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Can our standard digital tools predict the sound insulation in wooden buildings ? A systematic comparison with laboratory and field measurements on various floor constructions

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Within the research projects *AkuLite*, *Aku20* and the current *AkuTimber* at LTU, about 30 wooden buildings newly erected have been examined since 2010 by means of detailed field measurements of sound insulation and vibration transmission. In addition, questionnaire surveys have been made which gives us an opportunity to study new buildings with various types of structural design more in detail, where the residents are disturbed by poor sound insulation to some extent. The main focus in those research projects is to determine a new criterion for impact sound that takes very low frequencies (20-2500 Hz) into account. But the field results may also be used to look into another question: - When acoustic consultants apply the most commonly used calculation softwares as well as some own experience of building acoustics, how close to the real performance is reasonable to assume they will get, on the average? To find out, a selection of building cases examined in the research projects have been studied. 23 field measurements of D_{nT} and L_{nT} in buildings with cross laminated timber (CLT) floors taken from the project, 7 measurements on CLT-floors taken from other projects, as well as 17 measurements in concrete buildings have been compared to calculations made according to EN ISO 12354. Further comparisons were made between laboratory measurements of CLT bare floors were used to establish a draft for a database of CLT sound insulation data. This database was used in further comparisons to field measurements where a well defined raised floor had been applied. The results are presented as average (systematic) deviations and standard deviations in the comparisons. These values were also combined to indicate provisional safety margins for CLT and concrete buildings respectively. Some particular concerns that should be observed, e.g. on the apparent vibration reduction at the junctions between walls and floors, are discussed as well.

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1 Introduction

The acoustic performance of buildings with light weight timber floors have already been studied by many parties, e.g. recently by Homb[1] as well as within the joint European research project *Silent Timber Build*[2]. They conclude the theoretical SEA-models used in the *Silent Timber Build* project have severe limitations and they recommend measurements for further analyses of the constructions.

Within the previous research projects *AkuLite* and *Aku20* as well as the current *AkuTimber* at the Luleå university of Technology[3], about 30 wooden buildings built since 2010 have been examined by means of detailed field measurements of sound insulations and vibration transmissions.

Those field results gave this author the opportunity to look into a question of practical interest to acoustical consultants: - When we apply the most commonly used calculation softwares as well as our general experiences of building acoustics, how close to the real performance can we expect to come, on the average and with which uncertainty?

2 Method

In order to make the comparisons between theoretical calculations and field measurements, some of the building cases examined in the research projects *Aku20* and *AkuTimber* were selected.

- The first estimates of D_{nT} and L_{nT} were made from the drawings only, as a consultant would do during an ordinary project design work.
- The second estimates were supported by measurement results and vibration transmission measurements to refine the models of the junctions, as would be typical when the purpose is to understand measurement results and find out which part of a construction need to be improved in case the building regulations were not fulfilled.
- The calculated values in the figures below are from "the second estimate", i.e. some adjustments of input data have been made after comparisons with the measured values and the vibration levels.
- Input data for CLT floors were calculated on the basis of comparisons to laboratory results, clause 3.3.

The calculation tool used to combine elements, define junctions and calculate sound transmission in buildings according to the international standard EN ISO 12354 was Bastian® by Datakustik[4]. The analyses of floor and wall constructions, the software Insul v9.0.8 by Marshall-Day Acoustics was used. For analyses of buildings with concrete floors, the semi-empirical data for the elements in the SAU Nordic Database were applied[5].

3 Results

3.1 Buildings with various CLT floors, example results

Results from field measurements and theoretical calculations of the sound insulation through floors in living rooms of one example building (denominated as "B1") are presented in Figure 1, in the extended frequency range 20-5000 Hz.

This building is constructed with parquet flooring floating on a 246 mm massive CLT floor and a ceiling with two plasterboards attached to light weight joists that are disconnected from the CLT-floors. Walls are made with double plasterboards and a plywood board, attached on each side of two rows of wooden studs separated by a thin air gap.

Apparently, the calculated values of the airborne sound insulation (thick line) are somewhat on the safe side in the range 50-1000 Hz, but the impact sound insulation values on the other hand seem to be underestimated.

