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# Variability of results in acoustic measurements in buildings

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## ABSTRACT

Variability of results in acoustic measurements in buildings depends on different factors, which may lead to different results from those expected.

The main sources of variability can be linked to four factors: the measurement method, the nature of the materials, the setting conditions and the effect of workmanship.

The variability related to the measurement method (uncertainty) has already been studied in detail in several standards and papers[1,2,3], and it is not considered in this work.

On the other hand, the variability related to the other factors (the nature of the materials, the setting conditions, the effect of workmanship) has not been dealt with in detail in the literature[4]. However, the understanding of these factors is important during the design phase, in order to define the best technological solutions that will ensure acoustic comfort in buildings and the respect of legal limits.

This work aims to evaluate the contribution of each of these latter factors of variability through a statistical approach, applied to an extended campaign of acoustic measurements in buildings. In the present paper, the results of measurements made by the same operator, on the same type of specimen (partition wall and slab), in several flats in the same housing estate, built by the same property developer, are presented. In these conditions the variability due to the measurement method and the nature of the materials was almost constant, therefore it was possible to evaluate the variability due to the setting conditions and the effect of workmanship.

## 1. INTRODUCTION

Information about variability in acoustic measurements could help the acoustical designer to choose the most suitable technological solutions, in order to respect the predicted performance and the legal limits. The main sources of variability (the measurement method, the nature of the materials, the setting conditions and the effect of workmanship), referred to airborne sound insulation and impact sound, depend on other factors, as shown in the cause-effect diagram in figure 1. Factors related to the measurement method and to the setting conditions may be grouped under the same heading for each requirement (sound insulation and impact sound), although they may affect the results differently; instead, factors related to the nature of the materials and the mounting of specimens are better represented if differentiated.

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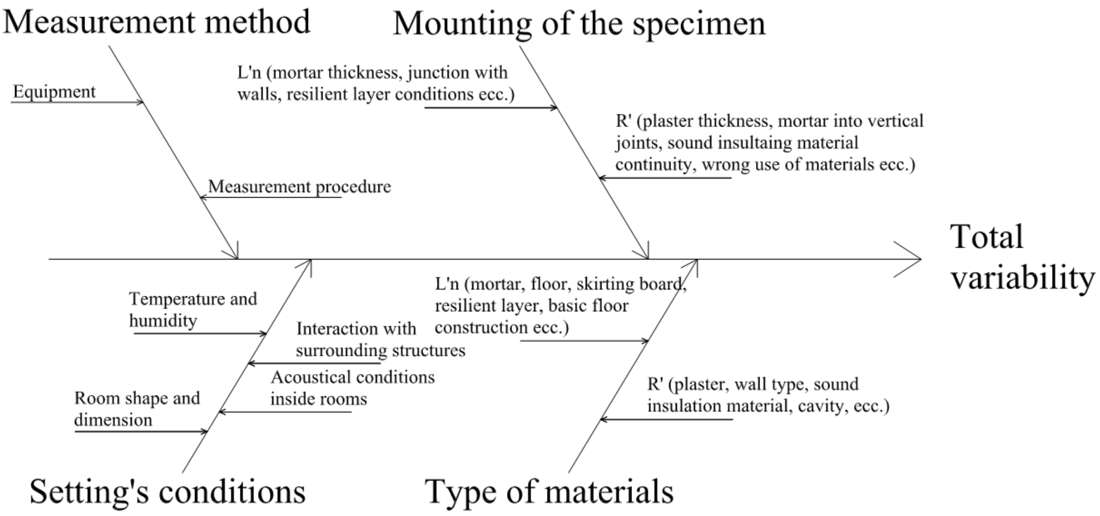

**Figure 1**: cause-effect diagram applied to variability.

An extended campaign of measurement of airborne sound insulation and impact sound was carried out in several flats in the same housing estate. The main feature of this campaign is that all the measurements were carried out by the same operator, with the same equipment, on the same type of wall or slab, built by the same property developer. This condition allowed some factors of variability, such as the measurements method and the type of wall and slab, to be to maintain almost constant. The wall and slab type tested are illustrated in figure 2.

