DOI: 10.61782/fa.2023.0982

IMPROVEMENT OF VERBAL COMMUNICATION IN THE JUBILEUMZAAL OF THE HISTORIC KU LEUVEN UNIVERSITY HALL

Edwin Reynders[1*] **Jan Van den Wyngaert**[1]
Marie Verlinden[2] **Gerrit Vermeir**[1]
[1] Department of Civil Engineering, Faculty of Engineering Science, KU Leuven, Belgium
[2] Monuments and Architectural Maintenance Division, Technical Services, KU Leuven, Belgium

ABSTRACT

The Jubileumzaal is a large room at the KU Leuven University Hall which is used for social gatherings such as receptions and technical exhibitions. The room has a nominal capacity of 800 persons and it suffered from long-standing complaints about high noise levels and poor speech intelligibility. The main cause was the excessive reverberation time, which amounted to an average value of 5.1s across the 500, 1000 and 2000 Hz octave bands. However, due to the historical character of the room, the options for acoustic renovation were extremely limited. In the end, custom-made sound-absorbing chandeliers with integrated lighting were retained as an architecturally acceptable option. A total of 20 chandeliers were placed in the room, which reduced the reverberation time to 2.2 s, in close agreement with a theoretical assessment that accounts for the sound field directionality. In order to assess the effectiveness of the refurbishment, noise measurements were conducted during busy receptions before and after renovation. They are in good agreement with a prediction model that accounts for the Lombard effect, at least when the number of persons in the room is increasing. When it is decreasing, the measured noise levels are substantially higher, and an extension of the prediction model is offered to explain this result.

Keywords: *room acoustics, verbal communication, social gatherings, noise control, Lombard effect.*

****Corresponding author***: *edwin.reynders@kuleuven.be.*

1. INTRODUCTION

The KU Leuven University Hall is a historic building (the oldest parts date back to the 14th century) in the centre of Leuven. The Hall is not only home to the University's central executive and administrative services, but also contains an auditorium with a nominal capacity of 385 persons and a multi-purpose room with a nominal capacity of 800 persons. The latter room is named the Jubileumzaal and mostly serves to host social gatherings and exhibitions (Fig. 1). The length and width of the room are $57.3\,\mathrm{m}$ and $18.1\,\mathrm{m}$, respectively, while the height is approximately $9.4\,\mathrm{m}$. The floor surface area is $1037\,\mathrm{m}^2$ and the volume amounts to approximately $9750\,\mathrm{m}^3$.

The room suffered from long-standing complaints about high noise levels and low speech intelligibility during events, where hundreds of people are present and involved in simultaneous conversations. These could be clearly attributed to the low sound absorption of the room surfaces' finishes, leading to excessive reverberation. The floor and vaulted ceiling are made of stone tiles and natural clay brickwork, respectively. The lower part of the walls consists of natural stone brickwork while the upper part additionally contains a series of large windows. There was virtually no furniture present in the room. However, due to the historical character of the room, the options for acoustic renovation were extremely limited. In the end, custom-made sound-absorbing chandeliers with integrated lighting were retained as an architecturally acceptable option and an acoustic renovation was initiated by the KU Leuven Technical Services. The Structural Mechanics Section of KU Leuven (Dept. of Civil Engineering, Faculty of Engineering Science) took care of the scientific and technical aspects of the renovation.

Figure 1. The Jubileumzaal during a social gathering. The sound absorbing chandeliers that have been placed in August 2020 are clearly visible.

Different types of sound absorbing chandeliers were designed by the KU Leuven Technical Services. In order to assess the effectiveness of the related arrangements of absorbing elements, the chandeliers were tested in the reverberation room of the KU Leuven Laboratory of Acoustics and the resulting absorption data were compared to predictions based on material data. One of these preliminary designs was retained and resulted in a final design after further minor alterations Twenty chandeliers of the final design were placed in the Jubileumzaal at the beginning of August 2020. Reverberation tests in the room before and after placement of the chandeliers were conducted and compared to predictions based on the reverberation room data. Finally, in order to assess the effectiveness of the refurbishment, noise measurements were conducted during busy receptions before and after renovation. They were compared with a prediction model that accounts for the Lombard effect. Relatively large differences were found between that model and the measurements when the number of persons in the room is decreasing, and the model was extended to explain the difference. In the remainder of this paper, the different aspects of the room acoustical study are further detailed and the scientifically relevant aspects are highlighted.

