Measurement and simulation of high sound insulation and identification of sound transmission paths in complex building geometries

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Summary

Prediction and measurement of high sound insulation and evaluation of sound transmission paths in complex building structures can be a difficult and challenging task. This paper reports on measurements and simulations in the Odeon software of airborne sound insulation between premises in neighbouring buildings, from the basement in one building to the 3rd floor in the next building.

Measurements employing 11 minute long sine sweeps and red noise as excitation signals achieved sound reduction indices of $R' \geq 95$, 70 and 50 dB at 500, 50 and 20 Hz, respectively, and $R'_w + C_{50\text{-}5000} = 90$ dB. The results were largely unaffected by background noise in 1/3-octave bands from 31.5 to 2000 Hz. The sound transmission paths included a source room, transmission through floors, doors and windows, multiple reflections outdoors between several buildings, and transmission through façades into receiving rooms.

An Odeon model was calibrated to measurements in and around the source room in order to estimate sound paths to the neighbouring dwellings. Such an approach does not include structure borne sound, but chosen sound paths can be eliminated completely in order to quantify their contribution to the total sound pressure levels. Results comparing measured sound pressure levels in and around the buildings with the corresponding levels calculated in Odeon gave good agreement in cases where structure borne sound was not dominant.

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1. Introduction

Prediction and measurement of high sound insulation between rooms separated by complex building geometries can be a difficult task. To identify and evaluate to which extent various sound paths contribute to the resulting sound pressure level (SPL) in receiving rooms can be even more challenging. This paper reports on measurements and simulations in the Odeon room acoustic software [1] of sound insulation between premises in neighbouring buildings, from the basement in one building to the 3rd floor (American convention) in the next building.

Measurements of high sound insulation indices are frequently limited by background noise levels (BGN) and consequently low signal-to-noise ratios (SNR), especially when noise type excitation signals are employed. More recent measurement methods such as the maximum length sequence (MLS) [2] and swept-sine methods [3], both of which integrate a measured impulse response to obtain the SPL, prove more resistant to BGN and enable measurements of higher sound insulation values [4]. Compared with noise type excitation signals they correspond to measurements with infinite integration time. Furthermore, sweeps can be argued to be superior to pseudo-noise signals such as MLS, as they exhibit significantly higher immunity against distortion and time variance [3].

To assess and quantify the predominant sound transmission paths (STP) in complex building structures is complicated, and requires an extensive measurement procedure. In the case at hand, STPs from the source room include transmission through floors, doors and windows, multiple reflections outdoors between several buildings, and transmission through façades into receiving rooms. Sine sweeps were employed to measure the sound insulation from the source room to receiving room, and to selected intermediate positions. An Odeon model was calibrated to measurements in and around the source room, which in this case is an 800 m^2, two-storey discotheque / night club, in order to estimate and quantify STPs to the neighbouring dwellings. Such an approach does not include structure borne sound, but selected STPs can be eliminated completely in order to quantify their contribution to the total SPLs, which will be discussed further below. Mobility measurements with a modal sledge hammer have also been carried out to quantify structure borne sound transmission, which will not be discussed here.

2. Building geometry and layout

As mentioned in Section 1, the building geometries are quite complex. Figure 1a) and b) show an overview of the building geometry from the street and backyard, respectively. The source room is located in the basement in building 1, and comprises two floors, where the upper floor is a mezzanine largely open towards the lower, main floor. The higher floors of building 1 are office premises, with a restaurant on the ground floor.