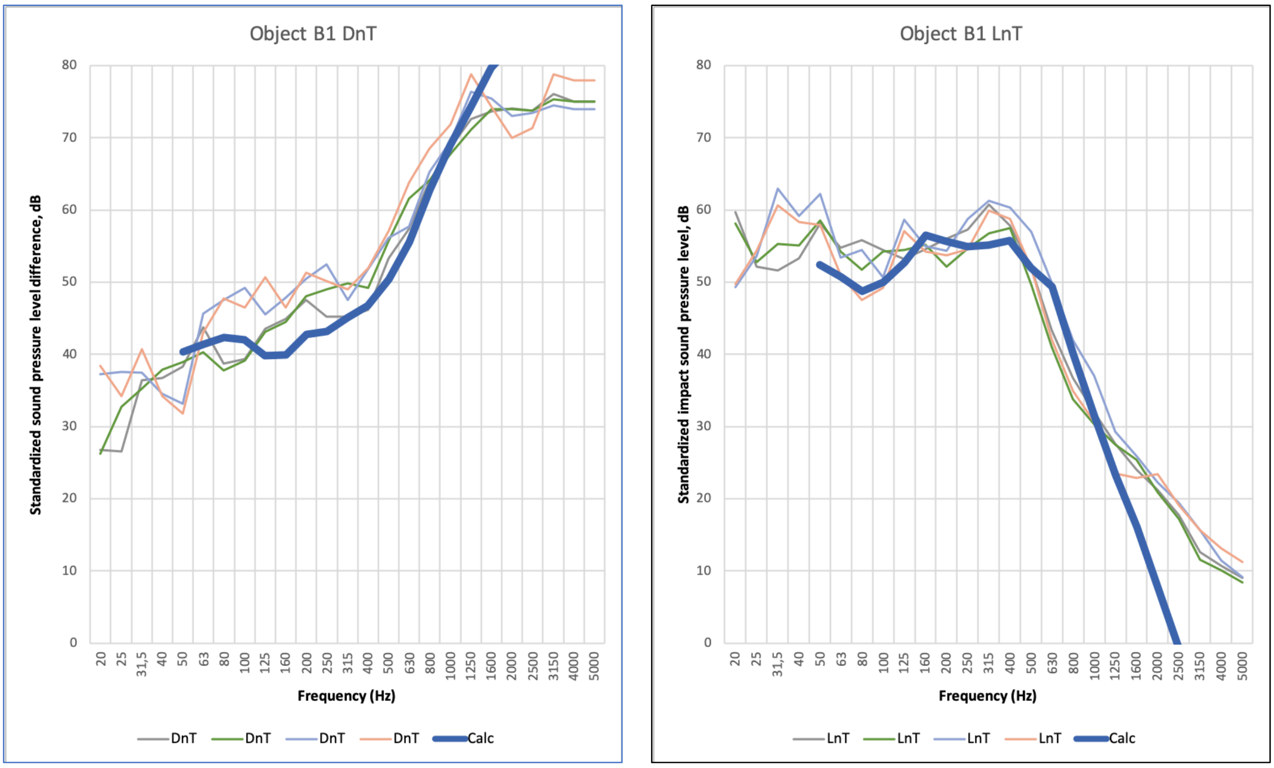

Figure 1: 4 measured and 1 calculated standardized airborne sound level difference and standardized impact sound level in object B1. Note: The frequency range is extended (20-5000 Hz) compared to the standardized (100-3150 Hz).

Results from another example building with a different construction (denominated as "B3") are presented in Figure 2.