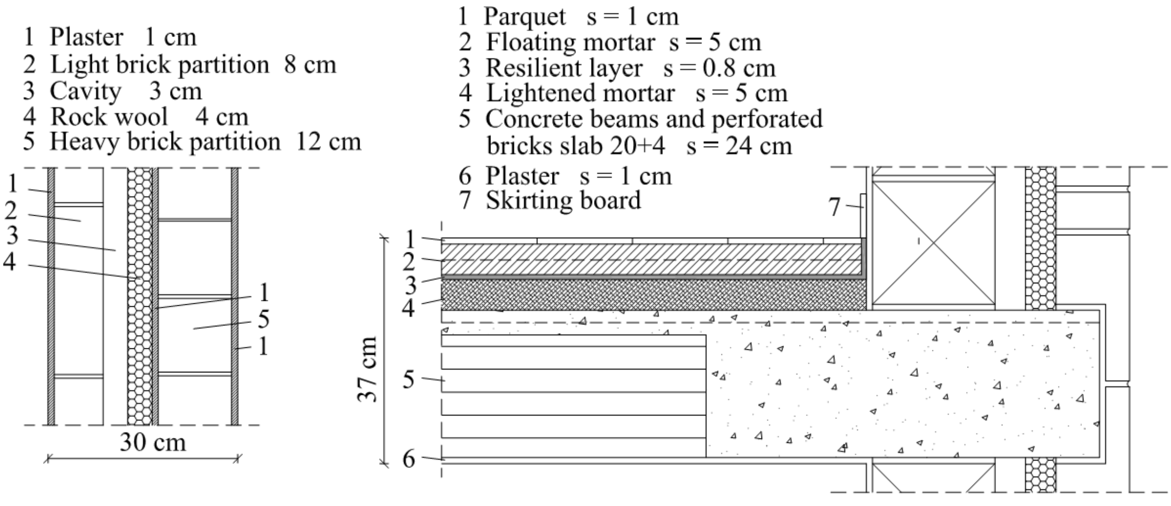

**Figure 2**: Wall type and slab type tested.

## 2. THE STATISTICAL APPROACH

Standards EN 20140-2[2] and ISO 5725-2[3] specify procedures for assessing the uncertainty in acoustical measurements, due to random and systematic influence, through the determination of repeatability value *r* and reproducibility value *R* in interlaboratory tests. Repeatability and reproducibility represent two extremes: the first refers to the minimum variability, the second to the maximum variability in test results. The standards specify the possibility to carry out intermediate measurements of variability between these two extremes, in order to evaluate each factor of variability. Standard ISO 5725-3[5] considers this alternative, and its statistical approach has been employed in this work.

This standard focuses on intermediate precision measures of a measurement method. Such measures are called intermediate as their magnitude lies between the two extreme measures of precision of a measurement method: repeatability and reproducibility standard deviation.

A three factor fully-nested experiment has been considered: the advantage of employing this type of experiment is that is it possible to estimate not only repeatability and reproducibility standard deviation, but also one intermediate precision standard deviation, in our case referred to the variability in mounting the specimens.

A schematic layout of a three factor fully-nested experiment, at a particular level of the test, is given in figure 3. In acoustics, a particular level of the test could refer to the sound reduction index or to each of the frequency components.

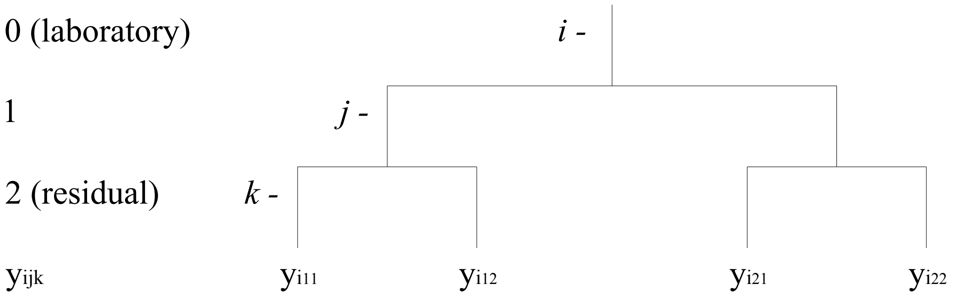

**Figure 3**: Example of a three factor fully-nested experiment.

Analysis of the results of a fully-nested experiment is carried out by the statistical technique called “analysis of variance” (ANOVA), separately for each level of the test. The estimate of the reproducibility variance is given by:

$$s_R^2 = s_r^2 + s_{(1)}^2 + s_{(0)}^2 \quad \text{dB} \tag{1}$$

where:

$s_r^2$ is the estimate of repeatability variance in dB;

$s_{(1)}^2$ is the estimate of intermediate condition variance in dB;

$s_{(0)}^2$ is the estimate of interlaboratory variance in dB.

