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by

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Evaluating Field Measurements of Impact Sound

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ABSTRACT
Analyzing data from an earlier investigation revealed uncertainties concerning data evaluation. Therefore, data points comprising 1/3-octave impact sound data and interview data from the earlier investigation are partly replaced by new data points. The data removed pertain to horizontal measurements. The investigation is then completed with data for 10 new housing units pertaining to vertical impact sound measurements. Including the new floor structures, a total number of 22 vertical data points are included. It was found that the current international standard method is unsatisfactory, and that the single-number value proposed in the earlier investigation suffers from shortcomings: when analyzing the new data sample, the correlation coefficient fell from 87% to 83%. The best choice proved to be a reference curve with a steep positive slope of 5.5 dB/octave between 50-100 Hz and the curve becomes a straight line. This reference curve resulted in a correlation coefficient again equal to 87%.

1. INTRODUCTION
Sound insulation requirements and applications have recently become more emphasised as new products and product combinations have come to be used in construction. Such new requirements result in technically more advanced buildings, but could raise building costs, indirectly resulting in unacceptably high rents. Some important qualities of buildings have more severe consequences than others if not accurately predicted. One such quality is sound insulation, which when poorly executed is often only discovered after the dwelling is occupied. Actually, tenants are willing to pay higher rents [1] if the sound insulation quality of the final building is better. If the sound insulation quality does not correspond to expectations, there is a risk that inhabitants, though otherwise satisfied with the dwelling, will soon become dissatisfied. To avoid such an outcome – undesirable to all parties – efficient and precise sound insulation prediction models are a crucial part of modern building planning.

From a Swedish perspective, sound insulation has attracted greater interest over the past decade, as less strict Swedish building fire regulations and changes in building practices have prompted the overhaul of the evaluation of sound insulation in buildings. In 1994 it became permitted to build wooden housing structures in Sweden.

Furthermore, it has become more common to use prefabricated, thin hollow concrete structures and large open-plan layouts in housing construction. Urban densification, which creates new dwellings on top of existing buildings, in former attics, is another modern design approach. These "attic dwellings", often with wooden floors, create new noise for the inhabitants below, who have never had any upper neighbours. Finally, new living habits, housing areas, and family mixes also affect housing production. Taken together, these factors require continual development of new housing design and highlight the need for the constant overhaul of legislation and evaluation standards. This need is even more pronounced given that new projects almost always include new design elements. Furthermore, new "high speed" product development requires at least the same speed of regulation development. Naturally, manufacturers work with current acoustic standards when developing new products. If these standards are not adapted to the latest building practices, there is the obvious risk that new products will be developed to meet obsolete standards, possibly causing unnecessary costs for manufacturers, contractors, and society.

Sound insulation in buildings is normally classified as either airborne or impact sound insulation. Impact sounds in dwellings are normally created by: people walking, children jumping, objects falling – i.e. any typical structure-borne sound [2]. Typical airborne sounds in dwellings come from television, kitchen appliances, shouting, etc. In Refs. 3, 4, and 5, for example, various sound sources are subjectively characterized and compared via interviews. Specifically, the studies compare sounds from airborne sources (TVs, stereos), impacts (footsteps), heating installations, elevators, and stairs, clearly finding that impact sound transmission causes the highest average subjective annoyance, particularly for lightweight structures.

Sound transmission in a building is determined using single numbers evaluated according to specific rules. Normally a reference contour covering a certain frequency range is adapted to measured sound insulation values. The reference contour concerning impact sound was determined early on in the process of standards formulation. Several attempts have been made over the years to alter the reference contour, to create a single-number quantity better adapted to the subjective evaluation of impact sound [2,6,7,9]. Suggestions differ considerably regarding the currently prevalent ISO contour, not only concerning its shape but also the frequency range covered (see Figure 1). The most extensive field study produced a reference contour represented by a straight line with a positive slope of 1 dB per octave [7]; the single-number value is denoted I_S. Changing the reference contour to improve the adaptation of the single-number quantity to subjective experience would be attractive, since the measurement principles would stay unchanged – only the evaluation would be altered. Simple calculations are used to improve the correspondence of the single number to subjective experience. Apart from the shape of the reference contour, other minor variables might be altered in the evaluation of the single number. ISO 717, part 2 [10], states that the single number, denoted $L'_{n,w}$, equals the value of the reference curve at 500 Hz, after it has been shifted in steps of 1 dB until the sum of the unfavourable deviations is as large as possible without exceeding 32.0 dB. The 32.0 dB limit may be replaced by any other value; however, such an alteration and its effect was investigated and evaluated in the earlier work by Bodlund [7] and was shown to have almost a negligible effect on the single-number quantity and its correlation to subjective experience. Furthermore, obstacles could be introduced into the evaluation procedure: for example, in the case of the prior 8 dB rule, if unfavourable deviation between the measured curve and the reference contour for any single 1/3-octave band exceeds 8.0 dB, this would determine the single-number value. Such obstacles are not considered in this investigation, as it was stated early on that such obstacles have not been shown significantly to improve the correspondence between the single-number quantity and subjective experience [11].

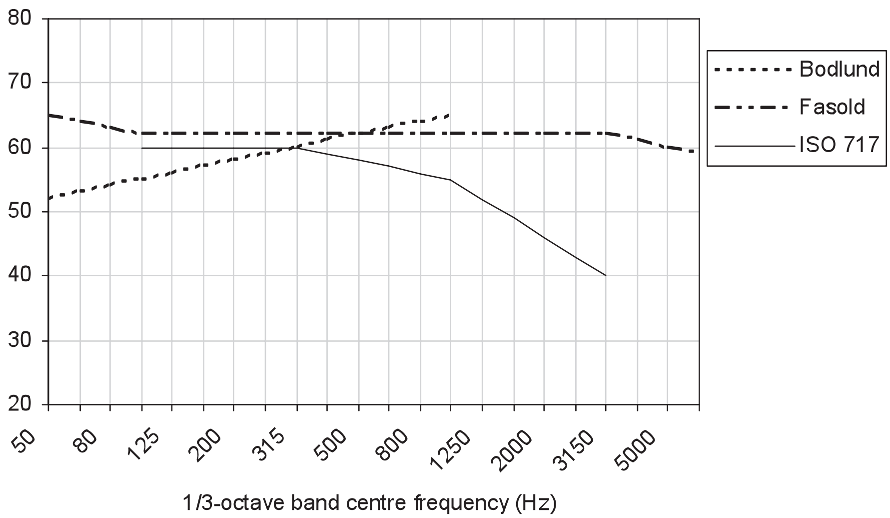

Figure 1. Evaluation contours: 1. ISO standard 717-2 (———); 2. Curve suggested by Fasold (—·—·—); and 3. curve suggested by Bodlund (-----).

The latest revision of ISO 717-2 [10] contains the option of adding an adaptation term to the single number, which creates the opportunity to extend the frequency range from 100–3150 to 50–3150 Hz. This term, which is included in the Swedish building code, is denoted $C_{I,50–2500}$, and if used, is simply added to the single-number value, $L'_{n,w}$. There is also an adaptation term, denoted C_I, that only considers the frequency range of 100–3150 Hz. The adaptation terms are calculated according to:

$$C_I \text{ or } C_{I,50-2500} = L'_{n,sum} - 15 - L'_{n,w} \quad (1)$$

where

$$L'_{n,sum} = 10 \cdot \lg \sum_{i=1}^{k} 10^{L_i/10}$$

and L_i is the normalized impact sound level in each 1/3 octave band.

