Technical University of Denmark

Concepts for evaluation of sound insulation of dwellings - from chaos to consensus?

Rasmussen, Birgit; Rindel, Jens Holger

Published in:
Forum Acusticum 2005

Publication date:
2005

Document Version
Publisher's PDF, also known as Version of record

Concepts for evaluation of sound insulation of dwellings - from chaos to consensus?

Birgit Rasmussen
VELUX A/S, W-Product Quality, Ådalsvej 99, DK-2970 Hørsholm, Denmark, **birgit.rasmussen@VELUX.com**

Jens Holger Rindel
Ørsted-DTU, Acoustic Technology, Technical University of Denmark, Ørsteds Plads, Bld. 352, DK-2800 Lyngby, Denmark, **jhr@oersted.dtu.dk**

Legal sound insulation requirements have existed more than 50 years in some countries, and single-number quantities for evaluation of sound insulation have existed nearly as long time. However, the concepts have changed considerably over time from simple arithmetic averaging of frequency bands in the beginning to a variety of more complex concepts developed in different countries and later included in EN ISO 717:1996, thus representing a cataloguing of concepts rather than a harmonization.

In 2004 a survey was carried out including 24 countries in Europe. A comparison of lega1 requirements and classification schemes revealed significant differences of concepts. This paper summarizes the history of concepts, the disadvantages of the present chaos and the benefits of consensus concerning concepts for airborne and impact sound insulation between dwellings and airborne sound insulation of facades.

The concepts suitable for evaluation should be well-defined under practical situations in buildings, be measurable, reproducible and, of course, correlate well with subjective evaluation. More noise sources - incl. neighbours' activities - and an increased demand for high quality and comfort together with a trend towards light-weight constructions are contradictory and challenging. This calls for exchange of data and experience, implying a need for harmonized concepts, including use of spectrum adaptation terms.

The paper will provide input for future discussions in EAA TC-RBA WG4: "Sound insulation requirements and sound classification - Harmonization of concepts", aiming at harmonization of concepts for legal requirements and classification criteria.

1 Introduction

In 2004 a survey describing the main sound insulation requirements between dwellings was carried out in 24 countries in Europe, see [1]. A comparison of requirements revealed considerable differences, not only in level of requirements, but also in terms of descriptors used and the frequency range applied. 10 and 6 different concepts were applied for airborne and impact sound insulation requirements, respectively, not counting variants and additional recommendations.

The first legal sound insulation requirements appeared more than 50 years ago, and the frequency range 100-3150 Hz became the "traditional" frequency range for European building acoustic requirements, field tests and laboratory tests. However, in countries with light-weight building practice, e.g. Sweden and Norway, the need to include lower frequencies (< 100 Hz) gradually became obvious.

The international concepts for evaluation of airborne and impact sound insulation are defined in ISO 717 [2], and these standards have also been published as European standards (EN ISO).

During the last decade low-frequency descriptors have been introduced in all 5 Nordic countries and in Lithuania. The low-frequency terms are included in the legal minimum requirements in Sweden and in the criteria for the higher, voluntary quality classes in classification schemes in all 6 countries.

In 2003 UK has taken a step in a different direction by introducing the spectrum adaptation term C_{tr} as a part of the required criterion for airborne sound insulation between dwellings in general, although C_{tr} is based on an average traffic noise spectrum and has a strong weight at low frequencies The "C_{tr}-spectrum" is intended for optimizing sound insulation against traffic and other sources with significant low-frequency contents, e.g. disco music.

The idea behind including C_{tr} for evaluation of sound insulation between dwellings is to take into account low frequencies without actually testing at low frequencies. The idea is interesting, but there seems to be no official reports or articles (except some early information in [3]), justifying that this is a cost-effective and balanced way to meet the needs for increased sound insulation in an optimized way. In 2004 Australia has followed UK by also introducing C_{tr} in the requirements for airborne sound insulation between dwellings and has in addition introduced C_i for impact sound insulation requirements, see [4].

In general, there seems to be a trend towards increasing the requirements and including the spectrum adaptation terms in the concepts defining the airborne and impact sound insulation requirements, although the process is slow.

In Section 2 brief information is found about the history of concepts for evaluation of sound insulation. Section 3 describes the present standardized concepts for evaluation of sound insulation and the suitability in practice. The importance of correlation with subjective evaluation is emphasized in Section 4. Section 5 summarizes the inappropriateness of the present chaotic situation, the need for investigations, and some recommendations for concepts to be applied in the future are given.

2 Brief history of concepts

In the 19th century, the building regulations were based on the need to reduce the risk for both the towns and the inhabitants in case of fire and the need to ensure structural stability. However in the beginning of the 20th century it was realized that insufficient sound insulation could initiate conflicts between neighbours and reduce the well-being of the occupants.

The early sound insulation requirements were often “comparative”, e.g. requiring “a sound insulation as good as a 1/1 brick wall or another construction providing at least the same sound insulation”. Later, more specific concepts appeared, e.g. R_m being an arithmetic average of 1/3 octave values.

The overall suitability of concepts for evaluation of sound insulation may be assessed by considering the following characteristics:

1. suitable, i.e. correlate well with subjective evaluation
2. well-defined, i.e. all parts of the basic equation should exist
3. reproducible, i.e. the measurement uncertainty should be low, so it is easy the determine compliance with requirements

The first international standard for rating of sound insulation of dwellings was ISO/R 717:1968, [5], which was based on extensive investigations, see e.g. Gösele [6] and Fasold [7], and supporting field measurements according to ISO/R 140:1960 [8]. The maximum allowable unfavourable deviation from the reference curve was 8 dB.

A revised ISO 717 consisting of 3 parts was published in 1982, [9], and the series supported the ISO 140 series published in 1978, [10]. The basic reference curves were the same as in ISO/R 717:1968 [5], but the 8 dB rule was removed. However, the 8 dB survived partly, in the sense that the maximum deviation must be indicated in the test report, if it exceeded 8 dB.

