SIMULATION-SUPPORTED ROOM ACOUSTICS RETROFIT OF OFFICE SPACES

Arzu Tugrul, Josef Lechleitner, Matthias Schuß, Ardeshir Mahdavi
Department of Building Physics and building Ecology, Vienna University of Technology, Vienna, Austria

ABSTRACT

This paper addresses the use of performance simulation within the framework of a case study pertaining to room acoustics. The target of the study is an existing office area. The study involves acoustical measurements and simulations, as well as interviews with the occupants before and after acoustical improvement measures. The results of the study contribute to the discussion concerning the effectiveness of acoustical simulation applications and the extent of necessary simulation calibration efforts in modeling the acoustical conditions in existing spaces and prediction of the implications of acoustical retrofit measures. Specifically, they show that simulation model calibration based on pre-retrofit measurements can substantially improve the quality of simulation's predictions for the post-retrofit conditions.

INTRODUCTION

The potential benefits of a simulation-aided approach to building design and retrofit have been widely discussed in the past (see, for example, Hensen and Lamberts 2011). The basic idea is to evaluate design intentions a priori using simulation, such that they can be improved and fine-tuned before realization. Currently, the potential of this simulation-aided design support strategy is not being fully exploited. The reasons are multi-faceted. Thereby, usability and reliability concerns with respect to performance simulation applications may play a role. Hence, it would be useful to collect, discuss, and evaluate actual experiences pertaining to the practical cases of simulation deployment in building design, retrofit, and operation.

This paper addresses the use of performance simulation within the framework of a case study pertaining to room acoustics. The target of the study was an office area within a university, consisting of closed and open spaces for different functions (workstations, seminar, service spaces). Certain indicators of the room acoustical performance of this office area were obtained based on both measurements and simulations. Subsequently, the simulation models were calibrated using the measurement results. The calibrated simulation models facilitated the prediction of the implication of acoustical retrofit measures. Upon the implementation of on such measure (installation of acoustical absorbers), measurements and simulations were conducted again and the results were compared. Moreover, occupants' subjective evaluation of the acoustical conditions before and after the acoustical retrofit measures were explored as well using appropriate questionnaires.

The results of the case study are relevant in view of a number of questions: How effective are acoustical simulation applications in modeling the existing conditions? What are the likely sources of uncertainty in simulation? What is the extent of the calibration needed? Can a calibrated simulation model reliably predict the implications of retrofit measures? The results allow, in addition, the exploration of possible change in the occupants' subjective evaluations of the acoustical conditions as a consequence of the executed retrofit measures.

APPROACH

The study involved the following steps:

i) The existing spaces were documented in view of geometry and material properties. Figure 1 shows a schematic plan of the office area. The study focused on two areas, namely the seminar room (SR) and the open-plan office area (OP). Figures 2 and 3 show the existing conditions in these two areas.

ii) Basic acoustical measurements – pertaining to reverberation time and sound distribution – were conducted to capture the existing acoustical condition. Measurements were conducted with a wireless building acoustic measurement system. For reverberation time measurements in OP, 3 speaker positions and 16 microphone positions were used. For reverberation time measurements in SR, 2 speaker positions and 8 microphone positions were used. For sound distribution measurements in OP, 1 speaker position and 11 microphone positions were used (see Figure 4). For sound distribution measurements in SR, 1 speaker position and 8 microphone positions were used.

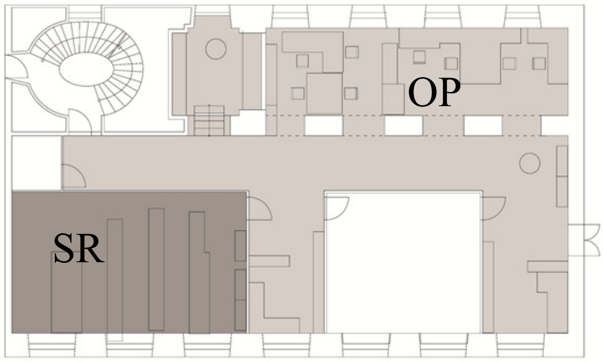

Figure 1 Schematic plan of the office area (SR: seminar room; OP: open-plan office area)

