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SCIENTIFIC ARTICLE

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Zwicker's Loudness model as a robust calculation method for assessment of adequacy of airborne sound insulation descriptors for partition walls in dwelling houses

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Abstract – The development and validation of single number quantities that are meant to serve for straightforward assessment and comparison of airborne sound insulation properties of partition walls are typically challenged by the necessity to perform large numbers of laboratory listening tests with human subjects. This is because a reliable validation of a single number quantity requires testing for many different wall types with multiple real-life stimuli that are representative for daily life soundscapes. In this article, an alternative approach is presented that allows to test a large number of "partition wall – real-life sound stimuli" combinations. This approach uses the well-established and nowadays generally accepted Zwicker's Loudness for quantifying the subjective loudness of sound passing through a wall, and derive from that the subjectively perceived sound insulation. Using the proposed assessment method, the adequacy of single number quantities that are currently in use, and a number of newly proposed single number quantities, are compared.

Keywords: Loudness, Airborne sound insulation, Dwellings, Single number quantity, Building acoustics

1 Introduction

Single number quantities (SNQs) as those defined in ISO 717-1 [1] and ISO 717-2 [2], respectively for airborne sound insulation and impact sound insulation, have been widely used to express acoustic performances in national building regulations and quality labels for the past decades. To be considered as reliable, it is essential that these simplified performance indicators provide an accurate estimate of the occupants' perception of the acoustic quality.

Recently, two main reasons led the building acoustics community to question the adequacy of the SNQs defined in ISO 717, which do not take into account frequencies below 100 Hz. The first reason is the evolution of construction techniques, characterized by a rapid growth of wood – towards more sustainable solutions with less cement-based materials and more generally bio-based – solutions. Their light weight and the presence of cavities in many of these solutions raised concerns about the acoustic performance of new buildings at low frequencies. The second reason is the emergence of powerful low-frequency noise sources in buildings, such as audiovisual equipment at the end of 20th century [3]. These concerns went along with an increase in complaints from building occupants [4].

Between 2012 and 2014, these questions were addressed in an attempt to revise the ISO 717 series (known as the prISO 16717 standard projects). New single number quantities were proposed, and different research teams tried to assess their perceptual relevance through sociological surveys (such as questionnaires) [5–7], and psycho-acoustic studies mostly using laboratory listening tests [8–10]. However, their results were difficult to compare because of methodological differences. These methods were also criticized because they were often based on an evaluation of the perceived annoyance or disturbance, both parameters being highly dependent on other physical factors, but also on social and cultural factors. Therefore, these psycho-acoustic parameters are hard to assess from a small population and in laboratory conditions. Criticisms also included the small variety of sound stimuli, which is imposed by listening test duration. In a short communication, Rindel [11]

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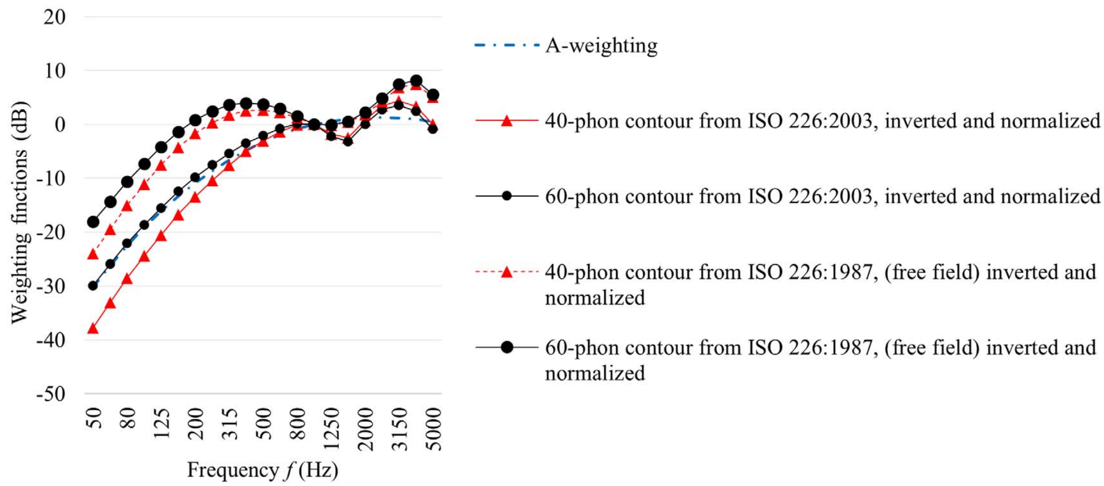

