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ACOUSTIC TRANSFORMATION OF AN ABANDONED INDUSTRIAL HALL INTO A MULTIPURPOSE VENUE, BY INCORPORATING THE EXISTING TECHNICAL FEATURES OF THE SPACE AND DFD APPROACH

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ABSTRACT

The most direct approach to sustainability in the building sector is to reuse the existing building stock. Industrial halls that are emerging in abandoned industrial areas are suitable for conversion into rock/pop venues. The challenge in this context is to perform the acoustic transformation efficiently and in an environmentally responsible manner. An example of such transformation is the former gunpowder factory in Kamnik, Slovenia, which is in process of establishing as Creative Quarter Barutana. To fulfill various requirements of the creative quarter a multipurpose hall is needed. The main focus of the presented case study is to use the existing industrial features of the hall to achieve variable room acoustics, which is usually considered a costly and sophisticated addition to the acoustic design. Furthermore, the design-for-disassembly approach was applied, and the creative community of users was involved to autonomously build sound absorbers. To this end, recycled textiles have been optimized and evaluated by impedance tube measurements. The obtained absorption coefficients were used in room acoustic simulations predicting a promising acoustic performance of the future venue. The main design steps are presented along with the specifics of the highly sustainable design approach.

Keywords: *acoustic renovation, design-for-disassembly, industrial heritage, multipurpose venue*

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1. INTRODUCTION

At the end of 19th and in the early 20th century numerous industrial complex were built, which were eventually abandoned due to changes in world economics. Now industrial complexes often form degraded areas within cities, posing issues as unutilised building stock and source of pollution. Revitalisation of those areas would implement circular economy in construction sector.

Among various renovation cases of industrial buildings is also the abandoned gunpowder factory Barutana in Kamnik, Slovenia. Nowadays the building is forming a creative quarter Barutana (later *KČB*), serving as the core space for public engagement, where local community can organise public events, e.g. concerts, forums, performances, and fairs. To meet the strong need for a well performing multipurpose venue, this study analysed potential acoustic renovation of the main industrial hall of KČB, where main focus was on incorporating existing technical features and design-for-disassembly (later, *DfD*) in order to incorporate a variable room acoustic design. The latter is imporant due to current wide-variety of organised events at Creative quarter Barutana but also future, yet unknown, requirements of the users.

2. METHODOLOGY

2.1 Acoustics

This study has been set in 4 consecutive steps:

- measurements of current room acoustic conditions in the main hall of KČB,
- analysis of measured data,
- design and development of actions and solutions accordingly to DfD,
- validations of proposed solutions with simulations.

Measurements of the current room acoustics have been done accordingly to the ISO 3382-1 standard [1]. Different acoustic parameters have been extracted from the measured impulse response, including reverberation time (RT), definition (D_{50}), bass-ratio (BR) and speech-transmission-index (STI).

The acoustic renovation of the hall has considered different types of public events, that can be grouped:

- Group 1, concerts of modern music styles, e.g. rock, pop concerts and raves,
- Group 2, speech events, e.g. lectures, theatre and poetry recitation,
- Group 3, acoustically undemanding events, e.g. markets, fairs and workshops

Table 1. Expected values of RT in octave bands between 63 and 4000 Hz for concert halls for modern music of size 1250 m^3, fulfilling the requirements of Adelman-Larsen [2].

Frequency (Hz)	Target values of RT (s)
63	0.89
125	0.68
250	0.75
500	0.82
1000	0.89
2000	0.95
4000	1.02

For Group 1 the targeted values for RT are presented in table 1. Accordingly to the Adelman-Larsen's study [2] targeted values for venues with size of 1250 m^3 are 0.81 for BR and 0.7 for D_{50} .

For events that fall into group 2 the acoustic renovation of the hall was investigating values of RT and STI. The targeted value of RT was determined accordingly to the standard DIN 18041:2005-05 [3] to be $RT_{targeted} = 1.0\ s$. For STI the standard IEC 60268-16 has been considered, where the requirement is minimum value of 0.6, however recommended is to be above 0.75 [4].

For group 3 only RT was considered for which the standard NS 8178 was used, which determines the targeted RT in the range between 1.45 and 1.75 s for venues, where quiet, unamplified music is playing [5].

