On Scattering Coefficients and Fitting Density for Room Acoustic Simulation of Industry Halls

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1. Introduction

Simulations with Geometrical Acoustics (GA) are performed with a simplified model of a room's acoustically relevant objects, assigning absorption and scattering coefficients to surfaces. Absorption and scattering coefficients should be based on physical reasoning taking into account surface roughness, size, shape and exposure. For real working rooms having complex internal fittings in terms of furniture, machines, beams and ducts this reasoning is especially difficult due to multiple uncertainties when transforming room-properties into a model suitable for GA:

− When modeling a room and its internal fittings, the required level of geometric detail is essentially inversely proportional to the room size and the distance of objects to sources and receivers [1, 2]. Fine details should be omitted to avoid creation of a model suited only for high frequencies. The lower level of detail should be compensated by increased surface scattering coefficients.

− Data sheets containing absorption coefficients for a range of construction materials and sound absorbers are usually available. Scattering coefficients of both, real room-boundaries with various structures and complex fittings in workrooms are generally unknown and hard to estimate by visual inspection. It should be noted that scattering significantly influences results in case of high and uneven absorption and non mixing room geometries.

− Sound power and directivity of sources (e.g noisy parts of production machines) are often unknown.

Round Robin Studies like [3] comparing simulation and measurement results show significant deviations due to inconsistent interpretation of uncertainties by software users even for rather simple rooms. A real industry hall, however, provides a level of uncertainty such that rule of thumb estimations of input data seem unrealistic given the accuracy expected by customers having to comply to labor laws concerning noise exposition of employees.

In case of acoustical renovation projects, the problem of inaccurate or incomplete input data might be alleviated by calibrating the simulation model to approximate acoustical measurements of the untreated room prior to investigating the effect of acoustical treatments. Note that model calibration suffers from an ambiguity problem, i.e. different sets of input parameters, such as combinations of absorption/scattering coefficients of multiple materials in a room, can result in the same value for the calibrated measure, possibly causing spurious prediction results. Consequently, keeping in mind physical reasoning during the calibration phase is important.

Postma & Katz present a detailed procedure for model calibration and its application to a cathedral [4]. Keränen et al. evaluate simulation accuracy for industrial noise control in several workplaces using model calibration [5], and Hodgson investigates Sound Pressure Level (SPL) predictions in an industry hall, however without comparing simulation and measurement results after the acoustical treatment [6]. Finally, a predecessor version of the present paper is focused on a least-effort empty room scenario as compared to a scenario with fittings [7]. Contrary to preceding work, the purpose of this case study is to evaluate the sensitivity of simulation results by systematically varying input parameters in terms of scattering coefficients and the level of geometric detail.

2. Room Description and Measurement Setup

The investigated room is a production hall with sawing and mortising machines for aluminum processing owned by Airambulance Technology GmbH in Ranshofen, Austria. The room has proportions of $30{\cdot}20{\cdot}4\text{m}^3$, constituting a typical flat working room. Measurement equipment:

− Loudspeaker: Norsonic 276. Amp: Norsonic NOR280, White Noise, Amp level -10dB; internal EQ activated.

− Measurement device: B&K 2260, calibrated.

− Microphone height 1.3m. Speaker height 1.6m.

− Noise excitation for T_{30} measurements: pistol shot

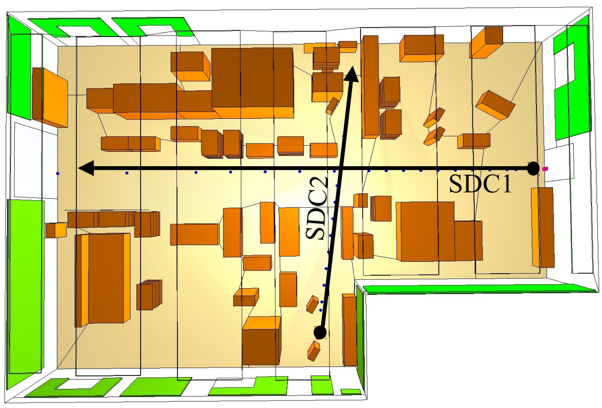

Figure 1: *High density (HD) model of the considered hall.*

T_{30} measurement points are evenly distributed over the room. In order to evaluate Spatial Decay Curves (SDC), SPLs are measured along two straight lines throughout the hall. SDC1 along the main corridor; SDC2 almost orthogonal to SDC1, see figure 1. Following the recommendations in [8], measurement points are located in 1m intervals as far as 10m, and in 2m intervals as far as 20m from the source. Receiver and source positions in measurement and simulation are identical for all measures.