This article presents research that builds on and analyses the research of Bodlund [7]; the data from the original study are modified and new data are gradually added to the original data sample [3,12]. In the present paper a total of 22 floor structures are analysed, twelve from Bodlund's original data sample [3,12] plus ten from ten different new housing units. Altogether, these data provide valuable information that facilitates insight into impact sound levels as dealt with in regulations and standards.

The main purpose of this research is to improve and optimize the single-number evaluation procedure, presuming that ISO measurement methods are to be used to find the most appropriate, generally applicable single number to capture impact sound levels in modern housing design. The data sample might be supplemented with new data as building practices progress.

The study also reflects on existing impact sound categories [13]. Hammer and Nilsson [14] question the resolution and range of sound classes in general, and of impact sound classes in particular. They show that distinctions between sound classes should not be too fine, and thus conclude that the number of impact sound classes in a classification system should not exceed three.

2. METHOD

2.1. Linear regression model

The research was carried out using linear regression analysis. Mean values from several objective impact sound measurements were compared with mean values of several subjective judgements within different housing blocks, and analysed using a linear regression model. The averaging procedure was applied to minimize the variations involved in the individual case, e.g. quiet or noisy neighbours, different inhabitants, different working hours and different sensitivity to noise, but also to make new data comparable to original data [3,12]. Considering the extremes in such dose–response relationships, i.e. covering instances of very bad or very good sound insulation, one would expect to find an *S*-shaped curve (Figure 2). This shape results from the horizontal scale being finite while the vertical scale has no upper limit (i.e. 0–infinity). This limits the linear model correlation coefficient, so the values in the outer regions will be uncertain. Since the most interesting region for the building industry is the central region of the sample, considerations are simplified and restricted to the middle part of the dose–response curve, in which it is assumed that the relationship can be approximated by a straight line. The linear regression is defined by two factors, *x* and *I*.

$$<L> = I + xS \tag{2}$$

where

$<L>$ is the mean value of the acoustic objective parameter (mean weighted impact sound level), the dependent variable (response)
S is the subjective mean score, the independent variable (predictor)
x is the regression coefficient indicating the slope of the regression line
I is the intercept giving the value of y where the line crosses the y-axis

Unnecessary constraints on the regression model are avoided by choosing housing areas that cover various sound insulation environments. This ensures that the model is applicable to buildings with poor to acceptable sound insulation.

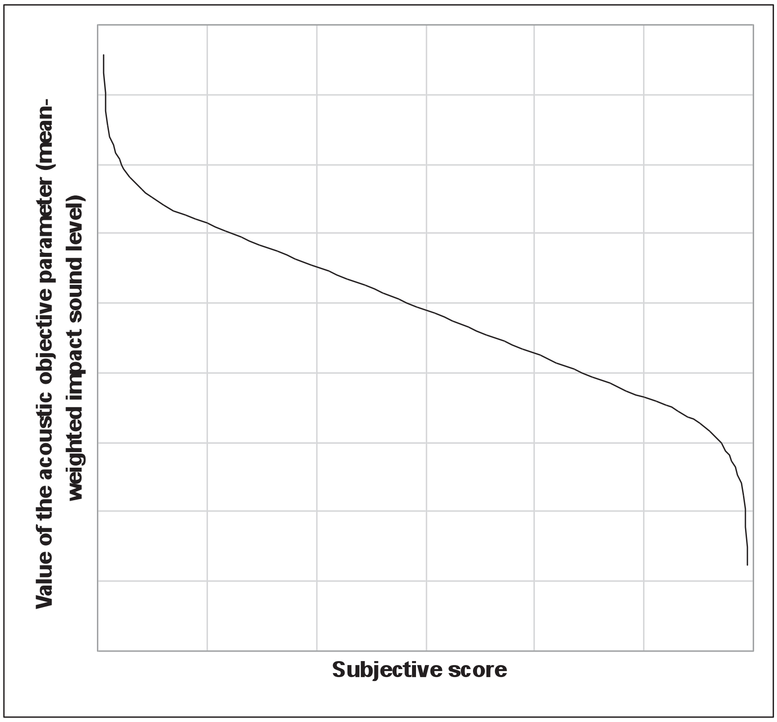

Figure 2. Expected idealized curve between the subjective mean score and the corresponding impact sound index.

2.2. Interviews

Quite apart from the objective impact sound measurements, tenants in each housing block were asked to rate the impact sound quality in their apartments. The interviews used for the ten additional housing units applied principles similar to those used in the earlier investigation [7].

The subjective investigation started by sending out questionnaires to all the tenants of the studied buildings (except those living on the top floors). In each block, the minimum time elapsed between the tenants moving into the studied dwellings and the questionnaires being sent out was one year. Tenants were asked questions concerning impact sound, and finally were to rate the impact sound quality of their flats by quantifying their judgments using a seven-point graded scale (see Table 1). In some cases the respondents gave answers that were not likely to correspond to the questions concerning impact sound. In those cases the questionnaires were followed-up with telephone interviews to ensure that respondents

I. genuinely understood the questions
II. correctly interpreted the scale system for subjective grading
III. grasped the concept of “impact sound”

Table 1. Rating scale for quantifying subjective judgements

Quite *un*satisfactory						**Quite satisfactory**
1	2	3	4	5	6	7

The lowest score is 1 (poor impact sound insulation) while the highest score is 7 (excellent impact sound insulation). Using the entire sample of original data it was stated that if the mean score is below 4.4, the overall performance should be regarded as unsatisfactory, and this score might be used as a limit of acceptability in the building code [7].

A total of 198 respondents were answering the questionnaires for the additional ten additional housing units, corresponding to a number of replies equal to 57%. These new interview data were averaged to obtain an overall subjective score for each housing block; then these new mean values were added to the original data. The procedure is similar to that used in the earlier investigation [7].

2.3. Impact sound level measurements

2.3.1. Original data collected by Bodlund

The initial source data [3,12] for Bodlund’s research [7] were gathered and evaluated in 1985, according to the formerly valid ISO/R 140/VII-1978 and SS-ISO 717, part 2, standards [15,16], which have since been revised. The final results of the research included a proposal for a revised evaluation contour (see Figure 1). Further analysis of the original data is hampered by the absence of 1/3-octave band data from the source data reports [3,12], which contain only plots of the curves – in ordinary impact sound level diagrams – and their corresponding single-number ratings. However, many overlapping curves are plotted in each diagram, making it difficult to estimate 1/3-octave values corresponding to the correct single-number quantity. Nevertheless, by enlarging the diagrams it was possible to estimate the 1/3-octave band data and make these data useful again. Note, however, that the estimates include a degree of uncertainty.

To ensure that the estimation procedure produced acceptable values, the estimated 1/3-octave values were recalculated as single-number figures and then compared these ($L'_{n,w}$ and the measure proposed by Bodlund, I_s) with those in the original reports [3,12]. Furthermore, the correlation coefficients were calculated and compared with the original equations. The new recalculated relationships became

$$\langle L'_{n,w} \rangle = 80.4 - 5.44\, S \quad [r = 75\%, n = 22] \tag{3}$$

$$\langle I_S \rangle = 85.9 - 5.43\, S \quad [r = 87\%, n = 22] \tag{4}$$

while the original relationships from Bodlund [7] were

$$\langle L'_{n,w} \rangle = 80.6 - 5.48\ S \quad [r = 75\%, n = 22] \tag{5}$$

$$\langle I_S \rangle = 86.3 - 5.53\ S \quad [r = 87\%, n = 22] \tag{6}$$

where S is the subjective score (ranging from 1 to 7) and n is the number of data points. The small differences between the equations might have resulted from rounding differences, or from the difficulty of estimating correct 1/3-octave values from the plots of the curves. Nevertheless, equations (3)–(6) indicate that the estimated data are sufficiently close to the original data; the original data may thus be regarded as recovered, and the estimated data as useable for recalculation and further analysis.

