Preface

The research presented in this licentiate thesis was carried out at the Department of Engineering Acoustics at Lund University, Sweden. This research forms part of the National research programme, The Building and its Indoor Environment, supported by KK-stiftelsen (the Swedish Knowledge Foundation).

In particular, I would like to thank my supervisor, Professor Per Hammer, for his encouragement, willingness to continue this important research, and for his advice and support. I am also most grateful to Professor Göran Sandberg for his final supervision of this project, to Lecturer Erling Nilsson and Technician, Dr. Jonas Brunskog for their invaluable comments. Special thanks go to Dr. Brunskog for all his support during conferences and other presentations. I would also like to thank the rest of the wonderful staff at the Department of Engineering Acoustics, Lund University, for their support and for interesting discussions over the years: during my daily work, I will miss these occasions very much.

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Finally many thanks to my wonderful family – Charlotte my wife and my children, Anna and Jesper – who are my source of inspiration: I promise to do no writing either during Christmas or next summer's holidays.

Lund 2005-09-09

Klas Hagberg

CONTENT

1 Introduction

In modern urban environments many people live in multi-storey buildings. One aspect of these buildings of particular importance for their habitants is the sound insulation. If this is not handled properly there will soon be complaints about lack of privacy. Also, if the standard measures formulated to rate the sound insulation are not adapted to the experienced effectiveness of the insulation, complaints may result even though attempts have been made to create adequate sound insulation. The aim of this thesis is therefore to suggest improvements regarding the sound insulation evaluation procedure in order to create more precise sound insulation measures.

In 1992 investigation started at the National Board of Housing Building and Planning in Sweden aiming to revise the national building regulations concerning sound insulation. The Board is a National Authority, which, among other matters, is responsible for the Swedish building code. One of its missions was to improve the regulations concerning sound insulation, to update them and make them better adapted to modern building methods and modern sound sources. The work was to be completed in less than two years. The goal was ambitious, but there was insufficient time to make radical changes; the new 1994 regulations remained almost the same as the old ones, apart from minor improvements.

Nevertheless those who worked with fire regulations were one step ahead. In 1994 the old fire regulations were revised and from 1 January 1994 it was permitted to build multi-storey, wooden housing structures in Sweden. This relaxation of fire regulations increased the need for improved sound insulation regulations, as it was well known that the then current sound insulation requirements suffered from shortcomings, particularly when applied in lightweight structures.

Figure 1. New Swedish fire regulations concerning multi-storey housing buildings were among the main reasons to accelerate work on improved sound insulation.

Swedish sound insulation requirements are a heritage from the first national regulations, enacted in 1945. Hence, the basis of modern building acoustic design criteria was formulated approximately 60 years ago. As long as most existing and newly built multi-storey housing buildings were built using old, well-tested heavy-concrete designs, poured *in situ*, the old sound insulation standards were acceptable and did not cause much acoustical trouble. However, as new methods were developed and as one area of the building code was revised, for example, fire regulations, possibly altering conditions for other important areas of the code, measures to adapt to these new conditions had to be taken.

In 1998 the first building code including a sound classification standard was introduced. This edition of the building code referred to a Swedish standard including four sound quality classes, A–D, the minimum acceptable one being class C (classes B and A may be used voluntarily). Hence, the purpose of introducing the standards was to create high sound quality on a voluntarily basis. The building industry could use the higher sound classes in marketing their new dwellings to purchasers who require a higher sound-insulation class. In all, the sound-insulation standards have increased awareness of noise conditions and improved the acoustical performance of new housing construction.

New housing constructions and the sound classification system described above have raised the sound insulation topic to a more general level. These facts involve demands that the sound insulation has to correspond to the expected sound insulation. This investigation presents results, which may be used to further adapt the sound insulation single number measures to new housing constructions, in particular light-weight structures.

2 Basis for the sound insulation

2.1 Airborne sound

Airborne sound in dwellings typically originates from equipment or from people shouting or talking; the sources include kitchen appliances or TV and audio equipment. If the sound insulation is unsatisfactory, then sound from these typical sources might be transmitted to some extent to neighbouring dwellings. Since low frequencies can be transmitted to a greater extent than others, the sound of neighbouring dwellings is typically apprehend as a low-frequency “thumping sound”, i.e. a separating construction acts as a low-pass filter. This annoying sound is more pronounced in lightweight than in heavyweight building structures. Modern audio equipment, which can produce high sound levels at the lowest frequencies, can become very annoying in adjacent dwellings, even in buildings with heavy structures.

Insulation against airborne sound is measured according to ISO 140-4 [1] in 1/3-octave frequency bands at least across the 100–3150 Hz frequency range. The results of the measurements are weighted according to standardised rules specified in ISO 717, part 1 [2], and one way to express the final field result is as a single numerical value, R'_{w}, where “w” represents “weighted”. The frequency range can optionally be extended with additional 1/3-octave bands to 50, 63, and 80 Hz in the low-frequency region. If these additional 1/3-octave bands are included, the single numerical value may be complemented with a low-frequency spectrum adaptation term (calculated according to certain rules specified in the standard), i.e specifying that a wider frequency range is covered by the single number. Many different spectrum adaptation terms can be included in the single-number value, and these are all described in reference [3]. Actually, there is a spectrum adaptation term covering the ordinary (100-3150 Hz) frequency range, but it is not particularly interesting to analyze [4]. Apart from R'_{w}, this study touches on the extended single numbers $R'_{w} + C_{50–3150}$ and $R'_{w} + C_{50–5000}$, where $C_{50–3150}$ and $C_{50–5000}$ are different spectrum adaptation terms.

2.2 Impact sound

Impact sounds vary depending on their origin. Such sounds could be “normal” footsteps, but these could be footsteps from a heavy person or perhaps a lighter person. The walker might be wearing soft shoes, hard-heeled shoes, or no shoes at all. Impact sound can also be produced by falling objects or possibly by a chair being moved, or it could be caused by running children. Each different impact source creates its own frequency spectrum, which also depends on the building structure. ISO 140-7, Annex A [5], specifies a specific machine to be used to produce impact sound, when measuring impact sound levels in a room adjacent to the sound source. Sound spectra from various sources were analysed and compared to the spectrum from the ISO impact source in the laboratory [6] (see Figure 2). Obviously, one machine cannot simulate all these sources, even though it is reasonable to assume that normal footsteps is one of the most common sources of impact sound in dwellings. An elaborated theoretical model of the tapping machine acting on light-weight floors can be found in [7]. The fact that the impact force can be predicted is an important aspect of maintaining the tapping machine. The ISO machine includes five steel-faced hammers, each weighting 0.5 kg, which strike the floor 10 times per second from a height of 40 mm, which obviously does not correspond to the typical walking sound.

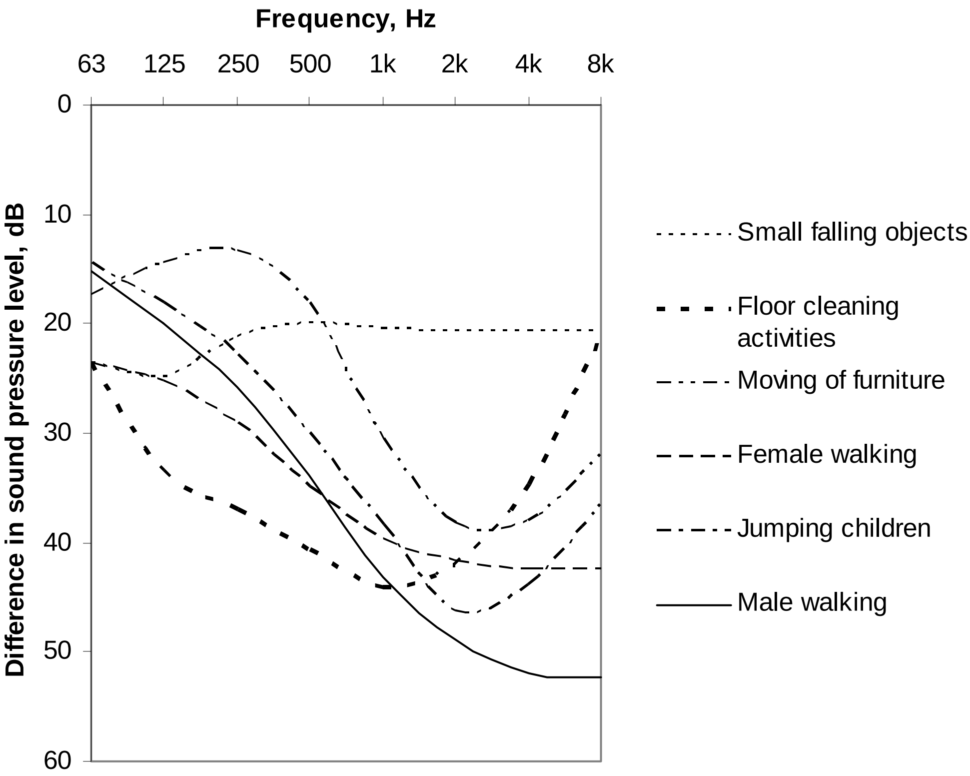

Figure 2. Sound pressure levels of some household activities relative to the tapping machine impact sound level [6].

Efforts have been made for decades, either to replace the ISO impact machine or to combine it with heavier "impactors", such as rubber balls or tyres, primarily so as to emphasise the important low-frequency impact sound created by a human "walker". Attempts have been made to use alternative standard impact sources, for example, a heavy rubber wheel according to the Japanese standard, JIS A 1418, or a heavy sand-filled ball [8], both of which use a heavier weight; these sources, however, are not globally standardised as the ISO impact source. These impact machines create far more energy in the low frequencies than the ISO machine does, which is important, particularly for lightweight structures. However, these heavier machines do not generate as much high-frequency sound as the ISO machine does, which may be important for heavy structures and hard floor coverings. From a practical point of view, it would be attractive to use only a single sound source, since the equipment used in the field should be kept to a minimum. The impact source and its application have been discussed in a number of papers and investigations [6,9,10], and there is agreement that the ISO tapping machine may actually generate enough energy in all frequency bands of interest, even in the low-frequency range. Therefore, it is far more effective to use this well-known ISO-approved impact source, but to improve and adapt the *evaluation* method to fit subjective experience. An advantage of this approach is also that old measurement data can still be used for further analysis.

Impact sound is measured using the same 1/3-octave frequency bands as are used for airborne sound. However, in this case the level is measured in one room while the tapping machine is set up to impact a neighbouring floor structure. The procedure is described in ISO 140-7 [5]. The results of these measurements are weighted according to standardised rules specified in ISO 717, part 2 [11], and one way to express the final field result is as a single numerical value, $L'_{n,w}$, where “n,w” represents “normalised” and “weighted”. Normalisation implies that the final result should be equal no matter when the measurements are performed, independent of the furnishing in the room, adding the term $A/10$ to the measured sound pressure level. Optionally, the frequency range can be extended with additional 1/3 octaves to 50, 63, and 80 Hz in the low-frequency region. If these additional bands are included, the single numerical value may be complemented with a low frequency spectrum adaptation term, i.e indicating that a wider frequency range is covered by the single numerical value. Two different impact spectrum adaptation terms can be included in the single number value, and these differ only as they concern the frequency range covered. The single numbers will then be expressed either as $L'_{n,w} + C_{I,50–2500}$ (50–3150 Hz) or $L'_{n,w} + C_I$ (100–3150 Hz).

3 Current evaluation methods

Normally, the single number values described above are used in many countries to verify the final sound insulation condition in a multi-storey building. However, are these quantities representative and which limit value should be prescribed? The ISO single-number evaluation methods suffer from shortcomings in a number of respects. Current evaluation curves, both for airborne and impact sound, are best suited to application to heavy structures and certain product combinations; in addition, the normalisation may cause errors, for example, in large-volume receiving rooms. However, in modern building construction heavy structures are not necessarily the obvious option; lightweight structures and prefabricated thin-floor constructions have become more common and might become even more so in the future. Due to large differences in modern building methods and to several other factors that influence final results, it is important to make critical judgements in each particular case, even though the traditional single-number value appears to be sufficient. In the long run it is important to be able to conduct investigations in actual situations, i.e. investigations in occupied dwellings with various building structures. In the laboratory it is very difficult to reproduce normal living environments, as several important aspects have to be considered and observed; these include:

- Building structure
  - Structural material
  - Joists
  - Floor coverings
- Type of dwelling
  - Size
  - Plan solution
  - Mixture of inhabitants in each housing unit
    - Students
    - Elderly people
    - Families with children
- Measurement direction
- Housing environment

A comprehensive literature review of a number of field studies conducted over the years was presented by Rindel [14]. Analyzing field measurement data from Langdon, Buller and Scholes [15], Bodlund [12,13], Weeber and Merkel [16], and Bradley [17], he found that results presented in references [15] and [16] might be usable in estimating suitable current single-number values concerning airborne sound insulation, i.e. R'_{w}, and that references [12] and [13] might be usable in estimating fairly reliable single-number values concerning impact sound levels, i.e. $L'_{n,w}$. The results are summarised in Table 1 below.

Table 1. Estimated values of the acoustic parameters R'_w and $L'_{n,w}$ corresponding to different levels of acoustic quality expressed in terms of the percentage of inhabitants finding the conditions poor (*P*) or good (*G*), respectively. Values in parentheses are extrapolations outside the range under investigation; after [14].

Subject of study		*G* = 80 %	*P* = 20 % *G* = 50 %	*P* = 50 % *G* = 20 %	*P* = 80 %
Airborne sound insulation					
Langdon [15]	*P*		55 dB	48 dB	(42 dB)
	G	(62 dB)	56 dB	47 dB	
Weeber [16]	*P*		57 dB	49 dB	(41 dB)
Impact sound pressure level					
Bodlund [12,13]	*P*		57 dB	64 dB	70 dB
	G	50 dB	57 dB	64 dB	

Referring to the data in Table 1, an airborne sound insulation value of R'_w, equal to 55–57 dB, can be stated to be acceptable; the corresponding value for impact sound, $L'_{n,w}$, may be equal to 57 dB. In reference [14] it was stated that one of the most comprehensive investigations of field impact sound levels and their impact on human responses, was conducted by Bodlund [12,13]. However, it was also concluded that there is a lack to state requirement levels on the basis of one single investigation. Nevertheless, the data from [12,13] are interesting and in the present study this investigation is used as a basis for further analysis.

The studies referred to above do not always include complete measurement data. One-third-octave band data below 100 Hz are missing in some cases, and measurement details, such as reverberation time, are not fully described. Hence, it is complicated and not always possible to further analyse the data from these investigations (see the article “Evaluation of impact sound in the field” included in this thesis).

