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The Possibility of Providing Acoustic Comfort in Hotel Rooms as an Element of Sustainable Development

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Abstract: The noise problem in hotel rooms is strictly connected to noise generated by heating, ventilating, and air conditioning (HVAC) devices. Hospitality industry companies in many countries have specific requirements and monitor the noise level with technical equipment inside the hotel room. To ensure an adequately low level of noise from the HVAC system, proper calculations and tests are performed before the final application of the system in the hotel room. One of the best methods for assessing the noise level from HVAC devices in hotel rooms is to create a testing room (mock-up) in a certain available space, e.g., in a warehouse, and to perform appropriate standard measurements for the noise level. This method is a popular choice in the hotel industry because the noise level can not only be verified, but also, the installation and operation of the HVAC system inside the room can be checked. The main factors in choosing the space in which the mock-up will be made are availability and appropriate volume. It is not always possible to provide a hall space with a very low background level of noise. This article shows that the selection of a mock-up space is also determined by the noise level in the selected space. The background noise level—thus, the noise level in the mock-up room—must be low enough to be able to reliably measure the noise level from the HVAC equipment to avoid the phenomenon of acoustic masking by other noise sources (background noise) not related to the measurement. Background noise at too high a level will lead to invalidation of the measurement results or overestimation of the actual noise level in the room from the tested HVAC devices. In this study, background noise level measurements made in the testing rooms are described. The results are discussed, and a conclusion is drawn.

Keywords: sustainable comfort; acoustic comfort; noise; HVAC devices

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1. Introduction

Sustainable development—including eco-development and also, more generally, the sustainability doctrine of economics, which is based on the quality of life allowed by a civilization's current level of development—has become an important issue in recent decades. In 2015, the 2030 Agenda was adopted by all member states of the United Nations. The 2030 Agenda is a very important initiative that aims to define the paths of development for the world by defining 17 Sustainable Development Goals. The third goal of this Agenda is good health and quality of life; noise comfort is a part of this goal.

Sustainable design has created many benefits and challenges to mechanical noise control efforts. From equipment selection to HVAC system noise suppression, these changes are influencing industry designs and acoustical effects. Engineers usually do not have much control over building design decisions or architectural choices, and thus, they must adapt to meet noise goals and requirements. When engineers incorporate improved acoustic design into sustainability efforts, they can positively impact the occupants' comfort while reducing energy consumption; this problem is significant mainly in hotels, where both energy consumption and noise can be determinants in the design of HVAC systems.

Sustainable indoor comfort is mainly understood as thermal comfort in connection with humidity [1,2]; however, comfort entails a whole spectrum of issues that affect whether one lives or works comfortably in a room, including indoor air quality [3], acoustic or vibration comfort [4], and sunlight [5]. These studies focused on one aspect of sustainable indoor comfort, namely, acoustic comfort, as disruption of this comfort may not only be annoying, but can also lead to physical and mental diseases. For example, long-time noise exposure can lead to hearing loss [6], headaches [7], cardiovascular disease [8], and cognitive impairment in children [9]. Psychologically, noise can cause anxiety, nervousness, and aggression, as well as sleep disturbances, depression, anxiety, and other mental disorders [10,11]. There is an economic aspect of acoustic comfort: its provision or absence may affect the price of the property or the rental price [12]. Therefore, owners of high-standard hotels also place great emphasis on ensuring acoustic comfort in hotel rooms.

There are various possible sources of noise and vibrations in hotel rooms, such as nightclubs and bars within the hotel; nearby restaurants; guests in adjacent rooms (for example, excessive snoring and overly loud televisions); disturbances and footsteps in corridors; roads, rail, and traffic outside the hotel; and air-conditioning. The variety of noises can be divided into two main problems: outdoor [13,14] and indoor noise.

Noise is an undesirable phenomenon. It causes irritation, fatigue, and tiredness in the whole organism, especially the hearing organs. Noise can damage hearing, but also has adverse, nonauditory effects. The stress-inducing effect of noise may contribute to the development of digestive system diseases (peptic ulcer disease), cardiovascular diseases (arterial hypertension), and neurotic reactions [15–17]; it can disturb sleep and concentration, reduce intellectual capacity, and cause fatigue and anxiety. The negative effect of noise depends on its intensity, nature, and duration. Short-term exposure to high-intensity noise can cause so-called acute acoustic trauma, resulting mainly in hearing impairment or damage. We talk about the chronic effect of noise when its exposure time is long, often counted in years. Not everyone is equally sensitive to noise. Teenagers, small children, and young people are particularly exposed to its harmful effects.

We use hotel and leisure facilities, as well as conference and training centers, for business and private purposes. Such facilities are usually surrounded by greenery. The aesthetics of such a building's surroundings are also its showpiece. Managers taking care of the green areas around the facilities most often use loud internal combustion engines for their work, thus disturbing the peace and quiet of the guests. The customers of the facilities—both business and individual—expect cleanliness and order, but also acoustic comfort, which allows them to calm down and relax from the hustle and bustle of everyday life. Silence has become a luxury at certain times. When looking for a place to relax, hotel guests are guided not only by the wide selection of attractions on site, but also by their desire to ensure that the place to which they are going will provide them with peaceful and noise-free rest. The ubiquitousness of noise in everyday life increases the longing for the contrast of undisturbed rest in a quiet environment, close to nature. The outdoor noise problem becomes most burdensome in spring and summer, when greenery works begin around the buildings with the use of noisy combustion engines. The well-kept area around the facility is its showcase, but the noise causes frustration for guests who expect acoustic comfort. This outdoor noise, which should be reduced by building partitions [18], windows, and doors, is one of the types of noise which can be found in hotels.

Even if outdoor noise in a hotel room is eliminated, the problem with acoustic comfort may remain. The problem may still be present due to the number of devices which cause the noise (Figure 1). Hotels have central heating, ventilation, and air conditioning (HVAC) systems which generate noise that may disturb guests' sleep [19,20]. The noise propagates through ducts and room surfaces. Individual room air conditioning units may also cause unpleasant noise. The HVAC system noise consists of:

(a) Low-frequency fan noise—fans generally produce sound in the 16 Hz to 250 Hz octave band range.

(b) Low to mid-frequency variable-air-volume (VAV) box noise—usually in the 125 Hz to 500 Hz octave band range.
(c) Mid-frequency airflow or turbulence-generated noise—velocity noise from airflow and turbulence in a duct ranges from 31.5 Hz to 1 kHz.
(d) High-frequency damper and diffuser noises—usually in the 1 kHz to 4 kHz band range.

In this article, the background noise (outdoor noise) problems in hotel rooms are considered, and the outdoor noise measurements are made and analyzed.

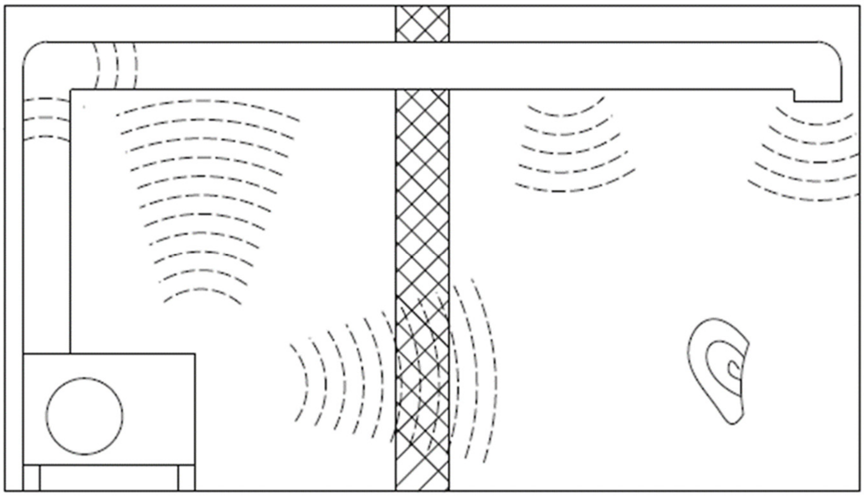

Figure 1. Indoor noise annoyance sources.

2. Measurement Site and Methodology

In this section, the details about the hotel mock-up rooms and background noise level assessment are presented. The testing site consists of two mock-up rooms: room 1 is the small one and room 2 is the large one. Plans of the mock-up rooms with measurement point positions are presented in Figure 2 (the green line shows walls exposed to noise originating from the hall). Measurements points were located as follows:

- The first two positions were chosen in the corner of the room at 0.5 m above the floor and 0.5 m from the nearest wall. The corner with the highest noise level C was selected;
- The other four measurement positions were selected in the scattered field. The distance between the measuring points was at least 1.5 m for large room 2. Due to the small size of room 1, this distance was reduced to 0.75 m. Each of these measuring points was located at least 0.75 m from any wall and at least 0.5 m above the floor, but not higher than 1.5 m.

The mock-up rooms reflect typical hotel rooms. The area of the small room—room 1—is 13.7 m^2, whereas the area of the second one—room 2—is 23.2 m^2. The room walls were made in accordance with the drywall system, with 12.5 mm gypsum plasterboard paneling on both sides with a mineral wool filling. The windows are built into the walls: for the small room, there are two identical windows of 120 $\times$ 140 cm, and for the large one, there are four windows of the same size. The mock-up rooms can be accessed through the high single-panel doors that are 90 $\times$ 200 cm.