2.2 Sustainability

Due to the climate changes the need for transformation into a sustainable society justifiably concerns also the construction sector. Buildings are using approximately between 30 to 40 % of all worldwide energy and causing between 40 to 50 % of all greenhouse gas emissions [6]. Reusing abandoned spaces in a sustainable way and waste as new construction material are crucial steps towards sustainable construction sector.

Therefore two actions towards this goal have been done within this study; firstly recycled textile was studied for production of acoustic elements needed for the designed acoustic renovation and secondly acoustic elements were designed by the DfD approach. The latter allows a fast and easy disassembly and consequently a faster and cheaper repairing of a product and component replacement [7]. This approach is valuable for both design of new spaces and equipment as well as for repurposed and retrofitted spaces, playing an important part in case of our acoustic renovation.

The temporary use permit limits the possible architectural interventions and poses a question of feasibility for allowed interventions. By designing acoustic elements with emphasis on adaptability an overall higher flexibility of the space was achieved for the foreseen activities. Ultimately this also enables any interventions and adaptations of the space in the future, when (and not if) public needs change throughout time.

2.3 Desired outcome

Main goal was to come up with 3 different plans of acoustic elements' positions for all each event group. These plans were required to use the same elements with variation only in position and quantity. The acoustic elements needed to be quickly adaptable and user friendly, so that room acoustics could be changed on spot without help of specialised personal, such as sound technician or engineer, simply following preset designs of acoustic elements' positions.

3. MEASUREMENTS

3.1 Room acoustics

Impulse response of main hall inside KČB has been measured accordingly to the standard ISO 3382-1 [1]. The hall has been preliminary emptied and all missing windows and doors were blocked using wooden boards in order to have a known enclosed volume with size of 1250 m^3. Measurements were performed at 9 different positions of microphone and at a single position of the loudspeaker, at the expected position of the stage. Positions are presented in figure 1.

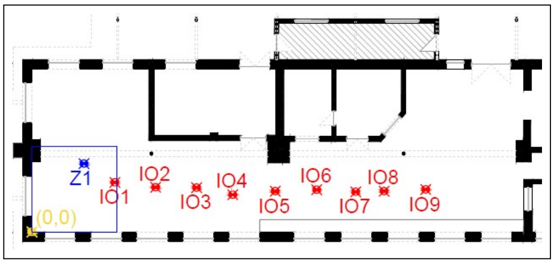

Figure 1. Positions of microphones during impulse response measurements in red and position of the loudspeaker in blue.

From the measured impulse responses acoustic parameters were calculated, among them reverberation time, RT, which has been measured on site also using method of interrupted noise [1]. These measurements were performed using two different positions of loudspeaker with corresponding 8 and 6 positions of the microphone per position of the loudspeaker. All positions of microphones were measured using 3D laser scanning in order to get precise coordinates of the microphone, as well as dimensions of the room [8, 9].

3.2 Sound absorption coefficients of recycled textiles

Waste textile has been used for the design of acoustic elements. Textiles are usually recycled by ripping them into fibers, which has been studied before by Islam et al. [10, 11], del Rey et al. [12], Danihelová et al. [13], and more. However for this study processes with lower demand for energy and time were considered, hence textile waste has been studied as a reused material only by stitching them together into covers of sound absorption panels and curtains.

Firstly gathered textile waste was separated into different clothing pieces and textile composition, which are presented on the table 2. Then each textile type has been measured for sound absorption coefficient, α, and sound transmission loss, T_L, accordingly to the standards ISO 10534-2 [14] and ASTM E2611 [15].

Both measurements were done as a single- and a double-layered textile, with the distance between the layers of 1 cm. Sound absorption coefficients were measured at 2 different distances from the rigid back surface of 1 and 20 cm distance and additionally at 40 cm distance for only double-layered composition, since this is also the distance between windows and inner walls.

Table 2. Measured textiles and their density.

Material Composition	Density (g/m^2)	Abbreviation
100 % Cotton	150	C100
60 % Cotton + 40 % Polyester	620	C60P40
70 % Viscose + 30 % Nylon	270	V70N30

Configuration of measurements is presented in table 3. This set-up provided sufficient results for both measurements of sound transmission loss and sound absorption coefficients. For later-on simulations it was needed to acquire single numeric value of transparency coefficient, which was calculated through sound transmission loss factor [15], T_L, at 1000 Hz.

