Applied Acoustics 129 (2018) 204–216

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Translation between existing and proposed harmonized impact sound insulation descriptors and alignment within a proposed common acoustic classification scheme for buildings

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ARTICLE INFO

Article history:
Received 18 May 2017
Received in revised form 28 July 2017
Accepted 31 July 2017

Keywords:
Building regulations
Descriptors
Impact sound insulation requirements
Acoustic classification scheme

ABSTRACT

An international standard defining a common acoustic classification scheme for dwellings is under development by ISO TC43/SC2/WG29, based on the outcomes of the European project COST Action TU0901. The proposal offers an opportunity for countries to establish building acoustic requirements using a harmonized set of descriptors. This harmonized set considers the possibility of using impact sound insulation descriptors including the impact spectrum adaptation term C_I or not. Furthermore, it also considers the possibility of using different frequency ranges for the impact spectrum adaptation term, C_{I50} and C_{I100}. In order to evaluate the potential effect of such changes, it is necessary to provide translation equations between existing and proposed harmonized descriptors.

The main objective of this paper is to provide, based on a statistical analysis of a large experimental data set, a translation equation for each pair (existing/proposed) of selected impact sound insulation descriptors. Additionally, the paper aims at investigating if the obtained translation equations are independent of the building type, so the same statistical analysis has been performed with two separated databases including either only heavy floors or only light floors. From the first results, it is concluded that the obtained translation equations are dependent on the building type when different assessment frequency range and rating methods are considered in both descriptors.

In spite of this conclusion and in order to provide a tool for estimating the potential consequences of adopting a different impact sound insulation descriptor, the existing impact sound insulation national requirements have been translated into two proposed harmonized descriptors ($L'_{nT,w}$ and $L'_{nT,50}$) using the translation equation obtained using the full data set, that is, not considering the building type. Additionally, the translated requirements have been aligned within the acoustic classification scheme, which is being developed by ISO TC43/SC2/WG29. The results show that, if the proposed common acoustic classification scheme is adopted, the existing requirements would lie, as expected, mainly within classes C and D, although, in some countries with more permissive requirements, the new built dwellings would be ranked class E or even class F. There is only one country where the requirements are such that the new build dwellings would be classified as B, concerning impact sound performance.

1. Introduction

The protection against noise, either outdoors or in the built environment, is being increasingly demanded by experts and society. One of the main reasons of that is the negative effects of noise, whether biological or not [1–4]. The protection of citizens' health in the field of building acoustics is covered by national regulations, but there is a growing demand for obtaining better levels of acoustic comfort. Several European countries have developed their own Acoustic Classification Scheme for buildings which all include, among other characteristics, the airborne and impact sound insulation performance of the built space. These schemes define acoustic classes according to different levels of sound insulation. Due to the lack of coordination among countries, there is a significant diver-

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http://dx.doi.org/10.1016/j.apacoust.2017.07.025
0003-682X/

sity in terms of descriptors, number of classes, and class intervals between national schemes [5].

ISO 717-2 [6] describes a standardized procedure for assessing impact sound insulation. Nevertheless, this assessment procedure has been discussed and researched since over half a century. The critical issues have been similar over the years: How well does a single number quantity (SNQ) correspond to the subjective judgment of different types of noise? Which of the many existing and proposed reference curves deliver a most adequate SNQ, if subjective judgment is considered? Should new impact sources be introduced to measure and assess impact sound insulation? Which assessment frequency range is most adequate? Can a spectrum adaptation index adequately reflect low frequency effects?

Over the years, rating methods have been modified [7–10], new impact sources have been considered [11–13] (i.e. soft impact sources such as the rubber ball, bang machine...), new descriptors have been introduced (i.e. impact sound pressure level) [14,15], the impact spectrum adaptation term (C_I) has been investigated and different assessment frequency ranges have been used [16–18]. The debate is still ongoing in the 21st century (see chapter 2 in [19]).

On top of the aforementioned changes, one more reason for the ongoing debate is the fact that impact sound insulation can be assessed using many different SNQs as already pointed out by some authors [20] and thus there is a widespread of sound insulation descriptors and requirements used around the world [20]. Aiming at harmonizing, improving sustainability and simplifying the understanding of the acoustic performance of a building, the European project COST TU0901 delivered both a proposal for harmonized sound insulation descriptors and an Acoustic Classification Scheme (ACS) proposal for dwellings (chapter 5 in [19]). All the information concerning this project as well as its outputs can be found at http://www.costtu0901.eu/.

The COST ACS proposal was designed using the preferred impact sound insulation descriptor (standardized impact sound pressure level) and allowing for two possible assessment frequency ranges for the spectrum adaptation term C_I. The selected descriptors in the COST ACS were $L'_{nT,50} = L'_{nT,w} + C_{I50\text{-}2500}$ (default) and $L'_{nT,100} = L'_{nT,w} + C_{I100\text{-}2500}$ (alternative). The proposal was taken into consideration by ISO and was used as first working draft by ISO TC43/SC2/WG29, the corresponding working group responsible of developing the ACS further. The draft ISO ACS proposal [21] which is considered in this paper does not include $L'_{nT,100}$.

During the development of the ACS within ISO TC43/SC2/WG29, and considering impact sound insulation, one of the critical issues has been how to adequately incorporate the low frequency performance of the horizontal partitions into the scheme. Concerning the upper frequency limit, although traditionally the most common frequency range has been 3150 Hz, it has been agreed that, for impact noise, it is enough to consider the floor performance up to 2500 Hz as remarked in [22]: "*The upper third octave center frequency of 2500 Hz was chosen to cover the same frequency range as with octave bands. Impact sound pressure levels above that seem to be less important*."

Some authors consider that the performance at low frequencies of certain constructive solutions (especially considering lightweight ones) shall be included in the corresponding impact sound insulation descriptor, since the percentage of people annoyed by impact noise is strongly related to the low frequency performance (walking noise). In these cases, the spectrum adaptation term $C_{I,50\text{-}2500}$ provides objective evaluation of the low frequency range down to 50 Hz [7,23,24]. There are also authors who consider using 20 Hz as low frequency limit and including an alternative spectrum adaptation term $C_{I;AkuLite;20-2500}$ [17].

An alternative option is to consider the impact spectrum adaptation term including only the 100–2500 Hz frequency range, $C_{I,100\text{-}2500}$, which also takes into account the characteristics of typical walking noise spectra, but only from 100 Hz.

On the other hand, when considering bare or ineffectively covered massive floors, the use of the impact spectrum adaptation term might have the effect of overestimating the performance of the floor, compensating for the "worse performance" at medium-high frequencies. In these cases, it can be convenient to consider using the impact sound insulation descriptor $L'_{nT,w}$ without the spectrum adaptation term [18].

A well performing floor should adequately protect the end user from sources of noise covering the typical building acoustics spectrum and thus, in this paper, the three following descriptors have been proposed as potential "harmonized" impact sound insulation descriptors. The following notation will be used:

$$L'_{nT,w} \tag{1}$$

$$L'_{nT,50} = L'_{nT,w} + C_{I50} \tag{2}$$

$$L'_{nT,100} = L'_{nT,w} + C_{I100} \tag{3}$$

where

$$C_{I50} = C_{I,50-2500} \tag{4}$$

$$C_{I100} = C_{I,100-2500} \tag{5}$$

The notations $L'_{nT,50}$ (2) and $L'_{nT,100}$ (3) do not correspond to the ISO 717-2 [6]. They are used as suggested in the COST TU0901 ACS proposal (chapter 5 in [19]). Note also that the upper frequency range of the spectrum adaptation term is 2500 Hz. Finally, in the context of this paper, the term "rating method" is used to distinguish descriptors that include a spectrum adaptation term, such as (2) and (3), from descriptors not including a spectrum adaptation term, such as (1).

Table 1 presents an extract from the ACS proposal developed within ISO TC43/SC2/WG29 as of December 2016, ISO/CD 19488.2 [21].

The selected descriptors $L'_{nT,w}$ (1), $L'_{nT,50}$ (2) and $L'_{nT,100}$ (3) have at some point been considered as potential "harmonized descriptors". This paper focuses on translating the existing descriptors used in regulations, into the proposed harmonized ones, including the corresponding spectrum adaptation term, as proposed in [22]: "*old measured values and requirements should be transferable into the new system, if possible*".