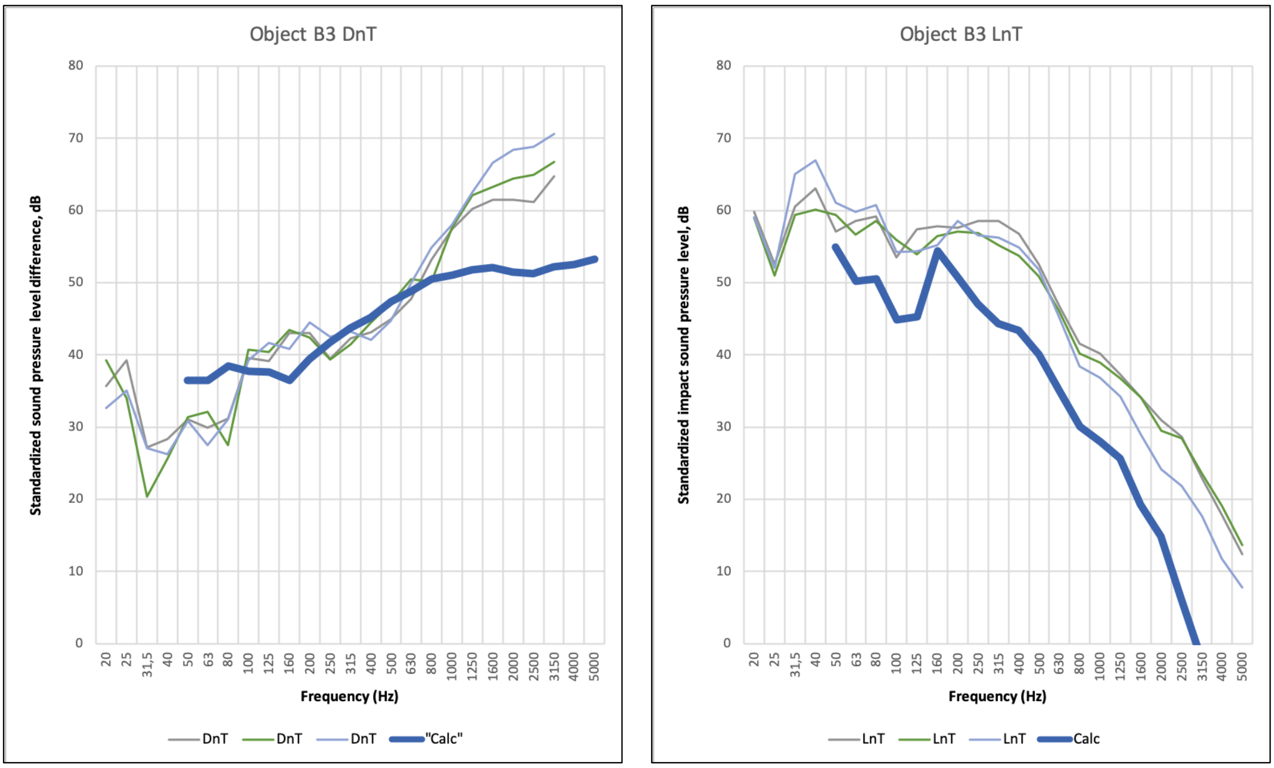

Figure 2: Measured and calculated standardized airborne sound level difference and impact sound level in object B3.

There are no suspended ceilings in the second example building "B3", but the sound (and fire) insulation of the 150 mm CLT floor has been improved by a 15,4 mm fire plasterboard attached with screws to its bottom face. The CLT floor is covered by a raised subfloor with a 22 mm chipboard, 30 mm gypsum screed and a parquet flooring on top of joists and elastic pads. The walls are made of 120 mm CLT and plasterboards attached firmly to those, connected to the CLT-floors with thin resilient strips, steel brackets and nails (of stability reasons).

Apparently, the theoretical estimate of the airborne sound insulation is somewhat on the safe side in the mid- frequency range but underestimates the insulation at low and high frequencies. The impact sound insulation is substantially underestimated at all frequencies except the highest, which is of course unsatisfactory.

In this building B3, looking at the measured values and the vibration transmission results did not really help understand how the construction works from an acoustic point of view. An attempt to find the reason for mismatch was based on the estimated flanking transmissions (as presented by the software). These results are displayed in Figure 3.

