AIRBORNE SOUND INSULATION: A STUDY ON THE CORRELATION BETWEEN 1/3 OCTAVE BAND VALUES AND ITS IMPACT ON THE RESULTING SNQ UNCERTAINTY

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Traditionally in the field of building acoustics no individual uncertainty calculations are performed for sound insulation measurements. One of the settled justification is that it is impossible to retrieve correlation between 1/3 octave bands when considering single number quantity uncertainty. To enlighten this issue, this paper presents, for airborne sound insulation, a study on the correlation between 1/3 octave bands values using a large set of in situ airborne sound insulation measurements. The results of this study enable to verify if it is possible to identify how big these correlations are or if there is a general rule, and its influence on single number ratings uncertainty calculations.
Keywords: Sound insulation uncertainty, ISO 12999-1, acoustic national requirement.

1. Introduction

Determining the uncertainty related to building acoustics measurements are relevant for communicating the accuracy of sound insulation tests results, above all for regulatory purposes. In some countries were building regulations are in force, the fulfilment or not of its regulatory requirements may result in legal proceedings and, in these cases its usual to take uncertainties reports into account [1].

Commonly in the field of building acoustics uncertainty estimations have been performed under a repeatability and reproducibility approach laying on the argument that no complete *model relating the uncertainty of the measured sound reduction index to quantities which can be determined in the actual measurement situation for sound insulation is available* [2]. ISO standard 12999-1 [3] adopts this philosophy and specifies procedures for assessing the measurement uncertainty of sound insulation by estimating the uncertainty of the measurand from the standard deviations determined by inter-laboratory tests. In the case that no data from an interlaboratory round is available, the standard provides general uncertainty values that should be used for the quantities obtained according to ISO series 16283 and 717 [4–8].

Among the many ways of estimating measurement uncertainties, the most common procedure adopted in the metrology field is the one expressed on the Guide to the Expression of Uncertainty in Measurement, GUM [9], which provides general rules for evaluating and expressing uncertainty. As mentioned above, a recurrent argument for not using GUM within building acoustics is that no complete model exists for the measurand in this context [10]. Despite the necessity to implement some kind of model when using GUM, there is no requirement that states that this model must be complete.

In a different direction from the traditional approach also adopted in ISO 12999-1, in the last years, interesting studies have proposed methods for uncertainty estimation of sound insulation measurements using the GUM approach [11–15]. Particularly, the study of Machimbarrena et al. [15] is dedicated to enlighten the need to make individual uncertainty calculations for in situ airborne sound insulation measurements, and shows that the average uncertainty estimations following the GUM recommendations converge with those reported in ISO 12999-1. One of the issues raised in this study is how to deal with correlation between 1/3 octave bands airborne sound insulation values when calculating the corresponding single number quantity uncertainty (SNQ). Wittstock's researches based on experimental data [2,10] have already shown the existence of correlation but stated that is not possible to identify its magnitude in all measurements. Assuming the full correlation as an upper limit of the uncertainty of the single number ratings it is recommended that a correlation coefficient equal to 1 should be used until more experience is acquired to make a better judgment.

This study intends to improve the method for SNQ uncertainty calculation presented in the research of Machimbarrena et al [15], by evaluating the influence of including the values obtained for correlations between 1/3 octave bands, using a large in situ airborne sound insulation measurements data set. Furthermore, the SNQ uncertainties obtained with the incorporation of the calculated correlations, are compared with those obtained in [15] which were calculated considering a full positive correlation.

2. Objectives

With the aim of providing more information to investigate the most appropriate procedure to evaluate the uncertainty of airborne sound insulation measured SNQs, the main objectives of this paper are:

1. To obtain the correlation values between 1/3 octave bands for the airborne sound insulation descriptor D_{nT}, based on a large in situ measurements data set
2. To incorporate the obtained correlation coefficients to the uncertainty calculation method proposed by Machimbarrena et al. [15]
3. For the full data set, to calculate the single number quantity uncertainty for two frequency ranges: 100–5000 Hz, $D_{nTA(100-5000)}$ and 50-5000 Hz, $D_{nTA(50-5000)}$, using the previously obtained correlation coefficients instead of assuming full positive correlation as in [15].
4. To compare the obtained single number quantity uncertainties with the results of Machimbarrena et al. [15] and to evaluate the effect of extending the lower frequency range on the SNQ uncertainty.

