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Airborne sound insulation between dwellings, from 50 vs. 100 Hz – A compilation of Swedish field surveys

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A B S T R A C T

It has for long been debated whether 50 or 100 Hz is the proper lower frequency limit when evaluating airborne sound insulation between dwellings. Although 100 Hz is the lowest third-octave band within most regulations, there is an ongoing interest in paying more attention to lower frequencies. In Sweden, evaluation from 50 Hz became mandatory already in 1999 wherefore unique experiences are available by now.

In this paper, extensive data in terms of field measurements and questionnaire surveys from in total 46 building objects of various constructions have been compiled. A number of single number quantities, standardized by ISO as well as alternatives, are compared concerning their correlation against the subjectively rated annoyance responded by the residents. The statistical evidence for a 50 Hz limit was found to be small considering the total database but when the lightweight buildings were analyzed by their own, the importance of frequencies below 100 Hz became clearer.

The overall recommendation is to include frequencies from 50 Hz in order to achieve good sound protection against a broad variety of sound sources, including music and other possible items generating low frequencies.

1. Introduction

The first modern international standard regarding evaluation of airborne sound insulation between dwellings was launched in 1968 [1]. The evaluation procedure was based upon a reference curve originating from the sound reduction properties of a 25 cm brick wall [2]. The frequency range was set to 100–3150 Hz and the single number quantity (SNQ) R_w – the frequency weighted sound reduction index – was defined. Later on, complementary spectrum adaptation terms ranging from 50 Hz were introduced in 1996 [3] in order to take sound insulation at low frequencies into account. The term $C_{50\text{-}3150}$ was adopted 1999 into the Swedish building code (BBR) in which requirements for $R'_w + C_{50\text{-}3150}$ were stipulated. This was a result of extensive complaints from residents, whereby Swedish authorities as well as the building industry realized that the legal regulations must be stricter.

Up to now, Sweden is still the only country that mandatorily requires sound insulation to be evaluated from 50 Hz and a lot of experience has been acquired over these almost twenty years. A reason for Sweden being a pioneer in this context is that lightweight constructions are more commonly used compared to most other markets and that lightweight buildings, especially at that time, were prone to suffer from poor sound insulation at low frequencies.

During the last few years, an increased interest in low frequency sound insulation has been noticed. As an example, the ISO standards regarding airborne and impact sound insulation nowadays include a specific low frequency measurement procedure to be applied under certain circumstances [4]. Other examples are to be found in the great amount of research activity in the field. Several studies based upon listening tests have been reported (2014–16) [5–8] but also attempts to optimize evaluation parameters against subjective perception can be found (2016) [9,10] as well as questionnaire surveys (2015) [11]. A common discussion in the given studies is whether airborne sound insulation between dwellings should be evaluated from 50 Hz or if it is good enough to keep 100 Hz as the lower frequency limit. A coarse general conclusion based upon these studies is that frequencies below 100 Hz are of no great importance when assessing sound insulation. This standpoint is however clearly rejected in the reflective paper by Rindel (2017) [12] who believes that the results of the studies in fact point in the opposite direction, i.e. that frequencies 50–80 Hz must not be kept out of the single number evaluation. Rindel also claimed that the authors severely have misinterpreted their own results and presented wrong conclusions. A key factor in the understanding of this problem is whether it is preferable to optimize the evaluation process in order to find the parameter that gives the highest possible correlation

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for a specific type of sound source (e.g. loud speech). Or is it better to apply a more protective perspective, from the residents point of view, leading to higher demand for sound insulation in terms of a broad banded SNQ that covers most sources in dwellings? Related to this, it is well known that various sound sources, as speech and music, put different demands on the frequency-weighting factor since many types of music contain proportionally more energy at low frequencies [13]. For the time being, it is obvious that no general consensus within the addressed question of 50 or 100 Hz exists.