Proposing one or two SNQs to be used as impact sound insulation descriptors in the standardized ACS, may have consequences at many different levels: product performance description, legislation, measurement procedures, correlation of the proposed descriptor to subjective impression of impact sound insulation...

This paper investigates on the translation of most commonly used impact sound insulation descriptors into the proposed harmonized ones. This will enable making fair comparisons between different countries requirements and estimating the corresponding impact sound insulation level requirement if expressed in terms of an alternative descriptor.

2. Objectives

The main purpose of this paper is to provide, based on a large set of in situ measurements, translation equations between some selected "*existing*" impact sound insulation descriptors and the previously "*proposed*" harmonized ones, and to investigate on the effect of the constructive solution type on the resulting translation equations. The selected existing descriptors are L'_w, $L'_{n,w}$, $L'_{n,w} + C_{I50\text{-}2500}$, $L'_{nT,w}$ and $L'_{nT,w} + C_I$ (chapter 2 in [19]). It might seem strange to select $L'_{nT,w}$ both as "*existing*" and "*proposed*" descriptor,

Table 1
Class criteria for impact sound insulation (in dB) as proposed in [21].

Type of space	Class A	Class B	Class C $L'_{nT,w}$	Class D $L'_{nT,w}$	Class E $L'_{nT,w}$	Class F $L'_{nT,w}$
In habitable rooms in dwellings from other dwellings, both in the horizontal and the vertical directions (MAIN REQUIREMENT)	$L'_{nT,50} \le 50$[a] and $L'_{nT,w} \le 46$	$L'_{nT,50} \le 54$[a] and $L'_{nT,w} \le 50$	≤54	≤58	≤62	≤66
In habitable rooms in dwellings from: - Common stairwells or access areas - Balconies or terraces or bath rooms not belonging to own dwelling[b]	$L'_{nT,w} \le 50$	$L'_{nT,w} \le 54$	≤58	≤62	≤66	≤70
In habitable rooms in dwellings from premises with noisy activities[c]	$L'_{nT,50} \le 44$[a] and $L'_{nT,w} \le 40$	$L'_{nT,50} \le 48$[a] and $L'_{nT,w} \le 44$	≤48	≤52	≤56	≤60

Notes
[a] Experience has shown that when applying the low-frequency rating, potentially disturbing high frequency sounds are not rated appropriately, and for this reason, an additional criterion for $L'_{nT,w}$ is applied. In order to account for both hard floor impact sounds, as well as low frequency footstep sounds, it is required to fulfil the limit values for both criteria $L'_{nT,50}$ and $L'_{nT,w}$. The limit values for $L'_{nT,w}$ are 4 dB lower than those specified for $L'_{nT,50}$.
[b] Impact sound from small balconies and rooms (area less than 4 m^2) are not included, e.g. toilets and utility rooms.
[c] Premises with noisy activities are rooms for shared services like laundries, central boiler house, joint/commercial kitchens or commercial premises like shops, workshops or cafés. However, in each case, noise levels shall be estimated and the sound insulation designed accordingly, e.g. for party rooms, discotheques, etc.

but this will enable to translate $L'_{nT,w}$ into $L'_{nT,50}$ and $L'_{nT,100}$ as well. For the pairs of descriptors $L'_{n,w}$ vs. $L'_{nT,50}$ and $L'_{nT,w}$ vs. $L'_{nT,50}$, our results will be compared to those proposed by Dunbavin and Gerretsen (Chapter 4 in [19]), which are based on basic building acoustics equations and geometrical assumptions.

The roadmap to achieve the objectives has been as follows:

- Based on a large set of in-situ impact sound insulation level measurements, to study the effect of the assessment frequency range when performing a pure mathematical translation between descriptors.
- Based on a statistical analysis of the same data set, to propose updated translation equations between existing impact sound insulation descriptors and the proposed harmonized ones $L'_{nT,w}$ (1), $L'_{nT,50}$ (2) and $L'_{nT,100}$ (3).
- To compare the obtained translation equations with those proposed by Dunbavin and Gerretsen (Chapter 4 in [19]).
- To investigate how the assessment frequency range affects the resulting translation equations for different types of building constructions (heavy and light weight floors).
- For 30 countries, to translate their current national requirements related to impact sound insulation into the descriptors used in ISO/CD 19488.2 [21]: $L'_{nT,w}$ (1) and $L'_{nT,50}$ (2).
- For the same countries, to evaluate how would their translated requirement fit within ISO/CD 19488.2 proposal [21].

This paper can be considered as a complement to Ref. [25], where a similar type of study is presented for airborne sound insulation descriptors.

3. Data set description

A set of 644 in-situ impact sound insulation measurements of 13 different types of floors (9 heavy and 4 light weight) were evaluated. All floors were constructed in the United Kingdom in compliance with the relevant Robust Details [26] specifications. Testing and on-site inspections were carried out on a sample of structures in dwellings under construction, to ensure compliance with the construction system by workmanship and with UK Building Regulations. Figs. 1 and 2 describe the floors used in this research.

Figs. 3 and 4 summarize some basic statistical data concerning impact sound insulation of the different types of floors used in this study. They show the average value and the standard deviation for $L'_{nT,w}$, $L'_{nT,50}$ and $L'_{nT,100}$ for each of the floor types (heavy and light) considered in this study. Below each floor type, the number of samples of each corresponding type is included in brackets. Notice that the number of heavy samples is much larger (466) than the number of light samples (178), so in order to avoid any bias for the least square regression lines due to the different size of the data sets, all studies where heavy and light floors are evaluated together have been made considering an equally sized group of samples for both types of floors.

4. Translation of most commonly used single number descriptors for impact sound insulation into the proposed harmonized ones $L'_{nT,w}$, $L'_{nT,50}$ and $L'_{nT,100}$

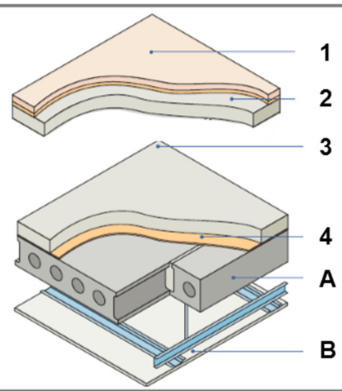
Sound insulation SNQs or single number descriptors are determined from the third octave values of the corresponding sound insulation parameter, using a rating method and considering a relevant assessment frequency range. For impact sound insulation, the commonly used rating method is the “w-reference curve” method described in ISO 717-2 [6] which leaves an open choice to include a spectrum adaptation term C_I or not. In this case, translating one single number descriptor into another, consists of two steps: translating one physical parameter into the other, e.g. $L'_{n,w}$ into $L'_{nT,w}$, and then taking into account the spectrum adaptation term and its assessment frequency range, e.g. $L'_{nT,w}$ into $L'_{nT,50}$. The translation between physical parameters can be done based on the mathematical relationship between them, but the translation between single number descriptors using different rating methods (with/without C_I) and/or different assessment frequency range is not obvious, so an empirical translation based on a statistical analysis of a large experimental data set is suggested.