2. ABSORTION OF ACOUSTIC CHANDELIERS

2.1 Preliminary designs

In the first stage of the acoustic renovation project, three types of acoustic chandeliers have been designed; they are designated as type A, type B and type C (Fig. 2). Type A consists of rectangular panels of 120 cm × 60 cm × 40 mm which are made from recycled glass wool fibers. They are radially arranged in 3 concentric rings with inner diameters of 40 cm, 100 cm, and 160 cm. These rings contain 6, 6 and 12 panels, respectively. The rings have a different height, such that the total height of the chandelier amounts to 240 cm.

Type B consists of cylinders with a height of 120 cm which are made from melamine foam. Both smal cylinders with a diameter of 15 cm and large cylinders with a diameter of 23 cm are employed. The cylinders are suspended at their axes from 3 concentric rings. The inner ring has a diameter of 70 cm and contains 8 small cylinders. The middle ring has a diameter of 150 cm and contains 12 large cylinders. For the outer ring, two alternative designs were made: one with a diameter of 240 cm and 20 large cylinders (type B1), and one with a diameter of 230 cm and 24 small cylinders (type B2). The rings have a different height, such that the total height of the chandeliers amounts to 245 cm.

Type C consists of trapezoidal panels with a thickness of 25 mm, lower and upper edges of 125 and 75 cm, respectively, and a height of 300 cm. They are made from PET fibers that are partly (± 30 %) recycled. Eight panels are radially arranged in a single ring with inner diameter of 50 cm. Two alternative designs were made: the first with the arragement as described (type C1) and the second with the panels upside down, such that the lower edge is the longer one (type C2).

The equivalent absorption area of individual chandeliers of all types has been experimentally determined with the reverberation room method [1] in the Reverberation Room of the KU Leuven Laboratory of Acoustics (room size: 197 m^3). The results are displayed in Fig. 3. Chandeliers C1 and C2 exhibit the best performance. They also have almost identical absorption, as expected; the differences are probably caused by the distance between the lower edge and the floor being small due to practical limitations. B1 has the next best performance, followed by A and finally B2.

The measured absorption has also been compared against simple predictions that are based on the available manufacturers' data (Table 1). For the glass fiber panels

