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Numerical and experimental evaluation of a working environment on the basis of a speech intelligibility mapping

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Abstract

In the area of workplace design, both the technical requirements of the workplace and inter-personal concerns of the employees are of decisive importance in order to establish a suitable working environment. Often conflicts of interest arise due to the antagonism between disturbing noise and desired speech intelligibility. An employee who has to concentrate a lot at his/her workplace can be distracted both by disturbing background noises (air conditioning, fans, aggregates etc.) caused by low sound absorption as well as disturbing high speech intelligibility of background conversations. When assessing such situations, the speech transmission index (STI) is an important parameter. Influenced by the reverberation time and the signal-to-noise ratio, calculating the STI is a powerful tool for assessing demanding work environments. The present work deals with the determination of an STI mapping on the basis of numerical simulations using ray tracing methods as well as calculations of the sound energy density distribution in room acoustics. The experimentally validated models can be used to optimize the workplace configuration to meet technical requirements as well as social concerns of employees.

Keywords: STI mapping, work environment, numerical and experimental test

1 INTRODUCTION

Computer-aided simulation models are used as a basis for the numerical evaluation of a working environment. The benefits of these models lie in the virtual analysis of the room acoustic specifications of the respective open-plan offices without having to resort to cost-intensive testings or structural measures without knowing the final performance. Within the simulation models, these measures can be realized, tested and their performance in relation to the desired criteria can be evaluated. This procedure makes it possible to analyze and optimize a large number of both structural measures and possible seat configurations before they are implemented or available in real operation.

Fundamentally, it must be said that the engineering field of room acoustics is primarily satisfied with variables such as background sound pressure level (background noise) and reverberation time (measure of reverberation in the room). These two parameters are not sufficient for the demands of a complex workplace design, since an evaluation of speech intelligibility and the associated potential distractions of the employees remain unnoticed. Consequently, the models are extended so that the evaluation of speech intelligibility can be addressed within the numerical environment[1, 2, 9, 11, 12, 13, 14, 16].

2 SIMULATION

The general procedure for the creation and application of such simulation models is described as follows. In order to obtain a basic overview, all documents, i.e. architectural plans of the rooms as well as the furnishings and the materials used, are first analyzed and studied. The first project-specific peculiarities arise here, which must be taken into account in the model. In addition to the geometric dimensions, which define the basic structure of the model, these include possibilities to scale and flexibly set up the model.

Based on the analyzed plans, first 3D models are created with which preliminary investigations regarding the expected room acoustic parameters are carried out. Figure 1 shows the developed simulation model of a workstation configuration in a workplace environment of a major European air navigation service provider.

