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Computational and empirical assessment of the acoustic performance of repurposed university spaces

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Abstract

Educational institutes located in historical buildings must frequently repurpose available spatial resources toward accommodation of new and emerging functional needs. This may lead, among other things, to problems regarding the acoustic performance of the repurposed rooms. Specifically, a central function of spaces in academic settings is information exchange, which requires suitable acoustic conditions. In this context, the present paper entails the acoustic study and evaluation of selected rooms in a university building, which have been repurposed to serve as multi-functional learning and working environments. To this end, both computational means and diagnostic methods were employed. The results of the study suggest that the room acoustics conditions in the repurposed rooms deviate in part from those recommended in pertinent standards.

Introduction

Most universities can benefit from increased availability of learning and working spaces for students. Particularly in case of universities located in historical buildings, infrequently used spaces are often repurposed, regardless of their original function. As such, the repurposed spaces could accommodate students' needs in view of activities such as lectures, review sessions, and collaborative work. This change of use process can have various implications, including those pertaining to room acoustics.

This paper specifically addresses potential challenges regarding room acoustics conditions in repurposed university spaces. Thereby, the reverberant field is investigated in a number of university spaces (Oldland, 2021), whose original functions (e.g., storage space, testing hall) did not necessitate the same acoustic requirements that their new functions do (e.g., seminar room, learning area). The acoustic performance of the repurposed rooms is in this case of essential importance for students' comfort, productivity, and learning ability.

Approach

Overview

The research design included the following steps:

i) Selection of three recently repurposed spaces in a university building (TU Wien campus, Vienna, Austria) based on criteria such as room geometry, size, and capacity as well as the original and new function. There rooms are referred to as A, B, and C (see Table 1);
ii) Measurement of the acoustic conditions (i.e., reverberation time, sound level distribution) in the selected rooms under unoccupied conditions;
iii) Acoustic simulation using two software tools (Odeon 11.0 Combined and Pachyderm Acoustical Simulation) (food4Rhino, 2021; Odeon, 2011; ORASE, 2021);
iv) Iterative adjustment of the simulation model using measured data;
v) Application of the calibrated simulation models to simulate the acoustic conditions in the occupied settings;
vi) Evaluation of the acoustic conditions based on applicable standards;
vii) Comparison of the utility of the employed simulation tools.

Table 1 and Figures 1 to 3 provide an overview of the selected university spaces, which differ in size (ranging from approximately 80 to 500 m²), maximum capacity of seats (ranging from 40 to 300), as well as their surface materials.

Table 1: Overview of evaluated university spaces

Space	**A**	**B**	**C**
Total interior surface area [m²]	904	398	2488
Usable Floor Area [m²]	266	80	484
Volume [m³]	1318	490	5910
Max. seat capacity	120	40	300
Initial function	Laboratory space	Storage space, occasional seminar space	Garage, testing hall
Current function	Multifunctional learning and working area	seminar room, workspace	Exhibitions, workspace
Occasional use for:	Dance lessons	Rehearsal space for university orchestra	Symposia

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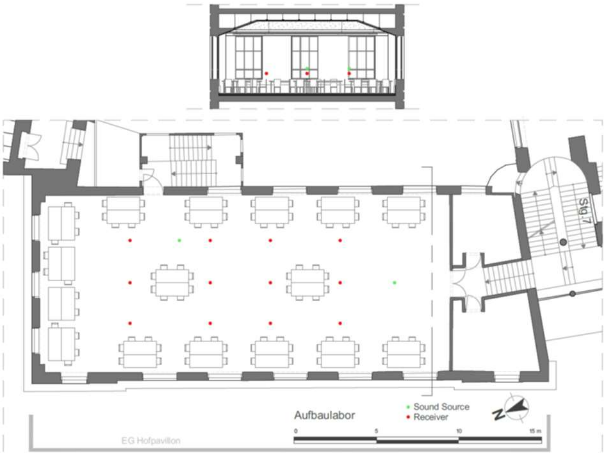

