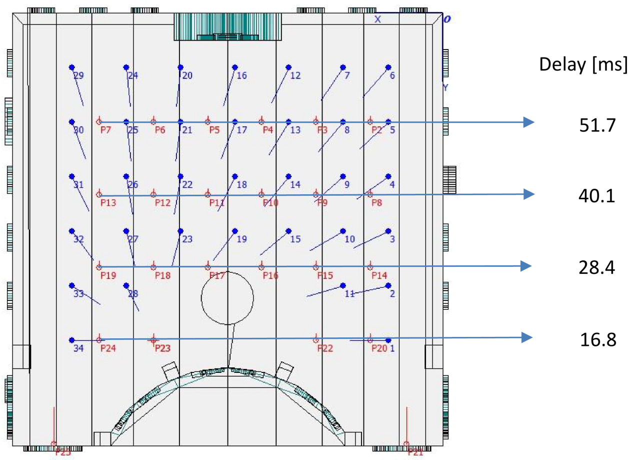

Fig. 12. Option II for distribution of speakers and microphones in the Courtyard.

After running several simulations, results for option II were not satisfactory, although the sound pressure distribution for different frequencies was more uniform than in option I. This is a positive result, since one of the main priorities when designing the sound system is the even distribution of sound pressure levels for all frequencies throughout the amplified area. In order to achieve the above effect, in *ODEON* frequency response correction for the speaker sets was applied (Bork, 2000), as shown in Table 3.

Table 3. Frequency response correction for the speaker sets used in the system.

Frequency [Hz]	125	250	500	1000	2000	4000	8000
Amplification	−10	−7	−5	0	0	3	5

While option II of the system provides higher D50 values in a small range, the average STI value for the second sound system is also 0.52, which means that both options obtain fair speech intelligibility. However, the distribution of places where speech intelligibility is fair is more uniform in option II (Fig. 13).

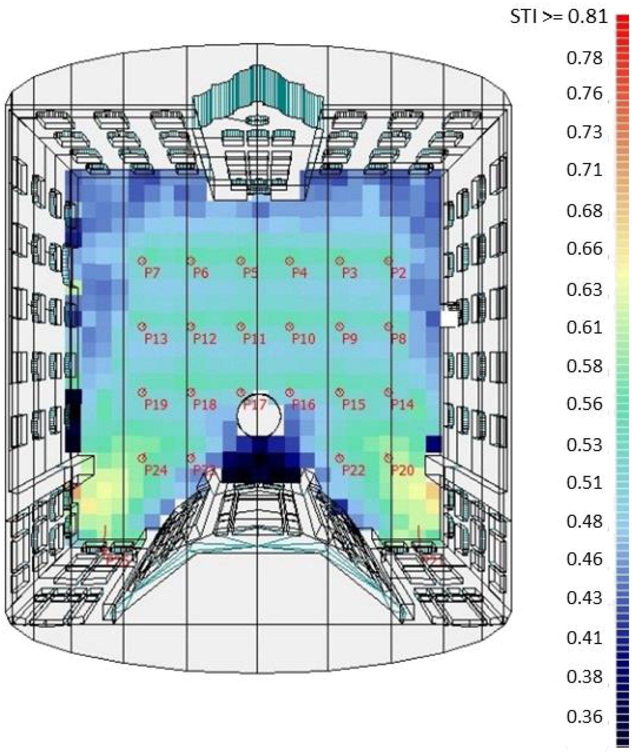

Fig. 13. Graphic distribution of STI parameter after using the sound system (Option II).

5. Acoustic treatment – the proposed solution

As mentioned before, Hevelius Courtyard is a historic building, thus the solution proposed may not be applicable due to heritage conservation restrictions. However, since this interior has a long reverberation time over 5 seconds, which negatively affects the intelligibility of verbal messages, thus it needs acoustics treatment. This is also a venue which hosts a number of official ceremonies, often combined with concerts. Acoustic conditions inside the Courtyard prevent implementation of a sound amplification system to match the status of the place, and make reception of any voice messages difficult for guests during ceremonies. Therefore, any acoustic treatment should be as invisible as possible, so as not to disturb the Courtyard interior too much. Any changes would have to be designed with preservation of aesthetic qualities in mind, while any covers used should match the look of the place.

