STATISTICAL ANALYSIS OF SAMPLING STRATEGIES FOR SOUND INSULATION VERIFICATION: A CASE STUDY

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Abstract

The in-situ verification of airborne and impact sound insulation in buildings relies on acoustic measurements that are necessarily limited in number. In practice, each country defines its own sampling approach based on local construction practices and economic feasibility. Typically, representative rooms are tested instead of the entire building, assuming repetition in architectural layout and construction solutions.

This paper analyses the relationship between sampling strategy, number of acoustic tests, and the accuracy of sound insulation assessments in residential buildings. A reference building model is used to generate a complete set of synthetic measurements by combining calculated sound insulation values with realistic experimental uncertainty. A bootstrap resampling approach is applied to quantify the deviation introduced by reduced sampling schemes and to identify optimal testing strategies for compliance verification.

The aim is to identify sampling strategies that balance measurement effort and reliability, providing quantitative criteria for minimum sampling. To the authors' knowledge, no prior study has systematically addressed the statistical basis of acoustic sampling in buildings. The main limitation of the study is that it relies on calculated acoustic data. Nevertheless, the validity of this assumption should be confirmed through a dedicated experimental measurement campaign.

Keywords: *sampling, verification of sound insulation, in situ testing, regulations*

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1. Introduction

In situ acoustic testing is a key element in assuring the acoustic performance and quality of a building. The acoustic performance of a building depends not only on the prescribed solutions and specifications, but also on the quality of workmanship and installation. Consequently, conducting a representative sample of pre-occupancy acoustic measurements provides the following benefits:

- The verification of compliance with building regulations.
- The early identification of construction defects, allowing corrective measures before the building is occupied.
- A reduction in the risk of complaints.
- Increased confidence in the quality of the construction.

In some European countries like England[1], France[2] and parts of Spain[3] acoustic testing is mandatory before the occupation of a building. The sample of tests performed varies from country to country. ISO/TS 19488[4], which contains the acoustic procedure to classify dwellings, specifies two procedures for the verification of conformity with an acoustic class:

- Procedure A, which is based on calculations, visual inspections and field measurements, specifies that a 5% of the structures and rooms must be measured.
- Procedure B, which is based exclusively on measurements, specifies that at least 10 % of the types of construction of separating walls and floors must be measured in such a way that they are sufficiently representative.

In several regional regulations in Spain[5] [6] [7], a sample corresponding to the 10% of the dwellings is also required for acoustic testing. In England[1] a set of tests for every 10 dwellings must be performed. This set of tests is composed of six individual sound insulation tests, two horizontal airborne sound insulation tests,

two vertical airborne sound insulation tests and two vertical impact sound insulation tests.
However, in large residential buildings, i.e. more than 500 dwellings, testing a 10% of the dwellings or elements, is impractical due to the time and financial resources required. Buildings contain a large number of repeated construction elements, with the same layout and therefore with similar acoustic performance.
On the other hand, reducing the number of tests inevitably introduces uncertainty regarding how well the measured sample represents the acoustic performance of the entire building.
This paper presents a theoretical study based on simulations of a case study building. Its objective is to investigate the influence of the sample size on the assessment of building acoustic performance and to determine the number of tests necessary to achieve a statistically representative evaluation for the case-study building.