In this paper, the Swedish experience of evaluating airborne sound insulation is given with the purpose to find out whether SNQ's ranging from 50 Hz show higher correlation against the residents' rated annoyance compared to $D'_{\mathrm{nT,w}}$ ranging from 100 Hz. Also the potential difference of correlation in between lightweight and heavyweight constructions will be covered. The following presentation is the compiled results from field measurements and studies of residents' rating of sound insulation during more than 30 years.

2. Method

Data from six Swedish research projects and consulting cases have been compiled to a common database. In total, 46 building objects of multi-storey residential houses are included. The objects cover a variety of building techniques and can be divided into lightweight (almost exclusively wooden based) constructions (24 of 46) and heavy concrete constructions (22 of 46). The projects/cases are *Aku20* (awaiting publications), *AkuLite* (2013) [14], *SBUF* (2011) [15], *Boverket Byggkostnadsforum* (2007) [16], *Bodlund* (1983) [17] and one additional *consultancy case* (2014). Only a minor part of the building objects [17] were designed before the building regulations were changed to include the lower third-octave bands 50–80 Hz. Although the objects range over 30 years in time, the vast majority is built in recent years i.e. representing modern building technology.

The data that have been collected, whenever available, are: (a) Residents' subjective rating of sounds related to the airborne sound insulation and (b) Vertical sound insulation measurements in terms of D'_{nT}, 50–3150 Hz.

2.1. Questionnaire and subjective rating

The residents were asked to rate the perceived sound insulation by means of questionnaire surveys. Within all the projects from 2011, the same questionnaire developed within the European cost action TU0901 [18] was used. This questionnaire contains a number of questions related to sound and vibration issues in dwellings.

For this study, the following two questions are in focus:

Thinking about the 12 last months in your home, how much are you bothered, disturbed or annoyed by these sources of noise?

(a) *Neighbors; daily living, e.g. people talking, telephone, radio, TV through the ceilings or floors*
(b) *Neighbors; music with bass and drums*

and the following two questions have been used mainly for comparison:

(c) *Neighbors; daily living, e.g. people talking, telephone, radio, TV through the walls*
(d) *Neighbors; footstep noise, i.e. you here when they walk on the floor*

Question (a) is assumed to be related with sound sources having a frequency spectrum with limited energy below 100 Hz while the sources related to question (b) should bring significant amount of energy in the 50–100 Hz range. The annoyance is rated on a numerical scale ranging from "0" to "10" where "0" means not at all annoying and "10" means extremely annoying. There was also an option to answer N/A, in case the source of sound did not exist, but very few used this option.

In the remaining two projects (11 of 46) [16,17], other questionnaires were used. Thus, the questions were not formulated in the exact same way as above and another divergence is the numerical annoyance scale, which was ranged 1–7. However, the meaning of the analyzed questions from these objects are assumed to be close to question (a) above and the answers were translated numerically to fit the annoyance scale from 0 to 10. There is no equivalent regarding the question of annoyance from music for these objects though.

Besides the acoustic related questions, the questionnaires contained a personal data section where complementary information e.g. sex, age, and No. of persons in the household were given. In general, the latter parameters were approximately evenly distributed among the residents within each building objects. However, a couple of the objects were dominated either by younger people (students, ≤25 years of age) or by older (≥65 years). Although a number of the building objects were new when they entered the study, no questionnaires were distributed before six months after the building was taken in use, but rather a year.

The response rate was considered satisfying, typically 50–60% with a total amount of about 1400 filled-in questionnaires.