Figure 2 Existing conditions in SR

Figure 3 Existing conditions in OP

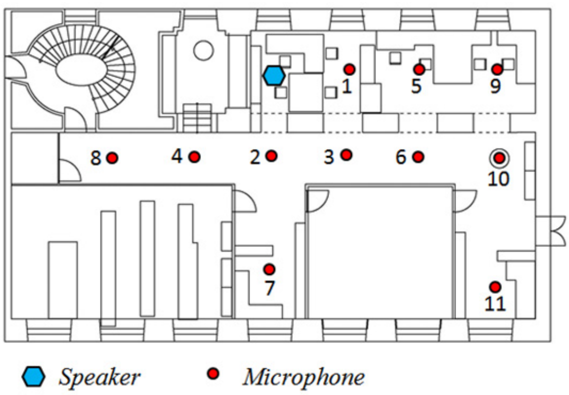

Figure 4 Speaker and microphone placements for sound distribution measurements

iii) Occupants were interviewed with respect to their perception of the acoustical conditions. The very small number of interviewed occupants (17) does not allow for a meaningful statistical analysis. Nonetheless, we have included some basic results (tendencies of the expressed opinions and expressions) to provide a general impression of the pre and post retrofit occupancy evaluations.

iv) Office spaces were modeled in an advanced room acoustics simulation program (ODEON 2009). Note that a documentation of the acoustical room surface properties (absorption coefficients) did not exist. An in-situ measurement of such properties was also not possible. Thus, assumptions were made based on the surface material types (e.g., plaster, glass, wood) and available general absorption coefficient data in literature (e.g., Fasold and Veres 2003) and the simulation application's database. A summary of these assumptions is given in Table 1.

Table 1 Summary of assumptions pertaining to the existing sound absorption properties (α) of the office area surfaces (included are also the assumed absorption coefficients of the virtual absorbers deployed for model calibration)

ELEMENT	**FREQUENCY [Hz]**					
	125	250	500	1000	2000	4000
Floor (wood)	0.04	0.04	0.07	0.06	0.06	0.07
Ceiling (CO)	0.20	0.15	0.10	0.08	0.04	0.02
Ceiling (OP)	0.02	0.02	0.03	0.04	0.05	0.05
Ceiling(SR)	0.02	0.02	0.03	0.04	0.05	0.05
Ex. wall (Brick)	0.02	0.02	0.03	0.04	0.05	0.05
Int. wall-(Brick)	0.02	0.02	0.03	0.04	0.05	0.05
Int. wall (Gyps. boa.)	0.28	0.14	0.09	0.06	0.05	0.01
Window, door(Glass)	0.25	0.15	0.10	0.05	0.03	0.03
Win. frame (Wood)	0.04	0.04	0.05	0.06	0.06	0.06
Door (wood)	0.20	0.12	0.10	0.07	0.05	0.05
Chairs	0.11	0.35	0.53	0.63	0.64	0.57
Virtual absorb. (SR)	*0.50*	*0.42*	*0.11*	*0.15*	*0.15*	*0.20*
Virtual absorb. (OP)	*0.68*	*0.57*	*0.24*	*0.31*	*0.31*	*0.32*

v) The simulation model was calibrated using the measurement data. The calibration was based on the comparison of the measured and simulated reverberation times and was realized in terms of virtual surfaces distributed in the office spaces.

vi) Existing acoustical conditions were compared with applicable criteria.

vii) Acoustical improvement measures – in this case, additional absorption – were conceived and modeled with the simulation tool. The additional absorption was introduced in the office spaces in terms of panels attached to and suspended from the ceilings, as well as suspended cubical elements. Tables 2 and 3 summarize the sound absorption properties of these elements.

ix) Post-retrofit measurements and simulations were performed and compared.

x) Occupants were interviewed again in view of the modified acoustical conditions (see also the clarification under point *iii* above).

xi) The results were processed, analyzed, and discussed.

viii) The acoustical improvement measures were realized. Figures 5 and 6 show the added absorption elements in the course of the acoustical retrofit.

Table 2 Sound absorption (α) of installed panels

ELEMENT	**FREQUENCY [Hz]**					
	125	250	500	1000	2000	4000
Panels	0.29	0.48	0.97	0.92	0.86	0.89

Table 3 Equivalent absorption area (in m^2) of one cubical element

ELEMENT	**FREQUENCY [Hz]**					
	125	250	500	1000	2000	4000
Cub. el.	0.60	1.40	1.80	1.80	2.10	1.70

Figure 5 Added absorption elements in SR

Figure 6 Added absorption elements in OP

RESULTS

As noted in the introduction and approach sections, the present research involved data collection pertaining to reverberation times and sound distribution in the office area as well as subjective evaluations by the office users before and after retrofit measures.

