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Sound insulation, residents' satisfaction, and design of wooden residential buildings

Fredrik Ljunggren[1,*]

[1]Engineering Acoustics, Luleå University of Technology, Sweden.

*fredrik.ljunggren@ltu.se

Abstract
Wood-based multi-family houses continue to gain popularity. Related to acoustics, low-frequency sound insulation as well as appropriate single number quantities for the evaluation of sound insulation have been in focus for a long time. In a series of Swedish research projects running for 12 years, the correlation between rated annoyance from residents and measured airborne and impact sound insulation, with alternative frequency ranges and weightings, have been studied. In total, 38 building cases of various constructions were involved and more than 1200 questionnaire responses were collected.
While the building code's present evaluation parameter for airborne sound insulation, $D'_{nT,w} + C_{50\text{–}3150}$, seems to be working well, the situation is different with respect to impact sound insulation. $L'_{nT,w}$ as well as $L'_{nT,w} + C_{I,50\text{–}2500}$ show weak correlation with the rated annoyance from the residents. The reason is that frequencies below 50 Hz are overlooked, although they dominate the response from walking in many common, particularly lightweight, floor constructions. The strongest correlation with the rated annoyance from impact sound, including both lightweight and heavyweight constructions, was found when the measured frequency range was extended down to 25 Hz, using $L'_{nT,w} + C_{I,25\text{–}2500}$. Because footstep noise rendered the highest degree of annoyance in the survey, a somewhat more restricted requirement than what it used today is suggested to offer a higher degree of protection against unwanted impact sounds.
It is a delicate challenge to design wood-based floor constructions with great sound insulation at low frequencies to meet the higher requirement. A tested innovative floor design based upon two high-density cross-laminated timber plates with an intermediate damping layer may serve as the basis for future constructions.

Keywords: sound insulation, impact sound, residents' annoyance, single number quantity, wooden floor design

1 Introduction

Residential buildings have gained increasingly popular in recent years. It is clear that the acoustic properties of wood-based houses differ from what is known from heavier constructions, like houses made of concrete. As a consequence, sound insulation may need to be evaluated in a different way than what is common today in order to apply to both lightweight (wood) and heavyweight (concrete) buildings. This topic has been in focus in three Swedish research projects – *AkuLite*, *Aku20* and *AkuTimber*, starting in 2009, where the latter project is nearing completion.
The objective of this paper is to summarize the extensive research carried out during more than a decade. The work focus primarily on how to evaluate sound insulation between dwellings to get best possible correlation between the measured airborne and impact sound insulation versus the reported annoyance from the residents. A second is to develop the design of wooden floors for superior low-frequency impact sound insulation.

2 Field measurements

2.1 Method

In total, 38 residential buildings of two to eight floor levels, were included in the study. The buildings represent a variety of mainly modern building techniques. The building case studies are divided into three sub-categories with respect to the construction of the separating floors, mainly related to the mass of the construction. Out of the 38 case studies, 17 are lightweight, 11 are of CLT and 10 are of concrete:

1. *Lightweight* – loadbearing structure of wooden or thin steel beams combined with various types of boards
2. *Cross laminated timber (CLT)* – semi-lightweight structure based upon layers of timber, glued together to form approximately homogenous slabs
3. *Concrete* – homogenous or hollow core slabs

All cases have been examined by field measurements of sound and vibration properties: a) airborne sound insulation, b) impact sound insulation with the standardized tapping machine as well as the ISO rubber ball, c) vibration levels close to junctions (as an indication of flanking transmission) and d) vibration levels of the floor surface at various distances from the impact source. Measurements a–d were performed in the frequency range from 20 Hz. Further details of the measurement procedures are given in [1].

In focus here, is the airborne and impact sound insulation, measured and evaluated according to the appropriate standards: ISO 16283-1 [2], ISO 16283-2 [3], ISO 717-1 [4] and ISO 717-2 [5], or in accordance with the corresponding former standards for the cases investigated at an early stage. The following single number quantities are used: weighted standardized level difference $D'_{nT,w}$ and weighted standardized impact sound level $L'_{nT,w}$, where the reverberation time in both cases is normalised to 0.5 seconds. For simplicity, $D'_{nT,w}$ and $L'_{nT,w}$ are from here on denoted as $D_{nT,w}$ and $L_{nT,w}$ respectively, i.e. without the symbol (′). The definitions of the standardized airborne and impact sound level follow from Equation (1):

$$D_{nT} = \Delta L_p + 10log\left(\frac{T}{T_0}\right) \tag{1a}$$

$$L_{nT} = L_p - 10log\left(\frac{T}{T_0}\right), \tag{1b}$$

where L_p is the sound pressure level, ΔL_p is the sound pressure level difference between two rooms and T_0=0.5 seconds.