2.2. Sound insulation measurement and evaluation

Since D'_{nT} is the current descriptor referred to in the Swedish building code, it has been used throughout the study. However, several objects have reported the measured data as sound reduction R', the previously used descriptor, and in such cases D'_{nT} was estimated as $D'_{\mathrm{nT}} = R'$-1, a relation that is valid for normal room heights of about 2.5 m (considering the vertical direction). The sound insulation was typically measured in two to six rooms for each building object. From the measurements, a variety of SNQ's has been calculated. The ISO standardized $D_{\mathrm{nT,w}}$, $D_{\mathrm{nT,w,50}}$ and $D_{\mathrm{nT,w,50tr}}$ (abbreviation for $D'_{\mathrm{nT,w}}$, $D'_{\mathrm{nT,w}} + C_{50\text{-}3150}$ and $D'_{\mathrm{nT,w}} + C_{\mathrm{tr,50\text{-}3150}}$ respectively) together with a couple of alternative SNQ's reported in the literature; The *optimized reference spectrum for living noise* $D_{\mathrm{nT,w,50opt}}$ ($D'_{\mathrm{nT,w}} + C_{\mathrm{opt}}$) by Virjonen et. al. [9] and the *modified reference spectrum* $D_{\mathrm{nT,w,50mod}}$ ($D'_{\mathrm{nT,w}} + C_{\mathrm{mod}}$) by Park/Bradley [13]. For the two latter cases, the respective evaluation parameter was reported to give slightly higher correlation against subjectively rated annoyance than the other tested frequency spectra. The spectrum related to C_{opt} is given in the frequency range 50–5000 Hz but is here adjusted to the interval 50–3150 Hz by adding + 1 dB to each third-octave band in accordance with the ISO definitions of $C_{50\text{-}3150}$ and $C_{50\text{-}5000}$. The reference levels of frequency spectra are compared in Fig. 1. Related to $C_{50\text{-}3150}$, C_{opt} and C_{mod} give less importance to the low frequencies while the opposite prevails for $C_{\mathrm{tr,50\text{-}3150}}$. The reference level L is a part of the definition of the spectrum adaptation terms in accordance with:

$$C_{50-3150} = -10\log\left(\sum_{i=1}^{19} 10^{(Li-DnTi)/10}\right) - D_{nT,w} \quad (1)$$

One reason to include only vertical, and not horizontal, measurements is the wide variety of floor plans. In some buildings there were hardly no partitions facing other dwellings but merely elevator wells, stairwells, bathrooms, storage spaces, etcetera. This is most likely a positive development, but makes the meaning of the measured sound insulation difficult to interpret. In the vertical direction, sounds from more or less loud events are expected to transmit to several rooms below. A second reason not to include horizontal measurements is that the participating residents have judged the annoyance from noise in vertical direction with, in average, about 70% higher score than noise coming from the horizontal direction. In a Norwegian survey [19], the similar relation between annoyance from vertically and horizontally directed noise was reported – both regarding sounds from daily living activities as well as music with bass and drums – despite the mean vertical sound insulation being about 2 dB higher ($D_{\mathrm{nT,w}}$ and $D_{\mathrm{nT,w,50}}$). These facts support the assumption that the vertical direction is of

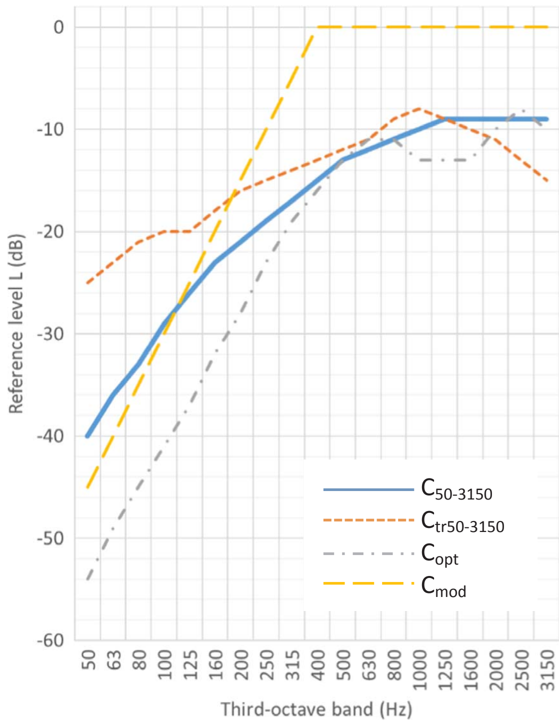

Fig. 1. Reference levels of the spectrum adaptation terms $C_{50\text{-}3150}$, $C_{tr,50\text{-}3150}$, C_{opt} and C_{mod}. (Note: The C_{mod} levels are not normalized to 0 dB weighted sound pressure levels).

