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Research Paper

Acoustic Panels Inspired by Nature

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The article presents the approach to the design process of acoustic panels based on the scientific research. This approach is based on combining the technical and the design competences to develop the innovative product value for the concept of acoustic panels. The article presents the concepts of two new acoustic panels – an absorbing and scattering panel and a panel reflecting sound waves. The first part of the article presents the starting point for the presented project – the acoustic research and the inspiration for both types of presented solutions. Next, the materials possible to use were discussed, which could reproduce the natural acoustic properties of the lava and glacier caves. The next part presents consecutive stages of the product development in a modern form, ensuring the expected acoustic properties. The last part of the article presents a fully functional solution and proposes further research and development directions.

Keywords: acoustic panel; absorption; reflection; design process; lava cave; glacier cave; geometrical method; 3D modelling; concept design.

1. Introduction

At the current rate of the technology development and the almost unlimited access to the information, it seems difficulty to discover or develop an innovative product. In 2016–2018, Professor Wiciak's team conducted the acoustic tests in a number of glacier and lava caves in Spitsbergen, Norway and Iceland (Czopek *et al.*, 2018; Małecki *et al.*, 2020). In addition to the above-mentioned studies, extensive photographic and descriptive documentation were also collected. During the analysis of the acoustic data, the idea of transferring the acoustic conditions of caves (Thomsen, 2015) to the public spaces appeared. The first challenge – of a technical aspect, was the mapping of the acoustic conditions. The second challenge – of a design aspect, was a visual interpretation of the natural lava and ice rock forms and capturing them in the form of the acoustic panels possible in mass production. An aesthetic mapping is inevitably connected with the function of these panels, because the maintaining of a system similar to the natural rock formation helps to obtain the initial, natural acoustic conditions. The acoustic panel solutions present on the market in large numbers are effective, although usually their wall composition is characterized by high repeatability, due to the continuous use of the same acoustic panel pattern. Ultimately, this causes an unnatural effect in the interior. In light of this, the use of the shape of the natural rock forms seems to be very beneficial, as it can avoid the visual monotony in the interior.

2. Acoustic panels – design process

The organic design is a direction derived from the modernist architecture, which assumes that the form should be shaped in relation to the nature. An example of this type of design is "Savoy Vase" from 1936 by Alvar Aalto (Fig. 1). It is inspired by the shape of Scandinavian lakes, and its name in Finnish means "a wave".

Fig. 1. "Savoy Vase" by Alvar Aalto (photo by Maija Holma (Alvar Aalto Museum, n.d.).

Nowadays, both product designers and architects equally willingly draw the inspiration from the nature, not only in relation to the form, but also to the function of the designed element. Therefore, the concept of biomimicry increasingly appearing in the architectural projects emphasizes a building in a sustainable way. One of the example could be the Reykjavik Harpa Concert Hall, the design of which is based on many of Iceland's iconic landmarks (Fig. 2). Its facade is inspired by nature. The geometric structure of the facades resembles basalt columns, which are characteristic for the volcanic landscape of Iceland. During the day, the grinded glass scatters the reflection of the sky and the harbor, while after dark it creates ashiny composition, sparkling with millions of lights.

The starting point for the development of the conceptual design concepts for the acoustic panels was the inspiration of the nature: the lava forms – for the absorbing panels and the glacier forms – for the reflecting panels, the structure and the color appropriate for them, and the acoustic properties of the surface. The concept was developed on the basis of the analysis of the subject in terms of the design and the photographic documentation carried out during the acoustic measurements (Spitsbergen in Norway, Iceland 2016–2018; Fig. 3).

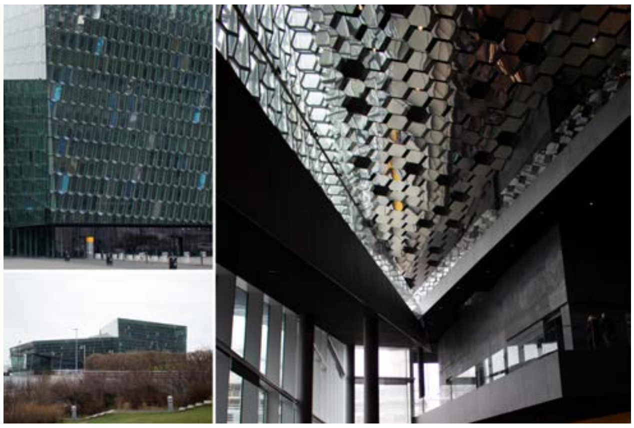

Fig. 2. Reykjavik Harpa Concert Hall (photo made by Kamil Bubak).

The design process included the following stages:

- market analysis,
- selection of the fragments of the photos from the photographic documentation of the lava and glacier caves,
- development of the mood boards,
- conceptual sketches,
- selection of the materials used,
- visualizations of the exemplary compositions of the acoustic panels.

At the initial stage, the analysis was carried out in terms of products offered on the market in the field of the acoustic panels, divided into the type of

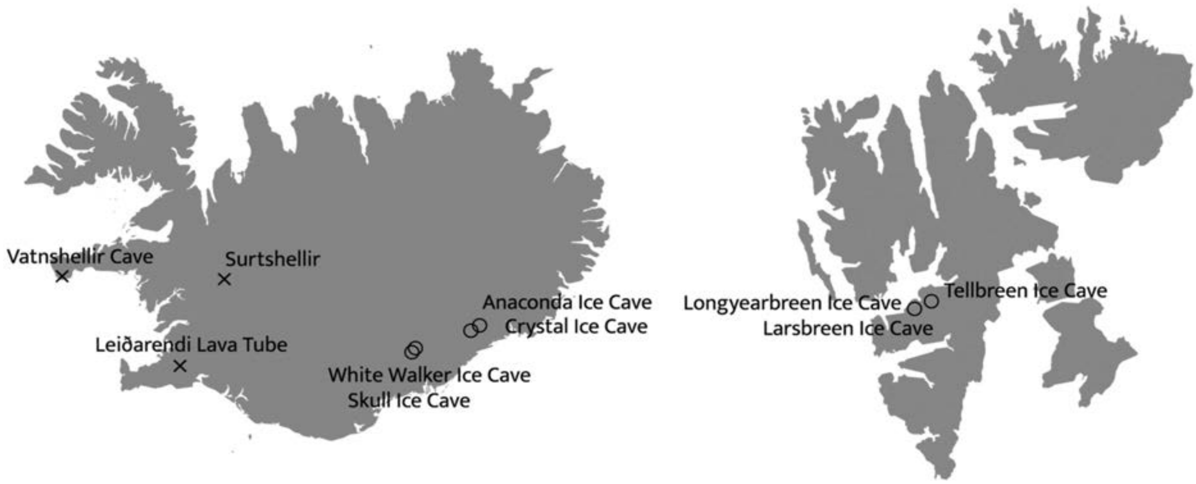

Fig. 3. Selected localizations of the acoustic measurements.

panels, the spaces for which they are intended and the type of materials from which they were made. The two types of products are listed: the acoustic panels absorbing sound, most often used in recording studios, office spaces and residential premises and the acoustic panels absorbing, reflecting or scattering sound for applications in dedicated rooms, e.g. in concert halls. Then, based on the photographic documentation, the fragments of the individual photos were selected, presenting the most characteristic material and visual features of the lava structures in the analysed caves, i.e. porous structure, black or dark gray color, no light transmission, irregular and sharp shapes, clearly block structure (Fig. 4) and the speleothem structures in the glacier caves – smooth and monolithic structure, blue color, irregular ice thickness (Fig. 5). The presented elements were reflected in the developed form of the acoustic panels.