First, it was decided that for the acoustic treatment of the Courtyard, the *sound absorbing plaster system* could be used (Catalog, 2014). It is a microscopically porous acoustic plaster placed on mineral wool panels. The energy carried by high frequencies passes through the pores into the mineral wool where it is converted into heat energy. The energy from low frequencies makes the porous surface vibrate like a diaphragm, turning the sound energy into heat energy. Plaster which could improve the Courtyard acoustic conditions should absorb frequencies for which the reverberation time is greatest. These include in particular: 125 Hz, 250 Hz, 500 Hz and 1000 Hz. The selected material is *70 mm plaster system*. The material absorption coefficients are presented in Table 4) (Catalog, 2014).

Table 4. Absorption coefficients of *70 mm plaster system* for different frequencies (Ceiling Materials, 2014).

Frequency [Hz]	125	250	500	1000	2000	4000
Absorption coefficient	0.45	0.92	0.99	0.84	0.84	0.7

The Courtyard auditorium space occupies mostly the center part since this is where the audience usually is during ceremonies. The highest number of reflections that reach the ears of the audience comes from the low parts of the walls which also have glazed windows. To minimize the number of reflections which directly influence the perceived reverberation time, that material in the lowest parts of the walls was placed. For the new cover to blend in with the original one, one may apply an individually designed pattern and color of the cover.

A simulation of acoustic conditions after putting acoustic plaster on approximately half of the wall surface was ran.

Figure 14 shows a diagram of D50 parameter values before and after the acoustic treatment using the sound system option II. After the treatment, parameter values for all frequencies up to 8000 Hz increased, which resulted in significant improvement in the clarity of speech communication. STI also increased as expected. Average STI value for the second system before the acoustic treatment was 0.52, and then it increased to 0.60, which is an indication of good speech intelligibility. Figure 15 shows the graphical distribution of STI for the second system. It was also checked that the average STI value for the sound system option I in the Courtyard after the acoustic treatment was 0.61, although the graphic distribution of this parameter is more favorable for the second system.

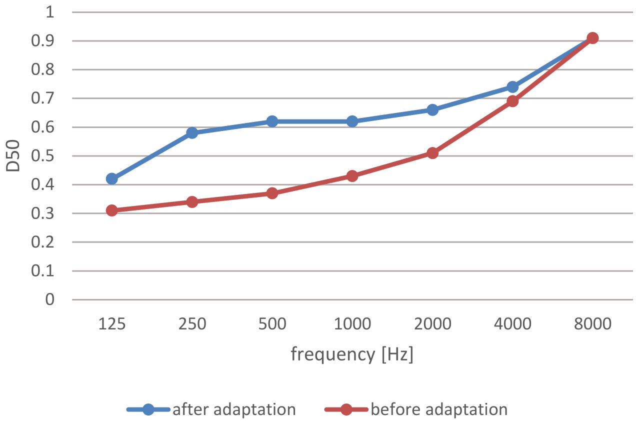

Fig. 14. D50 parameter values before and after the acoustical treatment (option II).

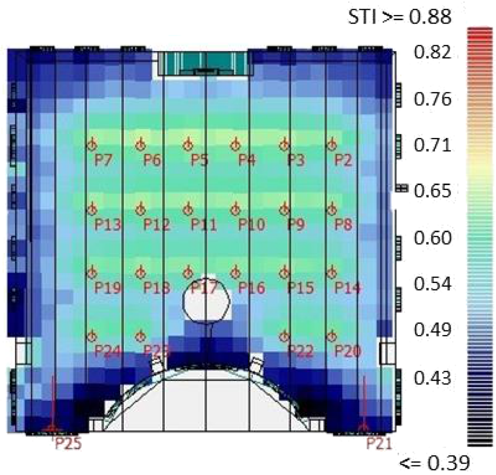

Fig. 15. The graphical distribution of the STI parameter in the Courtyard after the acoustic treatment using system option II.

Another option for improving the acoustic conditions in the Hevelius Courtyard is using wire mesh suspended at a height of about 6 meters. The market offers *metal mesh* which is made of stainless steel mesh which has integrated LEDs, designed to reflect one pixel (Media Panel, 2014). The *mesh* serves several functions. First of all, it is used for medialization of large front surfaces inside and outside buildings. Also, *metal mesh* has sound absorbing properties, thereby reducing reverberation time and improving speech intelligibility in space. Sound absorption coefficients for different frequencies for *metal mesh* are given in Table 5.