4.1. Translation based on the mathematical relation between descriptors

When performing a pure mathematical conversion, it is difficult to take into account that the original (input) and calculated (output) descriptor may consider different assessment frequency range or rating method. In order to study how these differences affect the translation, the mathematical/geometrical translation has been calculated for all the descriptors shown in Table 2,

Precast concrete plank based floors (group a)

A– 150mm(min) precast concrete floor plank 300 kg/m² (min)
B– Ceiling



1 HF

1- Floating Floor
2- 40mm (min) screed directly applied to plank, 80 kg/m²

2 HF

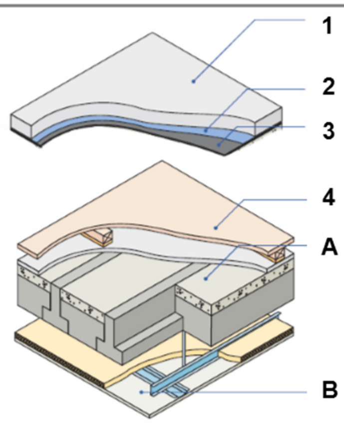
3– 65 mm (min) screed, 80 kg/m²
4– 6 mm resilient layer with flanking strip

3 HF

3– 65 mm (min) screed, 80 kg/m²
4– 10mm resilient layer with perimeter edging and tape for jointing

Beam and block based floors

A– Beam and block estructural floor, 100mm thick (min), dense aggregate infill blocks, 50mm concrete topping, min strengh class C20, 300 kg/m² combined mass per unit area
B– Ceiling



4 HF

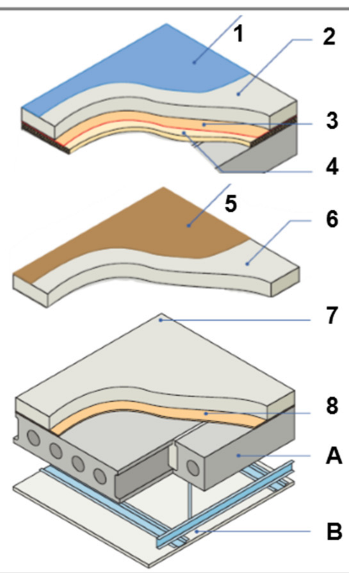
1– 65 mm (min) screed, 80 kg/m²
2– 0,2 mm (min) waterproof membrane
3– 8mm resilient layer with type for jointing

5 HF

4– Timber floating floor over 20 mm (min) levelling screed

Precast concrete plank based floors (group b)

A– 150mm(min) precast concrete floor plank 300 kg/m² (min)
B– Ceiling



6 HF

1– 4,5 mm (min) bonded resilient floor covering
2– 65 mm (min) screed, 80 kg/m²
3– 5 mm foamed polyethylene layer, 30-36 kg/m³
4– 25 mm mineral wool batt, 140 kg/m³ (min), 25 mm EPS, or extruded polystyrene insulation

7 HF

5– 3 mm thermal bonded resilient floor covering
6– 65 mm (min) screed, 80 kg/m²

8 HF

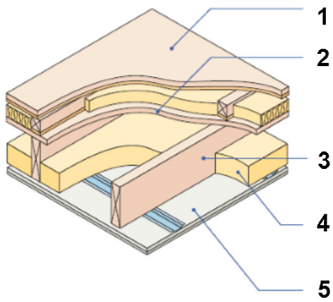
7– 65 mm (min) screed, 80 kg/m²
8– 10 mm TRANQUILIT resilient layer

9 HF

7– 65 mm (min) screed, 80 kg/m²
8– 3 mm resilient layer with flanking strip

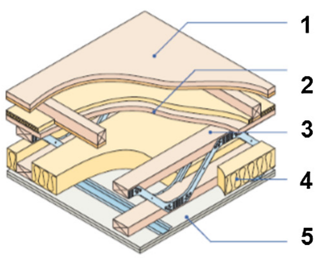
Fig. 1. Heavyweight floors description [26].

1 LF



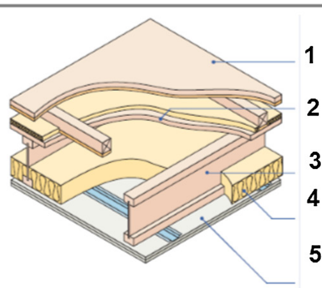
1– Floating Floor
2– 15 mm thick (min) wood based board, 600 kg/m³
3– 235 mm (min) timber I-joists
4– 100 mm (min) mineral wool quilt insulation (10-36 kg/m³) between joists
5– Ceiling

2 LF



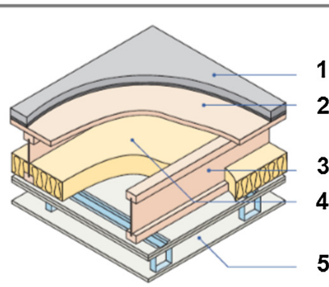
1– Floating Floor
2– 11 mm thick (min) wood based board, 600 kg/m³ or Walker Timber perforated deck system
3– 220 mm (min) solid timber joists at maximum 400 mm centres
4– 100 mm (min) mineral wool quilt insulation (10-36 kg/m³) between joists
5– Ceiling

3 LF



1– Floating Floor
2– 18 mm thick (min) wood based board, 600 kg/m³
3– 253 mm (min) metal web joist
4– 100 mm (min) mineral wool quilt insulation (10-36 kg/m³) between joists
5– Ceiling

4 LF



1– 28 mm screed board
2– 18 mm thick (min) wood based board, 600 kg/m³
3– 240 mm (min) timber I-joist
4– 100 mm (min) mineral wool quilt insulation (10-36 kg/m³) between joists
5– Ceiling

Fig. 2. Lightweight floors description [26].

according to Eq. (6), where V is the corresponding receiving room volume.

$$y = x - 10log\frac{0.16V}{T_0A_0} \quad \text{where} \quad T_0 = 0.5\ \text{s} \quad A_0 = 10\ \text{m}^2 \tag{6}$$

The calculated data sets have been compared to the corresponding descriptors obtained from the experimental field data. This comparison has been made separately for all the heavy floors and all the light floors. Table 3 summarizes the resulting linear regression equations of this comparison. As it can be expected, when considering the same descriptors, the results calculated with Eq. (6) are identical to the results obtained using the experimental field data (the diagonal in Table 3). But in the cases when the calculated and measured descriptors consider different rating method and/or assessment frequency range, the regression equations depend on the building typology, as it can be observed in Table 3. When trying to perform translations between descriptors that consider different rating method and/or assessment frequency range, there is a need for additional information not included in Eq. (6).

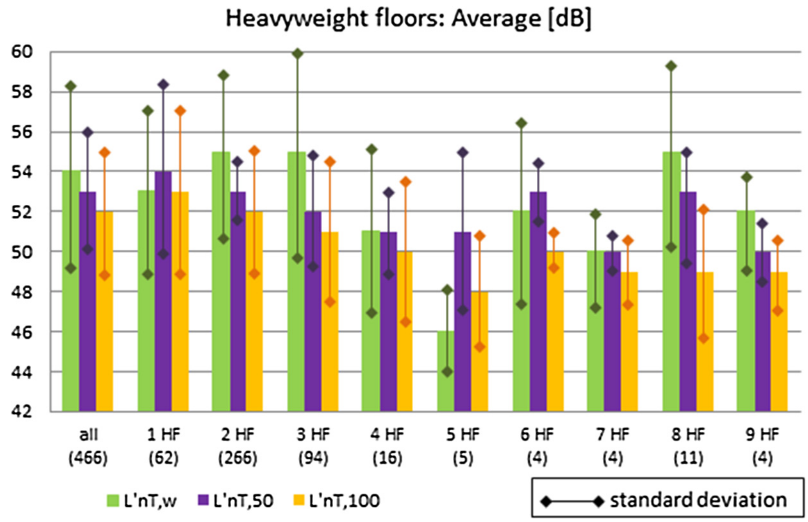


Fig. 3. Heavyweight floors data set information.

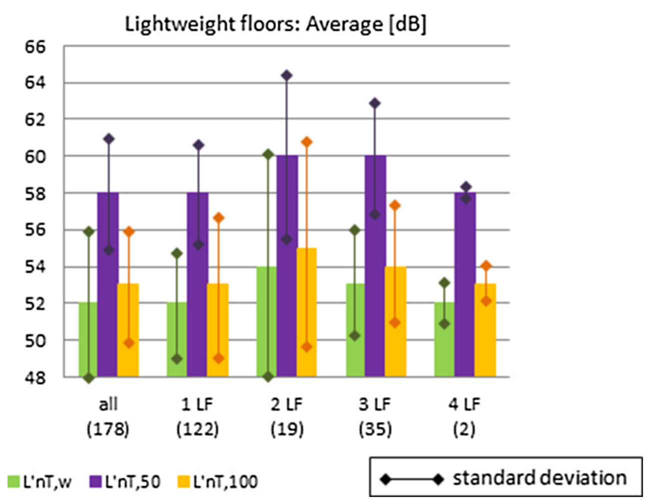


Fig. 4. Lightweight floors data set information.