Fig. 4. Interior of the lava cave – photo taken during the acoustic measurements (Małecki *et al.*, 2020).

Fig. 5. Interior of the glacier cave – photo taken during the acoustic measurements (Małecki *et al.*, 2020).

The important feature of the natural cave formations is their uniqueness, which can be obtained both thanks to the material from which the final product will be made, and thanks to the unitary, craft production method.

In the next stage, the mood boards were developed for each panel type, respectively for the lava cave (Fig. 6) and for the glacier cave (Fig. 7). The mood boards were created as collages of photos of the products available on the market and the fragments of landscape photos made during the acoustical measurements. They were supposed to create a visual mood for the designed acoustic panels. Mood boards contain

Fig. 6. Mood boards inspired by lava cave (photo on the right made by Kamil Bubak).

Fig. 7. Mood boards inspired by glacier cave.

both photographs of products with other functions, i.e. vases, lamps, decorative elements, etc., made of materials which structure resembles the structure of lava and glacier caves, as well as selected parts of photos from the collected documentation.

On the basis of the developed visual language of the product (Baskinger, 2005; Best, 2009), the series of sketches were prepared, which presenting the various concepts of the acoustic panels' forms, starting from the mapping of the natural structure of the cave, gradually going through the graphical simplifications, so that it will be possible to use a serial production for the developed design projects of the acoustic panels based on the forms of lava (Fig. 8) and glacier (Fig. 9).

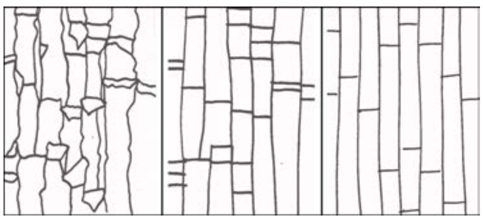

Fig. 8. Selected sketches presenting the concepts of the lava form structures and their graphic simplification.

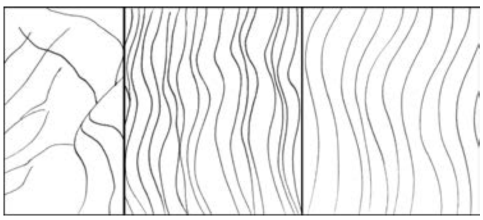

Fig. 9. Selected sketches presenting the concepts of the glacier form structures and their graphic simplification.

3. Selection of the base materials in terms of their acoustic properties

The choice of materials took into account both their acoustic parameters and the degree of the reflection of the visual features of the structure of lava or glacier form.

In the case of the panels inspired by the glacier caves, the two types of materials were selected – a glass and a polycarbonate. This choice was dictated by the obvious fact that it would not be impossible, but unprofitable to keep the acoustic panel made of ice. Comparing the acoustic properties of a glass and a polycarbonate, it turned out that both materials are usable, because glass is a material that strongly reflects sound waves falling on its surface, and its sound absorption coefficient does not exceed 0.15. A polycarbonate is characterized by similar acoustic properties, although, unfortunately, it also has a shorter time of aging. Due to this fact, it was decided to use glass for the panel construction. Glass panels can be freely formed, and in addition, in the production process it is possible to add admixtures in the form of dyes or phosphorescent impurities, which can additionally enhance their aesthetic values, faithfully reflecting the glacier forms.

In the case of the absorption panels inspired by the lava cave forms, it was necessary to examine lava rock sample and then, based on these tests, find an equivalent in the readily available materials.

In order to find the best material reflecting the properties of the lava rocks, a number of acoustic measurements of the selected materials were performed. These materials visually corresponded with their structure to the structure of the lava rock. The measurements were carried out using the standing wave method. The choice of the research method was determined by the availability of samples of the analysed material. The measuring stand (Fig. 10) consisted of the impedance tube, the probe microphone, the device for moving and positioning the probe microphone, the apparatus for processing the microphone signal, the speaker, the generator and the absorbing ends of the impedance tube. The impedance tube used for measurements is a circular cross-section Kundt tube, which is the equipment of the laboratory of the Department of Mechanics and Vibroacoustics at the AGH University of Science and Technology in Krakow. This set is composed of two tubes with the internal diameters equal to ϕ = 100 mm and ϕ = 30 mm. The tested samples had cylindrical shapes with similar diameters and the heights of 20 mm. Figure 11 shows the results of the carried measurements – the values of the sound absorption coefficient for the sound wave incident perpendicular to the sample of the lava rock.

Fig. 10. Measuring stand with lava rock samples.

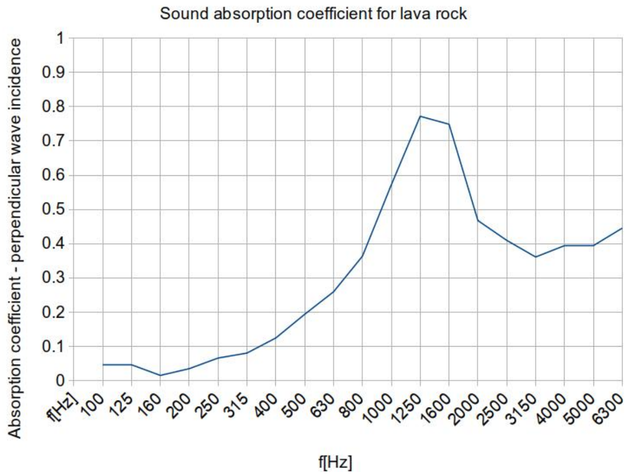

Fig. 11. Sound absorption coefficient for the sound wave incident perpendicular to the sample for lava rock.