In order to avoid the directional characteristics of the dodecahedron source at 2kHz and 4kHz octave bands, the speaker has been turned several times to measure average SPL in the near field of the source.

The acoustical treatment consists of melamine foam absorber panels glued on the ceiling and walls. A total of $408m^2$ have been mounted, $350m^2$ with a format of $100\cdot50\cdot5cm^3$ on the ceiling and walls and $58m^2$ sized $100\cdot50\cdot7cm^3$ on walls.

3. Research Question and Simulation Scenarios

For typical working rooms as considered in this paper high uncertainties will result in GA users showing high variation in setting scattering coefficients and fitting density. Thus we are interested in the sensitivity of GA results in case of extensively varying scattering coefficients and level of geometric detail. Three scenarios are considered concerning geometrical detail:

– empty room without any internal fittings.

– medium density (MD) with internal fittings considered having at least one edge > 2m.

– high density (HD), as shown in figure 1, with internal fittings considered having at least one edge > 1m.

For each level of geometric detail (empty, MD, HD) we examine a low (LS), a medium (MS), and a high scattering (HS) scenario.

Simulations are performed with CATT-Acoustic, v9.1.a [9] with auto-edge scattering enabled for fittings. Auto-edge scattering typically results in higher scattering coefficients for smaller and irregular surfaces and longer wavelengths. In order to be able to compare results of the empty, MD and HD scenarios with respect to their sensitivity concerning variation of scattering, the overall scattering coefficients (considering all simulated surfaces) for a certain level of scattering (eg. LS) are chosen identically for each level of density and octave band.

Table 1: *Overall Scattering Coefficients*

Scattering	Density	250Hz	500Hz	1kHz	2kHz	4kHz	Mean
LS	all	20	23	26	29	32	26
MS	all	47	50	53	56	59	53
HS	all	75	78	81	84	87	81

Overall scattering coefficients are shown in Table 1. See the accompanying report [10] for detailed scattering and absorption coefficients for fittings, room boundaries and sound absorbers as well as reasoning for their setting.

We emphasize that the approach for setting scattering coefficients used in this paper is not what an acoustic consultant would usually do in a practical project, i.e. set scattering based on physical reasoning. On the contrary, our aim is to evaluate the entire parameter space for scattering coefficients to understand better the sensitivity of GA results in case of possibly „wrong“ settings.

Further simulation parameter settings: Algorithm 1, Split order 0, diffraction disabled. $2\cdot10^6$ rays, ray tracing 2 seconds for the untreated room. $7\cdot10^6$ rays, 2 seconds ray tracing for the treated room. Air absorption is enabled. E (Energy) values are used for evaluations. See [9] for detailed explanations of the simulation parameters mentioned above.

4. Measures

In Industrial noise control typically reverberation time (T_{30}), SPL reduction, and DL_2 are of interest. DL_2 defines the SPL decay when doubling the distance to the source.

Let $L_{m,i,b}$ define the measured, and $L_{s,i,b}$ the simulated SPL at measurement point i before the acoustical treatment. Equivalently, $L_{m,i,a}$ and $L_{s,i,a}$ are defined after the acoustical treatment. Then SPL Calibration Error at point i (CE_i) is defined as

$$CE_i = |L_{m,i,b} - L_{s,i,b}| \quad (1)$$

Prediction Error at point i (PE_i) is defined as

$$PE_i = |L_{m,i,a} - L_{s,i,a}| \quad (2)$$

CE and PE, respectively, denote the mean over a set of measurement points. Let r define the distance between source and a measurement point. According to the recommendations in [8], DL_2 is computed in the near region $1\leq r\leq5$m and the middle region $5\leq r\leq 16$m.

T_{30} as well as EDT CE and PE are computed as the mean over all measurement points, having identical locations to receiver points in simulation. During the model calibration phase absorption coefficients of room boundaries are tuned such that the T_{30} CE is minimal [10].

Simulated SPLs are normalized during post processing such that measured and simulated SPLs at r=1m are identical. SPL normalization allows comparison of sound decays in different scenarios solely based on room properties for r>1m, avoiding errors in modeling the source.