The original source data [3,12] covered both horizontal and vertical impact sound transmission. This is cause for concern, since impact sound data originating from horizontal measurements belongs to one "group" with low impact indexes. In contrast, the vertical measurements belong to a "group" with higher indexes corresponding more closely to the levels set forth in the regulations (see Table 2); consequently, the contribution of the vertical measurement group to disturbance should be considerably higher than that of the horizontal group.

Table 2. Measurement direction in relation to the value of the acoustic parameter according to the original source data [3,12]

Measurement direction	Parameter	Number of data points	Range of acoustic parameter
Horizontal	$L'_{n,w}$	9	37–49
Vertical	$L'_{n,w}$	13	51–70
Horizontal	I_s	9	43–56
Vertical	I_s	13	59–72

Hence, all data from the horizontal measurement group exhibit mean values far below the minimum requirements of the current Swedish building code ($L'_{n,w}$ and $L'_{n,w} + C_{I,50–2500} \leq 58$ dB) and far below the values giving satisfactory ($S \geq 4.4 \Rightarrow I_s \leq 62$ dB) impact sound levels using I_s [7]. The low levels of impact sound in the horizontal group suggest that the subjective judgements may have been more influenced by other sound sources in the vicinity than was the case for the vertical group. Impact levels as low as 37–49 dB do not normally create much annoyance. Thus, the pattern of disturbance between the groups might have been unequal.

Quite apart from the above, there are additional reasons to examine the two different measurement directions separately. One is that impact levels are normally perceived as higher directly above the listener [17,18]. Given that, what happens if the two groups in Table 2 are separated in the analysis? Excluding the vertical measurements and only including the horizontal measurements gives the following relationships:

$$\langle L'_{n,w} \rangle = 59.8 - 2.59\ S \quad [r = 44\%, n = 9] \tag{7}$$

$$\langle I_S \rangle = 70.3 - 3.23\ S \quad [r = 53\%, n = 9] \tag{8}$$

which indicates weak correlation, for both the ISO 717 single number and for the figure suggested by Bodlund [7]. Analysing only vertical transmission, as captured in the source data, gives the following:

$$\langle L'_{n,w} \rangle = 70.1 - 2.48\ S \quad [r = 41\%, n = 13] \tag{9}$$

$$\langle I_S \rangle = 78.8 - 3.41\ S \quad [r = 81\%, n = 13] \tag{10}$$

Though the calculation precision decreases as the number of data points decreases, the calculations clearly indicate that it would be appropriate, to separate the horizontal part of data points from the vertical part. Furthermore, one housing floor structure captured in the data sample of the supplementary study [12] should be excluded, as it gave rise to extreme subjective responses: it was a concrete floor structure covered with hard linoleum in a bedroom. This structure may have received a high subjective ranking, despite its high impact sound levels, because the impact sounds were emanating from a sleeping room. There is reason to suspect that, in this case, real impact sounds from this room appear with reduced frequency and therefore their contribution is low Hence the final number of data points originating from Refs. 3 and 12 is 12. Most data were collected from occupied and normally furnished dwellings, and the housing units included in current investigation are compiled in table 3.

Table 3. Original housing units

Housing unit no	Structure	Floor covering	Built year	No of measurements	No of replies	Time for data capture
01	Timber	Parquet/vinyl	1983	5	4	1983–1985
02	Solid concrete	Carpet/vinyl	1962	10	64	1983–1985
03	Timber	Carpet/vinyl	1920/1979	5	11	1983–1985
04	Solid concrete	Block board ?	1982	5	12	1983–1985
05	Solid concrete	Vinyl	1981	7	21	1983–1985
06	Solid concrete	Vinyl	1981	6	16	1983–1985
07	Solid concrete	Raised timber floor and vinyl	1950/1982	12	23	1983–1985
08	Timber	Parquet/wood	? /1982	10	12	1983–1985
09	Timber	Vinyl	1935	8	22	1983–1985
10	Timber	Varnished parquet/wood	1935	8	18	1983–1985
11	Timber	Parquet	1940/1980	12	28	1983–1985
12	Solid concrete	Parquet	1981	5	14	1983–1985

2.3.2. Additional data

Additional data were also used in this research work. All additional objective measurements were made according to the international ISO 140-7 standard [19]. The impact sound was generated using the standardised tapping machine (Brüel & Kjaer, type 3204), and this impact source was presumed to create sufficient low-frequency energy. The 1/3-octave band values from 50 Hz to 3150 Hz are included in all measurements. In some cases, the 4000 and 5000 Hz bands are included even though these high-frequency 1/3-octave bands are of minor or no interest for the final results. The data were analyzed using a real-time frequency analyzer (Brüel & Kjaer, type 2260). The impact sound performance of each housing block was expressed by calculating the mean of several single measurements. The number of measurements made for each block depends on the number of dwelling units, and ranged between two and seven. A total of 41 additional measurements were made. Spatial averaging was done using discrete microphone positions according to the instructions in the latest version of ISO 140-7 [19]. Since the investigation [7] was performed, the standards for measuring impact sound in the field have been slightly revised, and the spatial averaging procedure using discrete microphone positions is now more extensively specified [19]. However, the spatial mean value for the original sample was determined using a rotating microphone boom, a situation covered both by the former and the revised standard; hence it is assumed that the rotating boom creates approximately the same spatial averaging as if five discrete positions were used.

The additional data capture a range of building types: two sampled housing areas have lightweight timber floor structures [4,5], one has a lightweight steel floor structure, five are in modern buildings with various-sized prefabricated hollow concrete elements covered with typical modern dry floating flooring (floor covering/surface of parquet) [20], and two buildings comprise homogenous concrete structures poured in situ. The housing units were chosen so as to cover a wide range of typical modern building technique, see table 4.

Table 4. Additional housing units

Housing unit no	Structure	Floor covering	Built year	No of measurements	No of replies	Time for data capture
13	Timber	Parquet	1996	4	6	1996/1997
14	Timber	Parquet	1996	2	11	1996/1997
15	Hollow concrete	Raised floor and parquet	2002	3	20	2003
16	Hollow concrete	Raised floor and parquet	2002	5	20	2003
17	Lightweight steel structure	Parquet	2000	2[2]	5	2000/2004
18	Hollow concrete	Raised floor and parquet	1999	2[1]	62	2000/2004
19	Solid concrete	Parquet on foam	1999	2[1]	10	2000/2004
20	Hollow concrete	Raised floor and parquet	2000/2001	2[1]	12	2001/2004
21	Solid concrete	Parquet on fibre board	1989	6	13	1989/2004
22	Hollow concrete	Raised floor and parquet	2002/2003	7	39	2003/2004

[1] Additional calculations according to EN 12354 [21] were performed to ensure that the results were reliable.

[2] This building was a two-storey housing building including five apartments in each storey. Only those who lived in the first floor were asked to judge the acoustic performance.