Influenced by the French concepts R_{rose} and R_{route} and the increasing need in other countries for evaluation of traffic noise insulation and for including low frequencies (down to 50 Hz), the next (and most recent) version of ISO 717 [2] was a thorough revision of [9] and included a range of spectrum adaptation terms, see Section 3. In parallel, ISO 140 was updated, [11].

3 Present standardized concepts and overall suitability

3.1 Overview field concepts

In table 1 an overview is found of the basic ISO 717 concepts (single-number quantities) and the spectrum adaptation terms intended for specification and test of:

- airborne sound insulation between dwellings
- airborne sound insulation for facades
- impact sound insulation between dwellings

The international concepts for evaluation of airborne and impact sound insulation are defined in ISO 717-1 and ISO 717-2, respectively, [2]. The spectrum adaptation terms have been introduced to take into account different spectra of noise sources: C and C_{tr} (corresponding to pink noise and road traffic noise, respectively) for airborne sound insulation, see Table 2, and C_i ($L'_{n,w} + C_i + 15$ correspond to the energy sum) for impact sound insulation. The spectrum adaptation terms - colloquially named C-corrections - may be calculated for the usual frequency range or for an enlarged frequency range including the 1/3 octave frequency bands 50+63+80 Hz (C, C_{tr}, C_i) and/or 4000+5000 Hz (C and C_{tr} only). 1/1 octave measurement results may be used for rating of field measurements. The C-corrections are equipped with indices specifying the type of spectrum and the frequency range, if enlarged (see Table 1). The maximum unfavourable deviation shall no longer be indicated, even if it exceeds 8 dB. However, the C-corrections are more restrictive to dips and peaks in the airborne and impact sound insulation curves, respectively, thereby to some extent substituting the former 8-dB rules.

The single-number quantities and the spectrum adaptation terms are derived from 1/3 octave values (laboratory and field) or 1/1 octave values (field only) measured according to ISO 140, [11]. The different C-corrections will enable to take into account different types of noise spectra, without leaving the well-known reference curve system. Thus, C, C_{tr} and C_i have not been included directly in any single-number quantities, but have been introduced as separate terms to be added.

A requirement may be expressed as the sum of a single-number quantity and a spectrum adaptation term or solely as the single-number quantity. Examples on statements of airborne and impact sound requirements:

$D_{nT,w} \geq 55$ dB; $D_{nT,w} + C \geq 55$ dB; $D_{nT,w} + C_{50\text{-}3150} \geq 55$ dB
$L'_{nT,w} \leq 50$ dB; $L'_{nT,w} + C_i \leq 50$ dB; $L'_{nT,w} + C_{i,50\text{-}2500} \leq 50$ dB

In Table 1 the "1/3 octave" ISO 717 single-number field quantities, spectrum adaptation terms and the total number of concepts are indicated. In the lower part of Table 1 – based on a survey in 24 European countries (see list below) - information has been added about the number of concepts actually applied. The table also indicates the number of countries applying spectrum adaptation terms (including low-frequency terms).

The survey was carried out in 24 countries: Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Iceland, Italy, Latvia, Lithuania, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom (all CEN members) and Russia.

Table 1: Overview single-number quantities for evaluation of sound insulation in buildings

ISO 717 concepts for evaluation of sound insulation Overview and applications in Europe			
	Airborne sound insulation between rooms	Airborne sound insulation of facades	Impact sound insulation between rooms
Basic concepts (single-number quantities)	R'_w $D_{n,w}$ $D_{nT,w}$	R'_w $D_{n,w}$ $D_{nT,w}$	$L'_{n,w}$ $L'_{nT,w}$
Spectrum adaptation terms (listed according to intended main applications, see Table 2)	**None** C $C_{50\text{-}3150}$ $C_{100\text{-}5000}$ $C_{50\text{-}5000}$	**None** C C_{tr} $C_{50\text{-}3150}$ $C_{tr,50\text{-}3150}$ $C_{100\text{-}5000}$ $C_{tr,100\text{-}5000}$ $C_{50\text{-}5000}$ $C_{tr,50\text{-}5000}$	**None** C_i $C_{i,50\text{-}2500}$
Total number of concepts	3 x 5 = 15	3 x 9 = 27	2 x 3 = 6
Number of concepts applied – based on survey, cf [1], in 24 countries in Europe	BC: 8 of 15 CS: 5 of 15 BC+CS in total: 9 of 15	Facades not fully included in survey	BC: 4 of 6 CS: 3 of 6 In total: 4 of 6
Number of countries, cf [1], applying spectrum adaptation terms in a BC or a CS	BC: 5 (1 lf) of 24 countries CS: 9 (7 lf) of 9 schemes	Some countries apply spectrum adaptation terms in BCs	BC: 2 (1 lf) of 24 countries CS: 7 (6 lf) of 9 schemes
BC = Building Code (legal requirements); CS = Classification scheme; lf = low-frequency			

Table 2: Relevant spectrum adaptation term for different types of noise sources.

Type of noise source	**Relevant spectrum adaptation term**
Living activities (talking, music, radio, tv) Children playing Railway traffic at medium and high speed (1) Highway road traffic > 80 km/h (1) Jet aircraft short distance Factories emitting mainly medium and high frequency noise	**C** (Spectrum 1: A-weighted pink noise)
Urban road traffic Railway traffic at low speeds (1) Aircraft propeller driven Jet aircraft large distance Disco music Factories emitting mainly low and medium frequency noise	**C_{tr}** (Spectrum 2: A-weighted urban traffic noise)
(1) In several European countries calculation models for highway road noise and railway noise exist, which define octave band levels; these could be used for comparison with spectra 1 and 2.	

Ref.: Table A.1 from ISO 717-1:1996. The spectra 1 and 2 are defined in ISO 717-1.