The noise level was measured with a class 1 analyzer, defined in [21], that consists of a two-channel Norsonic NOR150 with Nor1225 (mic)/Nor1209 (preamp) microphone sets and an Nor1256acoustic calibrator. The NOR1225 microphone used in NOR150 is a 1/2″ free-field, 50 mV/Pa sensitivity condenser microphone, which is a general purpose microphone covering the frequency range from 3.15 Hz to 20 kHz and has a frequency response of $\pm$1 dB 5 Hz–10 kHz, $\pm$3 dB 3.15 Hz–20 kHz. The calibration was performed with a Nor1256 calibrator, using 94 dB and 114 dB with the 250 Hz and 1 kHz sinusoidal signal. The combination of two different levels and frequencies allows both level and frequency linearity to be verified. Additionally, the sound calibrator measures the environmental conditions: air pressure, temperature, and humidity. The measurement system is shown in Figure 3.

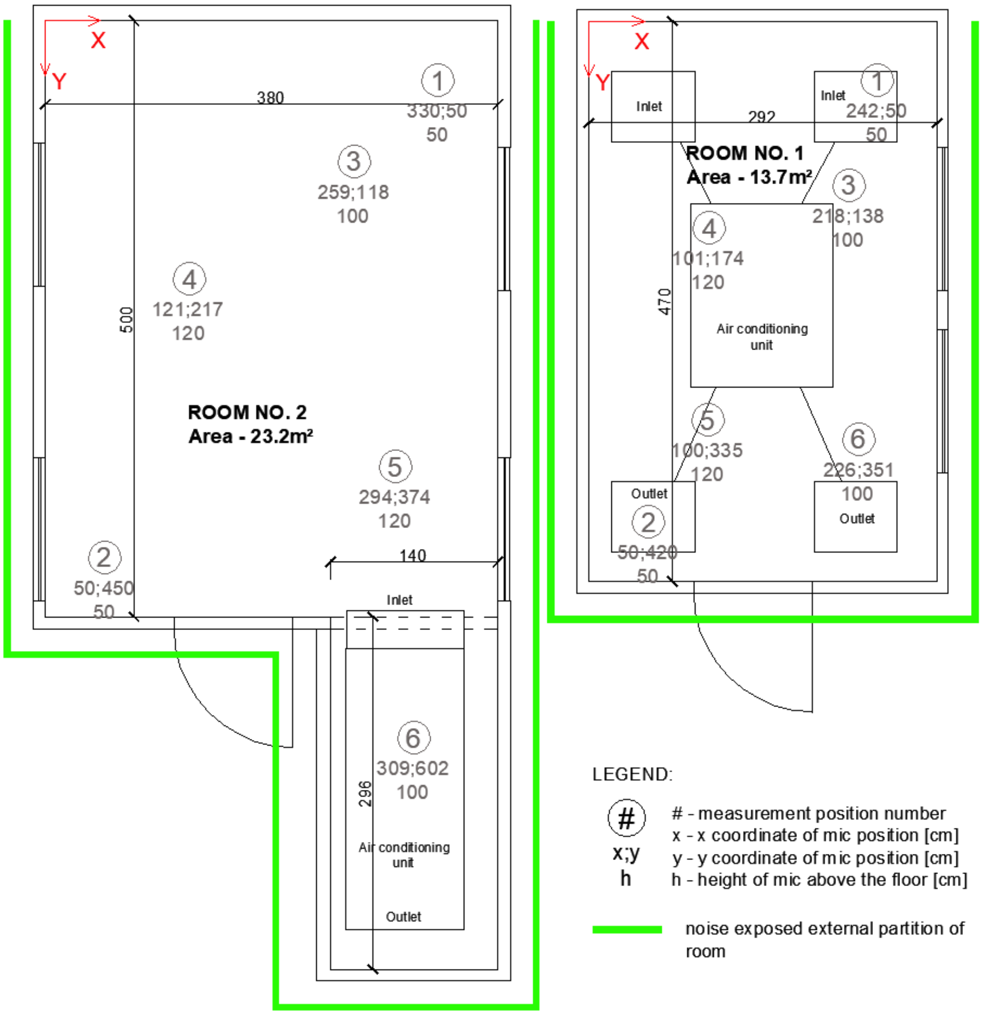

Figure 2. Plan of two mock-up rooms located inside the industrial hall.

Figure 3. Measurement equipment used for the tests.

The rooms are located inside the industrial hall, which has been divided into two floors. Activities related to the production and assembly of manufactured devices take place on the lower floor, generating a high level of noise with a wide frequency spectrum. On the upper floor, storage space is located where the mock-up rooms are set up. Since there is no significant noise protection for the storage space, noise from the lower floor production and assembly floor space is transferred to the storage space. This causes a high noise level to penetrate the mock-up rooms.

The mock-up rooms are used to measure the noise level from the HVAC devices. However, a high level of noise from industrial activities may cause the phenomenon of acoustic masking [22] due to room envelope sound insulation deficiency [23] and, consequently, can affect the measurement of the actual noise level from the tested HVAC devices. Therefore, a prior assessment of the noise is required.

The background noise level was assessed according to the standard [24]. The aforementioned class 1 acoustic analyzer, defined in [21], was used for the measurements. Calibration of the measured sound level was performed during each measurement with a class 1 calibrator compliant with the relevant standard [25]. For each of the rooms, 6 measurement points were selected that met the following rules:

- The first two positions were chosen in the corner of the room at 0.5 m above the floor and 0.5 m from the nearest wall. The corner with the highest noise level C was selected;
- The other four measurement positions were selected in the scattered field. The distance between the measuring points must be at least 1.5 m. Each of these measuring points was located at least 0.75 m from the walls and at least 0.5 m above the floor, but not higher than 1.5 m.

The duration of the measurement at a single point was 10 min to average the noise from various transient noise sources.

For each measurement point, the value of the average sound pressure level was determined during the 10-min measurement. Then, individual values of sound pressure levels at different microphone positions in each room were averaged according to Formula (1):

$$L_{Aeq} = 10\log_{10}\left(\frac{1}{n_{mes}}\sum_{i=1}^{n_{mes}} 10^{0.1L_i}\right) \quad (1)$$

where:

L_{Aeq}—equivalent sound pressure level in the room;
L_i—sound pressure level at i-th microphone positions;
n_{mes}—number of measurement points.

Measurements were made for two background noise scenarios. In the first situation, the equipment operators in the production hall were not informed about the need to maintain silence (high-level period), and the work was carried out in a regular manner for the production plant. In the second background noise situation, the production hall workers were asked to turn off the devices and remain silent during the measurement (low-level period).

3. Measurement Results

3.1. Evaluation of Average Levels

In this section, the results of the on-site measurements are presented. Figures 4–7 show the results of equivalent sound pressure levels at two different noise periods inside and outside the measured hotel mock-up rooms. These results are given in one-third octave frequency bands with given center frequencies. To minimize unnecessary graphs and provide clear visibility, the results are presented through a line graphs instead of bar graphs.

The measurement results shown in Figure 4 were obtained in a high-level period. The obtained results for the A-weighted sound level for the small mock-up room 1 is 35.7 dB, and for the large room 2 is 37.3 dB. The sound level outside the rooms—in the hall—is 62.3 dB.

In Figure 5, the A-weighted equivalent sound level during the low-level period is shown. For room 1 it is 27.4 dB, for room 2 it is 26.8 dB, whereas in the hall it is 46.5 dB.

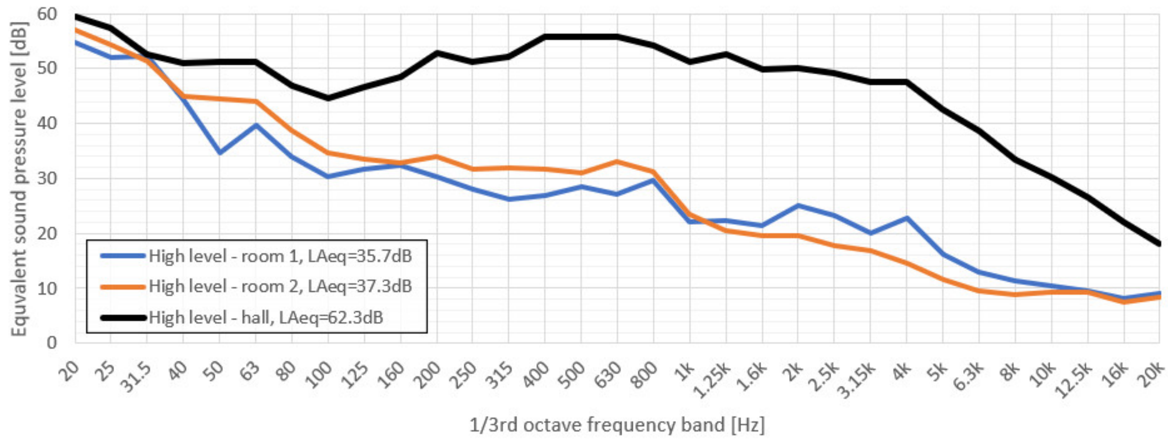

Figure 4. Measured equivalent sound level during the high-level period.