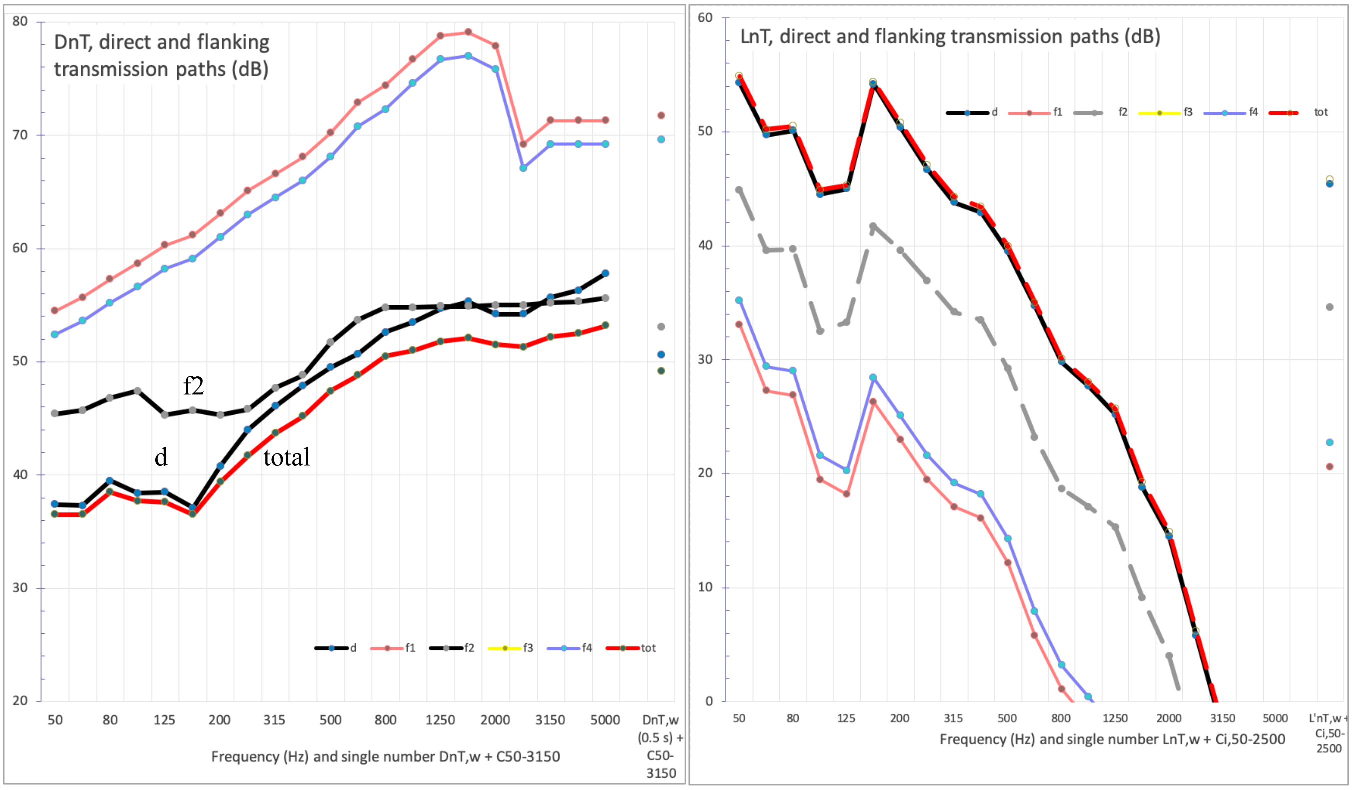

Figure 3: Direct and flanking sound transmissions calculated for object B3. The points to the right end of the scale are the frequency weighted single numbers with spectrum adaptation terms.

It appears in Figure 3, that for the airborne sound insulation, the flanking path f2 via one CLT wall determines the overall result in the range 250-500 Hz, which is physically reasonable to contribute to the thin wall CLT-elements with an expected coincidence limiting frequency in this range (according to Insul). The other paths may be disregarded from this point of view. From 1000 Hz and higher, the transmission seems to be somewhat exaggerated compared to the measured values, which indicates the resilient material used under the walls helps to reduce flanking transmission through the junction with the floor at high frequency, in spite of the rather stiff brackets that were nailed to the floor and the wall elements. This observation has been made in a few other projects as well. Certainly, it would be better to find stability measures which allow static forces from wind loads to act but isolates vibrations in the coincidence region.

The raised subfloor with resiliently supported joists and chipboards are efficient in attenuating the impact sound, but of course they cannot do much about a flanking path through the CLT-walls. On the other hand, the impact sound level is underestimated compared to the field measurements. A closer look at the pictures taken during their construction period indicated there could have occured short circuiting during the construction of the raised subfloors and the studs for the plaster board walls,. Furthermore, comparison to another building with a similar floor build-up, showed the impact sound level was again underestimated by about 5 dB in a wide frequency range, indicating this construction needs further analyses to find the reason for lower impact sound insulation than expected.

In other projects, the reduced effect of suspended ceilings caused by wall flanking transmission have been realistically indicated with Bastian, but of course the type of junction and data of resilient layers utilized have to be modelled to give correct results. There is an option to enter various modulus of elasticity of junctions with resilient layers in this software, but it remains to examine how a nailed steel bracket should be modelled as a resilient layer with a given E-modulus.

3.2 Average results with all CLT floors

The average results for 23 field measurements of D_{nT} and L_{nT} in 8 buildings with CLT made in the *AkuTimber* project are presented in Figure 4. Data from the object B3 were included since the kind of error is not uncommon to these kind of constructions. The safety margin plotted in the figures 4 is the average deviation increased by 1.35 x standard deviation.