Each variance parameter is determined as follows:

$$s_{(0)}^2 = \frac{\sum_i \left(\bar{y}_i - \bar{\bar{y}}\right)^2}{p-1} - \frac{\sum_i w_{i(2)}^2}{4p} \quad \text{dB} \tag{2}$$

$$s_{(1)}^2 = \frac{\sum_i w_{i(2)}^2}{2p} - \frac{\sum_i \sum_j w_{ij(1)}^2}{8p} \quad \text{dB} \tag{3}$$

$$s_r^2 = \frac{\sum_i \sum_j w_{ij(1)}^2}{4p} \quad \text{dB} \tag{4}$$

where:

$p$ is the number of laboratories participating in the interlaboratory experiment;

$\bar{y}_i$ is the mean value of two specimens in each laboratory;

$\bar{\bar{y}}$ is the total mean value of all the laboratories;

$w_{i(2)}$ is the range of two specimens in one laboratory;

$w_{ij(1)}$ is the range of two test results of each specimen;

The standard specifies that an *n-factor* fully-nested experiment requires $2^{n-1}$ test results from each laboratory. Thus, for the considered experiment, four test results for each laboratory are required.

## 3. APPLICATION OF THE STATISTICAL APPROACH

First of all the application of the method requires the definition of the three conditions of the test (figure 4): 0 (laboratory), 1 (intermediate), 2 (residual).

The laboratory condition (0) has been obtained using two identical configurations in situ. Each "laboratory" (pair of configurations) is composed of a pair of similar test rooms in terms of shape, dimensions and internal acoustic field. We hypothesize that this state makes it possible to maintain constant the variability due to the setting conditions.

Regarding the intermediate condition (1), each test configuration presents two hypothetically identical specimens (wall or slab): the dimensions, shape and materials are the same, the only variability factor regards the mounting of the specimens.

Two measurement tests have been carried out for each specimen (condition 2), by the same operator, with the same equipment and in short periods of time, following the ISO 140-4[6] and ISO 140-7[7] standards.

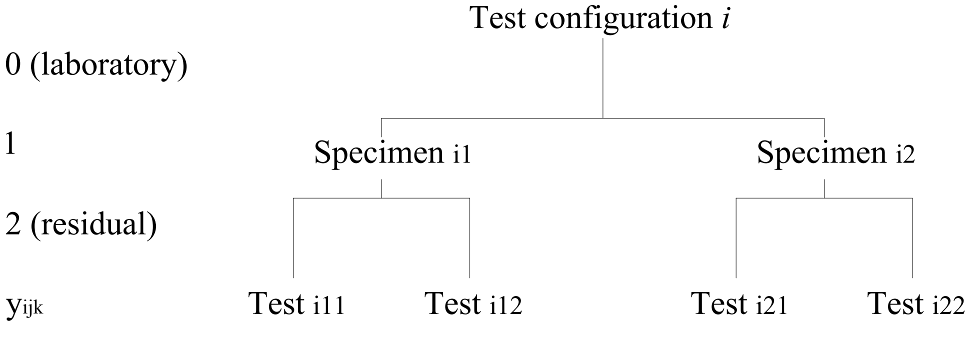

**Figure 4**: Example of a three factor fully-nested experiment.

Regarding the airborne sound insulation measurements a total of 19 test configurations have been considered, while a total of 11 test configurations have been taken into consideration for the impact sound measurements, in both cases with two specimens for each test configuration and two measures for each specimen.

The measurements were carried out in four buildings (blocks 2, 3, 4 and 5) of the same housing estate.

Figure 5 shows an example of two test configurations for the airborne sound insulation measurements.