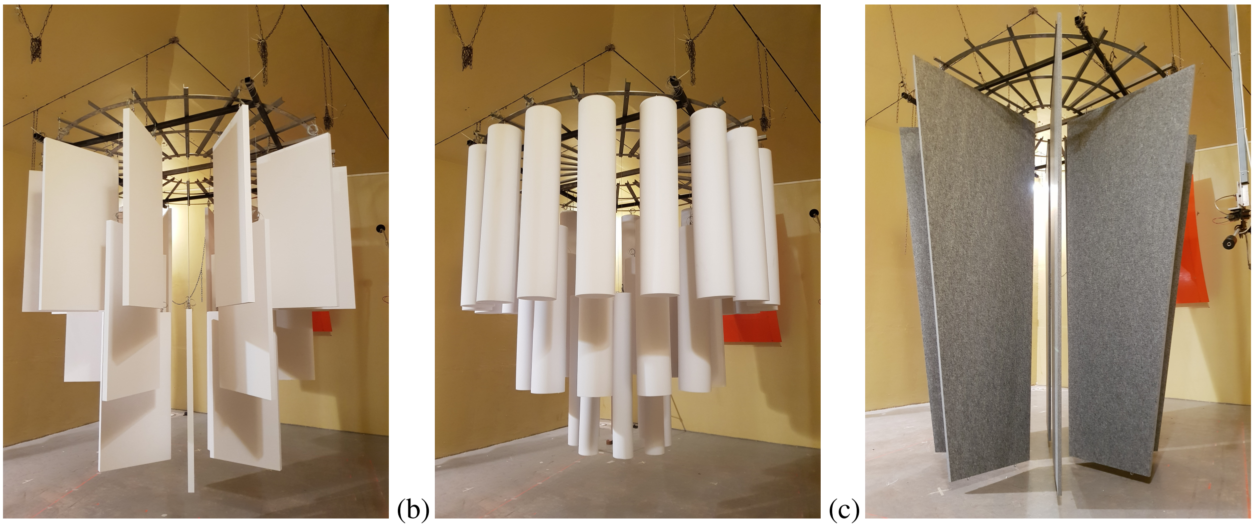

Figure 2. Sound absorbing chandeliers, tested in the Reverberation Room of the KU Leuven Laboratory of Acoustics: (a) Type A made from glass fiber panels, (b) Type B1 made from melamine cylinders and (c) Type C1 made from recycled PET fiber panels.

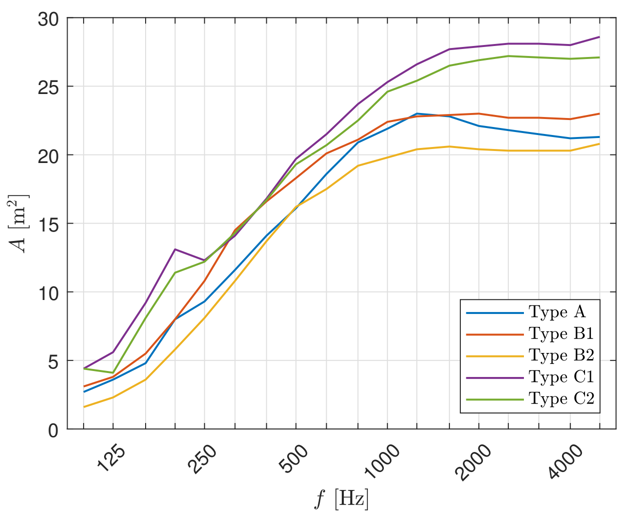

Figure 3. Experimentally determined equivalent sound absorption areas of the acoustic chandeliers.

employed in chandelier type A, absorption coefficient data are available for an arrangement as baffles with an 80 cm interval. Multiplying them with the nominal outer surface area of the chandelier (cylinder with piecewise constant diameter, 24.8 m^2) yields equivalent absorption areas that are close to the measured values in the 500, 1000 and 2000 Hz octave bands: the maximum difference amounts to 6 %.

For the melamine cylinders that are employed in chandelier type B, absorption coefficient data are available for a planar arrangement as baffles of small cylinders with a 40 cm inter-axis distance and a 185 cm plenum. Multiplying them with the nominal outer surface area of the chandelier, yet accounting for the vertical overlap (cylinder with piecewise constant diameter, 26.5 m^2), yields equivalent absorption areas that are close to the measured values in the 500, 1000 and 2000 Hz octave bands: the maximum difference amounts to 9 % for type B1 and 6 % for type B2.

For the PET panels employed in chandelier type C, absorption coefficient data are available for a free standing panel. Multiplying them with the nominal outer surface area of the chandelier (tapered cylinder, 33.8 m^2) yields equivalent absorption areas that are close to the measured values in the 500, 1000 and 2000 Hz octave bands: the maximum difference amounts to 7 % for type C1 and 3 %

for type C2. When also the 250 and 4000 Hz bands are considered, the difference remains below 13 and 9 %, for the respective types.

2.2 Final design

It can be observed from Fig. 3 that the sound absorbing chandelier types that have been considered in the preliminary design stage, have similar sound absorption curves. For aesthetic reasons, such as the fact that lighting could be smoothly integrated into the chandelier, type B was retained to be implemented in practice.