Even though current single-number values may be applied in some cases, it is well known that the frequency range covered is not sufficiently extended and the evaluation curve is not adapted to fit all design structures, product combinations, and plan solutions. The single-number values clearly suffer from some obvious shortcomings; notably, the frequency spectrum below 100 Hz is important and must not be neglected.

In 1996, Hammer and Brunskog introduced a design guide to ensure both the low- and high-frequency sound insulation quality of new housing construction [18]. This was the final result of an inter-Nordic research project, starting in the late 1980s, that aimed to explore the possibility of building multi-storey wooden buildings. The research projects resulted in Sweden in two successful lightweight, wooden multi-storey housing buildings [19,20]. The design guide included a low-frequency requirement equivalent to the single-number value suggested by Bodlund [10], and also a high-frequency requirement based on the ISO curve [11]. Furthermore, it included a minimum resonance frequency requirement.

4 Investigations within the Nordic countries

In 1993 an acoustics working group was established within The Nordic Committee on Building Regulations (NKB), an organisation operating under the aegis of the Nordic Council of Ministry. The main task of the working group was to devise a framework using current standards, or drafts of standards soon to be applicable, concerning sound insulation, in order to investigate prospects for improved standardised building acoustic regulations for the Nordic countries. The new revised versions of both the measurement standard series, ISO 140 [1,5] concerning building acoustic sound insulation measurements, and the corresponding evaluation series, ISO 717 [2,11], were in particular studied by the NKB working group.

4.1 Airborne sound

In the single number values from Table 1 only the ordinary frequency range is considered, i.e. 100–3150 Hz. However, we know from earlier studies [18,19,20,21] that it is proper to use an extended frequency range in the evaluation procedure. In the case of airborne sound insulation, the statements concerning the necessity of considering a wider frequency range are based on the empirical fact that modern sound sources generate more low-frequency sound than did sound sources of a few decades ago. Furthermore, it has become increasingly common to use only lightweight structures to separate different dwellings, structures such as plasterboard walls and wooden structures. These separating structures normally do exhibit enough sound insulation in the ordinary 100–3150 Hz frequency region; however, at frequencies below 100 Hz their sound insulation performance soon becomes unacceptable. Since modern audio equipment can generate potentially annoying sound far below 100 Hz, some Nordic countries have extended the frequency range covered by the building code (Sweden did 1998), even though there is a lack of field data concerning insulation against airborne sound in this lower-frequency region and its effect on human response.

In an attempt to arrive at some sort of conclusion regarding the airborne spectrum adaptation terms and their effects in terms of improving single-number evaluation, results from reference [12] were analyzed. The results in [21], based on 89 different measurements from 13 different housing constructions (floors and walls) separating dwellings indicate poor correlation between the objective measure, R'_w, and subjective evaluation using all data (see Figure 4). The results become

$$R'_w = 57.60 - 0.21S \qquad (r = -0.05,\ n = 13) \qquad (1)$$

where

S = the subjective score
r = regression coefficient
n = number of data points

which is equal to non correlation! This is in accordance with the conclusion from reference [14], that the results of investigation [12] are not applicable to airborne sound insulation.

However, if as seems reasonable, we instead exclude those measurements, which according to Bodlund [12] result in doubtful judgments due to the presence of disturbing traffic noise immediately outside the window and also a small number of interviews, the results become

$$R'_w = 45.74 + 2.14S \qquad (r = 0.43, n = 11) \qquad (2)$$

This gives a more reliable correlation, since the assessment naturally should become better as the sound reduction index, R'_w, increases. The results according to eq. 2 are outlined in Figure 5.

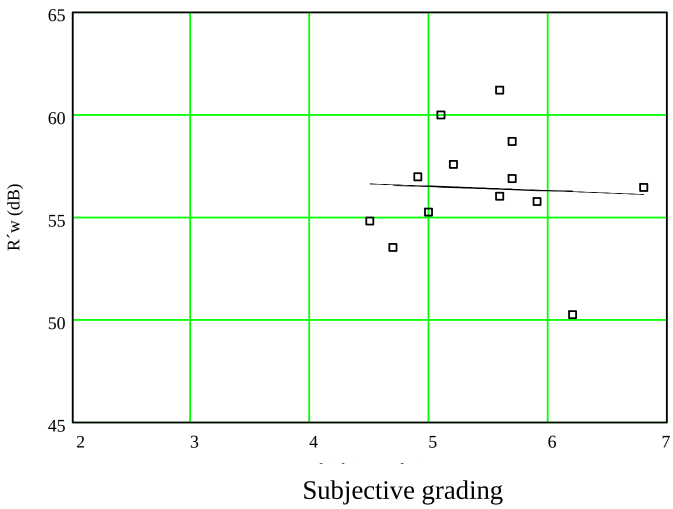

Figure 4. Correlation between the sound reduction index, R'_w, and subjective score according to reference [21].

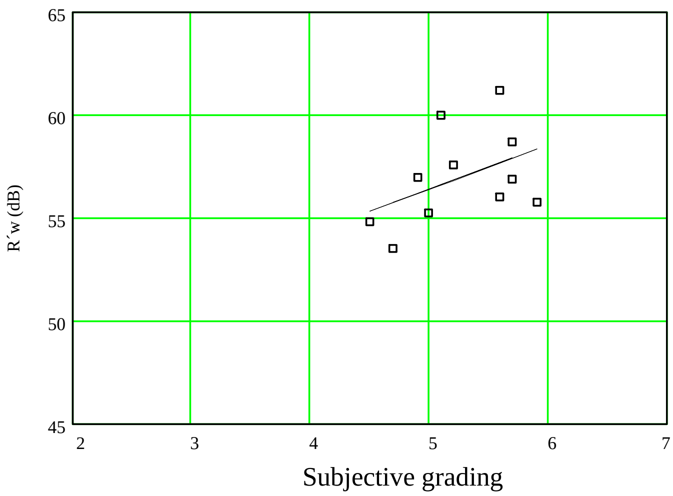

Figure 5. Correlation between the sound reduction index, R'_w, and subjective score according to reference [21] if measurements affected by traffic noise are excluded.

Furthermore, in the report [12] it appears that the two outliers in Figure 5 above emanate from lightweight plasterboard walls. If either of the spectrum adaptation terms, $C_{50–3150}$ or $C_{50–5000}$, were calculated and added to the measurements presented in the figure then, since the spectrum adaptation term for lightweight structures will exhibit lower values than those emanating from heavy structures [21] the points in the cluster would probably come closer together and the correlation would alter. Unfortunately, since complete data were not conveniently available,[1] it is not clear whether such an alteration would indeed lead to improved correlation; however, it would be an interesting topic for further investigation.

4.2 Impact sound

As earlier mentioned, one comprehensive field investigation of impact sound was conducted in Sweden in the 1980s [10,12,13] (Table 1). In this investigation an alternative reference curve was proposed. The alternative reference curve was developed using the former standard measurement method, ISO 140-VII [22], so the measurement results were related to the ISO tapping machine. The evaluation procedure for the alternative reference curve is identical to the standardised procedure in ISO 717, part 2 [11], hence it is only the shape of the evaluation curve that is altered. Single-number rating using the proposed reference curve showed far better correlation with subjective evaluation than the ISO-shaped reference curve did. Just as is the case for airborne sound measurements, the data in the reports [12,13] are shown in the form of sketched diagrams, while building construction is described in detail. The data are interesting and usable as a basis for deeper analysis. The finally suggested evaluation curve is shown in Figure 6; it starts at 50 Hz, has a positive slope corresponding to 1dB per 1/3 octave, and stops at 1000 Hz. The single number evaluated using this curve is denoted I_S.

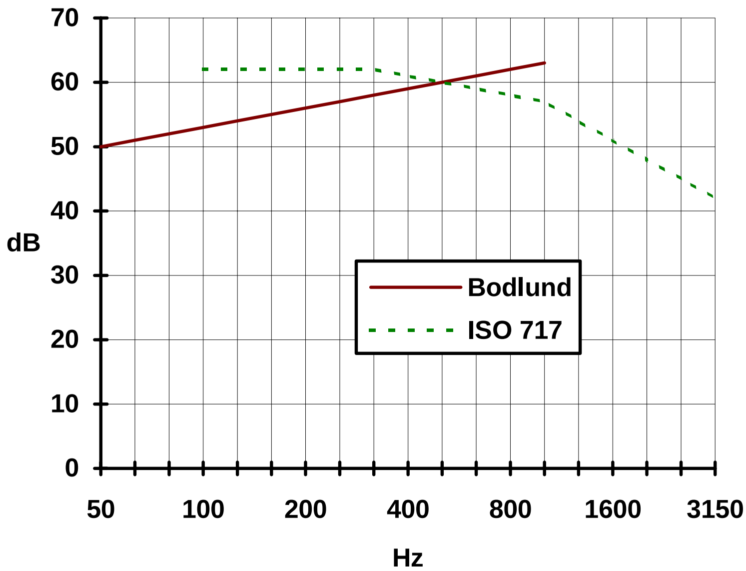

Figure 6. Single-number evaluation curves according to ISO [11] and Bodlund [10] respectively. Please note the huge difference between the contours.

The very best evaluation curve was found by comparing objective measurements and subjectively evaluated sound insulation in a number of housing units. The subjective responses were mainly collected via questionnaires completed during telephone interviews. The judgments were quantified using a seven-grade rating scale, in which 7 is the top score – quite satisfactory, and 1 is the bottom score – quite unsatisfactory. If the mean subjective score was below 4.4, the overall performance was regarded as unsatisfactory; this score could be used as a limit score when evaluating the correct level for the objective single-number values – a valuable tool when formulating requirements in building codes and standards.

[1] The results presented in references [10] may be reproduced from sketches (diagrams) contained in the reports [12,13].

The investigation results presented in the original investigation [10] covered a total of 22 different housing units with different building structures. The single data samples each consisted of many measurements and interviews. There was quite a large spread in the data, ranging from 37 to 70 dB in terms of the single-number value, $L'_{n,w}$, and from 2.2 to 7 in terms of the subjective grading, *S*. Both the objective measurements and the subjective scores were first calculated as mean values for each single object; after that, these scores were compared by means of linear regression analysis. The building structures and dwelling plans are described in detail and the corresponding objective measurement data are presented in a comprehensive report [12] and in an annex to the report [13]. This research includes a valuable database to use in future evaluations and in the development of building regulation criteria.

In an analysis of the proposed revision of ISO 717 [2,11], measurement data were collected and analysed by the Nordic Committee on Building Regulations (NKB) [21]. In this report, field data from 146 different floor constructions with $L'_{n,w}$ values ranging between 31 and 78 dB were analysed. Applying linear regression between Bodlund's measure, I_S, and the ISO figure, $L'_{n,w}$, the correlation, *r*, was found to equal 76%. Adding the spectrum adaptation term value, C_I, *not* covering the lowest frequency bands, i.e. 50, 63, and 80 Hz, to the ordinary single number value, $L'_{n,w}$, raised the correlation to 90%; however, the highest correlation, 96%, was found when the spectrum adaptation term $C_{I,50–2500}$, was added to $L'_{n,w}$. Consequently, the new ISO standard might be used so as considerably to improve both the measure and its agreement with subjective grading:

$$L'_{n,w} + C_{I,50\text{-}2500} = I_S - 6.4 \qquad (r = 96\%,\ n = 146) \qquad (3)$$

where *r* is the correlation coefficient and *n* is the number of floor structures included in the analysis. The relationship is also plotted in Figure 7, where LB is equal to I_S and L50 is equal to $L'_{n,w} + C_{I,50–2500}$.

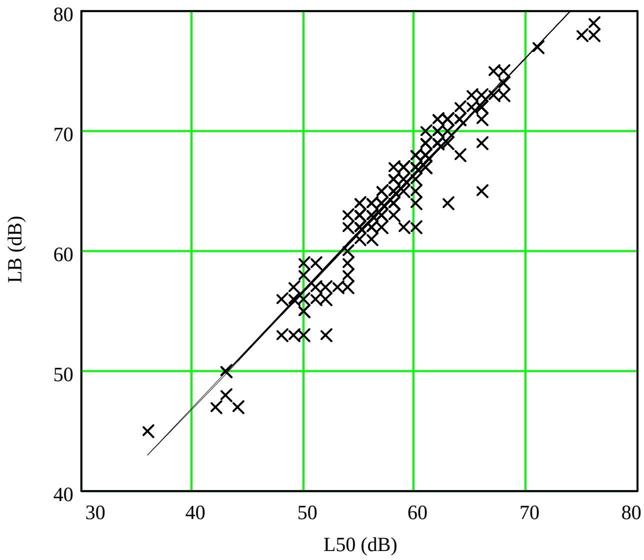

Figure 7. Correlation between the I_S (= LB) value and $L'_{n,w} + C_{I,50–2500}$ (= L50) value, *r* = 96% [21].

It was concluded that if $I_S \leq 62$ dB (which correspond to $S = 4.4$) the impact sound is fair or acceptable and hence many of those who live in multi-storey buildings will describe the acoustic performance as acceptable. To render this value into the ISO measure, $L'_{n,w} + C_{I,50-2500}$, eq. (3) might be used; consequently, the value should not exceed $L'_{n,w}+C_{I,50-2500} \leq 56$ dB ($S = 4.4$), which should result in approximately 20% of inhabitants judging the acoustic performance as quite or nearly quite unsatisfactory. However, there is a risk in just using the measure proposed by Bodlund as a basis for other measures, since the high frequencies are totally disregarded. If one does not apply a high-frequency limit this may lead to new unattractive hard floor coverings. Naturally, these types of floor constructions are not available and consequently not included in the investigation [10], since such technical solutions have been prevented due to the long history of requirements formulated using the $L'_{n,w}$ value. What happens if this “high-frequency obstacle” disappears? This is not known today, and therefore the frequencies above 1000 Hz should not be excluded. The exact shape of the high-frequency part of the reference curve does not necessarily resemble that of the ordinary ISO shape, but since there is a lack of data concerning this matter, the ISO curve should remain unchanged and be used in addition to $L'_{n,w} + C_{I,50–2500}$. The conclusion is that the impact sound requirement should remain, until contradictory results are found, as follows:

$$L'_{n,w} + C_{I,50–2500} \leq 56 \text{ dB}$$
$$L'_{n,w} \leq 56 \text{ dB}$$

This statement is emphasised in a report by Hammer and Brunskog [18].