Figure 1: Floor plan (bottom) and cross section (top) of room A

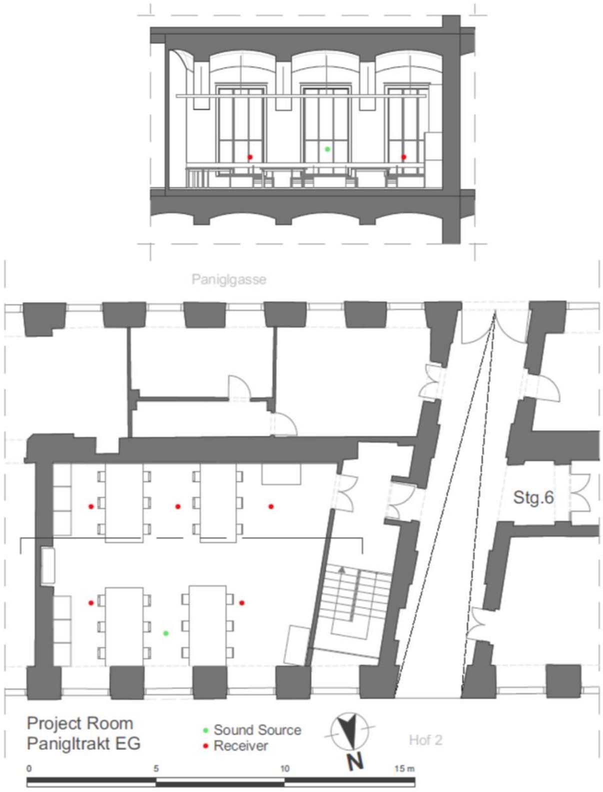

Figure 2: Floor plan (bottom) and cross section (top) of room B

These repurposed rooms are used for one or more of the following functions: assemblies, learning, studying, working, large-group instructions, lectures, events, and places to socialize and spend time between university courses. This considerably wide range of activities renders the provision of suitable room acoustic conditions a rather challenging task. Note that this small set of selected rooms does not represent the entire range and scope of functional reassignments in university buildings. As such, the study is not suggested to be representative of the mentioned classes of spaces. Rather, the intention is to exemplify certain acoustically relevant circumstances that may be encountered in similar settings.

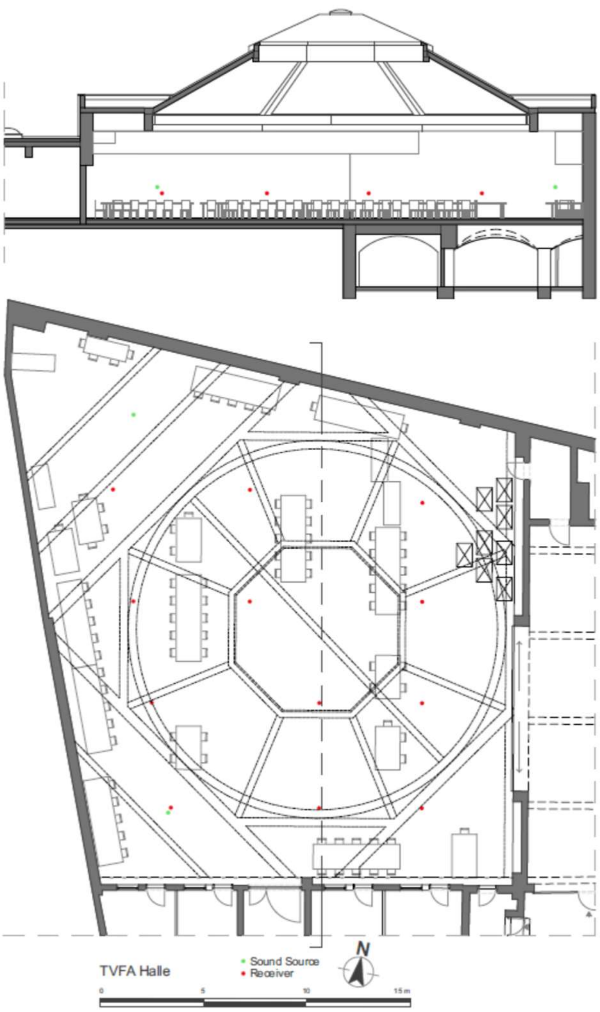

Figure 3: Floor plan (bottom) and cross section (top) of room C

Measurements

Measurements of reverberation time (unoccupied conditions), sound level distribution, and background noise levels were performed in the three selected spaces (see Norsonic (2020) for equipment specification) according to pertinent standards (ISO 3382-1 and ISO 3382-2) (ISO, 2008; ISO, 2009). The sound source was positioned 1.50 m from the ground. The receivers were distributed across a grid in each space relative to the space's size and geometry. During the measurements the temperature was recorded at 22°C and the relative humidity was 30%. The microphones were positioned at least 1.00 m from the surrounding surfaces and at a height of 1.20 m above the ground. The sound source and receiver positions are shown in Figures 1 to 3. Reverberation times were measured for octave band frequencies 125 Hz – 4000 Hz.

Simulations

Initially, the university spaces were modelled in the 3D CAD modelling software McNeel Rhinoceros (Robert McNeel & Associates, 2021) using plans provided by the university and on-site measurements. Room furniture elements (e.g., chairs, desks, shelves) were represented in the model in a somewhat simplified manner in terms of discrete areas with corresponding values of the scattering coefficients. The 3D geometry was then imported in DXF format into the acoustic simulation environment Odeon 11.0 Combined (Odeon, 2011).

