MEASUREMENT UNCERTAINTY IN SOUND INSULATION TESTING: COMPARISON OF FIELD TEST DATA FOR SEPARATING FLOORS

W. A. Whitfield

Noise.co.uk Ltd, Bretford, Warwickshire, England: email: bill@noise.co.uk

B. M. Gibbs

Acoustic Research Unit, University of Liverpool, England: email: bmg@liverpool.ac.uk

In The assessment, quantification and understanding of measurement uncertainty over the third octave band frequency range 100-3150Hz and for single number quantities is now part of UKAS laboratory requirements under ISO17025. It is also desirable to monitor if these uncertainties change or vary over time or by virtue of the components involved in the measurement process. This study introduces the methods that can determine this and defines the basic terminology that should be applied and provides a comparison of results using a separating floor construction as an example. A suggested method is suggested of how uncertainty can be managed over time and some examples are given of the value in making periodic measurement uncertainty investigations using floor tests as a comparison.
Keywords: sound insulation, uncertainty, round robin tests, analysis of variance, gauge R&R

1. Introduction

Measurement uncertainty relating to sound insulation testing in the field is now covered in the International Standard BS EN ISO12999: 2014 [1]. This follows BS5725-2 [2] procedures and is helpful but it does not exonerate the testing organisation from undertaking their own assessments in order to identify the components of variance associated with their measurement process and test equipment. Indeed, part of the UKAS accreditation process in the UK is that cross check sampling should be undertaken periodically to ensure that the testing laboratory keeps abreast of their ongoing uncertainty of measurement and if it identifies change over time to investigate what may of caused it in order to continually review and improve their measurement systems and protocols.

The testing process is onerous because for sound insulation measurement the data collection process is labour intensive and time consuming so it is essential that measurement uncertainty experiments obtain the maximum amount of information from any test or design of experimental scenario and, where possible can be combined for a global view of uncertainty.

In this paper we review how this cross check process for measurement uncertainty can be managed and list some examples of the value in making periodic measurement uncertainty investigations using floor tests as a comparison.

2. Methods of calculating uncertainty

Previous work by Whitfield and Gibbs [3] has demonstrated the shortcomings of the limited approach taken by BS5725 for field testing and Wittstock [4, 5] has highlighted the problems of using GUM [6] for assessing the uncertainties in the measurement of sound insulation. There is significant value of adopting a more sophisticated analysis technique and making slight modifications to the design of experiment (DOE) associated with BS5725 type round robin tests (RRT). The method is called a Gauge Repeatability and reproducibility study (GRR) and uses an advanced analysis of variance (ANOVA) model to produce the comparisons between factors and draw out the individual contributions from the components of variance without adding to the sampling burden on site.

2.1 GRR DOE

The Gauge R&R study (GRR) applies analysis of variance techniques (ANOVA) to a design of experiment that is described as a balanced two-factor crossed random model with interaction. That is, every level of one factor is run with every level of another factor (crossed) and each measurement is repeated the same number of times (balanced), e.g. every part in the test sample is measured by every operator the same number of times. This DOE is used to draw out the 'factors' influence on the measured results. Like a RRT it attempts to assess the same uncertainty due to repeatability and reproducibility but the experimental design also allows the user to draw out the contributions of components of variance due to the instrument, operator and part being measured as well as any interaction that may have occurred in the experiment between the operator and the part. As more than one part is measured it is particularly suited to the field measurement of sound insulation, indeed if the parts selected for measurement are identical in construction as well as the shape and size of the room, the measurement uncertainty of the construction itself can be determined and there is evidence to suggest that this may have its own uncertainty signature particular to the construction [3].

For our experiment, we can model the measurement X by operator *i* on part *j* at replication *k* by:

(1) $X_{ijk} = \mu + O_i + P_j + (OP)_{ij} + R_{k(ij)} \quad \begin{cases} i = 1,...,5 \\ j = 1,...,6 \\ k = 1,2 \end{cases}$, where O_i, P_j, $(OP)_{ij}$ and $R_{k(ij)}$ are random variables corresponding to the operator, the part, the operator by part interaction, and the measurement replications. We assume these variables are independent of each other, and normally distributed with mean 0 and constant variances σ^2_O, σ^2_P, σ^2_{OP} and σ^2_R respectively. μ refers to the overall mean of all the observations X_{ijk} .