In Tables 3, 4 and 5 are found the names of single-number quantities, the terms they are derived from, and a reference to a definition in the relevant standard. Equations are found in Section 3.2.

Table 3: Single-number quantities for airborne sound insulation between rooms in building.

Single-number quantities for airborne sound insulation between rooms in buildings				
Single-number quantity (100-3150 Hz)		1/3- or 1/1-octave band values		
Term	Symbol	Term	Symbol	Defined in
Weighted apparent sound reduction index	R'_w	Apparent sound reduction index	R'	ISO 140-4:1998; equation (6)
Weighted normalized level difference	$D_{n,w}$	Normalized level difference	D_n	ISO 140-4:1998; equation (3)
Weighted standardized level difference	$D_{nT,w}$	Standardized level difference	D_{nT}	ISO 140-4:1998; equation (4)

Table 4: Single-number quantities for airborne sound insulation of facades in buildings

Single-number quantities for airborne sound insulation of facades				
Single-number quantity (100-3150 Hz)		1/3- or 1/1-octave band values		
Term	Symbol	Term	Symbol	Defined in
Weighted apparent sound reduction index	$R'_{45°,w}$	Apparent sound reduction index	$R'_{45°}$	ISO 140-5:1998; equation (3)
Weighted apparent sound reduction index	$R'_{tr,s,w}$	Apparent sound reduction index	$R'_{tr,s}$	ISO 140-5:1998; equation (4)
Weighted normalized level difference	$D_{ls,2m,n,w}$	Normalized level difference	$D_{ls,2m,n}$	ISO 140-5:1998; equation (7)
Weighted normalized level difference	$D_{tr,2m,n,w}$	Normalized level difference	$D_{tr,2m,n}$	ISO 140-5:1998; equation (7)
Weighted standardized level difference	$D_{ls,2m,nT,w}$	Standardized level difference	$D_{ls,2m,nT}$	ISO 140-5:1998; equation (6)
Weighted standardized level difference	$D_{tr,2m,nT,w}$	Standardized level difference	$D_{tr,2m,nT}$	ISO 140-5:1998; equation (6)

Table 5: Single-number quantities for impact sound insulation between rooms in buildings.

Single-number quantities for impact sound insulation between rooms in buildings				
Single-number quantity (100-3150 Hz)		1/3- or 1/1-octave band values		
Term	Symbol	Term	Symbol	Defined in
Weighted normalized impact sound pressure level	$L'_{n,w}$	Normalized impact sound pressure level	L'_n	ISO 140-7:1998; equation (2)
Weighted standardized impact sound pressure level	$L'_{nT,w}$	Standardized impact sound pressure level	L'_{nT}	ISO 140-7:1998; equation (3)

Note: All ISO standards mentioned in this paper are also EN standards and thus implemented in the CEN member countries, which are the before-mentioned 23 countries and in addition Cyprus, Greece, Ireland, Luxembourg and Malta.

Although implemented in all CEN countries, ISO 717 field concepts are not necessarily applied in all national building regulations, e.g. national concepts $I_{lu;k}$ and I_{co} are applied in the Netherlands. Only products subject to free trade must apply concepts defined in the harmonized standards.

The above considerations concern concepts as defined in ISO 717. USA and Canada use ASTM standards, defining slightly different single-number quantities and no spectrum adaptation terms. For airborne sound the ASTM-method differs in two main aspects: Frequency range 125-4000 Hz and the 8 dB rule is included. The ASTM rating procedure for impact sound insulation is also similar to the ISO procedure, but again ASTM applies the 8 dB rule. For further information about the ASTM impact sound ratings, see [12, 13]. Japan has partly incorporated ISO standards in the Japanese standards, but they are seldom used in the field, see [14] for an overview of building acoustic standards in Japan.

3.2 Equations for sound insulation field properties

Check of compliance with requirements may be made by carrying out field tests in the finished building. The equations to be applied, when testing sound insulation in buildings are found in Tables 6, 7, 8. The evaluation concepts are found in Tables 3, 4 and 5.

The property to be measured in a specific situation is specified in the legal requirements or by the builder. The test results are to be compared with the limits, and the test methods are defined in the standards. Thus, it should be simple. However, in practice there are several precautions to take to ensure reliable sound insulation measurement results. Examples on questions and situations are:

What if S does not exist? (no common area)
Rooms with a small common partition area?
Irregular rooms?
Long and narrow rooms?
Shifted rooms?
Staggered rooms?
Partly divided rooms?
Extremely complicated room geometry?
Large rooms?
Big differences in room volumes?
Loudspeaker positions in the source room?
Tapping machine positions?
Microphone positions for SPL measurements in the source room and in the receiving room?
Which source and microphone positions to apply for T measurements?
What about low frequencies?

Concerning facade sound insulation measurements, there are some additional questions:
Which source to use? Traffic (road, rail, air) or loudspeaker?
If loudspeaker is used, which position to use and how to arrange it?
Outdoor microphone positions?

Due to severe difficulties in the field, a whole set of guidelines have been made and published in ISO 140-14, which is to be applied in combination with ISO 140-4 and ISO 140-7. Below are found some quotes from ISO 140-4 and from ISO 140-14.

ISO 140-4 Clause 3.4

NOTE 1 The standardizing of the level difference to a reverberation time of 0,5 s takes into account that in dwellings with furniture the reverberation time has been found to be reasonably independent of the volume and of frequency and to be approximately equal to 0,5 s. With this standardizing, D_{nT} is dependent on the direction of the sound transmission if the two rooms have different volumes.

ISO 140-4 Clause 3.5

In the case of staggered or stepped rooms, S is that part of the area of the partition common to both rooms. If the common area is less than 10 m², indicate this in the test report. S is then calculated by max. (S, V/7,5), where V is the volume of the receiving room (which is the smaller room in this case).
In this case that no common area exists, the normalized level difference D_n is determined.