Table 2
Input data and corresponding calculated (6) descriptor.

Input measured data (x)	Output calculated descriptor (y)
$L'_{n,w}$	$^{g}L'_{nT,w}$
$L'_{n,w} + C_{I50}$	$^{g}L'_{nT,50}$
$L'_{n,w} + C_{I100}$	$^{g}L'_{nT,100}$

Note: The descriptor calculated according to (6) is marked by a preceding superscript "g"- geometrical.

4.2. Translation based on the statistical analysis of a large data set

Bearing in mind that finding a unique translation equation independent of the building type would be of great interest in the field of building acoustics legislations, this paper proposes a different approach based on the statistical analysis of a large set of field measurements. The translation equations between most frequent existing descriptors and the potential harmonized descriptors used in the classification scheme proposals [19,21] have been determined, analyzed and discussed. The calculations have been performed according to the following steps:

a. Using the data of the complete set of the impact sound insulation measurements (644 different floors), the five most adopted single number descriptors for impact sound insulation around Europe [23] have been calculated. That is L'_{w}, $L'_{n,w}$, $L'_{n,w} + C_{I50}$, $L'_{nT,w}$, $L'_{nT,w} + C_{I}$.
b. The proposed harmonized descriptors $L'_{nT,50}$ and $L'_{nT,100}$ have also been calculated. ($L'_{nT,w}$ is also a proposed descriptor, but it has already been calculated in the previous step).
c. For three different data sets - only heavy floors, only light floors and an equally sized heavy and light floors data set (H&L) - a least square linear regression between the proposed harmonized descriptors and each of the existing descriptors has been made. These linear regressions are the corresponding translation equations between each pair of descriptors (existing/proposed).

Table 3
Relation between field data and calculated descriptors based on Eq. (6).

(y) Values obtained from experimental field data		(x) Calculated with Eq. (6) $^{g}L'_{nT,w}$	$^{g}L'_{nT,50}$	$^{g}L'_{nT,100}$
$L'_{nT,w}$	Heavy	y = x + 0.5[a]	y = 1.20x–9.1	y = 1.13x–4.2
	Light	y = x + 1[a]	y = 0.82x + 4.1	y = 0.99x–1
$L'_{nT,50}$	Heavy	y = 0.47x + 27.3	y = x	y = 0.82x + 10.6
	Light	y = 0.72x + 21	y = x	y = 0.80x + 15.6
$L'_{nT,100}$	Heavy	y = 0.59x + 19.4	y = 1.09x–6	y = x
	Light	y = 0.93x + 4.8	y = 0.86x + 3.1	y = x

[a] The regression equation should be y = x but, in this case, the measured descriptor was available with no decimals whereas the calculated used one.

Table 4
Translation equation proposed by Dunbavin and Gerretsen [19].

y	x	
	$L'_{n,w}$	$L'_{nT,w}$
$L'_{nT,50}$	y = 0.49x + 28.83	y = 0.49x + 27.7

d. In a last step, some of the translation equations obtained using the H&L data set are compared to those suggested by Dunbavin and Gerretsen in Chapter 4 [19], which are summarized in Table 4.

Table 5 summarizes all the translation equations obtained in "step c" above. As It can be observed, $L'_{nT,w} + C_I$ and $L'_{nT,100}$ descriptors can be considered equivalent, and thus in the following presentation of results and discussion, only $L'_{nT,100}$ will be considered. This result also shows that, for impact noise, it is enough to consider the floor performance up to 2500 Hz as remarked in [22].

Besides, just as in the previous section, it is possible to observe that the translation equations between existing (x) and proposed harmonized (y) descriptors are more dependent on the building system when different rating method and/or assessment frequency range are considered. These results point out that using one single translation equation independent of the building type can over/underestimate the translated descriptor, as it will be further explained in Section 5.1.

Nevertheless, the use of a single translation equation independent of the building type could be very useful as an estimation tool for constructors, legislators, etc. This has already been proposed by Dunbavin and Gerretsen in Chapter 4 [19]. If the equations based on a statistical analysis (Table 5) are compared to the ones suggested by Dunbavin and Gerretsen (Table 4), one can observe that equations in Table 5 for heavy floors (in blue and underlined) are close to the Dundavin's equations. The corresponding equations for lightweight floors (in red and underlined in Table 5) are more different. All these differences will be further investigated in the next section.

5. Evaluation of the translation equations obtained based on the statistical analysis

This section aims at investigating, on one hand, "how different" are each pair of equations (heavy/light) shown in Table 5 and, on the other hand, "how reasonable" it can be to use one single translation equation independent of the building type.

For the sake of simplicity, the results shown in this paper do not include L'_w translations (first column in Table 5) since this descriptor is used in only one European country. Besides, it has been observed that its behavior is almost identical to $L'_{n,w}$ and $L'_{nT,w}$ as far as the following analysis is concerned.

The investigation has been done, as in [25], in two stages:

- As a first step, in Section 5.1, the differences between heavy and light weight floors translation equations shown in Table 5 are evaluated.
- The second step, presented in Section 5.2, analyzes, for $L'_{n,w}$ and $L'_{nT,w}$, if it is acceptable to use one single translation equation to $L'_{nT,50}$, regardless of the building type, and how close is the proposed translation equation to Dunbavin and Gerretsen's proposal in Chapter 4 [19].

5.1. Translation equations obtained for different building type

Although the pair of equations heavy/light shown in Table 5 for each pair of descriptors may seem different, it could happen that, considering certain confidence interval, both equations would lie within the same limits. A graphical approach can help understanding such differences, so a selected set of translation equations will be represented hereinafter. All figures included in this section represent the corresponding regression lines including the 95% confidence intervals, represented as a shaded area. The line y = x is also included as a dashed line in all figures as a tool to better estimate when the proposed translated descriptor (output) results above or below the existing descriptor (input). Besides, in the following analysis, a limit of 1 dB has been chosen to consider two different translations as equivalent; this has been represented by two green vertical lines when applicable. The 1 dB limit was chosen considering that, according to ISO 12999-1 [27], 1 dB is the suggested value for in situ *standard deviation* for impact sound insulation SNQs.

5.1.1. Translating $L'_{n,w}$ and $L'_{n,w}+C_{I50}$ into $L'_{nT,w}$

Assuming that $L'_{nT,w}$ could be used as a harmonized impact sound insulation descriptor, Fig. 5(a) and (b) help to better understand the consequences of such a change for countries using $L'_{n,w}$ (first row - second column in Table 5), and $L'_{n,w} + C_{I50}$ (first row - third column in Table 5). The results for $L'_{nT,w} + C_I$ (first row - fifth column in Table 5) are not shown, since it has turned out to be very similar to the one shown for $L'_{n,w} + C_{I50}$. Notice that in the first case, $L'_{nT,w}$ and $L'_{n,w}$ consider the same assessment

Table 5
Translation equations between descriptors based on statistical analysis.

y \ x		L'w	L'n,w	L'n,w + CI50	L'nT,w	L'nT,w + CI
L'nT,w	Heavy	y=0.87x+4.9	y=0.90x+4.8	y=0.90x+6.4	--	y=1.14x-4.5
	Light	y=0.96x-0.2	y=0.93x+2.7	y=0.74x+8.2	--	y=x-1.0
	H&L	y=0.90x+2.7	y=0.92x+3.5	y=0.32x+35.3	--	y=1.07x-2.7
L'nT,50	Heavy	y=0.39x+30.7	y=0.42x+29.7	y=0.77x+11.9	y=0.47x+27.1	y=0.82x+10.6
	Light	y=0.68x+21.3	y=0.64x+24.6	y=0.94x+3.0	y=0.73x+20.4	y=0.80x+15.6
	H&L	y=0.31x+38.3	y=0.33x+37.6	y=0.91x+4.7	y=0.39x+35.0	y=0.81x+12
L'nT,100	Heavy	y=0.50x+23.2	y=0.54x+22.3	y=0.84x+7.0	y=0.60x+19.3	y=x+0.1
	Light	y=0.90x+4.3	y=0.89x+6.4	y=0.80x+6.2	y=0.95x+4.1	y=x
	H&L	y=0.55x+21.8	y=0.60x+20.4	y=0.60x+18.5	y=0.65x+17.9	y=x