The definition of reproducibility in the GRR is covered in Burdick et al [7, 8] and is shown in equation (2): it should be noted that unlike the definition in BS5725-2 it does not contain the repeatability component rather it describes the variance of the 'operator' (test engineer) and any interaction he may have with the parts (or in our case floors) they may measure. The combined Gauge variance components which represent the whole measurement system are shown in equation (3) and the total variance shown in equation (4) and incorporates the variance due to the performance of the part being measured (Floor). Obviously if significantly different floor constructions are contained within the test sample the variance they contribute will be large in comparison to the measurement system. If the surfaces being tested are identical and the room dimensions match for each test the variance of the part will describe the construction variability and this is a elegant way of assessing the performance of the floor due to construction alone. Craik et al [9, 10] referred to this variability as 'Workmanship' i.e. the floors are identical in construction and room size so the only difference affecting the floor performance would be due to the way they are assembled.

(2) $$\sigma^2_{reproducibility} = \sigma^2_O + \sigma^2_{PO}$$

(3) $$\sigma^2_{gauge} = \sigma^2_{repeatability} + \sigma^2_{Reproducibility}$$

(4) $$\sigma^2_{total} = \sigma^2_{gauge} + \sigma^2_{part}$$

A GRR DOE with 6 parts 5 operators and two repetitions the analysis of variance table would be as follows:

Table 2-1: Testing Schedule - Lightweight Timber Floor

Source of variation	Degrees of freedom	Mean Square Error	Expected mean square error
Parts (P)	5	S^2_P	$10\sigma^2_P+2\sigma^2_{OP}+\sigma^2_R$
Operators (O)	4	S^2_O	$12\sigma^2_O+2\sigma^2_{OP}+\sigma^2_R$
Interaction (OP)	20	S^2_{OP}	$2\sigma^2_{OP}+\sigma^2_R$
Replicates (R)	30	S^2_R	σ^2_R

3. GRR Experiments

In this paper we will be using three GRR experiments one for Timber floors carried out in 2007, a GRR experiment for concrete floors and one carried out to determine the linearity of the test system with 4 different performing test elements carried out in 2008. This will demonstrate that the individual GRR DOE can provide specific information on the element being measured as well as identifying the measurement uncertainty of the test system over time. The experimental DOE of each is detailed below.

Table 3-1: Testing Schedule - Lightweight Timber Floor

Test Site: Timber Floor	Separating Element Floor: Timber	Floor Type : E-FT-3
Operators	Parts	Repetitions
5	6	3

Table 3-2: Testing Schedule - Heavyweight Concrete Floor Tests

Test Site: Concrete Floor	Separating Element Floor: Concrete	Floor Type : E-FC-4
Operators	Parts	Repetitions
5	6	3

Table 3-3: Testing Schedule - Linear Tests – Concrete Floor Site

Test Site: Concrete Floor	Separating Element: Various	Additional Testing - Linear
Operators	Parts	Repetitions
5	4	3

3.1 Timber Floor GRR

The components of variance for the timber floor GRR for the single figure value ($D_{nT,w}$ + C_{tr}) are detailed in the Table below:

Table 3-4: Timber Lightweight Floor - Major Components of Variance ($D_{nT,w}$ +C_{tr})

dB (σ^2)	σ_{GRR2}	σ_r^2	σ_R^2	σ_o^2	$\sigma_{p.o}^2$	σ_p^2	σ_{Total}^2
$D_{nT,w}$ + C_{tr}	5.870	1.440	4.430	4.430	0.000	0.240	6.110
dB (σ)	σ_{GRR}	σ_r	σ_R	σ_o	$\sigma_{p.o}$	σ_p	σ_{Total}
$D_{nT,w}$ + C_{tr}	2.420	1.200	2.110	2.110	0.000	0.490	2.470

where:
σ_r^2 = Repeatability (instrument Variance)
σ_R^2 = Reproducibility (Operator Variance)
σ_p^2 = Part to part variance
$\sigma_{p.o}^2$ = Operator by part variance
σ_{GRR}^2 = total gauge variance = $\sigma_r^2+\sigma_R^2+\sigma_{p.o}^2$ see section 8.7.2 of [11]
(NB: in timber case $\sigma_{p.o}^2$ = 0 for single figure values)

The measurement due to the defined factors for the timber GRR are as follows:

Table 3-5: measurement s.d. due to defined factors - ordered by magnitude

Measurand		$D_{nT,w}$	$D_{nT,w} + C_{tr}$
Order	Factor	dB	dB
1	Operator σ_o	0.7dB	2.1dB
2	Instrument σ_r	0.6dB	1.2dB
3	Part σ_p	0.6dB	0.5dB