To conduct the initial simulations, material properties had to be assigned to the room surfaces (sound absorption coefficients, scattering coefficients). This was done by selecting materials from the Odeon materials library (Odeon, 2022) that appeared to best match the respective surfaces (see Tables 2 to 4). The position of the simulated receivers and sound sources correspond to the position of the on-site receivers and sound sources.

The comparison of the results of the initial simulations with the corresponding measurement results displayed considerable deviations. Hence, the simulation input assumptions were modified iteratively (again using plausible options from Odeon's material library), resulting in an adjusted model that generated a better fit to the measurements (see Tables 2 to 4). Note that both the initial and adjusted model represent the rooms in non-occupied settings, in order to facilitate the comparison with the measured values, which were likewise obtained under a non-occupied state (measurements under occupied conditions were not feasible due to the prevailing circumstances at the time when this study was conducted). However, in order to gauge the acoustic performance of the rooms in view of applicable standards, the conditions must be assessed for occupied conditions, which can greatly deviate from the conditions in non-occupied settings. To this end, the aforementioned adjusted model was further modified to include occupants in the model.

Principally, surface scattering coefficients were set to the Odeon default value of 0.05. Specific surfaces representing audience, furniture, and cluttered areas were assumed to have increased scattering coefficients of 0.30. Large fabric surfaces were assigned a scattering coefficient of 0.60.

The model assumptions in the initial simulation, the adjusted simulation, and the occupied simulation were also used to derive the sound distribution in the three spaces. Thereby, the source and receiver positions in the simulation models correspond to those used during the measurements. As such, the simulation results (for the initial and adjusted simulations) can be compared to the respective measurement results. Note that the model assumptions for the three simulations (initial, adjusted, occupied) were also applied to estimate the reverberation times using the well-known simple Sabine equation.

Table 2: Room A: Surface materials – for iterative models I (Initial), A (Adjusted), O (Occupied) (Odeon, 2022)

Room A									
Surface		**Iteration**	**Material Description**	**sound absorption coefficients by frequency [α]**					
				125 [HZ]	**250 [HZ]**	**500 [HZ]**	**1000 [HZ]**	**2000 [Hz]**	**4000 [Hz]**
Floor		I, A, O	parquet on counterfloor	0.20	0.15	0.10	0.10	0.05	0.10
Audience Zone	unoccupied	I, A	wooden chairs, unoccupied	0.05	0.05	0.05	0.10	0.10	0.15
	occupied	O	audience on wooden chairs, 1 per sq.m	0.16	0.24	0.56	0.69	0.81	0.78
Walls		I	painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02
		A, O	plaster, gypsum or smooth finish on lath	0.14	0.10	0.06	0.04	0.04	0.03
Walls (with furniture infront)		I	painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02
		A, O	plaster, gypsum or smooth finish on lath	0.14	0.10	0.06	0.04	0.04	0.03
Ceiling (plastered)		I, A, O	painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02
Suspended Ceiling		I, A, O	mineral fiber ceiling tiles	0.34	0.43	0.54	0.67	0.65	0.64
		A, O	(middle section) hardly pressed mineral fiber ceiling tiles	0.45	0.60	0.60	0.80	0.80	0.65
Sound Insulation Panels		I	plaster, gypsum or rough finish on lath	0.14	0.10	0.06	0.05	0.04	0.03
		A, O	mineral fiber board without cover flush to wall	0.15	0.30	0.65	0.85	1.00	1.00
Projection Screens		I, A, O	painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02
Entrance Door		I, A, O	painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02
Side Door		I, A, O	double glazing, 2-3mm glass, 10mm gap	0.10	0.07	0.05	0.03	0.02	0.02
Windows		I, A, O	double glazing, 2-3mm glass, >30mm gap	0.15	0.05	0.03	0.03	0.02	0.02

Table 3: Room B: Surface materials – for iterative models I (Initial), A (Adjusted), O (Occupied) (Odeon, 2022)