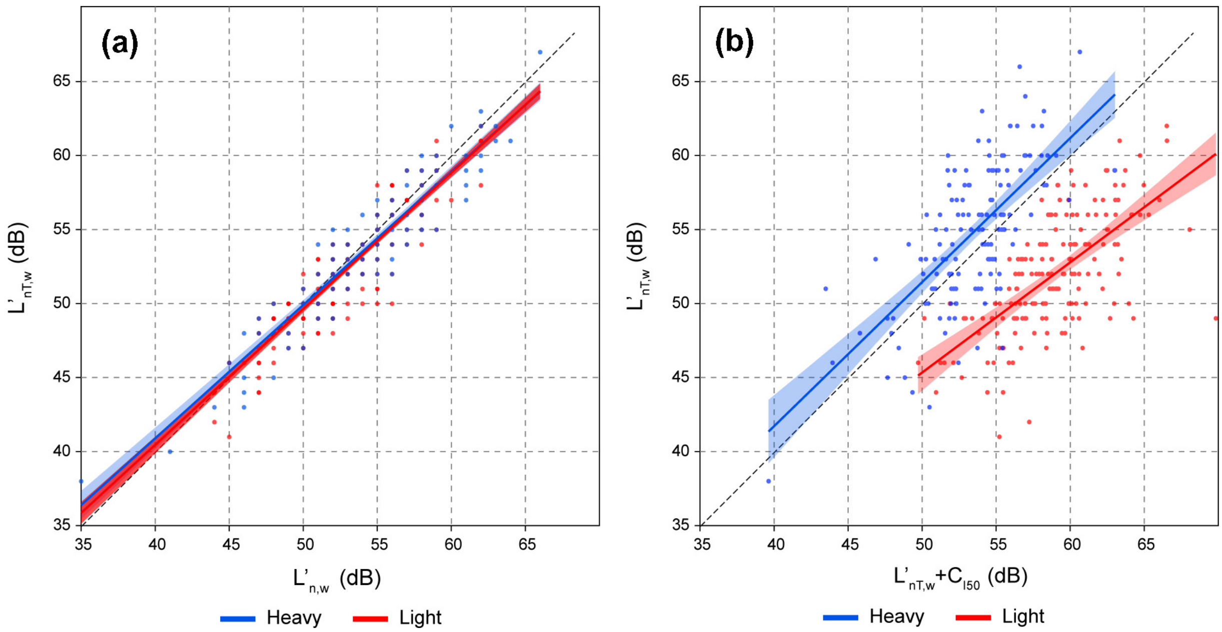


Fig. 5. Comparison of equations for the translation of $L'_{n,w}$ (a) and $L'_{n,w} + C_{I50}$ (b) to the descriptor $L'_{nT,w}$ for different building types (Heavy/Light weight floors).

frequency range whereas in the second case, $L'_{nT,w}$ and $L'_{n,w} + C_{I50}$ (and also $L'_{nT,w} + C_I$) consider different assessment frequency range.

As it can be expected, if the assessment frequency range remains unchanged (Fig. 5(a)), the translation is almost identical, independently of the building type. But, when considering the impact spectrum adaptation term and an extended assessment frequency range (Fig. 5(b)), the different characteristics of heavy and light floors affect the translation.

For example, if a requirement of $L'_{n,w} + C_{I50} < 56$ dB should be translated to $L'_{nT,w}$, the corresponding translation would be $L'_{nT,w} < 56.8$ dB for heavyweight floors and $L'_{nT,w} < 49.6$ dB for lightweight floors. This is not an optimal scenario and one should aim at having translation equations that, within a certain confidence interval, could adequately translate the requirements, independently of the building type, at least over a limited requirement range.

5.1.2. Translating $L'_{nT,w}$ and $L'_{n,w} + C_{I50}$ into $L'_{nT,50}$

This section analyzes the translation equations obtained assuming that $L'_{nT,50}$ could be adopted as a harmonized impact sound insulation descriptor. The results for L'_w, $L'_{n,w}$ and $L'_{nT,w} + C_I$ (first, second and fifth column in Table 5) are not shown, since they have turned out to be very similar to the ones shown for $L'_{nT,w}$ (fourth column in Table 5).

As in the previous section, when the rating method and/or assessment frequency range is changed, the translation equations show a strong dependence on the building type. Fig. 6(a) shows

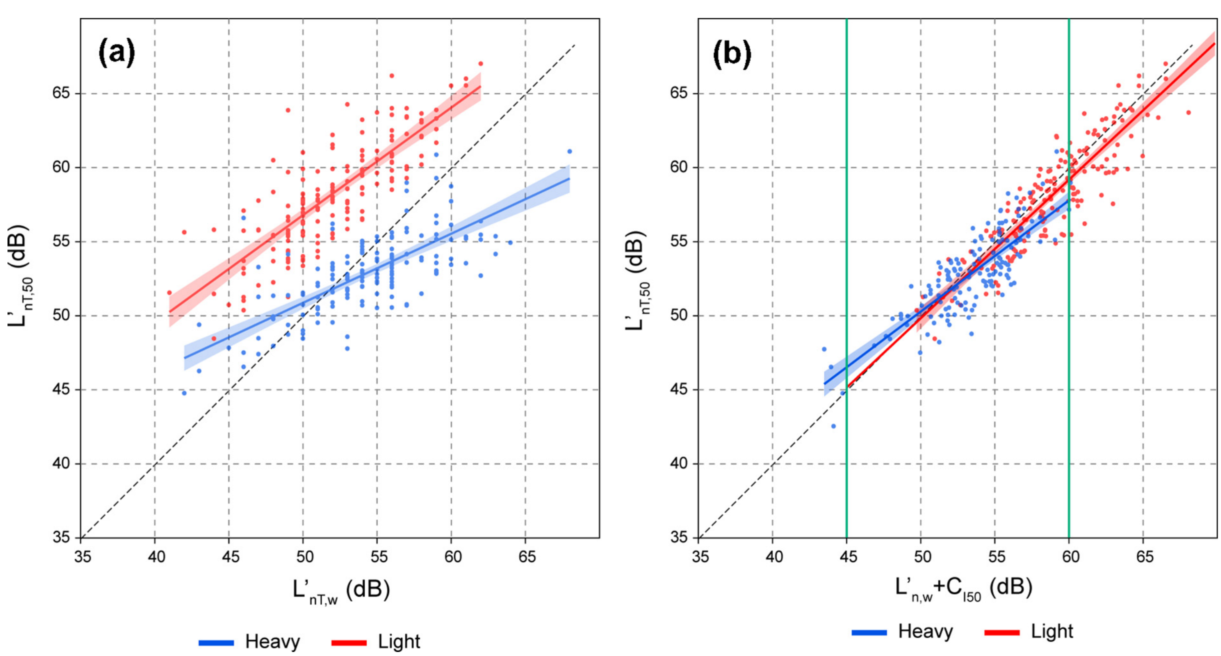


Fig. 6. Comparison of equations for the translation of $L'_{nT,w}$ (a) and $L'_{n,w} + C_{I50}$ (b) to the descriptor $L'_{nT,50}$ for different building types (Heavy/Light weight floors).