Figures 7 and 8 show, for SR and OP respectively, the measured values of the reverberation time together with corresponding non-calibrated simulation results. Note that the calibrated simulation results almost exactly match the measurements are thus not explicitly plotted in Figures 7 and 8.

As these results show, the existing reverberation times were found to be too long for both SR and OP. Hence, it was concluded that the addition of sound absorbing elements could reduce the reverberation times and improve the room acoustics in the office area. Toward this end, acoustical panels were considered for SR, and a combination of acoustical panels and cubical elements for OP. A reverberation time of around 1.0 s was targeted for the SR (occupied setting). For OP, the targeted reverberation time was around 0.8 s.

Figures 9 and 10 show, for SR and OP respectively, the measured and simulated post-retrofit reverberation time values. To illustrate the effect of calibration, these Figures include both non-calibrated and calibrated simulation results. To consider the effect of occupancy in SR, Figure 11 includes calibrated simulation results for the reverberation time under non-occupied and occupied (20 people) conditions.

Figures 12 and 13 depict the measured and simulated (non-calibrated and calibrated) sound distribution in OP for pre and post-retrofit cases respectively (non-occupied conditions). Note that the sound distribution in SR is not shown given the relative small size of the room and homogeneity of sound distribution. Microphone positions were labeled according to their distance to the sound source.

Figure 14 shows results of occupants' subjective evaluations with regard to indoor conditions. Figure

15 compares pre and post-retrofit percentage of occupants who expressed a specific improvement need. Likewise, Figure 16 documents the pre and post-retrofit degree of expressed annoyance (interference with concentration) due to various noise sources.

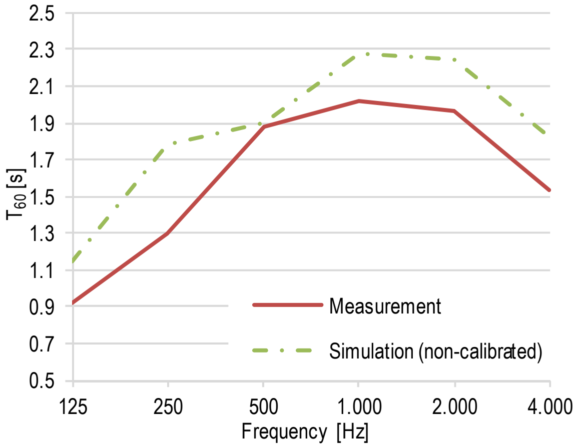

Figure 7 Measured and simulated (non-calibrated) reverberation times in SR (non-occupied)

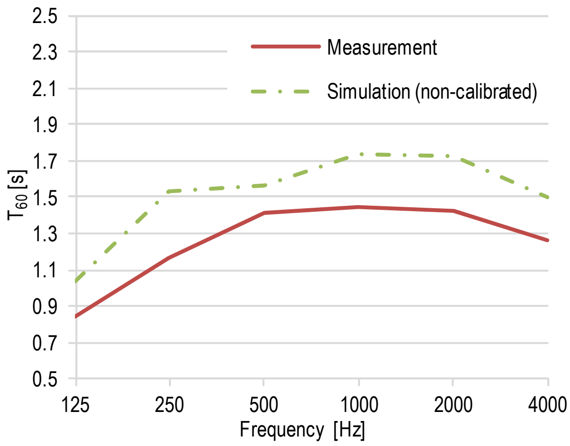

Figure 8 Measured and simulated (non-calibrated) reverberation times in OP (non-occupied)

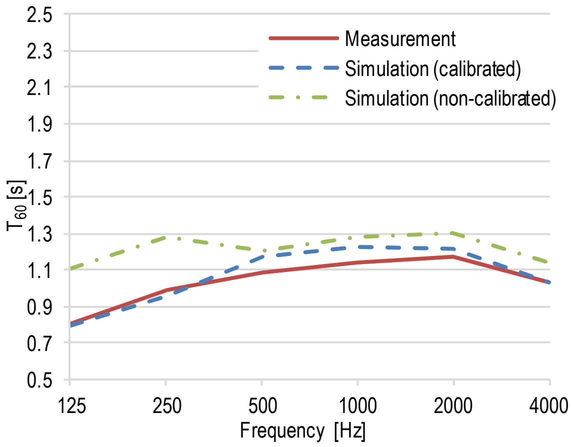

Figure 9 Measured and simulated (non-calibrated and calibrated) post-retrofit reverberation times in SR (non-occupied)