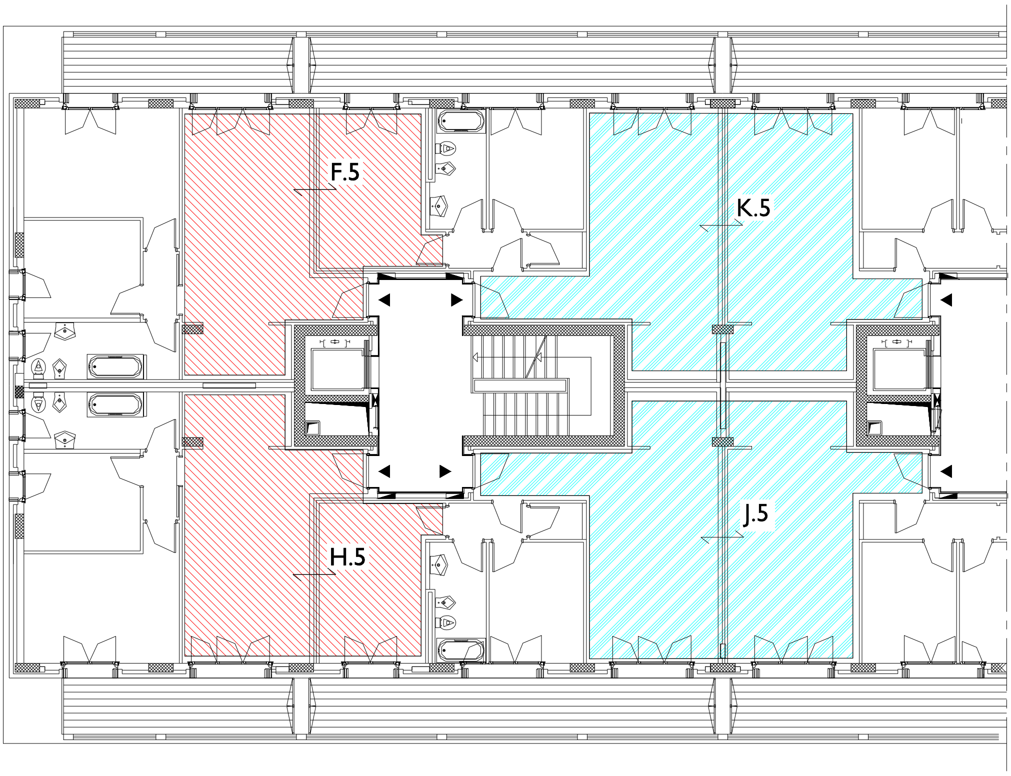

**Figure 5**: Example of a floor plan with two test configurations, block 5.

The estimates variances defined in (2), (3) and (4) correspond to the following:

- $s^2_r$ is the estimate of repeatability variance and corresponds to the random error related to the operator who carries out two measures on the same specimen;
- $s^2_{(1)}$ is the estimate of intermediate variance and corresponds to the variation between two specimen of the same test configuration. This parameter is related to the variability of the mounting of the specimens, and is calculated using the range between the two specimen, subtracting the random error contribution;
- $s^2_{(0)}$ is the estimate of interlaboratory variance and corresponds to the variation of the setting conditions between the test configurations. This parameter is calculated using the range between the mean value of each test configuration and the total mean value of all the configurations, subtracting the random error contribution and the variability due to the mounting of the specimens.

The standard considers the application of the experiment for different levels. In our case the levels correspond to the 1/3 octave frequency components between 50 and 5000 Hz, with a further level corresponding to the index $R'_w$ or $L'_{n,w}$

## 4. AIRBORNE SOUND INSULATION TEST RESULTS

Airborne sound insulation general mean values with the maximum and minimum bars are given in figure 6. the airborne sound insulation index values of each specimen, calculated according to the ISO 717-1[8] standard are given in figure 7.

Both diagrams show a similar trend for almost all the specimens, especially at medium and high frequencies, with index values of up to 56/57 dB. The higher differences, especially at low frequencies, are due to six specimens, with index values lower than 50 dB.