3. Methodology

3.1 D_{nT} Calculation of the correlation coefficients between 1/3 octave bands values

To obtain the correlation between each 1/3 octave band of $D_{nTA(100-5000)}$ and $D_{nTA(50-5000)}$, the Pearson correlation coefficient has been calculated. It is defined as the covariance of the two variables divided by the product of their standard deviations:

$$r(x,y) = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}} \quad (1)$$

Where x represents $D_{nT,i}$ and y represents $D_{nT,j}$, being "i" and "j" any two different third octave bands between 100-5000 Hz ($4 \leq i/\, j \leq 21$ in Table 1) and 50-5000 Hz ($1 \leq i/\, j \leq 21$ in Table 1).

The same study was performed by Wittstock [2] considering the results of a Round Robin Test, an homogeneous data set where all measurements were made on the same sample wall. In this study, a data set of 2090 in situ airborne sound insulation measurements has been used to obtain correlation coefficients. By using a large data set it is intended to identify if transcending the construction type, given a heterogeneous sample, some kind of pattern is observed in the obtained correlations.

The measurements were performed on 22 distinct types of separating walls, 1579 heavyweight and 511 lightweight, from dwellings constructed in the UK in compliance with the relevant Robust Details [16] specifications. Testing and on-site inspections were carried out on a sample of structures in dwellings under construction to ensure compliance with the construction system by workmanship and with Building Regulations.

Correlation coefficients values were calculated for each of the 22 construction systems and as the same pattern was observed, in this paper only results obtained for the full data set are presented are presented in Table 1.

Table 1: Correlation coefficients for one-third octave band sound insulation.

	j	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
i		50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
1	50	1,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
2	63	0,0	1,0	0,6	0,4	0,3	0,2	0,1	0,1	0,1	0,1	0,1	0,0	0,0	0,1	0,0	0,0	0,1	0,0	0,0	0,0	0,0
3	80	0,0	0,6	1,0	0,6	0,4	0,3	0,2	0,2	0,1	0,1	0,1	0,1	0,1	0,1	0,0	0,0	0,1	0,0	0,0	0,0	0,0
4	100	0,0	0,4	0,6	1,0	0,6	0,5	0,4	0,3	0,3	0,2	0,2	0,2	0,2	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,0
5	125	0,0	0,3	0,4	0,6	1,0	0,7	0,6	0,5	0,4	0,4	0,3	0,3	0,3	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,1
6	160	0,0	0,2	0,3	0,5	0,7	1,0	0,8	0,7	0,6	0,6	0,5	0,5	0,4	0,4	0,3	0,3	0,4	0,4	0,3	0,3	0,2
7	200	0,0	0,1	0,2	0,4	0,6	0,8	1,0	0,9	0,8	0,7	0,6	0,6	0,5	0,5	0,4	0,4	0,4	0,4	0,4	0,4	0,3
8	250	0,0	0,1	0,2	0,3	0,5	0,7	0,9	1,0	0,9	0,8	0,8	0,7	0,6	0,6	0,5	0,5	0,5	0,5	0,5	0,4	0,3
9	315	0,0	0,1	0,1	0,3	0,4	0,6	0,8	0,9	1,0	0,9	0,9	0,8	0,7	0,6	0,6	0,6	0,6	0,6	0,5	0,5	0,4
10	400	0,0	0,1	0,1	0,2	0,4	0,6	0,7	0,8	0,9	1,0	0,9	0,9	0,8	0,7	0,7	0,7	0,6	0,7	0,6	0,5	0,4
11	500	0,0	0,1	0,1	0,2	0,3	0,5	0,6	0,8	0,9	0,9	1,0	1,0	0,9	0,8	0,7	0,7	0,7	0,7	0,7	0,6	0,5
12	630	0,0	0,0	0,1	0,2	0,3	0,5	0,6	0,7	0,8	0,9	1,0	1,0	1,0	0,9	0,8	0,8	0,8	0,8	0,7	0,6	0,5
13	800	0,0	0,0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,0	1,0	0,9	0,9	0,8	0,8	0,8	0,7	0,7	0,5
14	1000	0,0	0,1	0,1	0,1	0,2	0,4	0,5	0,6	0,6	0,7	0,8	0,9	0,9	1,0	1,0	0,9	0,8	0,8	0,8	0,7	0,6
15	1250	0,0	0,0	0,0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,7	0,8	0,9	1,0	1,0	1,0	0,9	0,9	0,8	0,8	0,6
16	1600	0,0	0,0	0,0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,7	0,8	0,8	0,9	1,0	1,0	1,0	0,9	0,9	0,8	0,7
17	2000	0,0	0,1	0,1	0,1	0,2	0,4	0,4	0,5	0,6	0,6	0,7	0,8	0,8	0,8	0,9	1,0	1,0	1,0	0,9	0,8	0,7
18	2500	0,0	0,0	0,0	0,1	0,2	0,4	0,4	0,5	0,6	0,7	0,7	0,8	0,8	0,8	0,9	0,9	1,0	1,0	0,9	0,9	0,7
19	3150	0,0	0,0	0,0	0,1	0,2	0,3	0,4	0,5	0,5	0,6	0,7	0,7	0,7	0,8	0,8	0,9	0,9	0,9	1,0	0,9	0,8
20	4000	0,0	0,0	0,0	0,1	0,2	0,3	0,4	0,4	0,5	0,5	0,6	0,6	0,7	0,7	0,8	0,8	0,8	0,9	0,9	1,0	0,9
21	5000	0,0	0,0	0,0	0,0	0,1	0,2	0,3	0,3	0,4	0,4	0,5	0,5	0,5	0,6	0,6	0,7	0,7	0,7	0,8	0,9	1,0