The Schroeder frequency of the untreated hall equals 53Hz. In order to take GAs limitations in the low frequency range into account we consider the frequency range between 250Hz and 4kHz. Note that LA_{eq} is computed over 250-4kHz octave bands in order to enable comparison between measurement and simulation results.

5. Comparative Results

T_{30} CEs are smaller than 3%, see [10]. Figure 2 shows that T_{30} PEs are very high in case of the Empty-LS scenario (30% < PE < 50%). For Empty-MS, MDLS and HDHS scenarios T_{30} PEs are greater than 10%. In a medium range of scattering coefficients and fitting density (empty HS, MDMS, MDHS, HDLS, HDMS) T_{30} PEs are smaller than 10%. Generally, scenarios with fittings (MD, HD) are significantly less sensitive to variation of scattering than the empty room scenario and show small T_{30} PEs in case scattering is neither set low nor extremely high.

Figure 3 shows mean SDC1 PEs and error bars with 10% and 90% quantiles. Mean SDC2 PEs are similar to SDC1, quantiles are smaller, see [10] for details. Figure 3 shows that, as opposed to T_{30}, SPL is generally insensitive to variation of scattering and fitting density.

Furthermore, we find that SPL PE quantiles show high variation among measurement points. This is due to the simulated model not being capable of reproducing

