Determination of the Uncertainty of Predicted Values in Building Acoustics

Volker Wittstock, Werner Scholl

Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, volker.wittstock@ptb.de

Introduction

According to Annex I of the European Construction Products Directive [1], sound insulation belongs to the six main requirements a building has to fulfil. Usually this is demonstrated by a calculation in which the properties of a building are predicted from the properties of the building products used. A harmonised European prediction method was developed for this purpose [2] and will also be applied in Germany after the revision and introduction of the German Standard DIN 4109 "Sound insulation in Buildings"[3].

Besides the predicted value itself, its uncertainty plays a major role in the planning of a building. If the uncertainty is known, the planner can include a tolerance range and, thus, a statistical confidence level to meet a legal or otherwise agreed requirement. Within the current revision of DIN 4109, a transparent consideration of uncertainties is aimed at for the first time in building acoustics. This includes the entire chain of effects, from measurements in laboratories via product scatter, to the prediction and the verification by measurement in the erected building. Only this shows who contributes which uncertainties and how they are reflected in such an erected building.

After comprehensive investigations of the single uncertainty contributions, it was still open as to how these uncertainties affect the uncertainty of the predicted value. This is the topic of the investigation introduced here.

The aim is to demonstrate that an uncertainty calculation is possible. The investigation is, therefore, carried out for only one simple case, the airborne sound insulation between two adjoining rooms. This situation is treated according to the simple method in line with EN 12354-1 [2].

Uncertainty Determination

Solid Buildings

In general, the apparent sound reduction index R'_{w} is calculated from the input quantities X_i by a functional relationship f

$$R'_{\mathrm{w}} = f(X_i)\ . \qquad (1)$$

The input quantities are geometric or acoustic parameters according to EN 12354-1 [2]. Only the acoustic quantities and their uncertainties will be considered, since the uncertainty contribution from all the geometric quantities can be neglected. The input quantities for the situation in Figure 1 are, therefore, the:

- sound reduction index of the separating element $R_{\mathrm{S,w}}$
- sound reduction indices of the four flanking elements $R_{\mathrm{F,w}}$ in the sending room (Room 1)
- sound reduction indices of the 4 flanking elements $R_{\mathrm{f,w}}$ in the receiving room (Room 2),
- vibration reduction indices of 12 junctions K_{ij} and
- improvements of altogether 10 possible linings $\Delta R_{\mathrm{i,w}}$.

Depending on the number of linings, this leads to 21-31 acoustic input quantities. All these quantities are then summarised to 13 paths for the airborne sound transmission from Room 1 to Room 2.

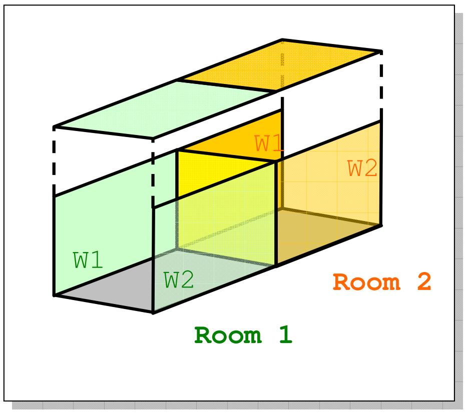

Figure 1 Investigated building situation consisting of two adjoining rooms

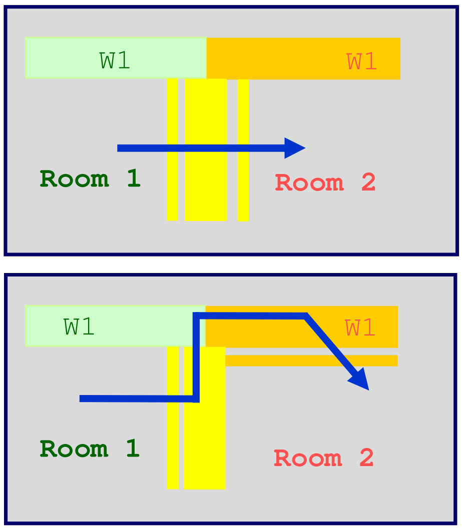

Figure 2 Two examples of the sound transmission from Room 1 to Room 2,

It is now important to note that all the acoustic input quantities except the vibration reduction indices K_{ij} contribute to more than one of the 13 transmission paths. For example, the sound reduction index of the separating element $R_{\mathrm{S,w}}$ contributes to both paths in Figure 2. Therefore, the sound transmission of the 13 paths is not independent of each other.