3.3 Simulations

Design of acoustic renovation was done using ODEON Auditorium [16], which is a geometrical room acoustic simulation software. Before running simulations, Schröder's frequency of main hall of KČB has been calculated as 70.7 Hz, therefore the study has been limited to octave bands above 125 Hz. Simulations of proposed acoustic renovation have been done on 3 groups of events, as stated in section 2, where a floor plan of acoustic elements has been designed for each group and iteratively improved until acquired values of acoustic parameters met the targeted values.

Acoustic renovation was designed to fit multipurpose venue, hence all the simulations were done using mostly variable acoustic elements and additionally some fixed

Table 3. Configuration of measurements with impedance tube accordingly to the standard ISO 10534-2 [14].

Configuration of measurements	
Type of tube	Widder tube
Tube's diameter	10 cm
Microphone-Microphone Distance	10 cm
Microphone-Specimen Distance	10 cm
Specimen-Sound source Distance	30 cm
Lower frequency limit	50 Hz
Frequency resolution	2 Hz
Number of steps	800
Number of averages	150
Used sound signal	random

Figure 2. Existing industrial indoor crane used for mounting the sound absorption panel.

elements. Latter was defined as double-faced acoustic panel, mounted on the already existing industrial indoor crane, see figure 2. The double-layered textile in dark colours and a rigid wooden background in white on the other side colour is allowing both projecting media on the wooden screen as well as absorbing sound simultaneously.

Simulations of acoustic renovation started by defining groups of variable acoustic elements designed as curtains, as presented in figure 3:

- over outside windows (yellow),
- on the ceiling above the stage (purple),
- on the ceiling longitudinal to the stage (green),
- partition curtains between stage and backstage (dark blue),
- over inside windows (red) and
- over lateral wall in the first half of the venue (orange).

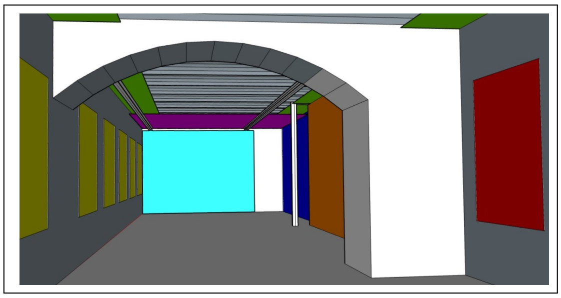

Figure 3. Proposed variable acoustic elements and their position in the industrial hall.

4. RESULTS

4.1 Room Acoustics

The measured RT values are presented in figure 4, where it is seen that the results gained from the two measuring methods are similar. On average difference between the two measuring methods is approximately 0.02 s, and largest is 0.10 s, hence it was concluded that correlation of the results is high.

On average reverberation time had to be reduced by half, however in the lower frequencies values of measured RT were almost 3-times of targeted. These frequencies are also key for quality concerts of modern music [2], therefore in the design of renovation the focus was brought to 125 Hz octave band.

From the figure 4 it can also be determined that the largest standard deviations are in the lower frequencies, below 125 Hz. This is expected due to the model nature of the sound field at lower frequencies. It can be also seen that RT is constantly decreasing above 400 Hz.

Measured BR and D_{50} were 1.13 and 0.361, respectively. This values are still considerably off of targeted values, 0.81 for BR and 0.7 for D_{50} . Reason for this is huge difference in early and late sound energy in case for D_{50} and in case of BR longer reverberation time at lower frequencies.

4.2 Sound Absorption Coefficients

Measurement of sound absorption coefficient, α, showed a high correlation with the density of the fabric, exposing the benefit of stacking textile in a double-layered composition and increasing the distance from the rigid background. On the figures 5, 6 and 7 measured values for different textile types at different configurations are presented.