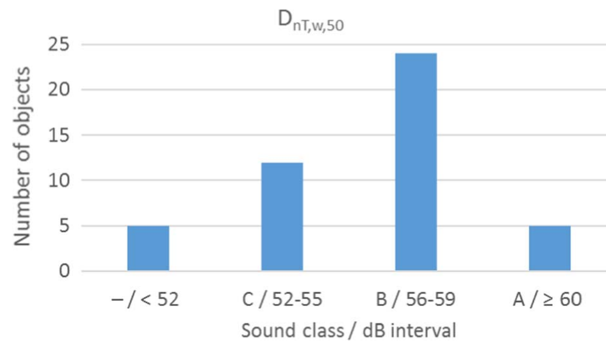

Fig. 2. Object distribution with respect to sound class.

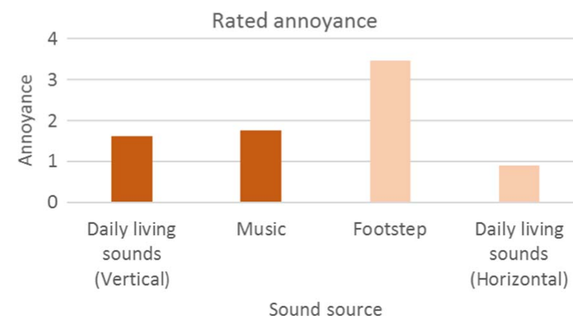

Fig. 3. Rated mean annoyance for various sound sources. Daily living sounds are represented both by the main (vertical) and horizontal direction.

superior interest for the tested objects and it should then also make sense to compare the measured sound insulation with the outcome of question (b) (about music) although no direction is specified.

The number of measurements performed within each building object were typically four to six, evenly distributed among living rooms and master bedrooms.

2.3. Statistical analysis

In order to reveal the correlation between the SNQ's and the subjective ratings from the residents, linear regression analyses were performed. Regarding the SNQ's, the mean value from each building objects has been used as the input parameter and for the questionnaires, the input parameter is the mean annoyance ratings for each of the questions from each building object. The regression analyses are assessed with respect of the coefficient of determination, R^2. It has also been studied whether – or not – a statistical relation on 95% confidence level between the annoyance and respective evaluation parameter exists, i.e. whether the 95% confidence interval of the regression line's slope contains "0" or not.

The analyses are in accordance with the authors foregoing papers [20,21] where the method, including the use of the mean annoyance, was further justified [20].

3. Results

3.1. Measured sound insulation

The reported values of $D_{nT,w}$ show a spread from 49 to 66 dB whereas $D_{nT,w,50}$ range from 47 to 64 dB. The overall average of $D_{nT,w}$ is 58.9 dB and the standard deviation is 3.8 dB. The overall average of $D_{nT,w,50}$ is 56.3 dB and the standard deviation is 3.5 dB. The distribution according to the Swedish sound classification [22], based upon $D_{nT,w,50}$, is shown in Fig. 2. Sound class *C* corresponds to the minimum requirement of the national building code, $D_{nT,w,50} \geq 52$ dB, while sound class *B* and *A* means successively 4 dB improved sound insulation. 5 of the 46 building objects (11%) do not fulfill the minimum requirement while 29 objects (63%) manage sound class B or better.