Furthermore, in the mid and late 1990s, Hammer and Nilsson [23] studied alternative psychoacoustic models pertaining to impact sound. The results of these studies showed that the correlation between the subjective response and the impact sound transmission was superior when using a loudness model for evaluation of impact sound instead of using the value $L'_{n,w}$. It was also proved to be significantly better than the suggested evaluation, I_S, according to ref. [10]. Similar tests have also been applied to walking noise [24] and speech transmission in classrooms.

4.3 Remarks – sound insulation evaluation procedure

New building methods and the development of commercially attractive lightweight structures accentuate the need for further improvement of the single-number evaluation procedure.

Usable field investigations regarding airborne sound insulation are performed during the last decades [15,16]. Nevertheless, partly due to the nature of the sound itself the author opinion is that it is severe to perform comprehensive airborne sound insulation field investigations. The sound level of the source differs, and any information possibly carried in the sound might itself be disturbing (e.g. shouting, high speech, partly identified music). Furthermore the authors experience is that buildings erected with lightweight structures actually do often exhibit acceptable airborne sound insulation, however the impact sound insulation is normally poor. These are the main reasons why this licentiate thesis is restricted to impact sound. Nevertheless, it would certainly be a challenge for future research to perform an extensive field investigation regarding airborne sound insulation as a complement to those already carried out [15,16].

Concerning impact sound, it would be interesting to use various impact sources simulating different natural sound sources in evaluating various structures. However, such a system is complicated and not particularly practical; using a single source, preferably the ISO-standardised tapping machine, but altering the evaluation procedure, is a far more attractive option. Probably this approach would reasonably allow one to improve the correlation between objective measure and subjective grading by several percent. In particular, some important aspects concerning low-frequency impact sound insulation behaviour in modern housing structures would need further investigation. As mentioned earlier, one of the most comprehensive field investigations of impact sound insulation [10] does not include all types of floor coverings. Furthermore, which is more important, the investigation includes measurements made both horizontally and vertically. It would be proper to separate the measurement directions from each other, since impact sound may be more annoying when it emanates from the floor immediately above the listener, as was concluded in [17] and emphasised in [25]. In an attempt to further improve single-number evaluation, it would be interesting to exclude horizontal measurements but instead include additional floor structures in the study and, using the "floor structure" approach, try to find a measure even better adapted to subjective response.

5 Requirements, regulations and sound classification

The work carried out by the acoustics working group within NKB soon led to the formation of another working group: INSTA–B, which refers to Inter Nordic STAndardisation–Buildings. This new working group had the mission of creating a common Nordic sound classification standard, a standard that should be based on new findings, be suitable for adoption in Nordic building codes, and hence not give rise to trade obstacles within the EU. The group drafted a proposal for a sound-classification standard [26]. This proposed standard was partly based on a concept presented in a Swedish governmental study [27]; this standard is intended for voluntary adoption in Nordic countries. In most Nordic countries this joint effort gave rise to national classification standards, which to some extent differ from the common proposal. Nevertheless, the work of INSTA–B has resulted in similar building regulations and classification standards regarding building acoustics being valid across Nordic Europe. This highly functional approach could well serve as a model for other countries.

The Swedish sound classification system (see Figure 8) is based on a standard comprising four sound classes, A, B, C, and D (similar to the INSTA proposal [26]). Class C is intended to be the minimum requirement in the national building codes. Classes A and B are recommended when the objective is an especially good sound climate, while Class D may be acceptable in certain rebuilding projects. The sound insulation requirements of classes A and B are based on an extended frequency range, meaning that the opportunity to include lower than usual frequencies in the single-number value was used. The frequency range referred to is either the traditional 100–3150 Hz range, or one of the extended ranges, i.e. 50–3150 Hz or 50–5000 Hz. For class C, use of the extended frequency range is recommended, while for class D, traditional single-number ratings, referring to the 100–3150 Hz range, are used. However, the Swedish national standards differ from the common Nordic proposal regarding one important point, namely, the performance levels required of the different classes.

In Sweden, participation in the joint Nordic effort resulted in another revision of the building code in 1999. The code now simply refers to class C in the Swedish classification standard SS 02 52 67 (2nd edition) [28] as the minimum requirement. Based on the results of the common Nordic work described above, Sweden decided to include a wider frequency range even in class C, i.e. the spectrum adaptation terms of an extended frequency range have to be applied even in class C. This additional requirement appears as an amendment to the regulation text [29], so the standard does not include the spectrum adaptation terms in the normative text for class C.

However, the Swedish standard has been revised yet again (SS 25267, 3rd edition) [30], and now the standard includes the spectrum adaptation terms as a normative figure even in class C.

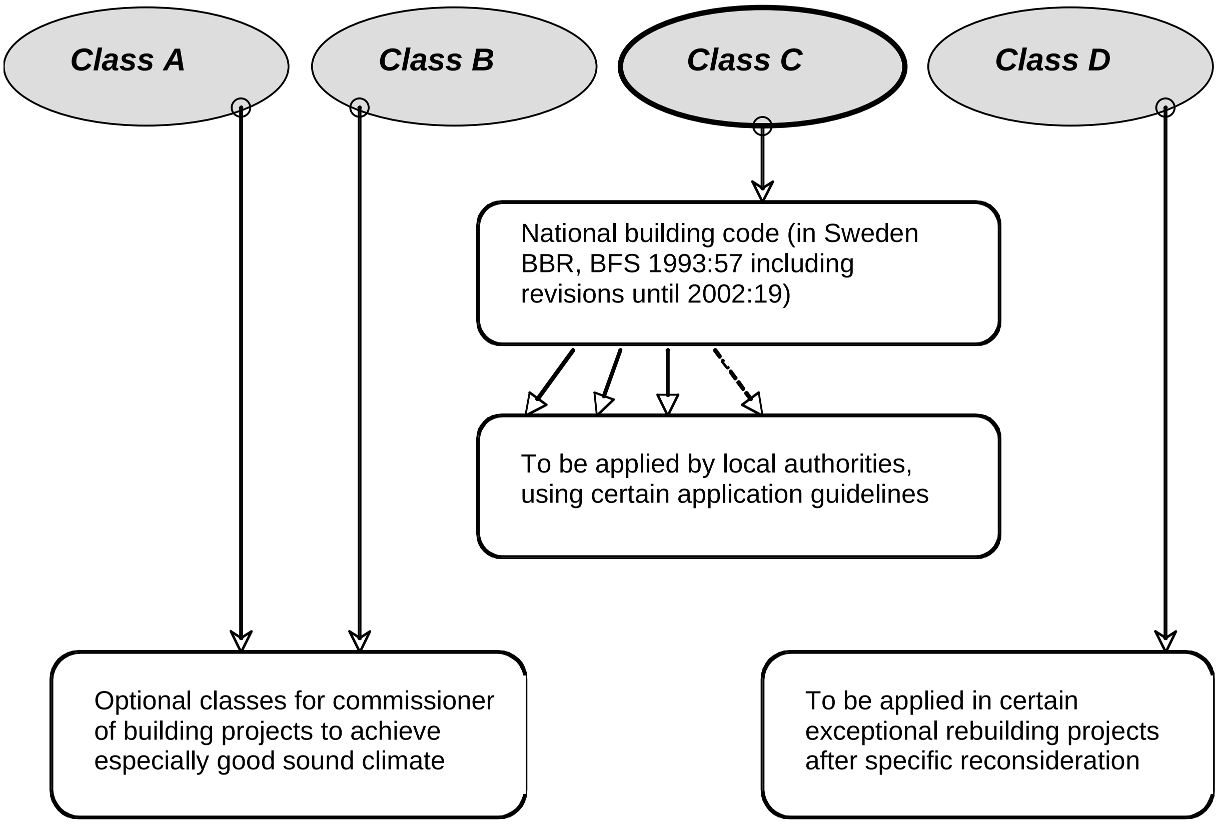

Figure 8. Sound classification standard/system and its connection to the building regulation system in Nordic countries.

The sound classification standard, particularly with the introduction of the latest revision (3rd edition) [30], has become a tool for local authorities and the building industry to deal with the sound climate in the housing environment in a more precise way. There is now a more pronounced link between the Swedish classification standard and other European and international standards possibly used by different actors involved in a building project (see Figure 9, after Simmons [31]). This system will facilitate sound climate management in a building project.

So as further to facilitate implementation of the standard, various application guidelines adapted to local authorities and their needs have been issued. These may simplify application of the standard in each project, as the standard itself is far too detailed for those who do not regularly work with building acoustics. The application guidelines may serve as a checklist to ensure that none of the requirements in the standard are omitted by mistake. They are accessible both for use by local authorities, i.e. sound class C, and for commissioners of housing projects who are striving for a sound class higher than the minimum requirement, i.e. sound classes A or B.

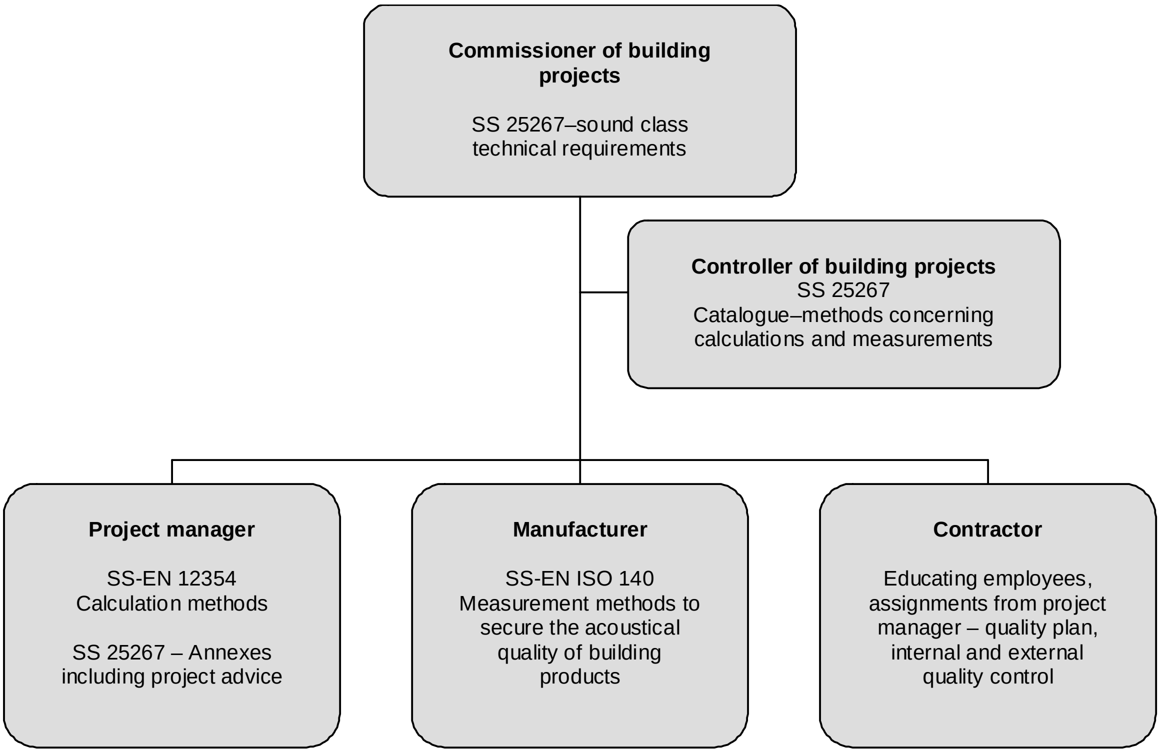

Figure 9. Scheme defining limits of responsibility regarding sound climate with the use of standards (after reference [31]).

5.1 Shortcomings in the evaluation procedure

The experience of the present author is that current standardised building acoustic measurement methods and evaluation procedures are not always the very best ways to describe the sound climate in a building. This observation appears to be valid, even if the standardised low-frequency spectrum adaptation terms are added to the single-number values. Nevertheless, for practical and juridical reasons, the building industry is directed to apply standardised methods. The acoustic performance of a building or a building product should be measured uniformly, no matter which laboratory is performing the calculations or measurements. Standardised methods secure similar results independently of those performing the calculations or measurements. Therefore, it is important always to analyse these widely used methods, particularly in those cases where they are applied to buildings employing new structural principles.

The efforts of Nordic and international standardisation groups and of the Swedish Standards Organization clarify some important aspects, namely:

1. There are a number of uncertain judgements and doubtful background data that have been used in constituting the basis for standardised building acoustic requirements.

2. New products and product combinations have been verified according to out-of-date evaluation rules that should be reconsidered.

3. Hence, there is a need for *field* studies in greater depth, to enable the adaptation of evaluation figures to modern housing design and building structures.

These factors provided the primary motivation of the research presented in this licentiate thesis.

Concerning impact sound, the NKB group stated that the ISO figure, $L'_{n,w}+C_{I,50–2500}$, proposed in the revised ISO 717, part 2 [11], combined with the ISO impact source is the most suitable standardised basis for evaluation in use today [21]. The Swedish national authority decided at an early stage that the conclusions presented in the NKB report [21] were significant enough to warrant incorporation into national regulations. With the introduction of the revised ISO 717 [2,11], standards are being applied as far as possible today, to prevent low-frequency noise in new housing buildings. Nevertheless, work remains to be done, until the single-number values are optimised to such an extent that they will fit any building structure to which it is applied.

In addition to the extended weighted impact noise single-number value (including the spectrum adaptation term), $L'_{n,w} + C_{I,50-2500}$, the old $L'_{n,w}$ value is retained in the Swedish building regulations [29]. Thus both values have to be applied. This approach was adopted because there are uncertainties concerning the future development of floor coverings. If the old value is excluded (i.e. simply adding the spectrum adaptation term), there is automatically a risk that hard floor coverings mounted on heavy structures may become common and new high-frequency impact sounds might appear. Another long-term effect might be new behaviour of the tenants, for example, use of hard coverings might inspire people to wear hard-healed, outdoor shoes indoors, possibly changing the impact spectrum on the floor. Furthermore, with such hard floor coverings, the noise of vacuum cleaning and other household activities might become more apparent.

6 Aim and scope

This licentiate thesis focuses on insulation against impact sound, primarily because such sound is the dominant noise disturbance in modern, timber or slender steel, lightweight structures. According to the author’s experience, airborne sound insulation often becomes acceptable if the impact sound is limited acceptably. However, this statement is somewhat of a generalisation, so further research is needed before one can define the connections between airborne sound disturbance from various sources and actual, field situations. Nevertheless, this thesis aims is to provide new impact sound data to authorities and commissioners of housing building projects, to be usable as a basis for future building regulations; as well, this thesis also aims to provide data for immediate use in research and pilot projects. The aim is not to state final conclusions, but instead to apply current findings as far as possible, and to create a database for use in the continuous development and improvement of building regulations.