Ideally the part measured would contribute the most and the operator and instrument contributions would be low. This can be represented graphically across the frequency spectrum::

3.2 Concrete Floor GRR

The components of variance for the concrete floor GRR for the single figure value ($D_{nT,w} + C_{tr}$) are detailed in the Table below:

Table 3-6: Concrete Heavyweight Floor - Major Components of Variance ($D_{nT,w}$ + Ctr)

dB (σ^2)	σ_{GRR}^2	σ_r^2	σ_R^2	σ_o^2	$\sigma_{p.o}^2$	σ_p^2	σ_{Total}^2
$D_{nT,w} + C_{tr}$	1.791	0.800	0.991	0.573	0.417	0.829	2.620
dB (σ)	σ_{GRR}	σ_r	σ_R	σ_o	$\sigma_{p.o}$	σ_p	σ_{Total}
$D_{nT,w} + C_{tr}$	1.340	0.890	1.000	0.760	0.650	0.910	1.620

The concrete $D_{nT,w} + C_{tr}$ results show that the components of variability are relatively low within 1dB standard deviation. The instrumentation (representing "repeatability" $\boldsymbol{\sigma_r}$) has a standard deviation of 0.89dB; the operator (represented by $\boldsymbol{\sigma_o}$) has a standard deviation of 0.76dB. The standard deviation of the operator in this case is different from the reproducibility σ_R as the interaction term ($\boldsymbol{\sigma_{p.o}}$) is 0.65dB.The measurement due to the defined factors for the concrete GRR are as follows:

Table 3-7: Concrete Floor - measurement variability due to defined factors - ordered by magnitude

Measurand		$D_{nT,w}$	$D_{nT,w}$ + Ctr
Order	Factor	dB	dB
1	Part σ_p	1.8dB	0.9dB
2	Instrument σ_r	0.7dB	0.9dB
3	Operator σ_o	0.5dB	0.8dB

In the concrete floor GRR, the part has the highest standard deviation, then the instrument and the operator, though the data tell us that the parts influence is proportionally greater in the $D_{nT,w}$ case (1.84dB) compared with repeatability and operator components than in the $D_{nT,w}$ + Ctr case where they are almost equal in size. The order is the reverse of the timber floor GRR. It is noted that the concrete floor GRR had non-identical test rooms which varied in size and volume (unlike the timber floor GRR where they were similar), the small changes in size and volume of the source and receiver rooms is likely to be the cause of this difference. The operator and instrument have very similar standard deviations for $D_{nT,w}$ + C_{tr} which, when rounded to 1 decimal place to reflect the instrument measurement resolution, are 0.8dB and 0.9dB respectively.

3.3 Linear GRR

The three individual GRR experiments can be combined to make one large test sample and the results for this combined GRR for the single figure value ($D_{nT,w}$ + C_{tr}) are detailed in the Table below:

Table 3-8: Linear GRR - Major Components of Variance ($D_{nT,w}$ + Ctr)

σ^2	σ_{GRR}^2	σ_r^2	σ_R^2	σ_o^2	$\sigma_{p.o}^2$	σ_p^2	σ_{Total}^2
dB DnTw+Ctr	1.07	0.53	0.54	0.00	0.54	137.76	138.83
σ	σ_{GRR}	σ_r	σ_R	σ_o	$\sigma_{p.o}$	σ_p	σ_{Total}
dB DnTw+Ctr	1.03	0.73	0.73	0.00	0.73	11.74	11.78

For $D_{nT,w}$ + C_{tr}, the results for the Linear GRR show the instrumentation (representing "repeatability" σ_E^2) is responsible for 0.53dB of the total variance of the results, this components value was 1.4dB for timber and 0.8dB for concrete. The reproducibility variance (σ_R^2) is 0.53dB; this is a combination of 0.0dB from the operator i.e. no significant uncertainty due to the operator (represented by σ_O^2) and 0.54dB from the operator by part interaction term σ_{po}^2. The reproducibility variances were 4.4dB for timber with no interaction and 1.0dB for the concrete GRR with 0.4dB interaction and 0.6dB due to the operator.

In the Linear GRR, the part has the highest standard deviation which is to be expected because the sample was chosen to test the linearity of the instrumentation. In this case the performance of the surfaces differed by over 10dB for the single figure value.