3.2. Rated sound insulation

The mean annoyance of all the building objects is shown in Fig. 3 for the questions regarding daily living sounds and music. The annoyance from footsteps, an impact sound source, serves as comparison. The mean annoyance from daily living sounds in the main direction (vertical) on the 0–10 numerical scale is 1.6, where the min/max scores are 0,1/4,2 with the standard deviation 0.8. In horizontal direction, the mean annoyance is 0.9, where the min/max scores are 0.0/3.0 with the standard deviation 0.7. The annoyance from vertical sounds is thus rated with about 70% higher score than in the horizontal direction. The mean annoyance from music is 1.8, where the min/max scores are 0.1/4.8 with the standard deviation 1,1. Note that the question regarding music disturbance was only available for 35 out of the 46 objects. All the airborne sound related questions show low annoyance, in average, indicating that the residents are in general quite satisfied. (As mentioned above, 63% of the objects have at least 4 dB higher insulation than the minimum requirement by the building regulations.) As a comparison, the residents rate the noise from footsteps with a score being about twice as high. This relation in annoyance between impact and airborne sound sources was established already in one of the underlying studies [20] where mean annoyance scores of 5–6 were reported for some objects. Thus, inadequate impact sound insulation is, for the included objects, a more noticeable problem whereas their airborne sound insulation seems rather satisfactory.

3.3. SNQ's vs. annoyance from daily living sounds and music

In Fig. 4, the linear regressions for $D_{nT,w}$ and $D_{nT,w,50}$ against the rated annoyance of daily living sounds in all included objects are presented. The coefficient of determination, R^2, is 8% for $D_{nT,w}$ and 11% for $D_{nT,w,50}$. The R^2 for the alternative evaluation parameters $D_{nT,w,50tr}$, $D_{nT,w,50opt}$ and $D_{nT,w,50mod}$ is 7%, 8% and 6% respectively.

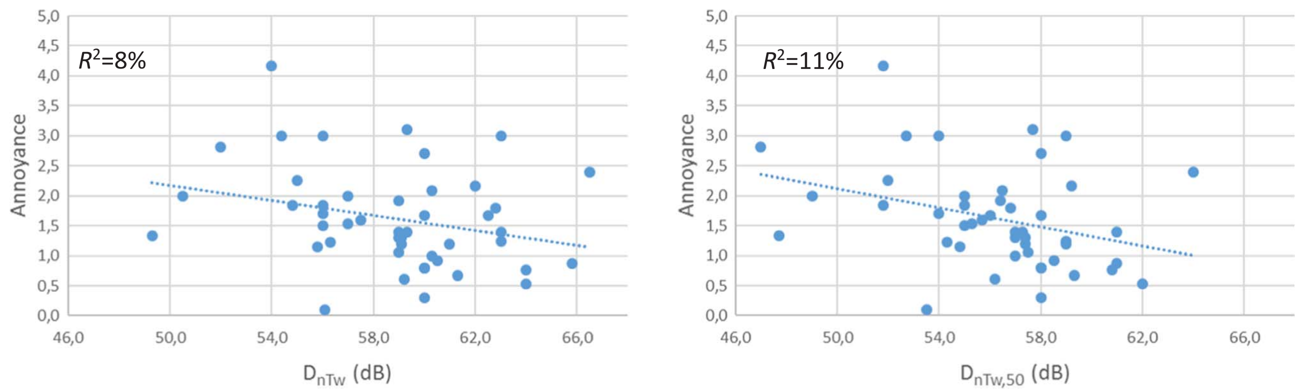

Fig. 4. Linear regression between $D_{nT,w}$ (left) and $D_{nT,w,50}$ (right) against the rated annoyance of daily living sounds.

