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Correlation between sound insulation and occupants' perception – Proposal of alternative single number rating of impact sound, part II

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ABSTRACT

A previous Swedish research project indicated the potential need for evaluating impact sound insulation from 20 Hz in buildings with lightweight constructions. This is a discrepancy compared to the commonly used frequency intervals starting from 50 or 100 Hz. The statistical significance of this groundbreaking suggestion was however not satisfactorily strong since the result was based upon a limited number of building objects.

The scope of the present paper is to secure the previous study by adding additional objects to the underlying database, thereby increasing the confidence of the results. The methodology is to perform impact sound insulation measurements in apartment buildings of various construction types and to perform questionnaire surveys among the residents. The measured sound insulation is compared to the subjective rating by the occupants in order to find the parameter giving the highest correlation with respect to frequency range and weighting.

The highest correlation was found when the impact sound insulation was evaluated from 25 Hz using a flat frequency-weighting factor. Frequencies below 50 Hz are of great importance when evaluating impact sound insulation in lightweight constructions.

1. Introduction

Impact sound insulation has been evaluated within the frequency range 100–3150 Hz ever since the single number quantities $L'_{n,w}/L'_{nT,w}$ were standardized in 1968 (ISO/R 717). These parameters are based upon a comparison with a specified reference curve originally designed for heavy building construction materials like masonry and concrete. Eventually it became apparent that the method was ill suited to lightweight constructions having frames of wood or thin steel profiles. The mismatch is explained by the lightweight constructions, at the time, normally suffered from significantly lower impact sound insulation at frequencies below 100 Hz. This mismatch was partly overcome by the introduction of the low frequency spectrum adaptation term in 1996 (ISO 717), $C_{I,50-2500}$, i.e. by considering frequencies down to 50 Hz. The use of $L'_{n,w} + C_{I,50-2500}$ was introduced as mandatory into the Swedish building code 1999 and has also been voluntarily used within other regulations. Even though the adaptation term was seen as an important improvement by the building industry and lightweight multi-storey residential housing constructions have been continuously developed during the last decades, there is still a mismatch in the correlation between objective measurements and subjective perception of sound insulation among residents. This was one of the key topics in the Swedish research project AkuLite (2009–2013) where it was found that the coefficient of determination, R^2, between $L'_{n,w} + C_{I,50-2500}$ and the subjective perception from residents was just 32%, a correlation so low that no statistical relation between the parameters could be established [1]. But when the frequency span was extended down to 20 Hz in terms of $L'_{n,w} + C_{I,20-2500}$ the corresponding correlation increased to 74%, a remarkable improvement that strongly indicated the need to evaluate frequencies below 50 Hz. In fact, the coefficient of determination got even higher, 85%, using a modified spectrum adaptation term called $C_{I,AkuLite,20-2500}$ which emphasizes the importance of the lowermost frequencies by successively adding 2 dB extra weight for each third-octave band at 20–40 Hz. In this frequency region, lightweight constructions are prone to having poor impact sound insulation. The adaptation terms also put 1 dB extra weight for each third-octave band at 500–2500 Hz to cover potential problems in concrete buildings, e.g. where tiles are glued on the top of the slab. The weighting curves are shown graphically in Fig. 1. The

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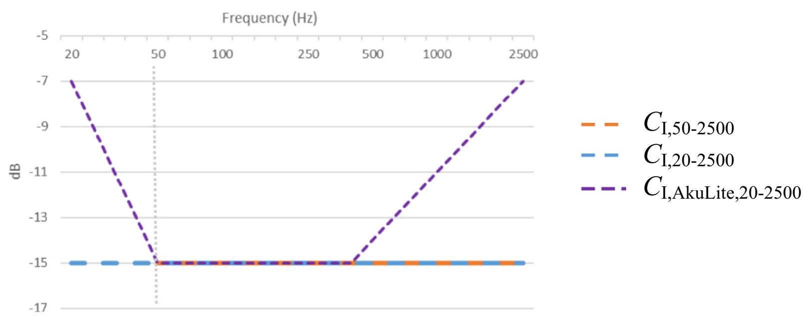

Fig. 1. Weighting curves of the spectrum adaptation terms $C_{I,50–2500}$, $C_{I,20–2500}$ and $C_{I,AkuLite,20–2500}$.

result was adopted into the Swedish standard for sound classification 2015 [2], where impact sound insulation, on voluntarily basis, is evaluated from 20 Hz for higher sound classes than the minimum requirement.

Despite these novel findings, the result should not be interpreted as the "final conclusion" but rather as an indication. The reason is that the referred study included only ten building objects, of which nine were of lightweight or semi-lightweight type and one made of concrete. It was concluded necessary to increase the number of building objects in order to verify the obtained indications.

The present study is a part of the Swedish national research project known as Aku20, an acronym for *New improved building technique neutral criteria for sound insulation evaluation*. The results presented below can be regarded as a direct continuation of the referred study [1]. In total, it involves 23 building objects that will give a considerably stronger statistical power to the analysis.

From here on, the original study [1] including 10 objects is referred to as part I and the present combined study of 13 additional building objects, 23 in total, is referred to as part II. Thus, part I involves the objects from AkuLite while part II deals with objects from both AkuLite and Aku20.

1.1. Objective

The objectives of this paper are:

– To find out whether it can be statistically shown that impact sound insulation evaluated from 20 Hz gives a higher correlation to subjectively rated annoyance compared to the standardized evaluation from 50 Hz.
– To find out whether an alternative, optimized frequency weighted spectrum adaptation term, can bring additional conformity between measured and perceived impact sound insulation.