The average sound absorption coefficient of a lava rock for a sound wave falling perpendicularly to the surface of the material is 0.31. The values of the absorption coefficient of the sound wave falling on the analysed material at any angle were determined on the basis of the diagram presented in Fig. 12. The re-

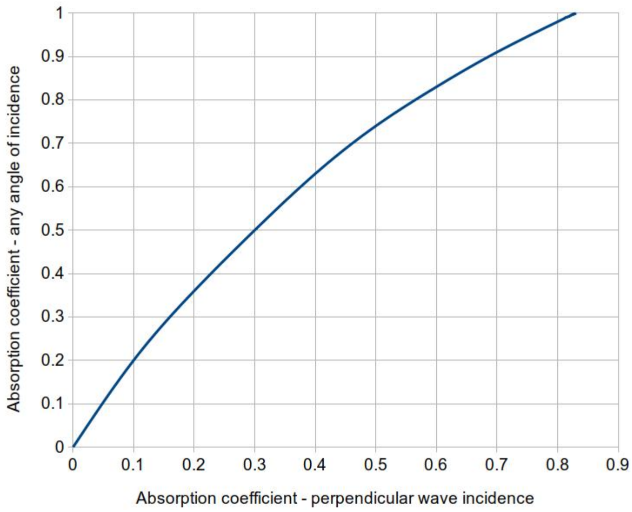

Fig. 12. Approximate relationship between the absorption coefficients for the perpendicular incident sound wave and the absorption coefficients for the sound wave incident at any angle on the material.

gression curve was determined with the coefficient of determination equal to $R^2 = 0.9999$.

As a result, the values of the sound absorption coefficient for the sound wave falling at any angle on the material were obtained. These results were presented in Fig. 13. The average sound absorption coefficient of the lava rock for the sound wave falling at any angle on the material was equal to $\alpha_{av} = 0.46$. Based on the above described analyses, it was proposed that the materials that would eventually replace the lava rocks were characterized by the sound absorption coefficients in the range of 0.38–0.58.

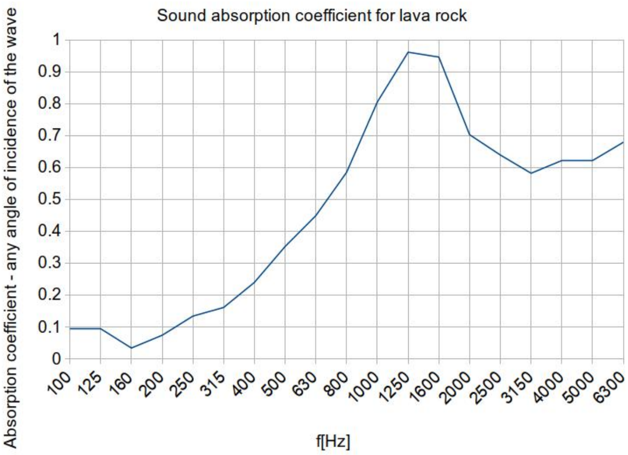

Fig. 13. Sound absorption coefficient for any angle of incidence of the sound wave on the material.

Taking into account the acoustic parameters and the visual values of the designed absorbing acoustic panels, a perlite concrete with an admixture of a black dye was proposed as a base material. It is a classic example of the porous absorbent materials (Fig. 14). This material is widely used in the construction for a thermal and sound insulation. It is characterized by high hardness and a low volumetric mass, and its porous structure well reflects the structure of the walls of the lava cave.

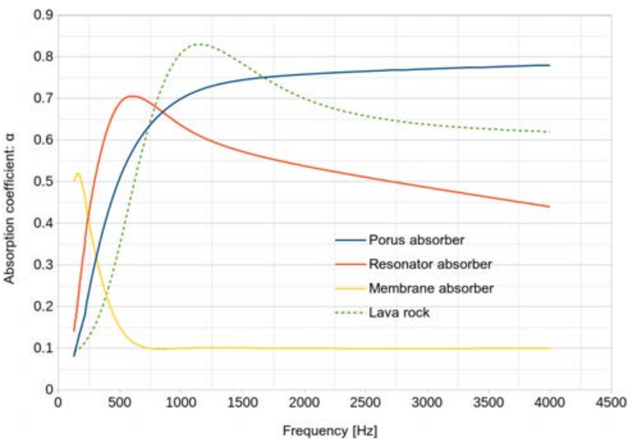

Fig. 14. Sound absorption coefficients of the sound-absorbing materials' selected groups (Sanner, Hoffmann, n.d.).

An additional advantage of the proposed material is the possibility of combining perlite and cement with the quality requirements, which can improve its acoustic properties by increasing its porosity. The process of moulding of the perlite concrete boards allows casting the material into any flat casts or milling in the material.

The final stage of a designing of the sound–absorbing panel was the visualization of the proposed composition on the wall (Fig. 15). The presented composition consists of the duplicate modules of three different lengths and three different depths, which refer to the lava forms both through the use of rough, black material and also through its characteristic shape.

Fig. 15. Acoustic panel concept inspired by lava form.

The final shape of the absorbing panel is not accidental. It is the result of modifying the original concept to improve its scattering properties, which allows to improve the acoustic properties of the object by obtaining a dispersed acoustic field (Sadowski, 1971). For example, assuming the width of the individual blocks of about 65 mm and a depth of about 150 mm, one can obtain the acoustic panel which will be effectively scatter the sound waves in the frequency range of 980–2650 Hz. Considering also the thickness of the entire panel above 50 mm, one can be expected that this solution will also have good sound-absorbing properties.

Similarly, as for the absorbing panel, the material for the reflecting acoustic panel was selected. In this case, it was decided to use glass with an admixture of phosphorescent paint. Thanks to this, a smooth structure was obtained with uniquely shaped colors that, when exposed, imitate the natural clearances in the ice structure of the glacier cave. The final effect is the visualization of the composition of the reflecting acoustic panels was created by duplicating an identical module in such a way that the effect of the natural ice formation is obtained (Fig. 16).

Fig. 16. Reflecting acoustic panel inspired by the glacier caves.

4. Analysis of the applicability in the interiors of a various type

The purpose of acoustic designing of a room is to achieve a homogeneous sound field, i.e. the one that guarantees similar listening conditions at every point of the room. Depending on the purpose of the room, it is recommended that it has appropriate proportions between its main dimensions. A room can be simultaneously treated as a set of resonators with the specific resonance frequencies (Sadowski, 1971). When the room's eigenfrequencies are evenly distributed in the frequency spectrum, the sound field will be close to the ideal diffuse field. The room's eigenfrequencies could be determined from the following formula (Sadowski, 1971)

$$f = \frac{c}{2}\sqrt{\left(\frac{n}{l}\right)^2 + \left(\frac{m}{b}\right)^2 + \left(\frac{k}{h}\right)^2}, \qquad (1)$$

where c is a sound speed [m/s]; l, b, h are dimensions of a room – length, width, and height, appropriately [m]; and m, n, $k = 0, 1, 2, 3, ...$ are any integers.