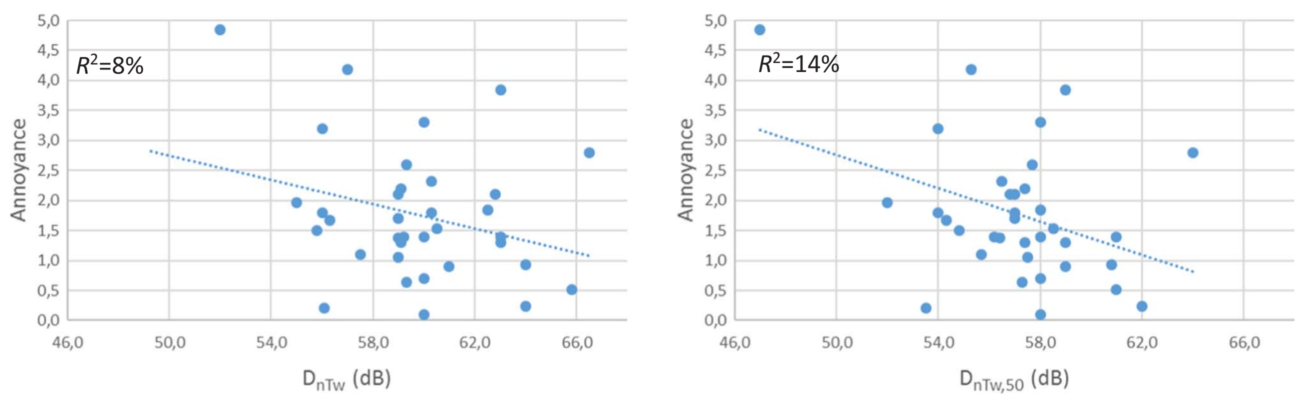

Fig. 5. Linear regression between $D_{nT,w}$ (left) and $D_{nT,w,50}$ (right) against the rated annoyance of music.

In Fig. 5, the linear regressions for $D_{nT,w}$ and $D_{nT,w,50}$ against the rated annoyance of music in all included objects are presented. The coefficient of determination, R^2, is 8% for $D_{nT,w}$ and 14% for $D_{nT,w,50}$. The R^2 for the alternative evaluation parameters $D_{nT,w,50tr}$, $D_{nT,w,50opt}$ and $D_{nT,w,50mod}$ is 8%, 9% and 6% respectively.

A summary of the outcome of the regression analysis is shown in Table 1. It also contains information whether, or not, there is a statistical relation on 95% confidence level between the annoyance and respective evaluation parameter. It can be seen that a statistical significant relation is only achieved for $D_{nT,w,50}$, which holds for both kinds of sound source.

3.4. Lightweight vs. Concrete constructions

It is often assumed that potential low frequency problems concern primarily lightweight constructions. Table 2 presents the results from similar regression analysis as above, but this time separated into two groups; 24 lightweight buildings (20 for the music annoyance) and 22 concrete buildings (15 for the music annoyance). The averaged sound insulation and annoyance are similar between the two groups. The mean $D_{nT,w,50}$ is 56.6 and 56.1 dB for lightweight and concrete buildings respectively and the mean annoyance from daily living sounds is 1.4 and 1.8 and from music 1.6 and 1.9 respectively.

The regression analysis of annoyance from daily living sounds shows the same coefficient of determination, 10%, for both $D_{nT,w}$ and $D_{nT,w,50}$ within the concrete objects. For the lightweight buildings, R^2 = 4% and 12% for $D_{nT,w}$ and $D_{nT,w,50}$ respectively, and R^2 increases to 20% for $D_{nT,w,50tr}$ which further emphasizes the lower frequencies. For the annoyance from the more low frequency source, music, R^2 = 0% in the concrete buildings for both $D_{nT,w}$ and $D_{nT,w,50}$. Among the lightweight objects, R^2 = 15% and R^2 = 31% for $D_{nT,w}$ and $D_{nT,w,50}$ against music while R^2 = 37% using $D_{nT,w,50tr}$. It should then be beneficial to include the 50 Hz term dealing with lightweight constructions while the same connection to concrete buildings is not evident here. The linear regressions for $D_{nT,w,50}$ against the rated annoyance from music for the concrete and lightweight objects separately are shown in Fig. 6.

Table 2
R^2 from regression analysis: Annoyance from daily living sounds and music against various evaluation parameters in concrete (Conc.) and lightweight (L.W.) buildings.