2. Building objects

The 23 involved objects are located in different parts of Sweden, representing a variety of modern building techniques. All buildings are categorized as multi-storey residential houses with 2–8 storeys. A majority of the objects are newly produced while some of them were a few years old when they were selected for this study, although none was older than ten years. With respect to their building techniques, the objects are divided into three subcategories:

1. *Lightweight* – loadbearing structure of wooden or thin steel beams together with various types of boards.
2. *Cross laminated timber* (*CLT*) – structure based upon layers of timber, glued together.
3. *Concrete* – homogenous or hollowed core concrete framework.

11 of the objects are of lightweight type while CLT (semi-lightweight) and concrete hold 6 objects each. A summary is shown in Table 1 where objects 1–10 originate from AkuLite and objects 11–23 are the additional ones from Aku20.

3. Field measurements

3.1. Method – field measurements

For each object, extensive field measurements have been performed concerning both sound and vibrations, see [1] for further details. The measurements with direct or indirect connection to impact sound are:

(a) Impact sound insulation using the standardized tapping machine:

Measurements and evaluations were performed according to the present standards ISO 16283-2 [3] and ISO 717-2 [4] and/or the former ISO 140-7 [5] and ISO 717-2 [6]. All measurements were recorded in the extended frequency range: 20–5000 Hz.

(b) Impact sound insulation using the rubber ball:

Measurements and evaluations were performed according to ISO 16283-2 [3]. All measurements were recorded in the extended frequency range: 20–630 Hz.

(c) Static deflection of the floor:

Measurements of the deflection due to a 1 kN point load in the center point, alternatively in the weakest point, of the floor.

The impact sound insulation was measured in 4–6 rooms for each object, typically evenly distributed between living rooms and master bedrooms. A couple of the objects though, are represented by a fewer number of measured rooms while the opposite occurs for an equal number of objects. The static deflection deviates in this respect since only *one* measurement was taken for each object.

3.2. Results

Unless otherwise stated, the results in the following diagrams are presented as the arithmetic mean value for each of the 23 objects presented in Table 1.

3.2.1. Impact sound using the tapping machine

The results are based upon the standardized impact sound level L'_{nT}, i.e. the impact sound level is normalized with respect to the

Table 1
Building objects.

No	City	Construction type	Construction	Research project	New building	Existing building
1	Stockholm	**Lightweight**	Wood	AkuLite	X	
2	Östervåla	**CLT**	Cross lam. timber	AkuLite	X	
3	Umeå	**Concrete**	Concrete	AkuLite		X
4	Växjö	**CLT**	Cross lam. timber	AkuLite		X
5	Växjö	**CLT**	Cross lam. timber	AkuLite		X
6	Falun	**CLT**	Cross lam. timber	AkuLite		X
7	Alingsås	**Lightweight**	Wood	AkuLite		X
8	Lindesberg	**Lightweight**	Wood	AkuLite		X
9	Örebro	**Lightweight**	Thin Steel	AkuLite		X
10	Varberg	**Lightweight**	Wood	AkuLite	X	
11	Stockholm	**Lightweight**	Wood	Aku20	X	
12	Malmö	**Lightweight**	Wood	Aku20	X	
13	Luleå	**Lightweight**	Wood	Aku20	X	
14	Stockholm	**CLT**	Cross lam. timber	Aku20	X	
15	Borås	**CLT**	Cross lam. timber	Aku20	X	
16	Göteborg	**Concrete**	Concrete	Aku20	X	
17	Stockholm	**Lightweight**	Wood	Aku20	X	
18	Uppsala	**Lightweight**	Wood	Aku20	X	
19	Växjö	**Concrete**	Homog. concrete	Aku20	X	
20	Växjö	**Lightweight**	Wood	Aku20	X	
21	Kristianstad	**Concrete**	Beam-plate concrete	Aku20	X	
22	Umeå	**Concrete**	Homog. concrete	Aku20	X	
23	Malmö	**Concrete**	Hol. core concrete	Aku20	X	

reverberation time 0,5 s for each third-octave band. The corresponding single number quantity (SNQ) $L'_{nT,w,50}$ is prescribed in the Swedish building code [7] since 2014 and in the Swedish standard for sound classification since 2015 [2]. The notation $L'_{nT,w,50}$ is used as an abbreviation of $L'_{nT,w} + C_{I,50\text{–}2500}$ and in the same way $L'_{nT,w,20,AL}$ is used as a shorter notation of $L'_{nT,w} + C_{I,AkuLite,20\text{–}2500}$. The SNQ's for each object are presented in Fig. 2.