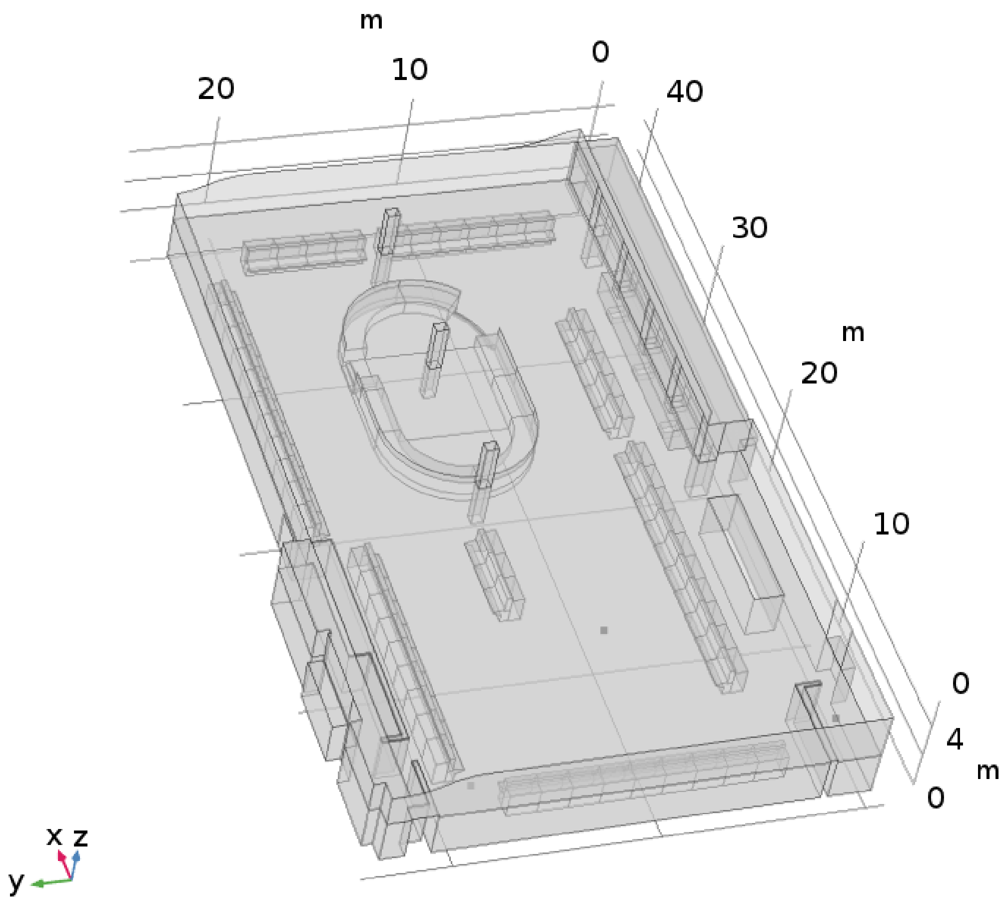

Figure 1. Simulation model of a workplace environment

2.1 STI calculation

The Speech-Transmission-Index (STI) is standardized and defined in DIN EN 60268-16 and is based on the investigations of Houtgast and Steeneken[1, 14]. For the calculation of the STI it is necessary to determine the modulation transfer function between transmitter and receiver with a total of 14 modulation frequencies from $\tilde{f}_1 = 0.63\,\text{Hz}$ to $\tilde{f}_{14} = 12.5\,\text{Hz}$ in the octave spectrum between $125\,\text{Hz} \leq f \leq 8000\,\text{Hz}$. The resulting 14x7 matrix of the modulation transfer values $m(k, \tilde{f}_n)$ can be calculated based on experiments as well as simulations. Assuming a diffuse sound field with an exponential decrease of the sound energy of the reverberation, the calculation $m(k, \tilde{f}_n)$ can be simplified. The result is

$$m(k, \tilde{f}_n) = \frac{1}{\sqrt{1 + \left(\frac{2\pi \tilde{f}_n T_k}{13.8}\right)^2}} \cdot \frac{1}{1 + 10^{(SNR_k/10)}}. \tag{1}$$

The parameters in equation (1) are the modulation frequency $\tilde{f}_n$, the reverberation time T_k and the signal-to-noise ratio SNR_k for the respective octave band k. In order to derive the speech intelligibility index, additional weighting factors and the consideration of different auditorical effects such as the hearing occlusion are accounted for. For a detailed description see DIN EN 60268-16 [1]. The resulting STI values range between zero and one, are location and room specific and contain information about the background noise level. This makes it possible to derive an optimal seating configurations based on the speech intelligibility to be expected or measured.

2.2 Determination of reverberation time T_k

Different models exist in room acoustics to estimate the reverberation time. The most widespread formulas are derived by Sabine or Eyring-Norris[5, 19]. However, these derivations are subject to special requirements or simplifications. If the models for estimating the reverberation time are not applicable, numerical simulations can be used. In the present case, the reverberation time was first estimated with the empirical formulas according to Sabine and Eyring-Norris and further verified utilizing the software tool Comsol Multiphysics[7]. Here the Ray-Tracing method was used, which is well known in the literature[4, 7, 15, 20, 21].

2.3 Determination of the signal-to-noise ratio SNR_k

To determine the signal-to-noise ratio of the respective speaker positions, all sound sources, i.e. speech spectra of persons in the room, cf. Byrne[6], air conditioners, computer sounds, etc. were integrated into the model and evaluated using the acoustic diffusion equation in the room[7, 10, 18]. Comsol Multiphysics was also available for this purpose.
Two simulations were carried out for each speaker configuration to determine the sound pressure level distribution throughout the room - once as a result of the speaker source and once as a result of all other sources in the room.

3 MEASUREMENTS

In order to be able to compare the simulation models and test their validity, extensive experimental investigations were carried out. In addition to the identification of the workplace noise sources (computer, fan, mobile table) and the air conditioning system as an acoustic source, measurements of the reverberation time at different positions where conducted. The results were used to correct the absorption coefficients of the acoustically effective surfaces and thus link the numerical model to the real system behavior of the room. This way, the quality of the simulation results could be verified.
Further, the STI was measured. Extensive measurement technology from Brüel & Kiær was available for the investigations. The following list is a compilation of hardware and software used.