A set of spectrum adaption terms are compiled to examine alternative single number quantities using abbreviated denotations. For airborne sound insulation: $D_{nT,w,50}$ corresponds to $D'_{nT,w} + C_{50\text{–}3150}$, and for impact sound insulation: $L_{nT,w,50}$ corresponds to $L'_{nT,w} + C_{I,50\text{–}2500}$ and $L_{nT,w,25}$ corresponds to $L'_{nT,w} + C_{I,25\text{–}2500}$. The latter adaptation term is presently not included in any ISO standard, although it is calculated in the same way as $C_{I,50\text{–}2500}$, but in the frequency range starting at 25 Hz. The definition is given by Equation (2)

$$C_{I,X-2500} = 10log\left(\sum_i 10^{\left(\frac{LnTi}{10}-15\right)}\right) - L_{nT,w}, \tag{2}$$

where X is 25 or 50 Hz.

The sound insulation was generally measured in four to six rooms in each building, evenly distributed among living rooms and master bedrooms. The arithmetic mean value of all measurement results within each building case is used for statistical evaluations.

2.2 Result

The single number quantities related to airborne and impact sound insulation among the 38 building cases are presented. The range is 52–69 dB for $D_{nT,w}$ and 47–65 dB for $D_{nT,w,50}$ concerning the airborne sound insulation. Regarding the impact sound insulation, the range is 38–62 dB for $L_{nT,w}$, 46–66 dB for $L_{nT,w,50}$ and 47–68 dB for $L_{nT,w,25}$. The histograms of the sound insulation are presented in Figure 1 and 2. There is a clear trend towards numerically lower airborne sound insulation as the lowest frequency shifts from 100 Hz ($D_{nT,w}$) to 50 Hz ($D_{nT,w,50}$). In a similar way, the impact sound pressure level increases as the lowest frequency is shifted from

100 Hz ($L_{nT,w}$) to 50 Hz ($L_{nT,w,50}$). Applying the extended frequency range from 25 Hz ($L_{nT,w,25}$) can, according to the definition, only increase the weighted impact sound pressure level since more one-third octave band levels are added to the single number quantity, i.e. the total amount of acoustic energy increases. However, the concrete buildings are almost unaffected by the frequency extension from 50 Hz to 25 Hz whereas the CLT and lightweight buildings show a significant increase in single number, which is illustrated by comparing the histograms in Figure 2.

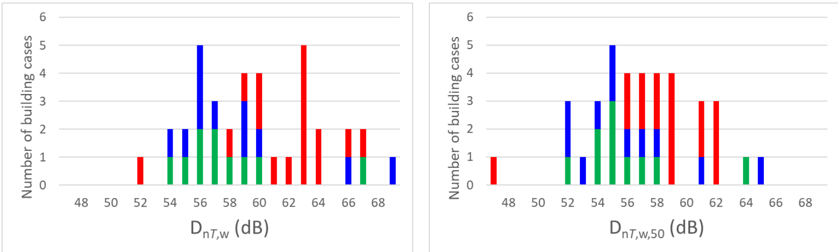

Figure 1. Histograms of the mean airborne sound insulation of the building cases with respect to category: ■concrete, ■CLT and ■lightweight.

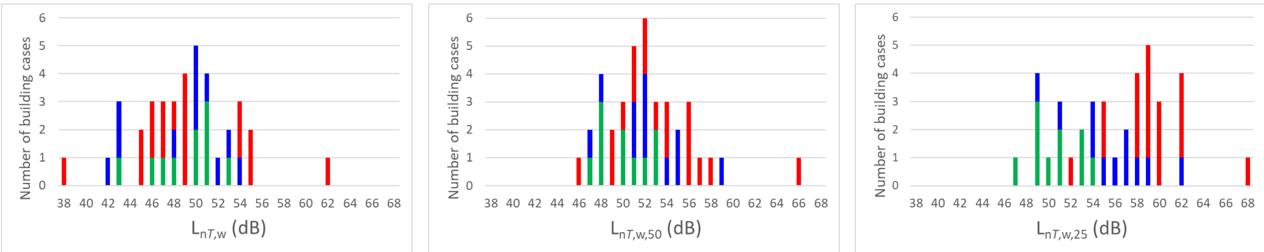

Figure 2. Histograms of the mean impact sound insulation of the building cases with respect to category: ■concrete, ■CLT and ■lightweight.