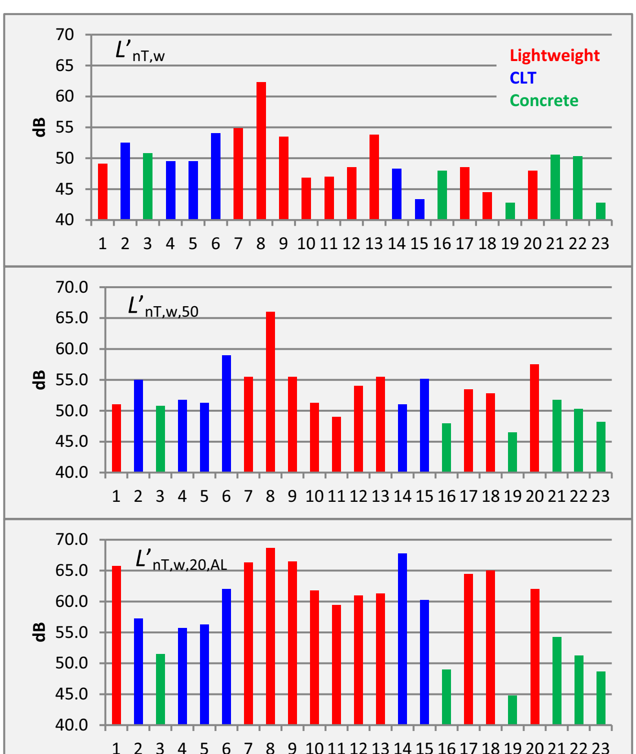

Fig. 2. Impact sound level for 23 objects (no. 1–23) in terms of $L'_{nT,w}$, $L'_{nT,w,50}$ and $L'_{nT,w,20,AL}$ with construction type indicated.

The overall span is 43–62 dB for $L'_{nT,w}$, 47–66 dB for $L'_{nT,w,50}$ and 49–69 dB for $L'_{nT,w,20,AL}$. The mean value increases in average by 3,6 dB when $L'_{nT,w}$ is replaced by $L'_{nT,w,50}$ and by 5,9 dB when $L'_{nT,w,50}$ is replaced by $L'_{nT,w,20,AL}$. There is a clear variation between the three different building construction types, see Fig. 3 in which also $L'_{nT,w,20}$, i.e. $L'_{nT,w} + C_{I,20\text{–}2500}$, is included. The difference between $L'_{nT,w,50}$ and $L'_{nT,w,20,AL}$ is, on average, 9,2 dB for the lightweight constructions, 6,0 dB for the CLT's but only 0,6 dB for the concrete buildings. This consolidates the hypothesis that impact sound insulation below 50 Hz, primarily is a potential problem related to lightweight, and semi-lightweight floor constructions.

3.2.2. Impact sound using the rubber ball

In the Aku20-project (except object no. 14) the impact sound level was, as a complement, also measured by using the standardized rubber ball. The results refer to maximum impact sound pressure level, $L'_{I,Fmax,V,T}$, described in ISO 16283-2 [3] and the used frequency range is 50–630 or 20–630 Hz. Since no guidance to SNQ's is given by ISO, the linear or A-weighted levels in the

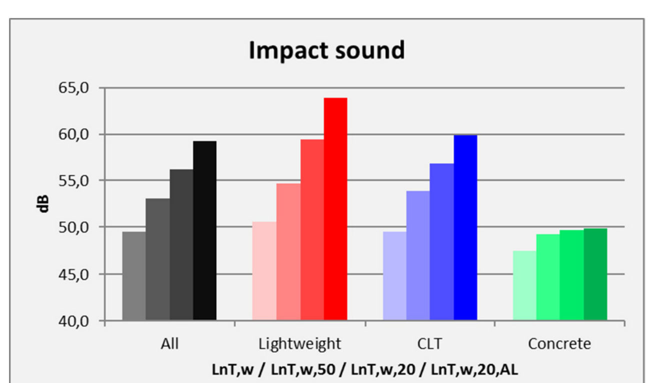

Fig. 3. Impact sound level in terms of mean value for all objects and divided into building construction type. From left to right, within each group: $L'_{nT,w}$, $L'_{nT,w,50}$, $L'_{nT,w,20}$ and $L'_{nT,w,20,AL}$.

third-octave bands were summarized to obtain representative single numbers.

The results from the 12 objects – 6 lightweight, 1 CLT and 5 concrete – can be seen in Fig. 4. As for the tapping machine, the sound pressure level increases more for the lightweight constructions compared to the concrete constructions when the frequency range is extended down to 20 Hz.

3.2.3. Static deflection

The outcome from the measurement of static deflection is presented in Fig. 5. The deflection ranges from 0,1 to 1,7 mm and the trend is that the lightweight objects show larger deflection than the concrete objects. The intention was to measure in the weakest point of the room, which intuitively should be in the room's center. In reality, this is not always the case though, and it can be hard to know the weakest point without access to detailed construction drawings. It is therefore likely that several of the reported results originate from positions other than the ones with the lowest stiffness. Together with the fact that only *one* measurement was taken for each object, the obtained results are likely to be less accurate compared to the sound measurements.

The concrete object No 23, shows the largest deflection, 1,7 mm, which is considerably larger than the other objects within the same constructional category. This is probably due to a raised subfloor including chipboards on a vibrational insulated framework on top of the hollow-core concrete slab.

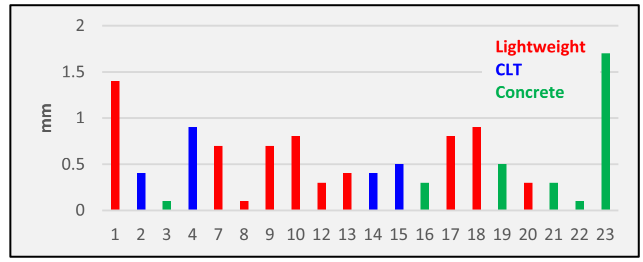

Fig. 5. Static deflection due to a point load of 1 kN for 20 objects (No. 1–4, 7–10 and 12–23).