The distribution of the eigenfrequencies in a spectrum is a function of the dimensions of a room. Therefore, in order to obtain an even distribution of the eigenfrequencies, the room dimensions must be properly selected, remembering that their values meet the inequality

$$l \neq b \neq h.$$

The basic quantitative parameter of the quality of the sound field in a room is its reverberation time. There are many formulas to determine its value. One of the possible options is the Eyring formula in the following form

$$T = -\frac{0.161V}{S \cdot \log(1-\alpha) - 4m_a \cdot V}, \qquad (2)$$

where V is the volume of the room [m^3]; S is the total surface of the walls [m^2]; α is the average sound absorption coefficient; and m_a is the factor of the attenuation of the sound energy in the air.

A number of the numerical analyses were carried out to assess the potential applications of the designed absorbing panels under their sound-absorbing properties. These analyses were aimed at assessing the impact of the designed panel on the sound field in a room. Two cases of rooms were considered: the laboratory room and the Krakow Opera Concert Hall. All numerical simulations were carried out in the EASE program in the AURA module. An omnidirectional sound source was used as the sound source, from which 90 000 sound rays were emitted each time. The calculations focused on the absorbing properties of the designed acoustic system, without taking into account its scattering properties, as their detailed assessment will be made at a later stage of the design work.

The analysed laboratory room has dimensions of $7 \times 7 \times 4$ m. It is a real room that has been experimentally and numerically studied in detail in (Suder-Dębska *et al.*, 2014). To investigate the impact of the newly designed acoustics panel on the sound field generated in this room, one should replace the original, existing material on one of the walls with the designed acoustic panels. As a result, a change in sound-absorbing material was obtained in an area of approx. 28 m^2. Numerical analyses were carried out for a room with original materials and for the same room, but with a designed acoustic panel based on a perlite concrete. In both cases, the sound source was localized in the geometric center of the room. For comparison purposes, the reverberation time values according to Eyring formula, SPL(A) sound pressure level distribution, STI (speech intelligibility index), and Clarity C_{50} were determined. The obtained results are shown in Figs 17–20.

Analysing the obtained results, it can be stated that after using the designed absorption panel in the laboratory room a slightly longer reverberation time was obtained in the low frequencies range, while in the medium and high frequencies the reduction in a reverberation time was achieved in the room. The distribution of the SPL parameter and its obtained ranges are practically the same in both variants and outside the area close to the sound source this parameter shows slight differences in the obtained values. Similar results were obtained for the STI and Clarity C_{50} parameters.

The obtained values of the estimated reverberation time determined based on the Eyring formula in both cases are in the range from about 0.8 s for the frequency of 500 Hz to about 0.25 s for the frequency of 8000 Hz. For low frequencies, slightly higher values were obtained for the second analysed case. However, they do not exceed 1 s. Obtained values of the rever-

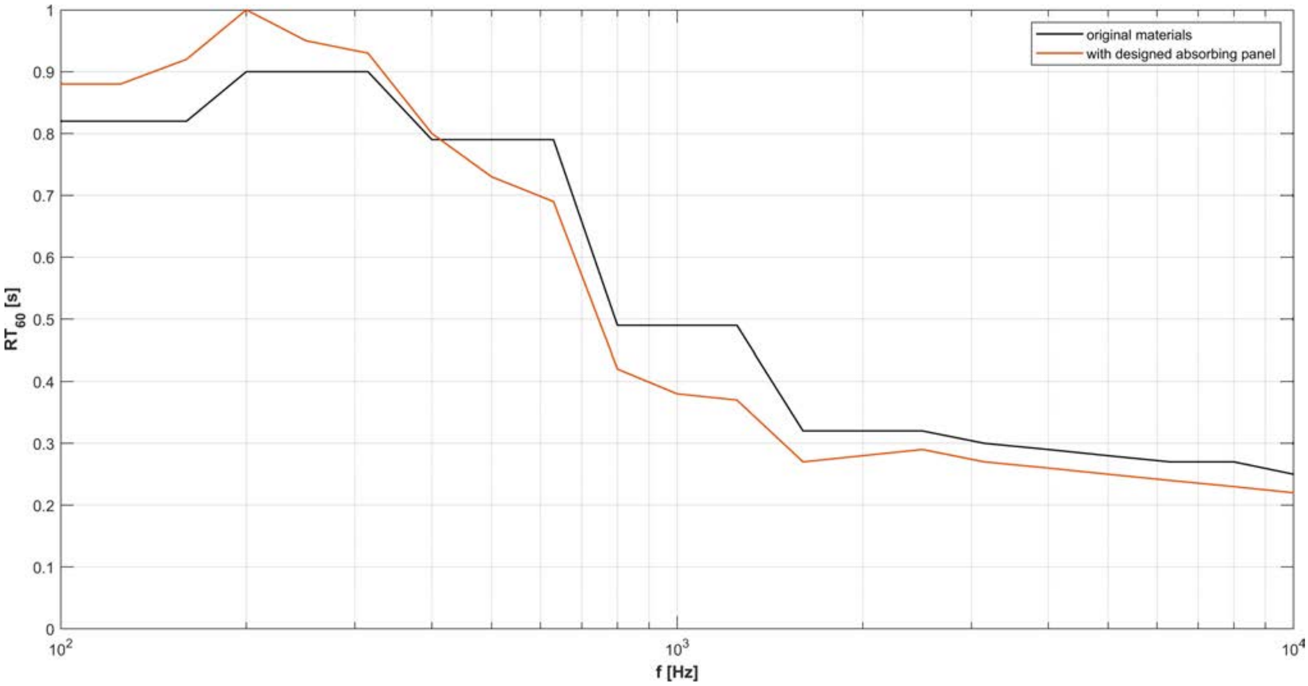

Fig. 17. Reverberation time according to Eyring formula in a laboratory room with original materials and with the designed absorbing panel.