Most of the new objective measurements were made before occupation, i.e. in the unfurnished flats. In some cases, however, the measurements were made in furnished rooms. Nevertheless, particular caution has been taken to ensure that all results are comparable. If necessary, diffusers were placed in the unfurnished rooms, and in those cases additional calculations were made according to EN 12354 [21] to ensure that the results are reliable. All measurements were made in completely constructed apartments.

2.3.3. Single numbers and further improvements

In the present study many different single-number quantities, emanating from different reference contours, are calculated, quite apart from the normal ISO single-number figures. The calculations are made using identical evaluation rules as those prescribed for the ISO single number [10]. The reference curves are then altered and until the very best curve is found, i.e. until the single-number value exhibits optimal correlation to the subjective response.

The new single numbers representing new evaluation contours are described by $L'_{\mathrm{n,w,new,0X}}$, where n indicates that the figure is normalized according to the rules specified in ISO 140-7 [19], w means weighted, “new” indicates that the curve is new, and 0X is one of a series of consecutive numbers starting at 01.

2.4. Limitations

The new data cover modern houses with structures and product combinations typical of modern housing, primarily constructed 1996–2003. The housing units consist of typical family apartments, though they are not necessarily always occupied by families with children. Ninety percent of the inhabitants asked to judge the acoustic performance were between 28 and 55 years of age, and it was assumed that they had normal hearing ability. The respondents were not asked about their sex. In those cases where the inhabitants answered questions via telephone interviews, they were also asked if they had any hearing impairment. Unfortunately, the mixture of inhabitants is not known for the original data presented in reference [7].

The original data suffer from yet another serious shortcoming. In Refs. 3 and 12, only *normalized* 1/3-octave band levels are recorded. Normalization implies that the measured levels are normalized to a sound absorption area of 10 m^2. In many cases this is an appropriate normalization area, if rooms are of standard dimensions and furnished in ordinary manners, i.e. a room area less than approximately 20 m^2 and a maximum reverberation time of 0.5 s – assumptions that apply for most of the original sampled housing areas [3,12].

On the other hand, if the room area is 50 m^2, normalization to an absorption area of 10 m^2 is too small. Fortunately, such large modern domestic rooms are commonly furnished sparsely, which tends to prolong reverberation time. This may compensate somewhat for the increased room size, though the effect is limited. Nevertheless, keeping the normalization to 10 m^2 may cause large errors, i.e. the single-number value will rise by 5-6 dBs in modern housing design, due solely to the evaluation procedure. Some additional data do include measurements in large rooms.

Furthermore, the reverberation time is not necessarily 0.5 s in all 1/3-octave bands. Normally, the reverberation time at the lowest frequencies is not affected by the furnishing density to the same extent as higher-frequency, 1/3-octave bands are. Example reverberation times for a large room in a sample apartment, both unfurnished and fully furnished, are shown in Figure 3. This effect might be even more pronounced at frequencies below those considered, and hence the normalization could result in marked variation depending on which 1/3-octave band is taken into consideration.

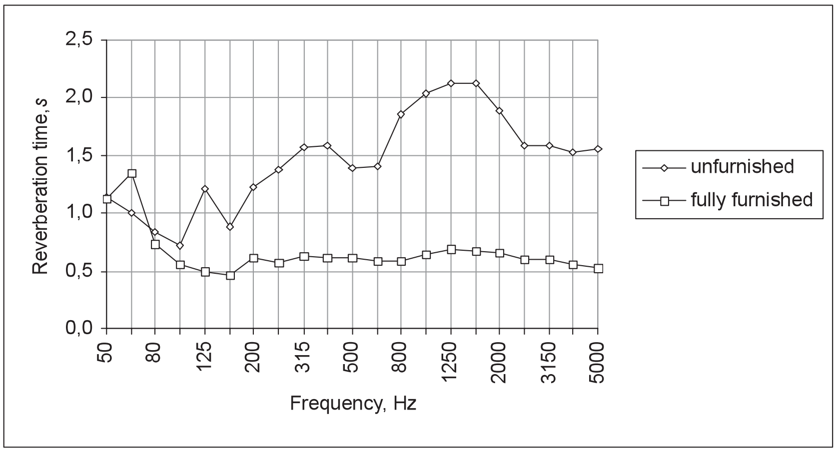

Figure 3. An example reverberation time curve for a large room in a modern housing building with a hollow concrete floor slab mounted on a steel structure; ◇ = the unfurnished room, □ = the fully furnished room.

All the above factors should be considered when the data are analyzed together. Summing up, given the variation in room volumes and reverberation times, the absolute sound pressure level may vary more than the cited impact index. Hammer and Nilsson [14] show that loudness correlates significantly better to the subjective score than to the aforementioned impact indexes. Thus, by using loudness in furnished buildings, the normalization problems regarding room volume and reverberation time may be circumvented. It should also be noted that Hammer and Nilsson consider impact sound in the 20 to 5000 Hz range, thus including the important frequency range below 50 Hz.

3. RESULTS

The sample data for this research were examined, along with the different reference curve contours, until the best fit was found. Optimisation was carried out to arrive at the best correlation to the subjective judgment, which is applicable independently of frame structure and floor construction. It was found that the curve should generally be quite flat, though probably exhibiting a negative slope at high frequencies. However, in the lowest-frequency region the reference curve should have an emphatically positive slope. The results from the calculations are first presented using a evaluation contour with a positive slope equal to the first part of the reference curve suggested in [7], however turning flat above 125 Hz. This curve resulted in slightly higher correlation than that of the curve suggested in [7] (see equations 12 and 13). Then, shifting the low-frequency part to a more positive slope further improves the correlation to the subjective score. This finally results in a curve that is particularly steep at low frequencies, so as to emphasise frequencies below 100 Hz (see Figure 4).

$$\langle I_S \rangle = 80.27 - 3.98\ S \quad [r = 83\%, n = 22] \tag{12}$$

$$\langle L'_{n,w,new,01} \rangle = 76.29 - 4.10\ S \quad [r = 85\%, n = 22] \tag{13}$$

$$\langle L'_{n,w,new,02} \rangle = 77.69 - 4.12\ S \quad [r = 86\%, n = 22] \tag{14}$$

$$\langle L'_{n,w,new,03} \rangle = 79.28 - 4.09\ S \quad [r = 87\%, n = 22] \tag{15}$$

The lowest frequencies are far more annoying than the earlier reference contour would suggest – an important consideration as lightweight structures enter the market. The curve shift from a straight line to an extreme positive slope should happen at 100 Hz and below. The grade of the positive slope then becomes 5.5 dB/third octave, giving the highest correlation, r, equal to 87%. Minor shifts from the suggested curve shape only have small effects on the correlation coefficient.

The extreme positive slope at low frequencies is partly explained by the fact that walking, jumping children, and other heavy impact sources generate sound levels including much higher levels in the low-frequency region than are considered in the ISO impact source [19]. Fully compensating for this difference requires a strongly positive slope.