2. Methods

A complete set of field measurements from an occupied building was not available for this study. Therefore, a synthetic dataset of sound insulation results was generated using the prediction models of ISO 12354-1[8] and 2 [9].
A residential development of 92 dwellings was selected as the case study. The airborne and impact sound insulation of all the living rooms and bedrooms was calculated using a software, that implements ISO-EN 12354 parts 1 [8] and 2[9] procedures.
The sound insulation predicted by ISO 12354 depends on several factors: the properties of the separating walls and floors, room dimensions, flanking paths, areas of adjoining elements, and the type of junctions. In order to isolate the influence of the building geometry and reduce unnecessary variability in the dataset, the same construction solutions were assigned to all separating walls, floors, and flanking elements throughout the building. Consequently, differences in the calculated sound insulation values were primarily associated with variations in room dimensions, layout, and junction configurations (T-junctions and cross-junctions).
The acoustic calculations provided a complete set of airborne and impact sound insulation results for all relevant room pairs within the case-study building. To account for the variability observed in real measurement campaigns but not represented in ISO 12354 predictions, a stochastic component was introduced into the dataset. A normally distributed random variable with a mean of 0 dB and a variability range of ±3 dB (corresponding to an interval containing approximately 95% of the realizations) was added to each calculated value to represent the combined effects of measurement uncertainty and construction tolerances.
The resulting synthetic dataset was subsequently used to evaluate the influence of sampling on acoustic assessment. A bootstrap resampling approach was employed, generating 1,000 random samples for each sample size considered. These simulations enabled the statistical behaviour of different sampling strategies to be investigated and the uncertainty associated with reduced numbers of tests to be quantified.
In particular, the analysis focused on the probability of detecting low-performing acoustic elements and on the reliability of the estimated building performance as a function of sample size. The methodology therefore provides a quantitative basis for assessing the representativeness of different sampling rates and for determining the minimum number of tests required to achieve a statistically reliable evaluation of the acoustic performance of the case-study building.

2.1 Descripción of the case study building

The case study building is located in Madrid, it has 92 dwellings with apartments of one and two bedrooms. Figures 1, 2 and Table 1 show its main characteristics

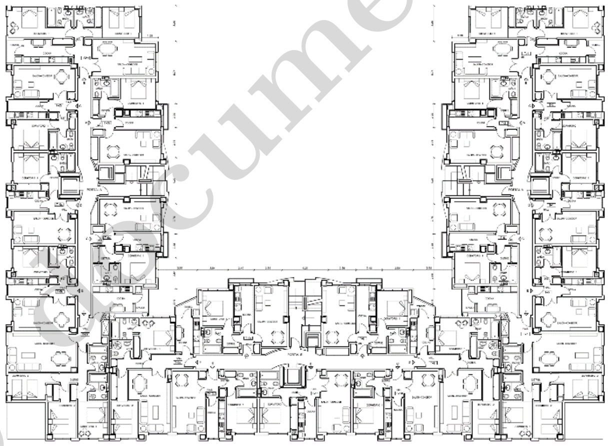


Figure 1. Typical floor plan of the building

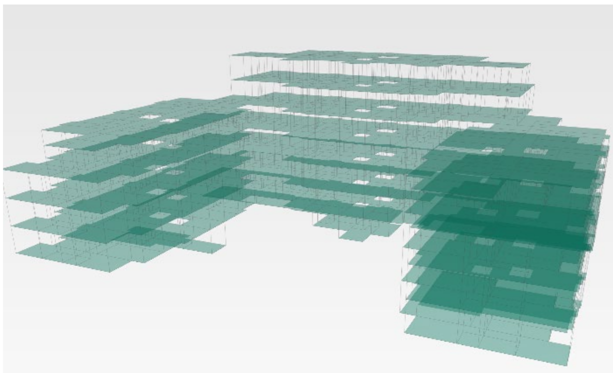


Figure 2. 3D model of the case-study building used in the simulations

The case-study building had a complex layout, with dwellings that were not arranged symmetrically around the separating walls and floors. Although the building had six floors, only three are typical floors and the layout changed on 3 levels. As a result, many different adjacency situations occur, including bedrooms next to neighbouring living rooms or bathrooms. This creates a wide variety of acoustic transmission conditions, making the building a suitable case study for analysing sampling strategies.

Table 1. Main characteristics of the case study building

Description	**Value**
1-bedroom dwellings	64
2-bedroom dwellings	28
Total dwellings	92
Storeys	Ground floor + 6 upper floors
Living rooms	92
Bedrooms	120
Habitable rooms[1]	332

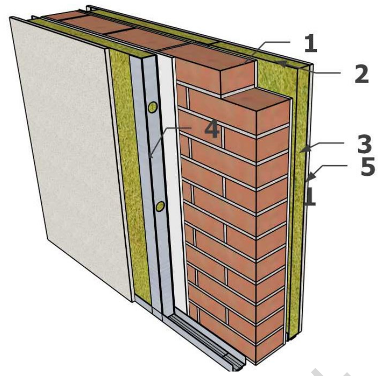
2.2 Construction system

The same separating wall and floor were used throughout the building to minimize variability arising from differences in construction systems and to focus the analysis on the effects of sampling. This approach also reflects common construction practice in residential developments. Figures 3 and 4 describe the separating walls and floors.