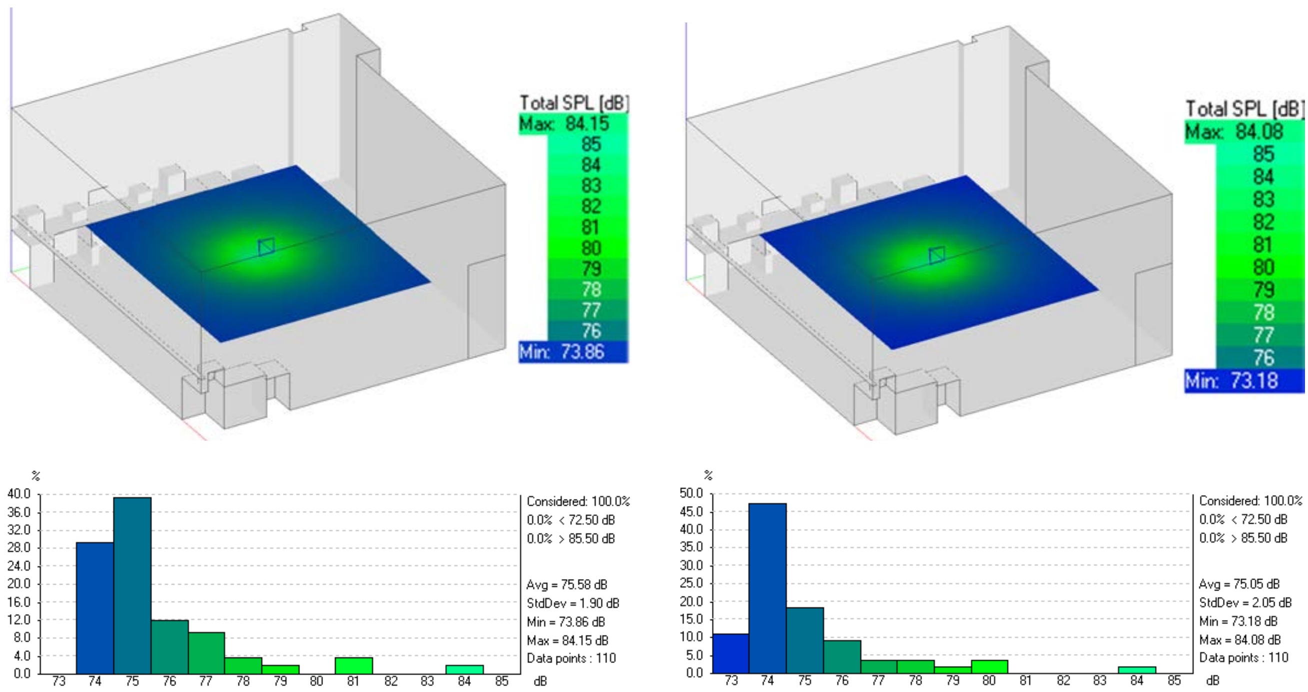

Fig. 18. SPL(A) distribution in a laboratory room with original materials (left) and with the designed absorbing panel (right).

beration time indicate good reverberation properties of the analysed laboratory room. The values of the SPL parameter for both cases, at a distance of at least 1 m from the sound source, are in the range of 73–77 dB. So it can be assumed that the listening conditions are very similar in the whole area. It should be emphasized, however, that in a modified room the SPL parameter with a value of 74 dB occurs in the area constituting 45% of the entire analyzed area. The obtained STI values in the range of 0.77–0.94 testify to very good speech intelligibility in the analyzed object and are slightly better than in the original room. This is also confirmed by the obtained values of the C_{50} parameter, which are at the level of 8–9 dB.

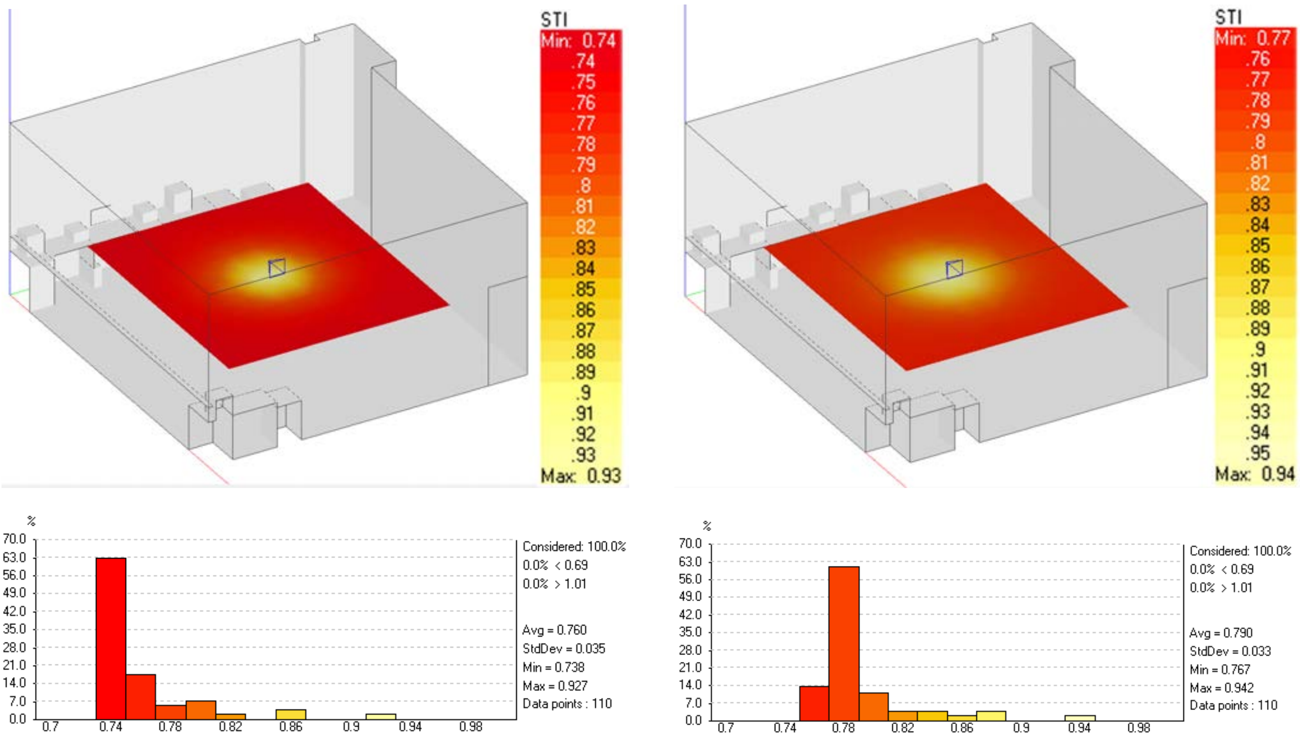

Fig. 19. STI distribution in a laboratory room with original materials (left) and with the designed absorbing panel (right).

