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Evaluation of Measurement Uncertainties for D_{2S} and L_{pAS4m} in open-plan offices

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ABSTRACT

Noise, and more particularly conversational noise, is a major source of annoyance for people working in open-plan offices. Measuring the acoustic quality of this type of work environment is therefore an increasingly important issue. For the purposes of standardization, the scientific community has defined indicators to evaluate the acoustic quality of open-plan offices, including the A-weighted level of speech at 4 meters from the source, its decrease by doubling the distance and the distance needed for the A-weighted level of speech to reach 45 dB(A), called comfort distance. The ISO 3382-3 (2012) standard [1] that defines these indicators makes no mention of their measurement uncertainties. The objective of this study is to address this shortcoming of the standard and to perform an evaluation of measurement uncertainties based on simulations of a typical call centre office.

INTRODUCTION

Noise constitute a major source of annoyance in open-plan offices. Among all noise sources in these rooms, conversational noise is the most detrimental one. Therefore, the office, its layout and its furnishings must be able to limit the propagation of speech signals. To evaluate this ability, the ISO 3382-3 (2012), which is currently being revised, defines four indicators including:

- The decrease of the A-weighted level of a speech signal by doubling the distance from the source (D_{2S});
- The A-weighted level of a speech signal at 4 m from the source (L_{pAS4m});
- The distance from the noise source needed for the A-weighted level of a speech signal to fall below 45 dB(A), called the comfort distance (r_c).

To evaluate these three parameters, a measurement path must be defined through the open-plan office. This path jumps from workstation to workstation, while being as straight as possible. A loudspeaker is placed at one end of the path and the A-weighted speech level as well as the distance from the loudspeaker is measured at each of the workstations composing the path. The three indicators are then defined from the linear regression of the level as a function of the base-2 logarithm of the distance from the source (**Figure 1**). The D_{2S} is the slope of the linear regression, L_{pAS4m} its intercept at 4 m from the source and r_c is the distance at which the regression line falls below 45 dB(A).

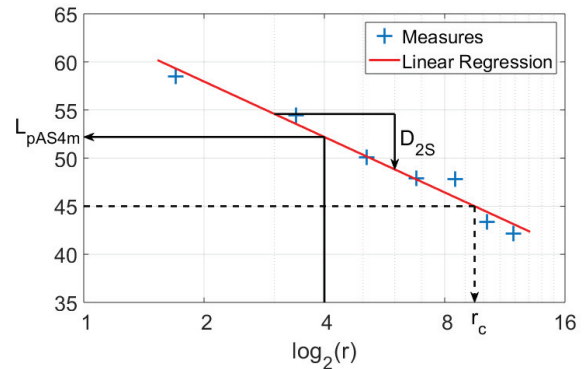


Figure 1. Example of a measure of D_{2S} , L_{pAS4m} and r_c

Analytic expressions for the indicators are given equations 1 to 3.

$$D_{2S} = - \frac{N \cdot \sum L_{pASi} \log_2(r_i) - \sum L_{pASi} \sum \log_2(r_i)}{N \cdot \sum \log_2(r_i)^2 - (\sum \log_2(r_i))^2} \quad (1)$$

$$L_{pAS4m} = \overline{L_{pASi}} + D_{2S} \cdot \overline{\log_2\left(\frac{r_i}{4}\right)} \quad (2)$$

$$r_c = 4 \cdot 2^{\frac{L_{pAS4m} - 45}{D_{2S}}} \quad (3)$$

The definition of these indicators represented a major step forward in the evaluation of the acoustic quality of open-plan offices because until then, acoustic indicators from the field of industrial acoustic were used. However, the ISO 3382-3 (2012) standard presents a major shortcoming: it does not mention the measurement uncertainties of any indicator it defines. Indeed, in the field of standardisation, it is important to report on the precision of the measure.

The aim of the study presented in this paper is to address this shortcoming of the standard and to evaluate measurement uncertainties using simulations. The paper will first identify the sources of uncertainty for the indicators, then present the simulations and the way each source of error are taken into account. Based on the results of the simulations, measurement uncertainties will be estimated.