A correlation coefficient of 0.5 indicates a significant correlation in this case. As it can be observed in the shaded cells, the magnitude of the correlation coefficient is larger than 0.5 for 8 to 14 neighbouring frequency bands above 160 Hz, indicating correlation between medium-high frequencies, while for low frequencies this correlation is not observed. This converges with the results obtained in [2] but it is important to notice that the lack of correlation between low frequencies is coherent with the fact that there is a spread in the low frequencies results, mainly due to the modal presence and non-diffuseness of the room when measurements are performed.

3.2 Single number quantity uncertainty calculation including calculated correlation coefficients

The calculation of the uncertainty for the corresponding SNQ was performed for the same 300 measurements data set presented in [15] which were selected from the complete 2090 measurements data set. The full procedure for the uncertainty calculation is described in [15] and was followed in this study likewise except in Step 4 where the assumption of full positive correlation is substituted by the obtained correlation coefficients shown in table 1.

1. Step 1: Collect raw measured data of the 300 selected separating walls: L_1, L_2, L_b and T_{20}
2. Step 2: Determine the standard uncertainty for each input estimate: $u(L_1)$, $u(L_2)$, $u(L_b)$, u_{ins} and $u(T)$
3. Step 3: Determine the D_{nTi}, combined uncertainty $u(D_{nTi})$ where ‘‘i’’ stands for each 1/3 octave band
4. Step 4: Calculate the uncertainty for the corresponding single number quantity according to [12] and using the obtained correlation coefficients between the 1/3 octave bands (Table 1).