3 Questionnaire survey

3.1 Method

The questionnaire according to Figure 3 was developed within the European COST action TU0901 [6] based on the technical specification ISO/TS 15666 [7]. The residents have been instructed to rate their perceived annoyance from several potential types of sound and vibration in their home. On a numerical scale ranging from 0–10 where "0" means not at all bothered, disturbed or annoyed and "10" means extremely annoyed. The respondents marked their rating for a total 17 questions.
The questionnaires were distributed by land mail six months or later after occupancy. In total, over 1200 filled questionnaires were returned, which corresponds to an average response rate of about 50%. As a starting point, the mean value from all questionnaires returned from each case was used for the statistical evaluation, but later on, parameters based upon fractions were included.

3.2 Result

Then mean annoyance from the individual sound sources, questions No. 2–14, are presented in Figure 4. The total score, including all buildings as well as the three subcategories, are shown. On average, taking all the sound sources into account, the occupants seem to be fairly satisfied with the acoustical indoor climate. The mean annoyance rating is typically around 1.0–1.5 on the numerical scale ranging from 1 to 10. However, the question regarding footstep noise, No. 5, stands out with an annoyance rating being roughly twice as high for two of the construction categories. The mean annoyance rating of footstep noise from occupants is 3.8 in the lightweight buildings, 3.2, in the CLT buildings and 2.0 in the concrete building. Thus, even though impact noise is often a severe source of annoyance, this is not the case in the concrete buildings, for which the annoyance is comparable to the other sound sources.

Instructions:
Choose an answer on the 0-to-10 scale for how much noise bothers, disturbs or annoys you when you are in your home.

*if you hear the noise but you are **not at all** disturbed by it,* ***choose 0***	*if you are extremely bothered, disturbed or annoyed by it,* ***choose 10***	*if you are somewhere in between,* ***choose a number from 1 to 9***	*if you do not hear anything at all, the source does not exist or if you cannot answer,* ***choose "Don't know"***

Thinking about the last 12 months in your home, how much are you bothered, disturbed or annoyed by	Not at all 0	1	2	3	4	5	6	7	8	9	Extremely 10	Don't know
1. Noise from neighbours, technical installations etcetera	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Thinking about the last 12 months in your home, how much are you bothered, disturbed or annoyed by these sources of noise	Not at all 0	1	2	3	4	5	6	7	8	9	Extremely 10	Don't know
2. Neighbours; daily living, e.g. people talking, telephone, radio, TV through the **walls**	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3. Neighbours; daily living, e.g. people talking, telephone, radio, TV through the **ceilings or floors**	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
4. Neighbours; music with bass and drums	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5. Neighbours; **footstep** noise, i.e. you hear when they walk on the floor	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
6. Neighbours; **impact or scraping** noise, i.e. from chairs, kitchen sink, lockers, toys, vacuum cleaning etcetera	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
7. Neighbours; rattling or tinkling noise from your **own** furniture when neighbours move on the floor above you	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8. Stairwells, access balconies; people **talking**, doors closing	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9. Stairwells, access balconies; **footsteps**, balustrade **impacts**	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
10. Water installations; plumbing, using or flushing WC, shower	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
11. Climate installations; heaters, air condition, air terminals	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
12. Services; elevators, laundry machines, ventilators, heatpumps	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
13. Premises; garages, shops, offices, pubs, restaurants, laundry rooms or other, heard indoors with windows closed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
14. Traffic (cars, buses, trucks, trains or aircraft); heard indoors with windows closed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

***Before** moving to your present home, how important to you was **then** the sound insulation, with respect to*	Not at all important 0	1	2	3	4	5	6	7	8	9	Extremely important 10
15. Noise from neighbours, technical installations etcetera	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

*How **sensitive** are you to*	Not at all sensitive 0	1	2	3	4	5	6	7	8	9	Extremely sensitive 10
16. Noise from neighbours, technical installations etcetera	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

*Thinking of **all other aspects** than noise, in your home*	Not at all satisfied 0	1	2	3	4	5	6	7	8	9	Extremely satisfied 10
17. How satisfied are you with your home all in all, overall	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Please comment, describe the types of noise, where the noises come from:

ID:_____

Figure 3: Questionnaire.