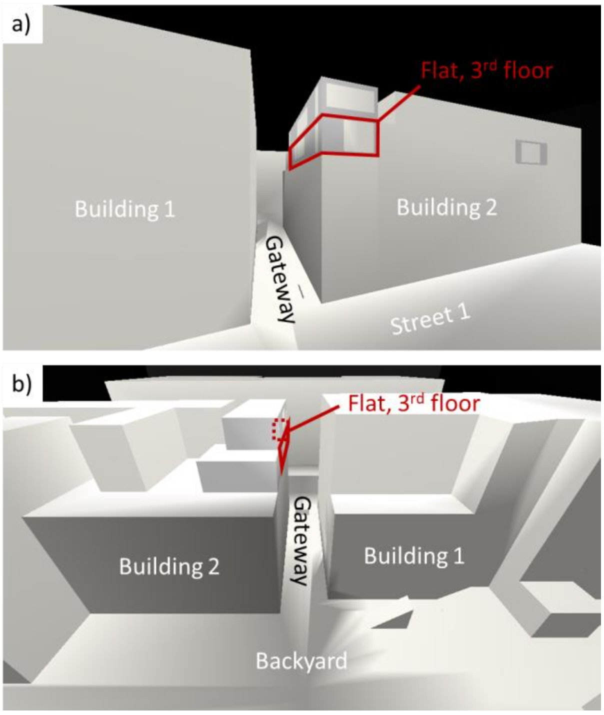

Figure 1. Overview of situation (Odeon model). a) View from the front street (Street 1). b) View from the backyard.

The concrete structures of buildings 1 and 2 are connected under the gateway that separates them from the ground floor upwards. The gateway leads to an open air backyard.

The nearest flat is situated on the 3rd floor in building 2, on the corner between Street 1 and the gateway. The façades towards the gateway and Street 1 consist of approximately 25 and 50 % windows, respectively, the rest being solid timber framework. There are commercial premises on the ground and 2nd floor of building 2, and residential apartments from the 3rd floor upwards. Measurements were done to a flat on the 4th floor and to flats further away on the 3rd floor also, but will not be discussed here.

3. Sound transmission paths (STP)

Figure 2 shows STPs from the source room, and also indicates the positions of the source and receiver rooms. The STPs indicated corresponds with the flow chart in Figure 3. The following STPs are identified:

1. Through an old vault on the upper basement floor, out in the backyard, and into the flat.
2. Through the floor to the restaurant on the ground floor, out through the façade to the gateway, and into the flat.
3. Out to Street 1 through the main entrance (stairs from the ground floor to the upper basement floor) to the discotheque, along Street 1, and into the flat from the gateway and Street 1.
4. Structure borne sound, mainly through the connected basements and up through building 2, but also through a laminated wood girder connecting the buildings across the gateway on the 2nd floor at the façade towards the backyard.
5. Through a 200 mm concrete wall into a transformer room with an open grating to the gateway, and into the flat.
6. Through the elevator shaft and staircases to the office entrance corridor, out to the backyard and Street 1, and into the flat.
7. Out to the backyard through the ground above parts of the discotheque in the basement, consisting of 300 mm concrete and insulation.

Two measurement series were done. Prior to the second series, STPs 1, 3 and 6 were improved by constructing temporary walls, as indicated by the red lines in Figure 2. A lining wall consisting of 3x13 mm plasterboards in each lining, mounted on