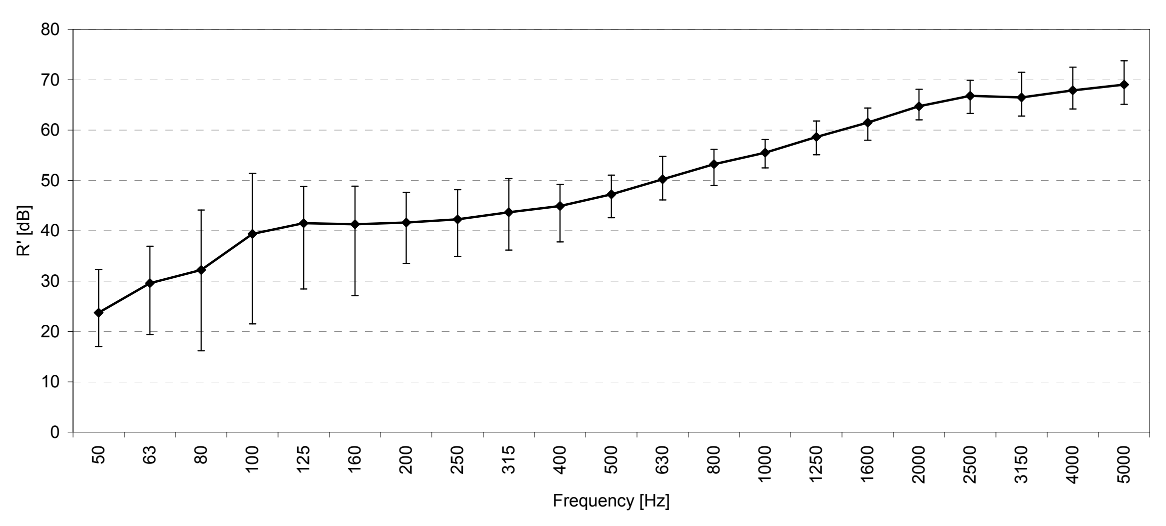

**Figure 6**: R' mean values with maximum and minimum bars.

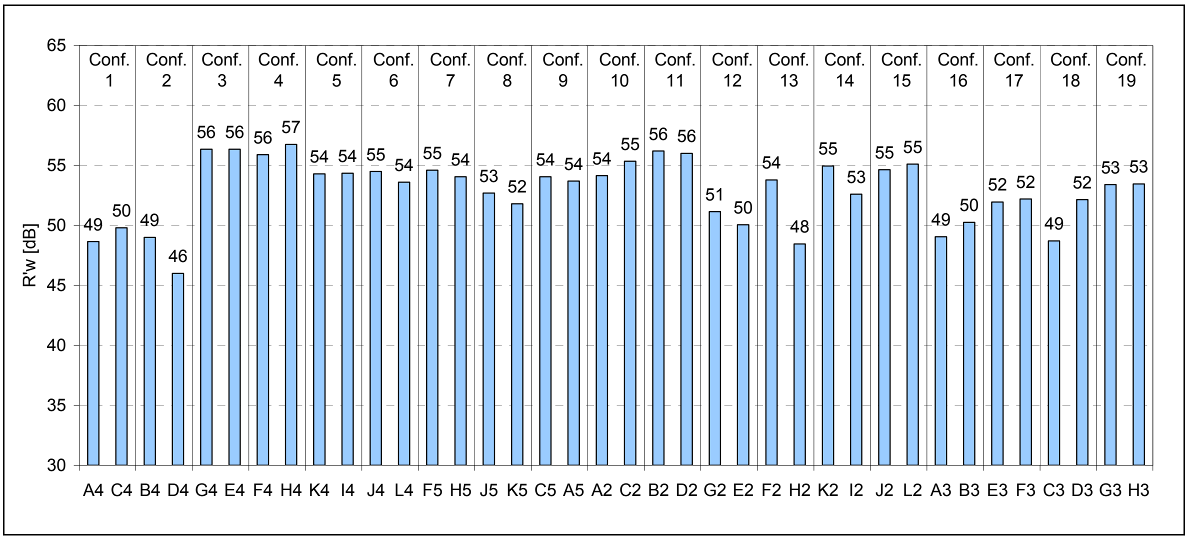

**Figure 7**: $R'_w$ values of each tested wall, sorted by test configuration.

The application of the statistical method made it possible to evaluate the variability contribution due to the setting conditions, mounting of the specimens and random error in measurements, in terms of airborne sound insulation index values (table 1) and frequency components (figure 8).

In terms of index value, reproducibility standard deviation depends more on the setting condition, as the variability contribution of the mounting of the specimens is lower but significant. The variability referred to repeatability is therefore less important.

Concerning the frequency content, at low frequencies the contribution of the setting conditions is the most important, but at medium-high frequencies the general variability depends both on the setting conditions and on the mounting of the specimen.

These values show quite good results, typical of measurements carried out on the same kind of specimen, built in the same housing estate by a properly trained and supervised workforce.

The high values of the setting condition variability do not depend on different shapes and dimensions, nor on the acoustic conditions inside the rooms. Therefore the main contribution is due to the specimen interaction with the contiguous structures. This contribution is higher when the airborne sound insulation of the specimen is high: therefore, as happened in our cases, the structural transmission through the contiguous walls and slabs is more important.