The determination of the combined uncertainty of the apparent sound reduction index thus requires the use of the 21 to 31 acoustic input quantities [4] which are assumed to be independent of each other:

$$u(R'_{\mathrm{w}}) = \sqrt{\sum_{i=1}^{31}\left[\frac{\partial R'_{\mathrm{w}}}{\partial X_i}\, u(X_i)\right]^2 + u_{\mathrm{prog}}^2} \; . \qquad (2)$$

Here, an additional uncertainty contribution for the prediction method is included. This contribution is estimated from comparisons between measured and predicted sound insulations in dwellings ([5])

$$u_{\mathrm{prog}} \approx 0.8 \text{ dB} \, . \qquad (3)$$

The partial derivations in eq. (2) are the sensitivity coefficients. They can be expressed in analytic equations, e.g. for the separating element

$$\frac{\partial R'_{\mathrm{w}}}{\partial R_{\mathrm{s,w}}} = \frac{10^{-R_{\mathrm{Dd,w}}/10} + \frac{1}{2}\sum_{i=1}^{4} 10^{-R_{i\mathrm{d,w}}/10} + \frac{1}{2}\sum_{i=1}^{4} 10^{-R_{\mathrm{D}i,w}/10}}{\sum_{j=1}^{13} 10^{-R_{\mathrm{j,w}}/10}} \qquad (4)$$

where $R_{\mathrm{Dd,W}}$ is the weighted sound reduction index of the direct path, $R_{\mathrm{id,W}}$ are the weighted sound reduction indices of the flanking paths Fd, $R_{\mathrm{Di,W}}$ are the weighted sound reduction indices of the flanking paths Df and the $R_{j,\mathrm{W}}$ are the weighted sound reduction indices of all 13 paths. The sensitivity coefficients for the other input quantities are less complicated.

An adequate choice of the input uncertainties is crucial for the combined uncertainty of the apparent sound reduction index. The input uncertainties are determined from the superposition of the standard deviation of reproducibility of 1.2 dB for the weighted sound reduction index [7], the standard deviation for the product scatter of 1.0 dB and an additional uncertainty for the difference between the laboratory and the in-situ situation of 0.8 dB

$$u(R_{\mathrm{ii,w}}) = \sqrt{1.2^2 + 1.0^2 + 1.0^2 + 0.8^2} \text{ dB} \approx 2.0 \text{ dB} \, . \qquad (5)$$

The product scatter has to be included twice, once for the measurement in the laboratory and once for the choice of the individual specimen in-situ. The value for the product scatter is estimated. It may be considerably larger for certain building products. The value of 0.8 dB for the difference between the laboratory and the in-situ situation is derived from extensive model measurements [8].

There is not much knowledge available on the uncertainty of the vibration reduction index and on the insulation improvement by linings. The input uncertainties are estimated to be 2.0 dB.

$$u(K_{\mathrm{ij,w}}) = u(\Delta R_{\mathrm{w}}) \approx 2.0 \text{ dB} \, . \qquad (6)$$

Light-weight Constructions

The calculation of the apparent sound reduction index for light-weight constructions is different. According to the findings of [6], only the direct path and the Ff-paths have to be considered (Figure 3) because the exchange of vibratory energy between the separating element and the flanking elements can be neglected.

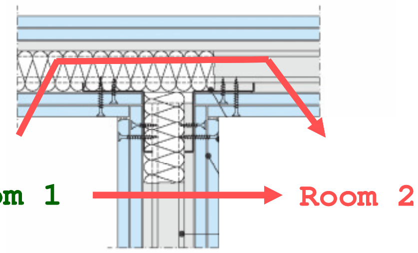

Figure 3 Sound transmission for light-weight constructions

Hence, the apparent sound reduction is calculated by

$$R'_{\mathrm{w}} = -10\lg\left[\sum_{i=1}^{5} 10^{-R_{i,\mathrm{w}}/10}\right] \text{dB} \, . \qquad (7)$$