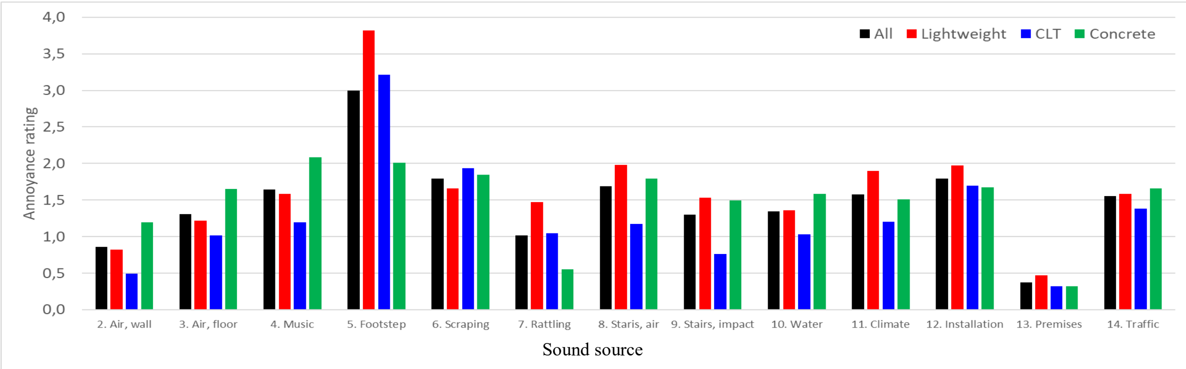

Figure 4. Mean annoyance rating for different building construction types from a variety of sound sources.

The responses from the survey questions related to airborne and impact sound insulations are presented below in the alternative way of using an ordinal scale with five alternatives: not at all, slightly, moderately, very and extremely annoyed. The numerical scale was translated into the ordinal scale according previous research [8–9]. The rating 0 on the numerical scale corresponds to not at all, ratings 1–3 correspond to slightly, 4–6 to moderately, 7–9 to very and 10 to extremely.

Three questions can be directly linked to airborne sound insulation. These include No 2: daily-living sound from the neighbours through the walls, No 3: daily-living sound from the neighbours through the floors or ceilings and No 4: music with bass and drums. As can be seen in Figure 5, music is somewhat more annoying than the other daily-living sounds from neighbours. Taking all cases into account, 17% of the occupants are moderately, very or extremely annoyed by music, while 13% are the corresponding annoyance ratings for other daily-living sounds through floors. The occupants of the concrete buildings are generally slightly more annoyed by airborne sounds than occupants living in lightweight or CLT buildings. The annoyance related to daily-living sounds through walls (question No 2) was found to be lower than through floors.

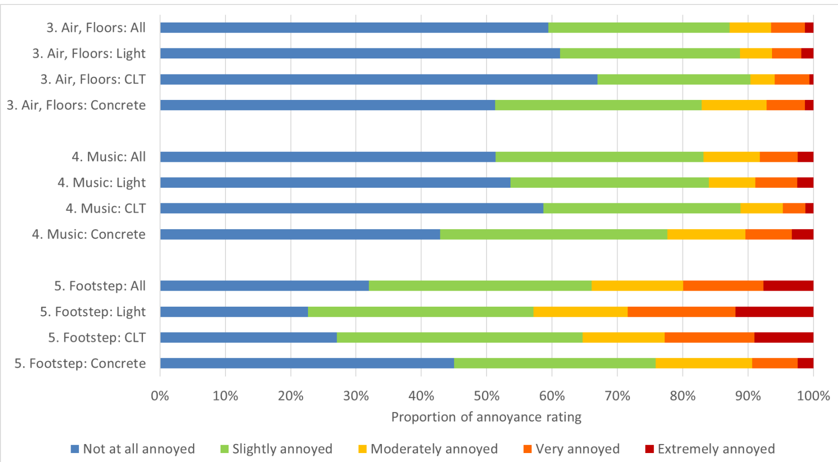

Figure 5. Proportion of annoyance rating from airborne sound sources; 3) daily-living sounds from neighbours through floors, 4) music and from 5) footstep.