Room B									
Surface		**Iteration**	**Material Description**	**sound absorption coefficients by frequency [α]**					
				125 [HZ]	**250 [HZ]**	**500 [HZ]**	**1000 [HZ]**	**2000 [Hz]**	**4000 [Hz]**
Floor		I	linoleum or vinyl stuck to concrete	0.02	0.02	0.03	0.04	0.04	0.05
		A, O	linoleum or vinyl + underlayer stuck to concrete	0.02	0.02	0.04	0.05	0.05	0.10
Audience Zone	unoccupied	I, A	wooden chairs, unoccupied	0.05	0.05	0.05	0.10	0.10	0.15
	occupied	O	audience on wooden chairs, 1 per sq.m	0.16	0.24	0.56	0.69	0.81	0.78
Walls		I	painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02
		A, O	plaster, gypsum or smooth finish on lath	0.14	0.10	0.06	0.04	0.04	0.03
Beams		I	painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02
		A, O	plaster, gypsum or smooth finish on lath	0.14	0.10	0.06	0.04	0.04	0.03
Vaulted Ceiling		I	painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02
		A, O	plaster, gypsum or smooth finish on lath	0.14	0.10	0.06	0.04	0.04	0.03
Pin Board		I	plaster, gypsum or rough finish on lath	0.14	0.10	0.06	0.05	0.04	0.03
		A, O	mineral fiber board without cover flush to wall	0.15	0.30	0.65	0.85	1.00	1.00
Locker Zone		I	solid wooden door	0.14	0.10	0.06	0.08	0.10	0.10
		A, O							
Ventilation Zone		I	painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02
		A, O							
Entrance Door		I, A, O	solid wooden door	0.14	0.1	0.06	0.08	0.1	0.1
Windows		I, A, O	double glazing, 2-3mm glass, 10mm gap	0.1	0.07	0.05	0.03	0.02	0.02

Table 4: Room C: Surface materials – for iterative models I (Initial), A (Adjusted), O (Occupied) (Odeon, 2022)

Room C									
Surface		**Iteration**	**Material Description**	**sound absorption coefficients by frequency [α]**					
				125 [HZ]	**250 [HZ]**	**500 [HZ]**	**1000 [HZ]**	**2000 [Hz]**	**4000 [Hz]**
Floor		I	smooth concrete, painted or glazed	0.01	0.01	0.01	0.02	0.02	0.02
		A, O	rough concrete	0.02	0.03	0.03	0.03	0.04	0.07
Audience Zone	unoccupied	I, A	wooden chairs, unoccupied	0.05	0.05	0.05	0.10	0.10	0.15
	occupied	O	audience on wooden chairs, 1 per sq.m	0.16	0.24	0.56	0.69	0.81	0.78
Walls		I	painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02
		A, O	plaster, gypsum or smooth finish on lath	0.14	0.10	0.06	0.04	0.04	0.03
Walls		I, A, O	concrete block, painted	0.10	0.05	0.06	0.07	0.09	0.08
Ceiling		I	painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02
		A, O	plaster, gypsum or smooth finish on lath	0.14	0.10	0.06	0.04	0.04	0.03
Sliding Garage Door		I, A, O	painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02
Side Doors		I, A, O	painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02
Windows		I, A, O	single pane of glass 3mm	0.08	0.04	0.03	0.03	0.02	0.02
Skylight Windows		I, A, O	single pane of glass 3mm	0.08	0.04	0.03	0.03	0.02	0.02
Skylight Panel Element		I, A, O	painted plaster surface						
Beams		I, A, O	smooth concrete, painted or glazed	0.01	0.01	0.01	0.02	0.02	0.02
Overhead Crane		I, A, O	painted plaster surface						
Canopy (shading element)		I, A, O	curtains, cotton cloth (0,33 kg/m²)	0.07	0.31	0.49	0.81	0.66	0.54
Stored Material		I, A, O	smooth concrete, painted or glazed	0.01	0.01	0.01	0.02	0.02	0.02
Ventilation System		I, A, O	painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02

Results

Figures 4 to 6 show the measured and simulated frequency-dependent reverberation times for the three analyzed spaces. Specifically, the graphs show the results from the initial and adjusted simulation models of Odeon and Pachyderm. The simulated reverberation times for occupied conditions are presented as well. Furthermore, the graphs include the estimated reverberation times based on the Sabine equation using the absorption coefficients assumptions of the three simulation cases (initial, adjusted, and occupied).

Figures 7 and 8 show the assessment results of the sound level distribution in the spaces. To this end, the graphs show the sound pressure level decrease as a function of the receivers' distance to the sound sources. The receiver closest to the sound source was selected as a reference receiver position. It was used to calculate the relative distances and relative sound pressure level differences (in dB(A)) between the individual receiver positions and selected reference receiver. The sound pressure level differences in room B were rather small, due to the small size and the corresponding small distances between the receiver positions and the source. As a result, they were not included in this paper.