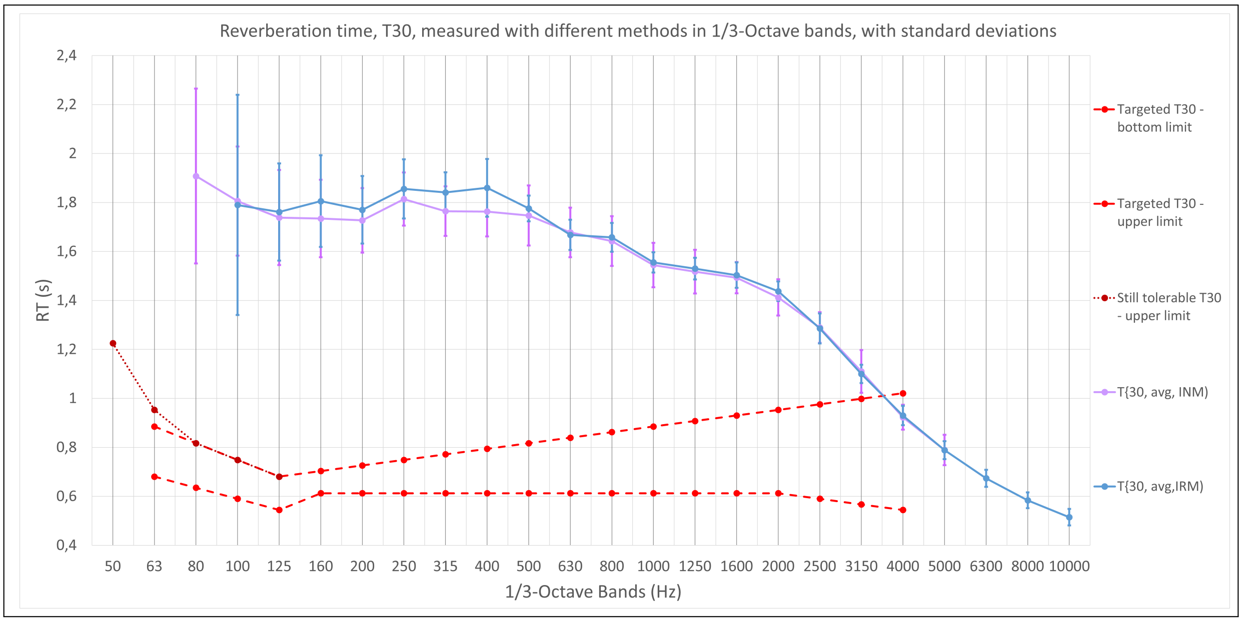

Figure 4. Average reverberation time in 1/3-Octave bands measured by interrupted noise method (label INM) and by impulse response method (label IRM) with related standard deviation and targeted reverberation time range accordingly to Adelman-Larsen et al. [2].

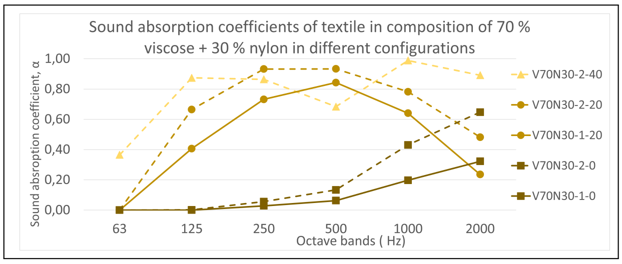

Figure 5. Measured values of the sound absorption coefficient in octave bands for 70 % viscose + 30 % nylon textile.

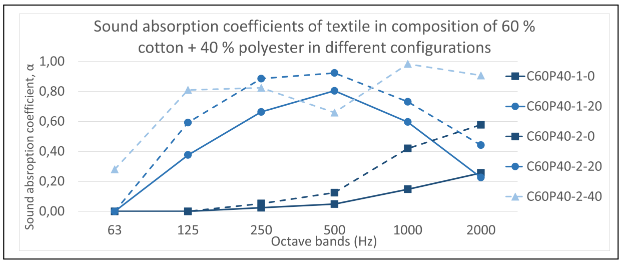

Figure 6. Measured values of the sound absorption coefficient in octave bands for 60 % cotton + 40 % polyester textile.

Double-layered composition with distance of 40 cm was recognized as the most suitable option, where average value of all measured textile types was used, since acquiring a material in composition of 70 % viscose and 30 % nylon, as best performing material, is virtually impossible.

4.3 Simulations

4.3.1 Group 1 - Concerts of modern music

In case of group 1 the final floor plan was determined after 6th iteration and is presented in figure 8.

With this proposed solution average values of D_{50} and BR were achieved at 0.74 and 1.06, respectively, which is in case of D_{50} within the requirement of 0.7 and in case of BR still off of required 0.81, but sufficiently close. On other hand this solution brings reverberation

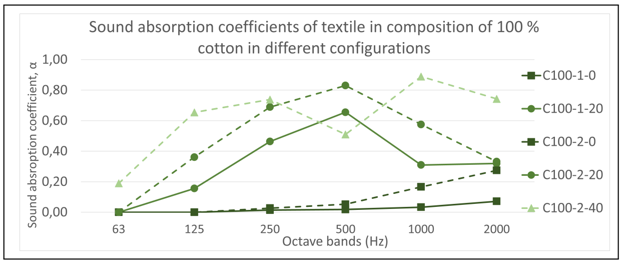

Figure 7. Measured values of the sound absorption coefficient in octave bands for 100 % cotton textile.