Impact sound insulation is directly associated with question No 5: footstep noise from the neighbours. The annoyance difference between the lightweight and concrete categories is considerable. The results show that 2% of the occupants in the concrete buildings, but 12% in the lightweight buildings, are extremely annoyed. In the latter category, 29% are very or extremely annoyed while as many as 77% are annoyed by footstep to some extent, i.e. being at least slightly annoyed.

Two more questions in the questionnaire can be related to impact sound insulation. These concern rattling or tinkling noise from the furniture in the respondent's own apartment, and impact or scraping noise from e.g. chairs, kitchen work and toys. The reported annoyance related to these sources were lower than those from walking neighbours and are not further discussed here, but analysis at an earlier stage was presented in [10].

4 Single number quantities for impact sound insulation

4.1 Method

Since footstep noise generated the highest rated annoyance, it should be examined whether this could be due to inadequate impact sound insulation descriptors, i.e. single number quantities. The statistical relationship between the rated annoyance from impact sound (question No 5) and various single number quantities derived from the standardized impact sound levels measured in one-third octave bands was investigated using linear regression analyses. The model is expressed by the relation $Y=a+bX$ where Y is the annoyance rating and X is the single number quantity in dB. The rated annoyance is represented by the mean value for each building case. From the statistical model, the coefficient of determination, R^2, (equivalent to the square of the correlation coefficient r) is determined. This way of handling the statistical analyses follows the methods used in the previous analysis of subsets of the complete data now available [1, 10]. The results presented within in this section presume that the sound pressure levels at frequencies below 50 Hz are evaluated without normalization of reverberation time, i.e. they represent L_p rather than L_{nT}. This approach may be justified from a practical point of view, since the procedure to measure the reverberation time at such low frequencies may be cumbersome and induce a great uncertainty in the related single number quantity [11].
There is no common standardized method for statistical evaluation of a subjective dose-response relationship to noise annoyance. One kind of analyses may be based on the mean annoyance according to the European Commission Services' [12]. Another alternative is to define a cut-off point as a basis for the analysis [9, 12], an alternative that divides the respondents into two groups with a specified rated annoyance level – at a given cut-off point. In this case, the fraction ≥ 7 has been used, showing the percentage of respondents who rated their annoyance ≥ 7, corresponding to a 64% cut-off point. Although not included in the paper, complementary analysis using other cut-off points as well as using the mean value instead of fraction were performed, and the results were found to be consistent when assessing the single number quantities.

4.2 Result

The resulting linear regression analyses are presented in Figure 6 including the coefficient of determination, R^2. Note that all symbols representing the building cases, share the same numerical value on the y-axes (the rated annoyance) in all the three figures, while the measured single number quantity on the x-axes varies with respect to frequency range. Evaluating the impact sound insulation by $L_{nT,w}$, results in the coefficient of determination of just 12%. A dramatic improvement is seen if $L_{nT,w,50}$ is used as R^2 increases to 40%. The correlation increases further as lower frequencies are included and evaluation from 25 Hz, $L_{nT,w,25}$, resulted in the strongest correlation, R^2=62%. It should be mentioned that in the foregoing studies [1, 10], the strongest correlation was instead found with evaluation from 20 Hz, which is not the case here after that the database has been extended. Evaluated from 20 Hz, $L_{nT,w,20}$, R^2 reached 49% (not covered in the figure).

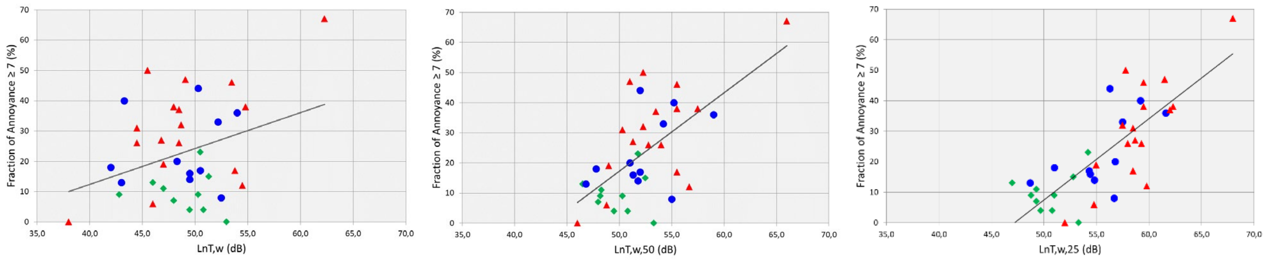

Figure 6. Linear regression of annoyance from footstep vs. the single number quantities $L_{nT,w}$, $L_{nT,w,50}$ and $L_{nT,w,25}$ with corresponding R^2 of 11, 40 and 62% respectively. Building types: ▲ lightweigth, ● CLT and ◆ concrete. No normalization of impact levels at 20-40 Hz to the reverberation time 0.5 s was applied.