3.3.1 Three GRR

The three GRR experiments on their own provide a valuable insight into the measurement uncertainty due to the instrumentation and the operator. They also explain the variability due to the part which in the special case of the Timber Floor also describes the variability due to the construction itself as the room effect is 'blocked' by choosing identical test samples. This is the 'workmanship' component identified by Craik et al and it is theoretically proposed by Whitfield and Gibbs [3] that the measurement uncertainty due to the part has a signature that can be attributable to the part. The data from all three experiments is valuable and one of the benefits of the GRR DOE is that it is possible to combine results if the parameters of the study remain the same i.e. number of operators and repetitions. The combined GRR is detailed below.

3.4 Linear Combined GRR

The three individual GRR experiments, timber, concrete and linear can be combined to make one large test sample Linear (Combined) GRR and the results for this combined GRR for the single figure value ($D_{nT,w}$ + C_{tr}) are detailed in the Table below:

Table 3-9: Linear Combined GRR - Major Components of Variance ($D_{nT,w}$ + Ctr)

dB (σ^2)	σ_{GRR}^2	σ_r^2	σ_R^2	σ_o^2	$\sigma_{p.o}^2$	σ_p^2	σ_{Total}^2
$D_{nT,w}$ + Ctr	3.1	1.0	2.2	0.9	1.3	43.0	46.1
dB (σ)	σ_{GRR}	σ_r	σ_R	σ_o	$\sigma_{p.o}$	σ_p	σ_{Total}
$D_{nT,w}$ + Ctr	1.8	1.0	1.5	0.9	1.1	6.6	6.8

For DnT,w + Ctr, the results for the Linear Combined GRR show the instrumentation (representing "repeatability" σ_E^2) is responsible for 1.0dB of the total variance of the results, this components value was 1.4dB for timber and 0.8dB for concrete, indicating the value aggregates across the larger test sample. The reproducibility variance (σ_R^2) is 2.2dB; this is a combination of 0.9dB from the operator (represented by σ_O^2) and 1.3dB from the operator by part interaction term σ_{po}^2. The reproducibility variances were 4.4dB for timber with no interaction and 1.0dB for the concrete GRR with 0.4dB interaction and 0.6dB due to the operator. Again the larger sample aggregates the components of variance terms.

4. Comparison

4.1.1 Timber GRR v Concrete GRR v Linear(Combined) GRR

The linear (combined) GRR individual repeatability, reproducibility and operator terms can be plotted on a graph with the timber and concrete GRR results to illustrate the effect of a combined GRR with extended range on the components of variance derived using ANOVA. The contribution of the measurement system repeatability and reproducibility is detailed in Figure 4-1 & Figure 4-2. The reproducibility is further sub-divided to show the operator contribution and the operator by part interaction in Figure 4-3 & Figure 4-4.

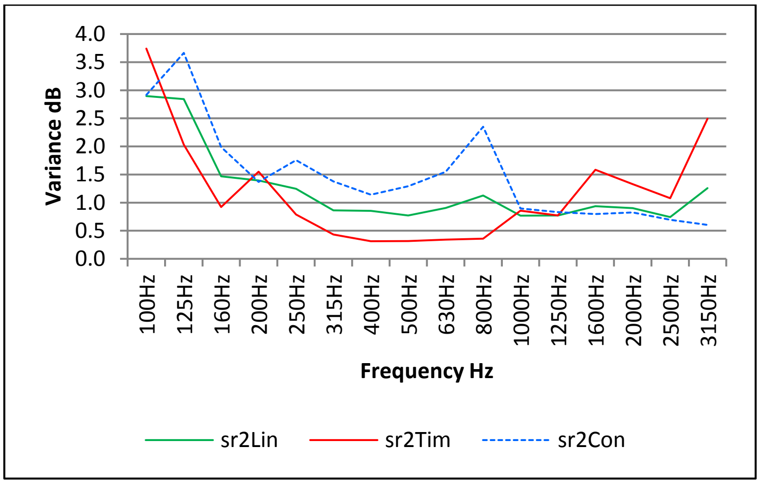

Figure 4-1: Repeatability Variance σ^2_r: Timber/Concrete/Linear(Combined) GRR

The repeatability and reproducibility variance levels across the frequency range show how measurement system analysis is dependent on the construction being measured and to some extent the conditions on site.

The repeatability variance component associated with the instrumentation was generally lower for the timber GRR than it was for the concrete GRR. The low frequency range for both timber and concrete GRR <250Hz is influenced by room effects, i.e. by a non diffuse field.