Table 5. Sound absorption coefficients for different frequencies for *metal mesh* (Media Panel, 2014).

Frequency [Hz]	125	250	500	1000	2000	4000
Absorption coefficient	0.29	0.53	0.68	0.62	0.79	0.88

A characteristic feature of the *mesh* is also transparency of 60%. This means that it transmits light at short distance. Though this may not be sufficient in terms of aesthetics, the mesh may serve other purposes such as displaying multimedia presentations, and at the same time, it could greatly improve the acoustic conditions in its interior. When there are no official ceremonies in the Courtyard, the *mesh* might be removed leaving only the supporting frames.

The effect of *metal mesh* on the Courtyard acoustics was simulated using *ODEON* software. In the simulation, option II of the above-described system was used. *Metal mesh* was placed at a height of 6 meters as illustrated in Fig. 16.

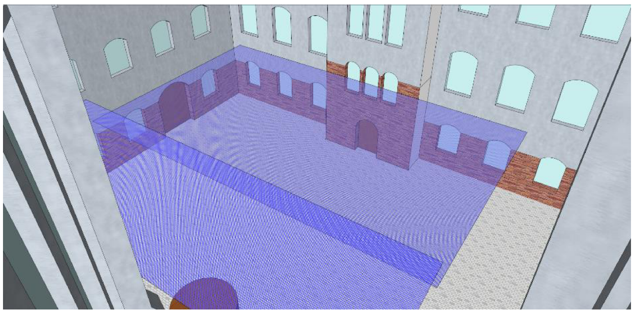

Fig. 16. Location of *metal mesh* in the 3D Courtyard model (top view).

Figures 17 and 18 present correspondingly average T30 and D50 values for the sound system options I and II without the *mesh*; with the *mesh*; with the *mesh* plus the acoustic plaster on the walls.

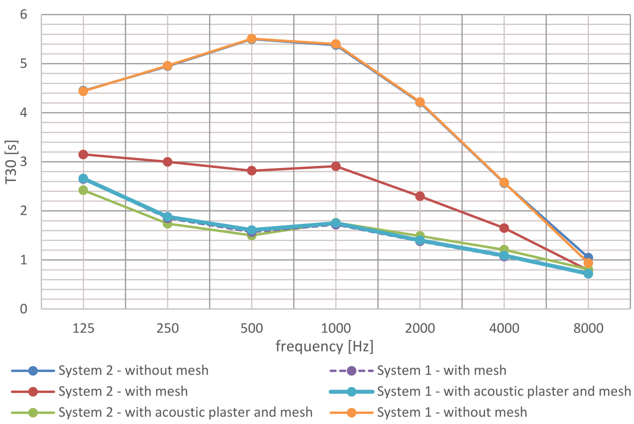

Fig. 17. Average T30 values for the Courtyard with the *mesh*; with the *mesh* plus the acoustic plaster; and without the *mesh*.

As shown in Fig. 18 D50 values increased with *metal mesh*, which indicates better clarity of voice communications. Even better results were obtained with the *mesh* plus the acoustic plaster applied partially. The simulation showed that the sound system installed in the Courtyard after such treatment would serve its purpose very well. Average STI value for the second system option placed in the Courtyard with the suspended grid and the acoustic plaster is 0.76. This value

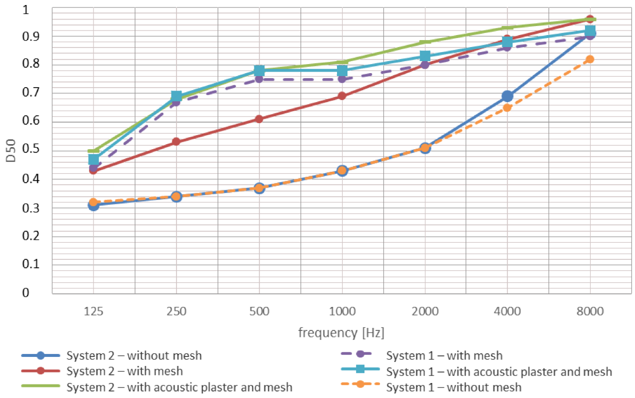

Fig. 18. Average D50 values for the Courtyard with the *mesh*; with the *mesh* plus the acoustic plaster; and without the *mesh*.

indicates excellent speech intelligibility. These findings are illustrated by the graphic distributions of speech intelligibility index STI shown in Figs. 19 and 20.