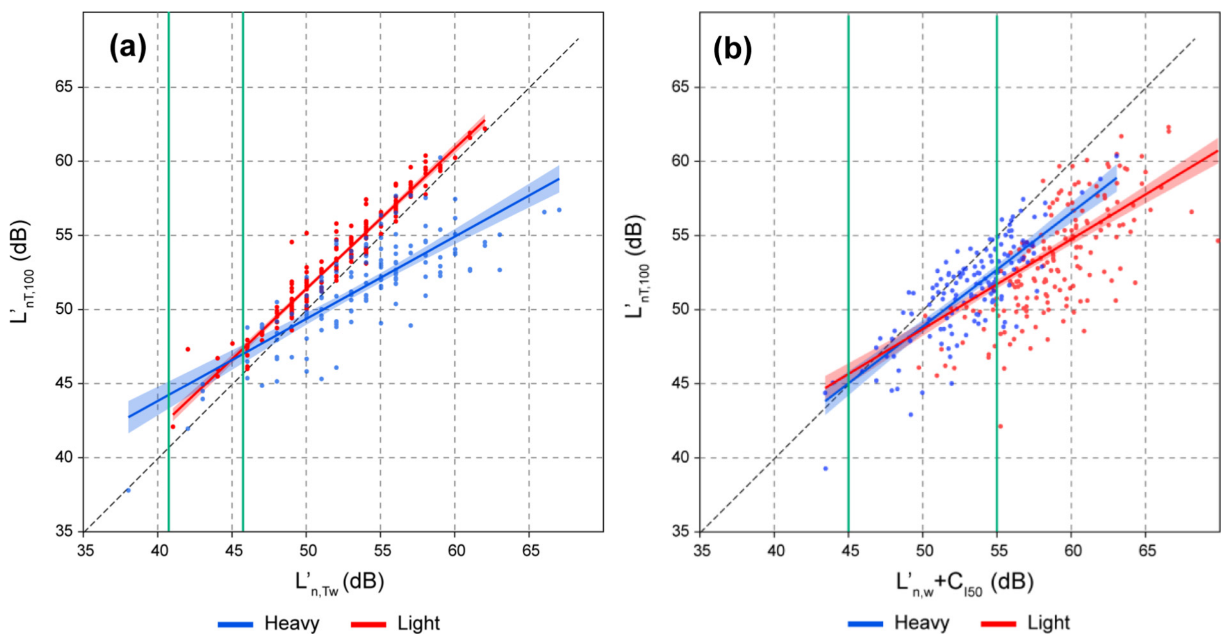


Fig. 7. Comparison of equations for the translation of $L'_{nT,w}$ (a) and $L'_{n,w} + C_{I50}$ (b) to the descriptor $L'_{nT,100}$ for different building types (Heavy/Light weight floors).

the effect of translating $L'_{nT,w}$ into $L'_{nT,50}$. Including the low frequency spectrum adaptation term into the descriptor does not affect in the same way to heavy and light weight floors. For example, a requirement $L'_{nT,w} < 65$ dB would be translated to the $L'_{nT,50} < 69.9$ dB for a lightweight floor and $L'_{nT,50} < 57.7$ dB for heavyweight floor; and a requirement $L'_{nT,w} < 48$ dB would be translated to $L'_{nT,50} < 57.5$ dB for a lightweight floor and $L'_{nT,50} < 49.7$ dB for heavyweight floor. This can be confusing for a non-expert in the field, but is a straightforward consequence of the spectral response of heavy/light floors.

In Fig. 6(b), these differences are much smaller since both descriptors include the spectrum adaptation term and consider the same assessment frequency range. Still, for floors with $L'_{n,w} + C_{I50} < 45$ dB or $L'_{n,w} + C_{I50} > 60$ dB the distinct behavior can clearly be observed and differences are above 1 dB (see green vertical lines).

5.1.3. Translating $L'_{nT,w}$ and $L'_{n,w} + C_{I50}$ into $L'_{nT,100}$

Finally, this section analyzes the translation equations obtained assuming that $L'_{nT,100}$ could be adopted as a harmonized impact sound insulation descriptor. The results for $L'_{nT,w} + C_I$ (fifth column in Table 5) are not shown, since this descriptor is equivalent to the translated $L'_{nT,100}$ analyzed in this section.

Fig. 7(a) shows the translation of $L'_{nT,w}$ into $L'_{nT,100}$. In this case, introducing the impact spectrum adaptation term, even if considering the same assessment frequency range, evidences the different behavior between heavy and light floors. Similarly, Fig. 7(b) shows the translation between two descriptors ($L'_{n,w} + C_{I50}$ into $L'_{nT,100}$) which both include the spectrum adaptation term, but considering a different assessment frequency range. The green vertical lines limit the range where the forecasted translations differ less than 1 dB and, evidence that again, the use of different assessment frequency range yields different translation equations depending on the building type.

5.2. Single translation equations – independent of the building type

In the previous section, it has been shown that, in some cases, there is a dependence on the building type when trying to translate existing impact sound insulation descriptors into proposed harmonized ones. But, from a practical point of view, it can be convenient to propose a single translation equation to be used regardless of the building type. Such translations could be of great support to legislators, at the stage of adopting a new impact sound insulation descriptor and/or setting new requirement levels.

In this section, two of the translation equations obtained for $L'_{nT,50}$ considering the H&L data set (Table 5) are compared to Dunbavin and Gerretsen's proposal (Table 4). These are represented in Fig. 8. As it can be observed, the differences between both suggested translations remain within 1 dB for $56 < L'_{n,w} < 68$ dB (Fig. 8(a)) and also for $52 < L'_{nT,w} < 70$ dB (Fig. 8(b)) (see green lines). Away from these intervals, the differences are above 1 dB.

Although both proposals agree within 1 dB, for the previously specified ranges of $L'_{n,w}$ and $L'_{nT,w}$ values, the differences away from that range rise up to 3 dB. These differences are due to using different translation procedures. Dunbavin and Gerretsen in Chapter 4 [19] propose a translation between impact sound insulation descriptors based on a two steps procedure: a) translation between descriptors according to (6) and assuming a compromise volume of 52.5 m^3; b) translation between descriptors considering the use of spectrum adaptation terms with different frequency assessment range. Step b) is based on data from a previous study [9], as explained in Chapter 4 [19], and suggests:

$$C_{I,50-2500} = 30.0 - 0.51 \cdot L'_{n,w} \quad (7)$$

In [9], the amount of floors considered in the study was 49 and all of them were heavy floors, whereas, in the present study, 644 in situ measurements have been used to obtain the translation equations, including different construction types, as described in Section 3. It is expected that the translation equations obtained using the latter data base will better fit the majority of possible cases, since it is a much larger data base and has an average volume $\overline{V} = 41$ m^3, which better corresponds with real situations.

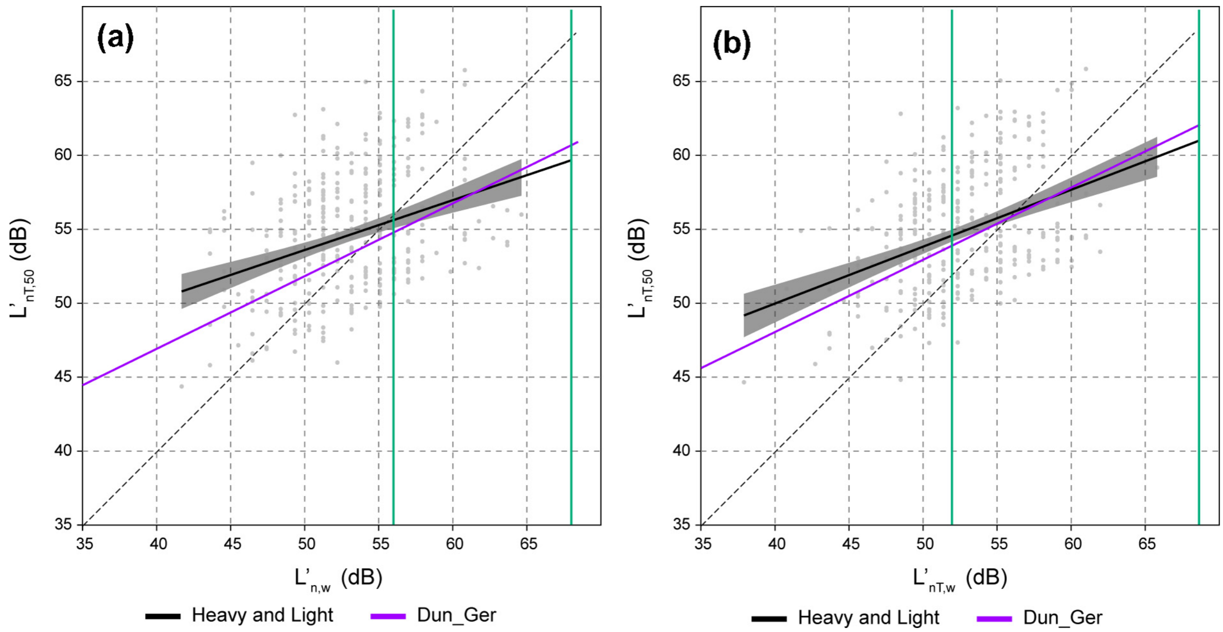


Fig. 8. Comparison of obtained single translation equations and "Dunbavin and Gerretsen's" proposal.