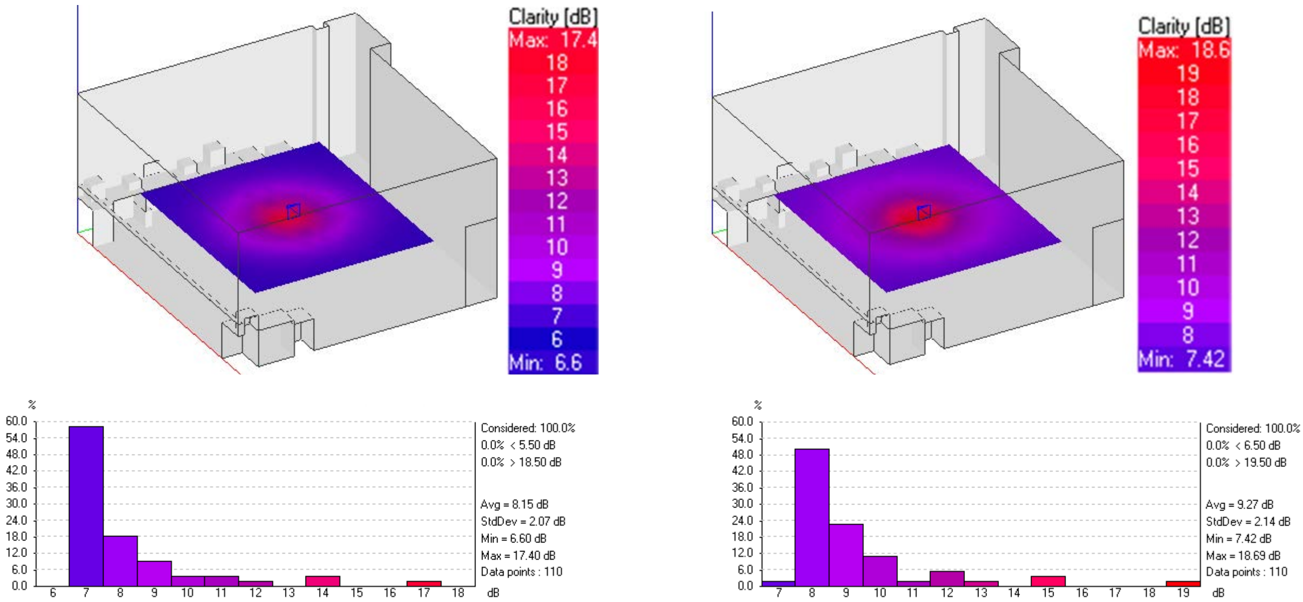

Fig. 20. Clarity C_{50} distribution in a laboratory room with original materials (left) and with the designed absorbing panel (right).

The Krakow Opera's Concert Hall was the second object under analysis. Similarly to the laboratory room's analyses, the analyses were carried out for the variant with the original, existing materials and the variant with the designed absorption panels. In the second variant of finishing of the room with the designed absorption panels, the existing absorbing acoustic panels were replaced, with which the side walls and the rear wall of the Concert Hall audience were finished. The detailed analyses of the original solution can be found in (Gołaś *et al.*, 2010). A number of acoustic parameters defining the sound field were determined for both variants of the object's finish. Figures 21–25 show the reverberation time according to Eyring formula, the SPL(A) sound pressure level, the STI (speech intelligibility index), Clarity C_{50} and Clarity C_{80} obtained as a result of the numerical calculations for both presented variants.

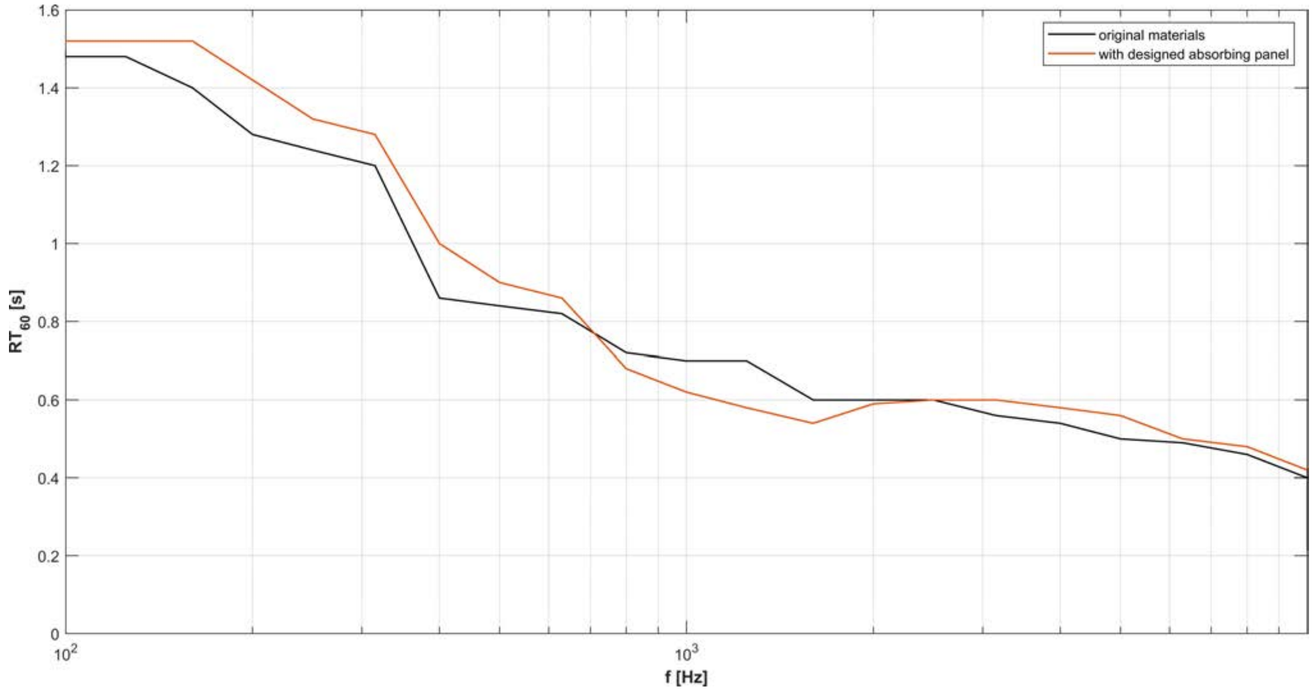

Fig. 21. Reverberation time according to Eyring formula in the Krakow Opera Concert Hall with original materials and with the designed absorbing panel.