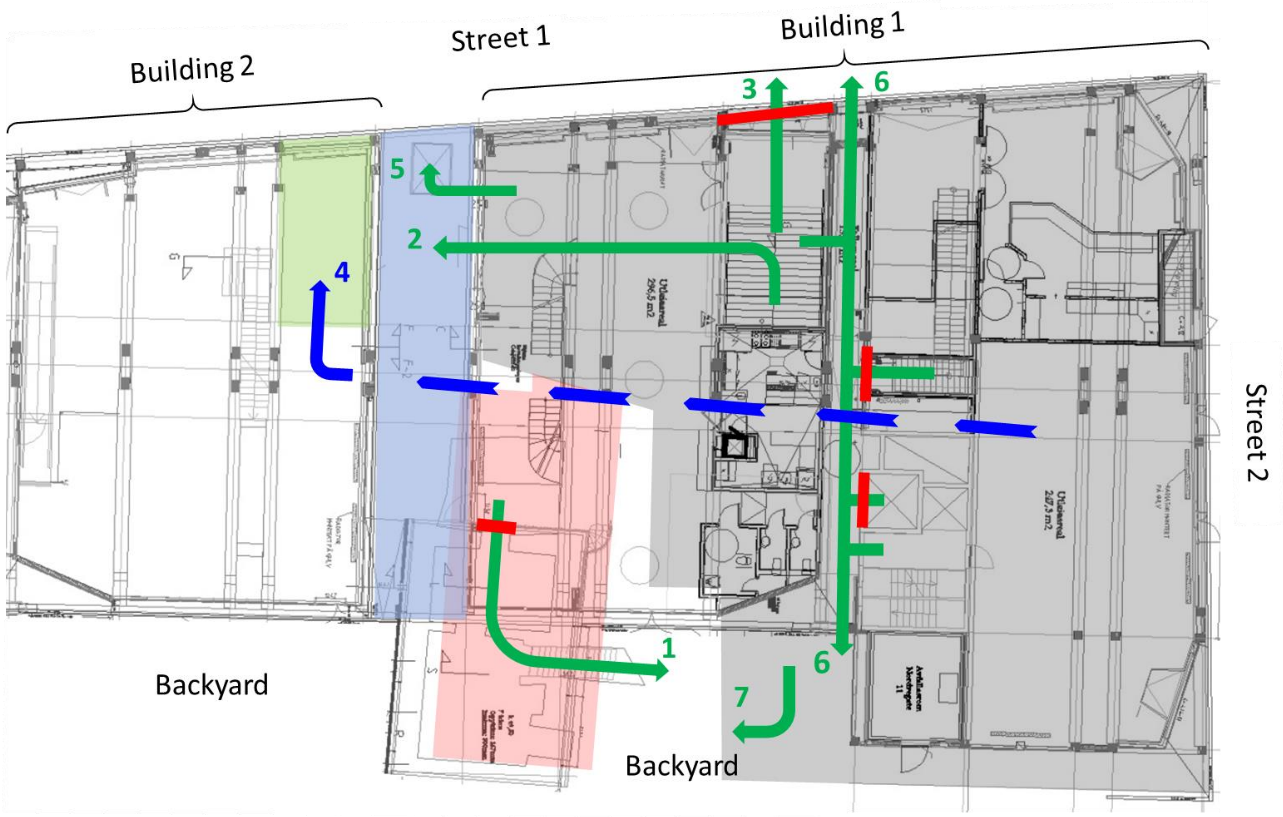

Figure 2. Overview of STPs, and source and receiver rooms. The floor plan shows the ground floor. The discotheque is located in the basement under the grey and red shaded area, where the red shaded area only extends on the upper basement floor. The blue and green shading indicates the gateway and the location of the living room in flat on the 3rd floor in building 2, respectively. Numbered arrows show STPs, which correspond to the STP flow chart in Figure 3. The red lines indicate where noise reduction measures were done.

2x100 mm separate steel studs, with a total air gap of approximately 800 mm and ≥ 200 mm mineral wool where built to limit STP 3, which is the main entrance to Street 1 from the discotheque in the basement. A similar wall was constructed to block off STP 1, but with a smaller air gap. To limit STP 6, single wall linings consisting of 3 and 4x13 mm plasterboards were mounted on 100 mm steel studs with mineral wool in front of the staircase and elevator, respectively, as shown in Figure 2.

4. Measurement results

Measurements of sound insulation were done employing 11 minute (672 s) long sine sweeps using a Norsonic 121 sound analyser [5]. However, presently sine sweeps generated by the Norsonic 121 sound analyser are limited to produce 1/3-octave band results from 50-5000 Hz. To account for the frequency range typically encountered in discotheques, the sine sweep measurements were complemented by noise type excitation using red noise in the 1/3-octave bands from 20-40 Hz.