- Sound level meter Type 2270
- Omnidirectional sound source Type 4292-L
- Calibration instrument Type 4231
- Microphone Type 4231
- Echo Speech Source Type 4720
- Software Type BZ5503
- Software Dirac6

4 RESULTS

In order to deliver reliable results, a model comparison with the aid of experimental investigations is required. Figure 2 shows the comparison of the numerically calculated reverberation times according to Sabine and Eyring-Norris and the measured reverberation times. There is a satisfactory agreement between the results of

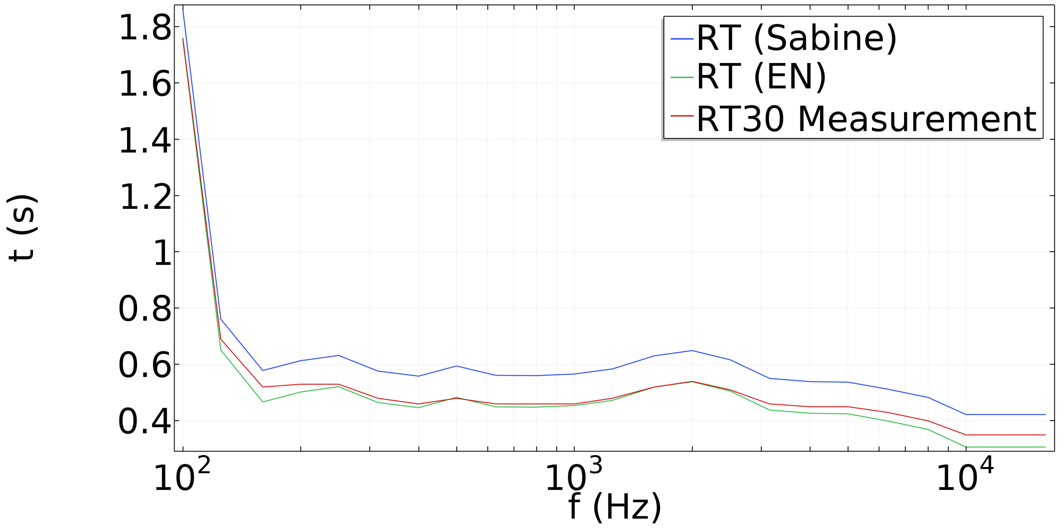

Figure 2. Comparison of the reverberation time of simulation and experiment

the simulation and the experiment. Furthermore, the calculation of the STI values could also be validated using experiments. For this purpose, a corresponding test scenario was set up and examined in the simulation model as well as in the experiment for two different positions. The result of this investigation are shown in Table 1.

		Position 1			Position 2		
	Frequency	SNR	Noise	Signal	SNR	Noise	Signal
Simulation	125	-4.72	28.18	23.46	-5.85	28.37	22.53
	250	3.83	39.30	43.12	2.33	39.81	42.14
	500	3.95	41.08	45.03	2.42	41.62	44.04
	1000	3.49	33.44	36.92	1.97	33.95	35.92
	2000	2.29	29.91	32.21	0.90	30.34	31.24
	4000	1.42	27.11	28.53	-0.07	27.52	27.45
	8000	-1.23	25.95	24.71	-2.84	26.31	23.47
	STI	0.52			0.47		
Measurements	STI	0.55			0.55		
Relative Error	ε in %	5.45			6.00		

Table 1. Comparison of STI values from simulation an experiments for two positions; SNR, Noise and Signal values in [dB]; Relative error calculated with respect to the measurements

In this table, the relative error is calculated with respect to the measurements utilizing the following equation:

$$\varepsilon = \frac{(STI_{sim,i} - STI_{exp,i})^2}{STI^2_{exp,i}}. \tag{2}$$

In equation (2), $STI_{sim,i}$ represents the STI values calculated from the simulation and $STI_{exp,i}$ from the experiment at position i, respectively. It can be seen that the results are in good agreement.
To illustrate the performance of the model, the results for a test scenario are presented below. The question was relevant to what distance employees in the working environment are influenced by other conversations in