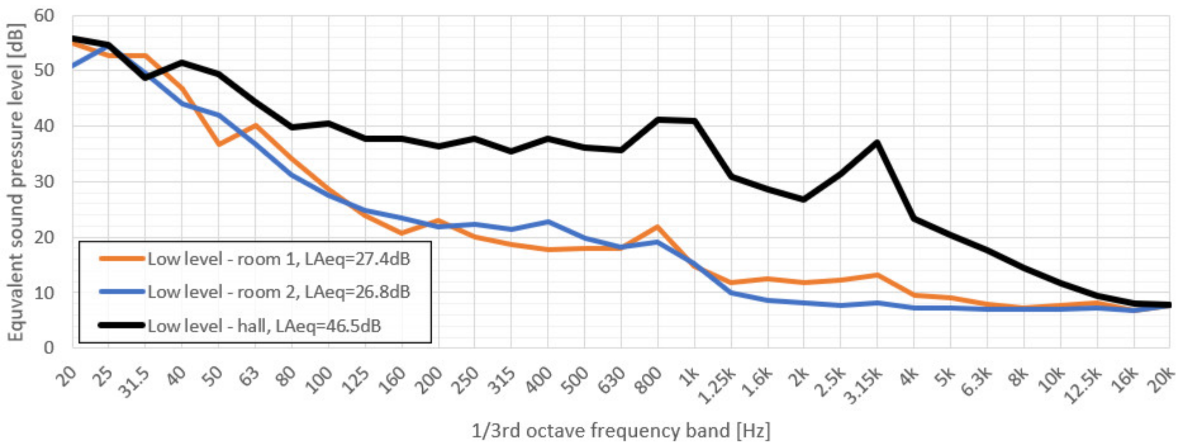

Figure 5. Measured equivalent sound level during the low-level period.

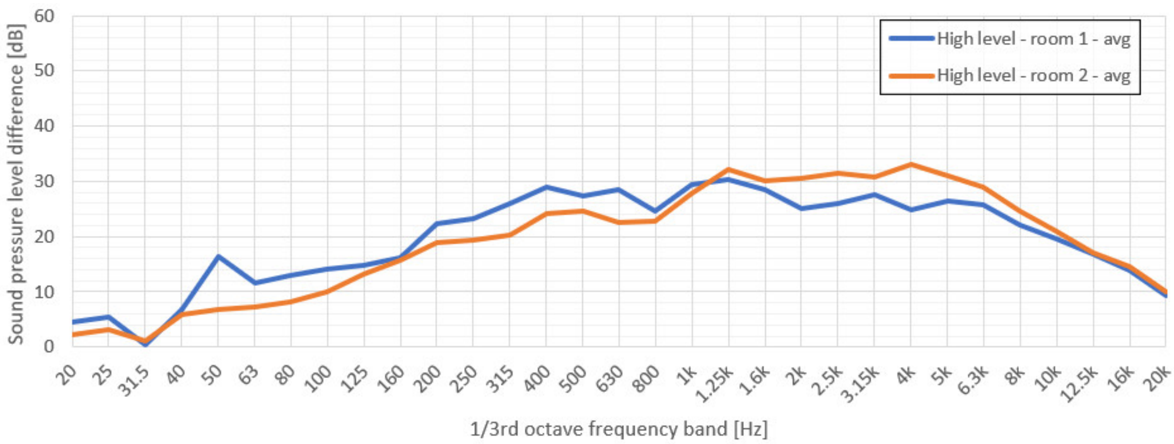

Figure 6. The estimated level difference between the hall and mock-up room during the high-level period. The level difference was obtained from the equivalent sound level in the hall minus the equivalent sound level in the room (1 or 2) recorded during the high-level period (Formula (2)).

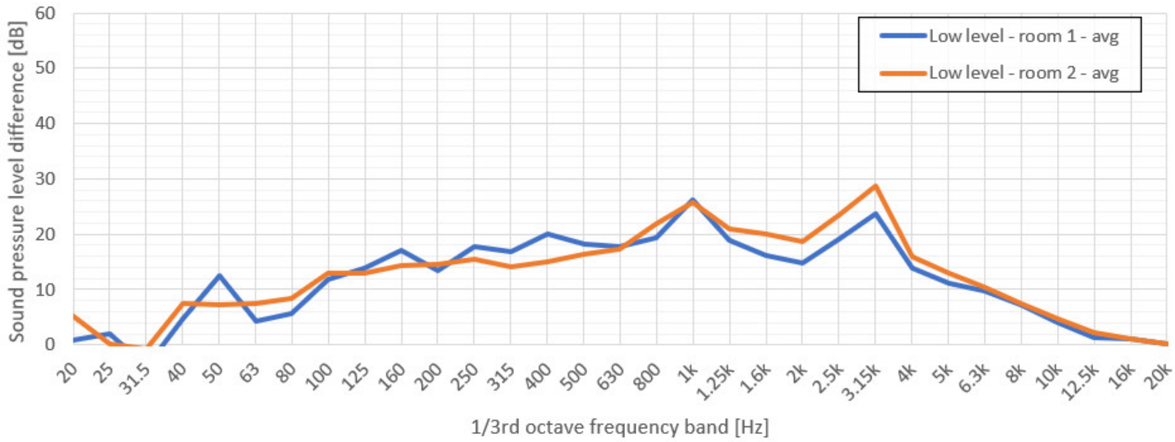

Figure 7. The estimated level difference between the hall and mock-up room during the low-level period. The level difference was obtained from the equivalent sound level in the hall minus the equivalent sound level in the room (1 or 2) recorded during the low-level period using Formula (2).

There is a clear difference between the high- and low-noise periods, which can be demonstrated using the A-weighted equivalent sound level. However, when looking at the individual one-third octave bands, this difference becomes blurred already from the 100 Hz band downwards. This is due to a heavy vehicle road in the vicinity of the building. The low-frequency nature and low insulation of the external partition at low frequencies resulted in a high level of low-frequency noise at the mock-up site.

Based on the measured noise levels, it is possible to estimate the sound insulation of the partitions surrounding the rooms using the level difference between the hall and the mock-up rooms. Such level differences are presented in Figures 6 and 7. Measurements at a high-level period and low-level period allow us to say, at least to some extent, how much noise in the hall would have to be lowered to achieve the desired background level in the mock-up rooms. The level differences presented in the article were calculated using the formula:

$$D_{1/3OB} = L_{1/3OB,hall} - L_{1/3OB,room} \tag{2}$$

where:

$D_{1/3OB}$—sound pressure level difference in the considered one-third octave band;

$L_{1/3OB,hall}$—sound pressure level in the considered one-third octave band recorded in the hall;

$L_{1/3OB,room}$—sound pressure level in the considered one-third octave band recorded in the analyzed room.

Particular attention should be paid to the noticeable differences between Figures 6 and 7. Measurements in the high-level period show a significantly greater level difference than in the low-level period. This is because, with a lower noise level in the hall, other noise sources may be measurable that are not recorded in the hall and are present, to a lesser extent, in the mock-up rooms.

Low-frequency sound insulation, presented as the level difference, is only residual. It is a common phenomenon in building partitions, especially in double-leaf partitions [26]. The sound level difference increases with the frequency up to a 3.15 kHz/4 kHz band. The drop in sound level difference above this band can be explained by the insufficient high noise level in the hall outside the mock-up rooms.

Summing up, it can be said that the industrial hall is not the only noise source in the mock-up rooms. The noise also comes from the building exterior, such as vehicles driving outside the hall, which penetrates the mock-up rooms through the hall roof, and comes from the rooms adjacent to the hall and the mock-up room at the same time, in which there was noise from other activities.

3.2. Evaluation Level Difference Using Statistical Levels with 5% and 95% Probability of Exceedance

Evaluation using average sound levels is a common practice in building acoustics. Still, because the noise in the hall was not constant, but rather transient, as shown in Figure 8, there might be a need to consider statistical levels of exceedance.

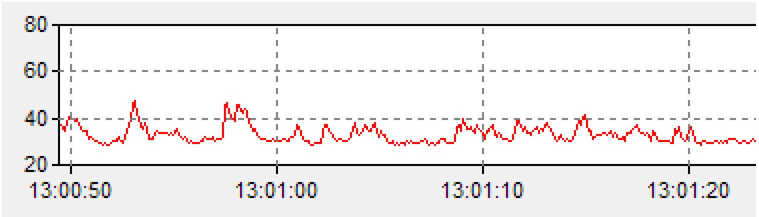

Figure 8. Fragment of measurement of sound level A-weighted as a function of time.

For this paper, two levels—L5% and L95%—are distinguished, which correspond to a 5% probability of level exceedance (highest levels recorded) and a 95% probability of exceedance (lowest levels recorded, mostly background noise). An example of the levels is shown in Figure 9 for room 1 with a high external noise.