5 Single number quantity limits to be considered

5.1 Method

The questionnaire survey is assumed to reflect the overall perspective of the occupants' satisfaction/annoyance regarding the acoustical comfort in modern apartments. But since the sound insulation varies considerably between building cases, variation in the acoustical satisfaction as well as in the rated annoyance is expected as a consequence. The relation between sound insulation and rated annoyance according to the ordinal scale is studied by logistic regression analysis. This is the probability that a given single number quantity of sound insulation will lead to annoyance within one or more of the ordinal categories. Mathematically, this is described by Equation 3:

$$Prob(Annoyance) = \frac{e^{k \cdot SNQ+m}}{1+e^{k \cdot SNQ+m}}, \tag{3}$$

where k and m have their counterparts in the coefficients of the linear regression $Y(x) = kx + m$ and SNQ refers to the dB-value of the single number quantity. Logistic regression analysis is applied to airborne and impact sound insulation separately. Multiple single number quantities and their respective probability to result in annoyance are studied for each specific survey question.

5.2 Result

The rated annoyance following the survey questions of airborne sound insulation is relatively low when $D_{nT,w,50}$ fulfils the Swedish minimum requirement of 52 dB. For daily-living sound sources and for music, 10% and 12% of the occupants respectively are expected to rate those sources as very or extremely annoying, and 21% and 26% respectively as at least moderately annoying, see Figure 7.

Figure 5 shows that 13% are moderately, very or extremely annoyed by daily-living sounds through floors and ceilings. The corresponding proportion for daily-living sounds through walls is 7% (not covered in the figure) and for music 17%. Overall, it is suggested that the current Swedish legislation, $D_{nT,w,50} \geq 52$ dB, works satisfactorily and offers adequate airborne sound protection to the occupants.

As shown, regarding the correlation between measured impact sound insulation and rated annoyance, $L_{nT,w,25}$ gives a stronger correlation than $L_{nT,w,50}$. According to the previous sections, despite fulfilling the present Swedish impact sound insulation class A ($L_{nT,w,50} = 48$ dB), the annoyance may still be greater than for airborne sound insulation that only meets the minimum requirement ($D_{nT,w,50} = 52$ dB). This indicates the need for a more restrictive requirement that offers a higher degree of protection against unwanted impact sounds, and for this purpose $L_{nT,w,25}$ is preferred.

The logistic regression analyses involving $L_{nT,w,50}$ and $L_{nT,w,25}$ in Figure 8 are compared. For $L_{nT,w,50} = 56$ dB, the Swedish minimum requirement, 32% of the occupants are expected to rate the annoyance as very or extremely annoying and 44% as at least moderately annoying. This level of annoyance corresponds to $L_{nT,w,25} = 59$ dB.

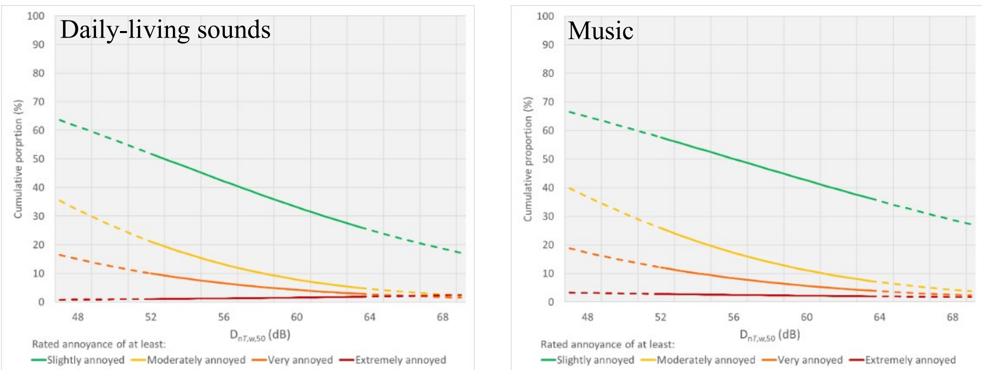

Figure 7. Cumulative proportion of rated annoyance due to daily-living sounds through floors (left) and music (right) as a function of $D_{nT,w,50}$. Solid lines represent 95% of the available data.