1. SOURCES OF UNCERTAINTY

The measure of the three indicators described above require the measurement of sound pressure levels and distances from the source of several workstations. Therefore, there are two sources of uncertainty. First, the

positioning of both the loudspeaker and the microphones. Then, the measurements of sound pressure levels and distances present a degree of uncertainty that affect the precision of the evaluation of the indicators.

1.1 Positioning uncertainty

The ISO 3382-3 (2012) standard specifies that the loudspeaker and the microphones must be placed at the position of the head of a person at its working position. It defines quite well the positioning of the measurement equipment. However, two persons carrying out the measurement will not place the instrumentation at the same location. These deviations in the positioning of the equipment lead to variations in the measured values of the single number quantities (D_{2S} , L_{pAS4m} and r_c , hereafter referred as SNQ). It is therefore essential to take into account this uncertainty of instruments positioning for the evaluation of the SNQs measurement uncertainty.

1.2 Uncertainty of measurement equipment

Level and distances measurements also suffer from some uncertainties. On the one hand, sound pressure levels are measured using a class 1 sound level meter as defined in the IEC 61672-1 (2003) standard [2]; on the other hand, distances are commonly measured using a laser rangefinder (or less often using a measuring tape). The uncertainty of the sound pressure level is extracted from the IEC 61672-1 (2003) that defines two classes of sound level meters based on tolerance on measurement uncertainty of 1/3-octave band levels. The uncertainty of octave-band levels are derived from the widest tolerance intervals for the three 1/3-octave bands within each octave band. The values of uncertainty thus obtained are given in Table 1.

f_c (Hz)	125	250	500	1000	2000	4000	8000
u (dB)	0.9	0.9	0.8	0.8	0.9	1.2	1.8

Table 1. Measurement uncertainty of octave band levels deduced from IEC 61672-1 (2003)

Concerning distances, the measurement uncertainty of the instrumentation is in the range of a few tenths of a millimeter, whatever the measuring device (laser rangefinder or measuring tape). However, in open-plan offices, the measurement conditions are not ideal: most often, there are obstacles between the microphone and the loudspeaker. It is therefore impossible to place one end of the measuring tape at the microphone and the other at the loudspeaker, while keeping it straight (or aiming at the microphone with the laser rangefinder from the loudspeaker). Therefore, the distances are measured between two points located above the microphone and the loudspeaker, which greatly increases the measurement uncertainty. Instead of a few tenths of a millimeter, the measurement uncertainty of distances is of a few centimeters. For the rest of the study, it will be considered to be of 2.5 cm, meaning that the measurement error is less than 5 cm in 95% of cases.

2. SIMULATIONS

The simulations were realized using RayPlus, a software developed by the INRS, based on ray tracing method [3].

2.1 The office

The office simulated for this study resembles a call-center's open-plan offices, and is represented in Figure 2. The room is a 13.6-meter long and 8.5-meter wide rectangle with a 2.7-meter-high suspended ceiling. The layout is quite simple: the office has two rows of offices on both sides of an aisle. Between workstations facing each other, freestanding acoustic screens are installed. On both side walls of the office, there are two very wide windows.

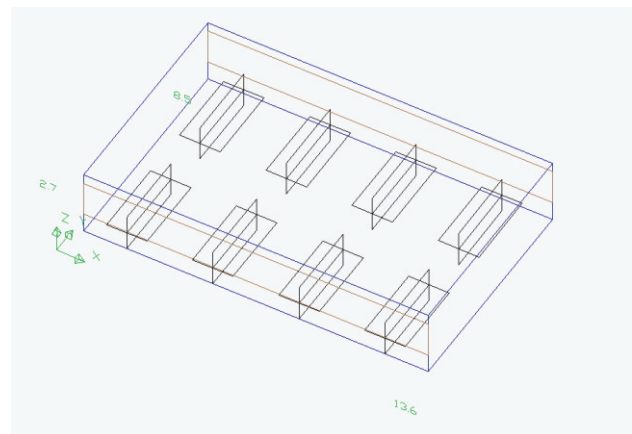


Figure 2. View of the simulated office

For each simulation, four measurement paths were defined in the office. These paths are represented in Figure 3.