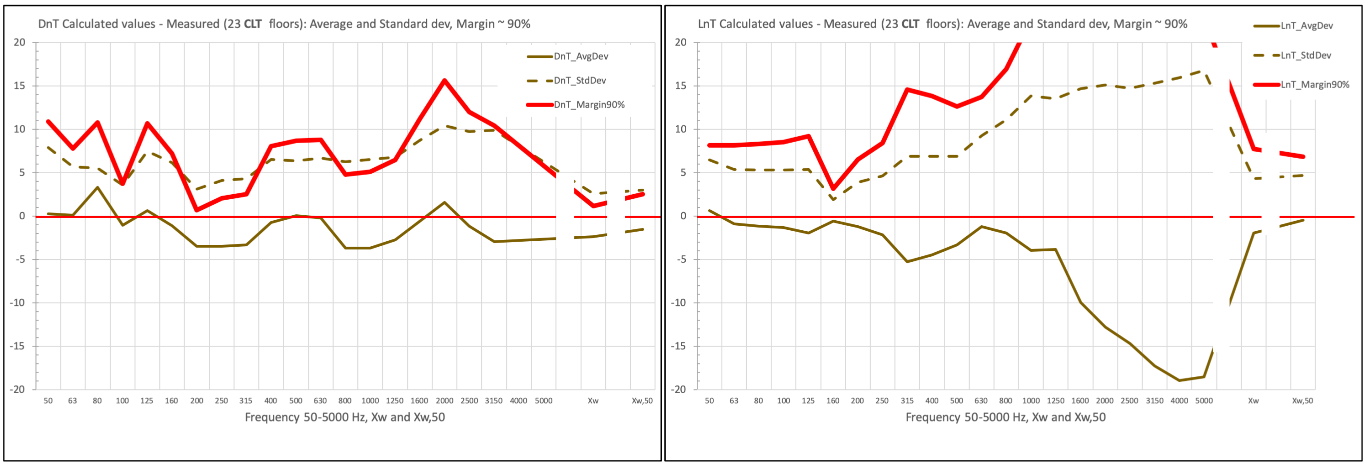

Figure 4: Average of differences between 23 sound transmissions measured in 8 buildings with CLT floors compared to the calculated values for each case. The safety margin curve (solid red) for impact sound is truncated above 1 kHz, but this part of the curve is not critical for the single numbers. The single numbers are indicated at the end of the x-scales; $D_{nT,w}+C_{50\text{-}3150}$ *in the left figure and* $L'_{nT,w}+C_{I,50\text{-}2500}$ *in the right figure.*

3.3 Sound insulation of bare CLT floors

One source of uncertainty may be related to the uncertainty of the laboratory data of the bare CLT floors used as input data in the calculations of the sound insulation *in situ*. When various laboratory results for more or less similar CLT floors are compared, there are variations between those. In order to establish a common basis for further comparisons between calculations and field measurements, a database of CLT sound insulation data was deemed necessary to establish.

Thus, calculations with Insul version 9.0.8 were compared to a set of 23 laboratory measurements of airborne sound reduction *R* (50-5000 Hz) and 29 measurements of impact sound levels *L*n (50-5000 Hz), some of them (but not all) where taken in the same laboratories.

After a first round of comparisons, the input parameters of the Young's modulus in two directions were changed to improve the results as compared to the measured data. The input parameters were adjusted to increase the anisotropy, i.e. widen the gap between the lower frequency of coincidence and the upper frequency. Also, the loss factor was increased somewhat, as suggested by Schoenwald et al.[6] The comparison between the calculated values and measured in the laboratories are displayed in Figure 5. The best cuve fit input data in Insul was (ρ: 495 kg/m^3, E_1: 0.20 GPa, E_2: 16 GPa, η: 0.040, f_{c1}: 63 Hz, f_{c2}: 567 Hz) for the airborne sound transmission and ((ρ: 495 kg/m^3, E_1: 0.55 GPa, E_2: 22 GPa, η: 0.025, f_{c1}: 54 Hz, f_{c2}: 342 Hz) for the impact sound level. Noticeably, those figures are not necessarily the true physical parameters of the CLT, but rather the "tweek" data resulting in a better fit compared to the laboratory measurements.

