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

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ABSTRACT

Traditionally, multi-family houses have been constructed using heavy, homogenous materials like concrete and masonry. But as a consequence of the progress of lightweight building systems during the last decades, it has been questioned whether standardized sound insulation evaluation methods still are appropriate.

An extensive measurement template has been applied in a field survey where several vibrational and acoustical parameters were determined in ten Swedish buildings of various constructions. In the same buildings, the occupants were asked to rate the perceived annoyance from a variety of natural sound sources. The highest annoyance score concerned impact sounds, mainly in the buildings with lightweight floors.

Statistical analyses between the measured parameters and the subjective ratings revealed a useful correlation between the rated airborne sound insulation and $R'_w + C_{50-3150}$ while the correlation between the rated impact sound insulation and $L'_{n,w} + C_{I,50-2500}$ was weak. The latter correlation was considerably improved when the spectrum adaptation term with an extended frequency range starting from 20 Hz was applied. This suggests that frequencies below 50 Hz should be considered when evaluating impact sound in lightweight buildings.

1. Introduction

Multi-storey residential buildings in Europe are conventionally constructed with heavy materials like concrete/steel or masonry. After new findings, e.g. in material combinations leading to improved fire safety, wooden framework is nowadays an alternative in the design of multi-family houses. In Sweden, the building regulations have permitted high-rise wooden residential buildings since 1994.

The acoustical consequences were not taken properly into account by then and it soon turned out that lightweight constructions with wooden or thin profiled steel joists often resulted in poor sound insulation at low frequencies. Since 1999, the requirements in Sweden prescribe measurements and evaluation in the extended frequency range 50–3150 Hz, whereas in other countries the standardized range 100–3150 Hz is used. Despite that new lightweight multi-family houses typically fulfil the sound insulation requirement, their occupants often perceive the impact sound insulation as being insufficient while occupants in heavy concrete buildings, having the same single number values, are satisfied [1]. Hence, the standardized single number evaluation of impact sound insulation according to ISO 717-2 cannot be considered as neutral with respect to building technique and materials.

A number of initiatives to increase the knowledge regarding low frequency sounds in multi-family houses have been taken. An extensive field study performed by Bodlund [2], led to the suggestion of new single number ratings of which some were introduced to ISO 717-2:1996 [3]. Cooperation between the Nordic building authorities (NKB) resulted in a field study regarding the application of single numbers [4]. Bodlund's investigation was further analysed by Hagberg [5] and examples of more field studies have been summarized by Rindel [6]. All the referred studies concluded that frequencies below 100 Hz must be considered regarding impact sound in lightweight buildings. This indicates that the informative

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annex of the current standard, ISO 717-2:2013 [7], that defines the single number quantity $L'_{n,w} + C_{I,50-2500}$, should be mandatory in building regulations.

The mentioned results from various studies together with the accumulated experiences from the academy as well as from the building industry and consultants resulted in the establishment of the Swedish research programme AkuLite, 2009–2013. One of its main objectives was to find neutral single number values for sound insulation that are independent of the building technique, i.e. parameters that do not favour one type of structural material to another. This paper describes the methods applied together with the main results. The steps were to (1) identify a number of relevant multi-family buildings, (2) measure several acoustical and vibrational parameters in these buildings, (3) ask the occupants, by means of a questionnaire, how they rate the sound insulation at home and (4) find out which measured quantities correlate well with the subjective ratings, by means of statistical analyses. The study is restricted to the relation between sound insulation performance and the mean subjective rating given by the occupants. Other factors, although not considered here, may influence the rating, e.g. personal sensitivity or specific sound generated in a neighbouring apartment.

2. Building objects

Ten building objects of various constructions were involved in the study which comprises both field measurements and questionnaire surveys. All of them may be considered relatively modern as all are less than ten years old. A majority of the buildings are designed with lightweight loadbearing structures. Four objects are based upon a traditional wooden framework and flooring boards (here denoted *wood*), one object utilizes a cold-formed thin-walled steel framework (denoted *thin steel*), four objects are made of cross laminated timber (denoted *CLT*) and one object has walls and floors made of massive concrete cast in situ (denoted *concrete*). The objects are located in various Swedish cities according to Table 1.

3. Field measurements

3.1. Method – measurement template

Within the AkuLite project, a special measurement template (procedure) was developed. The idea behind the template is to collect data and knowledge of a large variety of building acoustic parameters, including data which normally are not covered by standardized measurements. An overview is given here but the template is fully described in [8]. The template is divided into two parts; (1) General measurements and (2) Additional measurements. The procedure for each building object is to perform numerous general measurements between adjacent apartments/rooms in vertical direction, preferably up to ten, and to perform additional measurements for one of these cases. A special feature of all measurements is the low frequency content.

Table 1
Building objects.

No	City	Construction	New building	Existing building
1	Upplands Väsby	Wood	X	
2	Östervåla	CLT	X	
3	Umeå	Concrete		X
4	Växjö	CLT		X
5	Växjö	CLT		X
6	Falun	CLT		X
7	Alingsås	Wood		X
8	Lindesberg	Wood		X
9	Örebro	Thin steel		X
10	Varberg	Wood	X	

3.1.1. General measurements

The general measurements include airborne and impact sound insulation using the ISO tapping machine as the source but also sound and vibration measurements using the ISO heavy/soft rubber ball (ISO 10140-1 [9]).

(a) Impact sound insulation using the standardized impact tapping machine.
Measurement and evaluation according to ISO 140-7 [10], ISO 717-2 [3] and SS 25267 [11] but in an extended frequency range: 20–5000 Hz.
$L'_{n,w}$ and $C_{I,50-2500}$ are to be reported.
(b) Airborne sound insulation.
Measurement and evaluation according to ISO 140-4 [12], ISO 717-1 [13] and SS 25267 [11] but in an extended frequency range: 20–5000 Hz.
R'_w and $C_{50-3150}$ are to be reported.
(c) Impact sound using the rubber ball.
Excitation in the centre of the sending room where the ball is dropped from 1.0 m height. Measurement in two positions in the receiving room, in the centre and in one arbitrary selected corner with a microphone height of 1.0 m. Frequency range: 20–500 Hz.
Total L_{max} (with instrumentation time constant *F*, fast), linear and A-weighted are to be reported.
(d) Floor vibrations using the rubber ball.
Excitation of the floor by dropping the ball in the centre of the room from 1.0 m height. The response is measured in two points, 0.5 m from the source in orthogonal directions.
Total a_{max} (maximum acceleration with time constant fast) and fundamental frequency of the floor are to be reported.

3.1.2. Additional measurements

The additional measurements include vibration across junctions and over the floor surface. Natural frequencies of walls and static deflection of the floor are covered as well.

(a) Flanking vibrations on three sides of a junction using the ISO tapping machine (frequency range: 10–3150 Hz) and the ISO heavy/soft rubber ball (1–500 Hz).
Acceleration is measured along two perpendicular walls, in total 30 points on upper floor, lower ceiling and lower wall.
Mean accelerations from each surface are to be reported.
(b) Attenuation of floor vibrations using the tapping machine (10–3150 Hz) and the rubber ball (1–500 Hz).
Measurement is effected in total 10 points along two perpendicular lines, from the excitation in the centre of the floor towards the flanking walls.
Acceleration in each point is to be reported.
(c) Wall response.
Two walls in the room are excited separately by an impact hammer and the response is measured in two positions for each wall.
The lowest natural frequencies of the walls are to be reported.
(d) Static deflection of the floor.
The deflection due to a 1 kN point load in the weakest point of the floor is measured and reported.

3.2. Results

The results in the following diagrams are presented as the mean value for each of the ten objects presented in Table 1, where each mean value represents data from one to ten measurements. All original data is available in [14]

3.2.1. Airborne sound

The airborne sound insulation results are shown in Fig. 1. Taking R'_w (a) defined between 100 and 3150 Hz as a reference, it is clearly seen that the declared sound insulation drops when the spectrum adaptation term $C_{50-3150}$ (b) is added. When the frequency range is further extended, down to 20 Hz, $R'_w + C_{20-3150}$ (c), there is practically no difference from previous case. Since the ISO L_{ij} terms [13] of the trial spectrum adaptation term $C_{20-3150}$ is not defined for frequencies 20–50 Hz, these terms must be calculated. Based upon A-weighting a successive drop of 4–6 dB is obtained for each one third octave band below 50 Hz. To get a hint of the building objects' low frequency performance, the sound reductions were energetically summed up within the narrow range 20–100 Hz on one third octave band basis (d). In this respect, the concrete building, object No. 3, shows the highest sound insulation.