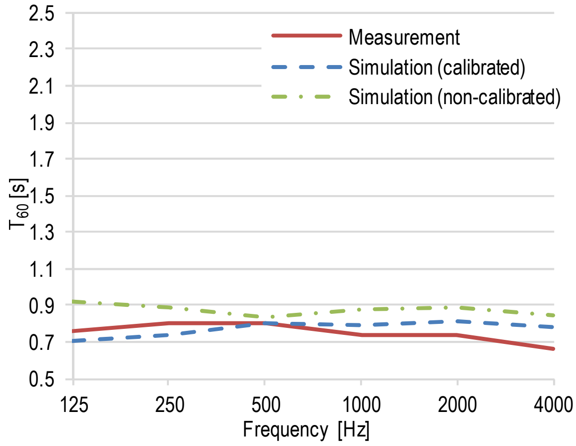

Figure 10 Measured and simulated (non-calibrated and calibrated) post-retrofit reverberation times in OP (non-occupied)

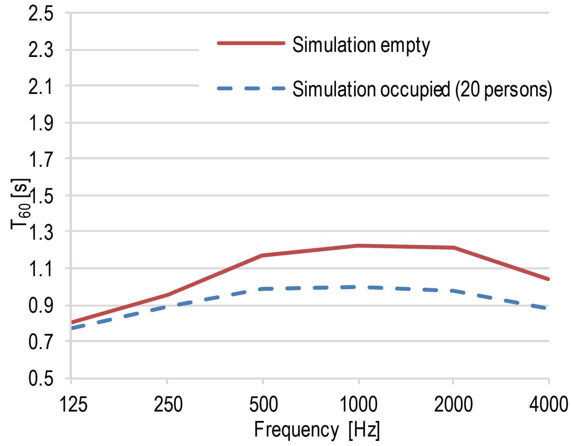

Figure 11 Simulated (calibrated) post-retrofit reverberation times in SR under non-occupied and occupied (20 people) conditions

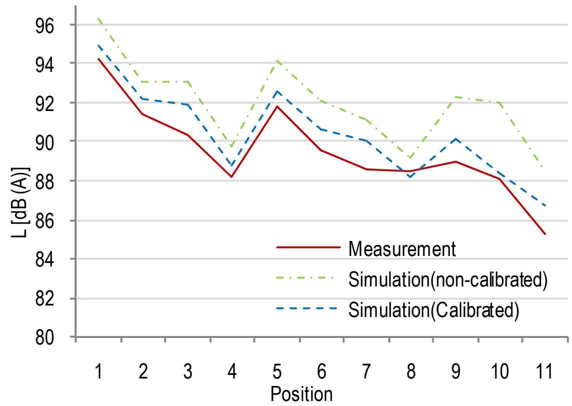

Figure 12 Measured and simulated (non-calibrated and calibrated) pre-retrofit sound distribution in OP

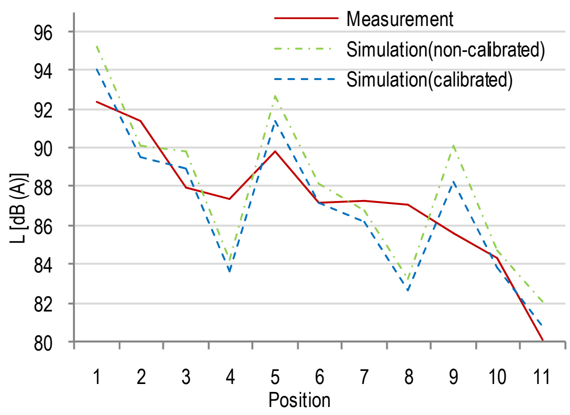

Figure 13 Measured and simulated (non-calibrated and calibrated) post-retrofit-sound distribution in OP