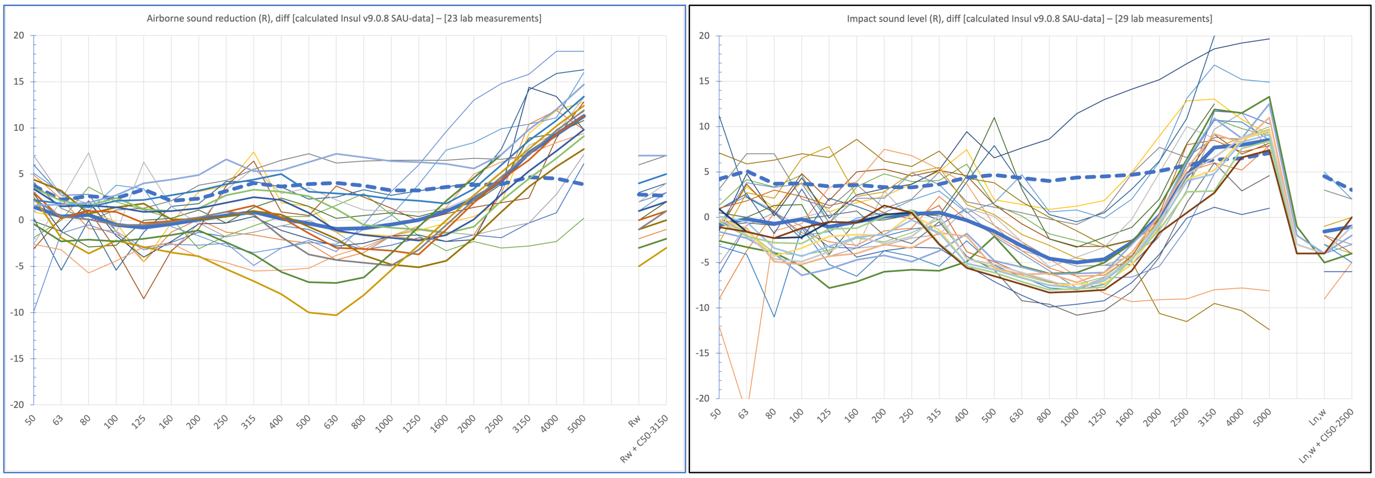

Figure 5: Average of difference between measured sound transmissions in various laboratories for 23/29 bare CLT floors and the calculated values (with Insul, using adjusted input parameters). The single numbers are indicated at the end of the x-scales ($D_{nT,w}+C_{50\text{-}3150}$ in he left figure and $L'_{nT,w}+C_{I,50\text{-}2500}$ in the right figure).

In order to facilitate further calculations of conditions *in situ* in buildings with CLT floors and walls, a database of 17 bare CLT floors ranging from 80 to 240 mm, with or without a fire protection plasterboard (12.7 kg/m^2) screwed to one side of the CLT, were calculated with Insul and corrected empirically for the average deviations presented in the Figures 5a and 5b. Of course, the deviations in results at about 1 kHz, most apparent in the impact sound, would be interesting to examine further, but for now they are only corrected for. This procedure is basically the same as was applied more than 20 years ago to concrete floors and walls,[8] and the database established then has been used extensively in the Nordic countries over the past 20 years with few modifications.[5] However, in case this new CLT database should be erroneous in spite of the efforts to mirror their real performances, upcoming comparisons between calculated and field measured sound insulations made in new projects should be collected and analysed to find whether there are good reasons to adjust this CLT-database. Application of a coordinated set of semi-empirical data facilitates systematic comparisons, which is preferred compared to the present order where different sources of input are used in each project, both for the CLT base structures and the additional floors and ceilings.

3.4 Average results with a specific Granab floating floor on various CLT floors

Some complementary analyses with field data have been made of another set of 12 field measurements, made in 7 buildings with similar combinations (although not identical) of a CLT floor and a specific type of floating floor by the manufacturer Granab. The CLT data was taken from the new database presented in clause 3.3. For the floating floor, Granab commissioned laboratory tests at RISE in Borås, Sweden, for both for ΔR and ΔL_n. The field data were measured by various acousticians which may add reproducibility errors as indicated in EN ISO 12999-1, but at the same time this natural variation minimize systematic errors when the results are averaged, e.g. measurement procedures, equipment etcetera. A similar comparison was made between calculations and measurements, as in the previous parts of this study. The results are displayed in Figures 6.