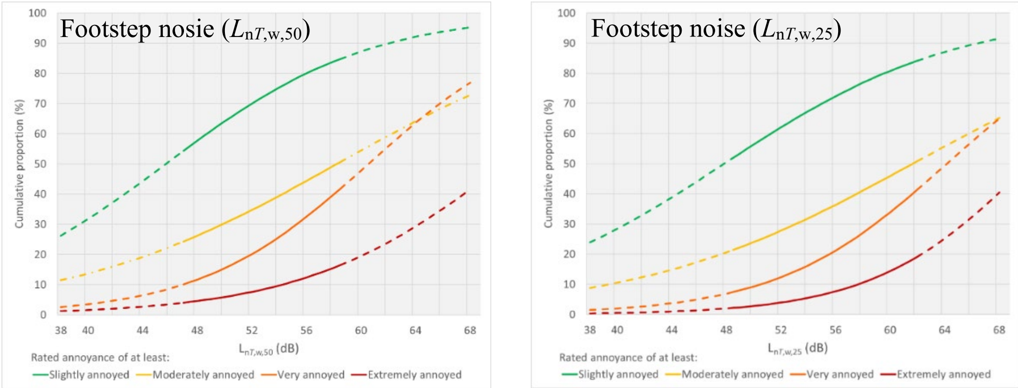

Figure 8. Cumulative proportion of rated annoyance due to footstep noise as a function of $L_{nT,w,50}$ (right) and $L_{nT,w,25}$ (left). Solid lines represent 95% of the available data.

If instead $L_{nT,w,25}$ is set to 56 dB, i.e. the same numerical value as today's Swedish requirement for $L_{nT,w,50}$, this expects to generate the proportion of 21% being very or extremely annoyed, and 36% being a least moderately annoyed.
Another further step further is to find a level of expected annoyance from impact noise that equals the annoyance from airborne daily-living sounds. Then the annoyance should match 21% and 10% being at least moderately, and very or extremely annoyed, occupants respectively. This level of annoyance corresponds to $L_{nT,w,25}$ being as low as about 50 dB. Even though arguments exist, such a dramatic shift compared to today's standard would probably be too difficult for the building industry to handle.

6 Floor design

It has been shown that wood-based floors show high impact sound levels at low frequencies, and thereby high annoyance rating among the residents. The issue is then how to design the floors to decrease the impact sound level. As the mass is a key factor, a solution could be to use a screeded floor, e.g. a layer of concrete on top of the timber construction. Although such a hybrid solution may be effective from a sound insulation perspective, the building industry search for solutions free from cement-based products.
Two ideas were tested in the *AkuTimber* project: to increase the density of a CLT floor and to increase the damping.

6.1 Method

Spruce, with a density of 400-440 kg/m^3 is the dominating wood species used for CLT panels in the Scandinavian market. As an alternative, panels made of birch having a density of 600-650 kg/ m^3 is tested. Another tested configuration is to use densified spruce. The planks are then compressed to ~55% of their original height before the CLT panels are manufactured. Such a panel have a density of about 1.8 times the density of a plate made from untreated spruce.
To increase the damping, a viscoelastic sheet [13] of various thickness, 2-12 mm, was put in between two 60 mm CLT panels. The viscoelastic material is designed to work by shear and to be efficient at low frequencies. Panels of the size 0.6x4.0 m and/or 0.6x2.4 m, were tested for the mobility averaged over the surface and modal analysis was performed to check for natural frequencies and damping ratios. The tested plate was hooked up by resilient ropes and was excited by an electromagnetic shaker. The response was measured by accelerometers in 27 positions (3x9) over the surface. All individual panels were 60 mm thick but were also tested in pairs, 2x60 mm, either glued together or using viscoelastic foil in between.

6.2 Result

The fundamental frequency of the 4.0 m panels was ~20 Hz for the 60 mm panels made of spruce or birch and ~32 Hz when two panels were glued together, 2x60 mm (no panels of densified spruce was available in 4.0 m length). Fir the shorter 2.4 m panels, 60 mm, the fundamental frequency was found to be 52 Hz for spruce, 50 Hz for birch and 44 Hz for densified spruce. With 2x60 mm, the fundamental frequency was measured to 87 Hz and 80 Hz for the original and densified spruce respectively. See Figure 9 for natural frequencies and mode shapes found in a 60 mm spruce CLT panel of 4.0 m length.