The single number quantity D_{nTA} is defined as:

$$D_{nTA} = \frac{\sum_i 10^{\left(\frac{D_{nTi}}{10}\right)}}{\sum_i^N 10^{\left(\frac{L_i - D_{nTi}}{10}\right)}} \tag{2}$$

The sensitivity coefficient C_i of the single number quantity is given by:

$$C_i = \frac{\partial X}{\partial D_{nTi}} = \frac{10^{\left(\frac{L_i - D_{nTi}}{10}\right)}}{\sum_i^N 10^{\left(\frac{L_i - D_{nTi}}{10}\right)}} \tag{3}$$

Therefore, the single number quantity uncertainty is calculated as follows:

$$u^2(X) = \sum_{i=1}^{N} C_i^2 u^2(D_{nTi}) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} C_i C_j u(D_{nTi}) u(D_{nTj}) r(D_{nTi}, D_{nTj}) \tag{4}$$

- X can be $D_{nTA(50-5000)}$ or $D_{nTA(100-5000)}$
- *N:* the total number of 1/3 octave bands included in the calculation
- The sub-indexes “i”, “j”, “k” stand for each 1/3 octave band frequency
- *L:* Standardized A weighted values
- D_{nT}: Standardized Level Difference
- $r(D_{nTi}, D_{nTj})$ are the correlation coefficients presented in Table 1 for frequencies “i” and “j”
- $u(D_{nTi})$ and $u(D_{nTj})$ are the combined uncertainty estimated according to [15]

The single number quantity uncertainty can be derived using the previous calculated data of individual uncertainties and correlation coefficients from the Table 1 :

$$u^2(D_{nTA(50-5000)}) = \sum_{i=1}^{N}\left(\frac{10^{\left(\frac{L_i-D_{nTi}}{10}\right)}}{\sum_k 10^{\left(\frac{L_k-D_{nTk}}{10}\right)}}\right)^2 u(D_{nTi})^2 + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left[\left(\frac{10^{\left(\frac{L_i-D_{nTi}}{10}\right)}}{\sum_k 10^{\left(\frac{L_k-D_{nTk}}{10}\right)}}\right)\left(\frac{10^{\left(\frac{L_j-D_{nTj}}{10}\right)}}{\sum_k 10^{\left(\frac{L_k-D_{nTk}}{10}\right)}}\right)u(D_{nTi})u(D_{nTj})r(D_{nTi},D_{nTj})\right] \quad (5)$$

The calculated uncertainties for the corresponding single number quantities are presented in Section 4 and compared with the results of Machimbarrena et al. [15].

4. Results

With the aim to evaluate the effect of including the lower frequencies, the corresponding SNQ uncertainties were calculated for the two frequency ranges: 100–5000 Hz, $D_{nTA(100-5000)}$ and the extended frequency range, 50–5000 Hz, $D_{nTA(50-5000)}$ using Eq. (4). This was done for the complete data set and considering data from measurements performed over heavyweight and lightweight walls separately.