The main hypothesis of this work is that the ISO impact sound insulation evaluation procedure is not adapted to either modern housing design or to the disturbances that might appear in such buildings. Using the current evaluation curve in the single-number evaluation process often causes large errors, e.g. the objective value does not correspond to subjective experience. These errors are reduced to some extent when the low-frequency spectrum adaptation term is added, but probably not enough to produce acceptable results in some typical lightweight structures. Hence, the housing building industry will use an erroneous value as their main object in development projects. The result might become expensive housing buildings occupied by dissatisfied tenants, which will impose unnecessary costs on the building industry and on society. The results from this licentiate thesis may be used to secure the final impact sound climate in new housing units. The results may also serve as basis for future overhaul of the ISO evaluation procedure; however, this process would require even a more thorough groundwork than is available today.

Summing up, the important low frequencies should be kept in mind when formulating requirements concerning impact sound insulation, particularly because

1. Modern lightweight structures cause higher levels in low frequencies than traditional heavy structures do.

2. Using only the old ISO evaluation curve, it is extremely easy to create objectively good but subjectively totally unacceptable structures. The low-frequency spectrum adaptation term does improve the low-frequency requirement, but probably not by enough.

The building methods used in modern housing buildings are more nuanced, which naturally places heavy demands on how new building code requirements are formulated.

7 Approach

This licentiate thesis is summarised in one article describing extended research into impact sound evaluation in the field. It includes statements concerning impact sound insulation in dwellings in multi-storey buildings. In this thesis, some important results are analysed and where possible, old data are included in the present analysis. Apart from this old reproduced data, new data were collected from typical modern housing units (see also the section, “Limitations”). All data were collected from housing areas in Sweden.

Both subjective and objective data were collected. The objective data were gathered via 1/3-octave-band measurements using standardised methods [5]. The frequency range considered is 50–3150 Hz. It would be interesting to extend the frequency range further, towards lower frequencies. However, it was decided at an early stage to stay within the standardised but still extended frequency region with the lower limit of 50 Hz. Furthermore, the measurement uncertainty increases the lower the frequency, which further confirms the choice to stay within the standardised frequency region. This approach makes it easier to include prior results in the investigation, and also makes the findings more applicable in regulations, since all regulations are built up using standardised methods and figures. Thus because of the use of the standardised method, new findings might be more easily and more quickly adopted. The subjective data were collected using questionnaires. 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. The tenants were asked to rate the acoustic performance of their places of residence using a seven-point scale, as was also done in other studies [10,18,19], where one is denoted “quite unsatisfactory” and seven is “quite satisfactory”. The subjective scores (as well as the objective measured values) are then averaged into mean values for each housing unit. The subjective mean values are compared to the objective mean values using a linear regression model. A total of 22 housing units were included in the investigation described in this thesis.

The objectively measured 1/3-octave values were evaluated according to ISO 717 [11]. In this standard, a certain reference curve is specified which is fitted to the measured impact sound curve. After this curve adaptation procedure, the reference curve value at 500 Hz becomes the single-number value to be applied in the building code. However, in an attempt to create a single value better adapted to the corresponding subjective scores, new reference curves were tested and the corresponding single number values were calculated. The new single numbers are compared to the subjective scores using a linear regression model.

8 Limitations

All data used in this investigation were collected from typical Swedish multi-storey housing units. The new data cover modern houses with structures and product combinations typical of modern housing construction of the 1996–2003 period. The housing units consist of typical family apartments, though not necessarily always occupied by families with children. Of the residents of these buildings who were asked to rate their acoustic performance, 90% were between 28 and 55 years of age, and it was assumed that these subjects had normal hearing. In those cases where the subjects answered questions via telephone interview, they were also asked if they had any hearing impairment. These limitations are only valid for the new data added, concerning 10 new housing units, since the mixture of residents is unknown for the data collected by the previous study consulted [10].

The analysis is based on a linear regression model, which describes the relationship between the objectively measured data and subjective mean scores. However, it is not certain that the linear regression model is the very best model to describe the relationship between subjective scores and objective measures. Considering the extreme regions, i.e. those representing very bad or very good sound insulation, one would expect an S-shaped curve, like that outlined in Figure 10. This limits the linear model correlation coefficient, and hence the values in these outer regions might become uncertain. Fortunately, enough of the most interesting region for the building authorities lies in the central part of the data sample. Furthermore, there is a natural scatter in the data within each housing unit arising from the particular characteristics of each unit and from the uncertainties of the measurements and interviews. This fact also limits the correlation coefficient.

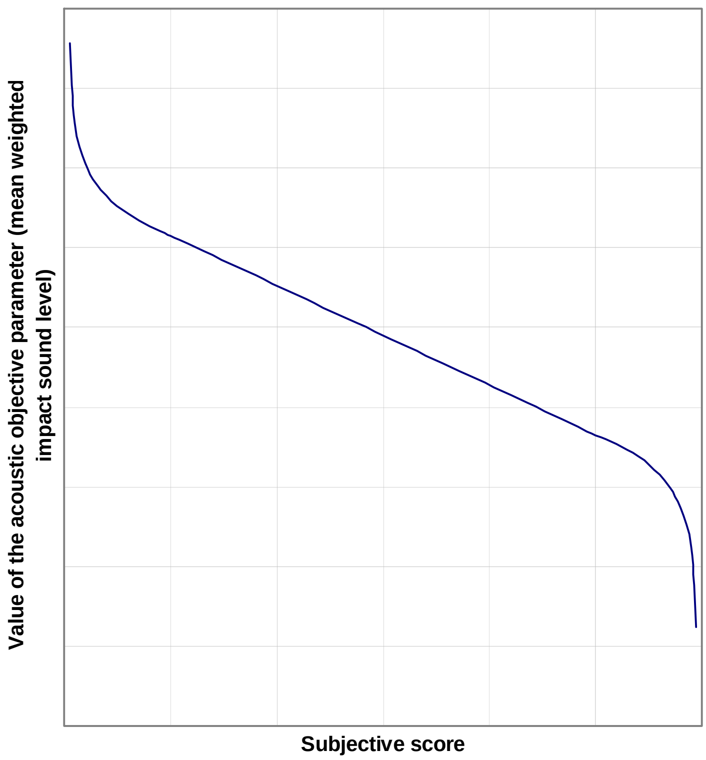

Figure 10. Expected idealised curve depicting the relationship between the subjective mean score and the corresponding impact sound index.

Apart from the shape of the reference curve, other minor variables might be altered in the evaluation of the single number. When shifting the evaluation curve to fit the measured curve, it is stated in ISO 717 [11] that the reference curve will be shifted in steps of 1 dB until the sum of the unfavourable deviations is less than or equal to 32.0 dB. Furthermore, some obstacles might be introduced in the evaluation procedure, for example the previous 8 dB rule, i.e. if the unfavourable deviation from any single 1/3-octave band exceeds 8.0 dB, this will determine the single-number value. These different alteration possibilities were investigated and evaluated in earlier research by Bodlund [10] and were shown to have a negligible effect on the final result.

9 Outline

The main purpose of the research presented in this licentiate thesis is to clearly propose the best way to evaluate impact sound in multi-storey housing units using a single-number value, independent of the building structure and building products in question. The aim was not to propose new measurement methods or other radical changes, but instead to use current standardised methods and find the best way to evaluate impact sound. The results of this study will be used for the further evaluation of impact sound. All data are combined in a database to which new data can easily be added. As new data are added, new curves can be created and calculated – a simple and valuable method for further refining the evaluation procedure as new building methods and structures are introduced to the market.

One paper is included in this thesis, a paper that reports on an extended field investigation. Apart from some original data [12,13] a number of new data are included in the investigation. The main aim is to include data from modern housing structures, so that evaluation figures can be adapted to current building methods.

Appendix A describes the construction details of the various buildings examined in the research.

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Thesis

Paper A - Evaluation of impact sound in the field.

Evaluation of impact sound in the field

Klas G. Hagberg
Department of Engineering Acoustics, Lund University
Box 118
SE-221 00 Lund, Sweden
klas.hagberg@wspgroup.se

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].

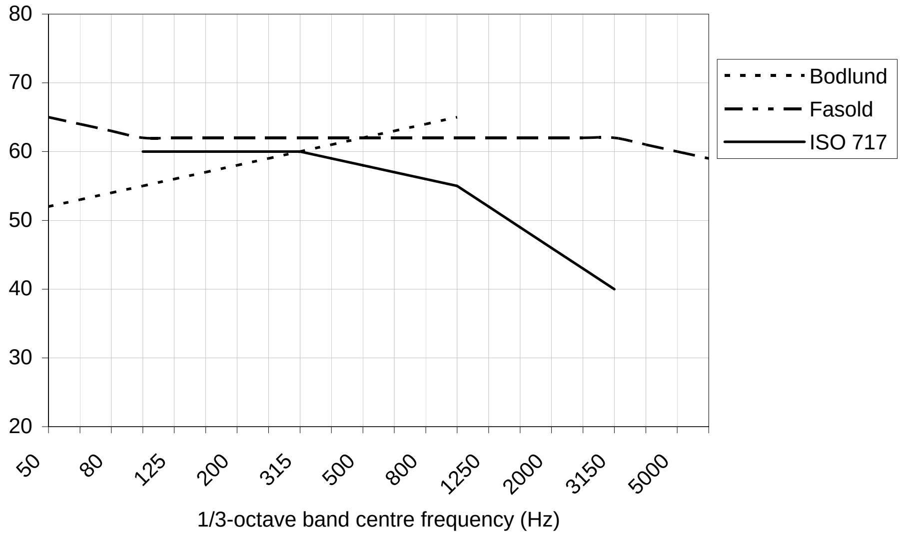

Figure 1. Evaluation contours: 1. ISO standard 717-2 (——); 2. Curve suggested by Fasold (— - —); and 3. curve suggested by Bodlund (---------).

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:

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

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 done 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. quite 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.

$$\langle L \rangle = I + xS \qquad (2)$$

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 57 % response rate. 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

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

$$\langle I_S \rangle = 85.9 - 5.43\,S \quad [r = 87\%,\ n = 22] \qquad (4)$$

while the original relationships from Bodlund [7] were

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

$$\langle I_S \rangle = 86.3 - 5.53\,S \quad [r = 87\%,\ n = 22] \qquad (6)$$

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 considerable 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:

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

$$\langle I_S \rangle = 70.3 - 3.23\, S \quad [r = 53\%,\ n = 9] \qquad (8)$$

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:

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

$$\langle I_S \rangle = 78.8 - 3.41\, S \quad [r = 81\%,\ n = 13] \qquad (10)$$

Though the calculation precision decreases as the number of data points decreases, the calculations clearly indicate that it would be proper 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 to a small scale. 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	1950/1982	12	23	1983–1985

		floor and vinyl				
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 $L'_{n,w,new,0X}$, 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 apartments (comprising 2-3 bedrooms), 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 many dBs in modern housing design, due solely to 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 be imprecise depending on which 1/3-octave band is taken into consideration.

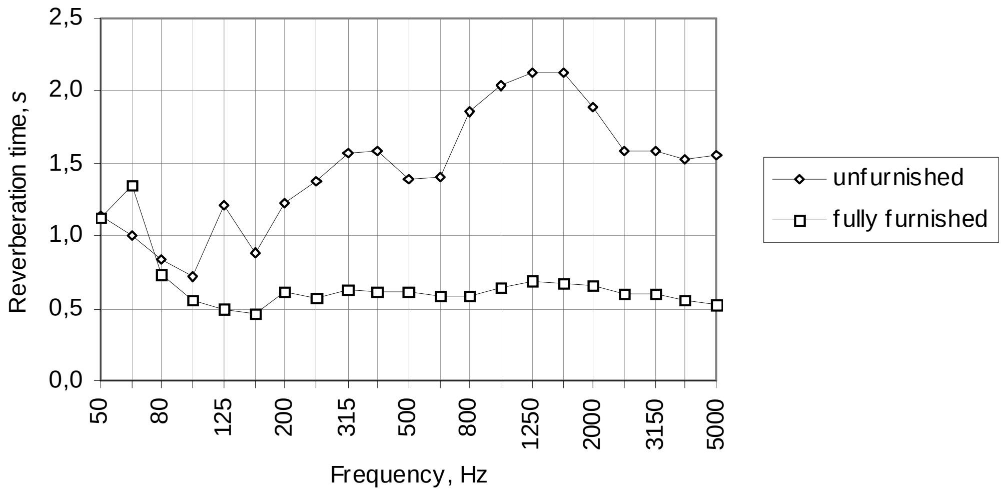

Figure 3. An example reverberation time curve for a large room in a modern housing building with a hollow concrete floor slab mounted on a steel structure; ◇ = the unfurnished room, □ = the fully furnished room.

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, 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 done 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).

$$\langle I_S \rangle = 80.27 - 3.98\,S \quad [r = 83\%,\ n = 22] \qquad (12)$$

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

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

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

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.

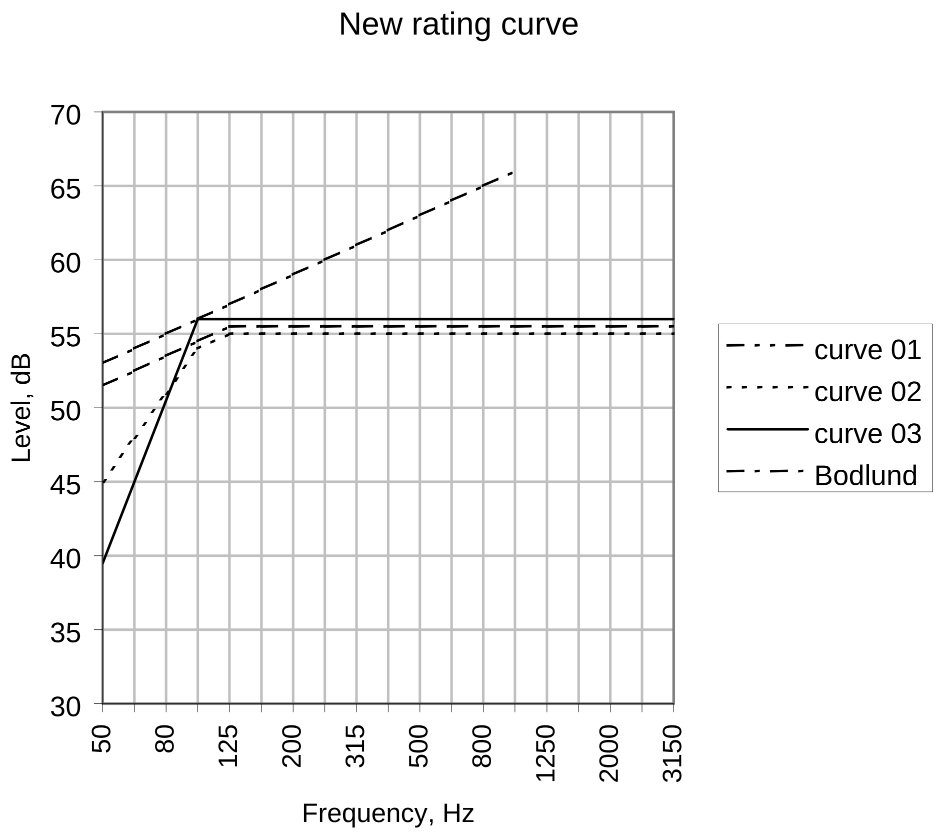

Figure 4. Shifting the curve from Bodlund's shape [7] to curve 03 raises the correlation coefficient, *r*, from 83% to 85% (curve 01), 86% (curve 02), and finally 87% (curve 03).