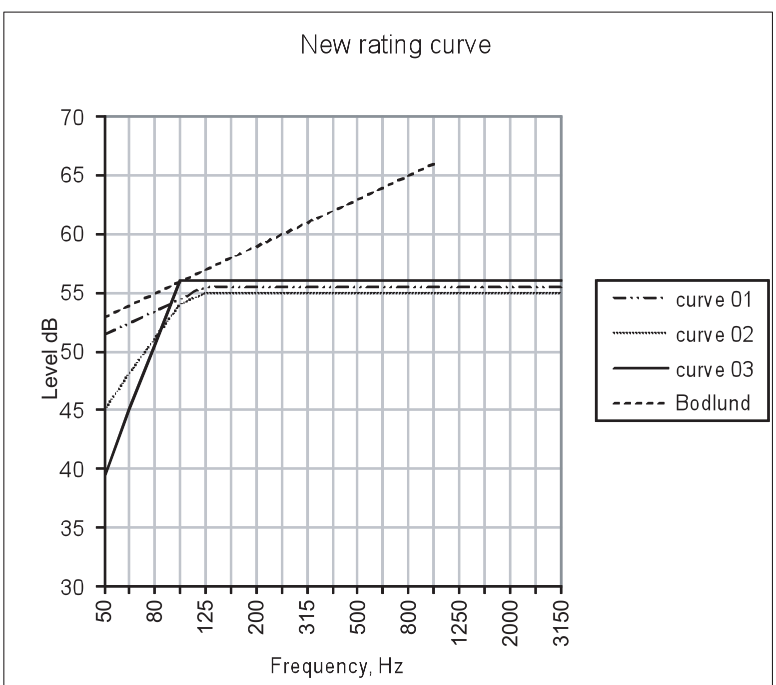

Figure 4. Shifting the curve from Bodlund's shape [7] to curve 03 raises the correlation coefficient, r, from 83% to 85% (curve 01), 86% (curve 02), and finally 87% (curve 03).

Evaluation curve 03 shown in Figure 4 exhibits the best correlation to subjective evaluation ($r = 87\%$), using the entire new revised data sample totalling 22 data points. A 4.1 dB reduction of the impact sound level corresponds to an experienced sound insulation improvement of one unit on the seven point scale (subjective score).

Furthermore, probably the curve should not terminate at 1000 Hz, or at any other frequency below 3150 Hz, as suggested by Bodlund [7]. This assumption is made due to uncertainties concerning future behaviour. Today, there is a lack of available housing units with hard floor coverings laid on concrete slabs, so it is impossible to draw any firm conclusions concerning the shape of the curve at high frequencies. To visualize the effect of a high-frequency negative slope, calculations were made using a reference contour with a shape identical to that of curve 03 in the 50–315 Hz range. However, above 315 Hz the curve has a positive slope equal to 1 dB/third octave (see Figure 5). Such an alteration only slightly affects the correlation equation, as would be expected due to the adaptation of building construction to the ISO reference contour. However, there is still a small alteration, due to one data point actually deriving from a housing unit with hard floor covering.

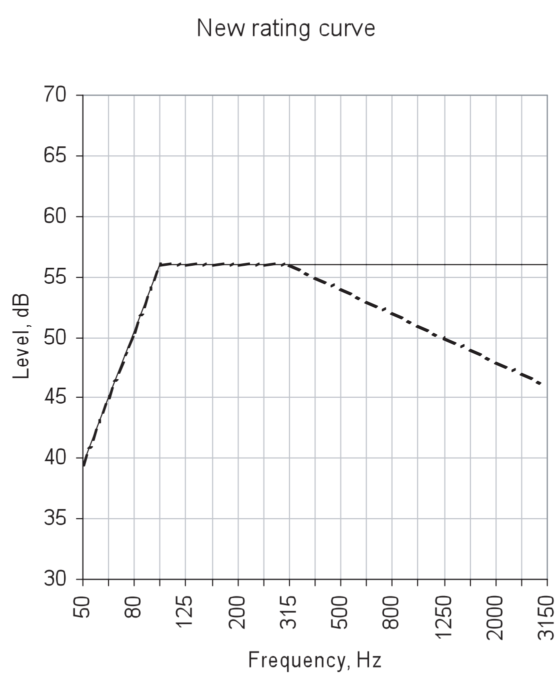

Figure 5. Shifting the curve from the suggested curve shape 03 to a curve including a positive slope of 1 dB per 1/3 octave (curve shape 04) above 315 Hz does not greatly influence the result. The correlation coefficient, r, retains its value of 87% even though the equation exhibits minor changes.

The relationship thus changes from that of equation (15) to

$$\langle L'_{\mathrm{n,w,new,04}} \rangle = 78.27 - 4.23\ S \quad [r = 87\%, n = 22] \tag{16}$$

The best-fit shape of the high-frequency part of the evaluation curve cannot be stated with confidence. Nevertheless, it is clear that there is insufficient field data to be able to exclude the high-frequency part of the curve from evaluation as irrelevant.On the contrary, the high-frequency range must be considered until proven not to affect the subjective score. In so far as the opposite is unproven, the old ISO contour [10] might be used in combination with a low-frequency contour.

3.1. Current evaluations available

We could not expect, a contour shift according to the results presented in this paper to be adopted as an ISO standard for many years. However, adding the adaptation term, $C_{\mathrm{I,50–2500}}$, to the single number, $L'_{\mathrm{n,w}}$, according to the current ISO standard [10] will considerably improve the correlation of the ISO single number with subjective evaluation – actually slightly better than the curve suggested in 1985 [7]. Equation (17) shows the relationship using $L'_{\mathrm{n,w}} + C_{\mathrm{I,50–2500}}$, and this may be compared to the relationship using $L'_{\mathrm{n,w}}$ (simply excluding the adaptation term) shown in equation (18). Further to verify the need to consider low frequencies, the results of adding the adaptation term, C_{I}, while only paying attention to the ordinary frequency range (100–3150 Hz), are shown in equation (19).

$$\langle L'_{\mathrm{n,w}} + C_{\mathrm{I,50–2500}} \rangle = 74.40 - 4.17\ S \quad [r = 84\%, n = 22] \tag{17}$$

$$\langle L'_{\mathrm{n,w}} \rangle = 75.35 - 4.58S \quad [r = 74\%, n = 22] \tag{18}$$

$$\langle L'_{\mathrm{n,w}} + C_{\mathrm{I}} \rangle = 73.31 - 4.22\ S \quad [r = 79\%, n = 22] \tag{19}$$

In light of the preceding, while still using current ISO standards and figures (as is appropriate to facilitate trade within the EU), it is proposed that EN-ISO 140-7 [19] be used as the measurement standard and that the normalized levels, L'_{n}, be settled in the 50–3150 Hz range. Furthermore, both the single-number value, $L'_{\mathrm{n,w}}$, and the spectrum adaptation term, $C_{\mathrm{I,50–2500}}$, should be evaluated according to EN-ISO 717-2 [10]. These figures should be used in estimating the acoustic performance of tested floor construction. Thus, assuming that the subjective grade of 4.4 [7] still might be used as a limit for building regulations (even though new data are added), the standardized ISO figures should be less than or equal to

- $L'_{\mathrm{n,w}} + C_{\mathrm{I,50–2500}} \le 74.40 - 4.17 \times 4.4 \approx 56$ dB.
- $L'_{\mathrm{n,w}} \le 75.35 - 4.58 \times 4.4 \approx 55$ dB

In Nordic countries sound classification has become integral to the construction process, this being supported by the establishment of national standards. The standards in each country are similar to [22] regarding its design, and include four classes, class

C corresponding to the minimum requirements of the national building code. There are two better classes – classes A and B – above the minimum standard and one class – class D – to be used occasionally in certain rebuilding projects with high requirement to preserve details from its origin [22]. In Figure 6 the exact ISO values are calculated using the linear regression equation (17) for two classes above the minimum requirement. In making the calculations, the subjective score was raised one step for each acoustic performance class. This choice was made because it is inappropriate to use a subjective score higher than 6.4 when estimating the best acoustic performance class, since the linear regression approximation probably fails more the closer to seven we get (see section 2.1).