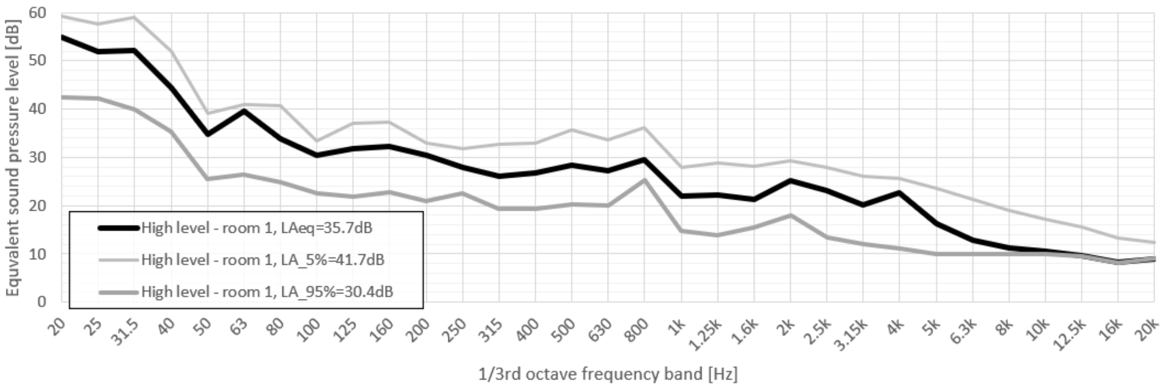

Figure 9. Statistical levels of 5% and 95% probability of exceedance for the small mock-up room during the high-level period.

Since statistical levels are not in line with the average level, which is not surprising considering the transient behavior of measured noise, it must be checked if there is a significant influence on the sound pressure level difference between rooms. Figures 10–13 show level differences for both rooms and noise level periods with an application of statistical levels. Statistical level differences were obtained as the difference of the corresponding statistical levels of the room and hall (e.g., L5% in the hall minus L5% in room 1).

Firstly, it has to be stated that the level difference calculated with Formula (2) may not follow the dependence in the one-third octave bands where L95% < L_{eq} < L5% (this dependence can be seen in Figure 9, where recorded levels are presented). This stems from the fact that the presented results of the level difference in Figures 10–13 are calculated from Formula (2), and in various cases, the dependence may not hold.

It can be highlighted that in all considered cases, L5% corresponds to the average sound level with an accuracy lower than 5 dB. The only higher differences are in low frequencies, below the 125 Hz band.

An interesting observation is that in higher frequencies—above the 1.25 kHz band—for L95%, the estimated level difference is lower than the average and L5%. This may stem from the fact that transient incidents are random in the frequency spectrum and those measured outside the mock-up room may not correspond to those measured in the hall.

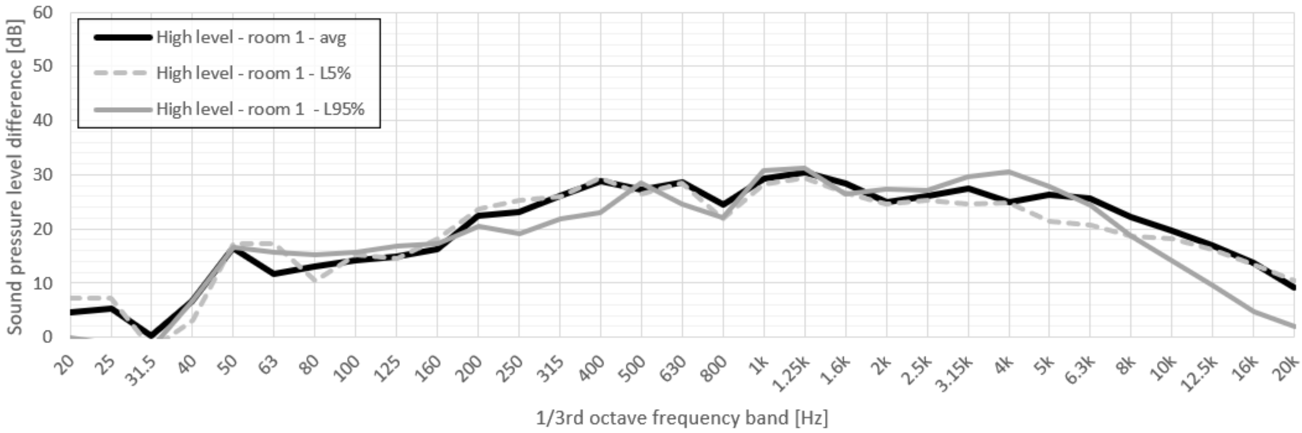

Figure 10. The estimated level difference between the hall and small mock-up room 1 during the high-level period with equivalent and statistical levels of L5% and L95% using Formula (2).

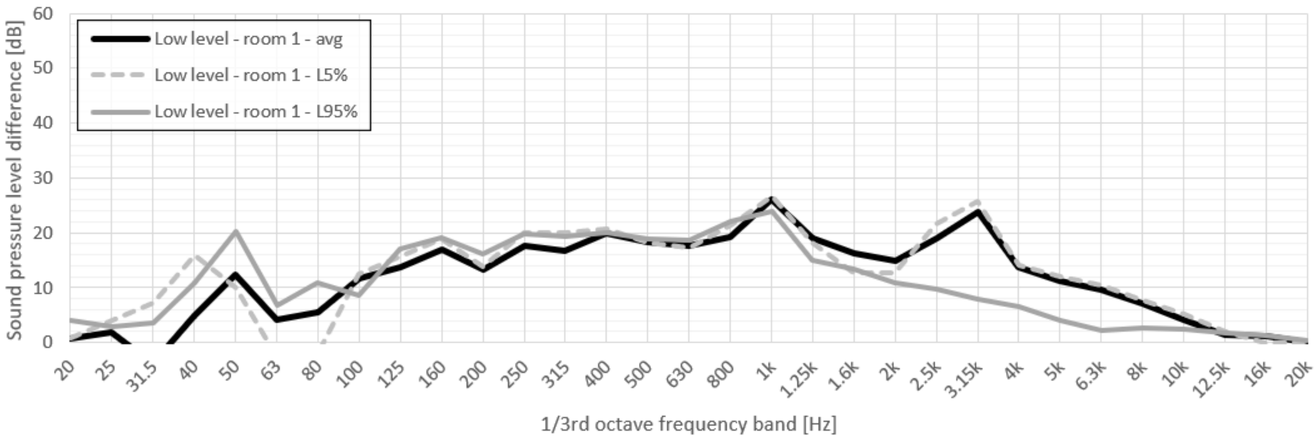

Figure 11. The estimated level difference between the hall and small mock-up room 1 during the low-level period with equivalent and statistical levels of L5% and L95% using Formula (2).

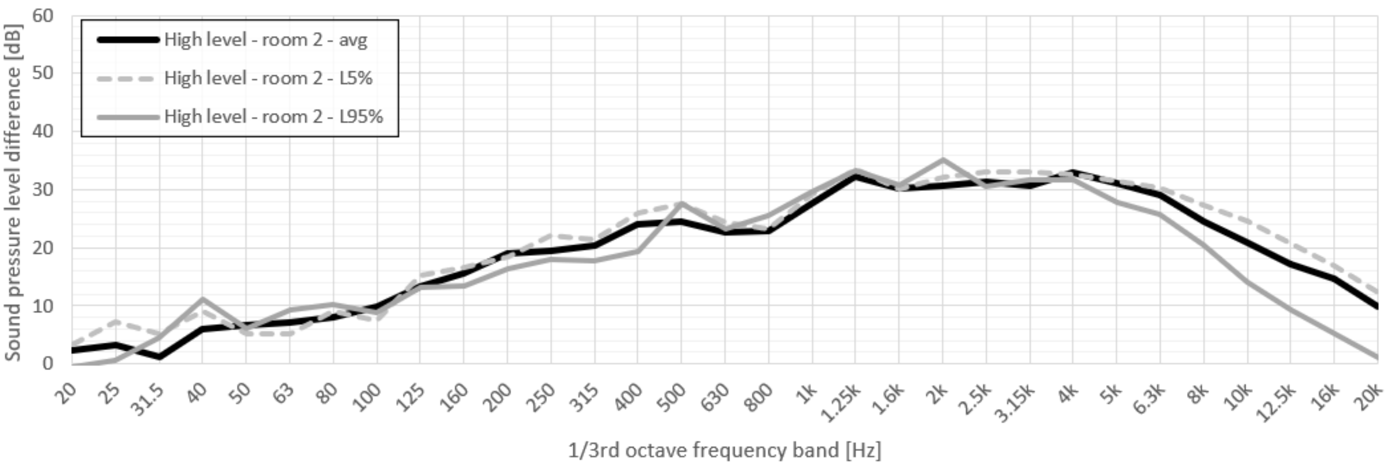

Figure 12. The estimated level difference between the hall and large mock-up room 2 during the high-level period with equivalent and statistical levels of L5% and L95% using Formula (2).