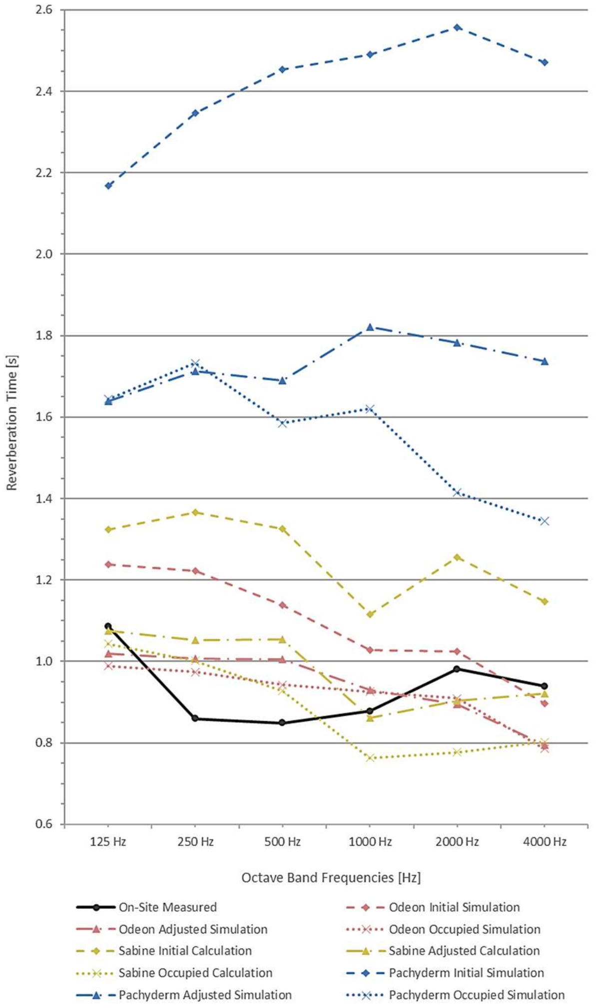

Figure 4: Calculated, measured, and simulated reverberation times for room A

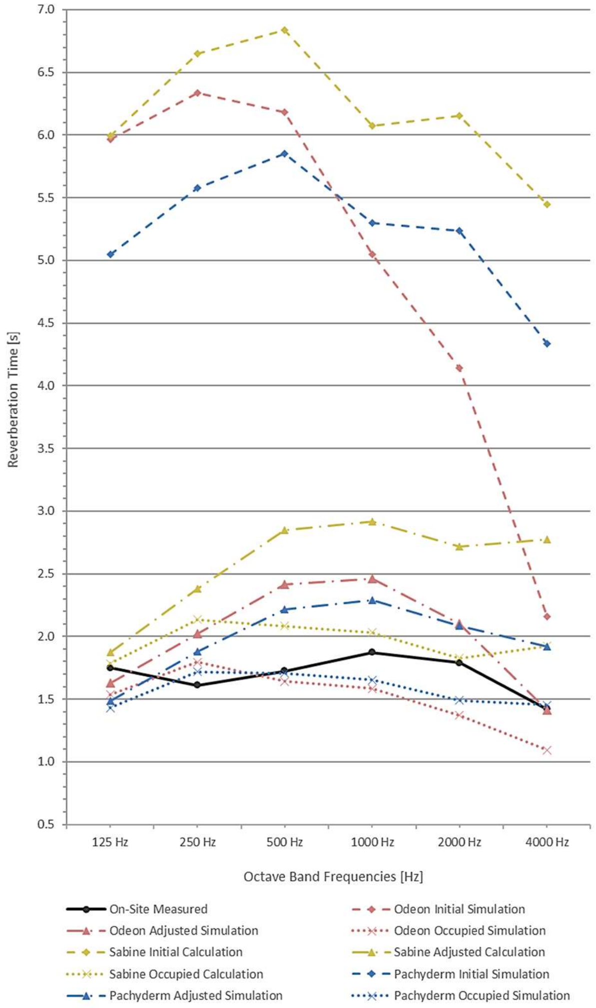

Figure 5: Calculated, measured, and simulated reverberation times for room B

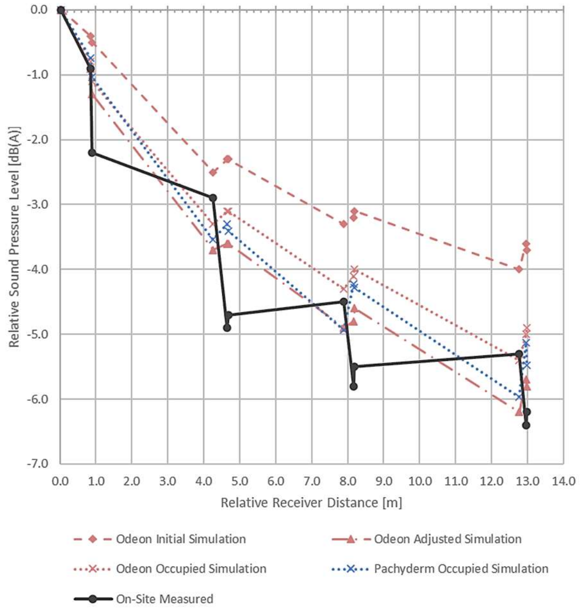

Figure 7: Measured and simulated relative SPL(A) decay results for S1 in room A

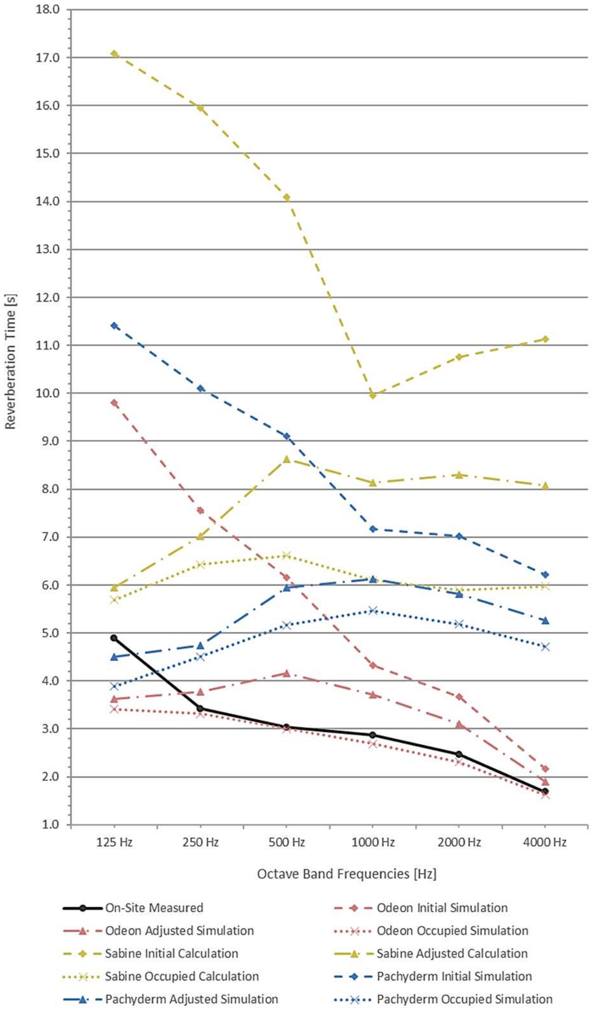

Figure 6: Calculated, measured, and simulated reverberation times for room C

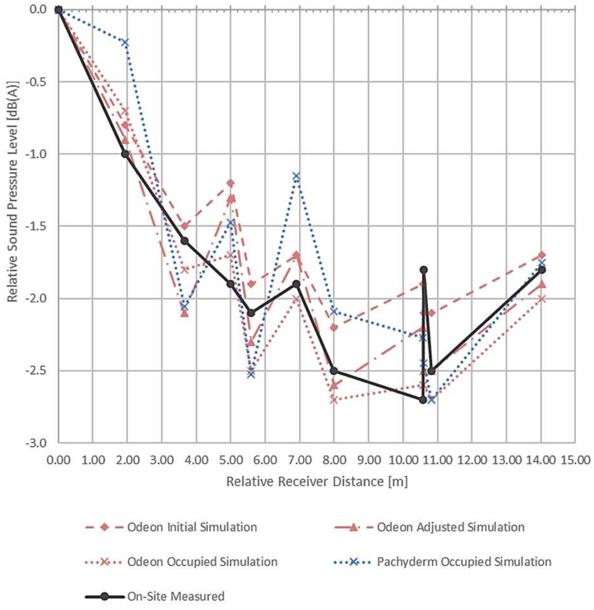

Figure 8: Measured and simulated relative SPL(A) decay results for S1 in room C

Discussion

A comparison of the measured and initially simulated reverberation times with Odeon showed that in case of all rooms (A, B, and C) the simulated values were overestimated (see Figures 4 to 6). Simulated reverberation times in room A were only slightly overestimated (mainly in the lower frequency range). The difference between the measured and initially simulated reverberation times in room B and C were clearly larger (see Figures 5 and 6). In a number of other comparable studies, where detailed information about the acoustical properties of the room elements was also not available, a similar overestimation tendency in the initially simulated reverberation times was observed (see, for instance, Vinca et al., 2021; Ferraz Madeira et al., 2022). However, note that due to the limited number of evaluated rooms, this finding cannot be generalized. A much larger number of similar case studies is needed to identify recurrent sources of error when using room acoustic simulation tools and help to further improve these tools in the long run.