4. Subjective perception by the occupants

4.1. Method - questionnaire survey

Except for some minor modifications, the used questionnaire in Aku20 is the same as was used in the foregoing part I [1], originally developed within the European COST action TU0901 [8]. The questionnaire in its latest version contains 17 questions where the residents are asked to judge the annoyance related to various aspects of sound insulation. A numerical scale from 0 to 10 is used where "0" means *not at all bothered, disturbed or annoyed* and "10" means *extremely annoyed*.

Three of these questions are potentially related to impact sound insulation:

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

1. *Neighbors; footstep noise, i.e. you hear when they walk on the floor*
2. *Neighbors; rattling or tinkling noise from your own furniture when neighbors move on the floor above you*
3. *Neighbors; impact or scraping noise, i.e. from chairs, kitchen sink, lockers, toys, vacuum cleaning etcetera*

The number of answers among the objects varied between 13 and 91 corresponding to a reply rate of 33–83%. In total, approximately 800 of the distributed questionnaires were returned filled. The questionnaires were distributed to the households no earlier than six months after completion of the actual new building object.

4.2. Results

Unless otherwise stated, the results in the following diagrams are presented as the mean value of all measurements made in each of the 23 objects presented in Table 1. All answers from residents living on the uppermost floor of the buildings were excluded since they are not exposed to impact sound from neighbors living above.

The outcome of the three questions described above can be seen in Fig. 6. Footstep noise clearly generates more annoyance than rattling/tinkling and impact/scraping noise. The two latter sources, in general, only cause moderate disturbance, as rated by the residents.

The difference in annoyance within the three building construction types is presented in Fig. 7, where it can be seen that footstep annoyance is at least twice as high as for the other sound sources. Further, the proportion of the annoyance from footstep and rattling/tinkling noise looks similar, suggesting a high correlation between these two sources. Note that the impact or scraping noise question was added in the updated questionnaire version, distributed to 12 objects only (instead of 23). The mean annoyance from this sound source is therefore not directly comparable with the others.

5. Correlation between field measurements and residents ratings (questionnaire surveys)

5.1. Method – statistical analyses

A series of regression analyses were performed to analyze the statistical relationship between the objective and subjective

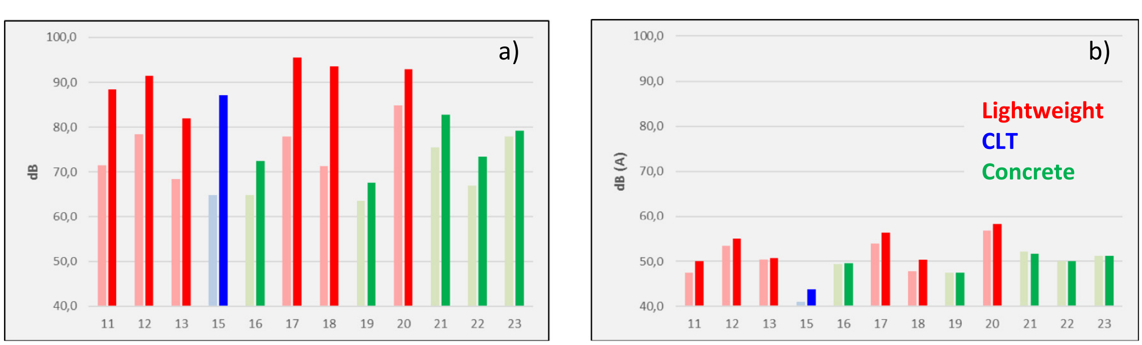

Fig. 4. Linear impact sound (left) and A-weighted impact sound (right) using the rubber ball for 12 objects (no. 11–13 and 15–23) in terms of $\sum L'_{I,Fmax,V,T}$. Within each object, the left bar represents the frequency range 50–630 Hz and the right bar 20–630 Hz.

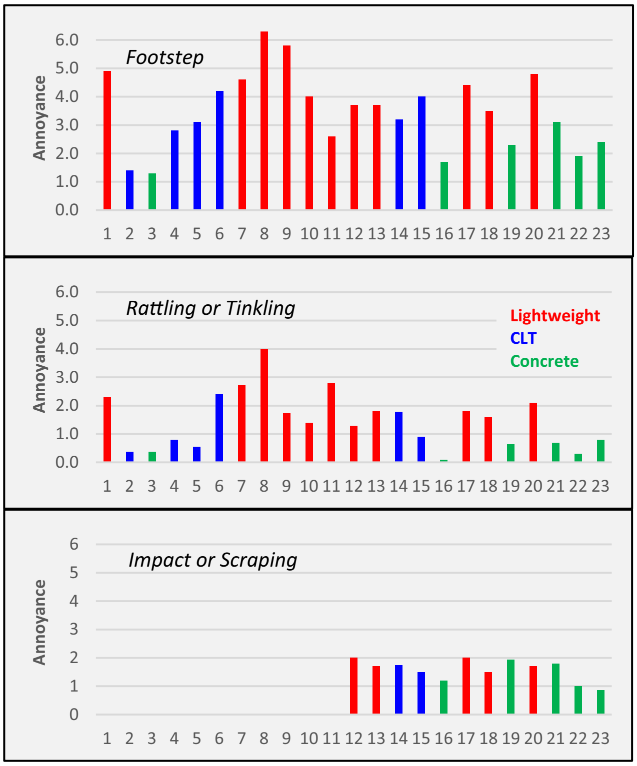

Fig. 6. Mean annoyance from three impact sound related sources for 23 objects (12 objects regarding impact or scraping, No 12–23). The numerical annoyance scale ranges from 0 to 10.