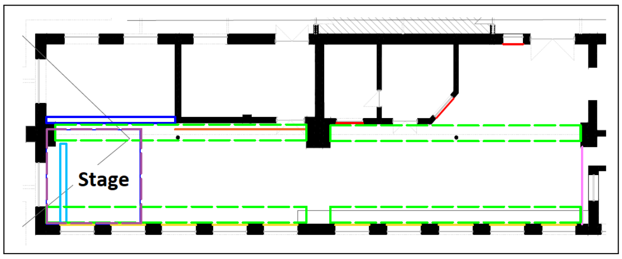

Figure 8. Final proposed solution for events of group 1 - colours are accordingly to the figure 3, full line represent vertical elements, dashed line are horizontal elements below the ceiling.

time into within the reachable goal. In table 4 it can be seen that the targeted reverberation time is achieved in all octave bands, with exception of 125 Hz. The cause of higher reverberation time in lower frequency is limit of used material, reused textile.

Table 4. Reverberation times of proposed solution for group 1.

f (Hz)	125	250	500	1000	2000	4000
$T_{30,targeted}$ (s)	0.68	0.75	0.82	0.89	0.95	1.02
$T_{30,current}$ (s)	1.78	1.83	1.75	1.55	1.41	0.94
$T_{30,solution}$ (s)	0.92	0.77	0.73	0.76	0.86	0.65

4.3.2 Group 2 - Speech-based events

For group 2, events based on speech, 3 different floor plans were prepared because a difference in requirements between theatre and lecture has been found during the study.

Firstly was studied theatre, which had similar requirements to concerts, since plenty of theatre plays include music performances. Proposed floor plan is very similar to the proposed solution for group 1, where only lateral element (see orange lines in figure 8) is either used or not depending on the amount of musical acts used in the theatre play.

For theatre and similar events reverberation time in octave bands 125 and 250 Hz is most important. Proposed solution fulfilled these requirements completely (see figure 5). Value of BR is slightly worse, being 1.14 compared to 1.06 in case of the group 1. D_{50} values are slightly lower compared to group 1 and in average is of 0.68.

Table 5. Reverberation times of proposed solution for group 2.1.

f (Hz)	125	250	500	1000	2000	4000
$T_{30,targeted}$ (s)	1.00	1.00				
$T_{30,current}$ (s)	1.78	1.83	1.75	1.55	1.41	0.94
$T_{30,solution}$ (s)	0.98	0.83	0.79	0.80	0.89	0.67

On other hand lectures have more loose requirements, therefore achieving those was simple and trouble-free. Additionally it was studied separately for larger and smaller lectures, where in the end smaller lectures differentiated from the larger lectures only in use of curtains over the stage, due to different position of the lectureres (in the top right side of the hall).

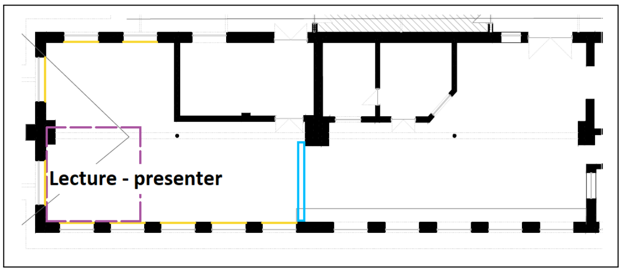

Figure 9. Final proposed solution for events of group 2.2 (lectures with larger audience) - colours are accordingly to the figure 3, full line represent vertical elements, dashed line are horizontal elements below the ceiling.

As seen on the table 6 values of reverberation time for the proposed solution for a larger lecture, 2.2, are within the desired range, whereas for smaller lecture, 2.3, are slightly over the requirements in case of octave band 125 Hz. Additionally the proposed solutions had calculated STI for larger lectures at 0.67 and for smaller lectures at 0.63, hence both fulfill the requirement of STI over 0.6.