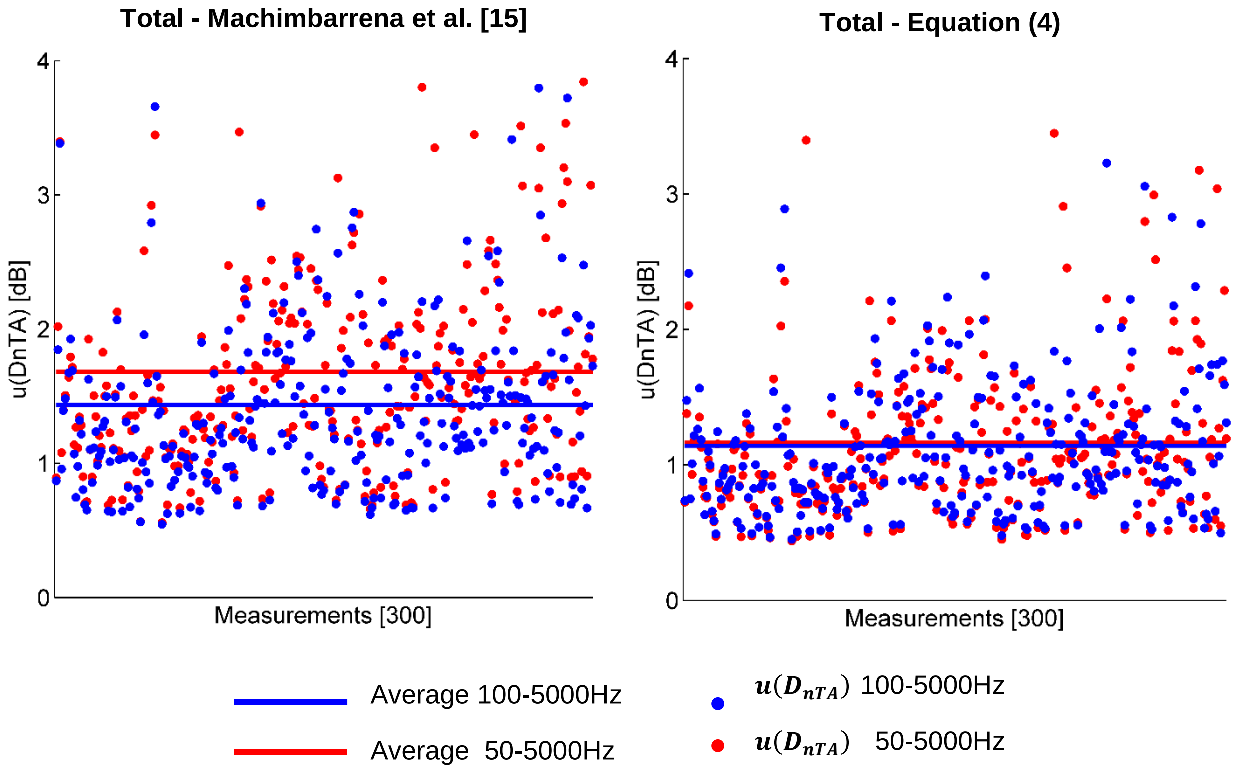

Figure 1: Spread of $\boldsymbol{u(D_{nTA})}$ values and average $\overline{\boldsymbol{u(D_{nTA})}}$ for the full dataset.