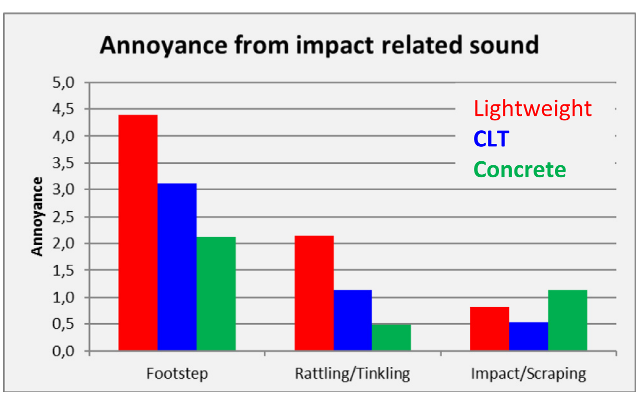

Fig. 7. Mean annoyance regards to building construction type from three impact sound related sources for 23 objects (12 regarding impact and scraping, No 12–23). The numerical annoyance scale ranges from 0 to 10.

parameters. The objective parameters in terms of measurements are represented by the mean from each of the 23 building objects while the subjective parameters are represented by the corresponding mean annoyances form the questionnaire. As mentioned, the question of impact or scraping was only used in 12 objects.

Of great importance is the coefficient of determination (R^2, equivalent to the square of the correlation coefficient) which is evaluated from the classical linear regression model $Y = a + bX$, where Y represents the annoyance and X represents the measured quantity. The confidence interval of the regression line's slope reveals whether, or not, there is a statistical relationship between Y and X related to 95% confidence, i.e. whether the interval includes the value "0" or not. This is here reported as "Stat. rel." – *yes* or *no*.

The results are presented in the following paragraphs, grouped with respect to the measurement method using the: (1) tapping machine, (2) rubber ball and (3) static deflection.

5.2. Results

5.2.1. Tapping machine

Four different SNQ's are compared with the annoyance for the three survey questions presented above. The achieved coefficients of determination are given in Table 2 and Fig. 8 shows the regression diagrams for footstep annoyance.

$L'_{\mathrm{nT,w}}$ – a common SNQ in many European countries [9] – gives a coefficient of determination of 18% related to annoyance from footstep. This is increased to 49% when the spectrum adaptation term from 50 Hz is added, i.e. $L'_{\mathrm{nT,w,50}}$. When the frequency span is extended down to 20 Hz, the coefficient of determination increases even further, 71% regarding $L'_{\mathrm{nT,w,20}}$ and 65% regarding $L'_{\mathrm{nT,w,20,AL}}$.

Correlating against the annoyance from rattling or tinkling, gives results that are very close to the footstep case while annoyance from impact or scraping shows considerably lower correlation and none of the SNQ's showed any statistically significant relation to the subjective rating.

5.2.2. Rubber ball

In Table 3 and Fig. 9, four different summarizing sound level parameters according to Section 3.2.2 are compared with the annoyance for the dataset of 11 objects. The parameters are calculated as the linear or A-weighted sum of the third-octaves $L'_{\mathrm{I,Fmax,V,T}}$ within two frequency bands, 50–630 and 20–630 Hz.

In general, the rubber ball shows poor correlation to subjective rating with one exception: When linear sound level summation is performed from 20 Hz, the coefficient of determination is 77%, even somewhat higher than using the tapping machine even though no exact comparison should be made due to discrepancy in the number of including building objects.

However, the correlations are to high extent affected by one single object. If that particular object is treated as an outlier and removed from the analyses, the difference in correlation between linear and A-weighted levels become smaller (77% using dB vs. 68% using dB(A), 20–630 Hz), i.e. the data favor neither linear nor A-weighting. It may be surprising that the A-weighting does not show better correlation against annoyance compared to the linear case. But the resulting sound pressure levels using the ball are clearly dominated by the low frequencies and it is a highly complex matter to weight them in a correct manner. E.g. sounds at very low frequencies are often considered annoying at levels that are just above the hearing threshold, which is taken as a limit in regulations on service equipment noise in some European countries.

5.2.3. Static deflection

No statistic relation between static floor deflection and annoyance could be found despite the underlying idea that the impact sound insulation might be correlated with the stiffness of the floor, see Table 4. The mismatch *could* be due to the practical problem of finding the weakest position when performing the measurements.

6. Complementary analysis and discussion

6.1. Comparison with the previous study

Table 5 shows a comparison of the obtained coefficient of determinations from the original 10 objects (part I) and the present 23 (part II). The correlations between various SNQ:s and annoyance from the neighbors' footstep are considered.

Table 2
Coefficient of determination R^2 and indication of existing statistic relation with 95% confidence.