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 (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.

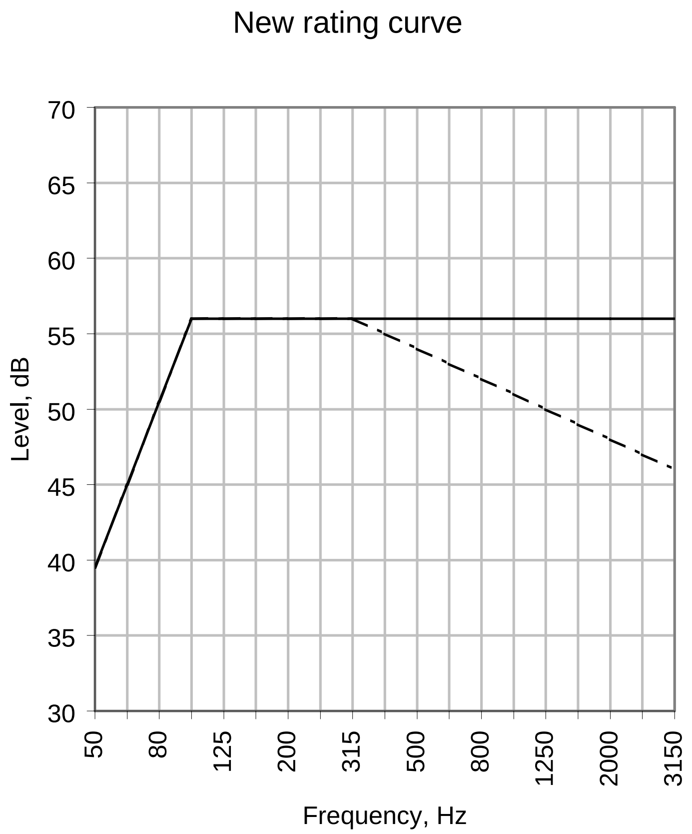

Figure 5. Shifting the curve from the suggested curve shape 03 to a curve including a positive slope of 1 dB per 1/3 octave (curve shape 04) above 315 Hz does not greatly influence the result. The correlation coefficient, *r*, retains its value of 87% even though the equation exhibits minor changes.

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

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

The best-fit shape of the high-frequency part of the evaluation curve cannot be stated with confidence. Nevertheless, it is clear that too much impact sound field data are missing 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. As 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

Naturally, a contour shift according to the results presented in this paper will not be adopted as an ISO standard for many years. However, adding the adaptation term, $C_{I,50–2500}$, to the single number, $L'_{n,w}$, according to the current ISO standard [10] will considerably improve the ISO single number and its concordance to subjective evaluation – actually slightly better than the curve suggested in 1985 [7]. Equation (17) shows the relationship using $L'_{n,w} + C_{I,50–2500}$, and this may be compared to the relationship using $L'_{n,w}$ (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).

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

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

$$\langle L'_{n,w}+C_I\rangle = 73.31 - 4.22\, S \quad [r = 79\%, n = 22] \qquad (19)$$

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, $L'_{n,w}$, and the spectrum adaptation term, $C_{I,50–2500}$, 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

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

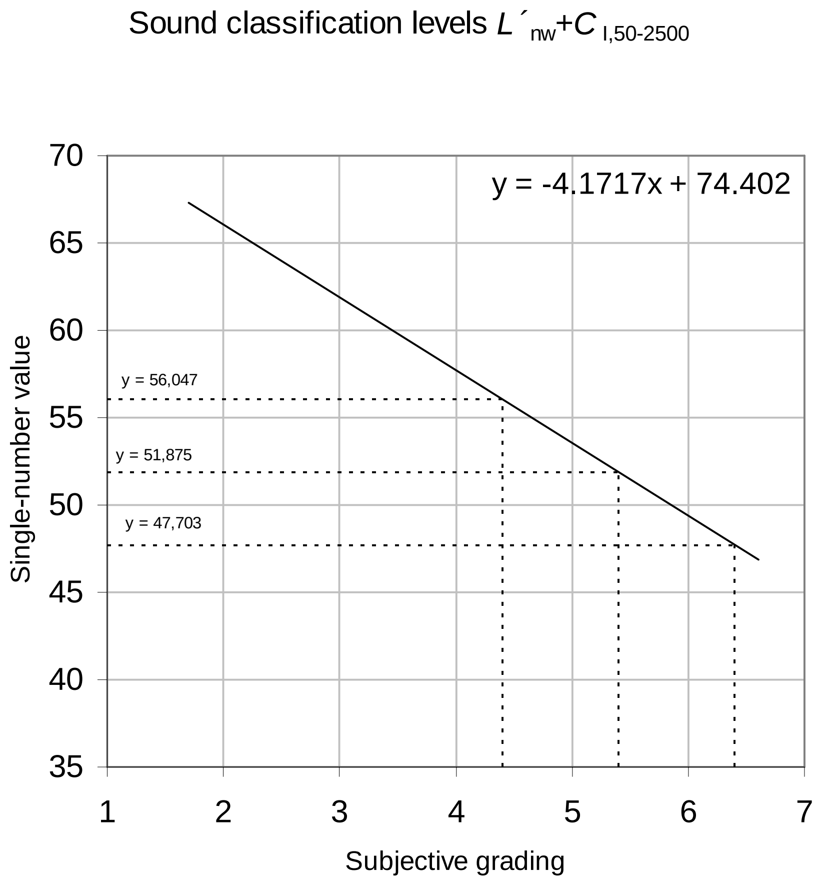

Figure 6. Possible levels for different sound classification standards using the ISO single number $L'_{n,w}$ + $C_{I,50–2500}$.

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. If used, horizontal errors bars could well supply information concerning perceived impact sound level in particular cases although equal in all diagrams below. In this investigation priority is given to the differences between the objective measures (as in reference 7); hence, horizontal errors bars are omitted from the presentation.

4.1. ISO measures and Bodlund measure I_S

Figure 7 plots the average impact sound level, $L'_{n,w}$, versus the subjective mean score, i.e. 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 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.

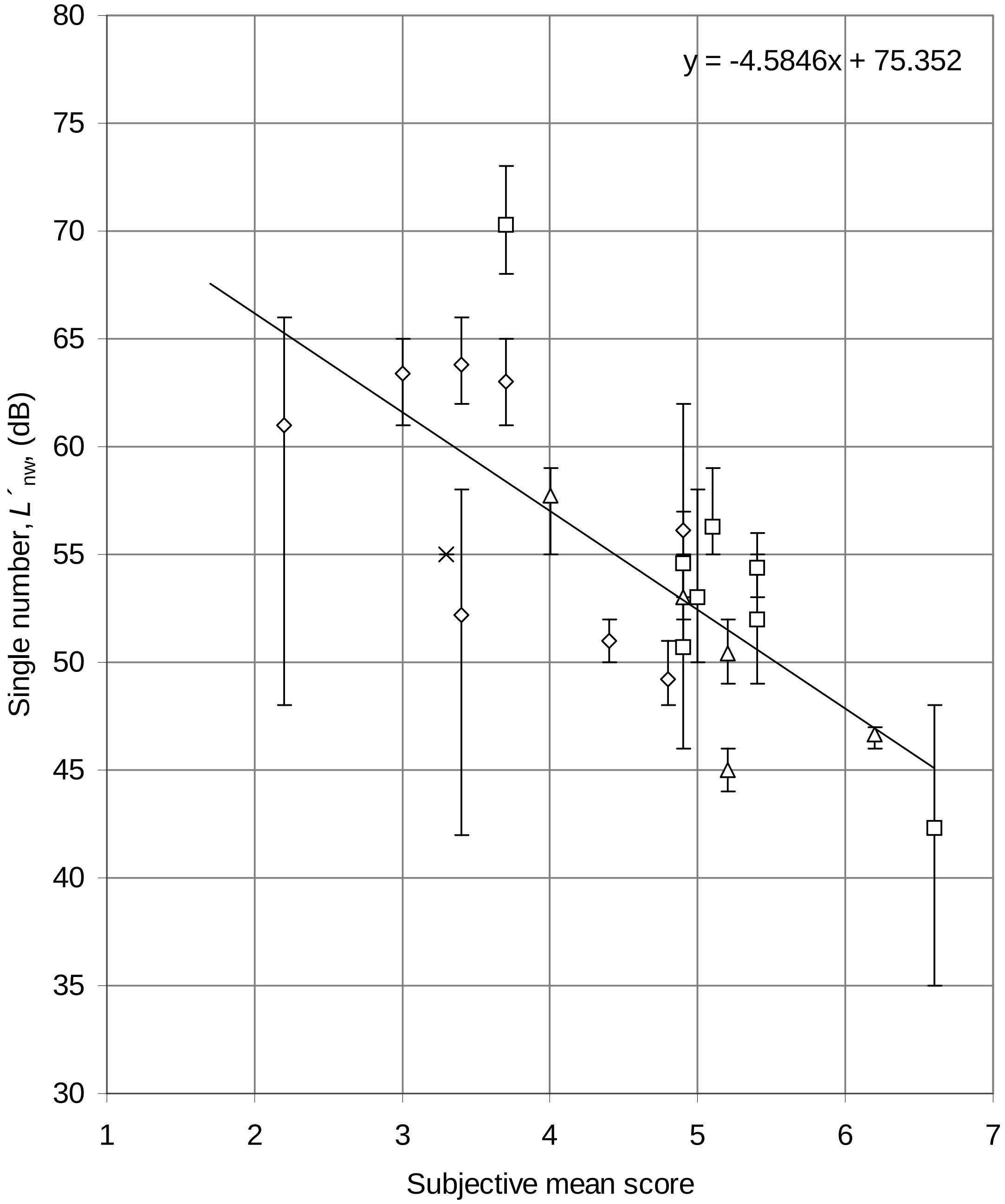

Figure 7. Linear regression for the whole data sample, $L'_{n,w}$ vs subjective grading; □ = concrete structures, Δ = hollow concrete structures, ◇ = wooden floor structures, × = lightweight steel structures.

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 types of 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). Obviously, concrete and hollow concrete structures, i.e. heavy structures, generally exhibit higher subjective scores and lower $L'_{n,w}$ values than do lightweight structures. Actually, 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).

Applying an identical plot while adding the ISO spectrum adaptation term, $C_{I,50–2500}$, to the weighted normalized single number – as in equation (18) – results in the shape displayed in Figure 8.

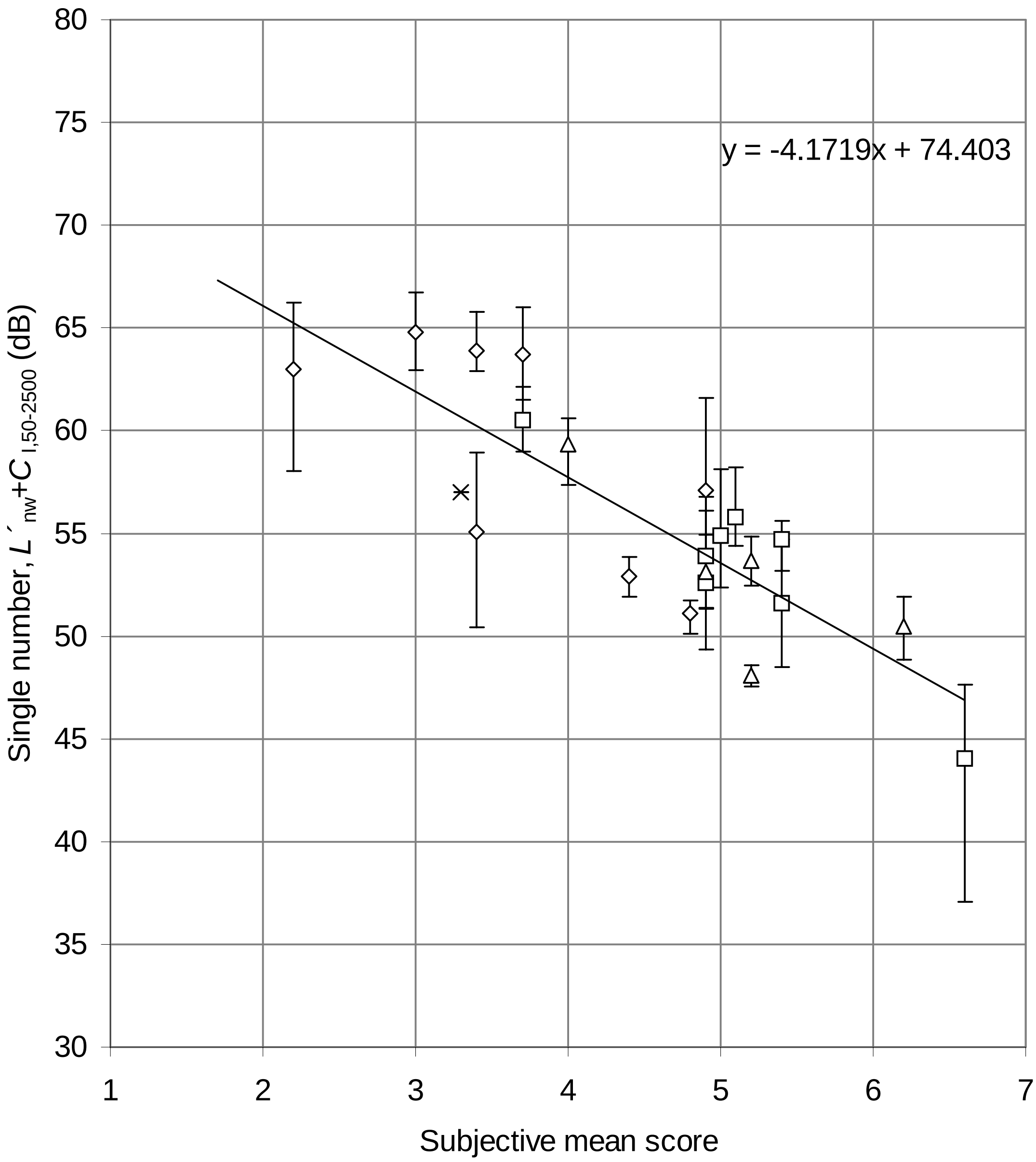

Figure 8. Linear regression for the whole data sample, $L'_{n,w}$ + $C_{I,50–2500}$ vs subjective grading; □ = concrete structures, Δ = hollow concrete structures, ◇ = wooden floor structures, × = lightweight steel structures.