Figure 9. Natural frequencies and mode shapes for a tested 60 mm CLT panel made of spruce, length 4.0 m.

In Figure 10a), the surface average of the mobility for three different 2x60 mm panel configurations, glued together and 2.4 m in length, are presented. As expected from the mass relation, the panel made of densified spruce shows the lowest mobility level followed by the birch panel.
In Figure 10b), 2x60 mm panels are used to study the effect of the viscoelastic sheet of different thicknesses compared to the referenced case were two panels are glued together. The thinnest viscoelastic layer, 2 mm, has hardly any effect while thicker layer, 4-12 mm, gradually lower the mobility as the thickness increases.

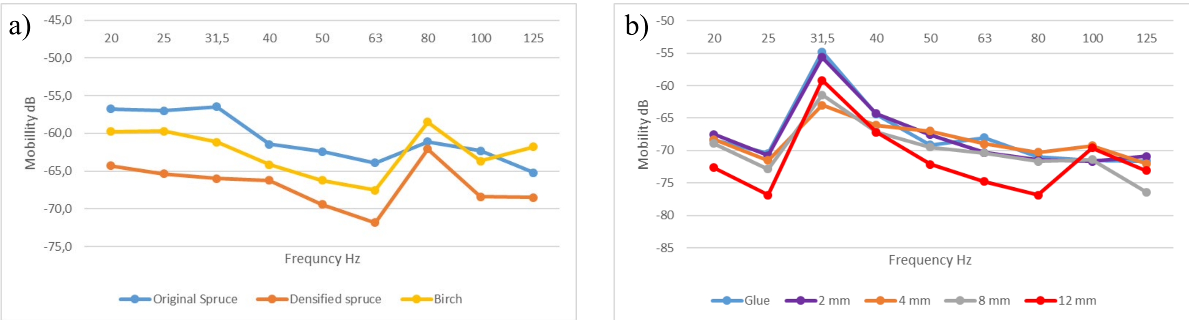

Figure 10. Mobility, averaged over the surface, with respect to a) different kinds of wood and b) viscoelastic layers of different thickness.

7 Conclusions

The importance of impact sound insulation, below 50 Hz has been actualised. The evaluation methods used today rely upon a frequency range starting from 100 or 50 Hz. At least the range starting from 50 Hz may be appropriate dealing with heavy constructions but for lightweight constructions, the correlation between measurement and residents' perception in terms of rated annoyance is weak. Among the 38 building cases of mixed constructions, the coefficient of determination between rated annoyance and measurement was just 11% when the impact sound insulation was evaluated from 100 Hz ($L_{nT,w}$), 40% evaluating from 50 Hz ($L_{nT,w,50}$), but 62% evaluating from 25 Hz ($L_{nT,w,25}$).
Based upon the results, evaluating impact sound from 25 Hz, by using $L_{nT,w,25}$, is better than using $L_{nT,w}$ or $L_{nT,w,50}$ in markets where both heavyweight and lightweight building constructions occur. However, using $L_{nT,w,25}$ means that sound energy over more third-octave bands are summed compared to $L_{nT,w,50}$, and any numerical single number quantity limit should therefore not be used without adjustment when changing from $L_{nT,w,50}$ to $L_{nT,w,25}$. Besides, when comparing the estimated annoyance at the levels of the present Swedish minimum requirements, $D_{nT,w,50} \geq 52$ dB and $L_{nT,w,50} \leq 56$ dB, it was found that footstep noise is expected to generate higher level of annoyance than airborne daily-living sounds and music. From this perspective, a somewhat stricter impact sound insulation requirement makes sense.

Lightweight constructions often show poor low-frequency impact sound insulation compared to heavy constructions. This is to high extent related to the mass difference, and it is a great challenge to design a wood-based floor with great sound insulation at low frequencies. A couple of potential solutions were tested experimentally and compared to a standard CLT panel made of spruce. First, the panel´s mass was increased, either by using birch, an alternative type of wood with about 50% greater density, or by using densified – compressed – spruce with 80% greater density than the original. Secondly, a layer of viscoelastic damping material was put in between two CLT panels to form a new unit. Both methods affected the measured mobility which was found to be up to 8 dB lower in single one-third octave bands below 100 Hz. The techniques do have potential, and further investigations – including a larger specimen (12 m^2) to be tested in a test house – are planned.

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