Since the initially simulated reverberation time values were overestimated, the simulation input assumptions were iteratively modified to create an adjusted simulation model that generated a better fit to the measurements. For instance, in case of room A, the absorption coefficient assumptions were already fairly dependable and were consequently only slightly adjusted. The material adjustments included using a higher-absorptive plaster for the walls. Moreover, for the middle section of the suspended ceiling, a slightly more absorbing mineral fiber material was used. The adjusted absorption coefficients for room A, B, and C are shown in Tables 2 to 4.

Moreover, the results show that the reverberation times that were simulated with Odeon greatly differ from the ones simulated with Pachyderm. In case of rooms A and C, the reverberation times, which were simulated with Pachyderm are clearly longer than the results from Odeon. This applies to the initial, adjusted, and occupied simulation results. Consequently, the simulation results from Pachyderm also differ more from the measurement results. In case of room B, the adjusted and occupied simulation results from Pachyderm as well as Odeon are more similar.

The relative sound pressure level decay graphs mostly correspond to how sound pressure levels are typically distributed in relation to distance and the rooms' total equivalent absorption areas. However, as Figures 7 and 8 illustrate, the respective functions are not necessarily smooth. Hence, in some cases, points further away from the source may display levels slightly higher than points closer to the source. In case of both acoustic simulation applications (Odeon and Pachyderm), the relative SPL values are rather close to the measured values (see Figure 7 and 8).

The reverberation time values, which were simulated with Odeon for occupied conditions, were compared to recommendations in pertinent standards and literature (Fasold and Veres, 2003; ÖNORM, 2005; DIN, 2016). Such recommendations are commonly formulated for different types of functions (e.g., speech, multi-purpose).

Several previous investigations have likewise referred to these recommendations and compared them to measured or simulated reverberation time values in order to analyze the acoustic performance of indoor spaces (see, for instance, Puglisi et al., 2015; Vinca et al., 2021; Zannin and Zwirtes, 2009).

Certain tolerance ranges are given for the recommended reverberation time values (Fasold and Veres, 2003; ÖNORM, 2005; DIN, 2016). In the mid frequency range (250 to 2000 Hz), the tolerance range from the recommended value is ±20%. At higher and lower frequencies these limits are extended (see Figure 9 and 10 for more details).

Depending on the volume of the room, the recommended reverberation times (RTopt) for speech are 1.0, 0.9, and 1.2 s for rooms A, B, and C, respectively. For the multi-purpose category, the recommended values are 1.2, 1.1, and 1.5 s for room A, B, and C, respectively.

Figures 9 and 10 show the ratio of the simulated reverberation times (occupied scenario; RT) to the recommended values at 500 Hz (RTopt) for the categories multi-purpose rooms and speech. The corresponding tolerance ranges are illustrated as well.

When considering the recommendations for speech, only room A meets the requirements. The RT/RTopt ratio of the other two rooms is at all frequencies above the tolerance range. When evaluating the simulated reverberation time values with Odeon based on the recommendations for the category of multi-purpose rooms, it is noticeable that for nearly all frequencies, rooms A, B, and C do not meet the requirements.

Note that while the comparison of the employed simulation application tools was not the focus of the present contribution, the experience in the course of modelling warrants a few remarks on their attributes and usability. Odeon is a frequently used room acoustics simulation tool. When using this tool, room geometry is exported from a drafting tool and afterwards imported into Odeon. Nonetheless, the exported geometry may be too complex and contain data, which is not needed for the simulation. Therefore, additional work is necessary to simplify the model so that it can be used in an acoustic simulation.

In comparison, Pachyderm is an open-source plug-in for Rhino and Grasshopper. An advantage of Pachyderm is that since it is a plug-in, the geometry of a building can directly be assessed from Rhino. This is specifically beneficial in an early design stage, when various adjustments are still conducted to the geometry and the resulting effects to the acoustic performance are to be examined. Nonetheless, Pachyderm is still in development. As a result, the plug-in has still some limitations and bugs have not been fully resolved (ORASE, 2021). Subsequently, only a few tutorials are available. In comparison, tutorials and detailed documentation are available for Odeon.