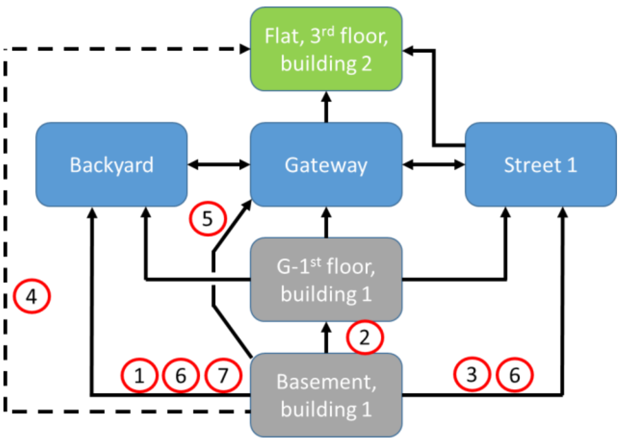

Figure 3. Flow chart showing energy analysis of STPs from basement in building 1 to the flat on the 3rd floor in building 2. Transmission paths for air borne noise are shown in solid lines, while the dashed line indicates structure borne sound. The numbers correspond to the transmission paths shown in figure 2.

Figure 4 shows differences in measured SPLs from the source room in the basement in building 1 to the living room in the flat on the 3rd floor in building 2. The blue and green lines

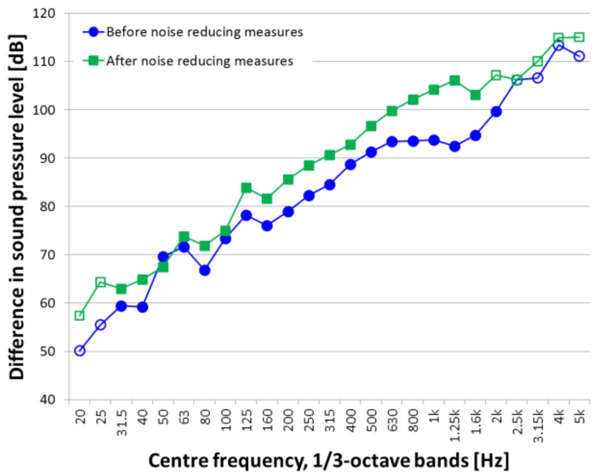

Figure 4. Difference in measured SPL from the basement in building 1 to the flat on the 3rd floor in building 2 before (blue line) and after (green line) sound insulation measures were done. Hollow markers indicate 1/3-octave band values influenced by background noise.

indicate measurement results before and after the sound reduction measures described in Section 3 were done, respectively. 1/3-octave frequency bands indicated by hollow markers denote influence of BGN, i.e. SNR ≤ 6 dB. As Figure 4 shows, the results were largely unaffected by BGN in 1/3-octave bands from 31.5 to 2000 Hz. The sound level difference increases relatively steady with frequency for both measurements. Results obtained before the measures were carried out showed a difference in sound level in the sending and receiving room of 50 dB at 20 Hz, though somewhat influenced by BGN, approximately 70 dB at 50 Hz, and around 95 dB at 500 Hz. Evaluation according to ISO 140-4 [6] (subsequently superseded by ISO 16283-1 [7]) and ISO 717-1 [8], thus just employing the sine sweep as excitation signal, resulted in $R'_w + C_{50\text{-}5000}$ = 90 dB. The effect of the sound insulation measures can be seen to be around 5 dB at each 1/3-octave band, except from 50-100 Hz, where the improvement is less, and at 800-1250 Hz, where the improvement is higher.

Figure 5 shows measured SPLs in the flat, with a SPL in the basement of $L_{pC,20\text{-}5000}$ = 128 dB. The blue line shows the SPL measured directly from the basement source room, while the blue dashed line indicates the BGN level. As explained above, these results are obtained using sine sweep in 1/3-octave bands from 50-5000 Hz, and red noise in 1/3-octave bands from 20-40 Hz. The BGN in 1/3-octave bands from 50-5000 Hz were obtained directly from the measured impulse response, thus