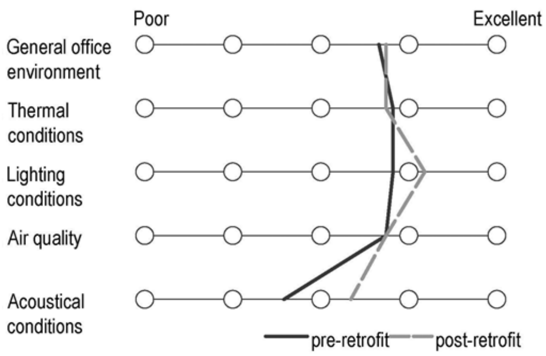

Figure 14 Occupants' subjective evaluations with regard to indoor conditions

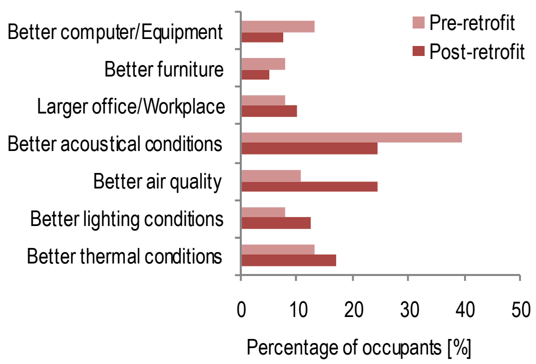

Figure 15 Percentage of occupants who wished specific improvement measures

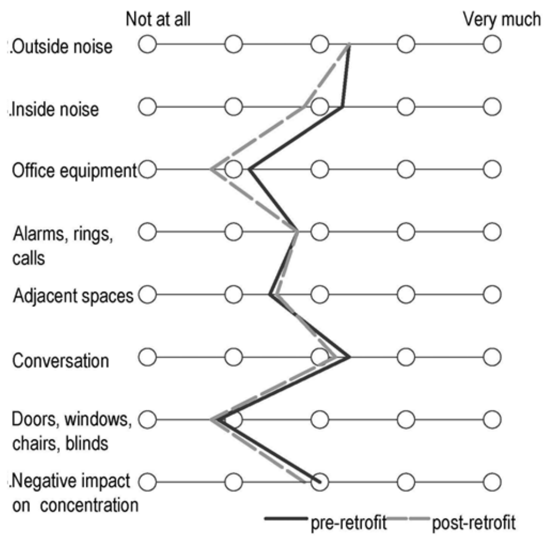

Figure 16 Annoyance levels (negative impact on concentration) due to various noise sources

DISCUSSION AND CONCLUSION

The above results warrant a number of observations and conclusions:

- Simulation results obtained via the non-calibrated simulation model display relatively large errors (see Figures 7 and 8). The errors are most likely due to the uncertainties associated with the assumptions pertaining to the sound absorption coefficients of the room surfaces. As mentioned earlier, a documentation of these coefficients for the existing conditions was not available. Nor was it possible to conduct an in-situ measurement of the absorption coefficients. Default assumptions (based on literature, experience, and simulation application's database) may have thus deviated from the "true" surface properties, leading to the aforementioned errors.
- The calibration process with the virtual absorption elements appears to be quite effective in the trivial sense that, after calibration, simulation results closely match the measurements.
- The calibration process may be also viewed to be effective in a non-trivial sense: There is a relatively good agreement between simulation-based predictions (based on the calibrated model) and measurement results for post-retrofit conditions. This inference is clearly supported by the comparison between the predictions of calibrated and non-calibrated simulation models for the post-retrofit conditions. Predictions based on the non-calibrated model show significantly higher

errors than those obtained from the calibrated model (see Figures 9 and 10).

- With regard to sound distribution, calibrated model predictions and measurement results for pre-retrofit conditions display good agreement (Figure 12). However, for post-retrofit conditions, high deviations are observed at certain positions (Figure 13). The simulation appears to underestimate the occlusion effect (positions 4 and 8) and overestimate direct exposure (positions 5 and 9).

As mentioned before, no statistically meaningful inference can be made from the interview results, given the small number of occupants. Nonetheless, the results do seem to suggest a certain improvement regarding the perceived acoustical conditions (see Figure 13). Before retrofit, the acoustical condition was the main occupants' concern when asked about desirable improvements. This circumstance change somewhat after retrofit (see Figure 15). A slight but consistent decrease of expressed noise-induced annoyance levels can be discerned from the results shown in Figure 16.

The case study presented thus suggests that the calibration of acoustical simulation models of existing spaces via measurement results can provide an effective way to improve the reliability of the simulation-based assessment of the implications of acoustic retrofit measures in buildings. Specifically, measures necessary to achieve the targeted values of the acoustical performance indicator (in this case, the reverberation times) could be realized and tested virtually using the calibrated simulation model, and implemented subsequently in reality.

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