In terms of $R'_w + C_{50-3150}$ (b), the mean results of the ten objects span from 48 to 62 dB.

3.2.2. Impact sound using the tapping machine

Results from the measured impact sound insulations are presented in Fig. 2. Note that the normalized single number rating $L'_{n,w}$ is evaluated according to the Swedish standard [11] in which the volume of the receiving room is restricted not to exceed 31 m^3. Thus, in any case where the real room is larger than 31 m^3, the volume 31 m^3 is used in the calculation of the normalized impact sound pressure level L'_n according to

$$L'_n = L_i + 10\log\left(0.016\frac{V}{T}\right), \quad (1)$$

where L_i is the impact sound pressure level, V is the room volume and T is the reverberation time. For the specific room size of 31 m^3, $L'_{n,w}$ is effectively equal to the standardized impact sound level $L'_{nT,w}$. In larger rooms, $L'_{n,w}$ shows somewhat lower value when evaluated according to the Swedish standard compared to ISO [3]. The difference is 3 dB in 60 m^3 rooms and 5 dB in 100 m^3 rooms.

Starting with $L'_{n,w}$ (a), defined from 100 to 3150 Hz, it is seen – similar to the airborne sound case – that the impact sound level increases for a large majority of the objects as the $C_{I,50-2500}$ (b) is added. It can also be seen – in contrast to the airborne sound case – that the impact sound level increases even more when the frequency range is extended down to 20 Hz (c). Here, the frequency weight of $C_{I,20-2500}$ was set to -15 dB for the one third octave bands 20–40 Hz as for all other frequencies 50–2500 Hz [3]. The concrete building, object No. 3, is again unaffected by the lowest frequencies which also is indicated by the lowest result when the impact sound levels between 20 and 100 Hz are summed up (d).

In terms of $L'_{n,w} + C_{I,50-2500}$ (b), the mean results of the ten objects span from 51 to 66 dB.

3.2.3. Alternative measurements related to impact sound

In Fig. 3, the results from measurements with alternative sources related to impact sound insulation are presented. Two examples of sound level from the ISO rubber ball (measurement template (c), Section 3.1.1) can be seen; A-weighted sound level measured in the centre of the receiving room (a) and linear sound

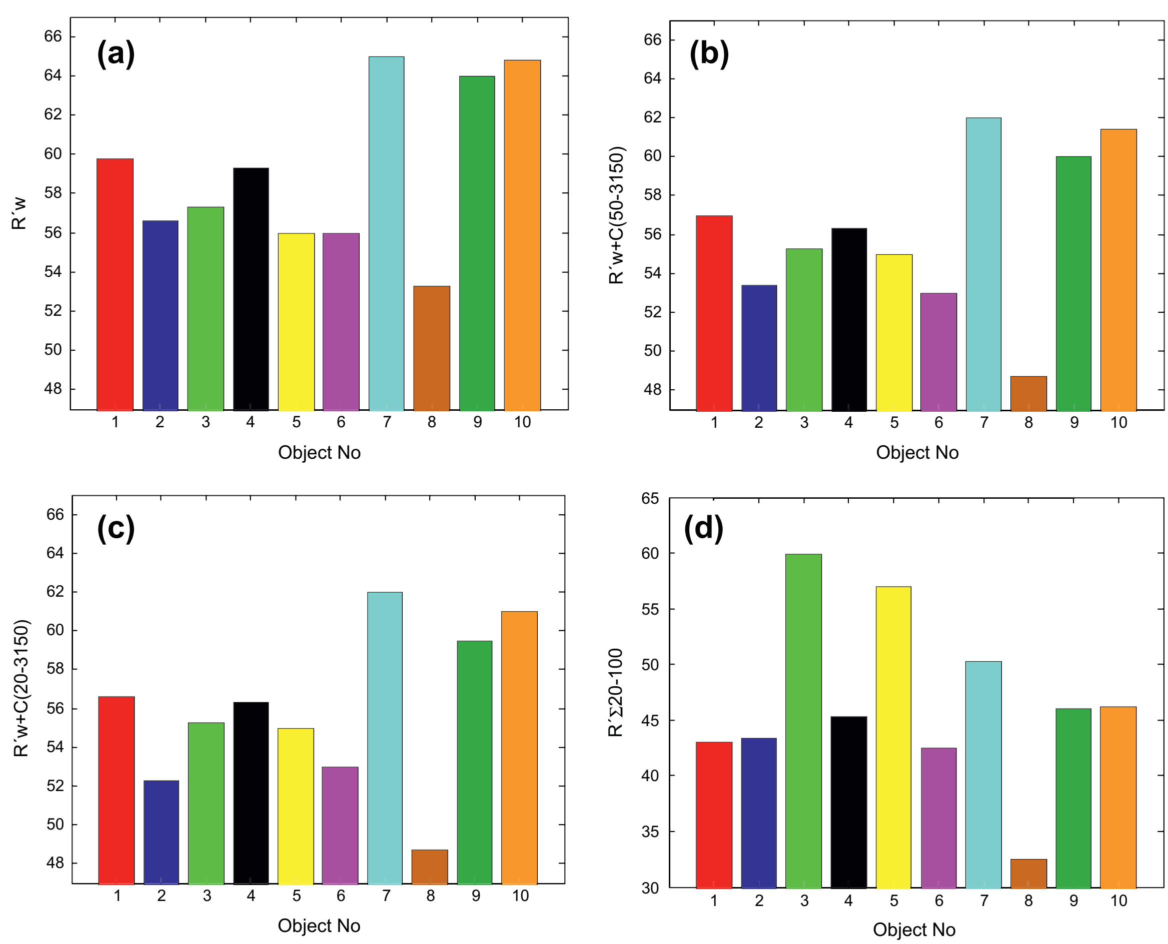


Fig. 1. Airborne sound insulation; (a) R'_w, (b) $R'_w + C_{50-3150}$, (c) $R'_w + C_{20-3150}$ and (d) $R'_{\sum 20-100}$.