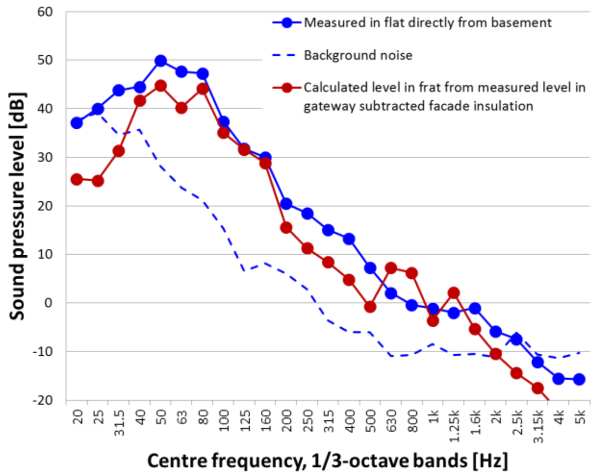

Figure 5. SPLs in the flat on the 3rd floor in building 2. The solid blue line shows levels measured directly from the source room in the basement in building 1, while the dashed blue line shows the background noise levels. The red line shows SPLs in the flat calculated by subtracting the measured sound insulation of the façades from the SPLs measured outside the façades from source room in the basement in building 1.

simultaneously as the SPL itself, while the BGN levels below 50 Hz were measured just after the SPLs with red noise were obtained The red line in Figure 5 shows SPLs in the flat found by subtracting the measured façade insulation of the flat from the sound level difference measured from the discotheque to positions in the gateway and Street 1 outside the flat. The intention behind this exercise was to avoid structure borne sound, which is likely to have limited contribution to positions outdoors. Good agreement can be seen in the 1/3-octave bands from 80-160 Hz; however, deviation at lower frequencies indicates influence of structure borne sound. Frequency bands from 200 Hz upwards does not contribute significantly to the total SPL (L_{pC}) in the flat.

Resulting SPLs in the flat during activity in the discotheque can be found by subtracting the difference in SPLs shown in Figure 4 from the SPLs measured in the discotheque during activity, thus including typical frequency spectrum from discotheque music.

5. Odeon simulations

An Odeon model for both buildings 1 and 2 was developed to identify and evaluate the extent to which various STPs contributed to the resulting SPL in the flat, as shown in Figure 1. The Odeon model was calibrated to measurements in and around the source room, in order to estimate STPs to the neighbouring dwellings. Such an approach does not include structure borne sound or weaknesses in the building structures not evident from architectural drawings, but chosen STPs can be eliminated completely in order to quantify their contribution to the total SPLs at given receiver locations. Calculations of sound transmission through a number of partitions require a vast number of rays to ensure reliable results. Convergence tests were done to validate the calculation parameters and limit calculation times. The final calculations were made with transition order 0, 10 million rays and impulse response length 3 s.

Figure 6 a) shows a snapshot of building 1 from Odeon, where a selection of materials is shown, while b) shows the corresponding sound reduction indices, *R′*. The walls and windows towards the gateway were adjusted according to earlier measurements; doors in STP 3 were estimated based on their type and data sheets, while doors from the ground floor out to Street 1 and the backyard were roughly estimated due to leaks in their connections with the walls. Sound reduction indices for all other structures were calculated in the Insul software [9]. Similarly are sound reduction indices for the façade elements and slab in the flat on the 3rd floor of building 2 shown in Figure 6 d), with a snapshot of the flat in c).