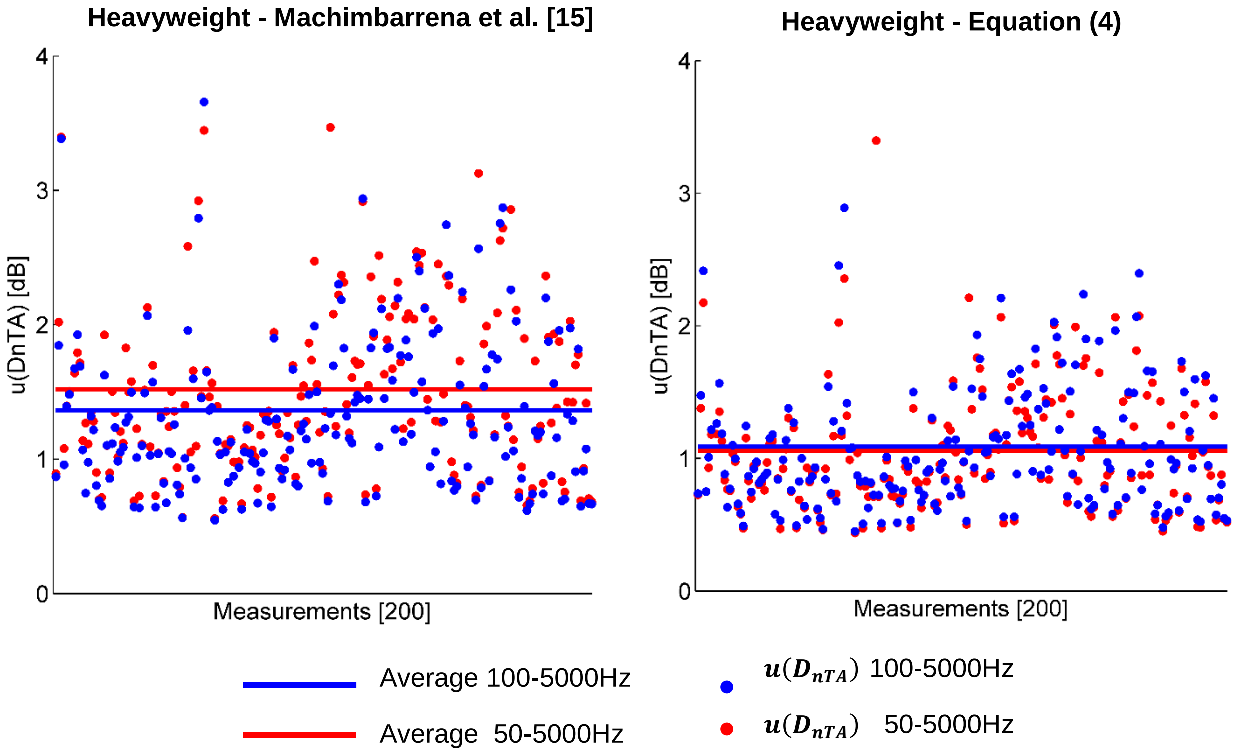

Figure 2: Spread of $u(D_{nTA})$ values and average $\overline{u(D_{nTA})}$ for the heavyweight walls dataset.

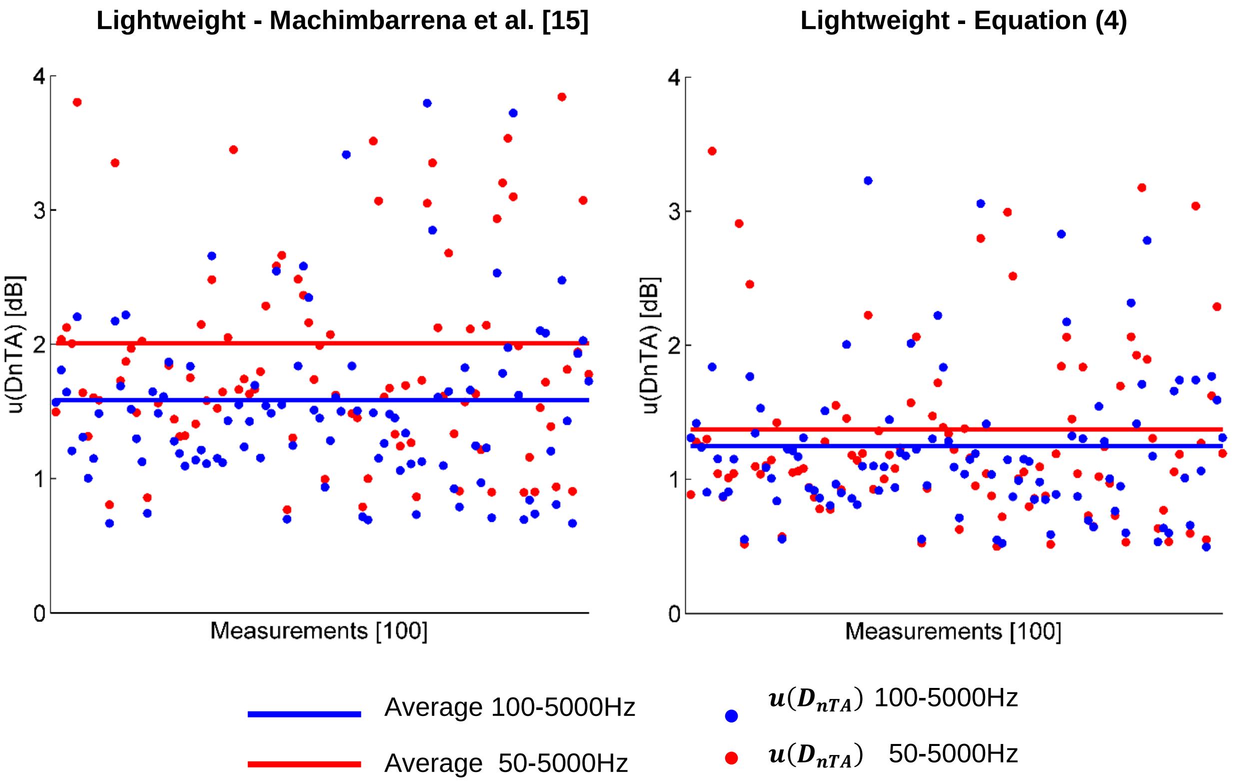

Figure 3: Spread of $u(D_{nTA})$ values and average $\overline{u(D_{nTA})}$ for the lightweight walls dataset.