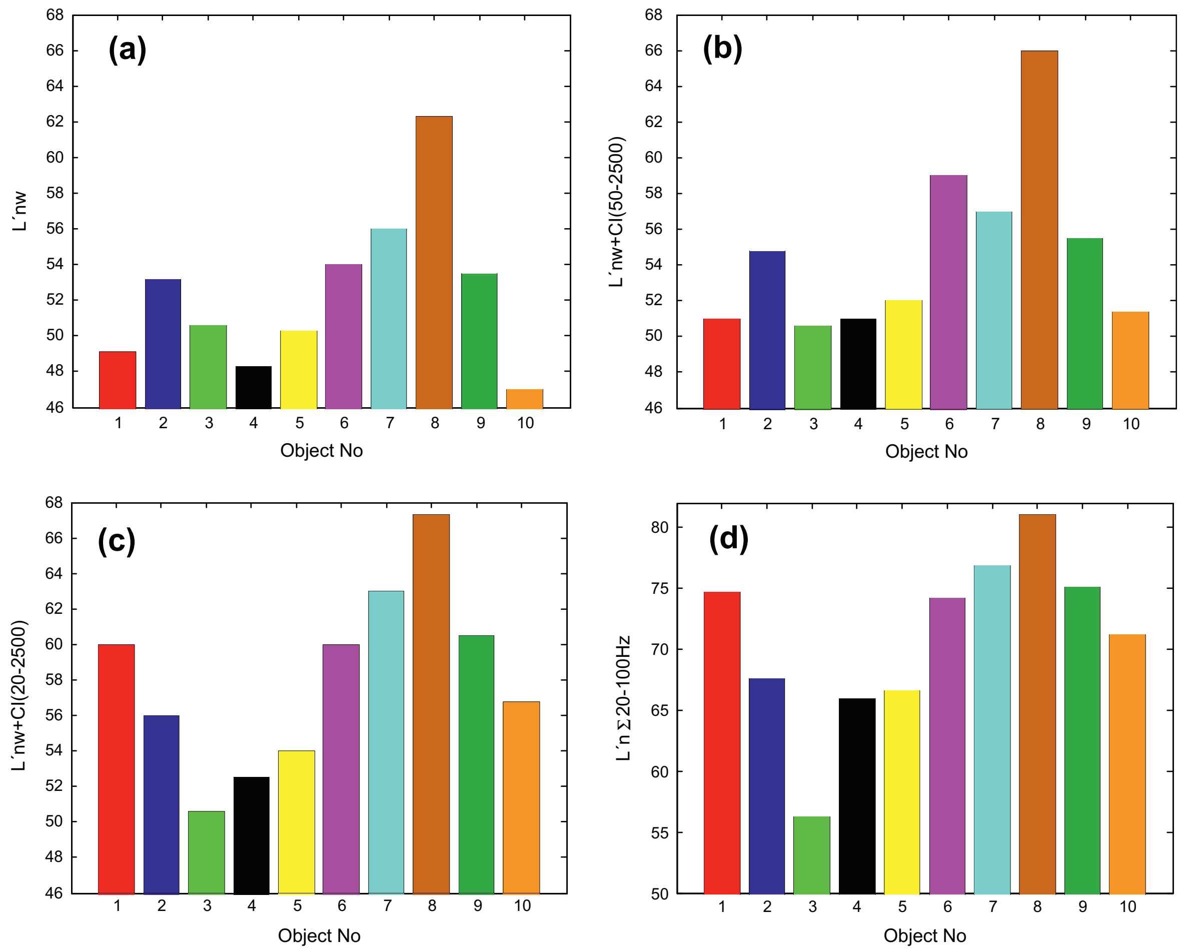


Fig. 2. Impact sound insulation; (a) $L'_{n,w}$, (b) $L'_{n,w}+C_{I,50-3150}$, (c) $L'_{n,w}+C_{I,20-3150}$ and (d) $L'_{n,\sum 20-100}$. ($L'_{n,w}$ is evaluated according to the Swedish national standard.).

level measured in a corner of the room (b). The variation of the weighted level from the centre position is large, from about 35 to 85 dB(A) while the linear levels from the corner positions are somewhat more homogenous, from about 70 to 105 dB. The obtained variations are probably higher compared to if a spatial averaging of the sound pressure levels in the room had been carried out [15].

The floor acceleration (template (d), Section 3.1.1) is presented as the mean value from the two measurement positions (c) with a variation from about 3 to 30 m/s^2. The static deflection (template (h), Section 3.1.2) has a spread from about 0.1 to 1.4 mm which can be seen in (d). Note that the latter case only represents one measurement per building object since it originates from the additional part of the measurement template. Also note that results from two of the objects (Nos. 5 and 6) are missing for this parameter.

4. Subjective perception by the occupants

4.1. Method – questionnaire

The COST action TU0901 [16] was established in 2009 in order to gather researchers from the member states of the European Union to develop a harmonized sound classification scheme. One goal of this COST action is to establish a questionnaire template for socio-acoustic surveys in dwellings. There is a need for a uniform and easy translatable questionnaire which can be applied for comparisons between measured quantities and occupants' ratings. For this purpose a questionnaire based upon the international technical specification ISO/TS 15666 [17] was developed [18], see Fig. 4. A Swedish version was used for the surveys reported in this paper.

The questionnaire contains 15 questions on the annoyance of airborne sounds coming through walls and floors, music with low frequency sounds, footstep noise, sounds from staircases and balconies, traffic noise, sounds from service equipment and more. It employs an 11-point numerical scale ranging from 0 – *not at all bothered, disturbed or annoyed* to 10 – *extremely annoyed* including face symbols to characterize the two extremes of the scale.

A great advantage of making a questionnaire study in occupied dwellings, as compared to listening tests with a small group of test subjects being exposed to short bursts of noise in a laboratory, is that most answers are based upon a realistic time of living in the actual house. All buildings in the study were occupied for a minimum period of six months.

There is a natural variation in the occupants' exposure to noise which depends partly upon the type of building construction and partly upon the neighbours' activities. This implies a greater uncertainty compared to listening tests which are conducted in artificial and well controlled environments. When the questionnaires were distributed to occupants, it included a cover letter that emphasized that the purpose of the survey was to find out about the building construction's acoustic performance. Note: The questionnaire has been further evaluated and developed and a final version is available in several languages on the TU0901 website [16].

4.1.1. Evaluation of the occupants' ratings

The evaluation of the occupants' ratings refers to the obtained mean value of the annoyance for each individual question, either

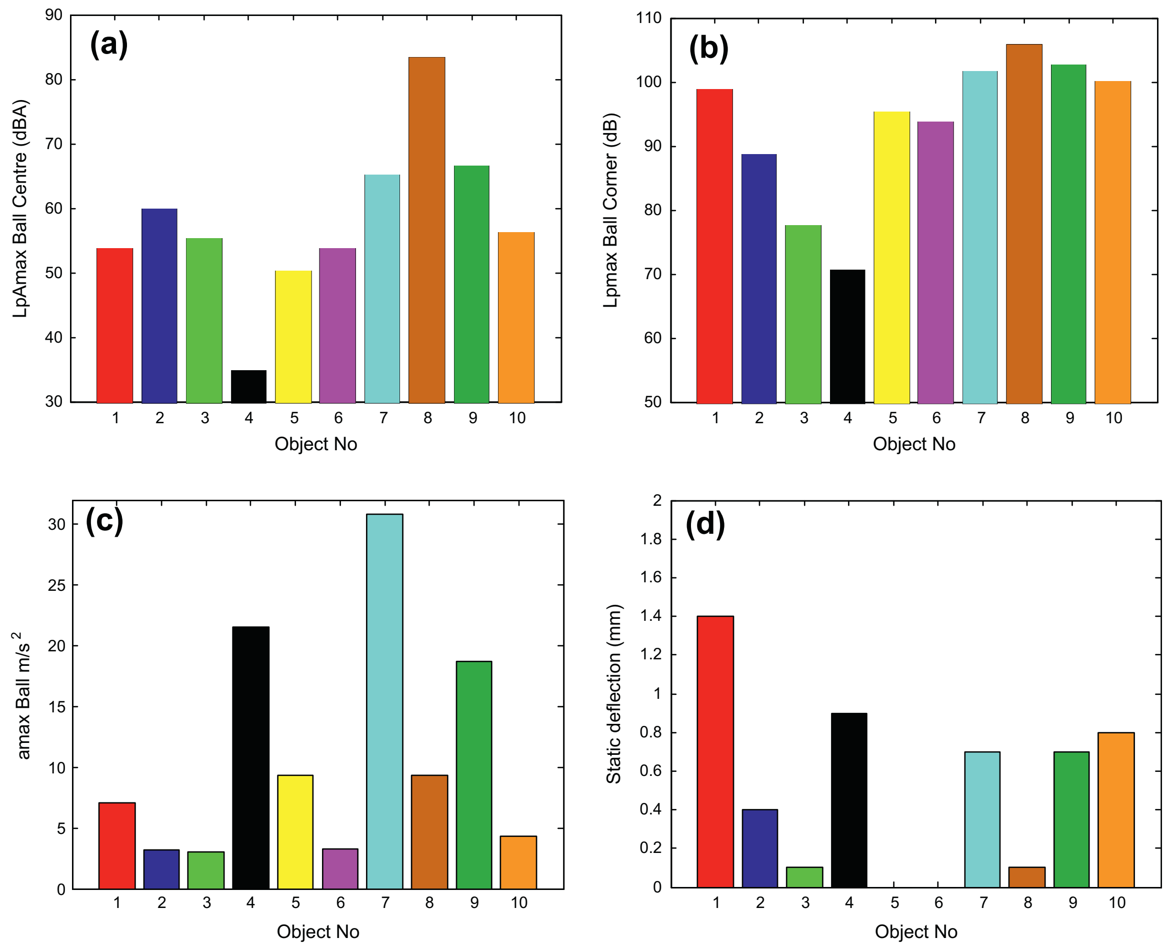


Fig. 3. Alternative measurements; (a) rubber ball, A-weighted sound in the centre of the receiving room (b) rubber ball, sound in one corner of the receiving room, (c) rubber ball, floor vibrations and (d) Static deflection due to a 1 kN load.

in terms of mean annoyance of the separate objects or in terms of the overall mean annoyance representing the average of all the ten objects' means. Other possible evaluation parameters have been considered, e.g. the percentage of the accumulated answers where occupants returned ratings 3 or higher, 5 or higher and 8 or higher. However, in the correlation analyse no significant differences were found between the mentioned evaluation parameters. This was also supported in a previous study [1] based upon a draft version of the same questionnaire. Since the actual questionnaire is relatively new, the obtained figures of annoyance cannot be calibrated.