The uncertainty is determined by eq. (2) with only 5 influencing acoustic quantities. The input uncertainty of the weighted sound reduction index of the direct path and the uncertainty of the prediction method itself are assumed to be equal to the case of solid buildings (eqs. (3), (5)). The input uncertainty for the flanking transmission is estimated from the uncertainty of the sound reduction index in the sending and receiving rooms $R_{\mathrm{F,W}}$ and $R_{\mathrm{f,W}}$ as well as from the uncertainty of the vibration reduction index K_{Ff}

$$u(R_{\mathrm{Ff,w}}) = \sqrt{\frac{1}{4}\left[\underbrace{u^2(R_{\mathrm{F,w}})}_{\approx(2\text{ dB})^2} + \underbrace{u^2(R_{\mathrm{f,w}})}_{\approx(2\text{ dB})^2}\right] + \underbrace{u^2(K_{\mathrm{Ff}})}_{\approx(2.5\text{ dB})^2}} \approx 3 \text{ dB} \, . \qquad (8)$$

Implementation into an Excel Sheet

All the equations for the case of solid buildings were implemented into an Excel sheet. The input quantities are the basic geometric parameters, the acoustic quantities and the uncertainties for all the acoustic quantities. A special input enables the use of the same sheet for light-weight constructions:

$$K_{\mathrm{Ff,w}} = R_{\mathrm{Ff,w}} \; ; \qquad u(K_{\mathrm{Ff,w}}) = u(R_{\mathrm{Ff,w}}) \qquad (9)$$

$$K_{\mathrm{Fd,w}} = K_{\mathrm{Df,w}} = 100 \text{ dB} \; ; \qquad u(K_{\mathrm{Fd,w}}) = u(K_{\mathrm{Df,w}}) = 0 \text{ dB} \qquad (10)$$

$$R_{\mathrm{F,w}} = R_{\mathrm{f,w}} = 0 \text{ dB} \; ; \qquad u(R_{\mathrm{F,w}}) = u(R_{\mathrm{f,w}}) = 0 \text{ dB} \, . \qquad (11)$$

The sheet is available for public use at the PTB homepage www.ptb.de/en12354.

Verification of the Prediction Results

The prediction results of the newly developed Excel sheet were compared to other independent prediction results to ensure the correct implementation. For the solid buildings, a data set consisting of 24 real building situations was available at PTB. All the cases were well documented and could thus be recalculated. Furthermore, the examples from [2], p. 51 were also used. The new prediction results comply well with the old ones (Figure 4). The largest deviation is 0.6 dB, the mean deviation 0.05 dB and the standard deviation 0.26 dB.

Another data set was used for the verification of the predictions for the light-weight constructions. It also consists of 24 well-documented building situations and comes from a joint research project [6]. The new results comply very well with the old ones (Figure 4). All deviations are smaller than 0.2 dB.

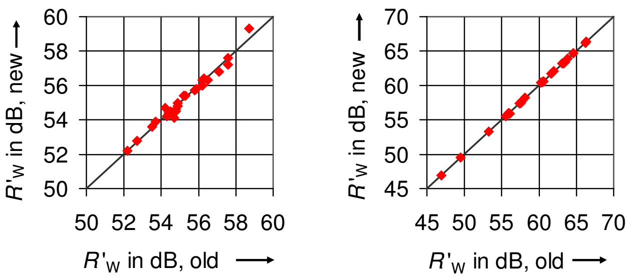

Figure 4 Comparison of the prediction results from the new Excel sheet and other predictions, left: solid buildings, right: light-weight constructions

Calculated Uncertainties

The uncertainty of the apparent sound reduction index was calculated using eqs. (1) - (11). An application to the 24 solid buildings from the internal data base yields uncertainties between 1.4 and 2.1 dB (Figure 5).