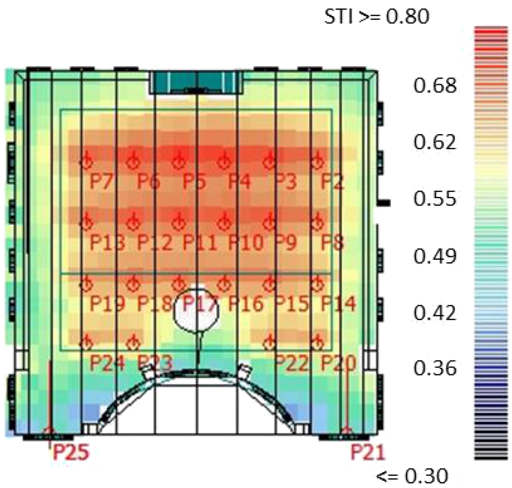

Fig. 19. Graphic distribution of STI values in the Courtyard after applying *metal mesh* (option II).

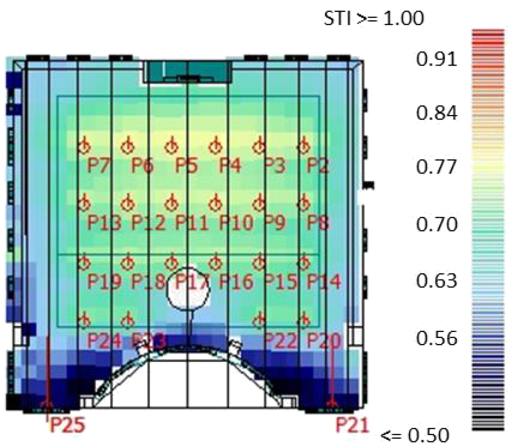

Fig. 20. Graphic distribution of STI values in the Courtyard after applying the acoustic plaster and *metal mesh* (option II).

The average STI value when using the *mesh* only, with no acoustic plaster, is 0.68, which indicates good speech intelligibility. For this case, the maximum STI values that occur in some places are 0.75, which is an indication of excellent speech intelligibility. Minimum values are 0.61, which refers to good speech intelligibility. After adding the acoustic plaster, STI minimum values are 0.69, while maximum are as high as 0.82.

Sound absorption provided by using *metal mesh* makes sound pressure levels for different frequencies no longer uniform. With the above solution, the EQ used for the speaker sets in option II had to modified. Modifications are shown in Table 6. By using the above modifications, a uniform distribution of sound pressure levels within the entire band was achieved.

Table 6. Frequency response correction for the speaker sets used in the system.

Frequency [Hz]	125	250	500	1000	2000	4000	8000
Amplification [dB]	−13	−10	−5	−3	0	3	0

Simulation of the first system option shows similar results to those for the second system. D50 parameter values are similar for both systems. However, significant differences can be seen for STI. STI values increased significantly for the first system after the treatment, but they are still lower than in the second system. When using the *mesh* alone, option I had an average STI of 0.71, which is an indication of good speech intelligibility. The highest value observed for the above situation was 0.76, while the lowest was 0.68. System simulation for the Courtyard with the suspended *mesh* and the acoustic plaster showed slightly better results. The average STI value was 0.72, the maximum value reached 0.75, while the minimum was 0.66. Graphic distribution of STI in the Courtyard is shown in Figs. 21 and 22.

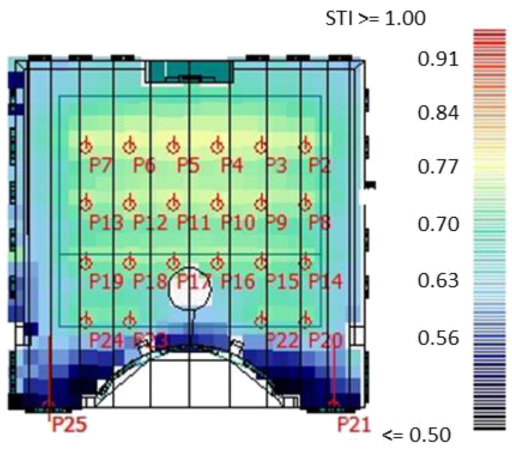

Fig. 21. Graphic distribution of STI in the Courtyard with the suspended metal *metal mesh* when using system I.