Table 6
$L'_{nT,w}$ and $L'_{nT,50}$ translation equations considering a balanced sample of heavy and light floors.

y \ x	L'_{w}	$L'_{n,w}$	$L'_{n,w} + C_{I50}$	$L'_{nT,w}$	$L'_{nT,w} + C_{I}$
$L'_{nT,w}$	y=0.90x+2.7	y=0.92x+3.5	y=0.32x+35.3	--	y=1.07x-2.7
$L'_{nT,50}$	y=0.31x+38.3	y=0.33x+37.6	y=0.91x+4.7	y=0.39x+35.0	y=0.81x+12

6. Translation of most EU countries' impact sound insulation requirements into a proposed common classification scheme: Evaluation and consequences

One consequence of adopting a common acoustic classification scheme based on harmonized descriptors, is that legislators from different countries will need to assess what would their sound insulation requirements be, if translated into alternative proposed descriptors, and to which class would that correspond.

Based on the translation equations shown in Table 6 (extracted from Table 5), the existing impact sound insulation requirements for multi-storey houses in most European countries have been translated, as an example, to the proposed descriptors $L'_{nT,w}$ and $L'_{nT,50}$ and aligned within the acoustic classification scheme proposal described in Fig. 9 [21]. Notice that the translation equation used correspond to a balanced sample of heavy and light floors. Due to the significant divergence observed between the heavy and light translation equations when different frequency range assessment is considered, the results shown in this section must be considered as rough estimates when the original and translated descriptor do not have the same assessment frequency range.

Fig. 9 shows, for each country, the current impact sound insulation descriptor in Chapter 2 [19] and existing requirement. It also includes the corresponding translated values (rounded to an integer value) both to $L'_{nT,w}$ and $L'_{nT,50}$, and the resulting classification according to the acoustic classification scheme proposal described in Table 1 [21]. Notice that classes C, D, E and F are based only on $L'_{nT,w}$ values, whereas classes A and B are based both on $L'_{nT,w}$ and $L'_{nT,50}$ values.

From the results in Fig. 9, it is possible to have a good estimation of what would be the corresponding requirement level, if a different descriptor was adopted. Besides, it is possible to estimate to which class such requirement would correspond. This is a powerful tool, which can be used by legislators to make a preliminary estimation of the impact of adopting a common acoustic classification scheme for dwellings/buildings. One should expect that the countries' basic requirement should correspond to the central classes (C and D), reserving higher classes (A and B) for high quality buildings and lower classes (E and F) for existing buildings and/or refurbished old buildings which have difficulties being upgraded to comply with basic acoustic requirements.

It is interesting to point out that, considering the proposed acoustic classification scheme [21] and considering impact sound performance, the existing requirements lie, as expected, mainly within classes C (13 countries) and D (8 countries), although, there are countries with more permissive requirements, where the new built dwellings would be ranked class E (5 countries) or even class F (3 countries). There is only one country where the requirements are such that new buildings would be classified as B, concerning impact sound performance. Remember that, according to Table 1, in order to be ranked class A or B, the floor must comply both with $L'_{nT,w}$ and $L'_{nT,50}$ requirements. This is a compromise solution to protect the end user effectively both from low frequency sound sources ($L'_{nT,50}$) and medium-high frequency sound sources ($L'_{nT,w}$).

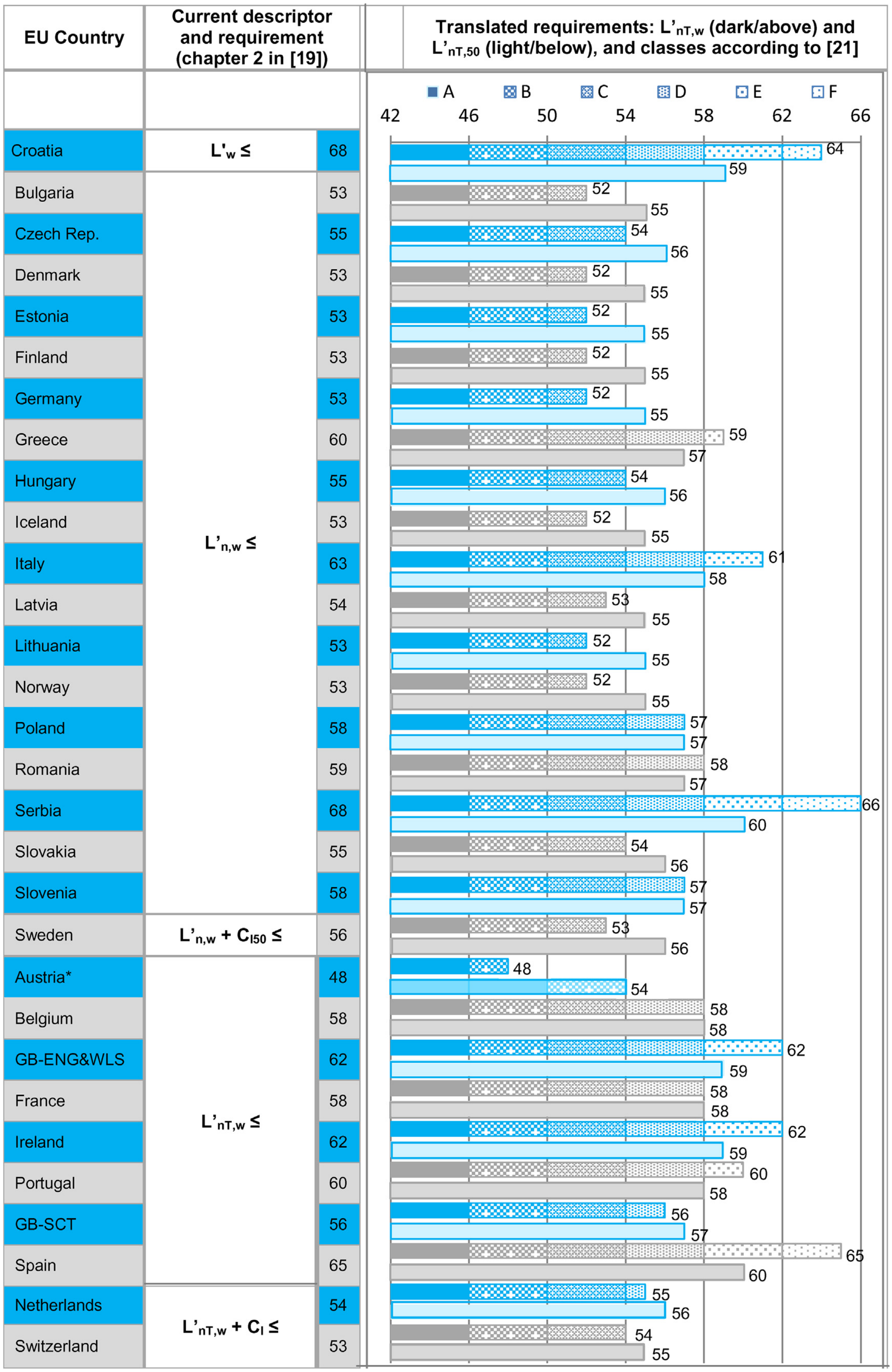


Fig. 9. Countries' impact sound insulation requirements (chapter 2 in [19]) for multi-storey housing, corresponding $L'_{nT,w}$ and $L'_{nT,50}$ translation and alignment within the common acoustic classification scheme proposal [21].

7. Conclusions

The main objectives of the paper, which were a) to research on the effect of building typology and assessment frequency range in impact sound insulation translation equations; b) to deliver existing current impact sound insulation national requirements translated into $L'_{nT,w}$ and $L'_{nT,50}$ and c) to align the translated requirements within the acoustic classification scheme proposed in ISO/CD 19488.2, have been accomplished.

After the analysis of all the data presented in this paper, the most relevant conclusions and outputs are the following:

When trying to perform translations between descriptors that consider different rating method and/or assessment frequency range, there is a need for additional information not included in pure mathematical relations. The mathematical approach is only valid for descriptors sharing identical assessment frequency range and rating method. Otherwise, additional assumptions should be made.