A final design was then made based on type B1, but with slightly different geometry and cylinders from a different manufacturer. The diameter of the inner ring of this final design is 90 cm and it contains 10 foam cylinders with a diameter of 15 cm and a height of 60 cm. The middle ring has a diameter of 165 cm and it contains 12 cylinders with a diameter of 24 cm and a height of 60 cm. The outer ring has a diameter of 240 cm and it contains 20 cylinders with a diameter of 24 cm and a height of 120 cm. Manufacturer data are available for both cylinder diameters, in the form of equivalent sound absorption area in a baffle grid arrangement (Table 2). A fourth ring with a 37 cm diameter was added for suspending 4 cylindrical lumaires which are not absorptive (Fig. 4).

Table 1. Manufacturers' data of the sound absorbing elements: absorption coefficient $\alpha_{\mathrm{gf,baffle}}$ of the glass fiber panels, arranged as baffles with a 80 cm interval; absorption coefficient $\alpha_{\mathrm{mel,baffle}}$ of the small melamine cylinders, arranged as baffles in a plane with a 40 cm inter-axis distance and a 1.85 m plenum; and absorption coefficient $\alpha_{\mathrm{PET,panel}}$ of a free standing PET panel.

f [Hz]	250	500	1000	2000	4000
$\alpha_{\mathrm{gf,baffle}}$ [-]	0.40	0.70	0.85	0.95	1.00
$\alpha_{\mathrm{mel,baffle}}$ [-]	0.19	0.63	0.80	0.86	0.85
$\alpha_{\mathrm{PET,panel}}$ [-]	0.42	0.57	0.76	0.85	0.91

Table 2. Manufacturers' data of the foam cylinders employed in the final design: equivalent absorption area $A_{\mathrm{cyl,15}}$ and $A_{\mathrm{cyl,24}}$ of a cylinder with diameter of 15 and 24 cm, respectively, and a height of 120 cm, applied as baffles in a 3-by-3 grid with a grid spacing of 70 cm in one direction and 120 cm in the other direction.

f [Hz]	250	500	1000	2000	4000
$A_{\mathrm{cyl,15}}$ [m^2]	0.18	0.49	0.65	0.65	0.62
$A_{\mathrm{cyl,24}}$ [m^2]	0.52	0.90	1.03	0.99	0.94

Figure 4. Final design of the sound absorbing chandelier, suspended from the ceiling of the Jubileumzaal.

3. EFFECTIVENESS FOR REVERBERATION TIME REDUCTION

A reverberation test has been carried out just before and after 20 acoustic chandeliers (corresponding to the final design) have been installed in the Jubileumzaal, on 27 July and 12 August 2020, respectively. The measurement procedure of ISO 3382-2 has been followed [2] using the T_{20} approach and the integrated impulse method [3]. Impulse sounds were generated with a Larson Davis BAS006 clapper and the decays were recorded and converted into reverberation time values with an NTi SL2-TA sound analyser.

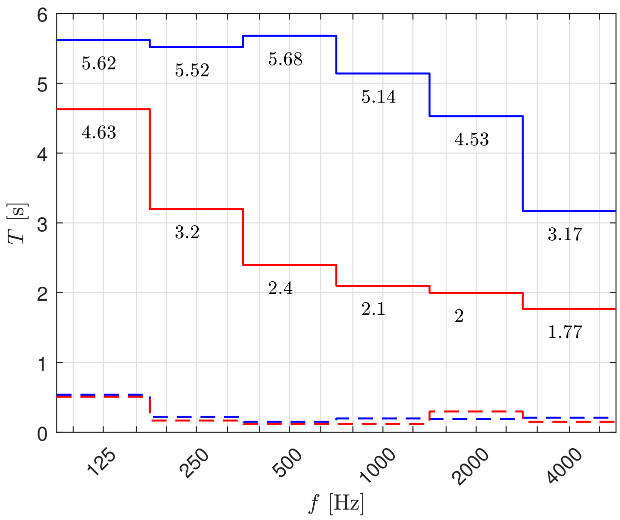

Figure 5. Measured average reverberation times in the Jubileumzaal before and after application of the acoustic chandeliers (solid lines) and standard deviations over the 58 source-receiver combinations (dashed lines).