ISO 140:14 Clause 1

NOTE The basic standards ISO 140-4 and ISO 140-7 specify the measurement procedure in detail under ideal conditions, but give only little information on how to establish a suitable measurement set-up in rooms differing from simple box-shaped rooms of normal living room size. When it comes to very large rooms, long and narrow rooms, staircases, coupled rooms, etc., no guidance is given in the basic standards, which is why the guidelines in this part of ISO 140 have been prepared. Use of the guidelines will contribute to improvement in the reproducibility of building acoustics field measurements and, furthermore, facilitate the performance of measurements by avoiding time-consuming considerations in actual measurement situations.

ISO 140:14 Clause 3

Notice that in two situations the guidelines might be in conflict with the basic standards. These situations are explained as follows …………………

ISO 140-14 has 5 Annexes with guidelines aiming at more reliable measurements measurements according to ISO 140-4 and ISO 140-7.

The extent of the guidelines indicates how important it is to choose concepts for building regulations that reduce the difficulties as much as possible, of course also taking into account the importance of correlation with subjective evaluation.

Table 6: Airborne sound insulation between rooms in buildings - Definitions of properties.

Airborne sound insulation - Definitions of field properties according to ISO 140-4:1998	
Equations	Explanations of symbols
(6) $R' = L_1 - L_2 + 10\ lg\ (S/A)\ dB$ (3) $D_n = L_1 - L_2 - 10\ lg\ (A/A_o)\ dB$ (4) $D_{nT} = L_1 - L_2 + 10\ lg\ (T/T_o)\ dB$ Note: Names of the properties and the corresponding single-number quantities are found in table 3.	L_1 is the average SPL in the source room L_2 is the average SPL in the receiving room S is the area of the separating element A is the equivalent sound absorption area in the receiving room A_0 is the reference absorption area, in square metres; A_0 = 10 m^2 T is the reverberation time in the receiving room T_0 is the reference reverberation time; for dwellings, T_0 = 0,5 s $A = 0,16\ V/T$

Table 7: Airborne sound insulation of facades in buildings - Definitions of properties.

Airborne sound insulation - Definitions of field properties according to ISO 140-5:1998	
Equations	Explanations of symbols
(3) $R'_{45°} = L_{1,s} - L_2 + 10\ lg\ (S/A) - 1,5\ dB$ (4) $R'_{tr,s} = L_{eq,1,s} - L_{eq,2} + 10\ lg\ (S/A) - 3\ dB$ (7) $D_{2m,n} = L_{1,2m} - L_2 - 10\ lg\ (A/A_o)\ dB)\ dB$ (6) $D_{2m,nT} = L_{1,2m} - L_2 + 10\ lg\ (T/T_o)\ dB$ Note: Names of the properties and the corresponding single-number quantities are found in table 4. Note: In ISO 140-5, Table 1, is found an overview of different measurement methods corresponding to different sound sources (loudspeaker a well as road, railway and air traffic). Guidelines for positioning of loudspeaker and outdoor microphone are also found in ISO 140-5.	$L_{1,s}$ is the average SPL on the surface of the test specimen L_2 is the average SPL in the receiving room $L_{eq,1,s}$ is the average value of the equivalent continuous SPL on the surface of the test specimen including reflecting effects from the test specimen and facade $L_{eq,2}$ is the average value of the equivalent continuous sound pressure level in the receiving room $L_{1,2m}$ is the outdoor SPL 2 m in front of the facade S is the area of the test specimen, determined as given in annex A A is the equivalent sound absorption area in the receiving room A_0 is the reference absorption area, in square metres; A_0 = 10 m^2 T is the reverberation time in the receiving room T_0 is the reference reverberation time; for dwellings, T_0 = 0,5 s $A = 0,16\ V/T$

Table 8: Impact sound insulation between rooms in buildings - Definitions of properties.

Impact sound insulation - Definitions of field properties according to ISO 140-7:1998	
Equations	Explanations of symbols
(2) $L'_n = L_i + 10\ lg\ (A/A_o)\ dB$ (3) $L'_{nT} = L_i - 10\ lg\ (T/T_o)\ dB$ Note: Names of the properties and the corresponding single-number quantities are found in table 5.	Impact sound pressure level, L_i, is the average SPL i in the receiving room when the floor under test is excited by the standardized impact source; it is expressed in decibels. A is the equivalent sound absorption area in the receiving room A_0 is the reference absorption area, in square metres¸ A_0 = 10 m^2 T is the reverberation time in the receiving room T_0 is the reference reverberation time; for dwellings, T_0 = 0,5 s $A = 0,16\ V/T$

3.3 Overall suitability

Based on the single-number quantities and spectrum adaptation terms found in Table 1, the ISO 717 concepts are listed in Table 9. However, most $D_{n,w}$-based concepts are omitted (due to only one known case of application in Europe), and $D_{nT,w}$ + C_{tr} is included for airborne sound insulation between dwellings, as this concept has been introduced in the legal requirements in UK (and Australia).

As a basis for future discussions and assessment of the overall suitability of the different concepts, it has been considered useful to rank each concept in Table 10 concerning the following three aspects:

Suitable: Correlate well with subjective evaluation
Well-defined: All parts of the equation should exist
Reproducible: Low measurement uncertainty; how to evaluate compliance with requirements

The ranking of "S", "W" and "R" has been estimated by the authors using an arbitrary scale, intended to reach from - - - to +++, although it is obvious from the results that the lower end of the scale is unused.

First the suitability is considered, i.e. the degree of correlation with subjective evaluation. This is discussed in greater detail in section 4, which also gives reference to various investigations in this field. In general it is found that the inclusion of low frequencies down to 50 Hz greatly improves the correlation with subjective evaluation and thus the suitability. On the other hand, there seems to be no additional benefit from applying the extended frequency range up to 5 kHz, implying that those C- and C_{tr}-terms might be removed. For impact sound, some countries have decided to apply only positive values of $C_{i,}$, thus adding a special rule.