Furthermore, when evaluating question No. 5, related to impact sound, all answers from occupants living on the uppermost floor of the buildings were excluded since impact sounds from above then do not occur.

The number of answers among the building objects varied between 13 and 79 with a reply rate of 33–83%.

4.2. Results

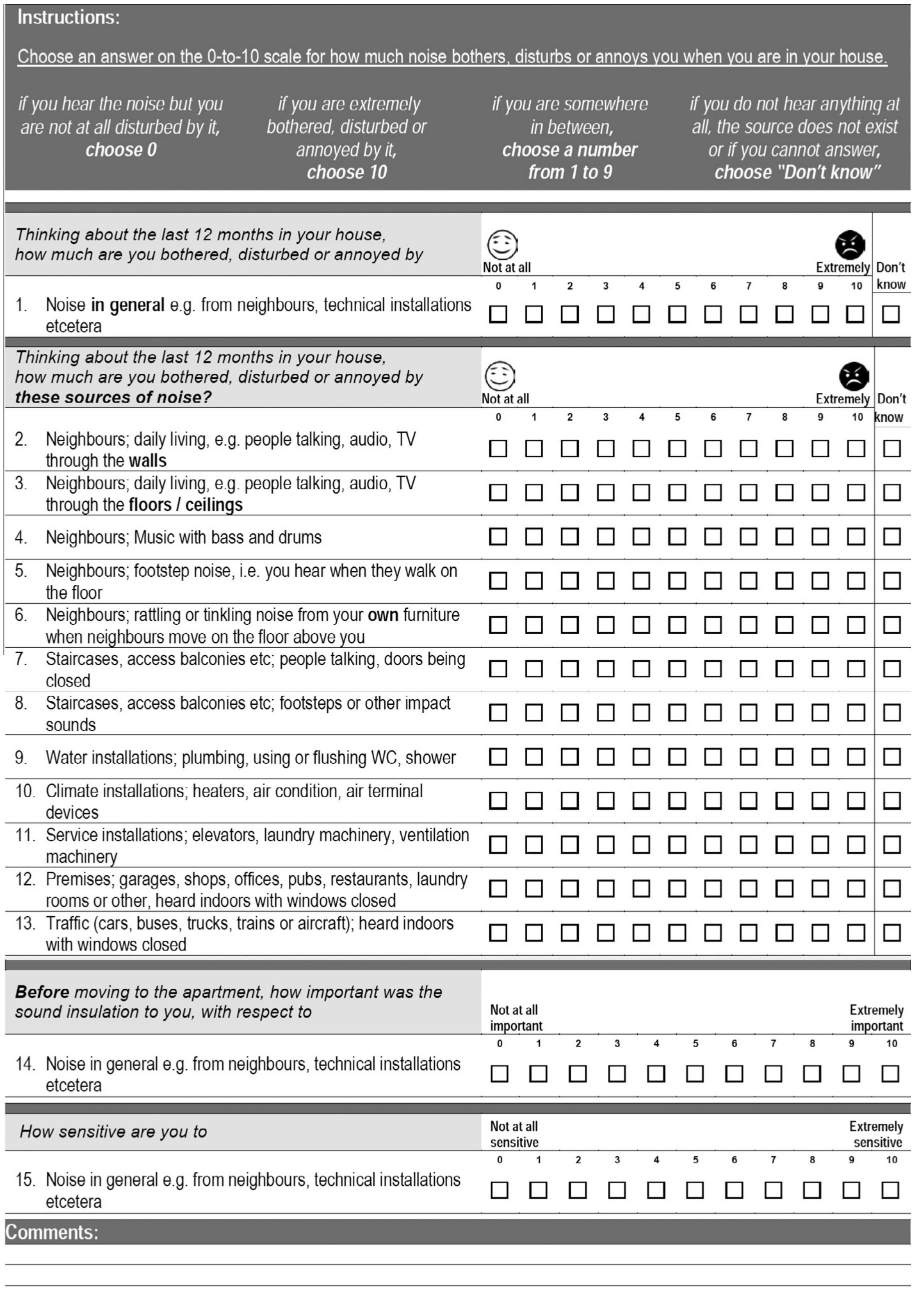
For a majority of the questions related to specific issues, question (Q) 2–13, the declared annoyance is fairly low with overall mean ratings about 2 on the scale ranging from 0 to 10, see Fig. 5. However, one of the questions stands out, the one about walking neighbours, Q5. Here the mean annoyance is 3.7, about twice as high compared to the others. The remaining matters of the questionnaire about the noise in general (Q1), the importance of noise (Q14) and the sensitiveness of noise (Q15) resulted in mean ratings of 2.4, 6.6 and 3.6 respectively. Thus, sound insulation is indeed an important factor for any potential occupant and impact sound seems to be especially crucial in lightweight buildings.

The pooled standard deviation, obtained by – for each question – combining the standard deviations from all the ten objects, was found to be about 2 for all individual questions, Q1-15. A number of matters (Q 1, 3, 4 and 5) are presented in Fig. 6 to get an idea of the spread between the individual building objects. Although the question related to impact sound (Q5) resulted in an overall mean score of 3.7 it can be seen (d) that allocated to the individual building objects, several of them are given men annoyance rating of about 5 or higher, with a total range from 1.2 to 6.3. The lowest value refers to the concrete building (object No. 3) and the highest value refers to a traditional wooden framed building (object No 8). The corresponding lowest-highest mean value is 0.6–4.3 for the overall annoyance (Q1) (a), 0.1–3.0 for the airborne sound through floors (Q3) (b) and 0.2–4.8 for the low frequency music (Q4) (c).

The complete results, including all individual questionnaires, are available in [14].

4.2.1. Assessment of the occupants' ratings

The subjective ratings in term of mean annoyance of each building object were presented above. The mean annoyance often takes a numerical value of 0.5–5.0 which could seem to be low compared to the maximum value "10". However, when the individual questionnaires are studied it is clear that the data is not normally distributed but shows a more bipolar characteristic [14]. Many occupants tend to be either practically not disturbed at all (ratings 0–2) or considerably disturbed (rating 8–10), i.e. despite a comparatively low



Instructions:

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

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 house, 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 **in general** e.g. from neighbours, technical installations etcetera	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Thinking about the last 12 months in your house, 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, audio, TV through the **walls**	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3. Neighbours; daily living, e.g. people talking, audio, TV through the **floors / ceilings**	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
4. Neighbours; Music with bass and drums	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5. Neighbours; footstep noise, i.e. you hear when they walk on the floor	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
6. Neighbours; rattling or tinkling noise from your **own** furniture when neighbours move on the floor above you	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
7. Staircases, access balconies etc; people talking, doors being closed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8. Staircases, access balconies etc; footsteps or other impact sounds	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9. Water installations; plumbing, using or flushing WC, shower	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
10. Climate installations; heaters, air condition, air terminal devices	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
11. Service installations; elevators, laundry machinery, ventilation machinery	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
12. Premises; garages, shops, offices, pubs, restaurants, laundry rooms or other, heard indoors with windows closed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
13. Traffic (cars, buses, trucks, trains or aircraft); heard indoors with windows closed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Before *moving to the apartment, how important was the sound insulation to you, with respect to*	Not at all important 0	1	2	3	4	5	6	7	8	9	Extremely important 10
14. Noise in general e.g. 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
15. Noise in general e.g. from neighbours, technical installations etcetera	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Comments:

Fig. 4. Questionnaire (early version by COST TU0901).

mean value, the fraction of occupants that are substantially annoyed cannot be ignored.