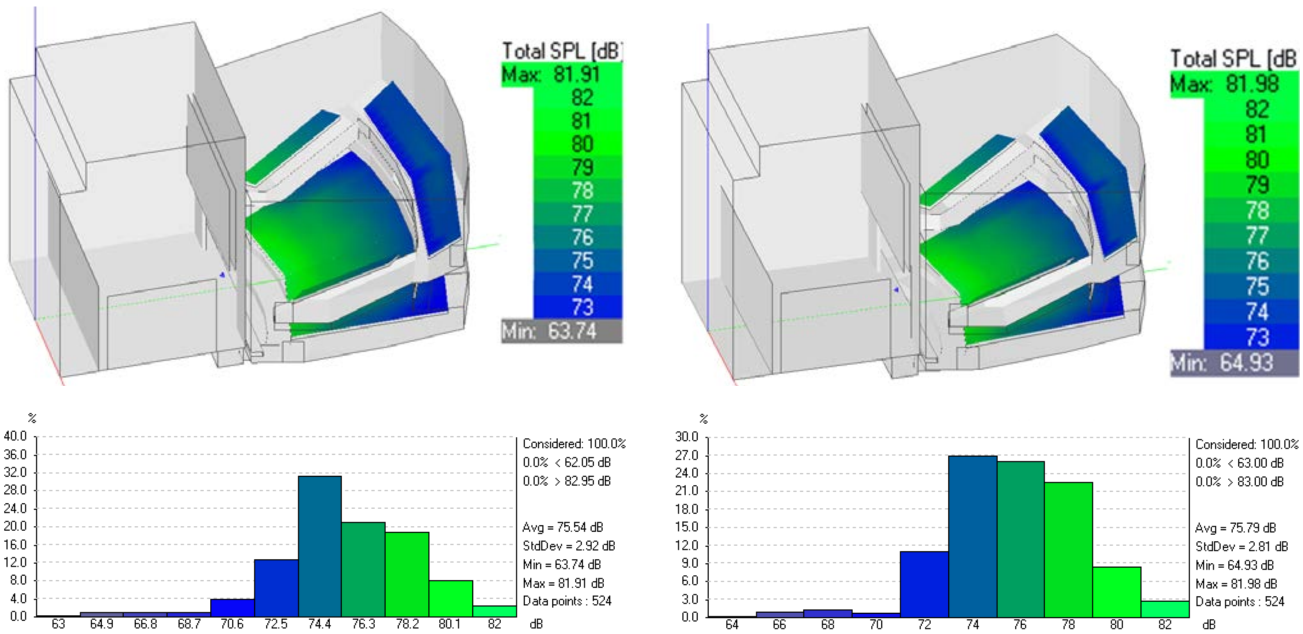

Fig. 22. SPL(A) distribution in the Krakow Opera Concert Hall with original materials (left) and with the designed absorbing panel (right).

The obtained values of the analysed acoustic parameters are practically the same in both cases. They testify to the good reverberation conditions and good speech intelligibility in the analysed Concert Hall. Although after applying the presented acoustic panels, the acoustic parameters of the sound field in the room seem to obtain even slightly better values than in the original room.

Similar SPL values of approx. 75–76 dB were obtained in both variants of the analyzed room. Speech intelligibility is at good/very good level in both analyzed variants. This is evidenced by the STI and Clarity C_{50} values of about 0.74 and 7 dB, respectively. The quality of the received music sounds is average in both cases. Although it is slightly better for the variant with the acoustic panels presented in the article, because on

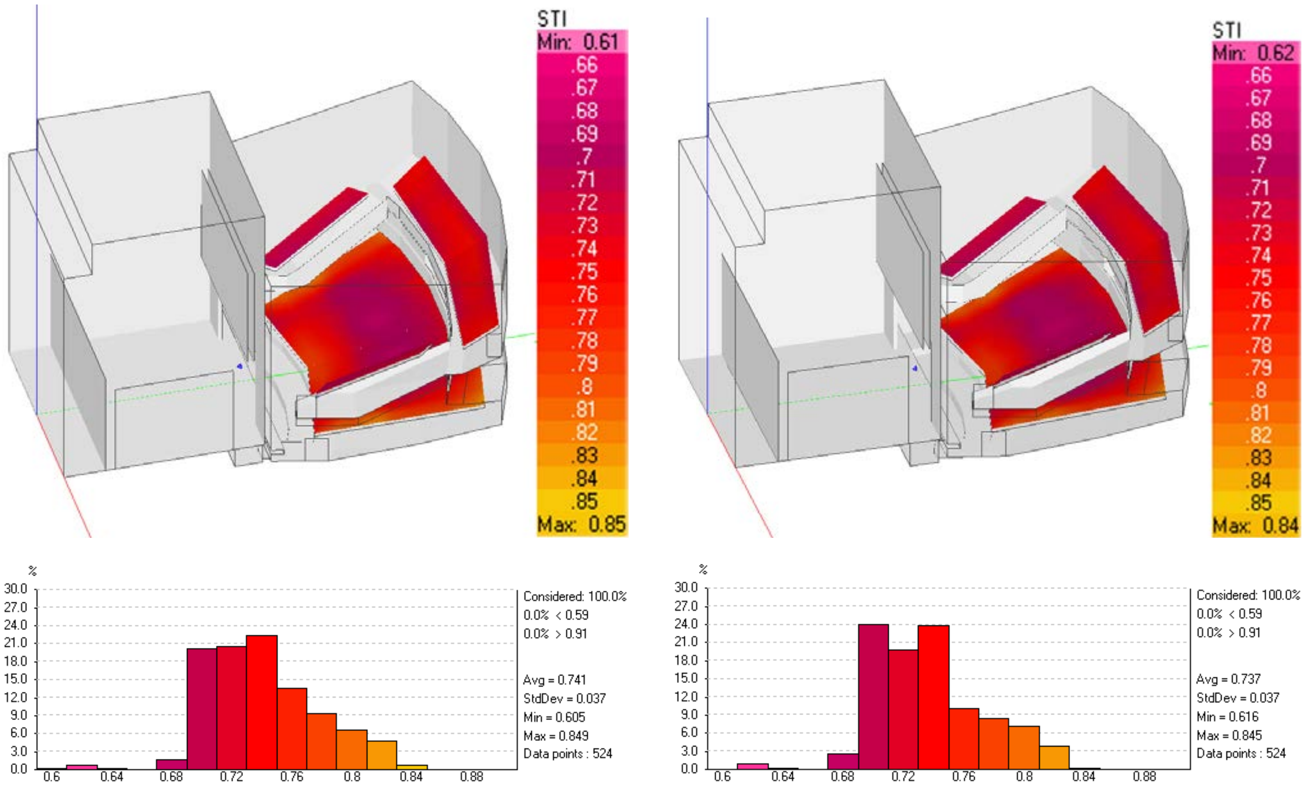

Fig. 23. STI distribution in the Krakow Opera Concert Hall with original materials (left) and with the designed absorbing panel (right).