Finally, what happens if the same plot is made for the single number, $L'_{n,w}$, while adding the spectrum adaptation term, C_I – i.e. considering the 100–3150 Hz range? This relationship is depicted in Figure 9, which represents the results of equation (19).

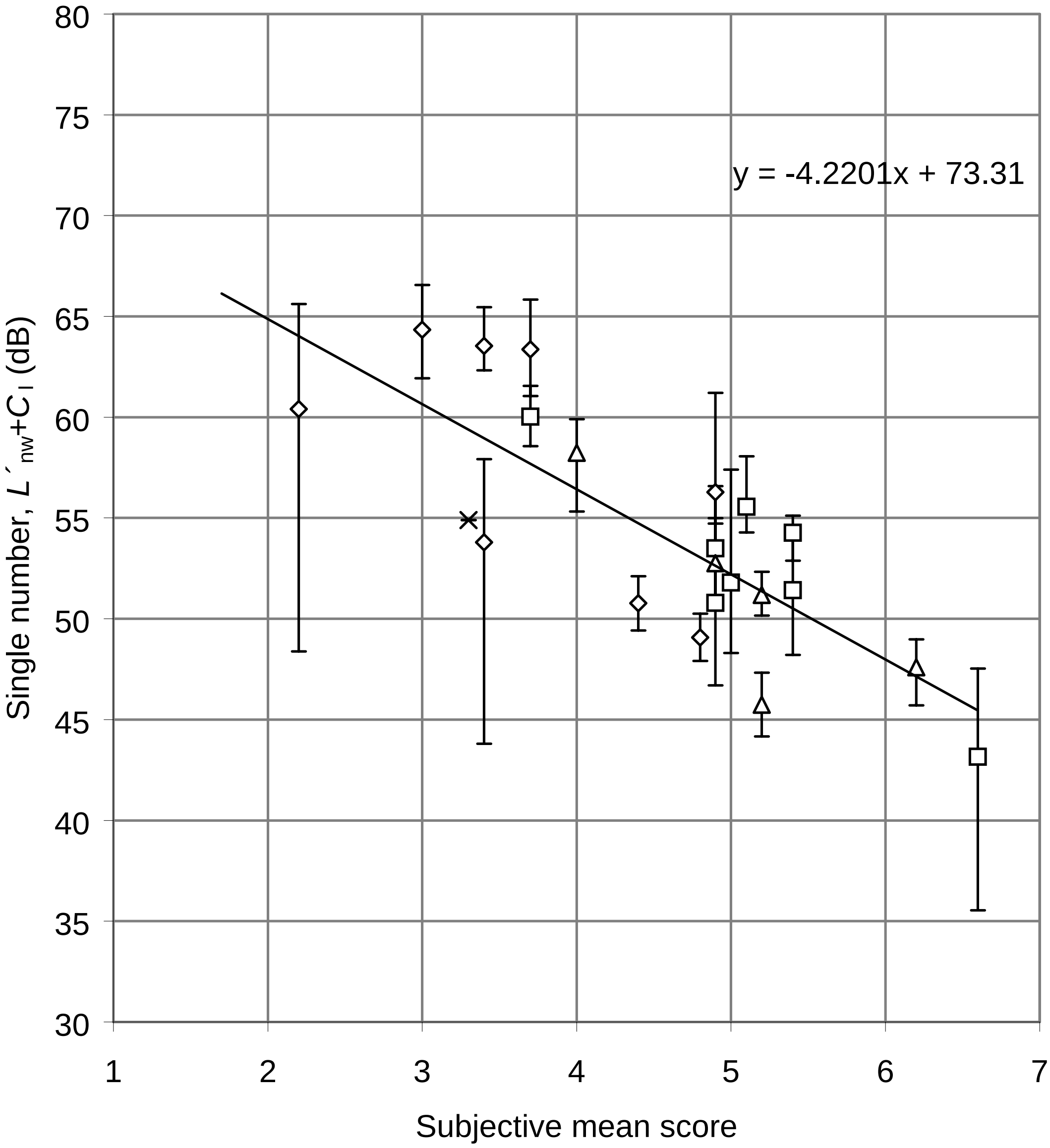

Figure 9. Linear regression for the whole data sample, $L'_{n,w} + C_I$ vs subjective grading; □ = concrete structures, Δ = hollow concrete structures, ◇ = wooden floor structures, × = lightweight steel structures.

Use of the single number, $L'_{n,w} + C_I$, is not recommended, even though it exhibits a slightly better correlation than $L'_{n,w}$ 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 $C_{I,50\text{–}2500}$) 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. In Sweden people normally do not wear shoes indoors;

should shoes be worn indoors, they are normally equipped with some type of 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.

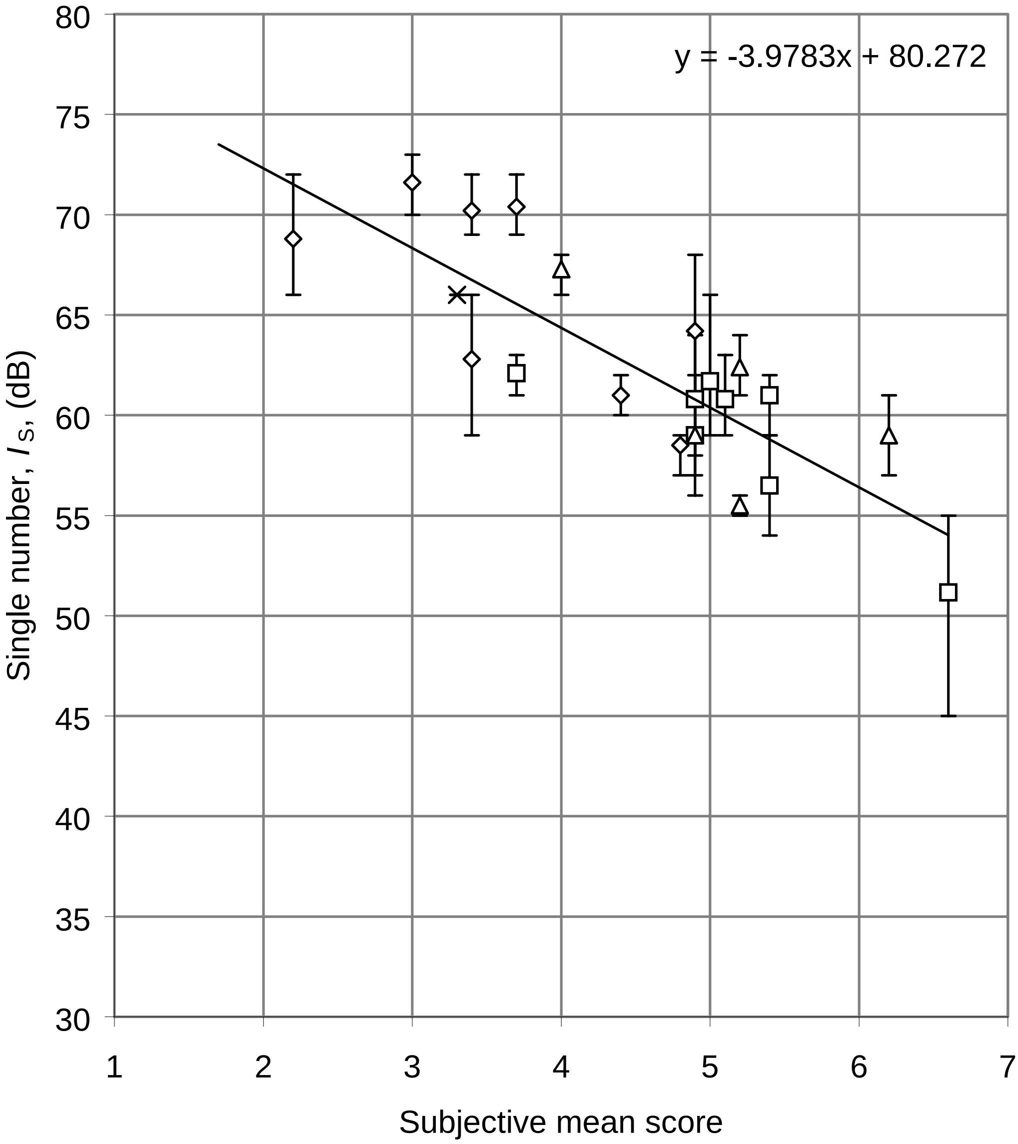

Figure 10. Linear regression for the whole data sample, I_S vs subjective grading; □ = concrete structures, Δ = hollow concrete structures, ◇ = wooden floor structures, × = lightweight steel structures.

No matter whether I_S or $L'_{n,w} + C_{I,50\text{–}2500}$ 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 $L'_{n,w} + C_{I,50\text{–}2500}$ 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 $L'_{n,w} + C_{I,50\text{–}2500}$ 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. Naturally, if stating a limit value, this value may be chosen in any other manner if adapting the single number to a value equal to current figures. Applying 4.4 [7] as an acceptable mean subjective score the new single number limit value, 61 dB, taken from Figure 11, may be subtracted with an appropriate value.

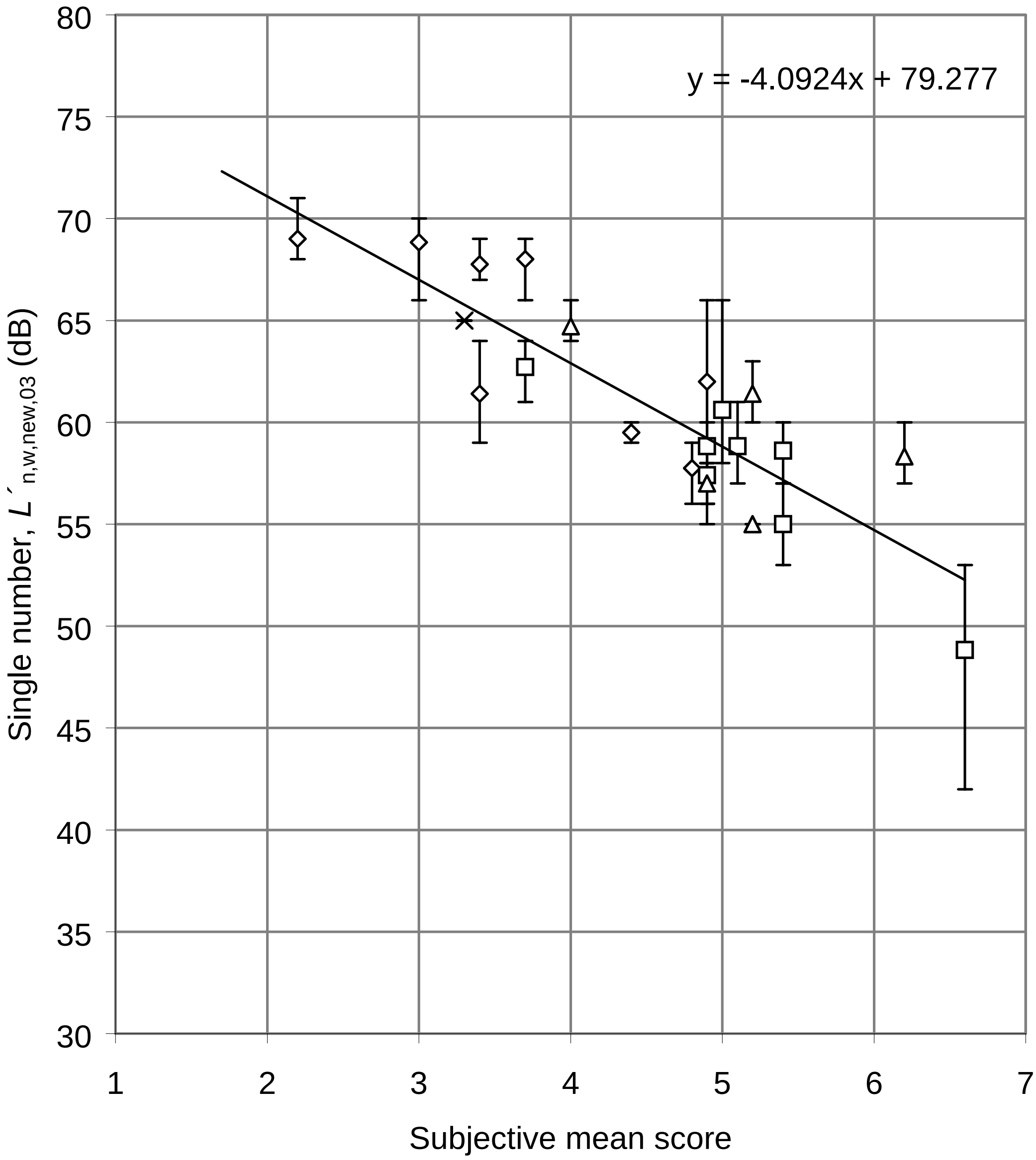

Figure 11. Linear regression for the whole data sample, $L'_{n,w,new,03}$ vs subjective grading; □ = concrete structures, Δ = hollow concrete structures, ◇ = wooden floor structures, × = lightweight steel structures.

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 this 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:

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

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 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.

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 article: 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.

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Appendix A – Floor structures included in the investigation

This appendix describes all floor structures included in the investigation. Each floor structure is shortly described and complemented with a small drawing. Connecting walls and flanking constructions are only briefly mentioned. For more detailed description it is referred to either the original reports or the author. Data concerning number of impact sound measurements performed for each object and information regarding subjective scores are shown. The most important single number mean values corresponding to the actual floor construction are presented in a table.

The first twelve objects (object 01 – object 12) are picked from the original investigation made by Bodlund, called “original data”. The following ten objects (object 13 – object 22) are new data, i.e. floor structures added in this investigation to extend the number of data.