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

5.1. Method – statistical analyses

Statistical analyses in terms of principal component analyses and linear regressions were performed to reveal correlations between the field measurements and the subjective ratings from the questionnaires regarding airborne and impact sound insulation. The overall mean annoyance for respective question has been used as the subjective parameter throughout the analyses and correspondingly the overall mean value of respective measured quantity from the ten building objects has been used as the field measurement parameter. Two questions from the questionnaire are directly related to airborne sound insulation, sounds transmitted through the walls (Q2) and through the floors/ceilings (Q3). The mean annoyance of these two questions correlates well with each other even though the mean annoyance is almost twice as high for the latter. The transmission through floors is then used as the subjective parameter for correlation against airborne sound insulation measurements. For impact sound measurements, the question of footstep noise (Q5) has been used.

5.2. Results

5.2.1. Airborne sound

The coefficient of determination (R^2, equivalent to the square of the correlation coefficient) from linear regression analyses regarding airborne sound is presented in Table 2 together with the

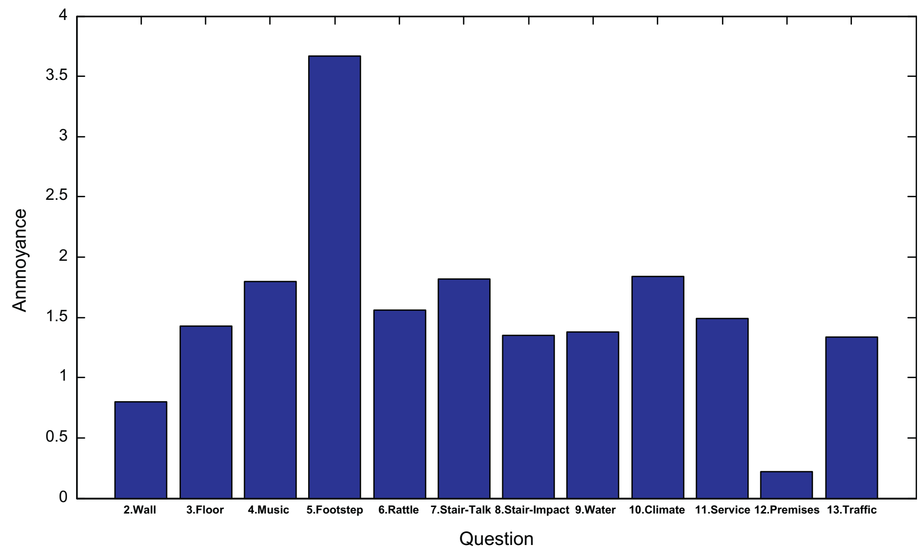


Fig. 5. Overall mean annoyance from question Nos. 2–13 of the questionnaire.

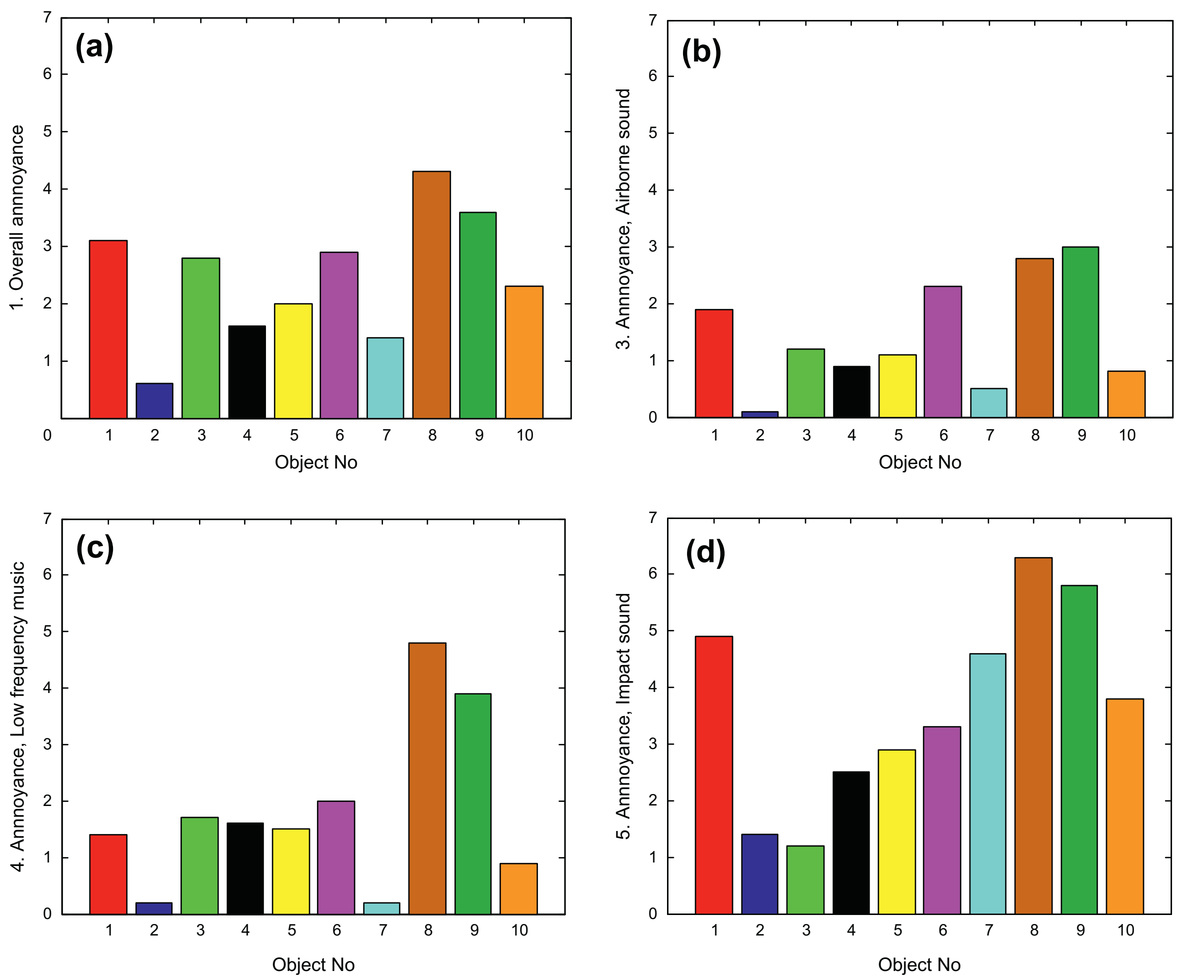


Fig. 6. Mean annoyance for selection of matters from the questionnaire: (a) overall annoyance, (b) airborne sound, (c) low frequency music and (d) impact sound.

coefficients a and b in the linear equation $Y = a + bX$, where Y represents the annoyance and X represents the measured quantity. The 95% confidence interval of the slope, b, is also given together with an indication whether the actual measured parameter shows any statistic significant relation (Stat. rel.) to the annoyance, i.e. whether or not the slope "0" is included in the interval.

When taking all 10 objects into consideration, a poor correlation is obtained between subjective ratings and measurements. This is mainly caused by two objects showing abnormal properties. Referring to the linear regression in Fig. 7, object No. 2 shows considerably lower subjective annoyance than expected. This is a new building where a great majority of the occupants are 65 years or older. It is reasonable to assume that these occupants generate less noise than an average occupant. And if less noise is generated, the complaints are few even if the construction does not offer top class sound insulation. Object No. 9 on the other hand is a house of student rooms occupied by young people. Here, it can be assumed that more noise is generated than on the average, i.e. despite approved sound insulation it is not good enough to get satisfactory protection against noise from the neighbours. Noise from corridors and other common areas might also have affected the ratings for this specific object. Therefore, complementary analyses – probably with better relevance – have been performed with these two outliers withdrawn.

The coefficient of determination, R^2, when R'_w is matched against annoyance is 58%. R^2 increases to 73% when the spectrum adaptation term from 50 Hz is added, $R'_w + C_{50-3150}$. For the correlation maintained with an ever further extension down to 20 Hz, $R'_w + C_{20-3150}$, R^2 = 75%. Note that the rated annoyance generally is low, 3 or less according to Fig. 6. It might therefore be inaccurate to extrapolate the results for predictions outside this range.

In a trial experiment, the impact sound pressure level obtained by the ISO rubber ball was correlated against the rated airborne sound annoyance. Due to the poor R^2, 11% and 17% using linear and A-weighted sound levels respectively, the ball cannot be suggested to be used as a uniform “hybrid source” applicable for both airborne and impact sound insulation.

5.2.2. Impact sound

The coefficient of determination together with other statistical parameters from linear regression analyses regarding impact sound is shown in Table 3. Here all ten building objects are included.