Table 6. Reverberation times of proposed solution for group 2.2 and 2.3.

f (Hz)	125	250	500	1000	2000	4000
$T_{30,targeted}$ (s)	1.00	1.00				
$T_{30,current}$ (s)	1.78	1.83	1.75	1.55	1.41	0.94
$T_{30,solution,2.2}$ (s)	1,00	0,79	0,74	0,78	0,91	0,68
$T_{30,solution,2.3}$ (s)	1,19	1,03	0,98	0,97	1,04	0,75

4.3.3 Group 3 - Acoustically undemanding events

Exceptions is group 3, since for acoustically undemanding events sound absorbing panel, as only element that is always in the hall, already fulfills the requirements.

5. DISCUSSION

Proposed solutions successfully incorporated the existing industrial crane, on which a modular absorption panel has been mounted. This panel introduces larger absorption area that can easily be moved around the space depending on the type of event and its needs. The panel is designed from dark textile on one side and white wooden boards on other to be used simultaneously as projection screen and absorber. On top of that design of the modular panel allows moving the panel to the central arched beam, closing the pathway and dividing the whole hall into two smaller parts.

The design of the panels follows 10 principles of DfD, with focus on connections. Different types of materials are jointed in a way to maintain visibility and simplicity of the joint. For connection between textile and wooden laths simple linear clamping, as is usually for posters, is allowing easier and faster repairing or improving of the panel. All the joints are mechanical, hence no chemical bonding was needed.

Bigger textile pieces are assembled with multiple T-shirts, sweaters and trousers by simply stitching them together. The curtains were designed in shape of reels, that can be unrolled when absorption is needed and rolled up when not needed so that the authentic look of the space remains unchanged as much as possible.

Solutions for different groups of events were expected to differentiate, hence amount of needed absorption varies among them as well. By coinciding the needed absorption areas it was possible to minimize the number of different variations. The proposed absorbers for group 1 were then included also into solutions of other groups, which were not acoustically as demanding as concerts of modern music styles. The total amount of reused textile needed for the proposed acoustic renovation is 565,96 m^2, due to double-layered nature of elements. This constitutes to approximately 24.1 % of all surfaces inside the hall, which is below the initial estimation of needed sound absorption areas to be 1/3 of all areas due to distinctly elongated shape of the hall.

Proposed solution fulfill the requirements for the type of events within certain group. Exception are concerts of modern music, where reverberation time in octave band 125 Hz is still above the desired value. Nonetheless the proposed solution has halved the reverberation time in this octave band. Adding more absorption is believed not to be a step forward, since it would contradict initial efforts of emphasizing existing architectural and industrial features. Together with absorption brought with audience this could result in too dry environment in the higher frequencies. Therefore it is proposed to solve the issue of lower frequencies using different type of absorber, e.g. Helmholtz on the other side of the movable panel or on inner walls. For all the other groups of events requirements for values of RT, D_{50}, BR and STI were met.

6. CONCLUSIONS

At the start of the study it was expected that existing architectural and industrial features are going to be an obstacle to incorporate into the renovation design. However, arched and waved steel ceiling cause minimal issues to room acoustics. With this study it has been proved that abandoned and degraded industrial buildings can be acoustically renovated into a multipurpose venue for concerts of rock and pop music using reused textile waste. Additionally a design approach DfD has been successfully exercised during this study together with creatively incorporating existing technical features of the space. Main benefits are economical, since any subsequent solution of room acoustics would be more expensive.

The initial gap between the current and desired room acoustics has been easily overcomed with reused textile, which showed great potential as second-hand resource. However, reused textile opened a new discussion on fire safety, time durability, health hazard, cleaning options and aesthetics. Nonetheless reused textile needs to be highlighted as highly workable material within the scope of deisgn-for-disassembly, since it is easy to combine it with different materials and simple to repair.

Acoustic requirements of all types of events were fulfilled with the proposed solutions. However, additional challenges were met during the design of renovation. Main challenge presents the shape of the main hall, which in a C-shape with an extra narrowing at the middle of the hall complicates achieving similar acoustics conditions throughout the whole hall. This poses a question of listeners experience when they are in the other half of the hall and a potential future research on finding most suitable geometry of the hall if changes of inner walls are possible.

Floor plans represent integration of sustainable design approaches and acoustic renovation, where adaptability of the space and recycled acoustic elements are main highlight of the study.

7. ACKNOWLEDGMENTS

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