Figure 1 shows the results obtained in this study (using correlations shown in Table 1 and Eq.5), and those from Machimbarrena et al. [15] (using full positive correlation), for the complete data set, whereas Figures 2 and 3 correspond to heavyweight and lightweight walls data set respectively.

All figures represent the spread of the uncertainty values for $D_{nTA(50-5000)}$ and $D_{nTA(100-5000)}$ and the corresponding uncertainty average, using both frequency ranges.

5. Discussion

Considering the results from Machimbarrena et al., in most of the cases the uncertainty of the extended frequency range SQN $\boldsymbol{u}(\boldsymbol{D}_{\boldsymbol{nTA}(\mathbf{50-5000})})$ is higher than the uncertainty of the corresponding frequency range SQN $\boldsymbol{u}(\boldsymbol{D}_{\boldsymbol{nTA}(\mathbf{100-5000})})$. Comparing with the results obtained in this study, it can be observed that when Eq. 5 is used with the correlation values from Table 1, the frequency range used for the evaluation will not affect the uncertainty of the single number quantity in most cases. It is worth to comment that when only lightweight data set is considered, there is a slight increase of the uncertainty obtained for the extended frequency range descriptor.

As expected, the values of the single numbers uncertainty calculated with Eq. 5 and Table 1 are lower than those obtained with the choice of full positive correlation between 1/3 octave bands. The correlations obtained in Table 1 are valid only for this study, but due to the extension of the data set, it can indicate that significant correlation exists between medium and high frequencies and it is possible to incorporated these correlations to uncertainty calculation.

It is worth to remark that there is still not enough knowledge about the correlation between 1/3 octave bands D_{nT} values, especially at low frequencies. The research on this field depends on data from field measurements which suffers from a technical issue concerned the fact that measurement procedures are prone to poor repeatability and reproducibility at low frequencies [17]. The new ISO series 16283 [4–6] tries to solve this issue by introducing new measurements procedure to improve repeatability and reproducibility in reduced volume rooms. Besides, all the measurements included in this study were performed according to former ISO140-4, using a manual scan procedure for the sampling of the SPL both in the source and receiving room, independently of the size of the rooms. The variability of the results below 100 Hz, even within one same location, was higher than above 100 Hz, which also contributes to the low correlation coefficients found at low frequencies. Consequently, with data obtained by the new procedure adopted by ISO series 16283 for reduced volume rooms, the obtained correlation coefficients between low frequencies might be different from those obtained in this study (Table 1) or by Wittstock [2].

6. Conclusions and future work

It was observed that the spread of the calculated uncertainty of the SNQ is in many cases considered quite large. This result reinforces the suggestion of undertaking individual uncertainty estimations as proposed by [15], especially when the results can be used to verify compliance with national requirements.

Subsequently to these preliminary results more research is needed to evaluate how the frequency range extension affects SNQs uncertainty. Heretofore, contradictory results were obtained by researchers and an improvement on the estimation of SQN uncertainties by introducing correlation coefficients may bring light to the discussion

When the Eq. 5 is used with the correlations values from Table 1, a reduction on the single number quantity uncertainty for both frequency ranges is noticeable if compared to Machimbarrena et al. [15] results, as well as less sensitivity to the SNQ frequency range choice. In other words, the calculated uncertainty based on estimated correlation coefficients between 1/3 octave bands D_{nT} values is less sensitive to the frequency range assessment than the full positive correlation model. It is worth to remark that this applies only for the results of this study.

The adoption of the full positive correlation model is in coherence with Annex B in ISO 12999-1 and with GUM, which recommends that a conservative model should be adopted when there is not enough knowledge to estimate the correlation between variables.