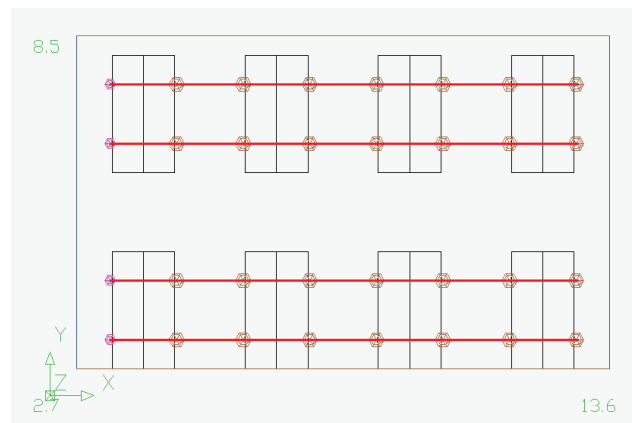


Figure 3. Plan of the open-plan offices used for the simulations. Four paths of measurement were used per simulation.

The simulation makes it possible to estimate measurement uncertainty for various acoustic quality of the office. In this paper, 12 cases were simulated depending on:

- The height of the acoustic screens, noted H1, H2 and H3, respectively for a height of 190, 150 and 110 cm.

- The acoustic quality of the acoustic screens, noted S1 (good quality) and S2 (bad quality), whose characteristics are presented Figure 4.
- The acoustic quality of the suspended ceiling, noted C1 (good quality) and C2 (bad quality), whose absorption characteristics are identical to those of the acoustic screens.

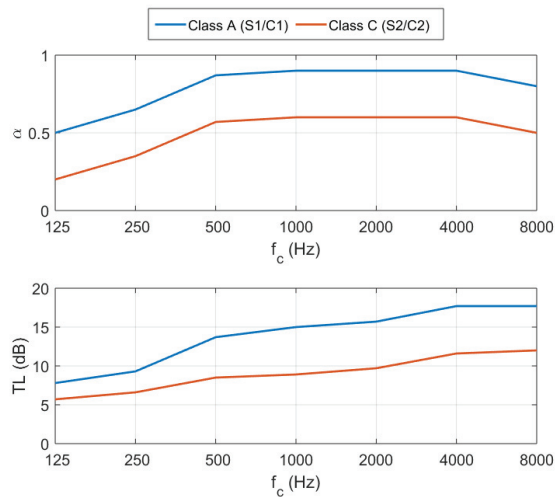


Figure 4. Sabine absorption coefficient and transmission loss for the two quality of acoustic furniture.

2.2 Accounting for measurement uncertainties

The uncertainty caused by the positioning of the instruments can be taken into account in a quite simple way: for each workstation, nine microphones (or loudspeakers) are defined, simulating several positioning errors for both the microphones and the loudspeakers. The nine instruments are positioned 10-cm apart on a 3-by-3 square grid centered on the workstation (according to Figure 5).

Measurement uncertainties of distance and octave-band level were taken into account by applying a Monte-Carlo approach: for each perfect measure drawn from the simulations, measurement errors were numerically added, resulting in several “real” measurements.

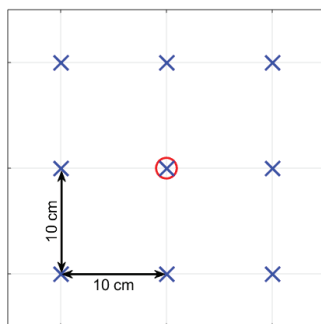


Figure 5. Illustration of the nine positions of the source (receiver) in RayPlus in order to simulate an error of positioning of the loudspeaker (microphone).

2.3 Evaluation of measurement uncertainty

The International Bureau of Weights and Measures issued guidelines describing a stochastic approach for the evaluation of measurement uncertainties [4]. This method, called Monte-Carlo method, consists in randomly drawing measurement errors and then quantify

the dispersion of the single-quantities obtained using these measurements with error. In this study, there are two type of errors: positioning error and error introduced by the devices used for the measurement. Therefore, a Monte-Carlo method was applied for both types of error, resulting in the following process.

The first step was to draw positioning errors: for each workstation on the path, a position is randomly selected among the nine possibility. That means that for each workstation, one of the nine simulated positions was randomly selected.