The timber GRR was affected by background noise at high frequency as represented in the repeatability component of variance from 1250-3150Hz. For the concrete GRR there is some background noise effect which occurs in the mid range frequencies. This is the reason the GRR shows higher repeatability variance than the timber GRR, between 125 – 800Hz. For 1000Hz – 1250Hz repeatability is similar for both timber and concrete floors. The timber GRR is affected more and has higher repeatability in the range 1600Hz – 3150Hz.

The pooled repeatability, which incorporates the data from the timber and concrete GRR, plus four new test elements, displays a trend between the two larger GRR studies.

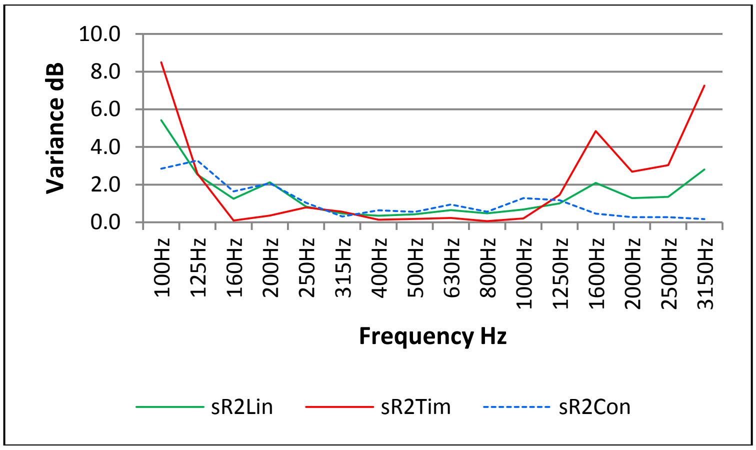

Figure 4-2: Reproducibility Variance σ^2_R: Timber/Concrete/Linear GRR

The reproducibility variances are also affected, below 250Hz, by the low modal density in the room and non diffuse field and in the timber GRR by the background noise correction term at the higher frequency bands 1250Hz – 3150Hz. The reproducibility derived from the combined data in the linear GRR ranges in between the variances of the two larger GRR studies though this does not necessarily mean that it will always take a middle route in all components of variance. The reproducibility component can be sub-divided into two further components for the operator and the operator by part interaction. These help describe where the variability associated with the reproducibility originates and also informs where the independence of these factors are compromised. They are detailed in Figure 4-3 & Figure 4-4.