The selected constructions correspond to solutions recommended by the simplified verification method of the Basic Document Protection against noise DB HR of the Spanish Building Code[10]. These systems were chosen because they are widely used in residential construction and generally provide robust acoustic performance.

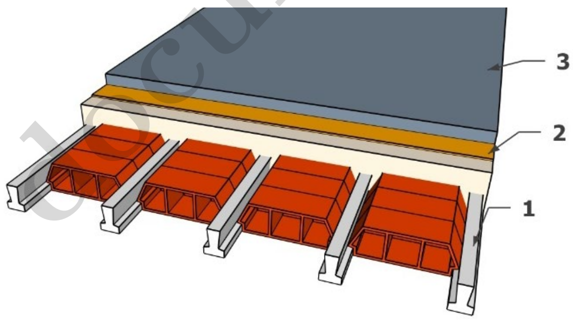
The internal walls consisted of steel-framed partitions with mineral wool insulation in the cavity, formed by 15 mm plasterboard panels fixed to 48 mm steel studs. The façades incorporated an internal lining comprising 15 mm plasterboard attached to steel studs, with mineral wool filling the 48 mm cavity. These construction systems provide good acoustic performance and are effective in reducing flanking transmission.

In addition, the selected wall is less sensitive to workmanship defects than alternative solutions. Their acoustic characteristics are also well suited to prediction using the ISO 12354 calculation method. Consequently, the variation in the calculated results is mainly attributable to differences in room geometry, building layout, and junction configurations rather than to the intrinsic properties of the construction elements themselves.



1. 120 mm perforated brick wall. m = 161kg/m^2; $R_w(C,C_{tr})$ = 48(-1,-4) dB.
2. 10 mm plaster on both faces
3. 50 mm mineral wool
4. 48 mm steel studs
5. 15 mm plasterboard. $\Delta R_w(C,C_{tr})$ = 10(-1,-1)

Figure 3. Description of the separating walls



1. 310 mm beam and block floor (26+5). Ceramic blocks. 10 mm plastered. m=305 kg/m^2; $R_w(C,C_{tr})$ = 54(-1,-3) dB; L_{nw}=87 dB.
2. Impact insulation layer. 5 mm polyethylene layer.
3. 70 mm cement screed with 200x200 mm reinforcing wire mesh. ΔL_w = 21 dB, $\Delta R_w(C,C_{tr})$ = 7(-2,-3) dB No floor covering was considered in the calculations.

Figure 4. Description of the separating floors

3. Acoustic dataset generation

The calculations considered three categories of sound insulation:

[1] According to the Spanish Building Code, DB HR [10], habitable rooms are those intended for normal occupancy like kitchens, bathrooms, corridors and hallways inside a building. Protected rooms are are a subset of habitable rooms for which specific sound insulation is required. In residential buildings, living rooms and bedrooms are classified as protected rooms.

- Horizontal airborne sound insulation, corresponding to sound transmission between horizontally adjacent dwellings through a separating wall.
- Vertical airborne sound insulation, corresponding to sound transmission between vertically adjacent dwellings through a separating floor.
- Vertical impact sound insulation, corresponding to impact transmission through separating floors.

Only pairs involving protected rooms, namely living rooms and bedrooms, were included in the analysis. Therefore, transmission paths involving kitchens, bathrooms, corridors, entrance halls, and other non-protected or service spaces were excluded from the dataset.

The descriptors calculated were: $D_{nT,w} + C_{100\text{-}5000}$ for airborne sound insulation and $L'_{nT,w}$ for impact sound insulation.