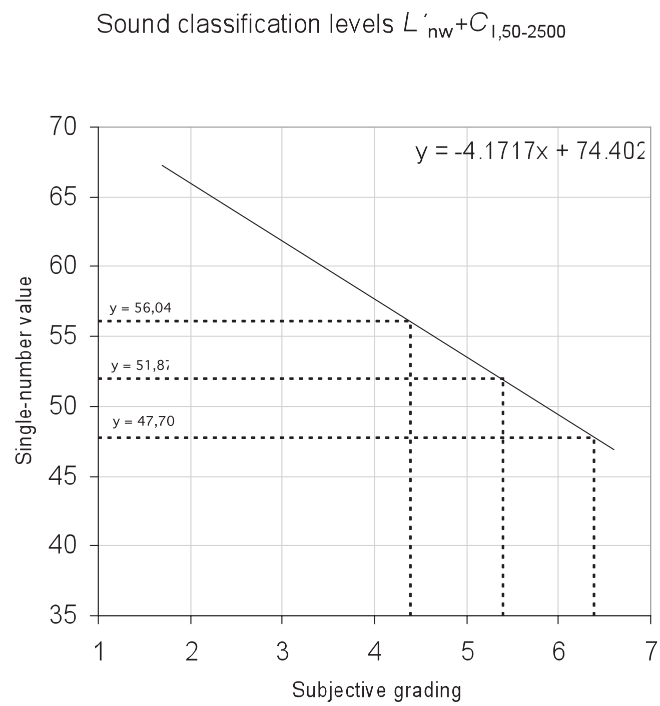

Figure 6. Possible levels for different sound classification standards using the ISO single number $L'_{n,w} + C_{I,50–2500}$.

To conclude, it is suggested to use both $L'_{n,w} + C_{I,50–2500}$ and $L'_{n,w}$ and using limit values lower than the following:

56 dB for minimum building regulations
52 dB for a sound class exhibiting higher acoustic performance
48 dB for a sound class exhibiting excellent acoustic performance

4. ANALYSIS

This section further analyses the results presented in the previous section. Various average impact sound indices are plotted versus the subjective mean score. The vertical error bars represent the maximum and minimum measured values – hence the objective measurement spread – within each housing unit. Only the vertical error bars are plotted in the figures, since they supply information concerning differences between single measurements within each housing unit. Whilst horizontal error bars could supply information concerning perceived impact sound level in particular cases, in this investigation priority is given to the differences between the objective measures (as in reference 7).

4.1. ISO measures and Bodlund measure I_S

Figure 7 shows the average impact sound level, $L'_{n,w}$, versus the subjective mean score and the straight line is the plotted result of equation (18).

The correlation between the objective mean value, $L'_{n,w}$, and the subjective mean score is almost equal to the original data sample, which included horizontal measurements, as in equation (5) [7]. However, there is a change in the slope of the regression line, x decreases from 5,48 to 4,58. The slope has been reduced, in accordance with expectations, since the horizontal part of the original data sample is

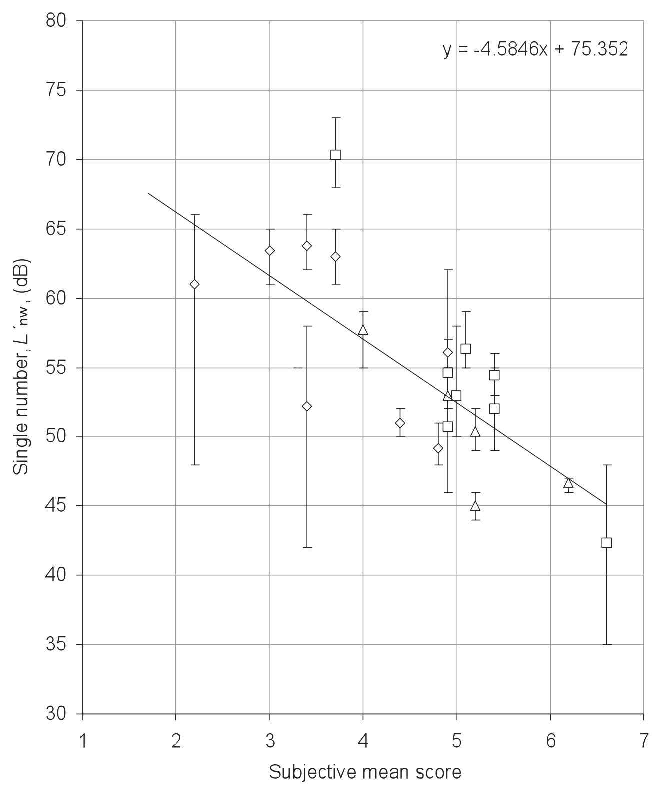

Figure 7. Linear regression for the whole data sample, $L'_{n,w}$ vs subjective grading; □ = concrete structures, △ = hollow concrete structures, ◇ = wooden floor structures, × = lightweight steel structures.

correlated to high subjective scores and low $L'_{n,w}$ values (see section 2.3.1). As shown in the present study, the correlation coefficient can be significantly improved.

There is considerable spread in some of the maximum and minimum measured values, as becomes obvious when examining the error bars. The largest spread is found for two cases between wooden lightweight structures, one dating from the 1980s and the other from the 1920s, see table 3, housing unit 01 and 03. This large spread for lightweight structures is understandable, as it is easy to alter the $L'_{n,w}$ value (i.e. within the 100–3150 Hz range) for wooden structures. Minor changes of floor covering, for example, installing a soft carpet instead of hard flooring, could noticeably improve $L'_{n,w}$ values, i.e. sufficiently improving the L'_{n} values in 1/3-octave bands above the lowest frequencies (approximately above 100 Hz). Concrete structures both solid and hollow i.e. heavy structures, generally exhibit higher subjective scores and lower $L'_{n,w}$ values than do lightweight structures. The aim is often to reach equal acoustic quality independently of structure at least for those housing units in the recorded sample, built or rebuilt according to modern building regulations (later than ≈ 1970).

Adding the ISO spectrum adaptation term, $C_{I,50–2500}$, to the weighted normalized single number – as in equation (18) – results in the shape shown in Figure 8.

Finally, what happens if we use just the spectrum adaptation term, C_I - i.e. considering the 100-3150 Hz range - is shown in Figure 9 (this shows the data for equation (19)).