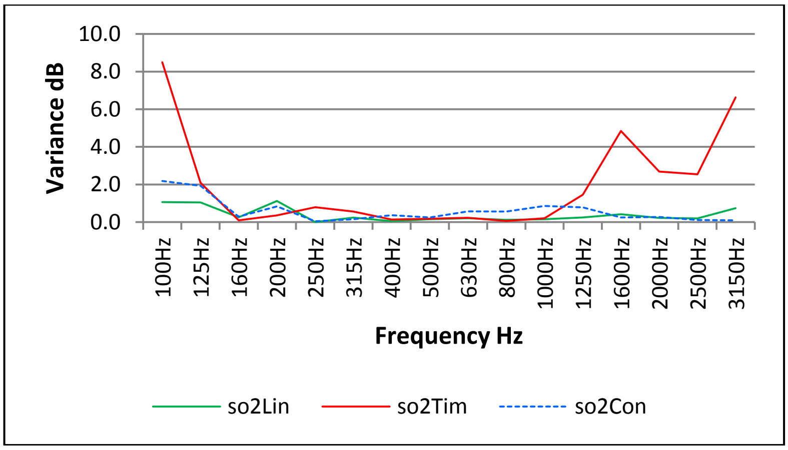

Figure 4-3: Operator Variance σ^2_o: Timber/Concrete/Linear GRR

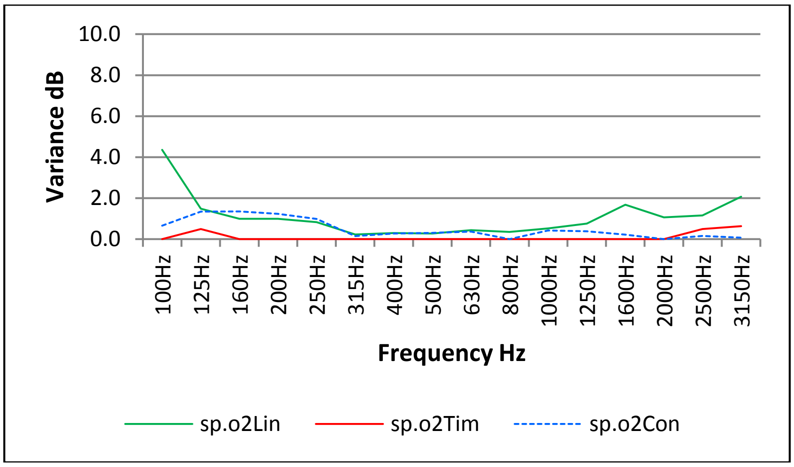

Figure 4-4: Interaction Variance $\sigma^2_{p.o}$: Timber/Concrete/Linear GRR

The timber reproducibility variance is calculated from a reduced model (without interaction) apart from 125Hz, 2500Hz & 3150Hz. It is therefore represented by the operator variance for the majority of the frequency range.

For the concrete GRR, interaction between part and operator is significant across most frequencies and it is the dominant factor in the reproducibility variance at the 125Hz – 250Hz bands.

The linear (Combined) GRR operator variance is lower than both the timber and concrete GRRs at 100Hz, see Figure 4-3. This is enhanced by an interaction term that is higher than the timber and concrete GRRs, the result is that the reproducibility variance for the Linear GRR 100Hz band is between the timber and concrete GRR values. A similar situation also occurs at the 1000Hz – 3150Hz frequency bands, where there is significant interaction identified between the part and the operator for the Linear GRR (0.5 – 2.1dB) though the operator variance at these frequencies is relatively low (0.2 – 0.74dB).

5. Conclusion

This paper has discussed a method that, without additional survey effort, can determine the uncertainty via the components of variance associated by the instrument (gauge), the operator and the part and can also identify if, during the survey process there was any interaction between the operator by part that could influence the results. This information is not available if the BS5725 DOE is followed.

In addition if the test elements are selected carefully supplementary information can be obtained with respect to the performance of the construction itself i.e. the variability of the part due to workmanship or assembly. Also if the GRR DOE is consistent throughout the experiments over time the individual studies can be combined into one global experiment in order to provide a robust assessment of the measurement uncertainty of the instrument, operator and operator by part components of variance, no experimental effort is wasted. The individual GRR experiments can target components of variance that give specific interest (Types of construction) while the progressive sampling can provide a laboratory with a robust data base of uncertainty overall over time or for specific situations or separating element constructions. The research in this respect is continuing and will be published in due course.

REFERENCES

1 BSI, *BS EN ISO 12999-1:2014: Acoustics — Determination and application of measurement uncertainties in building acoustics* in *Part 1: Sound insulation (ISO 12999-1:2014)*. 2014.

2 *Accuracy (trueness and precision) of measurement methods and results - Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method.*, in *BS ISO 5725-2:1994* 1994.

3 Whitfield W.A, G.B.M., *MEASUREMENT UNCERTAINTY IN AIRBORNE SOUND INSULATION: UNCERTAINTY COMPONENTS IN FIELD MEASUREMENT.*, in *ICSV 22*. 2015: Florence.

4 Wittstock, V., *Uncertainties in building acoustics.* , in *Proceedings of Forum Acusticum*. 2005: Budapest.

5 Wittstock, V., *On the Uncertainty of Single-Number Quantities for Rating Airborne Sound Insulation.* ACTA ACUSTICA UNITED WITH ACUSTICA, 2007. **Vol. 93**: p. 375 - 386.

6 (JCGM), J.C.f.G.i.M., *Evaluation of measurement data - Guide to the expression of uncertainty in measurement,* in *JCGM 100: 2008 - GUM 1995 with minor corrections*. 2008.

7 Burdick, R.K., Borror,C.M, Montgomery,D.C., *Design & Analysis of Gauge R&R Studies.* 2005: SIAM.

8 Burdick, R.K., Borror,C.M, Montgomery,D.C., *A Review of Methods for Measurement Systems Capability Analysis.* Journal of Quality Technology, 2003. **35**(4): p. 342-354.

9 Craik, R.J.M. and D. Evans, *The Effect of Workmanship on Sound Transmission through Buildings - Part 2 - Airborne Sound.* Applied Acoustics, 1989. **27**: p. 137-145.

10 Craik, R.J.M. and J.A. Steel, *The Effect of Workmanship on Sound Transmission through Buildings - Part 1 - Airborne Sound* Applied Acoustics, 1989. **27**: p. 57-63.

11 Montgomery, D.C., *Statistical Quality Control: A Modern Introduction.* 6th ed. 2009: John Wiley & Sons.