A total of 58 source-receiver combinations have been employed and the same measurements positions were used in both tests. The results are displayed in Fig. 5. The average reverberation time of the unoccupied space in the 500, 1000 and 2000 Hz octave bands was 5.1 s before renovation and it is 2.2 s after renovation. This amounts to a reduction of almost 60 %.

From the measured reverberation times before and after renovation (denoted as T_1 and T_2, respectively), the sound absorption of a chandelier A can be estimated. Two methods have been employed for this. The first method makes use of Sabine's formula, which leads to

$$A = \frac{0.161V}{N}\left(\frac{1}{T_2} - \frac{1}{T_1}\right), \qquad (1)$$

where V is the volume of the room and N the number of chandeliers. The resulting values can be found in Fig. 6.

Sabine's formula is known to be potentially inaccurate in rooms where one surface is significantly more absorbent than the others [4]. This is the case for the Jubileumzaal after renovation, since the chandeliers render the ceiling much more absorbent than the other walls. A second method for estimating the sound absorption of the chandeliers was therefore implemented. It makes use of the reverberation time prediction of Annex D from the ISO 12354-6 standard [5], which divides the total sound field into parts that graze the walls of the room and a part that is non-grazing; each part is taken to be a subsystem in a transient statistical energy analysis. The chandelier absorption A is determined such that the measured reverberation time T_2 matches the ISO prediction. The absorption coefficient of all walls before renovation is taken to be the same and estimated from T_1 using Sabine's formula. The resulting values of A are also displayed in Fig. 6. The chandelier absorption as estimated from the ISO method is significantly higher than the absorption as determined from Sabine's formula. This points to a loss of efficiency of the chandeliers when they are installed in the hall, caused by the inhomogenous absorption distribution and the related directionality of the sound field.

A crude prediction is also displayed, which was obtained by multiplying the equivalent absorption areas per cylinder from Table 2, with the number of cylinders employed; the tabulated values were reduced by half for cilinders with a length of 60 cm. It can be observed that the predicted chandelier absorption values match the experimental values well, at least when the more accurate ISO method is employed.

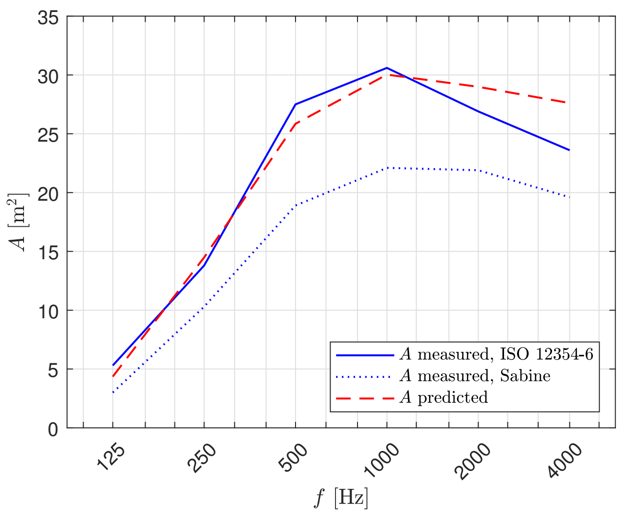

Figure 6. Equivalent absortion area of the final acoustic chandelier: in-situ values as determined from the ISO and Sabine methods, and a straightforward prediction from the manufacturer's data .