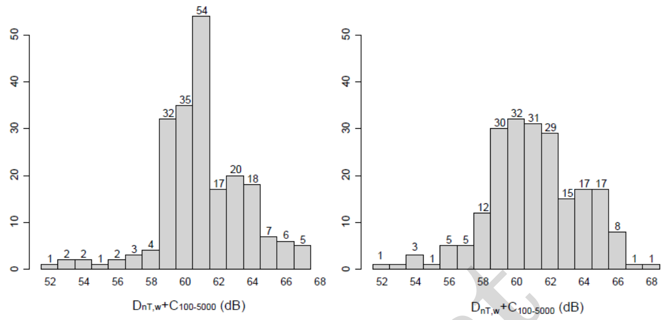
3.1 Calculated sound insulation

Figures 5.a), 6.a) and 7.a) present the frequency distributions obtained for the three sound insulation categories. The calculated results are concentrated within relatively narrow ranges, which is expected given that the same separating walls, floors, and flanking elements were used throughout the building. Consequently, the observed variability arises primarily from differences in room geometry, layout, and transmission paths rather than from variations in construction systems, workmanship, or measurement uncertainty. At this stage, the dataset reflects only the variability inherent to the building configuration; the effects of construction tolerances, workmanship, and measurement uncertainty were subsequently incorporated through the introduction of a stochastic variable, as described in the following section.

3.2 Modelling of variability

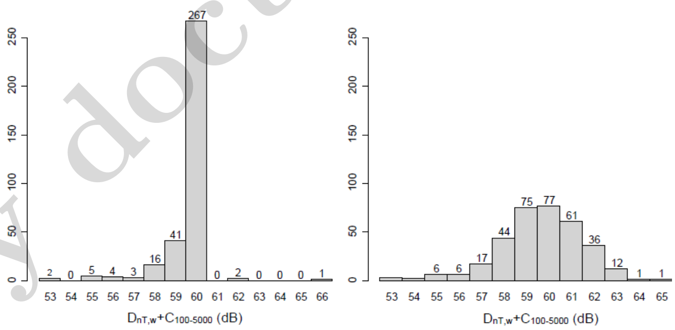
To obtain a dataset that more closely represents the acoustic performance of a real building, it is necessary to account for sources of variability that are not captured by the ISO 12354 calculations. These include measurement uncertainty as well as variations in the acoustic performance of construction elements resulting from workmanship. To model these effects, a stochastic variable was introduced and added to each calculated sound insulation value.

The stochastic variable was assumed to follow a normal distribution with a mean of 0 dB. A variability range of ±3 dB was adopted based on both measurement uncertainty and construction-related variations. According to ISO 12999-1 [11] the standard deviation for field measurements $D_{nT,w}+C_{100\text{-}5000}$ is 1,1dB ,and for $L'_{nT,w}$ is 1 dB, corresponding to expanded uncertainties of approximately 2.2 dB and 2.0 dB, respectively. In addition, a further allowance was considered to account for construction tolerances. Consequently, a total variation of ±3 dB was assumed.



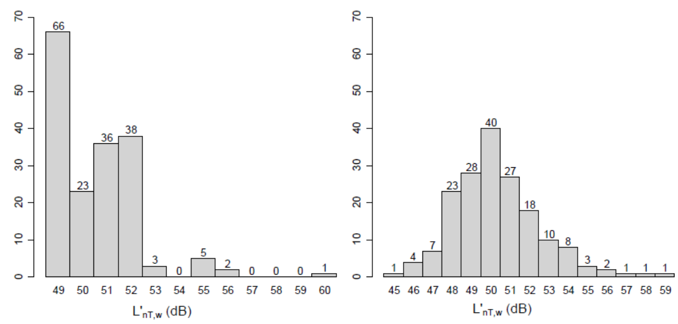
a) b)

Figure 5. Resulting distributions of calculated horizontal airborne sound insulation values (separating walls) a) ISO 12354 calculated values. b) calculated after the introduction of the stochastic variable.



a) b)

Figure 6. Resulting distributions of calculated vertical airborne sound insulation values (separating floors) a) ISO 12354 calculated values. b) calculated after the introduction of the stochastic variable.



a) b)

Figure 7. Resulting distributions of calculated impact sound insulation values (separating floors) a) ISO 12354 calculated values. b) calculated after the introduction of the stochastic variable.

The randomly generated value was added to the corresponding calculated result, and the final value was rounded to the nearest integer. This procedure produced a synthetic dataset representative of the sound insulation results that could have been obtained if measurements had been performed in all relevant room pairs within the building. Figures 5, 6 and 7 show the resulting distributions after the introduction of the stochastic variability.