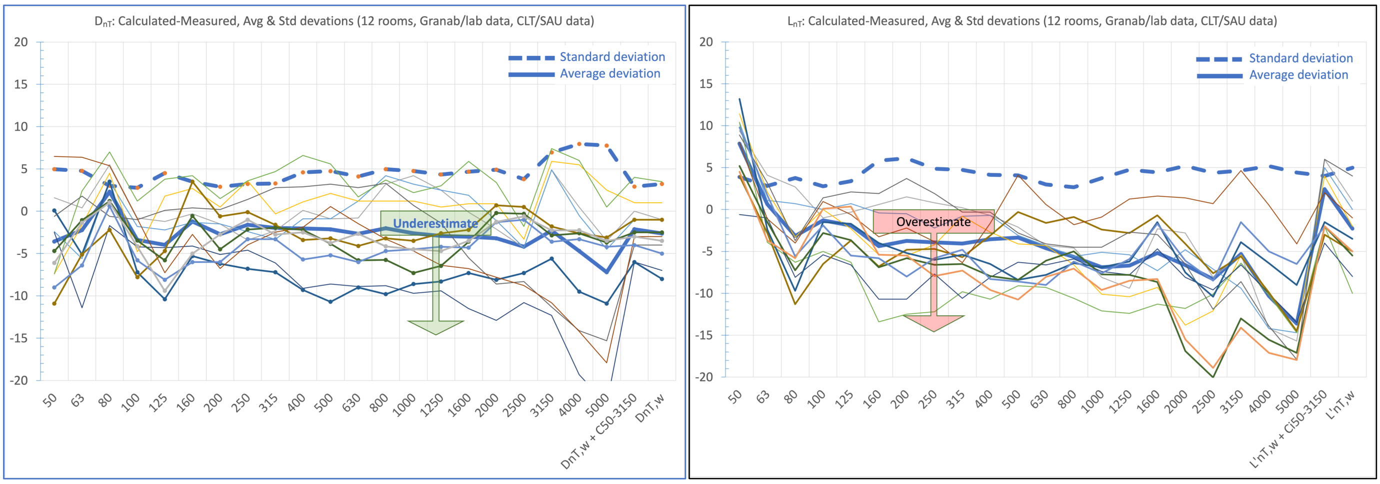

Figure 6: Average of difference between measured sound transmissions in 7 buildings with combinations of a CLT floor and a specific Granab floating floor, compared to the calculated values. The single numbers are indicated at the end of the x-scales ($D_{nT,w}+C_{50\text{-}3150}$ in he left figure and $L'_{nT,w}+C_{I,50\text{-}2500}$ in the right figure).

Some observations from Figure 6: The average deviation of the DnT-comparison has a similar tendency as of the data in Figure 4, but the variations between the third octave bands is smaller. The standard deviation of this comparison is substantially lower, which indicates the deviations are stable and could be corrected for (using the mean deviations).

The calculated impact sound levels are substantially lower than measured, which should be corrected for as well. In both the airborne and impact sound insulation results, a standard deviation in the order of 5 dB in third octave bands seem difficult to avoid. The reason for these random variations remains to explain.

The conclusion is that the input data for the floating floor could be corrected for the mean average differences found in Figures 6, which however implies there will be no margin between a calculated value and the expected field measurement. Thus, a calculated result using the corrected data may be fulfilled at a probability of 50% and a margin of at least 4-5 dB should be observed during design of a floor construction with this subfloor on a CLT floor where the requirements are strict, and where no deviations will be tolerated. The data of the CLT floors and the Granab floor (updated) will be included in the database[5] update in September 2021.

3.5 Average results with concrete floors

The uncertainty in weighted single number values of buildings with concrete floors and walls has previously been investigated by this author[7] as well as others[8]. Since 2004, a safety margin of 3 dB between a calculated insulation and a required value has been recommended by this author to minimize the risk of having underperforming result from field measurements with a probability of about 1 out of 10. Hence, it was certainly challenging to make the same comparison with the new data collected in buildings with concrete floors within the *AkuLite* project. The results in are in line with results from the previous comparisons, and show a good agreement between the theoretical estimates and the field results. However, a 2-3 dB safety margin still appears appropriate to observe during design of a building with concrete floors.