**Table 1**: *Averaged sound reduction index $R'_{W,avg}$ and different contributions of the standard deviation.*

| $R'_{W,avg}$ | s [dB] | $s_{(1)}$ [dB] | $s_{(2)}$ [dB] | $s_r$ [dB] |
|---|---|---|---|---|
| | Reproducibility | Setting conditions | Mounting specimen | Repeatability |
| 53 | 2.7 | 2.4 | 1.3 | 0.3 |

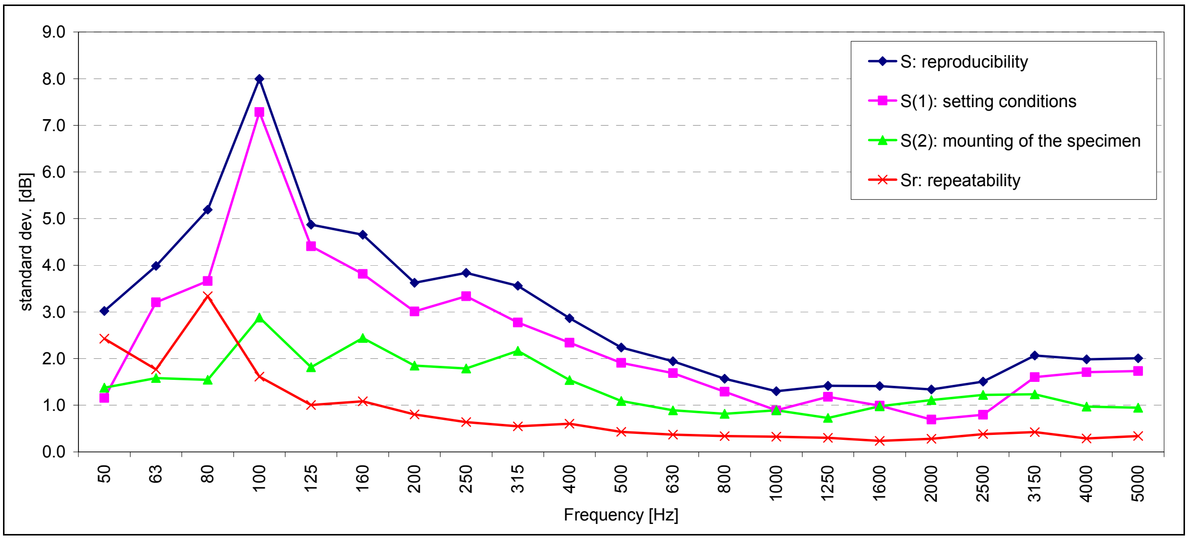

**Figure 8**: R' reproducibility standard deviation and its different contributions.

## 5. IMPACT SOUND TEST RESULTS

The overall mean of the impact sound, with the maximum and minimum bars, are given in figure 9. The impact sound index values of each specimen, calculated according to the ISO 717-2[9] standard, are given in figure 10.

Both diagrams show good results (considering the Italian legal limits), with a similar trend for almost all specimen, especially at medium and high frequencies, with index values up to 49/50 dB. The higher differences are at low frequencies.

The variability contributions due to the setting conditions, mounting of the specimens and random error in measurements, are shown in table 2 (index values) and in figure 11 (frequency components).