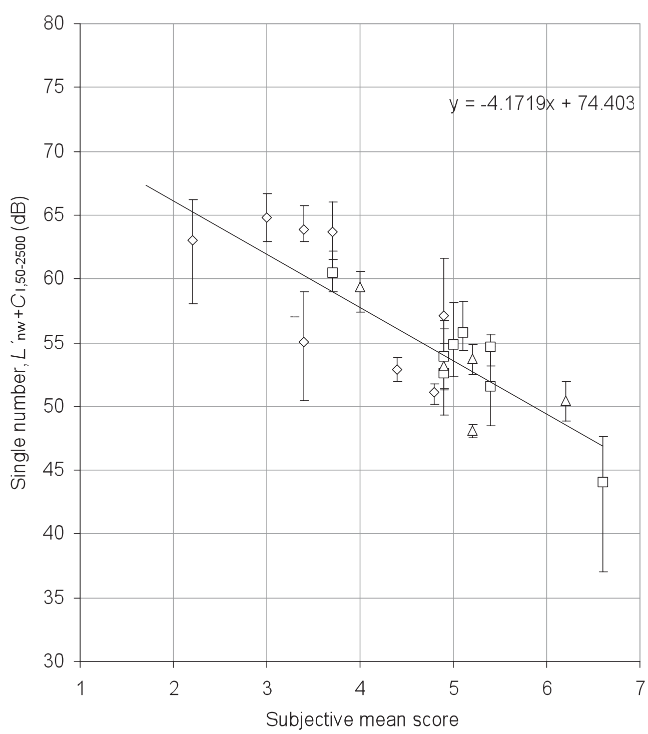

Figure 8. Linear regression for the whole data sample, $L'_{n,w}$ + $C_{I,50–2500}$ vs subjective grading; □ = concrete structures, △ = hollow concrete structures, ◇ = wooden floor structures, × = lightweight steel structures.

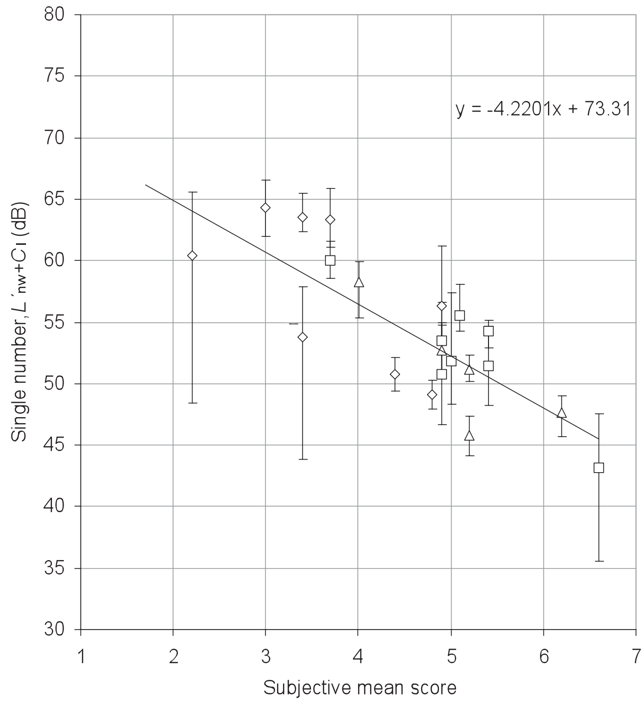

Figure 9. Linear regression for the whole data sample, $L'_{\mathrm{n,w}} + C_{\mathrm{I}}$ vs subjective grading; □ = concrete structures, △ = hollow concrete structures, ◇ = wooden floor structures, × = lightweight steel structures.

Use of the single number, $L'_{\mathrm{n,w}} + C_{\mathrm{I}}$, is not recommended, even though it exhibits a slightly better correlation than $L'_{\mathrm{n,w}}$ does. This recommendation is based on the fact that the single number is far too generous at high frequencies, while not acceptably taking account of low frequencies. C_{I} (and also $C_{\mathrm{I},50\text{–}2500}$) might exhibit values as low as –14 dB, and this could affect the choice of floor coverings in future residential buildings: for example, hard floor coverings could become more common on heavy concrete structures, which in the long run could cause unpredicted problems. Even so, where shoes are worn indoors they are normally a type having a resilient sole. However, impact sound is not only caused by footsteps – though this may be the dominant source – and future sound performance would be unknown if new hard floor coverings are permitted. Furthermore, to make new single numbers globally usable, the rating should not depend on "local area source behaviour".

On examining equations (12)–(15) it becomes obvious that giving greater consideration to low frequencies will automatically result in better agreement between the experienced impact sound level and the objective measurements, a finding in accordance with earlier investigations. However, by treating vertical sound transmission *separately* from horizontal transmission, the correlation (using the curve suggested by Bodlund) decreases from 87% to 83%; this is slightly lower than in the original data, where both vertical and horizontal sound transmission were taken into account (see equations 6 and 12) [7]. The relationship according to equation 12 is plotted in Figure 10.

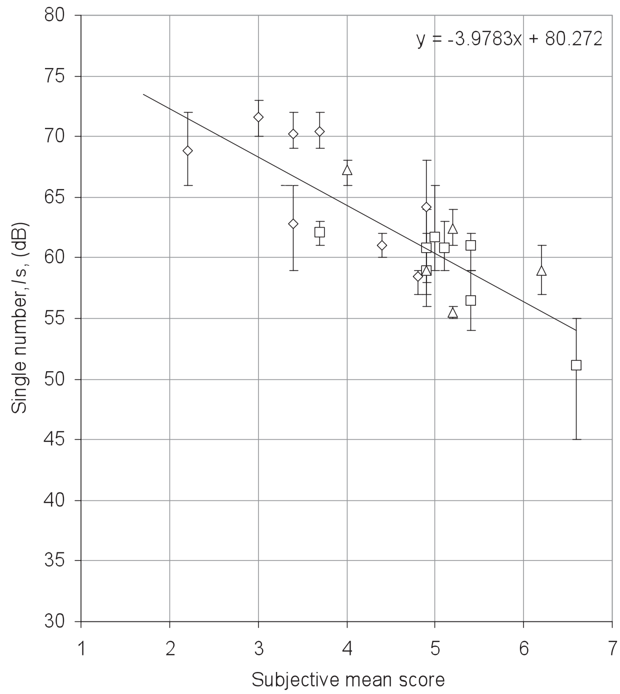

Figure 10. Linear regression for the whole data sample, I_S vs subjective grading; □ = concrete structures, △ = hollow concrete structures, ◇ = wooden floor structures, × = lightweight steel structures.

No matter whether I_S or $L'_{n,w} + C_{I,50–2500}$ is used, an improvement of one step in the horizontal, subjective scale corresponds to a decrease in the impact sound level of approximately 4 dB. The requirement in Sweden today states that both $L'_{n,w} + C_{I,50–2500}$ and $L'_{n,w}$ values must be below the 58 dB level. This requirement was the outcome of two projects conducted in Sweden [9,11]. Even though $L'_{n,w}$ values show worse correlation than do $L'_{n,w} + C_{I,50–2500}$ values, they still must be included, so as to prevent poorly performing construction in future buildings. Similar to the analysis concerning $L'_{n,w} + C_I$ above, the $L'_{n,w} + C_{I,50–2500}$ and I_S figures are far too "generous", primarily to concrete floor structures covered with hard floor coverings. Unfortunately for the calculations in this work, but fortunately for building residents, this is not a natural type of construction for examination, due to lack of residential buildings using such hard coverings. The purpose here is to prevent the occurrence of a construction type that is likely to cause problems, if permitted; the exact shape of the curve needed to prevent high-frequency disturbance will probably have to be evaluated in the laboratory, or in any country permitting those floor constructions.