Secondly, the concepts should be well defined. This is obvious, but still some widely used concepts like R'_w have significant problems in cases, where there is no common surface between the rooms, or where the common surface area is less than 10 m^2. For impact sound, some countries like Sweden and Norway have recently introduced special volume limits to $L'_{n,w}$, because this concept does not perform well in case of large receiving room volumes. This means that $L'_{nT,w}$ may be more suitable, although both concepts are well-defined.

Finally, the measurement uncertainty (reproducibility) is considered. When the frequency range is increased to include low frequencies down to 50 Hz, this increases the measurement uncertainty. In addition, measurements with loudspeakers may be more difficult, when applying the extended frequency range down to 50 Hz.

For a very rough assessment of the overall suitability, the total ranking is found by adding up the three rankings as shown in the next column in Table 9.

The two last columns indicate which concepts are in use in the 24 countries, cf Section 3.1 and [1], for legal requirements and for classification schemes. The low-frequency descriptors have been introduced in all 5 Nordic countries and in Lithuania, but in no other countries. The low-frequency terms are included in the legal minimum requirements in Sweden and in the criteria for the higher, voluntary quality classes in the classification schemes in all 6 countries. The importance of including low frequencies for impact sound is also emphasized in [12, 13, 17 18]. The Nordic schemes are based on a common Nordic draft, [19], following several investigations, e.g. [20, 21, 22]. A list of all European schemes is found in Section 4, Table 12. An overview of the main characteristics of the schemes existing in 2003 is found in [23]. For updated information, see [24, 25, 26, 27, 28, 29, 30, 31, 32] The different classes in classification schemes are intended to reflect different levels of acoustical comfort. Taking into account also economical factors, different classes in the same scheme may apply different concepts. Some considerations concerning the choice of concepts for new legal requirements and classification have been described in [33].

For years, there have been discussions about the sufficiency or insufficiency of the ISO tapping machine, and alternative sources, e.g. rubber balls, have been proposed. However, it seems as if the main problem might be, cf [18], that the low-frequency energy actually produced by the tapping machine is ignored in most countries. Sweden is the only country applying $C_{i,50-2500}$ for legal requirement, see also Table 1 and 9.

Concerning facade sound insulation requirements, there is a variety of ways to express these. Several countries specify the required sound insulation of facades as a function of the outdoor noise level (often in quite rough 5 dB steps), in some countries with different day and night requirements. Other countries require the indoor level $L_{A,eq,24h}$ to be below a certain limit, and there may be additional maximum limits for "events". In addition, the methods for determination of the exterior noise exposure vary considerably. In some countries there are no general, legal sound insulation national requirements, but only local. In total, the situation is quite complex. On a European level the environmental noise directive 2002/49/EC, see [34], defines two main indicators, L_{den} and L_{night} for description of annoyance and sleep disturbance, respectively. Future criteria for facades should be expressed by these harmonised environmental noise indicators.

The ultimate goal for concepts must be a high correlation between prediction, measurement results and subjective evaluation.

Table 9: Overview concepts for evaluation of sound insulation and "ranking"

Concepts for evaluation of sound insulation - Estimated ranking for further discussion								
Sound insulation concepts-			Suitable (*) (Correl. with subj. eval.)	Well-defined (*)	Repro-ducible (*)	Overall suitability S+W+R	Info (2) BC	Info (2) CS
Airborne sound insulation between dwellings								
ISO 717-1	R'_w		0	–	+	0	✓	✓
	$R'_w + C$		+	–	+	+1	✓	
	$R'_w + C_{50\text{-}3150}$		+ + +	–	–	+1	✓	✓
	$R'_w + C_{100\text{-}5000}$	(3)	+	–	0	0		
	$R'_w + C_{50\text{-}5000}$	(3)	+ + +	–	–	+1		
	$D_{n,w}$	(4)	0	+	+	+2	✓	
	$D_{nT,w}$		0	+	+	+2	✓	✓
	$D_{nT,w} + C$		+	+	+	+3	✓	✓
	$D_{nT,w} + C_{50\text{-}3150}$		+ + +	+	–	+3		✓
	$D_{nT,w} + C_{100\text{-}5000}$		+	+	0	+2	✓	
	$D_{nT,w} + C_{50\text{-}5000}$	(3)	+ + +	+	–	+3		
	$D_{nT,w} + C_{tr}$	(6)	+ + ?	+	0	+3?	✓	
Airborne sound insulation of facades (1), (5)			**tr / ls**	**tr / ls**	**tr / ls**	**tr / ls**		
ISO 717-1	R'_w		0 / –	0 / 0	0 / +	0 / 0	(7)	
	$R'_w + C_{tr}$		+ / 0	0 / 0	0 / +	+1 / 0		
	$R'_w + C_{tr,50\text{-}3150}$		+ + / +	0 / 0	– / –	+1 / 0		
	$R'_w + C_{tr,100\text{-}5000}$		+ / 0	0 / 0	0 / +	+1 / 0		
	$R'_w + C_{tr,50\text{-}5000}$		+ + / +	0 / 0	– / –	+1 / 0		
	$D_{nT,w}$		0 / –	+ / +	0 / +	+1 / +1		
	$D_{nT,w} + C_{tr}$		+ / 0	+ / +	0 / +	+2 / +2		
	$D_{nT,w} + C_{tr,50\text{-}3150}$		+ + / +	+ / +	– / –	+2 / +1		
	$D_{nT,w} + C_{tr,100\text{-}5000}$		+ / 0	+ / +	0 / +	+2 / +2		
	$D_{nT,w} + C_{tr,50\text{-}5000}$		+ + / +	+ / +	– / –	+2 / +1		
Impact sound insulation between dwellings								
ISO 717-2	$L'_{n,w}$		–	+	+	+1	✓	✓
	$L'_{n,w} + C_i$	(3)	0	+	0	+1		
	$L'_{n,w} + C_{i,50\text{-}2500}$		+ +	+	–	+2	✓	✓
	$L'_{nT,w}$		0	+	+	+2	✓	
	$L'_{nT,w} + C_i$		+	+	0	+2	✓	✓
	$L'_{nT,w} + C_{i,50\text{-}2500}$	(3)	+ + +	+	–	+3		