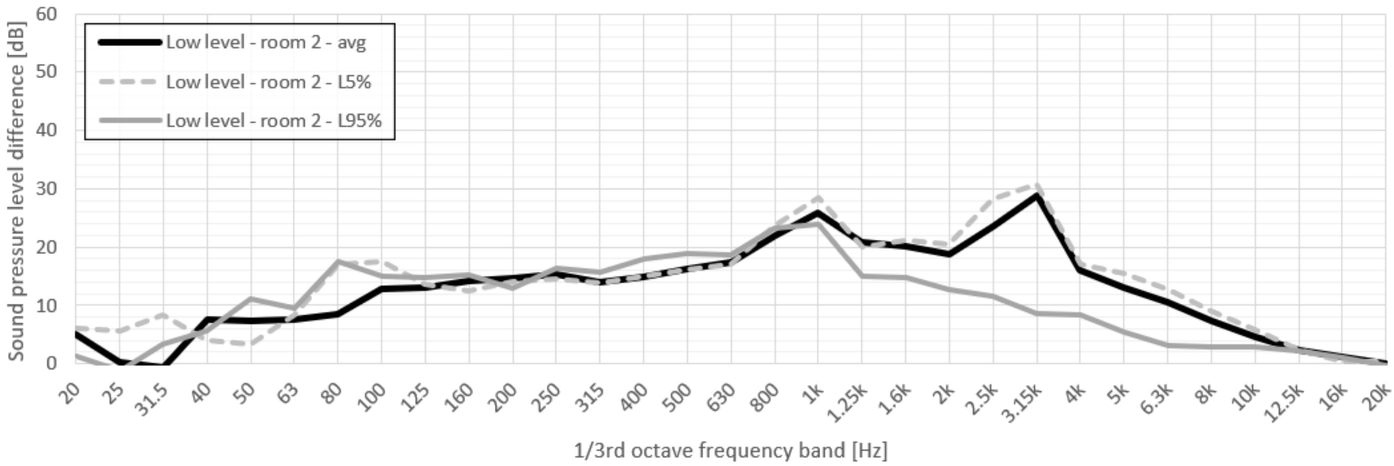

Figure 13. The estimated level difference between the hall and large mock-up room 2 during the low-level period with equivalent and statistical levels of L5% and L95% using Formula (2).

4. Analysis of the Possibilities of Noise Protection in the Mock-Up Room

4.1. Reliability of Measured Levels from HVAC Equipment

Initially, it is important to consider whether the measured A-weighted noise levels are a reliable measure of the noise level from the HVAC equipment. To answer this, it is necessary to determine what device noise level can be considered acceptable. The standard [27] indicates that the permissible model level of $L_{Aeq,nT}$ = 25 dB. The estimation of the maximum background level should be calculated based on the formula for the summation of noise levels from various sources:

$$L_{Aeq,tot} = 10 \log_{10} \left(\sum_{i=1}^{n} 10^{0.1 L_{Aeq,i}} \right) \tag{3}$$

where:

$L_{Aeq,tot}$—total equivalent sound level from all sound sources of a given measurement point;

$L_{Aeq,i}$—i-th equivalent sound level from a specific i-th sound source;

n—number of sound sources.

The demonstration of the background level effect on the total noise level measured in the mock-up room is presented in Figure 14.

The observation of statistical sound levels provides an interesting observation. Taking into account L5%, it has to be stated that this level may be considered background noise. Thus, the comparison between the floor noises, which are background noises, in the hall and inside the room is reasonable. This aligns quite well with average noise level differences, which also accounts for the average of all different transient noises.

The fact that L95% seems to underestimate the value of the level difference in higher frequency bands is an important observation. The randomness of transient noise incidents means that the highest level measured outside and inside the room may come from different types of sources, even though the measurement time was relatively long (10 min).

Noise from HVAC device [dBA]	Background level [dBA]																				
	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
20	21	21	22	22	23	23	24	24	25	25	26	27	28	29	30	30	31	32	33	34	35
21	22	22	22	23	23	24	24	25	25	26	26	27	28	29	30	31	31	32	33	34	35
22	23	23	23	23	24	24	25	25	26	26	27	27	28	29	30	31	32	32	33	34	35
23	24	24	24	24	24	25	25	26	26	27	27	28	28	29	30	31	32	33	33	34	35
24	25	25	25	25	25	25	26	26	27	27	28	28	29	29	30	31	32	33	34	34	35
25	25	26	26	26	26	26	26	27	27	28	28	29	29	30	30	31	32	33	34	35	35
26	26	26	27	27	27	27	27	27	28	28	29	29	30	30	31	31	32	33	34	35	36
27	27	27	27	28	28	28	28	28	28	29	29	30	30	31	31	32	32	33	34	35	36
28	28	28	28	28	29	29	29	29	29	29	30	30	31	31	32	32	33	33	34	35	36
29	29	29	29	29	29	30	30	30	30	30	30	31	31	32	32	33	33	34	34	35	36
30	30	30	30	30	30	30	31	31	31	31	31	31	32	32	33	33	34	34	35	35	36

(green)	Backgroung noise has no significant influence on measured noise level from HVAC device
(yellow)	Backgroung noise has significant influence on measured HVAC device noise which still could be estimated with limited reliability
(orange)	Background noise is too high to estimate noise from HVAC device properly

Figure 14. The influence of background noise level on measuring noise emitted from HVAC devices with a 3 dB safety margin and assumption of stable background and HVAC noise.

4.2. Noise Level Measurements in Mock-Ups from HVAC and Laboratory Measurements of Equipment Sound Power Level

The laboratory measurements of the HVAC equipment are conducted to obtain the value of the sound power level emitted from the device enclosure and released into air ducts (inlets and outlets). The laboratory-measured values are essential in the ventilation system design process. Using these values, a proper HVAC device can be comparatively selected among the preselected options [28].

The mock-up measurements are the validation process for HVAC device selection. This process is crucial to compare calculation results with reality. The calculation process always has some systematic errors. These errors may occur at different stages and include regenerated noise from airflow velocity, acoustic reflection from the duct end, inaccuracies in duct silencers' transmission loss, structure-borne noise from room elements excited by HVAC device vibration, the additional covering of the HVAC device with a suspended ceiling, and the calculation of an equivalent sound level in the room in the near field and diffuse field (room acoustics). The validation of results should, therefore, be performed before the designed HVAC solution is applied to the final stage of building construction.

The comparison of laboratory measurements of HVAC equipment and mock-up measurements is somewhat problematic. Firstly, there are two different measured quantities. The first one comes from the laboratory—sound power level. The second is from the mock-up–sound pressure level. As mentioned in the paragraph above, there are ways to recalculate the values to provide their equivalents. Still, there are always systematic errors resulting from the simplification of these calculations. The second issue is the room acoustics. During the calculation process, some assumptions are made about finishing the room and furniture to provide spectral characteristic variation in the sound level by considering sound reflection and absorption. The mock-up measurements are a solution to this problem. The main challenge is to provide the same finishing and furniture as planned in the final room. The third aspect is the changes that occur when finishing the room and adding furniture. Between the mock-up stage and the final stage of building construction, there may be some changes implemented considering room architecture. They may also change the room acoustics by changing the room reverberation time. The reflected wave state in the room will change, but it can be mitigated by applying the sound pressure level correction k to the current (measured before internal room changes) level using Formula (4). This formula can be applied for the total level (broadband), octave bands, and one-third octave bands:

$$k = 10\log_{10}\left(\frac{T_{new}}{T_{current}}\right) \tag{4}$$

where:

T_{new}—new or predicted reverberation time in the room (s);
$T_{current}$—current or measured reverberation time in the room (s).

4.3. Mock-Up Partition Preliminary Analysis

The key reason for noise penetration in the mock-up room is the acoustic condition of the partitions surrounding the room. Thus, there are two overlapping methods to provide low background noise in the mock-up room: low external noise and partitions with high sound insulation. With low external noise, partitions do not play a crucial role in mock-up room acoustic capabilities. Still, with a high external noise, partitions must provide proper sound insulation to protect against the noise.

In the analysis presented in this paper, typical drywall system elements are used to evaluate the theoretical capabilities of protection against the noise of the discussed mock-up rooms. The drywall system was used because it is the most convenient system to erect temporary structures such as mock-ups. Elements of the partitions are presented in Table 1. The total number of combinations of window–door–wall was 588.

The analysis was performed in the following manner. The acoustic field in the hall is assumed to be fully diffused, and thus, the same noise level is applied at every point of the mock-up partition. The noise-exposed external partition of the mock-up room consists of walls with doors and windows, as shown in Figure 2. The sound insulation of each element presented in Table 1 was calculated in one-third octave bands. Since the external partition includes the wall, windows, and doors, proper averaging of sound insulation was performed. The measured external noise was assumed to be the noise load on the partition. Internal noise was taken as a parameter for analysis. The aim was to verify which combination of window–door–wall can be applied to provide low background noise inside the mock-up room.

The sound insulation of partitions was calculated using MATLAB scripts based on scientific works for single- and double-panel sound insulation [29–31]. The air leakages for doors were assumed as the slit of 900 × 10 mm to imitate an opening for ventilation purposes in case the ventilation is not purely mechanical. The calculations were performed by estimating the transmission loss for air leakage [32]. Although the walls and doors were treated as mentioned before, the sound insulation for windows was overestimated. It was decided to support the glazing calculation with [33]. The calculated values are presented in Appendix A, Table A1. It was decided to limit the one-third octave frequency bands of the analysis to 50–5000 Hz because this is the dynamic range of the common application of sound reduction index R.

After obtaining estimated values of the sound reduction index R in one-third octave bands, the averaging of sound insulation was carried out using Formula (5) [34]:

$$R_{1/3oct,total} = 10\log_{10}\left(\frac{S_{wall}}{S}10^{-0.1R_{1/3oct,wall}} + \sum_{i=1}^{n}\frac{S_{el,i}}{S}10^{-0.1R_{1/3oct,el,i}}\right) \tag{5}$$

where:

S—the total surface of the partition exposed to noise (m^2);
S_{wall}—the total surface of the wall only exposed to noise (m^2);
$S_{el,i}$—total surface partition of i-th elements such as windows or doors (m^2);

$R_{1/3oct,wall}$—sound reduction index for the given one-third octave band for the wall (dB);
$R_{1/3oct,el,i}$—sound reduction index for the given one-third octave band for i-th element (dB);
n—number of partition elements (windows and doors).