$D_{nT,w}$		$D_{nT,w,50}$		$D_{nT,w,50tr}$		$D_{nT,w,50opt}$		$D_{nT,w,50mod}$	
Conc.	L.W.	Conc.	L.W.	Conc.	L.W.	Conc.	L.W.	Conc.	L.W.
Daily living sounds									
10%	4%	10%	12%	7%	20%	11%	3%	9%	1%
Music									
0%	15%	0%	31%	0%	37%	3%	11%	0%	8%

Table 1
Correlation of annoyance from two sound sources against various evaluation parameters, "st. sign." indicates whether a statistical relation exists on 95% confidence level.

Sound source	$D_{nT,w}$		$D_{nT,w,50}$		$D_{nT,w,50tr}$		$D_{nT,w,50opt}$		$D_{nT,w,50mod}$	
	R^2	st.sign.	R^2	st.sign.	R^2	st.sign.	R^2	st.sign.	R^2	st.sign.
Daily living	8%	no	11%	yes	7%	no	8%	no	6%	no
Music	8%	no	14%	yes	8%	no	9%	no	6%	no

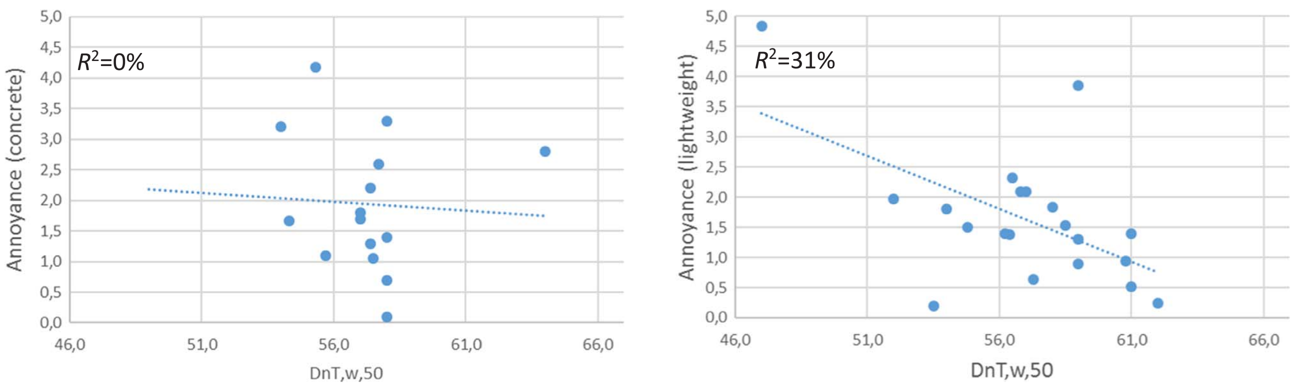

Fig. 6. Linear regression between $D_{nT,w,50}$ against the rated annoyance of music within the concrete (left) and lightweight (right) buildings.

The alternative adaptation terms, $D_{nT,w,50opt}$ and $D_{nT,w,50mod}$ performs relatively well for daily living sounds in concrete buildings. In lightweight constructions, for both daily living sounds and music, $D_{nT,w,50tr}$ shows the highest correlation among the evaluated SNQ's. This further strengthens the assumption that evaluation including the low frequency range is of essential importance regarding lightweight building technique.

4. Discussion

Overall, the analyzed relations between SNQ's and annoyance show low correlation. In most cases, the correlation is so weak that the statistic relation is insignificant. The reasons for this are important to discuss.