(*) Suitable: Correlate with subjective evaluation
Well-defined: All parts of the equation should exist
Reproducible: Measurement uncertainty should be low; easy to evaluate compliance with requirements

(1) tr = measurement with traffic; ls = measurement with loudspeaker

(2) Information about application in Europe (at least one of 24 countries)
BC = Building Code (legal requirements); CS = Classification scheme

(3) Concept not applied in any of the 24 European countries included in [1].

(4) Only $D_{n,w}$ included, although it could be combined with the C-terms (as for $D_{nT,w}$).
$D_{n,w}$ is applied in only one country in Europe, [1], and there is no evidence that this concept is preferable.

(5) Neither $D_{n,w}$ nor combinations with terms C_{tr} terms have been included, since they are not used and not preferable. For simplicity, all basic concepts R'_w , $D_{n,w}$, $D_{nT,w}$ with C-terms have not been shown, as they have been considered secondary compared to concepts including C_{tr}-terms.

(6) $D_{nT,w} + C_{tr}$ included due to application in UK.

(7) Facades not fully included in survey, implying that an overview is not yet available.

4 The importance of correlation with subjective evaluation

Information has been gathered from social surveys and from laboratory experiments on the dose-response functions for noise annoyance in relation to acoustical comfort, see [35, 36]. For all the relevant sources of noise in dwellings it is found that the dose-response relationship has a slope of approximately 4% per dB on the middle part of the regression line, i.e. between 20% and 80% annoyed or satisfied persons.

At the Technical University of Denmark a laboratory experiment has been carried out to investigate systematically the influence of low-frequency content in noise from neighbours [36]. Three sound signals were used: Music from a neighbouring room, footfall noise from a male walker in the room above and from two children running in the room above. Based on the results of this investigation it has been concluded that the use of the spectrum adaptation terms down to 50 Hz imply a significantly improved correlation between subjective and objective evaluation of sound insulation for airborne as well as impact sound insulation between dwellings. Other researchers have come to a similar conclusion; e.g. Warnock [12] who compared objective and subjective evaluation of impact noise from about 190 floors.

From the previously reported investigations of surveys on noise from neighbours it is possible to derive approximate relationships between the acoustic conditions and the expected percentage of people finding the conditions good or satisfactory, see Table 10. As an example the minimum requirements could be given as $R'_w + C_{50\text{-}3150} \geq 53$ dB and this can be estimated to give satisfactory conditions for approximately 40 %. However, if a sound classification is introduced, the higher classes could typically correspond to 60 % and 80 % satisfied people, see Table 11.

Classification schemes exist in 9 countries in Europe, se Table 12. The different classes are intended to reflect different levels of acoustic comfort, and the Nordic schemes include low-frequency adaptation terms, see also Section 3.3.

Several investigations have shown that the low-frequency sound insulation of dwellings is important for the acoustical comfort. As an alternative to the extended frequency range needed for the spectrum adaptation term $C_{50\text{-}3150}$, it has been suggested to keep the frequency range 100–3150 Hz, but apply the spectrum adaptation term for traffic noise C_{tr}. These two different procedures have been compared for typical examples of heavy and light-weight wall constructions, the latter (double gypsum) having rather poor sound insulation at low frequencies, see Table 11. Data are from [20]. While the 50 Hz adaptation term can make a significant difference in $C_{50\text{-}3150}$ between the two groups of constructions (around 9 dB in average), this difference is not so clear in the case of the traffic noise adaptation term (around 3 dB in average). Thus, it seems from these examples that C_{tr} cannot compensate for the extended frequency range in $C_{50\text{-}3150}$. It should be noted that the introduction of C_{tr} means a general shift of the values for sound insulation by approximately -5 dB, keeping the performance of heavy constructions (100-3150 Hz) as a reference.

Table 10: Relation between acoustic sound insulation design criteria for dwellings and the expected percentage of people finding the conditions satisfactory.

% finding conditions satisfactory	Airborne sound insulation $R'_w + C_{50\text{-}3150}$	Impact sound pressure level $L'_{n,w} + C_{i,50\text{-}2500}$
20 %	48 dB	63 dB
40 %	53 dB	58 dB
60 %	58 dB	53 dB
80 %	63 dB	48 dB

Table 11: Comparison of spectrum adaptation terms $C_{50\text{-}3150}$ and C_{tr} for typical heavy and light-weight walls. In each case min and max values are given.

Spectrum adaptation term	Heavy constructions	Light-weight constructions	Difference Heavy-Light
$C_{50\text{-}3150}$	-1 dB	-8 dB	7 dB
	-2 dB	-14 dB	12 dB
C_{tr}	-4 dB	-7 dB	3 dB
	-6 dB	-10 dB	4 dB

Table 12: European schemes for sound classification of dwellings.