OBJECT 01

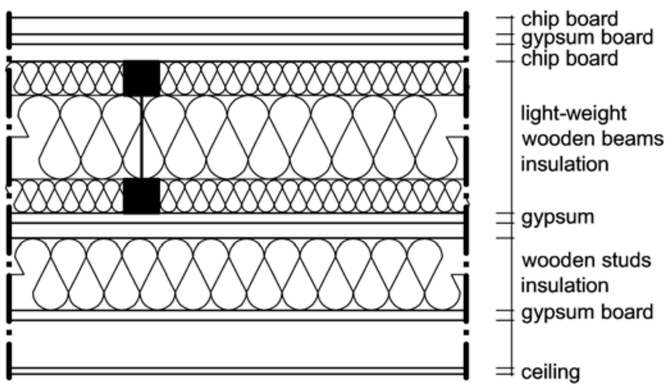
Report SP-RAPP 1983:37 section 4 / original data

BUILT IN YEAR: 1982/83 NUMBER OF STOREYS: 2 CONSTRUCTION TYPE: WOOD

This housing unit is constructed with prefabricated volume elements and located along a street with busy traffic and a bus stop. Each dwelling consists of three volume elements. Separating walls are wooden lightweight constructions, with a 13 mm gypsum plasterboard facing each dwelling. Floors are lightweight wooden constructions, with 22 mm fibrocement flooring and suspended ceiling.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 5

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 25% OF ANSWERS
GRADE 5 OR BETTER: 0 % OF ANSWERS
GRADE 2 OR WORSE: 75% OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 2,2

Based on interviews with 4 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
61	60	63	69	69	68

OBJECT 02

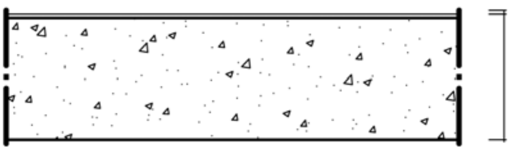
Report SP-RAPP 1983:37 section 5 / original data

BUILT IN YEAR: 1961/62 NUMBER OF STOREYS: 8 CONSTRUCTION TYPE: CONCRETE

The structure of this housing unit is built up by concrete, cast-in-situ. It is located in a typical urban environment, close to a busy road. External walls are built of 250 mm aerated concrete blocks and separating walls between the dwellings are made of 150 mm solid concrete. Floors are made of 150 mm solid concrete, covered with vinyl flooring.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 10

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 88% OF ANSWERS
GRADE 5 OR BETTER: 64% OF ANSWERS
GRADE 2 OR WORSE: 6 % OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 5

Based on interviews with 64 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
53	52	55	62	61	59

OBJECT 03

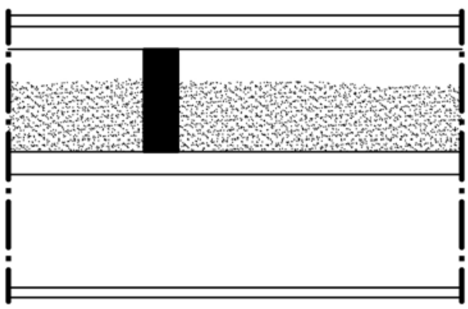
Report SP-RAPP 1983:37 section 6 / original data

BUILT IN YEAR: 1920, RENOVATED 1979 NUMBER OF STOREYS: 3 CONSTRUCTION TYPE: WOOD

The construction of these housing units is partly unknown and the original drawings are missing. However, the floor structures are a timber structure. Separating walls between the dwellings are built of 250 mm solid brick walls, in some cases supplemented with a timber frame wall. Suspended ceilings are added to the original timber floors, as well as boards and flooring on top of the old timber flooring.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 5

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 36% OF ANSWERS
GRADE 5 OR BETTER: 36% OF ANSWERS
GRADE 2 OR WORSE: 55 % OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 3,4

Based on interviews with 11 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
52	54	55	63	61	59

OBJECT 04

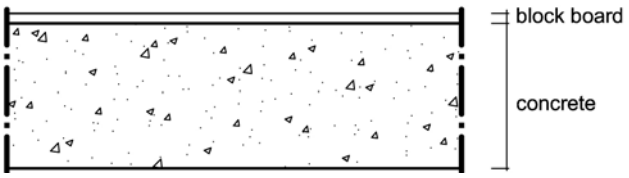
Report SP-RAPP 1983:37 section 8 / original data

BUILT IN YEAR: 1981/82 NUMBER OF STOREYS: 2 CONSTRUCTION TYPE: CONCRETE

All units within this housing area are built up with concrete structures, cast in situ. The housing units are provided with external galleries to access the dwellings. Separating walls between the dwellings are made of 150 mm solid concrete and separating floors between the dwellings are made of 190 mm solid concrete.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 5

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 75% OF ANSWERS
GRADE 5 OR BETTER: 67% OF ANSWERS
GRADE 2 OR WORSE: 8 % OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 4,9

Based on interviews with 12 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
55	54	54	59	57	56

OBJECT 05

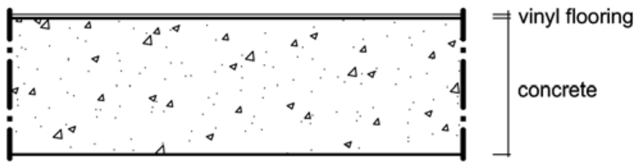
Report SP-RAPP 1985:01 section A1 (a) / original data

BUILT IN YEAR: 1979/81 NUMBER OF STOREYS: 2 CONSTRUCTION TYPE: CONCRETE

All units within this housing area are built up with concrete structures, cast in situ. The housing units are provided with external galleries to access the dwellings. Separating walls between the dwellings are made of solid concrete and separating floors between the dwellings are made of 180 mm solid concrete covered with a hard 1,5 mm vinyl flooring.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 7

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 62% OF ANSWERS
GRADE 5 OR BETTER: 33% OF ANSWERS
GRADE 2 OR WORSE: 24% OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 3,7

Based on interviews with 21 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
70	60	61	62	63	66

OBJECT 06

Report SP-RAPP 1985:01 section A1 (b) / original data

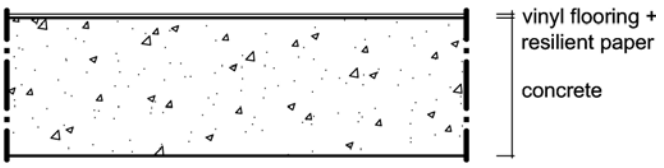
BUILT IN YEAR: 1979/81 NUMBER OF STOREYS: 2 CONSTRUCTION TYPE: CONCRETE

The structure of this housing unit is equal to the structure in object 05 however completed slightly later.

Due to poor impact sound insulation achieved in the housing unit completed first (object 05) this stage of the housing area was improved by using a resilient paper lining under the linoleum flooring.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 6

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 81% OF ANSWERS
GRADE 5 OR BETTER: 69% OF ANSWERS
GRADE 2 OR WORSE: 13% OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 5,1

Based on interviews with 16 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50\text{-}2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
56	56	56	61	59	58

OBJECT 07

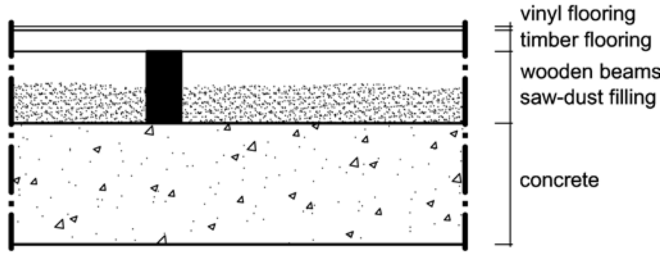
Report SP-RAPP 1985:01 section A2 / original data

BUILT IN YEAR: 1950 RENOVATED 1982 NUMBER OF STOREYS: 3 CONSTRUCTION TYPE: CONCRETE

The building units in this housing area are three-storey residential houses. A moderately frequented street passes the short side of the housing units. All floor structures consist of a 160 mm reinforced concrete slab, covered with a wooden floor on battens. The gap is filled with sawdust.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 12

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: - % OF ANSWERS
GRADE 5 OR BETTER: 59% OF ANSWERS
GRADE 2 OR WORSE: 14% OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 4,9

Based on interviews with 23 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
51	51	53	61	59	57

OBJECT 08

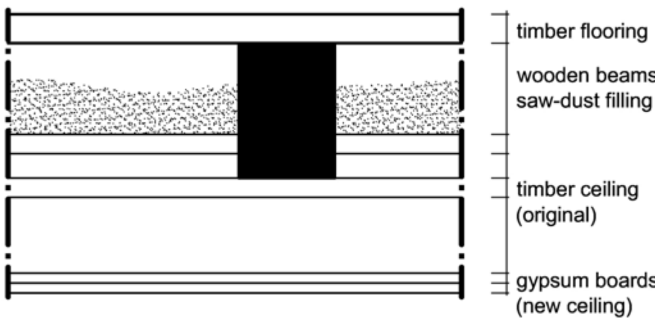
Report SP-RAPP 1985:01 section A3 / original data

BUILT IN YEAR: ? RENOVATED 1982 NUMBER OF STOREYS: 3 CONSTRUCTION TYPE: WOOD

The housing units in this area are provided with external galleries to access the dwellings. They are three-storeys residential houses situated in quiet surroundings. During renovation, the original timber joist floor was completed with a suspended ceiling. The new ceiling is constituted by two gypsum boards, mounted on a framework of steel studs suspended by steel bar joists c-c 1200 mm.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 10

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: - % OF ANSWERS
GRADE 5 OR BETTER: 58% OF ANSWERS
GRADE 2 OR WORSE: 17% OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 4,9

Based on interviews with 12 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
56	56	57	64	62	60

OBJECT 09

Report SP-RAPP 1985:01 section A4 (a) / original data

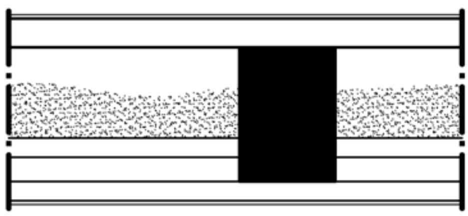
BUILT IN YEAR: 1935 NUMBER OF STOREYS: 3 CONSTRUCTION TYPE: WOOD

These three-storey housing units are located in a silent neighbourhood. In Sweden the type of housing unit is called “Governors-houses”. The ground floor is built up by brick walls - above this ground floor there exist two storeys made of timber walls – floors are generally made of timber joists. The timber joist floor are made by 3”x 8” timber beams, c-c 600, with timber board flooring. The ceiling is covered with a plasterboard.

Party floors are covered with vinyl flooring.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 8

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 45% OF ANSWERS
GRADE 5 OR BETTER: 27% OF ANSWERS
GRADE 2 OR WORSE: 23% OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 3,7

Based on interviews with 22 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
63	63	64	70	68	66

OBJECT 10

Report SP-RAPP 1985:01 section A4 (b) / original data

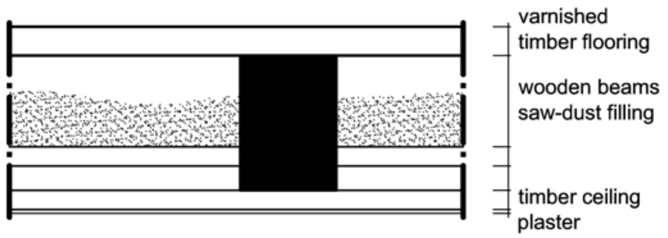
BUILT IN YEAR: 1935 NUMBER OF STOREYS: 3 CONSTRUCTION TYPE: WOOD

These three-storey housing units are located in a silent neighbourhood. In Sweden the type of housing unit is called "Governors-houses". The ground floor is built up by brick walls - above this ground floor there exist two storeys made of timber walls – floors are generally made of timber joists. The timber joist floor are made by 3"x 8" timber beams, c-c 600, with timber board flooring. The ceiling is covered with a plasterboard.

Linoleum flooring is removed and timber flooring varnished.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 8

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 39% OF ANSWERS
GRADE 5 OR BETTER: 17% OF ANSWERS
GRADE 2 OR WORSE: 22% OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 3,4

Based on interviews with 18 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
64	64	64	70	68	66

OBJECT 11

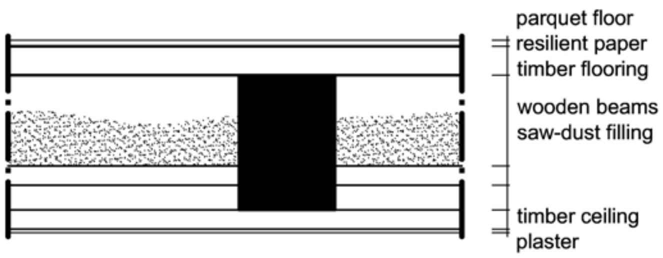
Report SP-RAPP 1985:01 section A5 / original data

BUILT IN YEAR: 1940 RENOVATED: 1979/80 NUMBER OF STOREYS: 3 CONSTRUCTION TYPE: WOOD

These “Governors-houses” are located in a silent environment, with a limited amount of traffic noise exposure. During renovation, the board floors were provided with new floor covering consisting of paper lining and parquet floor. The construction of the timber joist party floors was not changed.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 12

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: - % OF ANSWERS
GRADE 5 OR BETTER: 11% OF ANSWERS
GRADE 2 OR WORSE: 36% OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 3

Based on interviews with 28 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
63	64	65	72	69	67

OBJECT 12

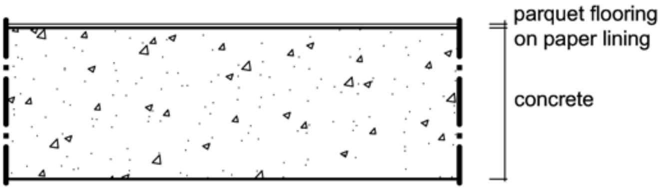
Report SP-RAPP 1985:01 section A6 (b) / original data

BUILT IN YEAR: 1981 NUMBER OF STOREYS: 4 CONSTRUCTION TYPE: CONCRETE

All structural elements in this housing unit are built of concrete and the party floors are made by 200 reinforced concrete slabs. The parquet flooring is provided with a flexible paper lining.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 5

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: - % OF ANSWERS
GRADE 5 OR BETTER: 74% OF ANSWERS
GRADE 2 OR WORSE: 7 % OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 5,4

Based on interviews with 14 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
54	54	55	61	59	57