The coefficient of determination, when $L'_{n,w}$ is matched against annoyance is just 26%. This is marginally improved to 32% when the spectrum adaptation term from 50 Hz is added, $L'_{n,w} + C_{I,50-2500}$, but when the frequency range is extended to include 20–50 Hz a remarkable improvement can be seen, R^2 = 74% for $L'_{n,w} + C_{I,20-2500}$.

When the ISO rubber ball is used as the impact sound source, with a single microphone position, the correlation is still respectful. Taking the measurement in the corner, R^2 = 64% for linear weighting, which drops to 43% when A-weighting is applied. The static deflection shows practically no correlation to the perceived annoyance from impact sound since R^2 = 5%.

6. Ideas for improved impact sound spectrum adaptation terms

6.1. Experiences about the present use of $L'_{n,w} + C_{I,50-2500}$

The spectrum adaptation term $C_{I,50-2500}$ is defined by ISO 717-2 [3] according to:

$$C_{I,50-2500} = 10\log\left(\sum 10^{L'ni/10}\right) - 15 - L'_{n,w}, \tag{2}$$

where L'_{ni} is the normalized impact sound pressure level in the one third octave band i. Thus, $C_{I,50-2500}$ is the numerical differential between two evaluation procedures, the summation of the

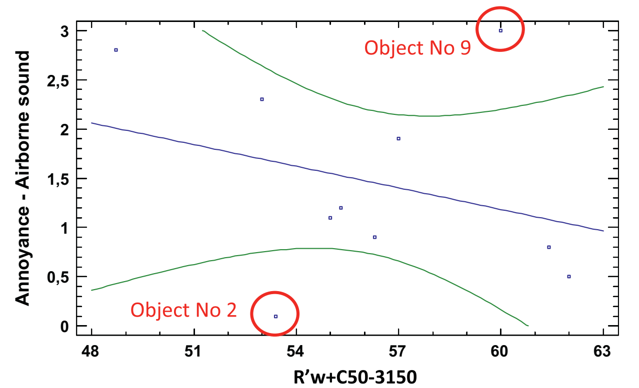


Fig. 7. Linear regression of airborne sound annoyance vs. $R'_w + C_{50-3150}$ including 95% confidence intervals. Two outliers are highlighted within the circles.

normalized impact sound pressure levels, L'_{ni} (−15), and $L'_{n,w}$. This term was introduced in the Swedish building regulation (1999) in order to prevent lightweight separating floors with poor impact sound insulation at low frequencies from being used in residential buildings.

However, the requirements were shortly thereafter amended such that *both* $L'_{n,w}$ and $L'_{n,w} + C_{I,50-2500}$ have to fulfil the stipulated limit, i.e. negative values of $C_{I,50-2500}$ must not be taken into account. Otherwise, this would have been favourable for a concrete slab covered by flooring with a negligible reduction of impact sound at higher frequencies, e.g. ceramic tiles or linoleum carpets without acoustic underlays. In such cases $L'_{n,w} + C_{I,50-2500}$ can be 10 dB less than $L'_{n,w}$, i.e. $C_{I,50-2500}$ = −10 dB. Practical experiences showed that occupants did not accept such floors because the impact related noise was clearly audible and annoying, e.g. from walkers with hard shoes and chairs being moved on the floor.

The collected experience from 1999 has indicated that $L'_{n,w}$ in combination with $L'_{n,w} + C_{I,50-2500}$ generally work quite well as a regulatory parameters although they do not prevent unsatisfactory sound insulation in every type of building construction.

6.2. Frequency extension to 20 Hz, $C_{I,20-2500}$

As already discussed, when a constant frequency weighting of −15 dB in the range of 50–2500 Hz is used to define a spectrum adaptation term, in analogy with the $C_{I,50-2500}$, the coefficient of determination R^2 was improved from 0.32 for $C_{I,50-2500}$ to 0.74 for $C_{I,20-2500}$. In fact, using only the narrow frequency range 20–100 Hz for the frequency weighting resulted in R^2 = 0.78. Although it is not realistic to evaluate the impact sound insulation in general in such a narrow frequency range, the need for consideration of low frequencies is clearly indicated.

6.3. A-weighted difference between tapping machine and living activities, $C_{I,20-2500,AwLiving}$

One interesting approach is to define new frequency weights to replace the constant value of −15 dB, on the basis of spectra from living activities that may be assumed to act on floors in dwellings,

Table 2
Statistics in terms of linear regression $Y = a + bX$, where Y is the annoyance of airborne sound and X is the measured parameter.

Airborne sound	R^2 (%)		a	b	95% conf. interval (b)	Stat. rel. (b)
R'_w	4[a]	58	10.0	−0.146	[−0.266 −0.026]	Yes
$R'_w + C_{50-3150}$	9[a]	73	10.4	−0.160	[−0.254 −0.066]	Yes
$R'_w + C_{20-3150}$	9[a]	75	10.7	−0.166	[−0.258 −0.074]	Yes
ISO Ball corner	19[a]	11	−0.590	0.0218	[−0.0378 0.081]	No
ISO Ball corner (A)	18[a]	17	−0.103	0.0256	[−0.0283 0.0795]	No

[a] Denotes value with two outliers included.

Table 3
Statistics in terms of linear regression $Y = a + bX$, where Y is the annoyance of impact sound and X is the measured parameter.

Impact sound	R^2 (%)	a	b	95% conf.interval (b)	Stat. rel. (b)
$L'_{n,w}$	26	−6.65	0.197	[−0.072 0.466]	No
$L'_{n,w} + C_{I,50-2500}$	32	−7.41	0.202	[−0.033 0.437]	No
$L'_{n,w} + C_{I,20-2500}$	74	−13.4	0.294	[0.154 0.434]	Yes
ISO Ball corner	64	−7.69	0.121	[0.047 0.195]	Yes
ISO Ball corner (A)	43	−2.15	0.0952	[0.008 0.183]	Yes
Static deflection	5	3.19	0.983	[−3.23 5.20]	No

e.g. from walking persons, chairs moved, toys dropped on the floor etc. The impact sound pressure levels obtained with the ISO standardized tapping machine could hypothetically be "translated" into a single number value being representative for the sound pressure level from daily life impact sounds. Following the procedure in ISO 717-2, this translation could be made by means of adding a spectrum adaptation term, $C_{I,20-2500,AwLiving}$, to the normalized single number value $L_{n,w}$ measured with the tapping machine. The sum $L_{n,w} + C_{I,20-2500,AwLiving}$ would then be assumed to represent the A-weighted sound pressure level of such living sources. The $C_{I,20-2500,AwLiving}$ is calculated as:

$$C_{I,20-2500,AwLiving} = 10\log\left(\sum 10^{(L'ni - X_i - Aw)/10}\right) - L'_{n,w}, \qquad (3)$$

where L'_{ni} is the sound pressure level measured with the ISO tapping machine in the one third octave band i. X_i is the difference between L'_{ni} and a level chosen to represent an upper estimate of sound pressure levels that may come from a variety of typical 'living sources'. This difference is A-weighted according to IEC 61672 [19] and denoted "A-weighted sound pressure level difference".

It should be noted that this approach may be questioned since it is only applicable to force sources having considerably higher force mobility than the mobility of the floor assembly. The influence of the source and floor mobility on the injected structure-borne sound power is described in the European standard EN 12354-5 and the force source assumption is explained in [20]. The possibility of translating impact sound levels obtained with one specific source to the sound level due to another source, e.g. the ISO tapping machine and walking persons respectively was analysed in [21]. It was there concluded that the source and receiver mobility must be taken into account. The data indicated that the force source approximation works reasonably well for wooden floors at medium and low frequencies (approximately below 1 kHz), but for concrete floors with soft carpets the approximation may be erroneous above about 100 Hz (depending of the stiffness of the carpet). This certainly restricts the applicability of the "translation" concept in buildings with such floorings, but it may still be useful if a single number values with a modified spectrum adaptation term would correlate better to the annoyance experienced by the occupants compared to the standardized term. The force source approximation could thus be expected to be approximately valid at low frequencies for the small and light sources, when they act on hard floorings typical for most (Swedish) dwellings. But discrepancies may be expected at higher frequencies where the source mobility from falling hard objects increases to be of the same order as the mobility of the floor assembly.