The acoustic performance of heavy and light floors is essentially different at medium/low frequencies and thus it is difficult to find a single equation that can accurately estimate the performance including the low frequency range (< 100 Hz) using as input the measured performance from 100 Hz and above. The translation equations obtained using a large data set and a statistical approach, are strongly dependent on the building type, when different assessment frequency range and/or rating method are considered in both descriptors. It is recommended to use specific translation equations in such cases.

Nevertheless, for the sake of providing a preliminary translation of impact sound insulation descriptors independent of the building type, the translation equations obtained using a balanced sample of heavy and light floors are proposed to be used.

Comparing the proposed translation equations obtained using a large data set and a statistical analysis approach with the results proposed by Dunbavin and Gerretsen, it is concluded that both proposals agree within 1 dB for a limited range of $L'_{n,w}$ and $L'_{nT,w}$ values. Away from that range the differences rise up to 3 dB, which can be due on one hand to having different basic assumptions and on the other hand to the different size and composition of the corresponding data base (644 heavy and light floors in this study versus only 49 heavy floors in Dunbavin and Gerretsen's study).

Lastly, based on translation equations obtained using a balanced sample of heavy and light floors, most EU countries' impact sound insulation requirements for multi-storey housing have been translated to their corresponding $L'_{nT,w}$ and $L'_{nT,50}$ values. The translated values have been aligned within the ISO/CD 19488.2 acoustic classification scheme proposal. This table enables all interested parties to estimate the effect of adopting a new impact sound insulation descriptor and evaluate to which acoustic class the current existing requirement would correspond. Notice that, since the suggested translated values have been obtained using a balanced sample of heavy and light floors, the results in Fig. 9 shall be considered as preliminary estimations. In the cases where the original and translated descriptor do not have the same assessment frequency range it is recommended to use the corresponding different translation equations shown in Table 5.

From the results, it is concluded that, if the proposed acoustic classification scheme was adopted, most European countries' requirements would lie within classes C and D, although some European countries would find their existing requirement fall into classes E or F, which in principle are considered classes for old or renovated buildings with low acoustic performance. Only one country would have an impact sound requirement corresponding to class B.

It is the hope of the authors that the results presented in this paper will kick off further research including in situ impact sound insulation data from a variety of different countries' typical constructions. It is also the hope that it will launch debate at national level and encourage authorities to understand the importance of having harmonized sound insulation descriptors and acoustic classification schemes for buildings, in a globalized world.

Acknowledgements

The authors would like to express special gratitude to ISO TC43/SC2/WG29 for its continuous efforts in reaching agreements, developing an acoustic classification scheme and creating awareness of the relevance of protection against noise in buildings. Additionally, we would like to thank all members of COST Action TU0901 and Robust Details Ltd for inspiring and supporting this research.

References

[1] Basner M et al. Auditory and non-auditory effects of noise on health. Lancet 2014;383:1325–32. http://dx.doi.org/10.1016/S0140-6736(13)61613-X.
[2] Basner M et al. ICBEN review of research on the biological effects of noise 2011–2014. Noise Health 2015;17:57–82. http://dx.doi.org/10.4103/1463-1741.153373.
[3] Stansfeld SA. Noise pollution: non-auditory effects on health. Br Med Bull 2003;68:243–57. http://dx.doi.org/10.1093/bmb/ldg033.
[4] Hänninen O et al. Environmental burden of disease in Europe: assessing nine risk factors in six countries. Environ Health Perspect 2014;122:439–46. http://dx.doi.org/10.1289/ehp.1206154.
[5] Rasmussen B. Renovated housing acoustic classification schemes in Europe – applicability for new, existing and renovated housing. In: Proc Balt Acoust Meet; 2016.
[6] ISO 717-2 acoustics – rating of sound insulation in buildings and of building elements — Part 2: Impact sound insulation; 2013.
[7] Bodlund K. Alternative reference curves for evaluation of the impact sound insulation between dwellings. J Sound Vib 1985;102:381–402. http://dx.doi.org/10.1016/S0022-460X(85)80149-8.
[8] Mariner T. Comparison of three methods of rating floors for impact noise. J Acoust Soc Am 1967;42:1170. http://dx.doi.org/10.1121/1.2143999.
[9] Gerretsen E. A new system for rating impact sound insulation. Appl Acoust 1976;9:247–63. http://dx.doi.org/10.1016/0003-682X(76)90007-4.
[10] Scholl W. Revision of ISO 717: why not use impact sound reduction indices instead of impact sound pressure levels? Acta Acust United with Acust 2011; 97: 503–8. doi: http://dx.doi.org/10.3813/AAA.918430.
[11] Van den Eijk IJ. Some problems in the measurement and rating of impact sound insulation. Appl Acoust 1969;2:269–77. http://dx.doi.org/10.1016/0003-682X(69)90004-8.
[12] Josse R. How to assess the sound-reducing properties of floors to impact noise (footsteps). Appl Acoust 1972;5:15–20. http://dx.doi.org/10.1016/0003-682X(72)90003-5.
[13] Shi W, Johansson C, Sundbäck U. An investigation of the characteristics of impact sound sources for impact sound insulation measurement. Appl Acoust 1997;51:85–108. http://dx.doi.org/10.1016/S0003-682X(96)00071-0.
[14] ISO 10140- Acoustics – Laboratory measurement of sound insulation of building elements - parts 1 to 5; 2010.
[15] Okano T. Correspondence between two types of rating indices for the heavy weight floor impact sound insulation of residential buildings. Appl Acoust 2016;106:10–5. http://dx.doi.org/10.1016/j.apacoust.2015.12.010.
[16] Smith S, Mackenzie R, Mackenzie R, Waters-Fuller T. The implications of ISO 717 spectrum adaptation terms for residential dwellings. Proc Inst Acoust 2003; 25: Pt 5.
[17] Ljunggren F, Simmons C, Hagberg K. Correlation between sound insulation and occupants' perception - Proposal of alternative single number rating of impact sound. Appl Acoust 2014;85:57–68. http://dx.doi.org/10.1016/j.apacoust.2014.04.003.
[18] Bettarello F, Fausti P, Baccan V, Caniato M. Impact Sound Pressure Level Performances of Basic Beam Floor Structures. Build Acoust 2010;17:305–16. http://dx.doi.org/10.1260/1351-010X.17.4.305.
[19] Rasmussen B, Machimbarrena M, Fausti P, TU0901 C. Building acoustics throughout Europe. Volume 1: Towards a common framework in building acoustics throughout Europe; 2014.
[20] Rasmussen B. Sound insulation between dwellings - requirements in building regulations in Europe. Appl Acoust 2010;71:373–85. http://dx.doi.org/10.1016/j.apacoust.2009.08.011.
[21] ISO/CD 19488.2: 2016-12; acoustics – acoustic classification of dwellings - (internal committee document); 2017.
[22] Scholl W, Lang J, Wittstock V. Rating of sound insulation at present and in future. The revision of ISO 717. Acta Acust United with Acust 2011; 97: 686–98. doi: http://dx.doi.org/10.3813/AAA.918448.

[23] Rasmussen B, Rindel JH. Sound insulation between dwellings – descriptors applied in building regulations in Europe. Appl Acoust 2010;71:171–80. http://dx.doi.org/10.1016/j.apacoust.2009.05.002.
[24] Mortensen FR. Subjective evaluation of noise from neighbours with focus on low frequencies. Technical University of Denmark; 1999.
[25] Monteiro C, Machimbarrena M, Tarrero AI, Smith RS. Translation between existing and proposed harmonized airborne sound insulation descriptors: A statistical approach based on in-situ measurements. Appl Acoust 2017;116:94–106. http://dx.doi.org/10.1016/j.apacoust.2016.09.017.
[26] Robust Details Ltd., Robust details handbook. Part E: Resistance to the passage of sound. 3rd ed. Milton Keynes, UK; 2013.
[27] ISO 12999-1 acoustics – determination and application of measurement uncertainties in building acoustics – Part 1: Sound insulation. Geneva, Switzerland: International Organization for Standardization; 2014.