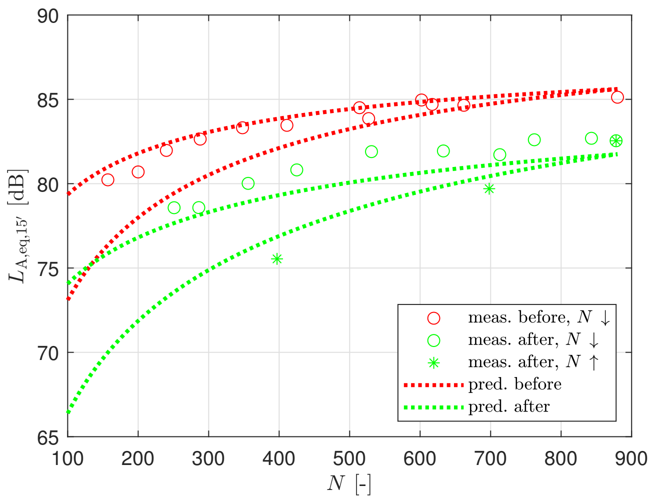

Figure 7. Sound pressure level due to speach as a function of the number of persons in the room N: measured values (equivalent levels per 15 minutes, $L_{\mathrm{A,eq,15'}}$) and predicted values (lower curves: for increasing N; upper curves: for decreasing N).

4. EFFECTIVENESS FOR NOISE REDUCTION DURING SOCIAL GATHERINGS

4.1 Experimental data

In order to assess the effectiveness of the acoustic chandeliers on the background noise in the room during social gatherings, experiments have been performed before and after the renovation, under similar circumstances: during the University's Christmas receptions of 19 December 2019 and 22 December 2022. The background noise due to simultaneous conversation was measured with a sound level meter, and at the same time, the number of people that are present in the room was monitored.

The resulting data, which were subdivided into segments of 15 minutes, are displayed in Fig. 7. The chandeliers result in a clear reduction of the background noise. However, there are also substantial differences in background noise when the number of people is increasing or decreasing.

4.2 Application and extension of a noise prediction formula

The influence of the number of people on the background noise during social gatherings can be compared against predictions such as provided by Rindel's formula [6]:

$$L_{\mathrm{N,A}} = 93\,\mathrm{dB} + 20\log\frac{N}{g(A_{\mathrm{e}} + A_{\mathrm{p}}N)}, \qquad (2)$$

where $L_{\mathrm{N,A}}$ denotes the A-weighted background noise, N the number of persons present in the room, g the group size, A_{e} the total absorption in the empty space and A_{p} the average sound absorption of one person. The group size g is defined as the total number of persons present divided by the number of persons speaking simultaneously. This prediction formula assumes a diffuse sound field in the room and it includes a linear empirical model for the Lombard effect, which means that speakers will raise their voice when the background noise is increasing and that a linear relation between both is assumed. In the considered setting, the Lombard effect results in the cocktail party effect: when the background noise is increasing, the speaking persons at the social gathering raise their voice, causing a further increase in the background noise until a maximum is reached. The parameters involved in the model were estimated as $g = 2.75$ (4 out of 11 people are speaking simultaneously) and $A = 0.5\,\mathrm{m}^2$ (standing person in moderately thin clothing [7, p. 426]). Since the prediction formula assumes a diffuse sound field, A_{e} has been estimated from Fig. 5 using Sabine's formula.

Fig. 7 provides a comparison between the measured noise values and the predicted ones. It can be observed that the predictions are accurate when the number of persons is increasing. When the number of persons is decreasing, the noise level decreases less significantly than could be expected based on the prediction formula.

This indicates that the cocktail party effect works differently when the number of persons is increasing than when it is decreasing. If the number of persons present in the room is decreasing, the remaining persons continue to speak at the same vocal effort, such that the background noise decreases to a lesser degree.