Table 1. Mock-up external partition elements used in preliminary analysis of noise protection in the room.

Windows (120 × 140 cm)	Doors (200 × 90 cm)	Walls—Gypsum Plasterboard
(W1) 4/16/4	(D1) frame with an air gap (30 mm) and MDF paneling on both sides (6 mm)	(GP1) single-layer 12.5 mm board with steel studs (CW50 0.55 mm, 600 mm spacing), 60 kg/m^3 Rockwool
(W2) 6/12/6	(D2) frame with 60 kg/m^3 Rockwool (30 mm) and MDF paneling on both sides (6 mm)	(GP2) double-layer 12.5 mm board with steel studs (CW50 0.55 mm, 600 mm spacing), 60 kg/m^3 Rockwool
(W3) 44.1/16/6	(D3) frame with an air gap (30 mm), timber studs (300 mm spacing, 45 mm width), and MDF paneling on both sides (6 mm)	(GP3) triple-layer 12.5 mm board with steel studs (CW50 0.55 mm, 600 mm spacing), 60 kg/m^3 Rockwool
(W4) 10/16/66.2	(D4) frame with 60 kg/m^3 Rockwool (30 mm), timber studs (300 mm spacing, 45 mm width), and MDF paneling on both sides (6 mm)	(GP4) single-layer 12.5 mm board with steel studs (CW100 0.55 mm, 600 mm spacing), 60 kg/m^3 Rockwool
(W5) 4/12/4/12/4	(D5) D1 with air leakage	(GP5) double-layer 12.5 mm board with steel studs (CW100 0.55 mm, 600 mm spacing), 60 kg/m^3 Rockwool
(W6) 4/12/4/12/33.1	(D6) D2 with air leakage	(GP6) triple-layer 12.5 mm board with steel studs (CW100 0.55 mm, 600 mm spacing), 60 kg/m^3 Rockwool
(W7) 68.4/15/4/12/88.2	(D7) D3 with air leakage	
	(D8) D4 with air leakage	
	(D9) solid MDF (30 mm)	
	(D10) solid MDF (42 mm)	
	(D11) D9 with air leakage	
	(D12) D10 with air leakage	
	(D13) aluminum frame with 60 kg/m^3 Rockwool (30 mm) and aluminum paneling on both sides (2 mm)	
	(D14) aluminum frame with 60 kg/m^3 Rockwool (40 mm) and aluminum paneling on both sides (2 mm)	

The assumption for the noise inside the room was an inverted A-weighting curve with 0 dBA in each one-third octave band. The spectral characteristics of noise are presented in Figure 15. That type of curve provides an equal influence of every frequency band on the total A-weighted level. Further analysis will translate the curve upwards (increase the A-weighted level) to gather information about the minimum levels for given quantities of combinations of external partition elements.

To use the sound reduction index, the reverberation time of the room is needed (see Formula (6)). The reverberation time of the small and large rooms is presented in Figure 16. The measurement procedure complied with [35]. The reverberation time was measured in the same positions as the sound level recorded inside the mock-ups.

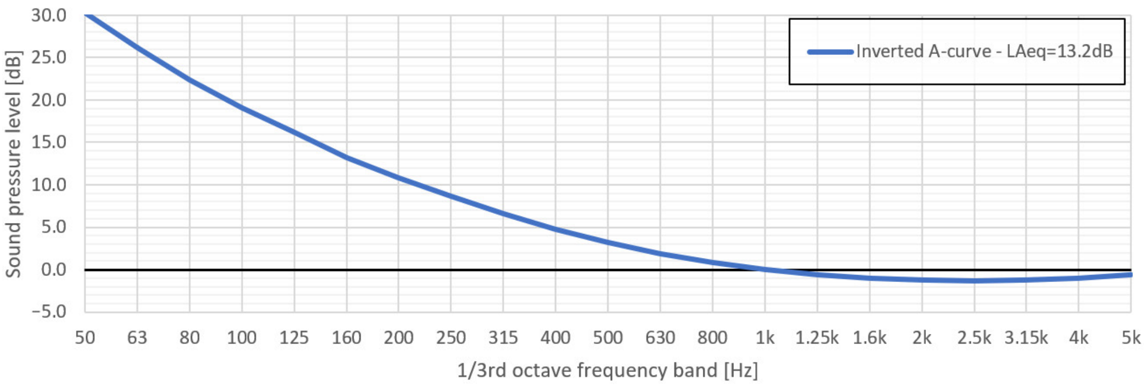

Figure 15. Inverted A-curve assumed as internal noise for analysis in mock-up rooms. For the analysis, the curve was shifted up to increase the theoretical noise level in the room.

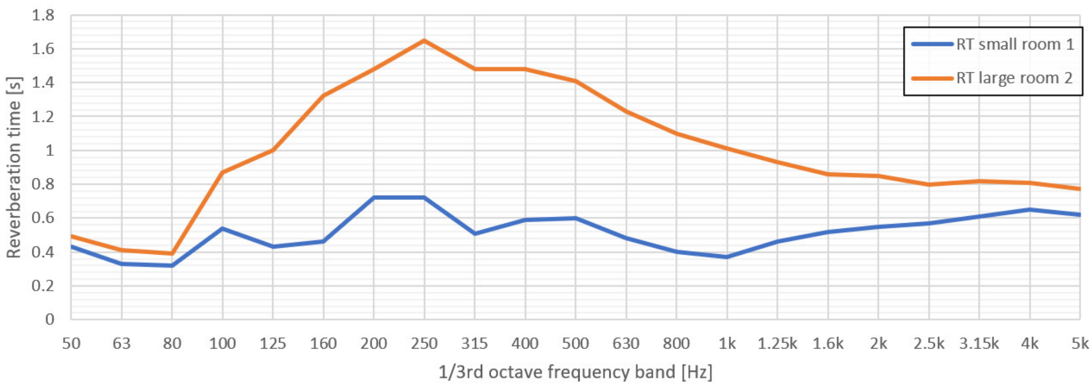

Figure 16. Reverberation time measured in mock-up rooms using impulse response.

The necessary sound reduction index for external partitions with assumed internal noise and measured external noise (in the hall) is calculated using Formula (6). The measured reverberation time in the mock-up rooms is applied together with the existing geometry:

$$R_{1/3oct} = L_{1/3oct,out} - L_{1/3oct,in} + 10\log_{10}\left(\frac{S}{0.16\frac{V}{T_{1/3oct}}}\right) + 3, \quad (6)$$

where:

$L_{1/3oct,out}$—the total surface of the partition exposed to noise (dB);
$L_{1/3oct,in}$—the total surface of the wall only exposed to noise (dB);
S—the total surface of the partition exposed to noise (m^2);
V—room volume (m^3);
$T_{1/3oct}$—reverberation time in the room in the one-third octave band (s).

The algorithm for the presented method is shown in Figure 17.

To show the large and small rooms' ability to properly isolate the external noise, the number of combinations is calculated (Figures 18 and 19). This number helps to answer the question: is the mock-up room able to isolate recorded noise during the measurements presented in this paper?

A large room needs more effective soundproofing than a small room. This stems from a larger surface area being exposed to external noise (more noise influx) and a higher value of reverberation time (more unwanted acoustic reflections).

The step in Figures 18 and 19 results from analyzing the very weak isolating doors with air leakage, which comes from the slit under the door. A significant growth in the noise level will occur inside the mock-up if these doors are applied.

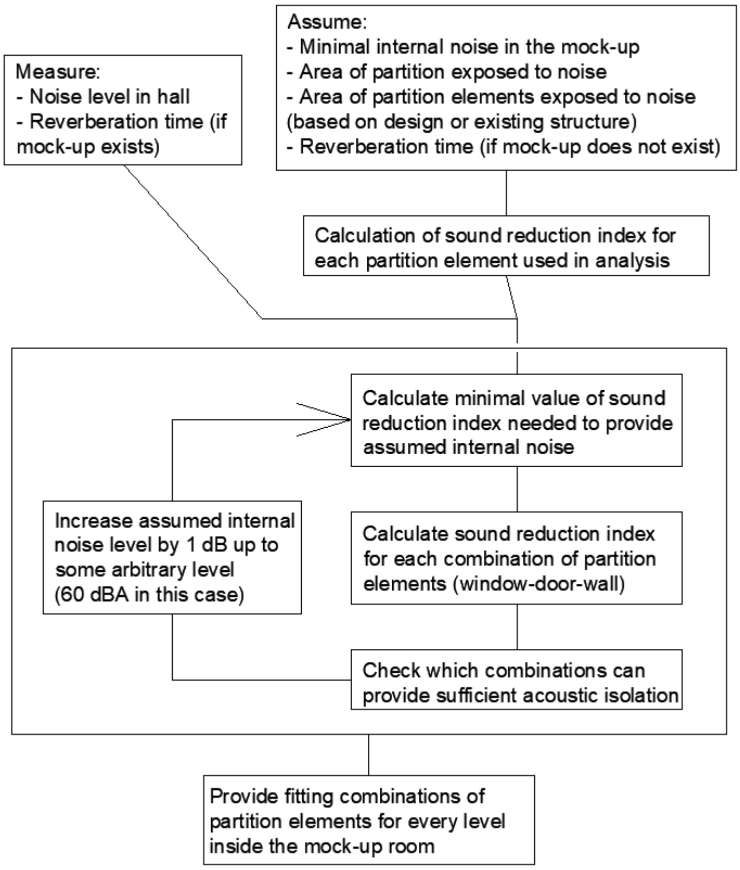

Figure 17. The algorithm used in the preliminary analysis of external mock-up partitions.