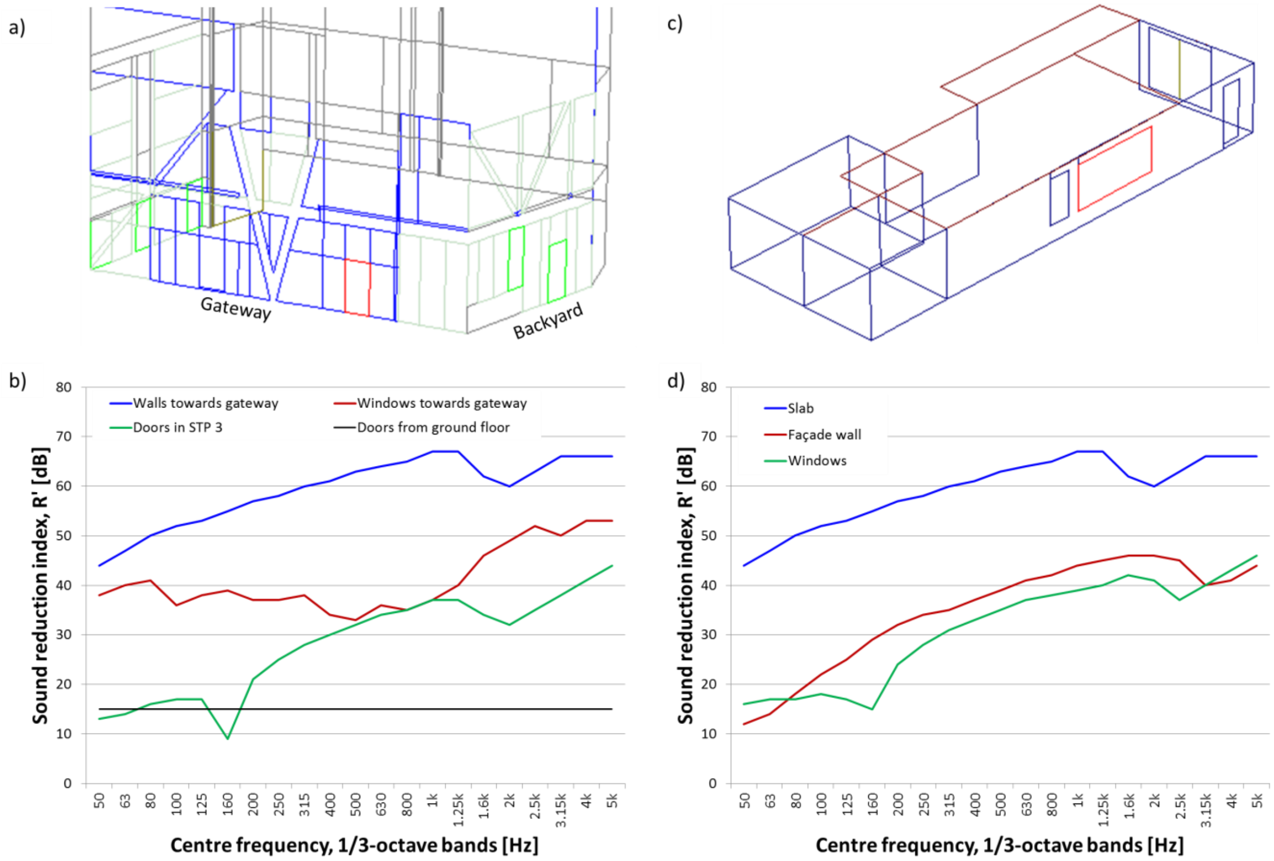

Figure 6. a) Overview of part of building 1 in the Odeon model, showing a selection of the materials employed, b) Sound reduction indices for a selection of the materials in building 1, c) Part of the Odeon model showing the flat on the 3rd floor in building 2, and d) Sound reduction indices for the façade elements and slab employed for the flat.

The first step in the analyses is to calibrate the source and source room to the measurements, and evaluate a selection of receiving positions in doing so. To obtain good and reliable results, sound absorbing materials should be added to the relevant surfaces. Figure 7 a) shows excellent agreement between results from Odeon calculations (red squares) and measurements (blue crosses) in the discotheque in the basement. By allocating the correct sound reduction indices for all materials in the model as explained above, SPLs at chosen locations can be estimated. Figure 7 b) shows the corresponding SPLs calculated in the flat on the 3rd floor in building 2, where good agreement with the measured SPLs can be seen, especially from 250-2000 Hz. The deviation at 63 and 125 Hz can be due to inaccurate estimation of sound reduction indices in Insul, influence of structure borne sound, or weaknesses and structural factors in the building structures not accounted for in the Odeon model.