	Footstep		Rattling/tinkling		Impact/scraping	
	R^2 (%)	Stat. rel	R^2 (%)	Stat. rel	R^2 (%)	Stat. rel
$L'_{nT,w}$	18	*Yes*	26	*Yes*	10	*No*
$L'_{nT,w} + C_{I,50-2500}$	49	*Yes*	43	*Yes*	15	*No*
$L'_{nT,w} + C_{I,20-2500}$	71	*Yes*	64	*Yes*	25	*No*
$L'_{nT,w} + C_{I,20-2500,AL}$	65	*Yes*	61	*Yes*	25	*No*

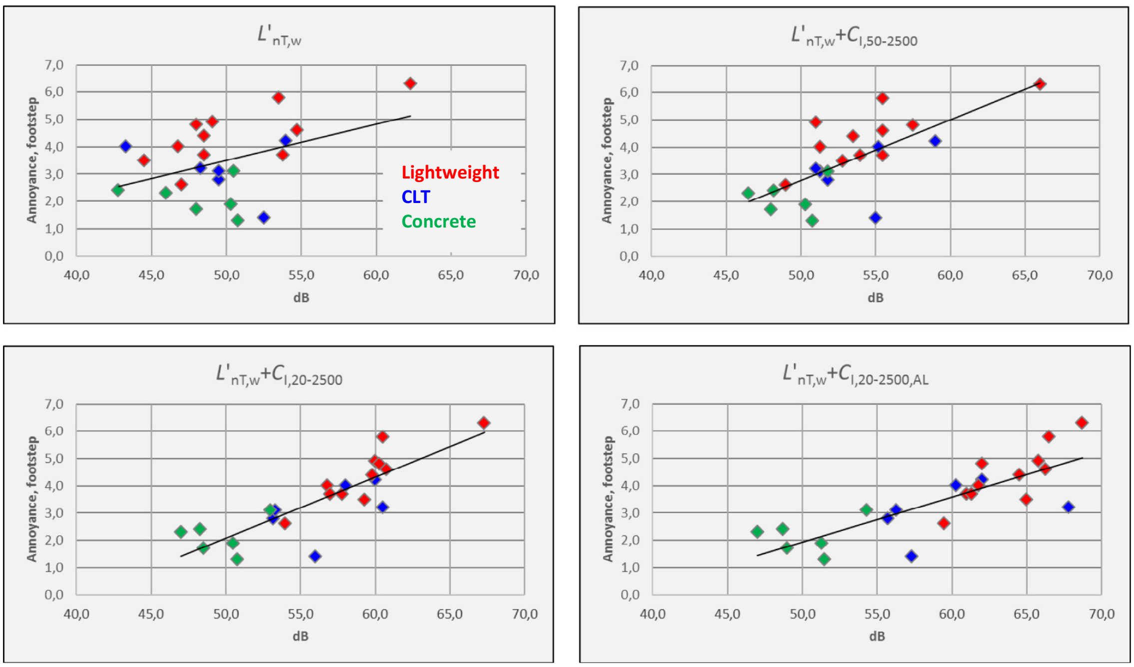

Fig. 8. Linear regression of annoyance from footstep vs. SNQ's from impact sound measurements in 23 objects.

Table 3
Coefficient of determination R^2 and indication of existing statistic relation with 95% confidence.

	Footstep		Rattling/tinkling		Impact/scraping	
	R^2 (%)	Stat. rel.	R^2 (%)	Stat. rel.	R^2 (%)	Stat. rel.
Ball 50–630 Hz, dB	35	*No*	38	*Yes*	5	*No*
Ball 50–630 Hz, dB(A)	8	*No*	19	*No*	6	*No*
Ball 20–630 Hz, dB	77	*Yes*	64	*Yes*	17	*No*
Ball 20–630 Hz, dB(A)	23	*No*	37	*Yes*	11	*No*

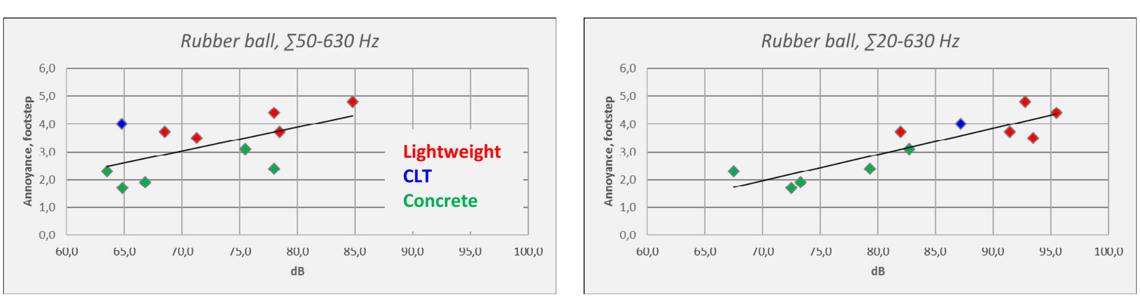

Fig. 9. Linear regression of annoyance from footstep vs. summarized sound levels from rubber ball measurements in 11 objects.

Overall, the two studies show similar results although it can be seen that when evaluating from 50 Hz, the correlation is somewhat higher for all the 23 objects while the opposite is true when evaluating from 20 Hz. This is probably because the original 10 objects were dominated by lightweight and semi-lightweight buildings while the additional 13 objects contain a larger amount of concrete buildings. Heavy constructions are less prone to be affected by impact sound annoyance below 50 Hz.

It should also be noted that whereas the part I objects obtained the highest correlation using an increased frequency weight for

Table 4
Coefficient of determination R^2 and indication of existing statistic relation with 95% confidence.

	Footstep		Rattling/tinkling		Impact/scraping	
	R^2 (%)	Stat. rel	R^2 (%)	Stat. rel	R^2 (%)	Stat. rel
Static deflection	2	*No*	0	*No*	13	*No*

Table 5
Coefficient of determination R^2 and indication of existing statistic relation with 95% confidence.