European schemes for sound classification of dwellings (May 2005)			
Country	Class denotations	Year of implementation	Reference
Denmark	D / C / B / A	2001	[24] DS 490 (2001)
Norway	D / C / B / A	1997/2005	[25] NS 8175 (2005)
Sweden	D / C / B / A	1996/1998/2004	[26] SS 25267 (2004)
Finland	D / C / B / A	2004	[27] SFS 5907 (2004)
Iceland	D / C / B / A	2003	[28] IST 45 (2003)
Germany - VDI	I / II / III	1994	[29] VDI 4100 (1994)
France	QL / QLAC	1993/1995/2000	[30] Guide Qualitel (2000)
Netherlands	5 / 4 / 3 / 2 / 1	1999	[31] NEN 1070 (1999)
Lithuania	E / D / C / B / A	2004	[32] STR 2.01.07 (2003)

5 From chaos to consensus?

The current evaluation methods as based on ISO 717 offer a great variety of options, many of which have also been adopted in various countries. This means that in recent years the development of evaluation methods for sound insulation has been the opposite of harmonization. However, based on the discussion above it may be possible to give some recommendations for the future development.

Because the building technology may gradually change over time, many countries have realised that it is important to have an evaluation system that can work equally well for heavy and light weight constructions. So, a good correlation with the subjective evaluation of the sound insulation is very important, and several investigations have concluded that this can only be achieved by extending the frequency range below 100 Hz. Thus, looking at the overall suitability as discussed above, the following concepts are recommended for harmonization in the future:

Airborne sound insulation between dwellings:

$D_{nT,w} + C_{50\text{-}3150}$

Airborne sound insulation of facades:

$D_{nT,w} + C_{50\text{-}3150}$

$D_{nT,w} + C_{tr,50\text{-}3150}$

Impact sound insulation between dwellings:

$L'_{nT,w} + C_{i,50\text{-}2500}$

However, it is important to realize that in a longer perspective the current methods in ISO 717 may be inappropriate, and there is a need for actions and further investigations. The following topics can be suggested:

- Collect information about the reasons for national, special rules made in addition to a “clean” application of the ISO concepts.
- For airborne sound insulation, remove those C- and C_{tr}-terms extended to 5000 Hz, thus reducing the number of terms to the half.
- Improve measurement methods, especially in the low frequency range 50-100 Hz.
- Investigate the influence of the receiving room volume and reverberation time on the subjective evaluation of sound insulation (both airborne and impact).
- Optimize noise spectra for evaluation of airborne sound insulation - both noise from neighbours and traffic noise.
- Investigate how to define facade sound insulation requirements based on mapping values using the European outdoor noise indicators L_{den} and L_{night}.
- Clarify, whether the ISO tapping machine is sufficiently good for impact sound measurements, or if an alternative source or technique is needed.
- Is it possible to derive new evaluation methods with better correlation with subjective evaluation by implementing results from psychoacoustics, e.g. loudness?

A comment to the last point is that by introducing more advanced signal processing, the benefit might be better and more reliable concepts in building acoustics. Loudness can be calculated from third-octave band measurements according to method B in ISO 532, [37]. This procedure specifies the third-octave bands below 200 Hz to be combined into broader bandwidths, which may prove advantageous compared to 1/3 octave measurement results, when considering the measurement uncertainty at low frequencies.

6 Concluding remarks

This paper is intended to provide input for discussions in the working group EAA TC-RBA WG4: "Sound insulation requirements and sound classification - Harmonization of concepts", [38] aiming at harmonization of concepts for legal requirements and classification criteria in Europe. The working group has been established in order to gather information and share experience more systematically.

EAA TC-RBA WG4 is a working group under the European Acoustical Association (EAA), Technical Committee Room and Building Acoustics (TC-RBA).

References

[1] Birgit Rasmussen, "*Sound insulation between dwellings- Classification schemes and building regulations in Europe*", InterNoise 2004, Prague, Czech Republic. Paper ID 778.

[2] ISO 717, Acoustics - Rating of sound insulation in buildings and of buildings elements
– Part 1: Airborne sound insulation, 1996
– Part 2: Impact sound insulation, 1996

[3] Philip Wright, Les Fothergill, *"The Spectrum Adaption Terms in BS EN ISO 717-1:1997"*. Acoustic Bulletin Nov. / Dec. 1998.

[4] Matthew J. Patterson, *"Recent Changes to the Sound Insulation Provisions of the Building Code of Australia",* Professional Services, Australian Building Codes Board, Canberra, Australia. Acoustics Forum, 2004.

[5] ISO/R 717:1968, Rating of sound insulation for dwellings, (First edition, 7 pages).

[6] K. Gösele, "*Zur Bewertung der Schalldämmung von Bauteilen nach Sollkurven*", Acustica Vol. 15, 1965, p 264-270.

[7] W. Fasold, *"Untersuchungen über den Verlauf der Sollkurve für den Trittschallschutz im Wohnungsbau*", Mitteilung aus dem Institut für Elektro- und Bauakustik der Technischen Universität, Dresden. Acustica Vol. 15, 1965, p. 271-284.

[8] ISO/R 140:1960, Field and laboratory measurements of airborne and impact sound transmission, (First edition, 11 pages).

[9] ISO 717, Acoustics - Rating of sound insulation in buildings and of buildings elements
– Part 1: Airborne sound insulation in buildings and of interior building elements, 1982
– Part 2: Impact sound insulation, 1982
– Part 3: Airborne sound insulation of facade elements and facades, 1982

[10] ISO 140:1978, Acoustics – Measurement of sound insulation in buildings and of building element, Parts I, II, III, IV, V, VI, VII, VIII; extended by part 9 in 1985 and part 10 in 1991 (Parts I-VIII revised 1991-1998, see [11]).