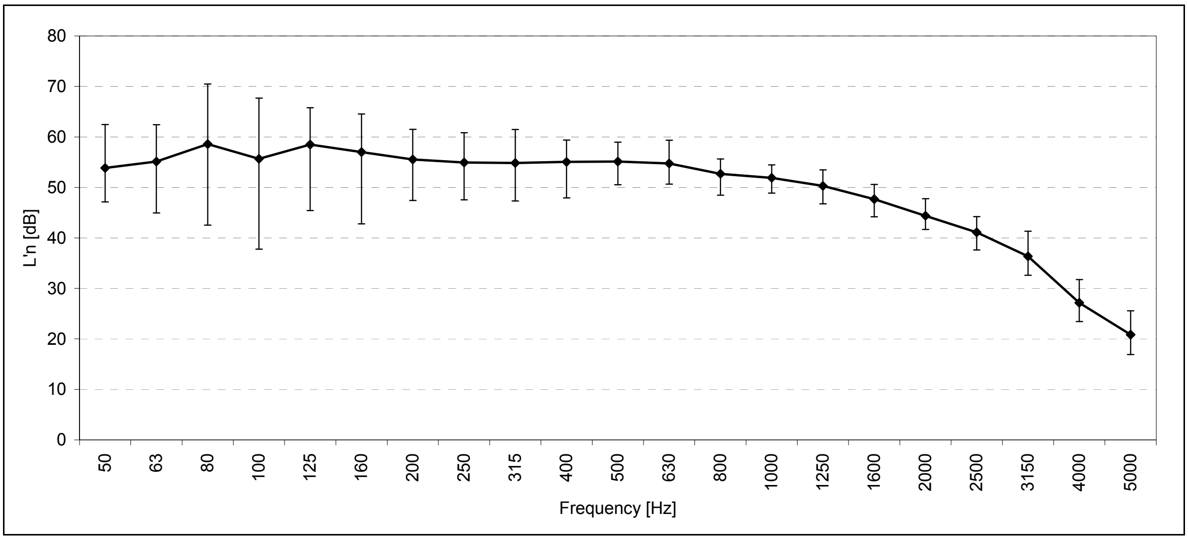

**Figure 9**: L’$_n$ mean values with maximum and minimum bars.

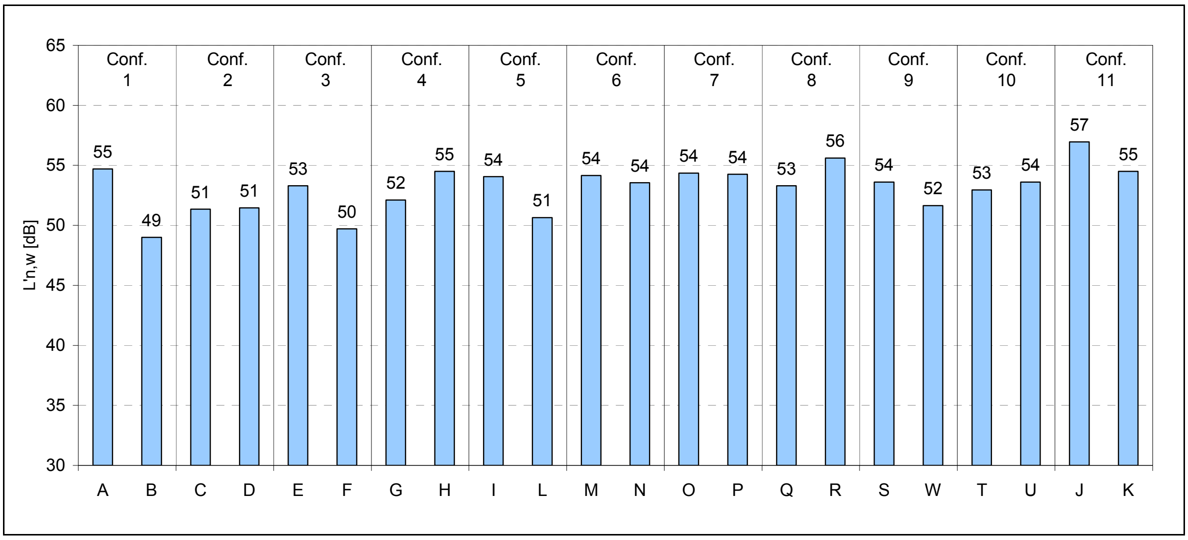

**Figure 10**: L’$_{n,w}$ values of each tested slab, sorted by test configuration.

In terms of the index values, the reproducibility standard deviation exclusively depends on the mounting of the specimens; the variability contribution of the setting conditions and the variability referred to repeatability are not significant.

Concerning the frequency content, the trend is almost the same: above 200 Hz the total variability depends only on the mounting of the specimens. The reason why the variability due to the setting conditions between 200 and 800 Hz is zero has to be found in the statistical procedure. The ISO 5725-2[3] standard, which refers to part 3, contemplates the need to exclude outliers from the variance calculation, through some numerical tests (Mandel’s *h* and *k* statistics, Cochran’s test, Grubbs’s test). For this reason some values between 200 and 800 Hz should be excluded. However the aim of this work is not to evaluate the variability of a measurement method, but the variability due to the mounting of the specimens. In this case all the outliers were due to large variances (between 200 and 800 Hz) among some specimens in the same test configuration, probably caused by mounting differences. For this reason they were not rejected. This has caused some errors in the results in the frequency range between 200 and 800 Hz, so it was decided to maximize the standard deviation due to the mounting of the specimens, to emphasize the real source of variability. The effect of this operation is the minimization of the variability due to the setting conditions.