4. Statistical analysis of sampling strategies

Because acoustic compliance is assessed on a pass/fail basis, with all individual test results required to meet or exceed the regulatory limit, the analysis was not focused on the mean performance of the tests conducted on each sample. Instead, the objective was to quantify the probability that a given sampling strategy would identify the worst-performing elements within the building. For this purpose, the study evaluated the probability of detecting results belonging to the lowest-performing 5% of the complete population

By sampling strategy, we mean the selection of a representative subset of rooms or building elements for acoustic testing.

A bootstrap resampling approach was employed, whereby 1,000 random selections were generated for each sample size considered. Sample sizes of 4, 8, 10, and 15 tests were evaluated, and the 5th percentile (5% quantile) of the complete population of results was used as the detection threshold. For each random sample, it was determined whether at least one value fell below this threshold, and the proportion of samples satisfying this condition was subsequently calculated. This probability provides an indication of the likelihood that a given sampling strategy or a number of tests will identify the poorest-performing elements within the building.

The analysis was performed for sample sizes representative of practical testing campaigns, with 10 tests per acoustic characteristic corresponding approximately to 10% of the dwellings in the case-study building, a sampling rate commonly adopted in regulations. Table 2 shows the percentage of samples in which values below the 5th percentile are detected for sample sizes of 4, 8, 10 and 15 tests for each acoustic characteristic.

5. Discussion

Table 2 shows that the probability of identifying at least one result below the 5th percentile increased from approximately 20% for a sample of 4 tests to approximately 53% for a sample of 15 tests for the three acoustic characteristics studied.

Table 2. Percentage of samples in which values below the 5th percentile are detected for sample sizes of 4, 8, 10, and 15 tests.

Acoustic characteristic	Sample size			
	4	8	10	15
Horizontal airborne sound insulation	19.9%	36.2%	45.7%	56.6%
Vertical airborne sound insulation	18.9%	35.1%	37.6%	52.8%
Impact sound insulation	18%	30.4%	41.6%	52.2%

These findings are not unexpected. Increasing the number of tests reduces the uncertainty associated with the assessment and avoids masking poor performance remains due to the randomness of the sampling process. However, the results raise an important practical question: What proportion of the dwellings should be tested to achieve an adequate level of confidence in the acoustic assessment of the building?
The answer is not purely statistical. A balance must be achieved between confidence in the assessment and the practical constraints associated with measurement campaigns: cost, time, and access to dwellings.
In Spain, there is currently interest from the national authorities in reducing the number of pre-occupancy tests. If smaller samples are adopted, guidance on the selection of rooms and partitions should be provided to ensure that the sample remains representative of the building.
This study is based exclusively on sound insulation calculations of a single case-study building with a specific construction system. Therefore, the findings cannot be generalized without further investigation. To address this limitation, the same methodology should be applied to other building typologies and construction systems.
Other building typologies would include: low-rise and high-rise residential buildings, row houses, buildings with different layouts and buildings employing different structural and partition systems (e.g., masonry, concrete, lightweight, timber, and modular construction).
Furthermore, future work will extend the analysis to real buildings to validate the statistical results through in situ measurements.

6. Conclusions

This study investigated the influence of sample size on the acoustic assessment of a residential building through a simulation-based approach. The results show that the probability of detecting low-performing acoustic elements increases as the number of tests included in the sampling strategy increases. For the three acoustic characteristics analysed, the probability of identifying at least one result below the 5th percentile increased from approximately 20% for a sample of 4 tests to approximately 54% for a sample of 15 tests.

Determining how many tests are necessary to asses a building is still an open question, regulations in some countries specify minimum number of tests, and these decisions have been made based on current practices and feasibility.

If the number of tests for verification is limited, some guidance should be given for the selection of test locations. Rather than relying solely on a random sample, the selected rooms should represent the range of acoustic situations present in the building, including bedrooms and living rooms, horizontal and vertical separating elements, different construction systems, partitions adjacent to common areas, and locations where unfavorable flanking transmission conditions may occur. Such a targeted sampling strategy would improve the representativeness of the assessment maintaining a reduced number of tests and associated costs.

This leads to an interesting conclusion: it may be preferable to improve the quality of the sample rather than simply increase its size.

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