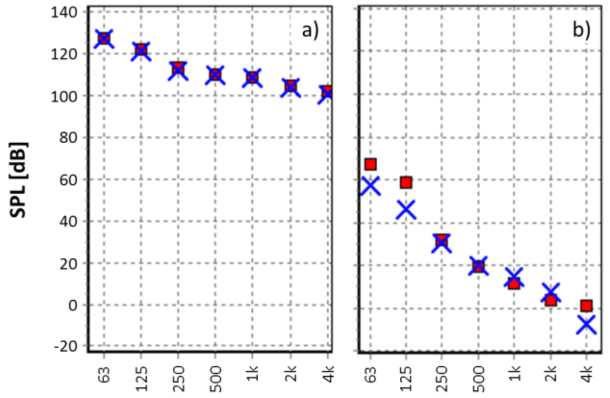

Figure 7. Results from calibration of the Odeon model with measurements; red squares and blue crosses indicate simulation and measurement SPLs, respectively. a) SPLs in the basement; b) SPLs in the flat on the 3rd floor.

Figure 8 shows SPLs at 1 kHz at various locations, where red squares and blue crosses indicate simulated and measured SPLs, respectively. Good agreement as found throughout, which enables the user to investigate the effect of introducing sound reducing measures at given STPs. Further analyses through model optimisation or measurements can also be done to pursue suspected weaknesses in the buildings.

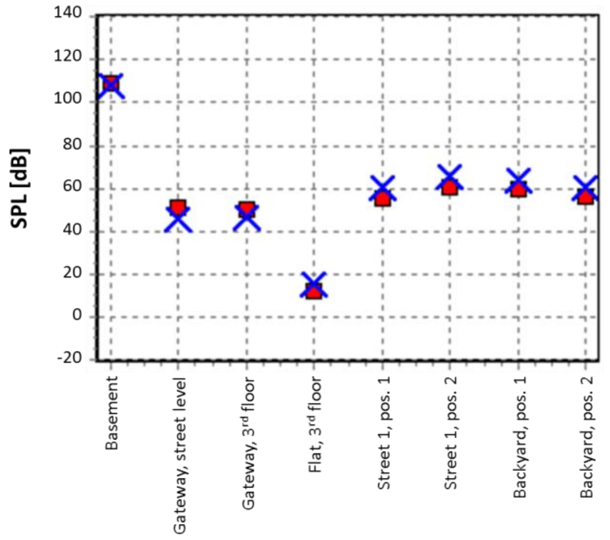

Figure 8. Results from calibration of the Odeon model with measurements; red squares and blue crosses indicate simulation and measurement SPLs, respectively. Results at 1 kHz are shown.

6. Conclusions

Sound insulation and sound transmission paths (STP) from a discotheque in the basement in one building to a flat on the 3rd floor in the next building have been evaluated through extensive measurements and simulations in the Odeon software.

Measurements employing 11 minute long sine sweeps and red noise as excitation signals achieved sound reduction indices of $R' \geq 95$, 70 and 50 dB at 500, 50 and 20 Hz, respectively, and $R'_w + C_{50\text{-}5000} = 90$ dB. The results were largely unaffected by background noise in 1/3-octave bands from 31.5 to 2000 Hz. A comparison between SPLs obtained in the flat on the 3rd floor from the source room in the basement of the neighbouring building and results obtained by subtracting the sound insulation of the façades to the flat from SPLs measured outside the façades from the source room gave good agreement over a large frequency range; however, deviation at low frequencies indicate possible influence of structure borne transmission.

An Odeon model was calibrated to measurements in and around the source room in order to estimate STPs to the neighbouring dwellings, an approach that does not include structure borne sound, but selected STPs can be eliminated completely in order to quantify their contribution to the total SPLs. Comparisons between measured SPLs in and around the buildings with the corresponding levels calculated in Odeon gave good agreement in cases where structure borne sound was not dominant. Good agreement was seen throughout the locations tested, indicating that the Odeon software can be used to evaluate the influence of various STPs on the total SPL at given locations.

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