In order to check this hypothesis, the vocal effort has been computed. The vocal effort can be defined as the sound pressure level that is measured in anechoic conditions at 1 m distance in front of the speaker; following [6], this quantity is denoted as $L_{\mathrm{S,A,1m}}$. From the relation betwen the sound power level of a point source and the diffuse sound pressure level due to that source, one finds that

$$L_{\mathrm{S,A,1m}} = L_{\mathrm{N,A}} + 10\log\frac{g(A_{\mathrm{e}} + A_{\mathrm{p}}N)}{4N} - 8\,\mathrm{dB}. \qquad (3)$$

With the measured values of $L_{\mathrm{N,A}}$, N and A_{e} and the previously employed estimates of g and A_{p}, the vocal effort

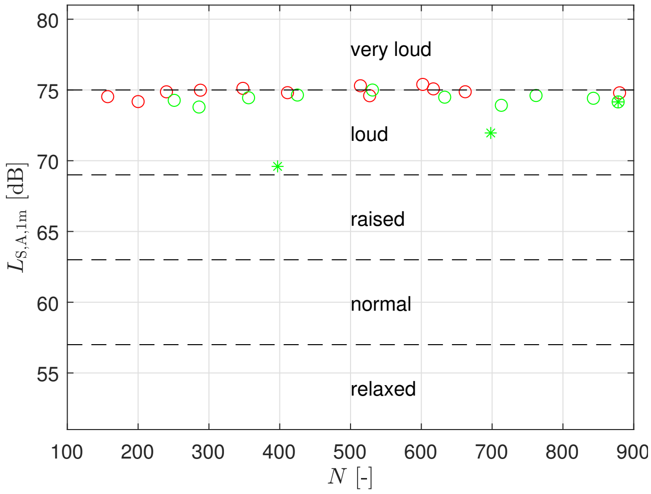

Figure 8. Vocal effort as a function of the number of persons N before (red) and after (green) renovation during an increase (*) or decrease (o) of N.

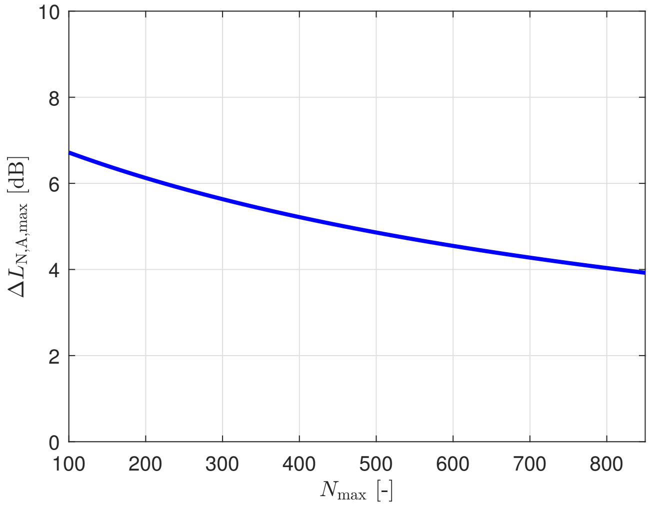

Figure 9. Estimated difference in A-weighted sound pressure background noise level in the Jubileumzaal due to the renovation with acoustic chandeliers as a function of the maximum number of people present during a social gathering.

of Fig. 8 is obtained. It is clear that the vocal effort remains constant when the number of persons is decreasing, even when the decrease is very substantial.

Predicting the noise level for a decreasing number of persons $L_{N,A,dec}$ is then possible by applying (3) twice: first for obtaining the vocal effort at maximum room occupation $L_{S,A,1m}(N_{max})$ and then for predicting the noise level for a different number of persons N but the same vocal effort:

$$L_{N,A,dec} = L_{S,A,1m}(N_{max}) - 10 \log \frac{g(A_e + A_p N)}{4N} + 8\,\text{dB}. \quad (4)$$

This extension to the noise prediction model has also been added to Fig. 7. It can be observed that the extended prediction model agrees well with the measured data.

4.3 Effectiveness assessment

Based on the previous analysis, the effectiveness of the renovation can be quantified as the difference between the background sound pressure level due to simultaneous speech before and after renovation, as computed from Rindel's formula for a given *maximum* number of persons present N_{max} during a social gathering in the room (Fig. 9). The effect is significant, but decreases with N_{max} because the total sound absorption by the persons increases; this can also be observed from (2).

At the nominal capacity of the room (800 persons), the background noise level has decreased from 85 to 81 dB(A). Although this is a clear improvement, the noise value remains high and further absorptive treatment has been advised.