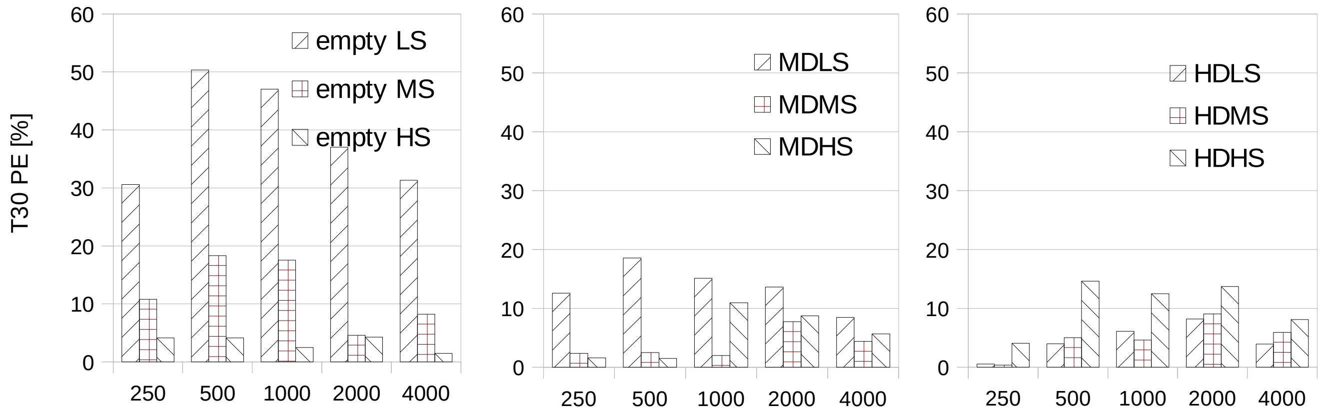

Figure 2 a-c: *T_{30} Prediction Error [%]. Empty room, MD, HD scenario*

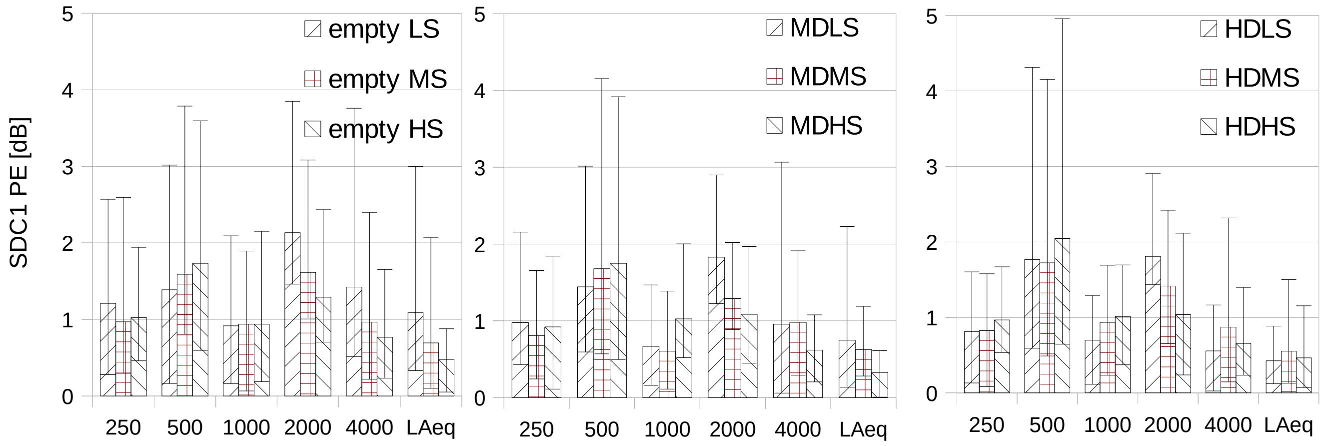

Figure 3 a-c: *SAK 1 SPL Prediction Error [dB] including 10% and 90% quantiles. Empty room, MD, HD scenario*

measured local SPL variation in some cases. See for instance the SDC1 500Hz band, HDMS scenario in Figure 3 with a 90% PE quantile of 4dB. Figure 4 shows the corresponding spatial decay curve, indicating the reason for the high PE quantile: between r=11m and r=14m from the source the measured SPL curve shows a spike, not followed by the simulated curve. Note that the measured decay curve before carrying out the acoustical treatment shows the same spike, though less pronounced as compared to the curve after the treatment. In case of a smooth SPL decay, simulated SDC curves approximate measured SDC curves adequately. See for example Figure 4, 1<r<11m. SPL measurements repeated in February 2019 [10] confirm the measured SDC1 results achieved in 2018.

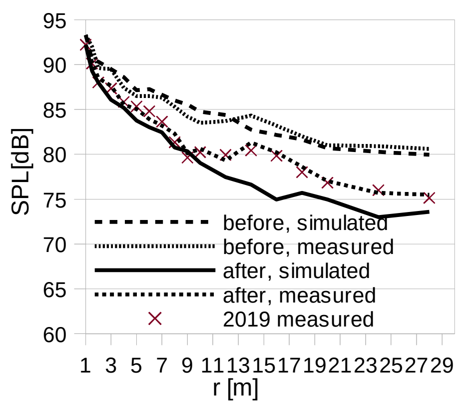

Figure 4: *SDC1 500Hz, HDMS*

Mean octave-band SPL PEs are smaller than 2dB, with 90% quantiles smaller than 5dB for SDC1 and 3dB for SDC2 (see [10] for SDC2 figures). Comparing per measurement point octave-band PEs to LAeq or mean SDC PEs, we observe that, obviously, averaging tends to minimize PEs.

Table 2 shows middle region SDC 1 DL_2 PEs, with values > 2 in bold font. Similar to SPL results, no indication for dependency of DL_2 PEs on variation of scattering or fitting density can be observed. Local spikes or dips in measured SDCs, however, cause higher DL_2 PEs in the middle region: see for instance, SDC1, HDMS 500Hz in Table 2 and figure 4 revisited. Note that Dl_2 PEs in the range of 2db are significant given the fact that DL_2 ranges between 2 and 5 dB in usual rooms. DL_2 PEs are smaller than 1 dB in the near region, SDC2 results are comparable to SDC1, see [10] for details.

Table 2: *SDC1, DL_2 PE, middle region [dB]*

SDC1 PE middle	250	500	1000	2000	4000	LAeq
empty LS	0,2	0,8	0,7	0,6	**2,1**	1,3
empty MS	0,1	1,7	0,3	0,7	1,4	0,8
empty HS	0,5	1,4	0,8	0,3	0,7	0,1
MDLS	0,6	1,0	0,8	0,5	1,1	0,6
MDMS	0,9	1,6	0,1	0,1	1,2	0,5
MDHS	1,3	1,8	0,4	0,4	1,1	0,3
HDLS	1,0	**2,4**	0,3	0,1	0,8	0,1
HDMS	1,2	**2,4**	0,1	0,6	0,9	0,1
HDHS	1,4	**2,8**	1,1	0,9	0,1	0,7

Using identical measurement points, additional impulse response measurements were performed in february 2019 with Dirac [11], a class 1 USB microphone and the Norsonic speaker and amplifier mentioned in section 2.