To obtain the necessary frequency weights, a number of laboratory measurements of various impact sound sources [22–24] were analysed.

Results are displayed in Figs. 8 and 9 as A-weighted differences in sound pressure level between various living sources and the tapping machine, for various floor types. The differences shown in Fig. 8 are largely scattered, especially for the floors with concrete tiles or massive concrete and they are diverging even more at higher frequencies. The differences shown in Fig. 9 indicate that rather large variations between different activities may be expected as well, even between walkers. However, even if the results are somewhat dissatisfying, the curves have in general a similar shape, which justify the attempt to find a better spectrum adaptation term.

The frequency weights X_i for Eq. (3) are plotted in Figs. 8 and 9. The weights were chosen such that $L_{n,w} + C_{I,20-2500,AwLiving}$ could be assumed to be higher than the A-weighted sound pressure level from most living sources and many typical floor constructions, according to the results of Figs. 8 and 9. Hence, the slope of the weighting curve was defined positive in contrast to the constant value of −15 dB in the ISO spectrum adaptation term $C_{I,50-2500}$. A similar idea, although restricted to high frequencies, has been proposed previously [25] in terms of a slope of 2 dB per one third octave band starting from 400 Hz. The purpose was to handle sounds from hard floorings (e.g. tiles on concrete slabs).

When $L'_{n,w} + C_{I,20-2500,AwLiving}$ is correlated to the ratings given by the occupants with respect to the annoyance of impact sounds (Q5), the coefficient of determination R^2 is 0.39, This is somewhat higher than for the standardized sum $L'_{n,w} + C_{I,50-2500}$, but still not satisfactory for a potential regulation requirement applicable to all types of buildings.

6.4. Further increased weights at low frequencies, $C_{I,AkuLite,20-2500}$

Indications of the importance of low frequencies combined with the special high frequency consideration [25], discussed in previous section, lead to the suggestion of a spectrum adaptation term denoted $C_{I,AkuLite,20-2500}$. It is defined as:

$$C_{I,AkuLite,20-2500} = 10\log\left(\sum 10^{(L'_{ni} - X_i)/10}\right) - L'_{n,w}, \qquad (3)$$

where X_i here are the new proposed frequency weights in third octave bands 20–2500 Hz. In the range 50–400 Hz, the weights are −15 dB as in ISO 717-2. They increase by 2 dB per one third octave band below 50 Hz. At frequencies above 400 Hz the weights increase 1 dB per one third octave band, see Fig. 10.

Applying $L'_{n,w} + C_{I,AkuLite,20-2500}$, the correlation against the subjective impact sound rating (Q5) leads to an improved coefficient of determination of 85%. The linear regression can be seen in Fig. 11.

A compilation of the obtained R^2 for the cases where frequencies from 20 Hz are included is given in Table 4.

7. Discussion including examples of other closely related findings within AkuLite

7.1. Improved correlation of impact sound by low frequency extension

Adding more weight to the low frequency sounds, in contrast to the present ISO evaluation method, improved the correlation against subjective ratings given by occupants in the light-weight residential buildings. One hypothesis to explain this strong influence on impact sounds at 20–50 Hz, is that the perceived sound in the buildings varied from barely audible to clearly audible and even annoying. The linear sound pressure levels obtained with the tapping machine varied from 66 dB to 81 dB in the one third

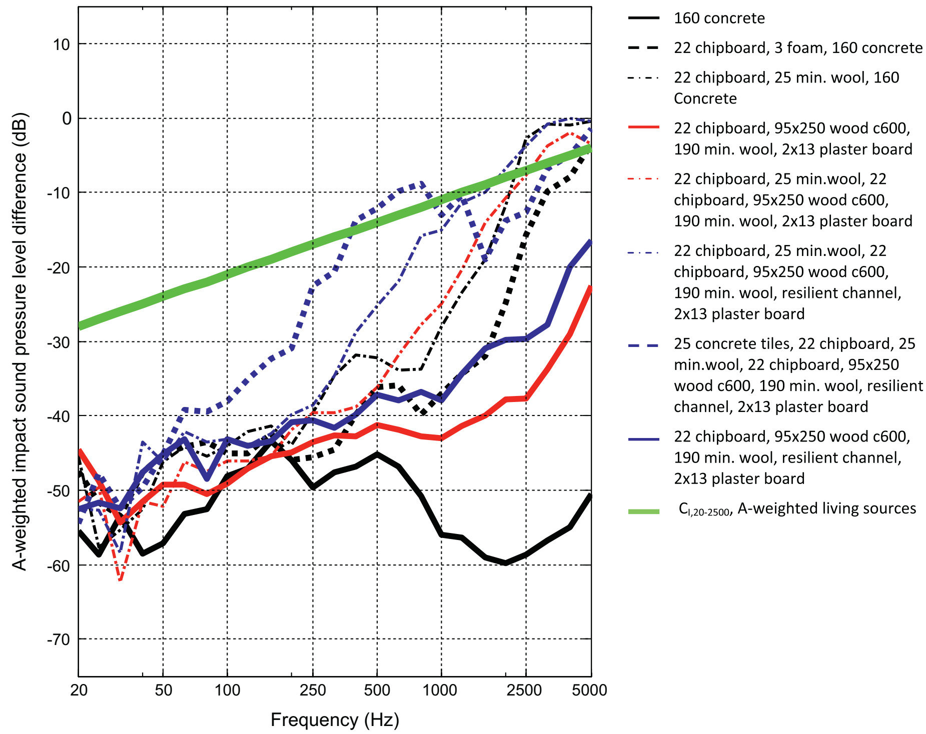


Fig. 8. A-weighted differences between normalized impact sound pressure levels from a male person walking on *various floor constructions*.

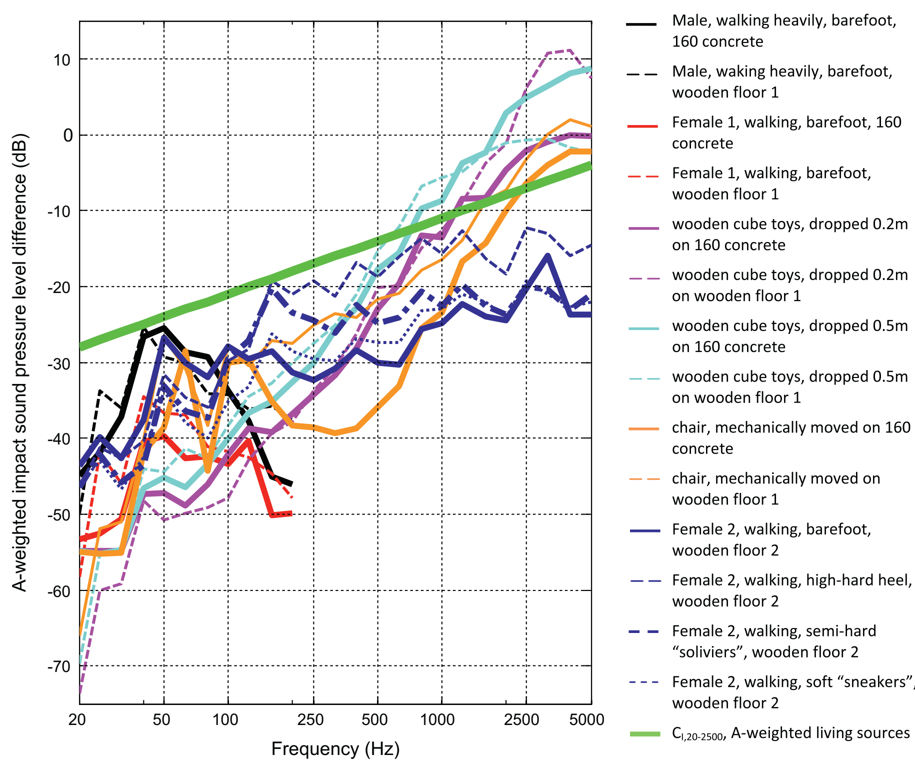


Fig. 9. A-weighted differences between normalized impact sound pressure levels measured with *various impact sources* and the levels obtained with the tapping machine.

octave bands within 20–100 Hz as was shown in Fig. 2d (omitting the concrete building).