OBJECT 13

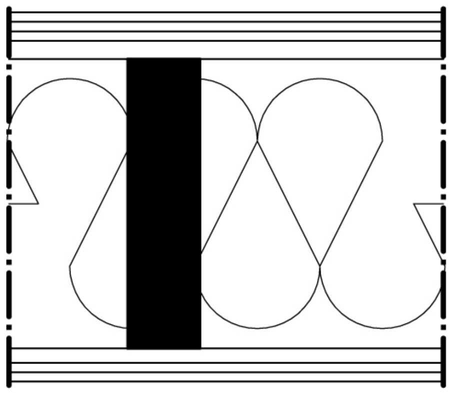
Wooden floor structure / New data (WS01)

BUILT IN YEAR: 1996   NUMBER OF STOREYS: 5   CONSTRUCTION TYPE: WOOD

The floor structure in this housing unit is constructed with specially prefabricated timber floor elements constructed to meet high acoustic performance. Separating walls are built of 2 ×13 mm plasterboards / 95 mm wooden studs / 95 mm wooden studs / 2×13 mm plasterboards (the air gap is filled with 200 mm mineral wool). Floors are lightweight wooden constructions, with 22 mm fibre cement topping and a suspended ceiling comprising 2 layers of 13 mm plasterboards mounted on resilient steel channels. Total floor height is 530 mm

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 4

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 88 % OF ANSWERS
GRADE 5 OR BETTER: 62 % OF ANSWERS
GRADE 2 OR WORSE: 8 % OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 4,8

Based on interviews with 6 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
49	49	51	59	58	56

OBJECT 14

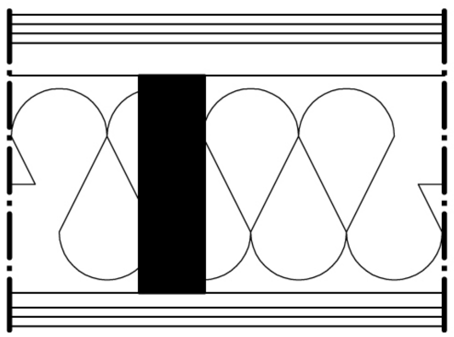
Wooden floor structure / New data (WS02)

BUILT IN YEAR: 1996 NUMBER OF STOREYS: 5 CONSTRUCTION TYPE: WOOD

The floor structure in this housing unit is constructed with specially prefabricated timber floor elements constructed to meet high acoustic performance. Separating walls are built of 2 ×13 mm plasterboards / 95 mm wooden studs / 95 mm wooden studs / 2×13 mm plasterboards (the air gap is filled with 200 mm mineral wool). Floors are lightweight wooden constructions, with floor topping comprising parquet and two layers of 13 mm plasterboards mounted on steel plate, TRP 45 22, and a suspended ceiling comprising 2 layers of 13 mm plasterboards mounted on resilient steel channels. Total floor height is approximately 490 mm.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 2

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 75% OF ANSWERS
GRADE 5 OR BETTER: 40 % OF ANSWERS
GRADE 2 OR WORSE: 10 % OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 4,4

Based on interviews with 11 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
51	51	53	61	60	58

OBJECT 15

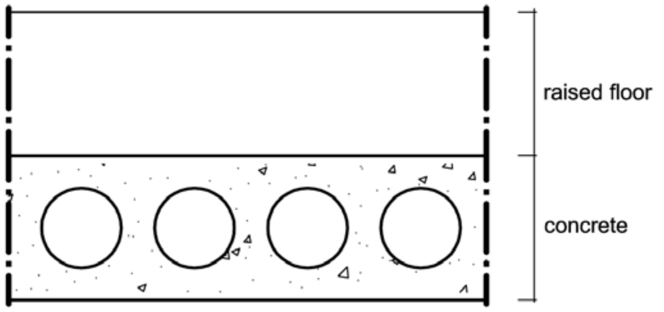
Hollow concrete structure / New data (HC01)

BUILT IN YEAR: 2002   NUMBER OF STOREYS: 7   CONSTRUCTION TYPE: HOLLOW CONCRETE

The floor structure of this housing unit consists of prefabricated hollow concrete elements (HD/F 120/19). Party floors are hollow concrete slabs, with a sound insulating raised floor (*h*= 150 mm). Floor covering consists of 15 mm parquet on 22 mm particle board.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 3

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 100% OF ANSWERS
GRADE 5 OR BETTER: 92% OF ANSWERS
GRADE 2 OR WORSE: 0 % OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 6,2

Based on interviews with 20 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
47	48	50	59	58	56

OBJECT 16

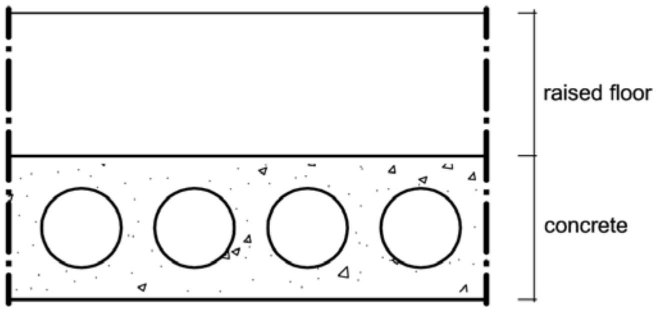
Hollow concrete structure / New data (HC02)

BUILT IN YEAR: 2002 NUMBER OF STOREYS: 5 CONSTRUCTION TYPE: HOLLOW CONCRETE

This structure of this housing unit consists of prefabricated hollow concrete elements (HD/F 120/19). Party floors are hollow concrete slabs, with a sound insulating raised floor (*h*= 150 mm). Floor covering consists of 15 mm parquet on 22 mm particle board.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 5

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 86% OF ANSWERS
GRADE 5 OR BETTER: 83% OF ANSWERS
GRADE 2 OR WORSE: 14% OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 5,2

Based on interviews with 20 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50\text{-}2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
50	51	54	62	61	59

OBJECT 17

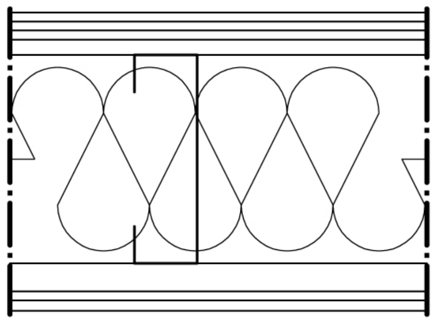
Lightweight steel structure / New data (LS01)

BUILT IN YEAR: 2000 NUMBER OF STOREYS: 2 CONSTRUCTION TYPE: LIGHTWEIGHT STEEL STRUCTURE

The floor construction of this housing unit consists of prefabricated lightweight steel structure elements. Separating walls are built of 2×13 mm plasterboards / 70 mm steel studs / 70 mm steel studs / 2×13 mm plasterboards (the air gap is filled with 150 mm mineral wool). Floors are supplied with parquet 15 mm on 13 mm gypsum plasterboard glued to 22 mm particle board / 200 steel channels c 600 / and a suspended ceiling comprising 2 layers of 13 mm plasterboards mounted on resilient steel channels. Total floor height is 300 mm.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 2

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 43% OF ANSWERS
GRADE 5 OR BETTER: 29% OF ANSWERS
GRADE 2 OR WORSE: 43% OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 3,3

Based on interviews with 5 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50\text{-}2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
55	55	57	66	65	63

OBJECT 18

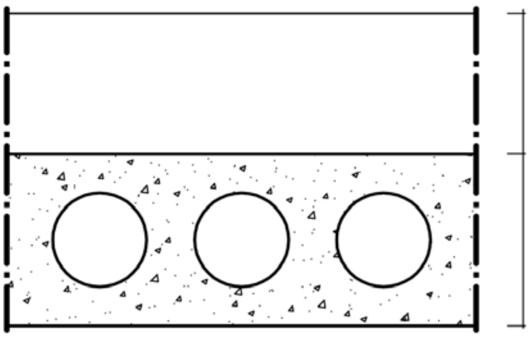
Hollow concrete structure / New data (HC03)

BUILT IN YEAR: 1999 NUMBER OF STOREYS: 7 CONSTRUCTION TYPE: HOLLOW CONCRETE

This structure of this housing unit consists of prefabricated hollow concrete elements (HD/F 120/19) with a sound insulating raised floor (*h*=150 mm). Floor covering consists of 15 mm parquet on 22 mm particle board. Connecting walls, between the dwellings, are made by 180 mm solid concrete, exterior walls consist of 350 mm aerated concrete.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 2 (+ CALCULATIONS ACC TO EN 12354)

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 73% OF ANSWERS
GRADE 5 OR BETTER: 66% OF ANSWERS
GRADE 2 OR WORSE: 15% OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 4,9

Based on interviews with 62 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50\text{-}2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
53	53	53	59	57	55

OBJECT 19

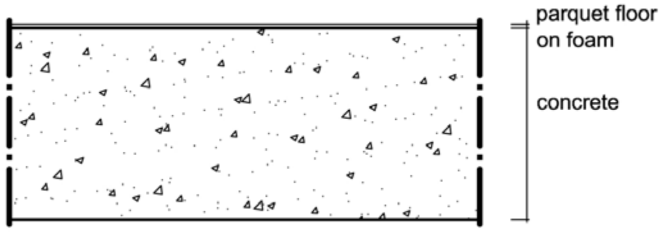
Solid concrete structure / New data (SC01)

BUILT IN YEAR: 1999 NUMBER OF STOREYS: 5 CONSTRUCTION TYPE: SOLID CONCRETE

The party floors of this housing unit consist of 250 mm solid concrete covered with parquet on 3 mm foam. Walls between the dwellings are made by 200 mm solid concrete.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 2 (+ CALCULATIONS ACC TO EN 12354)

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 83% OF ANSWERS
GRADE 5 OR BETTER: 75% OF ANSWERS
GRADE 2 OR WORSE: 8 % OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 5,4

Based on interviews with 10 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
52	51	52	57	55	54

OBJECT 20

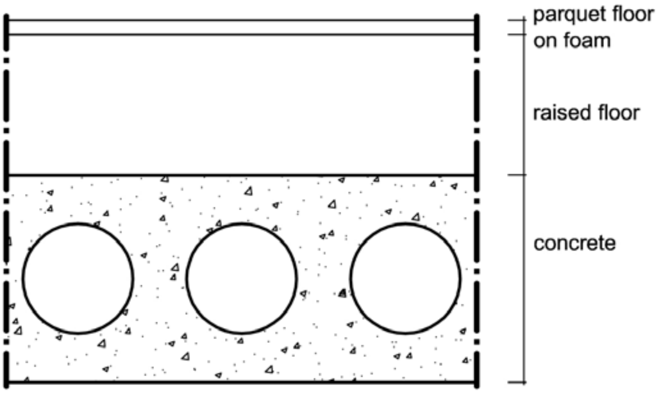
Hollow concrete structure / New data (HC04)

BUILT IN YEAR: 2000/01 NUMBER OF STOREYS: 4 CONSTRUCTION TYPE: HOLLOW CONCRETE

The party floors of this housing unit consist of hollow concrete elements (HD/F 120/27) with a sound insulating raised floor on top (*h*=150 mm). Floor covering consists of 15 mm parquet on 3 mm foam floating on 22 mm particle board. Connecting walls, between the dwellings, are made by 200 mm solid concrete, wooden beams with insulation and two gypsum boards. Exterior walls are lightweight wooden structure.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 2 (+ CALCULATIONS ACC TO EN 12354)

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 83% OF ANSWERS
GRADE 5 OR BETTER: 75% OF ANSWERS
GRADE 2 OR WORSE: 8 % OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 5,2

Based on interviews with 12 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
45	46	48	56	55	53

OBJECT 21

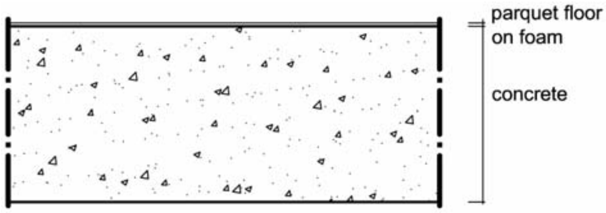
Solid concrete structure / New data (SC02)

BUILT IN YEAR: 1989 NUMBER OF STOREYS: 4 CONSTRUCTION TYPE: SOLID CONCRETE

This structure of this housing unit consists of solid concrete cast in situ specially designed to meet high acoustic performance. The floor structure has a thickness of 290 mm and the floor covering consist of either plastic floor on 22 mm particle board or 15 mm parquet mounted on 20 mm mineral wool (soft board). The separating walls are 240 mm thick.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 6

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 100% OF ANSWERS
GRADE 5 OR BETTER: 100% OF ANSWERS
GRADE 2 OR WORSE: 0 % OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 6,6

Based on interviews with 13 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
42	43	44	51	49	47

OBJECT 22

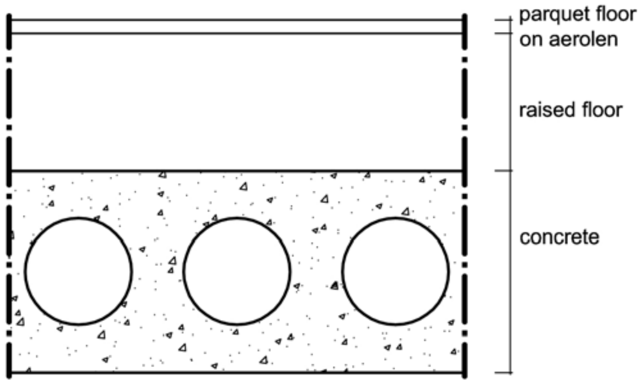
Hollow concrete structure / New data (HC05)

BUILT IN YEAR: 2002/03 NUMBER OF STOREYS: 5 CONSTRUCTION TYPE: HOLLOW CONCRETE

The party floors of this housing unit consist of hollow concrete elements (HD/F 120/19) with a sound insulating raised floor on top (*h*=150 mm). Floor covering consists of 15 mm parquet on 3 mm foam floating on 22 mm particle board. Connecting walls, between the dwellings, are made by 200 mm solid concrete. Exterior walls are lightweight wooden structure.

CROSS SECTION, FLOOR:

Drawing scale 1:10



NUMBER OF MEASUREMENTS: 7

SUBJECTIVE SCORES:

GRADE 4 OR BETTER: 64% OF ANSWERS
GRADE 5 OR BETTER: 36% OF ANSWERS
GRADE 2 OR WORSE: 39% OF ANSWERS

MEAN SUBJECTIVE COEFFICIENT = 4

Based on interviews with 39 residents.

SINGLE NUMBER MEAN VALUES:

L'_{nw}	$L'_{nw} + C_i$	$L'_{nw}+C_{I,50-2500}$	I_S	$L_{n\ new\ 03}$	$L_{n\ new\ 04}$
58	58	59	67	65	63