SNQ	Part I - 10 objects		Part II - 23 objects	
	R^2 (%)	Stat. rel	R^2 (%)	Stat. rel
$L'_{nT,w}$	26	*No*	18	*Yes*
$L'_{nT,w,50}$	32	*No*	49	*Yes*
$L'_{nT,w,20}$	74	*Yes*	71	*Yes*
$L'_{nT,w,20,AL}$	85	*Yes*	65	*Yes*

20–40 Hz, $L'_{nT,w,20,AL}$, the flat weighting curve, $L'_{nT,w,20}$, obtained the highest correlation when all 23 objects were analyzed.

6.2. Alternative frequency ranges and weightings

Even though the results clearly indicate that the correlation increases when the impact sound insulation is evaluated from 20 instead of 50 Hz, it is unclear whether it is beneficial to increase the weighting factor at the lowermost frequencies. An additional question is whether the 20 Hz third-octave band is the preferable lower limit or if equal, or even higher, correlation may be achieved by a limited extension of the frequency range?

Regression analyses between annoyance and stepwise extension of the frequency range have been performed as well as applying various frequency weightings to the spectrum adaptation term. It is shown in Table 6 how the coefficient of determination gradually increases as the frequency region of evaluation is extended by one third-octave band at a time until 25 Hz is reached. Including the 20 Hz band does not increase R^2.

So far, no extra weight has been applied to the lowermost frequencies but does such an arrangement alter the outcome? Table 7 deals with two parameters, evaluation from 20 or 25 Hz and various frequency weighting at 20–40 Hz where the weighting curves have a slope of 0–3 dB, similar to Fig. 1. Note that the cases 1, 2, and 3 dB contain the same high frequency modification as $C_{I,AkuLite,20-2500,}$ which means that a slope of 2 dB is equivalent with the SNQ $L'_{nT,w,20,AL}$ (and $L'_{nT,w,25,AL}$). The case 0 dB represents a weighting curve that is flat throughout the whole frequency range. The SNQ with the highest R^2, 77%, is obtained for $L'_{nT,w,25,AL}$, i.e. applying the previous term $C_{I,AkuLite,20-2500}$ but omitting the 20 Hz third-octave band. However, the modification of the low frequency weighting down to 25 Hz, within the here presented limits, only give rise to small effects since the overall coefficient of determination is maintained within the interval 72–77%.

The regression line for the case with the highest correlation, $L'_{nT,w,25,AL}$, is shown in Fig. 10. One of the objects (No. 2) is somewhat abnormal since the rated annoyance is much below from what should be expected according to the model. A closer look at that specific object reveals that almost all the residents are of the age 65 or older, which makes it stand out from all the other objects. Although not proven, it is likely that this group of people have a

Table 6
Coefficient of determination R^2 for various SNQ:s vs. perceived footstep noise annoyance.

SNQ	$L'_{nT,w}$	$L'_{nT,w,50}$	$L'_{nT,w,40}$	$L'_{nT,w,31}$	$L'_{nT,w,25}$	$L'_{nT,w,20}$
R^2 (%)	18	49	53	64	72	71

Table 7
Coefficient of determination R^2 for SNQ:s with various frequency weighting at 20–40 Hz vs. perceived footstep annoyance. The weighting concerns increased dB per third-octave band, relative to −15 dB.

SNQ	$L'_{nT,w,25}$	$L'_{nT,w,20}$	$L'_{nT,w,25,}$	$L'_{nT,w,20}$	$L'_{nT,w,25}$	$L'_{nT,w,20}$	$L'_{nT,w,25,}$	$L'_{nT,w,20}$
Weight 20–40 Hz	*0*	*0*	*1*	*1*	*2*	*2*	*3*	*3*
R^2 (%)	72	71	75	67	77	65	75	61

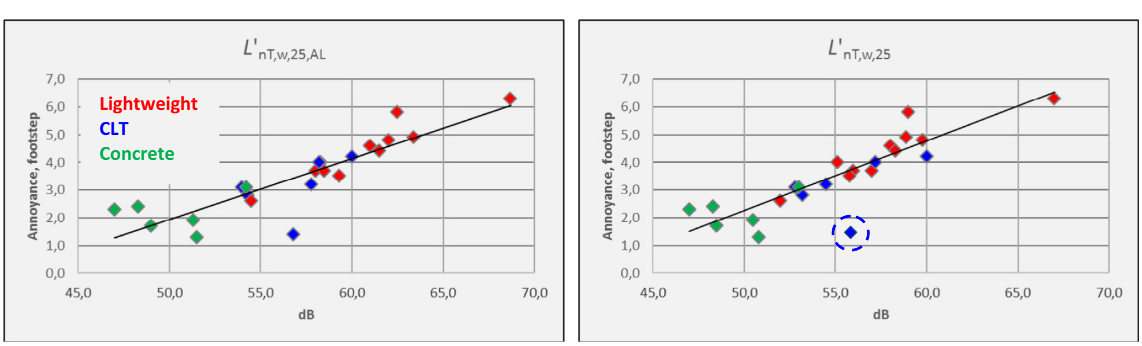

Fig. 10. Linear regression for SNQ's from 25 Hz. $L'_{nT,w,25,AL}$, R^2 = 76% to the left and $L'_{nT,w,25}$, R^2 = 85% to the right (after the removal of one outlier in the circle).

way of living that is less noisy than the average tenant, leading to less annoyance. Thus, this object can be considered as an outlier since it is not representative for a "standard" apartment building with mixed ages among the occupants. If this object is removed from the set of data, the remaining 22 objects yield a coefficient of determination of 86%. Almost the same result is obtained for the flat frequency spectrum, $R^2 = 85\%$ for $L'_{nT,w,25}$, see Fig. 10.