The second step was to draw measurement errors: for each “measure” (meaning for each distance and octave band level) a random error is drawn. It follows a normal distribution centred on the true value (given by the simulation software) and its standard deviation was as described in paragraph 1.2.

The third step was to compute the SNQs for the drawn measurement.

The first step was repeated 1000 times and for each of these iterations, the second step was reiterated 50 times. This resulted, for each of the acoustic configuration and each of the measurement path, in 50.000 possible values for the SNQs. The distributions of these values of SNQs and more precisely the standard deviations of the distributions correspond to the measurement uncertainties for each SNQ.

Therefore, this process enable the evaluation of measurement uncertainties from simulations.

3. RESULTS

3.1 Effect of the acoustic configuration

The results of the simulations are presented on Figures 5 to 7, in the form of Tukey’s boxes. For each SNQ, twelve Tukey’s boxes synthesize the 50.000 simulated measurements for each of the acoustic configuration of the office.

First of all, the results are in line with expectations: the improvement in the acoustic quality of the offices is reflected in the simulated SNQs values. Indeed, increasing the height of the screens and improving the acoustic quality of the screens and the ceiling leads to an increase in D_{2s} and a decrease in L_{pAS4m} and r_D .

Regarding the D_{2s} (Figure 6), it is worth noticing that when acoustic screens are lower than receivers and source, the quality of both the ceiling and the screens does not influence the measured value. Indeed, in this configuration, the spatial decay of speech is constrained by the direct propagation from the loudspeaker to the microphones. Increasing the height of acoustic screens, even when above 120 cm leads to an increase in D_{2s} . Another observation is that improving the quality of the ceiling is more efficient when the acoustic screens are of good quality.

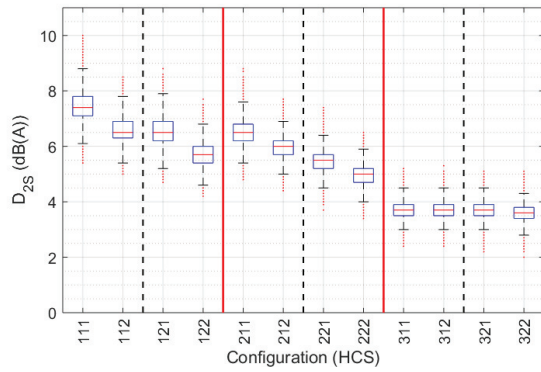


Figure 6. Dispersion of the D_{2S} measurements for each configuration and effect of acoustic furnishing (the configuration 312 is the configuration H3 C1 S2).

Regarding the speech levels at 4 meters from the source, similar observations can be made: for lowest acoustic screens, both their quality and the one of the ceiling have very little impact over the measured value. Indeed, improving the overall absorption of the office globally reduces sound pressure levels. In that case, the direct propagation is prominent. Observation are similar to those made for the D_{2S} : increasing the height and acoustic quality of the screens and the quality of the ceiling leads to a decrease of L_{pAS4m} , which reflects an increase in the acoustic quality of the office.

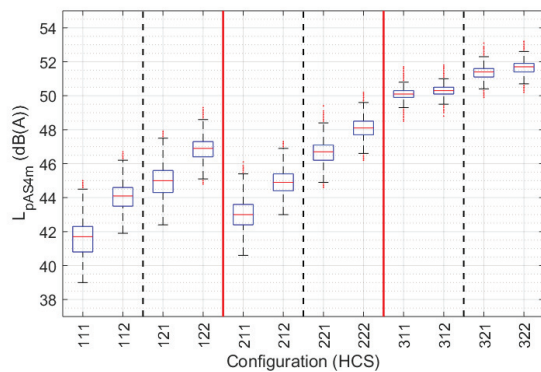


Figure 7. Dispersion of the L_{pAS4m} measurements for each configuration and effect of acoustic furnishing (the configuration 312 is the configuration H3 C1 S2).

Finally, since the comfort distance is computed from the D_{2S} and the L_{pAS4m} , the effect of the acoustic configuration on r_c (Figure 8) is very similar to that on D_{2S} and L_{pAS4m} . If acoustic screens are lower than 120 cm, the office is of (very) poor acoustic quality, regardless of the quality of both the ceiling and the screens.