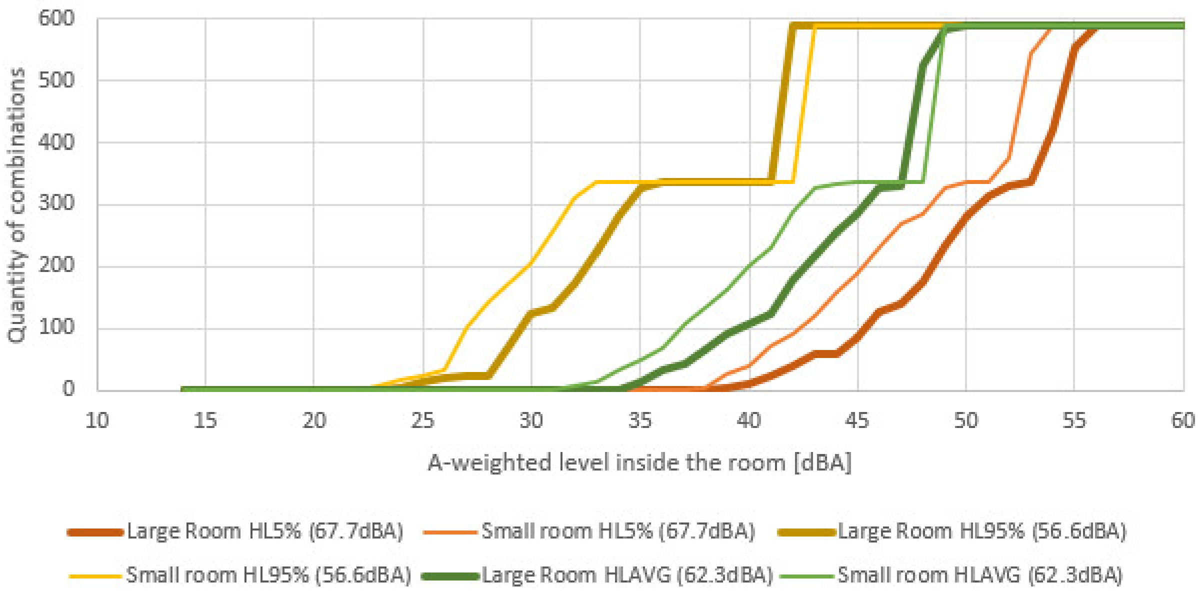

Figure 18. The number of combinations meeting the required A-weighted noise level inside the mock-up room (*X*-axis) for a high-level noise period.

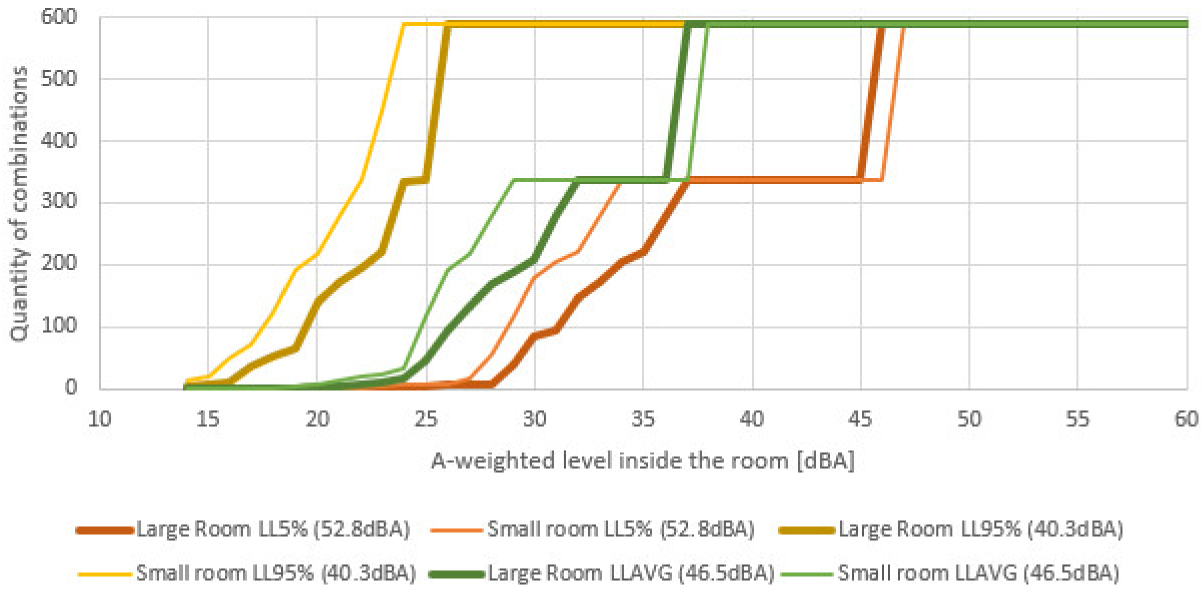

Figure 19. The number of combinations meeting the required A-weighted noise level inside the mock-up room (*X*-axis) for a low-level noise period.

The measured high-level period presents too high of a noise level to provide low background noise inside rooms for the measurements of quieter HVAC units. Only constant noise units generating at least 24 dBA could be measured using a 95% level approach.

Measurements of variable noise-generating units need low and stable background noise levels. The calculation, therefore, needs to be based on a 5% statistical noise level. In the best-case scenario, the small room with the best combinations provides 23 dBA of background noise. Based on Figure 14, it could be concluded that noise from the HVAC unit should be at least 24 dBA. However, it has to be emphasized that this prediction is made using constant noise. If random noise incidents will be "out of phase", which is highly probable during nonsimultaneous inside/outside level measurements, this conclusion will not be valid.

From the conducted analysis the best combination (the one fitting most of the analyzed internal noise levels) of external partition elements can be found. The best combination is shown in Table 2.

Table 2. Combination of mock-up external partition elements providing the lowest internal noise according to the combination analysis.

ID Wall	ID Window	ID Door
GP3	W7	D14
GP5		
GP6		

As shown in Table 2, the most noise-isolating window with triple glazing ((W7) 68.4/15/4/12/88.2) and aluminum door ((D14) aluminum frame with 60 kg/m^3 Rockwool (40 mm) and aluminum paneling on both sides (2 mm)) were selected. This conclusion was expected because these partition elements have the highest sound reduction index R in most of the one-third octave frequency bands. A more interesting fact is that three wall types were selected:

- (GP3) triple-layer 12.5 mm board with steel studs (CW50 0.55 mm, 600 mm spacing), 60 kg/m^3 Rockwool;
- (GP5) double-layer 12.5 mm board with steel studs (CW100 0.55 mm, 600 mm spacing), 60 kg/m^3 Rockwool;

- (GP6) triple-layer 12.5 mm board with steel studs (CW100 0.55 mm, 600 mm spacing), 60 kg/m^3 Rockwool.

There is a thinner profile plasterboard wall with a profile of 50 mm (CW50) and a triple layer of 12.5 mm boards on both sides, resulting in a total partition thickness of 125 mm. Additionally, a thicker profile of 100 mm (CW100) can be fitted as the best result. With this profile, two and three layers of plasterboard fit the best result status.

On the other hand, the most economic combination can be discussed. As it is a function of the material price which varies in different countries and is not part of the scope, the lowest possible level with all combinations (558 combinations) should be considered. Table 3 provides information about the best (lowest) possible levels in the mock-up rooms to be obtained for the best combination. Moreover, the corresponding lowest levels in mock-up rooms provided by all combinations are shown as the "economic combination".

Table 3. Summary of noise infiltrating the mock-up rooms with the calculation of method error of combination corresponding to existing state (W1, D10, GP2). An average method error with credible interval of 95% totals 0.59 dB (−1.29 dB; 2.58 dB, CI95).

Location and Type of Level	Corresponding Level for Best Combination (dBA)	Corresponding Level for Economic Combination (dBA)	Measured Levels in Mock-Ups (dBA)	Calculated Level for Combination Corresponding to Existing State (W1, D10, GP2) (dBA)	Method Error (dB)
Large room HL5% (67.7 dBA)	39	56	41.7	48	6.3
Small room HL5% (67.7 dBA)	38	54	41.7	43	1.3
Large room HL95% (56.6 dBA)	24	42	30.1	32	1.9
Small room HL95% (56.6 dBA)	23	43	30.4	28	−2.4
Large room HLAVG (62.3 dBA)	35	50	37.3	42	4.7
Small room HLAVG (62.3 dBA)	32	49	35.7	37	1.3
Large room LL5% (52.8 dBA)	25	46	31.5	33	1.5
Small room LL5% (52.8 dBA)	23	47	33.1	30	−3.1
Large room LL95% (40.3 dBA)	<14	26	21.5	21	−0.5
Small room LL95% (40.3 dBA)	<14	24	20.7	18	−2.7
Large room LLAVG (46.5 dBA)	20	37	26.8	28	1.2
Small room LLAVG (46.5 dBA)	19	38	27.4	25	−2.4

Each method of analysis should provide a validation of the obtained results. In the presented analysis, the sound reduction index for elements is calculated using a theoretical approach and the averaging of the sound reduction index is carried out using a simplistic approach (see Formula (5)). The types of walls, windows, and doors that were used in the mock-up rooms are known:

- (W1) 4/16/4;
- (D10) solid MDF, 42 mm;
- (GP2) double-layer 12.5 mm board with steel studs (CW50 0.55 mm, 600 mm spacing), 60 kg/m^3 Rockwool.