In a future work, the authors intend to propose an uncertainty calculation model based on generic correlation coefficients, obtained from multi-country measurement data set. Besides, it is also proposed to evaluate if better correlation coefficients between low frequencies will be observed if they are derived from measurement data obtained from the low frequency procedure adopted in ISO series 16283.

7. Acknowledgements

Authors want to thank COST Action TU0901, Robust Details Ltd. And Harmonia Davi Akkerman + Holtz Research Centre for inspiring this research and providing the data.

REFERENCES

[1] Rasmussen B, Machimbarrena M, Fausti P, TU0901 C. Building acoustics throughout Europe. Volume 1: Towards a common framework in building acoustics throughout Europe. 2014.

[2] Wittstock V. *Determination of Measurement Uncertainties in Building Acoustics by Interlaboratory Tests. Part 1: Airborne Sound Insulation*. Acta Acust United with Acust 2015;**101**:88–98. doi:10.3813/AAA.918807.

[3] ISO 12999-1:2014 Acoustics -- Determination and application of measurement uncertainties in building acoustics -- Part 1: Sound insulation. International Organization for Standardization; 2014.

[4] ISO 16283-1:2014 Acoustics - Field measurement of sound insulation in buildings and of building elements - Part 1: Airborne sound insulation. Geneva, Switzerland: International Organization for Standardization; 2014.

[5] ISO 16283-2: 2015 Acoustics - Field measurement of sound insulation in buildings and of building elements - Part 2: Impact sound insulation. International Organization for Standardization; 2015.

[6] ISO 16283-3:2016 Acoustics - Field measurement of sound insulation in buildings and of building elements - Part 3: Façade sound insulation. International Organization for Standardization; 2016.

[7] ISO 717-1: 2013 Acoustics -- Rating of sound insulation in buildings and of building elements -- Part 1: Airborne sound insulation. International Organization for Standardization; 2013.

[8] ISO 717-2: 2013 Acoustics -- Rating of sound insulation in buildings and of building elements -- Part 2: Impact sound insulation. International Organization for Standardization; 2013.

[9] Joint Committee for Guides in Metrology 100:2008. Evaluation of measurement data — Guide to the expression of uncertainty in measurement. vol. 50. Joint Committee for Guides in Metrology; 2008. doi:10.1373/clinchem.2003.030528.

[10] Wittstock V. *On the uncertainty of single-number quantities for rating airborne sound insulation*. Acta Acust United with Acust 2007;**93**:375–86.

[11] Michalski R. *Metodologias para medição de isolamento sonoro em campo e para expressão da incerteza de medição na avaliação do desempenho acústico de edificações*. Universidade Federal do Rio de Janeiro - COPPE, 2011.

[12] Mahn J, Pearse J. *The Uncertainty of the Proposed Single Number Ratings for Airborne Sound Insulation*. Build Acoust 2012;**19**:145–72. doi:10.1260/1351-010X.19.3.145.

[13] Navacerrada MA, Pedrero A, Díaz C. *Study of the uncertainty of façade sound insulation measurements: Analysis of the ISO 12999-1 uncertainty proposal*. Appl Acoust 2016;**114**:1–9. doi:10.1016/j.apacoust.2016.03.033.

[14] Castillo JC. *Evaluación de la incertidumbre de medida en un supuesto de aislamiento in situ a ruido aéreo*. Universidade de Vigo, 2007.

[15] Machimbarrena M, Monteiro CRA, Pedersoli S, Johansson R, Smith S. *Uncertainty determination of in situ airborne sound insulation measurements*. Appl Acoust 2015;**89**:199–210. doi:10.1016/j.apacoust.2014.09.018.

[16] Robust Details Ltd. *Robust details handbook. Part E: Resistance to the passage of sound*. 3rd ed. Milton Keynes, UK: 2013.

[17] Hopkins C, Turner P. *Field measurement of airborne sound insulation between rooms with non-diffuse sound fields at low frequencies*. Appl Acoust 2005;**66**:1339–82. doi:10.1016/j.apacoust.2005.04.005.