The single numbers for lightweight floor structures exhibit a noticeably narrower spread within each housing block if adding the low frequency spectrum adaptation term (50–3150 Hz range), than if either excluding the spectrum adaptation term or adding the spectrum adaptation term not covering the low frequencies (100–3150 Hz) (see Figures 7, 8 and 9). This might be explained by the fact that the frequency bands determining the single numbers all lie in the typical low-frequency region. This region is unaffected by typical floor structure improvement measures (as $L'_{n,w}$ is), and changes that decrease the $L'_{n,w}$ value immediately result in an increased adaptation term, $C_{I,50–2500}$. This "compensating effect" that the low frequency adaptation term exhibits, is exactly what is needed to create a single number that corresponds to subjective experience. However, the effect of using the ISO adaptation term is too small to compensate fully for the need.

4.2. Suggested contour and corresponding single number

Finally, it is interesting to study the results corresponding to equation (15). These results are plotted in Figure 11. As with earlier calculations, the results are obtained using the value at 500 Hz as the single-number figure after the contour shifting procedure. The value becomes higher, since the low-frequency curve contour irresistibly creates higher values, particularly regarding lightweight structures. Applying 4.4 [7] as an acceptable mean subjective score, the new single number limit value will become 61 dB, taken from equation (15), Figure 11.

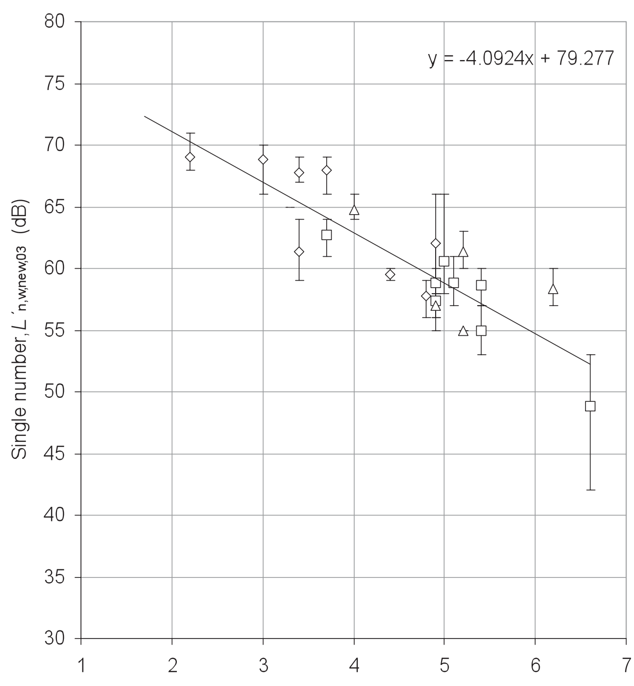

Figure 11. Linear regression for the whole data sample, $L'_{n,w,new,03}$ vs subjective grading; □ = concrete structures, △ = hollow concrete structures, ◇ = wooden floor structures, × = lightweight steel structures.

5. DISCUSSION

The main, long range aim of this research is to create an accessible database containing substantial field data pertaining to residential buildings. As well as carefully considered subjective evaluation data, the important factors for making correct judgments concerning various parameters and their influence on the final results are

- floor structure design
- connected flanking constructions
- design of dwelling: receiving room volumes
- 1/3-octave band data from field measurements: not only normalized levels but also measured impact levels and reverberation time data, etc.

As new building techniques are developed and introduced into the market, new data might be inserted into the database and different reference curve shapes (or other parameters) examined. It is reasonable to assume that the suggested curve contour might alter slightly if the data are further extended. New evaluation methods are easily calculated for the whole "new sample". This will become a valuable tool for authorities and other institutions whose mission is to establish building regulations and standards. The regulatory regime should always be developed and analyzed in line with construction industry progress which, in the long run, will create regulations better supported than they are today.

This investigation observed two typical outliers concerning room volumes, i.e. measurements made in extraordinarily large room receiving room volumes. Both these cases comprised heavy, slender hollow concrete structures. Using suggested curve shape 03 and making corrections according to expected real reverberation times in each 1/3-octave band in these cases, creates the following relationship:

$$\langle L'_{(\mathrm{n}),\mathrm{new}} \rangle = 78.99 - 4.08\ S \quad [r = 88\%, n = 22] \tag{20}$$

The notation "n" is now put within brackets, since the normalization to 10 m^2 is no longer consistently valid. Other single-number values do not exhibit any improvements. However, there are still uncertainties, since all measurement data must be corrected to suit their particular receiving room volumes until fairly certain conclusions can be drawn. Furthermore, room furnishings do not normally influence reverberation times at the lowest frequencies, i.e. 10 m^2 normalization might be acceptable in the lowest-frequency region. If so, the single-number rating using the proposed curve might be acceptable, because the single-number determining frequency bands will be evaluated correctly and hence errors in the high-frequency part will not be of interest. These effects might be further analysed since the database will be expanded in future. Furthermore, the original data sample measurements do not include reverberation time data, which are necessary in order to recalculate the correlation coefficients continuously as new data are included in the database. Yet another matter requiring further analysis is reverberation time evaluation according to diffuse field theory. In typical housing environments this theory is not in line with actual conditions, particularly in the typical low-frequency region. As this work progress, we will become increasingly aware of the complexity of finding a proper single descriptor of impact sound insulation for describing impact sound insulation in the field, independent of building frame structure. Old measurements included in the original data sample will gradually be replaced with more detailed measurement data points, which in turn will facilitate more detailed analysis, an analysis also including loudness calculations. Despite the shortcomings of our current methodology, we have still arrived at some important findings, namely:

- Low frequencies must be considered to a greater extent.
- High frequencies must be considered so as to prevent the future adoption of new, heavy floor structures with hard floor coverings.
- Normalization to 10 m^2 should be taken into account in the evaluation procedure, i.e. perhaps L'_n should be replaced by the standardized figure L'_{nT}. Hence, the reverberation time, $T_0 = 0.5$ s, might be a preferable reference value instead of $A_0 = 10$ m^2. However, further analysis concerning this matter is necessary.
- Room volumes and furnishing density are mutually dependant.
- An objective decrease of approximately 4 dB in sound level in the analysed measures equals a one-unit improvement in subjective grading when a seven point evaluation scale is used.

This extended investigation considers two new wooden structures (see Refs. 4 and 5). Both these structures were developed to achieve high acoustic performance; lowering building costs was not a prime consideration. The floor structures are slightly more than 500 mm thick and the structural design is complicated. However, it has become obvious that such structures are far too complicated and not commercially attractive; consequently, these floor structures are not found on the market. The commercial alternatives are prefabricated, often more slender and less low-frequency resistant structures. The aim of exceeding minimum standards of acoustic performance has not always been achieved, and the success of lightweight structures has so far been limited. However, these structures often do satisfy minimum Swedish acoustic requirements, even though these requirements are quite strict in terms of reducing low-frequency sound transmission. When introducing new products and in research, acceptable performance should be ensured by using the evaluation curve proposed in this paper: if using proposed curve contour 03, the level should not exceed $L'_{n,w,new03}$ 61 dB (see equation 15); for dwellings aiming for particularly high acoustic performance, the level should not exceed 57 dB.

Finally, are the differences in correlation coefficients significant from a strictly statistical point of view? The question is raised since the correlation coefficients were calculated from a single sample, so common methods for testing the equality of correlation coefficients do not apply. Fortunately, the original investigation [7] considered the applicability in this particular case of specially designed test procedures for dependent correlation coefficients. The shift in reference contour from ISO (equation 17) to the new contour (equation 15) implying an improvement of the correlation from 84% to 87 %, could mean that certain light weight constructions and their objective rating decrease at least one sound class [23].

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