The overall average sound insulation was found to be 56.3 dB for $D_{nT,w,50}$ which indicates that 70% of the residents should be "not at all annoyed" according to the large study carried out in Norwegian dwellings 2002–2015 [23]. The residents in the study of our paper are in general nor particularly annoyed about noise from airborne sound sources since most of the building objects have "good" sound insulation. The combination of low annoyance and high sound insulation makes it hard to find strong mathematical connections between them. If the range in sound insulation had been wider, it is likely that the correlation against annoyance had become higher. Furthermore, it must be assumed that the perceived annoyance is not a function of the sound insulation solely but involves other aspects. The authors are convinced that the neighbors' behavior and the individual preferences are as well as important. These human aspects are likely the dominating factors of annoyance from airborne sounds, among the relatively few residents being severely annoyed, when living in buildings with high sound insulation.

From the underlying data, it is hard to make any clear statement whether airborne sound insulation should be evaluated from 50 or 100 Hz. But strictly statistically, no significant relation against rated annoyance could be found when using 100 Hz as the lower frequency limit. Evaluation from 50 Hz with $D_{nT,w,50}$ does establish a significant relation although the coefficient of determination is low and the differences compared to $D_{nT,w}$ are small. A possible explanation is that all of the buildings, except 4 of them, were constructed after 1999, i.e. after that the 50 Hz limit became mandatory in Sweden. Thereby, it can be assumed that the constructions were designed to give better insulation at lower frequencies than was the case before the regulation was introduced. Earlier, it was in a way possible to design the construction such that structural resonances, that naturally occur, could be avoided above 100 Hz and instead be put at slightly lower frequencies with no further action taken. In this respect, heavy concrete constructions are less sensitive since they, due to their high mass, better can withstand low frequencies. However, any used SNQ should not only be related to a specific type — but to all kinds — of construction. Bear also in mind the ability of a SNQ, used as a requirement, to force the building industry to use constructions with sufficient sound insulation to all types of noise being prevalent more than occasionally in neighboring dwellings.

Even though no big difference in the correlation was achieved concerning evaluating from 50 or 100 Hz, it is important to reflect about whether high correlation or high protection is the most important. The alternative spectrum adaptation terms $D_{nT,w,50opt}$ and $D_{nT,w,50mod}$ certainly do consider frequencies from 50 Hz, but their weighting curves reduce the importance of lower frequencies compared to $D_{nT,w,50}$. These alternative terms have been developed to obtain high correlation rather than high protection against all kinds of disturbing noise. Any regulation that neglect lower frequencies do risk the situation where limited protection from specific sound sources is given as well as sub optimization of the constructional design. Dimensioning must be performed in accordance with the weakest case in order to be protective for all cases.

In Sweden, the 50 Hz spectrum adaptation terms have been used regularly during almost 20 years. The fact that relatively few residents in the presented study complain about the airborne sound insulation could be taken as a justification of the low frequency requirement in the national building code. An innovative idea is to include even lower frequencies, i.e. below 50 Hz. However, a primitive investigation including 10 building objects evaluated down to 20 Hz was done in the earlier presented study [20] but no support to that idea was given (regarding airborne sound).

5. Conclusions

The extensive data of measurements and questionnaire surveys from 46 objects of apartment houses suggest that the evaluation of airborne sound insulation from 50 Hz by $D_{nT,w,50}$ is a slightly better choice than evaluation from 100 Hz by $D_{nT,w}$. However, since most of the included buildings were originally designed to fulfill the requirements of the Swedish building code, based upon $D_{nT,w,50}$, the result could possibly have been different if they were designed for a 100 Hz criterion. Airborne noise generates generally low annoyance rating from the residents in these constructions, a fact that confirms the national regulation.

A criterion including frequencies from 50 Hz puts higher demands on the buildings' construction. Even though many daily living sounds contain just a small amount of energy below 100 Hz, the residents will obtain a certain protection towards low frequency sources, e.g. music, if criteria from 50 Hz are used. The authors' understanding is therefore to encourage evaluation from 50 Hz, on the basis that the disturbances that after all occur often are due to music.

Note that the given conclusions are based upon Swedish living conditions, which mean that tenants are used to live rather independently in their own home as well as staying indoors because of the climate. On other markets, the conditions can be different in these respects.

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