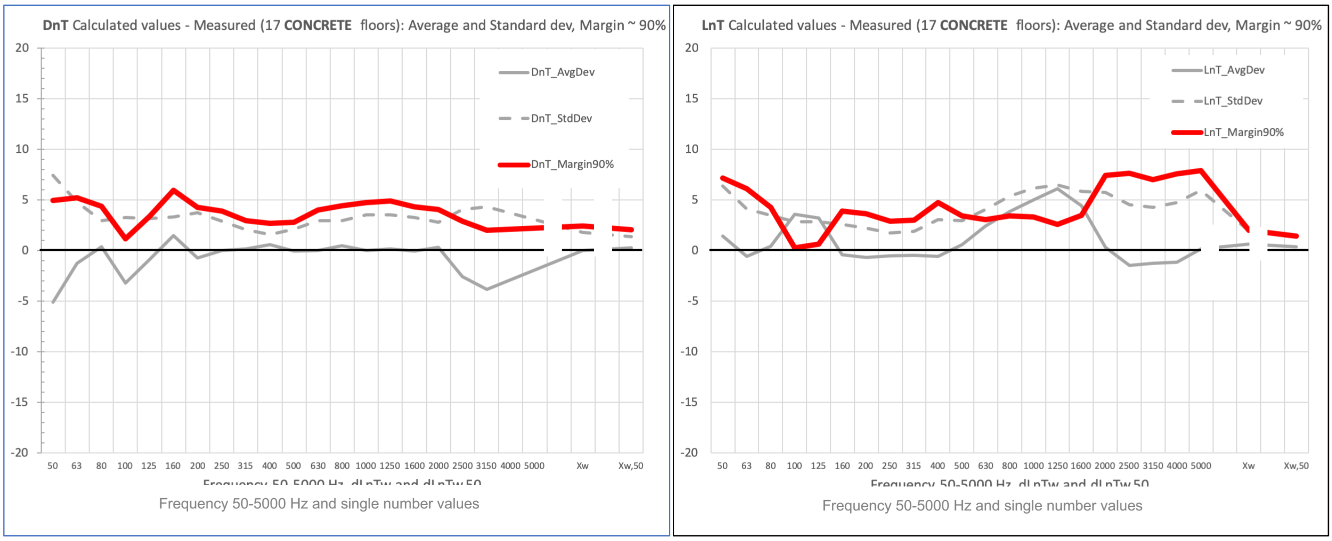

Figure 7: Average of difference between 17 measured sound transmissions made in 7 buildings with concrete floors to the calculated values. The single numbers are indicated at the end of the x-scale ($D_{nT,w}+C_{50\text{-}3150}$ in he left figure and $L'_{nT,w}+C_{I,50\text{-}2500}$ in the right).

4 Discussion and conclusions

The average agreement between calculated D_{nT}-values and the measured values in laboratories as well as in buildings with CLT-floors have been used to establish input data for calculations according to the EN ISO 12354 methods. Indications on flanking transmission paths that short circuit suspended ceilings will be a result from such a calculation, but the calculated flanking transmission may be erroneous if the effect of resilient layers at high frequency is not modeled correctly. The results of the comparisons are reasonably satisfying, compared to what this author expected or even feared at first.

As pointed out by Wittstock[9] during data analysis work with the international standard ISO 12999-1, deviations in third octave bands may be assumed partly uncorrelated and the uncertainty in the single numbers should not be estimated from the third octave bands but preferably directly from the collected single numbers.

For concrete floors, the average agreement between measured values and the calculated values for each case is indeed satisfaying. The standard deviation is less than 5 dB in the frequency range that determines the single number values (200-800 Hz) and the statistical 90% margin of the single numbers (with a coverage factor 1.35, single sided *Student t*'s distribution of probability) is about 2-3 dB. Thus, the 3 dB margin used since many years, still seem to be applicable. Previously made comparisons indicate that measurement uncertainty (inherent in the ISO 16283 standards) is likely to explain some of the variation, adding to uncertainties inherent in prediction methods, input data, material properties and workmanship errors.

For CLT floors, a provisional safety margin of at least 8 dB should be observed for buildings with more or less unknown layered solutions on top of or below the CLT-floors, unless there are specific experiences of the same construction as is under study that supports a lower margin, in particular the junctions and any type of lining used. It may be questionable whether calculations with such an uncertainty has any meaning at all. But with a well known construction with a low risk of workmanship errors, as for the Granab subfloors with Sylodyn resilient pads presented in Figures 6, a margin of 5 dB may be sufficient to expect 8-9 measurements *in situ* out of 10 to fulfil the requirements, i.e. there is a 10%-20% risk.

Most noticeably, ΔR and ΔL_n values measured with a lining above or below a heavyweight base construction should not be applied to CLT floors and walls without prior correction for the difference in mobility, which typically means the low frequency sound insulation improvement for the lining is smaller on a CLT floor than on a concrete floor. For this purpose, a indicative estimate by means of Insul calculations may be useful but laboratory tests or extensive comparisons with field results are preferred. In the database adapted to the software Bastian, there are some provisional data for CLT floors as well as for ceilings, wall linings and floating floors, that allow consultants to make their own estimates and compare those to their own field measurements. The intention of presenting data is not intended to "guarantee" accurate predictions but at least allow analyses to identify main transmission paths and risk factors (e.g. constructions sensitive to workmanship). By time, those data may be refined where field results indicate a need for this and the reliability of theoretical estimates may then be improved.

4 References

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