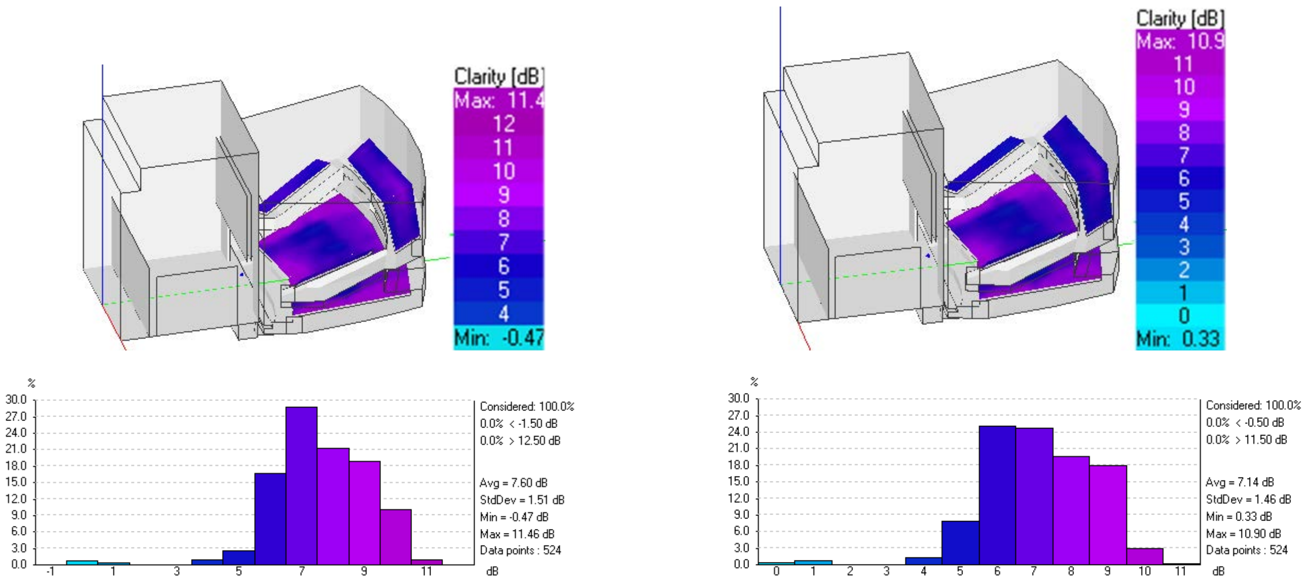

Fig. 24. Clarity C_{50} distribution in the Krakow Opera Concert Hall with original materials (left) and with the designed absorbing panel (right).

approx. 22% of the audience area Clarity C_{80} parameter achieves recommended values below 8 dB. For the original room variant, this situation occurs in about 10% of the audience area. Also the average value of the Clarity C_{80} parameter is slightly lower (of about 0.5 dB) and closer to the recommended values for the variant with the presented acoustic panel.

The analyses show that the designed absorption panels can successfully replace the classic solutions in terms of their absorbing properties. Even the replacement of materials on such a large surface as the surface of the walls limiting the Opera Concert Hall auditorium did not cause any adverse changes in the sound field obtained in the auditorium area. The obtained

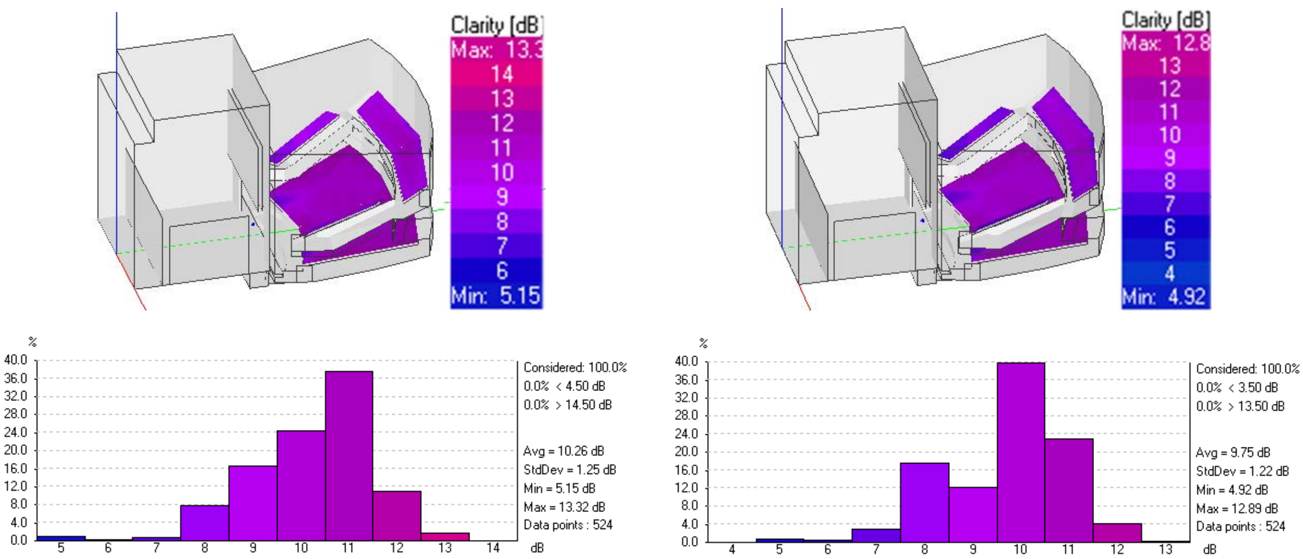

Fig. 25. Clarity C_{80} distribution in the Krakow Opera Concert Hall with original materials (left) and with the designed absorbing panel (right).

values of the presented acoustic parameters in both variants of the room model are very similar.

5. Conclusions

Combining competences and the cooperation between scientists from various disciplines as well as artists and designers to develop innovative solutions (Design Science Research) is popularized by the leading scientific centres in the world (MIT's Media Lab, Stanford's Centre for Design Research, Carnegie-Mellon's Software Engineering Institute).

The main advantage of the proposed concept of the acoustic panels is their unique composition, interpreting and mapping both the form and the acoustic properties of lava and glacier caves. The unique composition of the acoustic panels dedicated to the interior allows for the precise creation of the sound field and also the interior architecture. The assumed low cost of production of the acoustic panels presented in the article would allow for their wide application in public spaces, such as concert halls, conference rooms, lecture halls, communication routes and halls of railway stations or airports. The application of the presented solutions is also possible on the facades of buildings and inside the religious buildings such as Roman Catholic churches (Kosała, Engel, 2013), Orthodox churches (Małecki *et al.*, 2017; Kosała, Małecki, 2018) and temples of other religious denominations. In the interiors of this type, especially the modern ones, the acoustic issues are often overlooked at the design stage, which in turn can lead to problems in their use due to the excessive reverberation. Then there is a need to make an acoustic adaptation (Kosała, 2012; Kosała, Turkiewicz, 2015) using appropriate materials, which do not disturb the architectural assumptions of the designer, can turn out to be very expensive. In light of the above, the appearance of new acoustic panels with a unique appearance is of great importance for this type of interior.

The proposed solutions are in the laboratory testing phase. The next stage is the creation of the full-size prototypes for further research on the acoustic properties (planned for August 2020). Already on the basis of the pilot studies it can be stated that the proposed solutions can contribute to the improvement of the sound field's quality in the room. The presented solution is an alternative to the traditional acoustic panels with a repeatable, unnatural form. In addition, the freedom in creating the compositions of proposed panels, by using different systems, can allow getting not only the interesting visual impressions, but also the desired acoustic phenomena.

The panels have been designed in such a way that their production will be as simple as possible and will not generate unnecessary post-production waste.

The solution presented in the article was appreciated by two silver medals at the International Invention and Innovation Show INTARG 2019 in the category "Everyday objects".

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