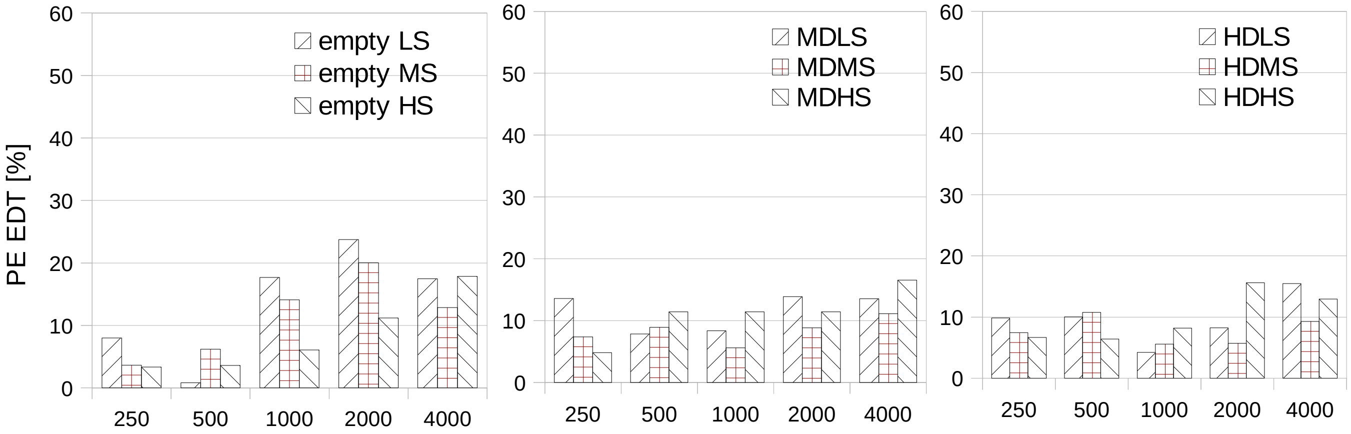

Figure 5: *Early decay Time (EDT) Prediction Errors [%]*

The difference between T_{30} measurement results in 2019 as compared to 2018 ranges between 2 and 5% considering single octave bands. Differences may be due the use of sine sweeps in 2019 as compared to pistol shots in 2018.

Figure 5 shows EDT PEs. Comparing EDT and T_{30} results in figure 2 we observe that EDT is significantly less sensitive to variation of scattering and fitting density than T_{30}. Note that the same finding holds true for SPL as compared to T_{30}, see above. Consequently, we reason that for the considered scenarios measures related to the late parts of the energy time curve of impulse responses show higher sensitivity with respect to variation of fitting density and scattering coefficients as compared to measures related to the early part of energy time curves.

6. Discussion and Conclusions

Investigating the sensitivity of simulation results with respect to variation of fitting density and scattering-level we find that

− there exists a medium range of scenarios with small T_{30} prediction errors. T_{30} prediction errors are very high in case of low scattering and low fitting density, especially considering the empty room scenario. Generally, scenarios with fittings are less sensitive to variation of scattering than the empty room scenario and show small T_{30} PEs in case scattering is neither set low nor extremely high.

− Contrary to T_{30}, SPL as well as DL_2 prediction errors are generally independent of fitting density and scattering-level for the considered room. Although measured curves are generally approximated very well, GA is not always able to reproduce measured local SPL spikes or dips. Consequently, per octave band prediction errors may be significant at specific measurement points. Considering LA_{eq} or averages over several measurement points, however, SPL prediction errors are reasonably small.

− Similar to SPL, we observe that EDT shows significantly less sensitivity than T_{30}. Consequently, we find that measures related to the late part of the energy time curve show higher sensitivity to variation of fitting density and scattering-level as compared to measures related to the early energy decay.

We emphasize that results in this paper provide qualitative indications only for the considered measures, assuming model calibration, and closely related scenarios:

− flat room, dense fittings, similar size and proportions

− absorbent treatments on most walls and ceiling

− line of sight between sources and receivers.

The focus on a single room encourages future comparative studies analyzing simulation errors in additional working rooms by systematically investigating the multidimensional space of input parameters to better understand the limitations of geometrical acoustics.

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