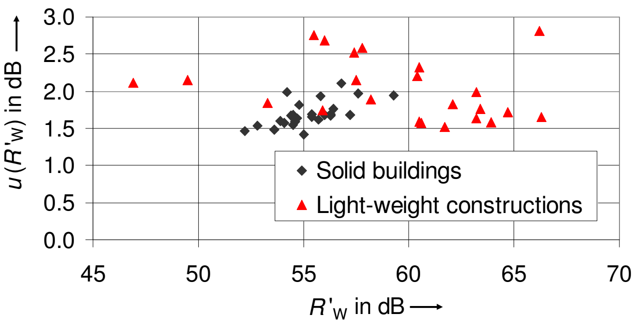

Figure 5 Calculated uncertainties for solid buildings and light-weight constructions

The spread of the uncertainties is much larger for the data base containing the light-weight constructions. Uncertainties assume values between 1.5 and 2.7 dB. Thus, they are to some extent larger than for the solid buildings. The reason is the number of uncorrelated input quantities. This number is 21 – 31 for the solid buildings and only five for the light-weight constructions. The apparent sound reduction index as a weighted average has a smaller uncertainty, the more quantities contribute to the sound transmission from Room 1 to Room 2.

Comparison to Measurement Results

A further advantage of using available results is that prediction and measurement results can be compared to each other, including the uncertainties. The in-situ standard deviation of the apparent weighted sound reduction index of 0.8 dB [7] is used as the measurement uncertainty.

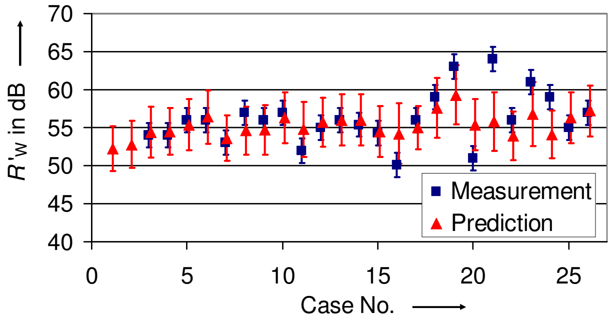

Figure 6 Measured and predicted airborne sound insulations for solid buildings including 95% confidence intervals

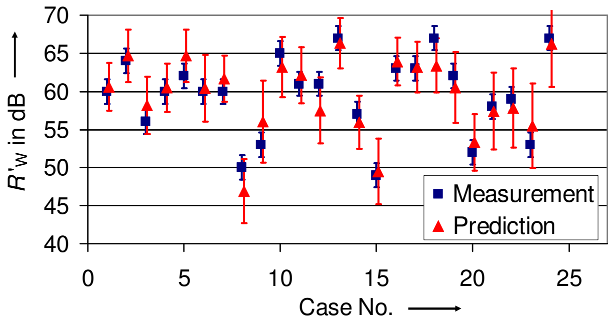

Figure 7 Measured and predicted airborne sound insulations for light-weight constructions including 95% confidence intervals

In general, a good agreement between measurement and prediction results is observed for the solid buildings (Figure 6). Cases one and two are the examples from [2], p. 51. For this reason there are no measurement results for these cases. Out of 24 cases, 14 show a complete coverage of both confidence intervals. A satisfying coverage of between 50 and 100% is observed in six more cases. A disagreement between measurement and prediction occurs only in two cases.

The comparison between prediction and measurement yields even better results for the light-weight constructions (Figure 7). 18 cases show a full coverage and five cases a coverage between 50 and 100%. There is only one case with a smaller coverage and there is no case with a clear disagreement between measurement and prediction.

These results demonstrate that the input uncertainties and all the further assumptions are realistic for both construction methods.

Variation of Parameters

In addition, the Excel sheet gives one the opportunity to investigate how a variation of the input uncertainties affects the combined uncertainty of the apparent weighted sound reduction index. This parameter variation was applied to the reference case of [2], p. 51.

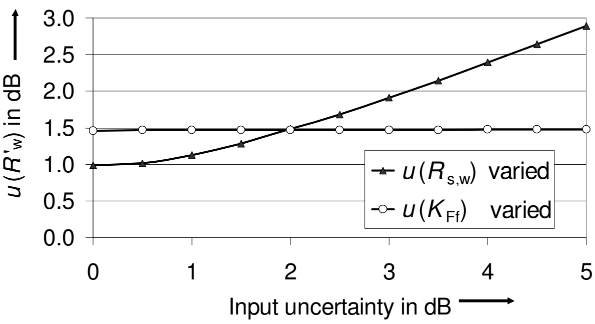

Figure 8 Uncertainty of the apparent sound reduction index R'_W under variation of the uncertainty of $R_{S,W}$ and K_{Ff}