According to the standardized isophon curves in ISO 226 [26], this 15 dB raise of the impact sound level, starting at 66 dB, corresponds to a change from slightly below the auditory threshold to exceed 15–20 phons, which make these impact sounds clearly audible. Since these isophon curves were developed for the perceived loudness of pure tones, they are not necessarily applicable to this interpretation, but they may at least be taken as an indication and basis for further research on the sensitivity to impact sounds.

The authors' experience is that when walking occurs at a normal, gentle speed, the impact sound is often barely audible but as soon as the walking speed, and thereby also the force, increases,

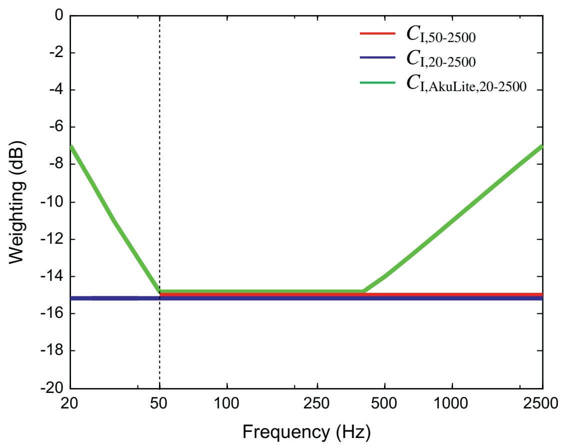


Fig. 10. Frequency weights of three spectrum adaptation terms.

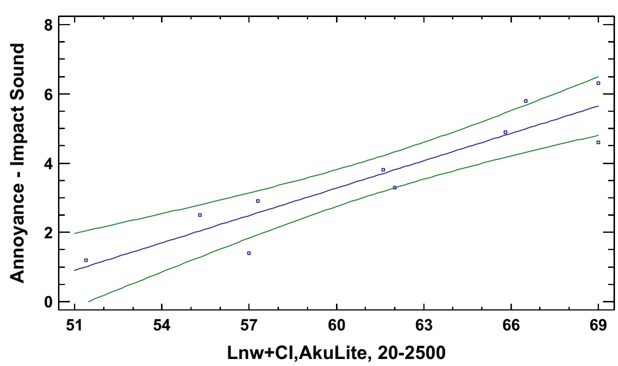


Fig. 11. Linear regression of impact sound annoyance vs. $L'_{n,w} + C_{I,AkuLite,20-2500}$ including 95% confidence intervals.

the impact sound quickly becomes very disturbing. It can therefore be suspected that this dynamic range is very narrow, as is indicated by the shape of the isophon curves. This, in turn, means that listening tests should be performed with realistic background levels and with impact sound pressure levels as they were determined in field.

7.1.1. Tapping machine vs. rubber ball

The subjective rating of impact sounds was correlated against various measured parameters in Table 3. Accordingly, the evaluations based upon the ISO tapping machine show better correlation than the correspondent ISO rubber ball measurements. But while the tapping machine measurements strictly follow the appropriate ISO standards in terms of number of measurement positions (tapping machine and microphones), the measurements using the ball was performed in a more simplified way using only one excitation point and one microphone position. In that respect, the results are not fully comparable and thus it cannot be concluded, from this study, that any of the impact sources is to prefer ahead of the other.

7.2. Low frequency measurements

Performing indoor sound measurements at low frequencies, typically below 100 Hz, might be more erroneous compared to measurements at higher frequencies. The reason is mainly due to the lack of a diffuse sound field in the room where the dimension of the wavelengths is comparable with the dimensions of the room. Within the frequency region where the first standing waves appears, the strength of sound field varies due to low modal overlap which requires an expanded amount of sampling positions in order to represent the mean sound pressure in the room. On the other hand, at the very lowest frequencies, below the first mode of the room, the sound pressure can again be assumed to be more uniformly distributed.

In the actual ISO standards [10,12], special guidance is given when dealing measurements in the low frequency bands. E.g. it is stated that sampling of the sound field should take place in an increased number of microphone positions, the averaging time should increase and the number of loudspeaker configurations when performing airborne sound insulation should increase from two to three.

For the present paper, the ISO guidance was applied when collecting the low frequency sound data according to the measurement template. But since the ISO standards cover frequencies down to 50 Hz (through the spectrum adaptation terms), additional arrangement might be necessary in order to guarantee a satisfactory measurement procedure down to 20 Hz in possible forthcoming recommendations. Some investigations into the effect of different methods of spatial averaging have been reported previously [15].

7.3. Listening test

A listening test was performed within the AkuLite project in order to evaluate the subjectively perceived loudness of recorded footsteps [23]. It was conducted in two ordinary office rooms where the test subjects were exposed to various footstep sounds emitted by a hidden loudspeaker system, including or excluding sounds in the frequency ranges 20–50 or 20–100 Hz. Sound recordings from a person walking on one timber framed floor and one concrete floor were used for pair comparison tests, "A–B". The results indicate that when frequencies below 50 Hz are filtered out from the timber floor (floor "B"), the test subjects add about 4–7 dB to make the sound equally loud compared to the unfiltered recording (floor "A"). In the case where the frequencies below100 Hz part was removed, the test subjects added 16–20 dB to make the sound equally loud. When the timber framed floor recording was compared to a recording from a concrete floor with similar $L'_{n,w} + C_{I,50-2500}$ (57 dB and 56 dB respectively), the test subjects compensated by adding 8–12 dB to the concrete floor in order to make the sound equally loud. Filtering below 50 Hz had no effect on the subjectively perceived level from the concrete floor. These listening tests suggest – independently from the other findings in this paper – that impact sounds of 20–50 Hz play an important role as it affect the subjective rating.

Table 4
Statistics in terms of linear regression $Y = a + bX$, where Y is the annoyance of impact sound and X is the measured parameter starting from 20 Hz.

Impact sound	R^2 (%)	a	b	95% conf. interval (b)	Stat. rel. (b)
$L'_{n,w} + C_{I,20-2500}$	74	−13.4	0.294	[0.154 0.434]	Yes
$L'_{n,w} + C_{I,20-2500,AwLiving}$	39	−10.2	0.267	[−0.002 0.536]	No
$L'_{n,w} + C_{I,AkuLite,20-2500}$	85	−12.5	0.263	[0.175 0.351]	Yes

7.4. Vibration annoyance

A separate survey was carried out in nine of the ten building objects (No. 8 omitted) specifically addressing the annoyance of floor springiness and vibrations from daily activities [27]. Similar methodologies as for the previously described questionnaire and analysis were applied. The results indicate that vibrations are perceived as annoying from numerous sources like neighbours walking on their floor or on the stairs, closing the doors as well as family members walking on their own floor.

The annoyance rating from "Vibrations in the floor or in the furniture, in general" correlated to the static deflection of the floors with a coefficient of determination, R^2, of 85%. The lowest annoyance ratings were obtained in the concrete building (No. 3) while the highest annoyance was obtained in one of the lightweight wooden framed buildings (No. 1). The remaining five objects had all similar ratings and deflections and in order to establish a more confident relationship, additional stiffer and weaker floors would be needed to achieve a wider range of data.

8. Conclusions

The presented results indicate that low frequencies are of essential importance when evaluating sound insulation in lightweight buildings.

An extension of the frequency range down to 20 Hz improved the correlation of measurements to occupants' rating of annoyance from impact sounds. The coefficient of determination, R^2, increased from 32% using $L'_{n,w} + C_{I,50-2500}$ to 85% when including the new spectrum adaptation term $L'_{n,w} + C_{I,AkuLite,20-2500}$. This finding has also been supported by a separate listening test, conducted independently.

Regarding airborne sound insulation, it was indicated that the frequency range covered by $R'_w + C_{50-3150}$ Hz is adequate as compared with subjective perception. It is important though, that the frequency range start at 50 Hz since R^2 decreased from 73% to 58% with R'_w solely, i.e. when starting from 100 Hz. In this case, no further improvement was obtained with a frequency extension down to 20 Hz.

Due to the limitations in the number of building objects, and thereby also in the variety of data, the findings are only valid within the actual data range, extrapolation to higher or lower value could be erroneous. And although several of the relations between annoyance and the measured parameters are proven to be statistically significant, this is not the case regarding the difference in between the corresponding correlation coefficients, for the same reason. For validation purpose, it is therefore important to gather complementary information from other type of buildings, preferably on international bases.

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