[11] ISO 140, Acoustics – Measurement of sound insulation in buildings and of building elements
– Part 1: Requirements for laboratory test facilities with suppressed flanking transmission, 1998
– Part 2: Determination, verification and application of precision data, 1991
– Part 3: Laboratory measurements of airborne sound insulation of building elements, 1995.
– Part 4: Field measurements of airborne sound insulation between rooms, 1998
– Part 5: Field measurements of airborne sound insulation of façade elements and façades, 1998
– Part 6: Laboratory measurements of impact sound insulation of floors, 1998
– Part 7: Field measurements of impact sound insulation of building elements, 1998
– Part 8: Laboratory measurements of the reduction of transmitted impact noise by floor coverings on a heavyweight standard floor, 1997.
– Part 9: Laboratory measurements of room-to-room airborne sound insulation of a suspended ceiling with a plenum above, 1985.
– Part 10: Laboratory measurements of room-to-room airborne sound insulation of a suspended ceiling with a plenum above it, 1991.
– Part 11: Laboratory measurements of the reduction of transmitted impact noise by floor
– Part 12: Laboratory measurements of room-to-room airborne and impact sound insulation of an access floor, 2000.
– Part 13: Guidelines, ISO/TR 140-13:1997
– Part 14: Additional requirements and guidelines for special situations in the field, ISO/TR 140-13:1997

[12] A.C.C. Warnock, *"Floor Research at NRC Canada*", Conference in Building Acoustics "Acoustic Performance of Medium-Rise Timber Buildings", Dec. 3-4, Dublin, Ireland. 1998.

[13] Warnock, A (2004), *"Impact sound ratings: ASTM versus ISO"*. InterNoise2004, Prague, CZ. PaperID 694.

[14] Konasu, Yoshimura, Tachibana (2004) *"Building acoustics classifications for sound insulation in Japan"*. InterNoise2004. PaperID 773.

[15] ISO 10848, Acoustics – Laboratory measurement of the flanking transmission of airborne and

impact noise between adjoining rooms
– Part 1: Frame document, 2005
– Part 2: Application to light elements when the junction has a small influence, 2005
– Part 3: Application to light elements when the junction has a substantial influence, 2005
– Part 4: All other cases. ISO/CD 2004

[16] EN 12354, Building Acoustics – Estimation of acoustic performance of buildings from the performance of elements (4 parts, 2000)
– Part 1: Airborne sound insulation between rooms (2000)
– Part 2: Impact sound insulation between rooms (2000)
– Part 3: Airborne sound insulation against outdoor sound (2000)

[17] Bodlund, K. (1985): "*Rating of impact sound insulation between dwellings*", Technical Report SP-RAPP 1985-01 Includes the article: "*Alternative reference curves for evaluation of the impact sound insulation between dwellings*", Journal of Sound and Vibration **102**(3), pp. 381-402, 1985.

[18] Blazier, W.E., DuPree, R.B. (1994): "Investigation of low-frequency footfall noise in wood-frame, multifamily building construction." J. Acoustic. Soc. Am. **96** (3), pp. 1521-1532.

[19] INSTA 122, *"Sound classification of dwellings"* Revised Final DP INSTA 122, Aug. 1998.

[20] Hagberg, K. (1996), "*Ljudkrav med stöd av ISO/DIS 717*" (Acoustic requirements supported by ISO/DIS 717). NKB Committee and Work Reports 1996:02. Nordic Committee on Building Regulations, Helsinki, Finland.

[21] Hveem, Homb, Hagberg, Rindel (1996), *"Low-frequency footfall noise in multi-storey timber buildings"* NKB Report 1996:12E. Nordic Committee on Building Regulations, Finland.

[22] Rasmussen, B. (1996), "*Implementation of the new ISO 717 building acoustic rating methods in Europe"*. NKB Report 1996:04E. Nordic Committee on Building Regulations, Finland.

[23] Rasmussen, B., "*Sound insulation of dwellings - Overview of classification schemes in Europe*". EuroNoise 2003, Naples, Italy. Paper ID 547.

[24] DS 490, 2001, *"Lydklassifikation af boliger"*. (Sound classification of dwellings), Denmark.

[25] NS 8175:2005, *"Lydforhold i bygninger, Lydklassifisering av ulike bygningstyper"* (Sound conditions in buildings - Sound classes for various types of buildings), Norway.

[26] SS 25267:2004, "Byggakustik – Ljudklassning av utrymmen *i byggnader – Bostäder"*. (Acoustics – Sound classification of spaces in buildings – Dwellings). Sweden.

[27] SFS 5907:2004, *"RAKENNUSTEN AKUSTINEN LUOKITUS"* (Acoustic classification of spaces in buildings), Finland.

[28] IST 45:2003, "*Acoustics - Classification of dwellings*", Iceland.

[29] VDI 4100:1994, "*Schallschutz von Wohnungen - Kriterium für Planung und Beurteilung*", Germany.

[30] *"La méthode qualitel"*, 2000, Association Qualitel, France.

[31] NEN 1070:1999, "*Geluidwering in gebouwen – Specificatie en beoordeling van de kwaliteit"* (Noise control in buildings – Specification and rating of quality), The Netherlands.

[32] STR 2.01.07 (2003). Dél Statybos Techninio Reglamento Str 2.01.07:2003, "*Pastatu Vidaus Ir Isores Aplinkos Apsauga Nuo Triuksmo*" (Lithuanian building regulations. Protection against noise in buildings). Patvirtinimo, Lithuania.

[33] A. Jagniatinskis, B. Fiksa, "*Application of different descriptors for in situ sound insulation*". InterNoise2004. PaperID 609.

[34] Europe - Environment - Noise Policy, http://www.europa.eu.int/comm/environment/noise/home.htm

[35] Rindel, J. H. (1999), "*Acoustic quality and sound insulation between dwellings"*. Journal of Building Acoustics 5, 291-301.

[36] Rindel (2003), "*On the influence of low frequencies on the annoyance of noise from neighbours*", InterNoise 2003, Korea, 2003. PaperID N1038.

[37] ISO 532:1975, Method for calculating loudness level.

[38] EAA TC-RBA WG4, "*Sound insulation requirements and sound classification – Harmonization of concepts"*. See: http://www.eaa-fenestra.org/TCs/RBA/Workgroups/WG4. European Acoustical Association (EAA), Technical Committee Room and Building Acoustics (TC-RBA).