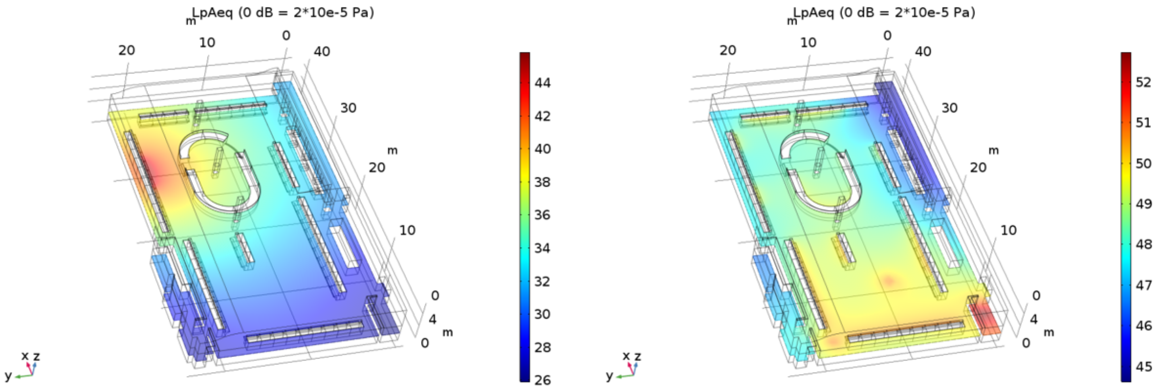

Figure 3. Sound sources in the example scenario; Speech source left, noise sources right

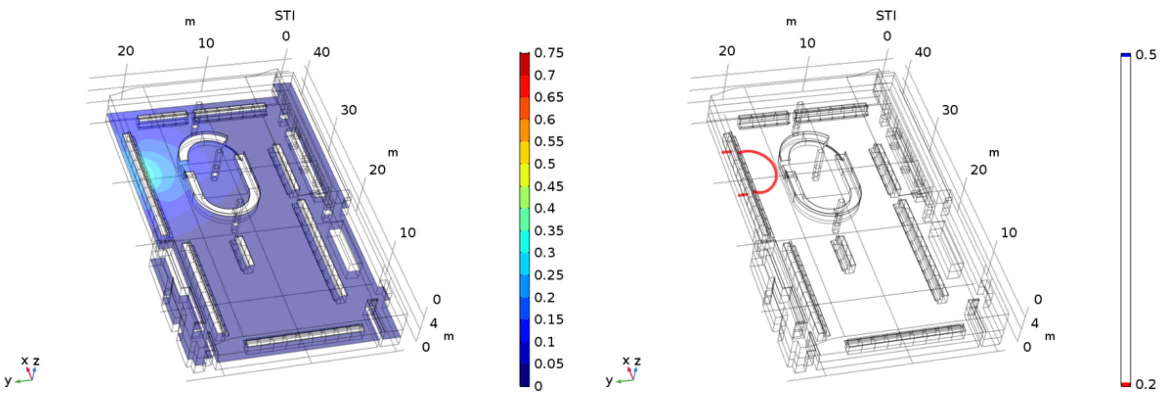

Figure 4. STI mapping of the example scenario; STI color coded left and two discrete values right

the room or whether a possible distraction can occur due to a conversation. Figure 3 shows in the left part the position of the source of interference from which a potentially disturbing noise in the form of a conversation emanates. The right half of the picture shows the main sound sources in the room. These include conversations at the workplaces or in the room and all other acoustic sources emanating from technology as well as the air conditioning system.

Figure 4 shows the results of the STI mapping, where on the left side the mapping is realized in color gradations and on the right side delimitations are set with an STI of STI = 0.5 and STI = 0.2. These deliminations, known as Distraction Distance (STI = 0.5) and Privacy Radius (STI = 0.2), provide information to which extent speech can be used as an information carrier (STI > 0.5), up to which distance it can be considered as a potential disturbance ($0.5 \leq$ STI ≤ 0.2) and from which distance (STI < 0.5) speech is lost in the background noise and thus no longer causes interference[1]. It can be seen that within the working environment a natural decrease of the STI value with respect to distance is present for this room scenario. Additionally a natural conversation can be carried out within a group of three workplaces. Beyond this group, conversations will not disturb other members in the working environment.

5 CONCLUSION

With the developed and experimentally validated models it is possible to identify room-specific peculiarities in speech intelligibility at an early stage and, if necessary, to derive and test measures. For this purpose, an example scenario was identified and examined. Future measures can be derived from the presented results and the know-how regarding room acoustic factors can be increased.

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