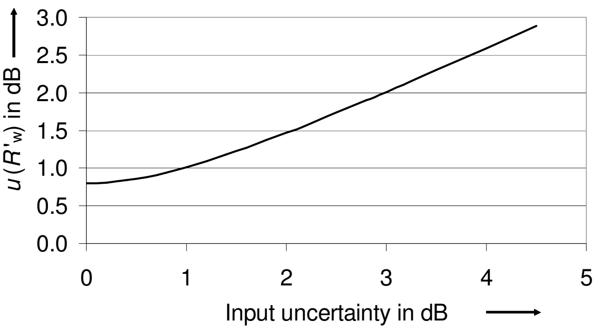

Figure 9 Uncertainty of the apparent sound reduction index R'_W under variation of the uncertainty of all input quantities

If only the uncertainty of the sound reduction index of the separating element $R_{S,W}$ is increased from 0 to 5 dB, the combined uncertainty of R'_W increases from about 1 to 2.8 dB (Figure 8). Merely part of the input uncertainty appears in the combined uncertainty due to the weighted averaging of different contributions. The considered case is much less sensitive to a variation of the uncertainty of one of the vibration reduction indices K_{Ff} (Figure 8). Obviously, the corresponding path does not contribute to the sound transmission and, thus, the uncertainty of K_{Ff} has no influence on the combined uncertainty of R'_W.

A further test was carried out under the assumption that all uncertainties of the acoustic input quantities are equal. This common input uncertainty was varied between 0 and 4.5 dB for the example of [2], p. 51. This variation leads to an increase of the combined uncertainty of R'_W from 0.8 dB to 2.8 dB (Figure 9). The lower limit is, in this case, given by the uncertainty of the method of 0.8 dB (see eqs. (2) and (3)). Again, only a fraction of the input uncertainty is observed in the combined uncertainty of R'_W. It must be accentuated that these findings are related to the building situation investigated. The combined uncertainty of R'_W may exhibit a completely different behaviour for other situations.

Summary

An Excel spreadsheet has been developed for the calculation of the uncertainty of the predicted airborne sound insulation. It was verified for solid and light-weight constructions. The uncertainties of the predicted values assume reasonable values between 1.5 and 2.7 dB for the 50 considered cases. Deviations between measurements and predictions can be well explained by including the uncertainties. This indicates that the uncertainty of the prediction method of 0.8 dB is adequate. The spreadsheet allows for a parameter variation showing which of the input uncertainties are critical with respect to the uncertainty of the prediction result. The Excel spreadsheet can be obtained at www.ptb.de/en12354.

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References

[1] The Council Directive 89/106/EEC of 21 December 1988 on the approximation of laws, regulations and administrative provisions of the Member States relating to construction products.

[2] EN 12354-1:2000 *Building acoustics. Estimation of acoustic performance in buildings from the performance of elements. Airborne sound insulation between rooms.*

[3] DIN 4109: *Schallschutz im Hochbau, Anforderungen und Nachweise*, November 1989, in German

[4] *Guide to the expression of uncertainties in measurement.* First edition, 1993, corrected and reprinted 1995, International Organization for Standardization (Geneva, Switzerland)

[5] Heinrich A. Metzen: *Berechnungsmodelle & Berechnungsansätze für den Holzbau* in: Werner Scholl, Heinrich Bietz: *Integration des Holz- und Skelettbaus in die neue DIN 4109*. PTB-Report, Braunschweig, 2004, in German

[6] Schumacher, R.; Saß, B.; Pütz, M.: *Grundlagenuntersuchungen zum Stoßstellendämm-Maß im Holzbau*. ift-Report, Rosenheim, 2001, in German

[7] Wittstock, V.: *On the calculation of the uncertainty of single number ratings in bulding acoustics.*. Proceedings of ICA 07, Madrid, 3. – 7. September 2007

[8] V. Wittstock, M. Schmelzer and C. Kling: *On the use of scaled models in building acoustics*. Proceedings of Acoustics ’08, 29.06. – 04.07.2008, Paris