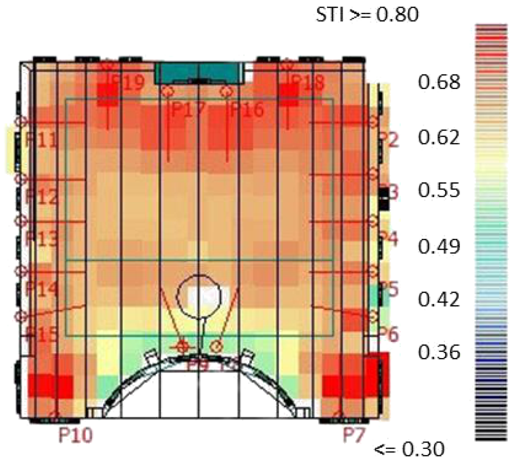

Fig. 22. Graphic distribution of STI in the Courtyard with the suspended metal *metal mesh* and the acoustic plaster when using system I.

6. Summary and conclusions

The aim of this study was to analyze the acoustic conditions in the Hevelius Courtyard of the Main Building of Gdańsk University of Technology. In addition to measurements and analysis of acoustic conditions, two options for the sound system along with the acoustic treatment were proposed. A virtual model of the Courtyard which was used to map the actual conditions was created. This model was then employed to simulate the impact of the proposed sound systems on the facility acoustics and acoustic conditions, taking into account the acoustic treatment.

The analysis in *ODEON* software did not account for the effect of absorption and scattering by an audience inside the Courtyard during ceremonies, and other elements that could be therein. Therefore, the results presented in this paper might prove in practice more advantageous due to sound absorption by people and scattering by other objects.

The Hevelius Courtyard has challenging acoustic conditions. Reverberation time reaches 5 seconds, so the intelligibility of voice communications is very poor. Sound systems proposed for this facility did not meet original expectations, since speech intelligibility indexes were not satisfactory. In addition, with the large volume of the interior, all concepts that involve putting speakers on the walls do not provide the same level of sound pressure in the desired frequency band. The best results were obtained using a sound system based on rows of suspended speaker sets directed towards the audience area. However, this option is difficult to implement in practice as it involves considerable visual disruption of the Courtyard, which is a historic building.

The Courtyard acoustic conditions were significantly improved only after the acoustic treatment. The first acoustic treatment was designed to interfere with the aesthetics of the building as little as possible. About half of the lower surface of the walls of the Courtyard was covered with acoustic plaster. There are manufacturers that offer individual finishes designed to specific needs. In the case of the Courtyard, the material can be as inconspicuous as possible, to blend in with the original cover. The appearance of this material can be designed in consultation with an interior designer. A simulation of the acoustic treatment, which had a significant effect on the appearance of the Courtyard interior, was also performed. The acoustic plaster was supplemented with steel *metal mesh* with incorporated LEDs. The *mesh* improves the acoustics in the space significantly. When combined with the sound system in which speaker sets were placed above the audience, STI values that in the range of good to excellent intelligibility were obtained. Apart from improving the acoustic conditions, the *mesh* also provides media presentation. Thus, this option for future improvement of acoustic conditions in the Hevelius Courtyard could be considered, especially as it may be placed only during the officials events requiring better intelligibility. There are also other solutions possible that may be applied in a historic room, e.g. a concept of the variable reflection acoustic wall system (Omoto *et al.*, 2014). It consists of the absorbing material, microphone, the loudspeaker mounted behind the material, and optional effect device. In fact these are movable walls that may serve as acoustic panels, in which the incident sound is reradiated after passing through the effector with arbitrary amplitude.

As a general comment, it may be said that media panels may offer a flexible solution for the acoustic treatment of historic interiors that do not necessarily have acceptable acoustic conditions but at the same time they should be protected by heritage conservation.

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