Using measured levels inside the mock-up rooms and outside in the hall, and the sound reduction index of the existing combination of external partition elements, the theoretical noise level inside the mock-up rooms can be calculated. The reverberation time in the rooms is assumed to be constant, as the finishing layers and furniture are not changed with the measured state. As a validation, the difference is obtained between the measured noise in the mock-ups and calculated using the method presented in this paper. Additionally, the average error and its 95% credible interval are presented.

As shown in Table 3, the average error of the method is 0.59 dB (−1.29 dB; 2.58 dB, CI95). The presented method tends to overestimate the noise level in the room, especially in the large mock-up room 2 with high external noise. Considering lower levels of external noise, the underestimation of the predicted level is observed.

5. Result Discussion

The measurements made in the mock-up rooms fall in between the laboratory and in situ measurements (closer to real-structure measurements), which is why it is difficult to compare them to the results obtained either in the laboratory or in a real structure. Such a comparison can be more qualitative and less quantitative.

In Ref. [36], the differences between indoor and outdoor sound levels depending on opened, tilled, and closed windows are investigated. As expected, the greatest differences are observed when the windows are closed. Yet, for comparison purposes with this article, indoor sound levels are important. They mostly vary from 10 to 40, and even reach 50 dB depending on the frequency, which agrees with the results presented in the article.

Background (traffic) noise measured inside the hotel rooms was also investigated in Ref. [37]. The measurements were made in the room located on the 10th floor of the hotel in Cairo. The mean value varies from 35 to 50 dB depending on the time of the day.

These articles confirm the correct performance of the measurements.

6. Conclusions

6.1. General Conclusions

The article presents the possibilities of making reliable in situ measurements of the HVAC system noise outside the laboratory area and proposes a method to estimate the external noise protection capabilities of mock-up rooms. The measurements taken at the testing site lead to several main conclusions:

- The measured noise levels prevent the reliable measurement of the noise level from HVAC equipment.
- Due to strict requirements regarding the permissible noise level from technical devices in the building, these devices should be taken to be relatively quiet (a level below 25 dBA). This means that in a hotel mock-up room located in an industrial hall, a relatively low noise level should be ensured.
- To reliably carry out such measurements, they must be performed outside the working hours, without the presence of industrial equipment and site employees.
- Evaluation of level difference can be carried out using the statistical level difference of L5% or an equivalent sound level. The reliability of the level difference estimation may be limited only in lower frequencies below the 125 Hz band.

With the proposed method for mock-up acoustic-condition prediction, the following conclusions can be stated:

- Prediction of the internal noise level with known external noise helps to decide the external partitions to be used to provide the desired level of background noise.
- The method is found to be on the safe side of estimation (overestimation) of the internal noise level considering high noise levels in the industrial hall, which are most harmful to measurement results.

- There is a noticeable underestimation of the internal noise level considering lower levels of external noise. Using this method in a quieter environment, it is advised to apply 3 dB safety margins.
- Without using the laboratory data of partition elements, it is possible to estimate the noise penetrating the mock-up room from its surroundings.

6.2. Limitations

The method of noise estimation has a few limitations:

- The noise outside the mock-up room must be low enough to provide reliable measurements inside the mock-up room. This limitation can be mitigated by providing massive and well sound-isolating partitions such as concrete, but this will increase the cost excessively compared with simple double-leaf room partitions.
- The measurements can be made generally only for HVAC devices inside the room. It must be emphasized that not only noise from the “final” room HVAC device may be present inside the room, but also noise from other HVAC devices such as roof ventilation units located outside; this must be considered during the mock-up test. Noise from these units can propagate through ducts and end up inside the “final” hotel room.
- The availability of space for building a mock-up room: depending on the size of the mock-up room, it might not be possible to find a valid location for such measurements.

The method of mock-up acoustic-condition prediction also has a few limitations:

- The assumed noise spectrum inside the mock-up room is dictated by A-weighting. If any other weighting is needed (e.g., C or Z (linear)), the analysis must take it into account.
- The theoretical approach to the calculation sound reduction index is valid for perfect conditions. This is the cause of errors in the presented method. Providing perfect tight mounting of doors or windows is impossible, and thus, safety margins are proposed to be used.
- The reverberation time is crucial for the estimation of the internal sound level. This value takes into account any possible wanted or unwanted sound wave reflections inside the room. Without this value known, it can be assumed, but will result in a higher error in the presented method.

Knowing these limitations, this method is called the preliminary method of sound insulation estimation.

6.3. Further Studies

In further studies, it would be useful to verify the types of mock-up room partition doors and windows that are economically justified to be applied within such a noise evaluation method using laboratory data of partition elements. Additionally, other types of noise pollution sources in the final localization of the tested room should be taken into account. This will validate the information about the type of HVAC systems to be tested in mock-ups, providing the most reliable data.

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Appendix A

Table A1. Summary of sound reduction indexes R for every partition element used in the analysis. Windows and doors are assumed to be actual dimensions (window, 120 × 140 cm; door, 200 × 90 cm).

Partition Element	Sound Reduction Index R (dB)																					
	1/3 Octave Frequency Band (Hz)																					Weighted Sound Reduction Index R_W
	50	63	80	100	125	160	200	250	315	400	500	630	800	1k	1.25k	1.6k	2k	2.5k	3.15k	4k	5k	
(W1)	22	22	23	23	23	22	19	19	25	30	33	37	39	41	43	45	46	46	41	36	40	35
(W2)	23	24	25	26	26	24	19	22	28	32	36	38	40	42	43	43	41	34	36	40	44	36
(W3)	27	27	27	27	27	24	25	29	33	37	40	42	44	46	47	46	50	45	48	52	56	42
(W4)	30	30	30	29	25	27	31	35	38	41	43	44	45	45	46	41	45	49	53	57	61	44
(W5)	30	28	27	26	25	22	14	18	24	26	32	38	42	45	46	47	45	45	40	53	55	33
(W6)	32	29	28	27	26	23	22	27	32	30	35	41	45	47	48	49	47	50	49	56	58	39
(W7)	38	34	31	29	31	34	37	39	40	42	44	44	43	45	53	55	56	58	60	61	63	47
(D1)	18	17	17	17	17	17	18	16	17	21	25	29	32	35	38	40	47	48	48	45	40	29
(D2)	18	17	17	17	17	18	17	17	21	25	29	33	37	41	44	47	51	52	52	51	49	32
(D3)	17	16	17	17	17	18	18	14	16	19	24	27	31	34	37	39	44	46	46	44	40	28
(D4)	17	16	16	17	17	18	16	16	19	24	28	32	35	39	41	44	46	47	48	47	45	31
(D5)	7	8	9	10	10	11	12	12	13	15	16	17	18	19	19	19	18	15	10	10	15	17
(D6)	7	8	9	10	10	11	12	12	14	15	17	17	18	19	19	19	18	15	10	10	15	17
(D7)	7	8	9	10	11	11	12	11	12	14	16	17	18	19	19	19	18	15	10	10	15	17
(D8)	7	8	9	10	11	11	11	12	14	15	16	17	18	19	19	19	18	15	10	10	15	17
(D9)	25	23	23	24	25	26	27	28	29	30	31	31	30	27	30	33	36	39	42	45	48	32
(D10)	28	26	26	27	27	29	30	31	32	32	32	29	28	31	34	37	40	43	46	49	51	34
(D11)	8	9	9	10	11	12	13	14	15	16	17	17	18	18	19	19	18	15	10	10	15	17
(D12)	8	9	10	10	11	12	13	14	15	16	17	17	18	18	19	19	18	15	10	10	15	17
(D13)	21	20	19	19	19	20	18	22	26	31	35	40	44	48	52	56	64	65	66	66	62	36
(D14)	21	19	19	19	19	17	19	24	29	34	38	43	47	51	55	62	64	65	66	66	63	37
(GP1)	16	16	16	17	14	19	25	30	35	40	44	48	52	55	58	60	60	59	48	50	54	40
(GP2)	20	19	16	18	25	32	38	43	47	51	55	58	61	63	65	66	66	65	55	56	60	50
(GP3)	22	19	19	26	34	40	45	50	54	57	60	62	65	66	68	69	70	69	59	59	63	57
(GP4)	14	14	12	14	20	27	33	38	43	47	50	53	55	57	59	60	60	59	50	50	54	45
(GP5)	17	13	19	27	34	40	45	49	52	55	57	60	61	63	65	66	66	65	56	56	60	57
(GP6)	14	19	28	36	42	47	51	54	57	59	61	63	65	67	68	69	70	69	60	59	63	62

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