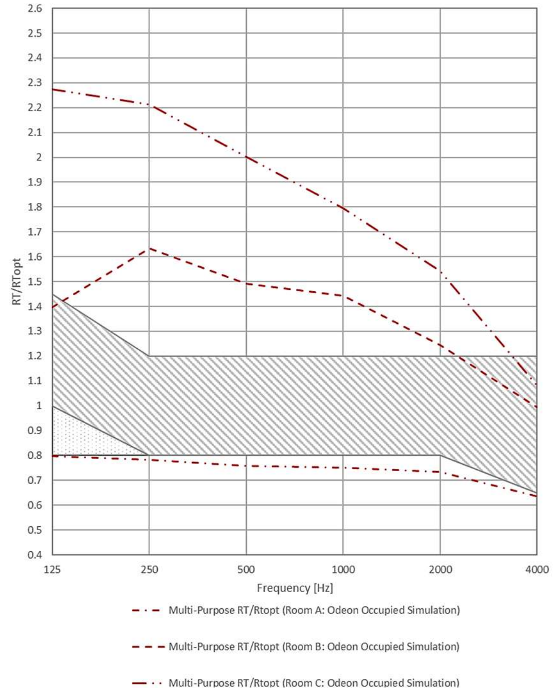

Figure 9: RT/RTopt ratio for all evaluated spaces for multi-purpose uses

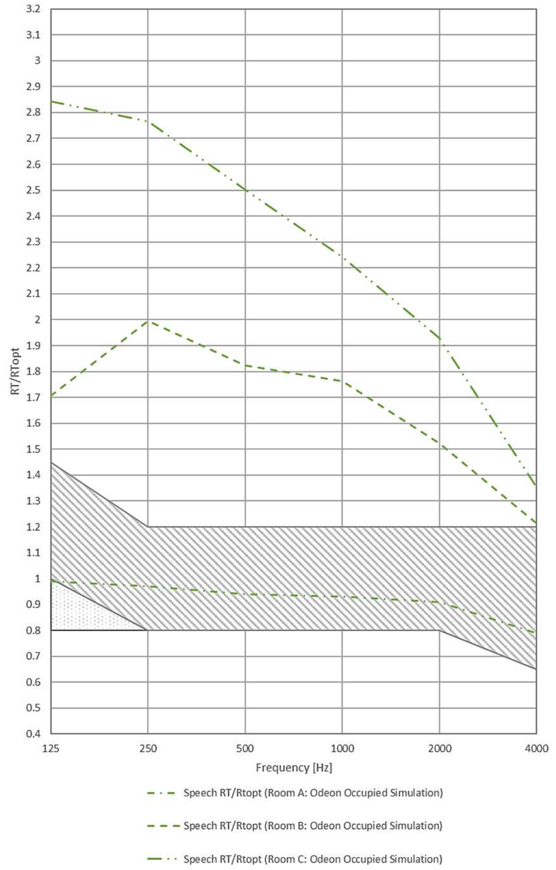

Figure 10: RT/RTopt ratio for all evaluated spaces for speech uses

Another main difference between the two tools observed in the course of this study is the simulations' running times. While the simulation durations in Pachyderm ranged from 40 minutes to 4 hours, the Odeon simulations took less than two minutes.

Conclusion

This contribution explored the acoustic performance of three repurposed university rooms in a university. Two common attributes of room acoustics, namely reverberation time and sound pressure level distribution were considered toward assessing the acoustic performance of these rooms. The values of these room acoustics indicators were obtained via on-site measurements, simulations with two room acoustics simulation tools (Odeon and Pachyderm), and simplified calculations using the Sabine formula.

Measurements could only be conducted under unoccupied conditions. The initial simulations were also conducted for unoccupied conditions. The same input data (specifically, absorption coefficients of the surface materials) was used in both Odeon and Pachyderm.

One of the main objectives of the present study was to contribute to the efforts that compare acoustic measurements to simulation results in order to gain insights on the potential and limitations of room acoustic simulation models. As mentioned before, the study's finding cannot be generalized due to the limited number of assessed indoor spaces. Nonetheless, the findings can support the formulation of future meta-studies that would entail a larger number of objects and hence more confidently identify the recurrent sources of error in room acoustics simulation.

In case of the present study, the initial simulations with Odeon revealed major deviations from the measurement results. A likely contributing factor to this circumstance is the absence of verified information on the rooms' surface materials (i.e., absorption coefficients). Hence, the simulation input assumptions were iteratively modified so as to obtain a better fit to the measurements. These adjusted simulation models were used to estimate the acoustic conditions under occupied settings.

The resulting reverberation times revealed lager differences depending on whether they were simulated with Odeon or Pachyderm. As such, the reverberation times obtained from Odeon were found to be closer to the measurement results.

The reverberation times obtained from the occupied simulation model in Odeon were compared to optimal reverberation time values, which are specified in pertinent literature and standards. The results of this study suggest that the three analysed repurposed university spaces in most cases do not meet the requirements for speech and multi-purpose uses. This implies, in the specific context of the present study, the need for acoustic retrofit measures. More generally, the lessons from this study highlight the essential utility of calibrated simulation models in the design and implementation of such retrofit measures.

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