The equation for the latter model is: Annoyance $\approx 0{,}25\ L'_{nT,w,25} - 10{,}3$.

6.3. 20 vs 25 Hz with respect to measurement technique

To skip the 20 Hz band could be preferred from some practical points of view. The extension down to 25 Hz means that exactly one octave band is added compared to the current limit of 50 Hz. At these low frequencies the reverberation time must usually be measured in octave bands instead of third-octave bands in order not to get results affected by the measurement analyzer. Additionally, the uncertainty at the 16 Hz octave band, representing the 20 Hz third-octave band is larger compared to the 31,5 Hz octave band representing the 25, 31,5 and 40 Hz third-octave bands [10]. The same empirical study reported that the measurement uncertainty of reverberation tine in terms of standard deviation for the 16 and 31,5 Hz octave bands was about 0,6 and 0,4 s respectively. However, if the number of microphone positions are increased from the prescribed three, to five, the accuracy is just marginally lower as for higher frequencies.

A possible simplification of the potential reverberation measurement difficulties below 50 Hz could be to evaluate the SNQ by using the sound pressure level L_p instead of L_{nT} for the lowermost frequencies 20–40 Hz. The authors have no substantiated opinion on whether it is justified to standardize to 0,5 s, given that the sound level is affected by furnishing. This remains to be investigated.

From a number of field measurements in other buildings, impact sound levels at 20 Hz being substantially higher than at 25 Hz have been reported. A resiliently mounted ceiling of double layer of gypsum board (≈25 mm in total) often come with an eigenfrequency of around 20 Hz which is an example of a used construction detail in lightweight floors. In this respect, it may then be wise to include the 20 Hz in the evaluation process, since the 25 Hz third octave filter attenuates frequencies below 22 Hz.

It can accordingly be argued both for and against a frequency limit of 20 and 25 Hz and the amount of research that addresses these problems, within the given frequency range, is currently too limited to support a decision.

6.4. When is the impact sound insulation "good enough"?

Referring to the right diagram of Fig. 10, there is a group of five concrete objects to the left that do not follow the proposed regression model very well. It looks like the rated annoyances from these objects are randomly distributed around an annoyance level of about 2. This suggest that the model is inappropriate where $L'_{nT,w,25}$ falls below ≈52 dB. The *experience* of sound insulation is not a matter of the measured sound insulation solely but could depend on other aspects, like the neighbors' behavior and personal preferences. According to the actual set of data, the minimum annoyance (for the specific question related to footstep) is around 2 on the used numerical scale, i.e. further improved impact sound insulation from a relatively low level is not expected to result in decreased annoyance.

From this standpoint the annoyance can then, after excluding the discussed 5 objects, be predicted: <!——>

$$\text{Annoyance} \approx 0,26 \cdot L'_{nT,w,25} - 10,5 \quad \text{for } L'_{nT,w,25} \geqslant 52\ \text{dB}$$

$$\text{Annoyance} \approx 2 \quad \text{for } L'_{nT,w,25} < 52\ \text{dB}$$

If an average annoyance rating of 3, on the used scale 0–10, should be used as an appropriate degree of satisfaction for future building regulations, this would correspond to a minimum requirement of $L'_{nT,w,25} \approx 52$ dB. A somewhat more tolerant annoyance rating of 4, corresponds to $L'_{nT,w,25} \approx 56$ dB.

6.5. Rubber ball vs. tapping machine

Using the rubber ball as sound source showed promising results in Fig. 9 where the linear summation of $L'_{I,Fmax,V,T}$ between 20 and 630 Hz gave the coefficient of determination of 77% which is comparable to what was obtained using the tapping machine. But since the outcome is based upon a limited number of objects, and since 4 out of 11 of them are likely to be within the minimum annoyance discussed above, it is wise to be cautious until further objects have been reported.

Note that the corresponding results using the rubber ball that was presented in the former study [1] were based upon a simplified measurement procedure and are therefore not included here.

7. Conclusions

The study has clearly shown that evaluation parameters starting from 100 Hz, like $L'_{nT,w}$ or $L'_{n,w}$, correlate poorly with perceived impact sound insulation. The coefficient of determination for $L'_{nT,w}$ was found to be 18%. As the established spectrum adaptation term ranging from 50 Hz was added, i.e. $L'_{nT,w,50}$, the correlation increased considerably to 49%, and when the frequency range was extended even further, down to 25 Hz, $L'_{nT,w,25}$, the best correlation was obtained with $R^2 = 77\%$ (85% after the removal of one notable outlier).

Linked to the specified objectives of Section 1.1 we conclude that:

- Impact sound insulation evaluated from 20 or 25 Hz gives a higher correlation to subjectively rated annoyance compared to the standardized evaluation from 50 Hz.
- A spectrum adaptation term using a flat frequency spectrum, gives good conformity between measured and perceived impact sound insulation.

The presented part II study confirms to high extent the results originally achieved from part I [1] but since the present study involved more than twice as many building objects as the previous, the statistical significance of the conclusions has increased.

The overall conclusions are based upon the 23 included building objects and it is essential to point out that the validity concerns primarily lightweight and semi-lightweight building constructions. The frequency bands below 50 Hz do not seem necessary to include when dealing with heavy materials, like concrete, since these constructions do not tend to generate loud impact sounds at frequencies below 50 Hz.

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