The relatively large differences between background noise for increasing and decreasing number of persons present in the room N as observed from Fig. 7 also suggests that, when N decreases substantially after attaining the maximum value N_{max}, the background noise can be reduced by interrupting the sumulatenous speech, e.g. via an interrupting public announcement. When the speech starts again after the announcement, the background noise is expected to be lower than before for the same number of people present, as N_{max} has been reset to a lower value. This strategy has yet to be tested in practice.

5. CONCLUSIONS

The improvement of the verbal communication during social gatherings in the Jubileumzaal of the KU Leuven University Hall has been a challenging task due to architectural constraints. The application of sound absorbing chandeliers, which are custom made from commercially available sound absorbing baffles, was deemed acceptable from an aesthetical point of view and effective (although not yet optimal) from a room acoustics point of view. In a preliminary design phase, several chandelier types have been subjected to a reverberation room test. Since the measured sound absorption curves are roughly similar, one type was selected for aesthetic reasons and applied in the Jubileumzaal after further modifications. The sound absorption of this final design was obtained from reverberation tests in the room itself. The measured equivalent absorption values of all chandelier types were found to agree reasonably well with manufacturer's absorption coefficient data in the predominant octave bands for speech.

When deriving the chandelier's absorption from reverberation time tests in the Jubileumzaal itself, two methods were employed. The first one assumes an omnidirectional sound field while the second one accounts for the nonuniform absorption distribution in the room after renovation. The difference between both is significant, which indicates that the efficiency of the chandeliers for reducing the reverberation time in the hall is lower than in a reverberation room.

The effectiveness of the chandeliers in improving the verbal communication has been assessed experimentally, by measuring the background noise due to simultaneous speech during a busy reception before and after the acoustic renovation. The reduction at the maximum capacity of the room was found to be in good agreement with predictions from Rindel's formula. However, when the number of people present in the room is slowly decreasing, the background noise level remains substantially higher than predicted by this formula. This indicates that the coctail party effect works differently when the number of people is decreasing rather than increasing. When the number of people is decreasing, the vocal effort remains at the maximum level, such that the background noise decreases with a significantly lesser amount. An extension of Rindel's formula that accounts for this effect has therefore been presented. This finding also suggests that when the number of persons has decreased significantly after reaching a maximum, interrupting the simultaneous speech e.g. by a public announcement may help in reducing the background noise.

6. ACKNOWLEDGMENTS

This work was partially funded by the KU Leuven Technical Services, by the Research Foundation-Flanders (FWO project G.0A77.17N AcOpt) and by the European Research Council (ERC Starting Grant 714591 VirBAcous). The authors thank Jasper Vastiau and Stijn Moons for assisting with the experiments on 22 December 2022.

7. REFERENCES

[1] International Organization for Standardization, *ISO 354: Acoustics – Measurement of sound absorption in a reverberation room*, 2003.

[2] International Organization for Standardization, *ISO 3382-2:2008: Acoustics - Measurement of room acoustic parameters - Part 2: Reverberation time in ordinary rooms*, 2008.

[3] M. Schroeder, "New method of measuring reverberation time," *Journal of the Acoustical Society of America*, vol. 37, no. 3, pp. 409–412, 1965.

[4] E. Nilsson, "Decay processes in rooms with non-diffuse sound fields. Part I: ceiling treatment with absorbing material," *Building Acoustics*, vol. 11, no. 1, pp. 39–60, 2004.

[5] European Committee for Standardization, *EN 12354-6:2003: Building Acoustics - Estimation of acoustic performance of buildings from the performance of elements - Part 5: Sound absorption in enclosed spaces*, 2003.

[6] J. Rindel, "Verbal communication and noise in eating establishments," *Applied Acoustics*, vol. 71, no. 12, pp. 1156–1161, 2010.

[7] W. Fasold, E. Sonntag, and H. Winkler, *Bau- und Raumakustik*. Berlin: Rodolf Müller, 1987.