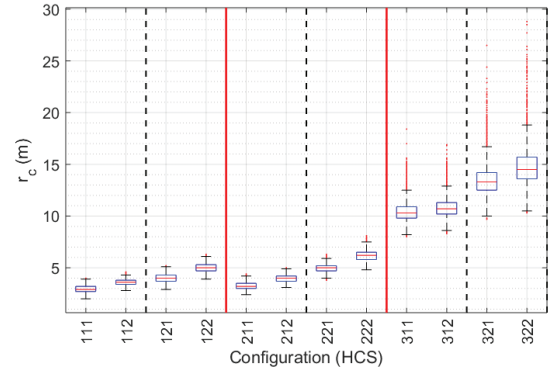


Figure 8. Dispersion of the r_c measurements for each configuration and effect of acoustic furnishing (the configuration 312 is the configuration H3 C1 S2).

3.2 Measurement uncertainties

The results from the simulations enable to assess not only the dependence of the SNQs on the acoustic configurations, but also the SNQs measurement uncertainty.

The measurement uncertainties of the D_{2S} and for each acoustic configuration of the office are presented in Table 2. The measurement uncertainty varies between 0.3 and 0.6 dB(A) and seems to increase with increasing D_{2S} .

		H1	H2	H3
C1	S1	0.6	0.5	0.3
	S2	0.4	0.4	0.3
C2	S1	0.5	0.4	0.3
	S2	0.4	0.3	0.3

Table 2. Standard uncertainty of the D_{2S} (in dB(A)) for each acoustic configuration of the office.

The measurement uncertainties of the speech level at 4 meters from the source are given in Table 3. It varies between 0.3 and 1.0 dB(A) and seems to increase with decreasing L_{pAS4m} .

		H1	H2	H3
C1	S1	1.0	0.8	0.3
	S2	0.7	0.6	0.3
C2	S1	0.9	0.6	0.3
	S2	0.6	0.5	0.3

Table 3. Standard uncertainty of the L_{pAS4m} (in dB(A)) for each acoustic configuration of the office.

The measurement uncertainties of the comfort distance are given in Table 4. It varies between 0.3 and 1.5 m and seems to increase with the comfort distance.

		H1	H2	H3
C1	S1	0.3	0.3	0.8
	S2	0.3	0.3	0.9
C2	S1	0.4	0.4	1.3
	S2	0.4	0.4	1.5

Table 4. Standard uncertainty of r_c (in m) for each acoustic configuration of the office.

4. CONCLUSION AND FUTURE WORK

The study described in this paper aimed at evaluating measurement uncertainties of the single-number quantities described in the ISO 3382-3 (2012) standard, using acoustic simulations. To that end an open-plan office, resembling a call centre office with different acoustic configurations, was. A Monte-Carlo method was applied to the results of the simulation enabling the evaluation of measurement uncertainties for each of the acoustic quality of the office.

The results of the simulations suggests that, for the simulated office, the measurement uncertainties vary from 0.3 to 0.6 dB(A) for the D_{2S} , from 0.3 to 1.0 dB(A) for the L_{pAS4m} and from 0.3 to 1.5 m for the comfort distance. It also seems that measurement uncertainties for the SNQs increases when the acoustic quality of the office is improved.

Overall, the measurement uncertainties are of reasonable size and do not raise any new practical problems for the characterization of the acoustic quality of offices.

There are very few measurement uncertainty evaluation in the literature. Haapakangas *et al.* [5] and Yadav *et al.* [6] both evaluated measurement uncertainties during a measuring campaign. They respectively report an uncertainty of 0.6 dB(A) and 1 dB(A) for the D_{2S} , and an uncertainty of 1.5 dB(A) and 1.0 dB(A) for the L_{pAS4m} . Although uncertainties obtained with simulations are lower than those reported by these two studies, they are rather close. Both studies give little information about the measurement paths and especially the number of points composing each of them. Since the SNQs are derived from linear regressions, it does not seem unreasonable to assume that the measurement uncertainties depend of the number of measurement points considered.

The next step of this work will be to evaluate measurement uncertainties in a real office, to implement this office in the simulation software and to compare the measurement uncertainties determined in the field with that obtained from the simulations.

5. REFERENCES

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