These values show a reproducibility standard deviation value lower than the airborne sound insulation and due mainly to the variability in the mounting of the specimens.

**Table 2**: *Averaged sound reduction index $L'_{n,W,avg}$ and different contributions of the standard deviation.*

| $L'_{n,W,avg}$ | s<br>[dB] | $s_{(1)}$<br>[dB] | $s_{(2)}$<br>[dB] | $s_r$<br>[dB] |
|---|---|---|---|---|
| | Reproducibility variability | Setting conditions variability | Mounting specimen variability | Repeatability variability |
| 53 | 1.9 | 0.3 | 1.9 | 0.2 |

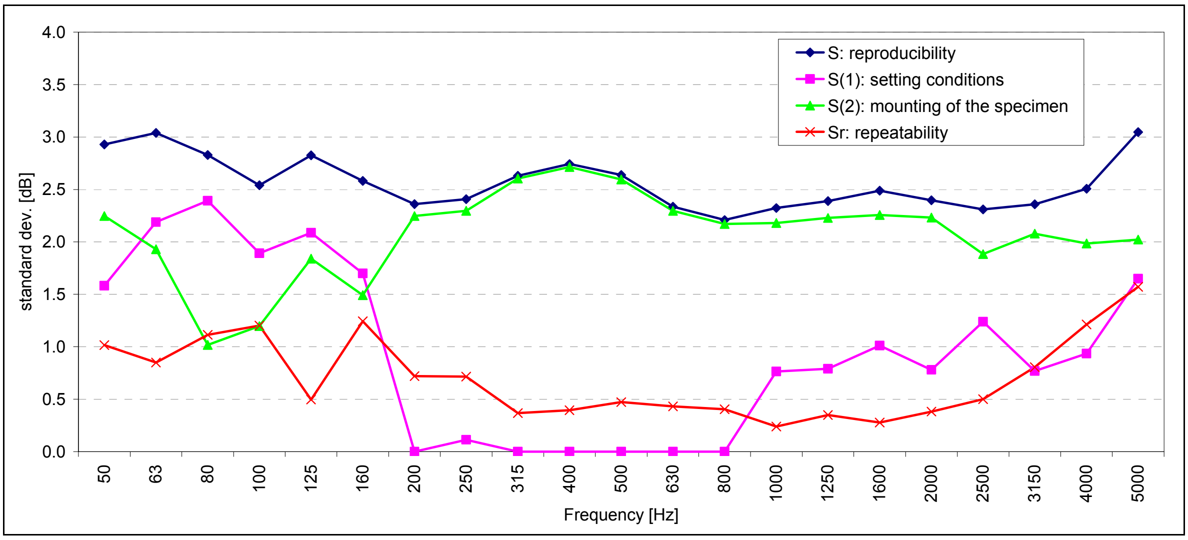

**Figure 11**: $L'_n$ reproducibility standard deviation and its different contributions.

## 6. CONCLUSIONS

In order to define robust technological solutions, information about variability of results in acoustic measurements in buildings, as a function of the main source of variability, could be useful.

In the present paper, an example of application of a statistical approach to evaluate the variability due to the setting conditions and the effect of workmanship in mounting the specimens was presented. The obtained results only refer to the described conditions, those types of specimens and that housing estate. For the application of the methods it was necessary to consider some hypotheses which could have slightly affected the results, for example the hypothesis that the use of two identical pairs of configurations could represent a laboratory, by making it possible to maintain constant the variability due to the setting conditions.

The measurements were made in buildings in which the workmen were well trained and the activity in the worksite was continuously checked. These are very important conditions in order to avoid mounting errors and obtain good acoustical behavior of the building elements.

The results obtained for the airborne sound insulation have shown that, in the presence of quite high sound insulation performances of the partition, the main factor of variability is the setting condition and the interaction between the partition and the surroundings. For the impact sound insulation, despite the constant checks, the mounting condition was the main factor of variability.

The statistical approach used was very useful in order to separate and estimate the contribution of the different factors of variability.

The results presented in this paper represent one of the possible approaches to estimate the variability of results of the acoustic measurements in buildings. The method could be extended to façade sound insulation and noise from hydraulic and HVAC systems. Our intention is to repeat the evaluation for other technological solutions.

Further development will be devoted also to the study of the variability given by the same type of wall or slab, but inserted into different buildings by different constructors.

## ACKNOWLEDGMENTS

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