Figure 1. A-weighting compared to equal-loudness-level contours in a pairwise comparison scheme.

gave a comprehensive overview of the studies conducted at that time and of their limitations. Finally, the revision process was suspended due to the lack of consensus among the standardization committee.

Currently, the protection against transmission of indoor sounds is evaluated through a SNQ composed of the weighted sound level difference or sound transmission index, to which is added a spectrum adaptation term C. The latter term was introduced in ISO 717-1 when it was revised in 1996. The calculation procedure is based on the use of A-weighted pink noise as reference sending sound. The choice of pink noise and A-weighting was a compromise between the rating methods used in Germany and in France at that time. Although it has a strong influence on the final result, it has not been well documented in the bibliography section of the standard.

In 1983, a listening test experiment by Vian et al. [12] concluded that "the A-weighted level difference method of rating party wall sound insulation does correlate well with annoyance caused by music when bandlimited (125 Hz – 4 kHz) pink noise is used as the source in the rating procedure". Even though it was not referenced in the standard, this work – or other similar studies – may have been the background for the use of A-weighting in the calculation of the C spectrum adaptation term. It should be noted that this study suffered from the same methodological weakness as the more recent studies mentioned above. Moreover, low-frequency noise was excluded from the experiment. Interestingly, the same study also pointed out that "this correlation was not present when broadband (40 Hz – 10 kHz) pink noise was used for the proposed performance rating", and therefore that "the advent of modern high-fidelity systems may necessitate re-evaluating the effectiveness of sound insulation rating methods to account for the lower frequencies between 125 Hz and 300 Hz". While this study focused on music sounds, more recent research by Park et al. [13] has found that "an A-weighted sound transmission loss measure, STA, was reasonably well related to annoyance and loudness ratings of transmitted speech and music sounds", considering a broader frequency range (63–6300 Hz). On this basis, Scholl et al. [14] recommended to keep using A-weighting in the frame of revision of ISO 717. In the latest version of ISO 717-1, no explicit justification is given about the choice of A-weighted pink noise, and the bibliography section still does not mention any paper supporting this choice.

As reported by Hohmann [15], A-weighting was based on an early version of the 40-phon equal- loudness-level contour, as defined by Fletcher and Munson [16]. It should be noted that, for the calculation of single number quantities, it seems reasonable to use a moderate loudness level as reference, considering that proper sound insulation should ensure low to moderate sound pressure levels in the receiving room.

A-weighting was rapidly given a standard definition, first in an American standard for sound level meters, later revised in [17], and afterwards also in IEC/EN 61672-1 [18]. Equal-loudness-level contours were also standardized, but separately, in ISO 226 [19]. When analysing the evolution of the standards, it can be noticed that equal-loudness-level contours were significantly modified during the revision of ISO 226 in 2003, including experimental data from 12 new studies. However, A-weighting values were never updated accordingly. Note that isophone contours are based on loudness perception of pure tones, which are quite different from daily life sounds. However, the isophone contours are probably the best approximation to human hearing sensitivity available at this moment.

Figure 1 shows different weighting functions: A-weighting, the inverted 40-phon and 60-phon curves (former and revised versions), all having been normalized so that their reference value at 1 kHz is 0 dB. This representation shows that the A-weighting curve has a similar slope in the lower frequency range as the functions based on the former and revised 60-phon contours. In comparison, the weighing function based on the revised 40-phon contour is 8 dB lower at 50 Hz. This means that the calculation procedure in ISO 717-1 assumes relatively high sound levels on the receiving

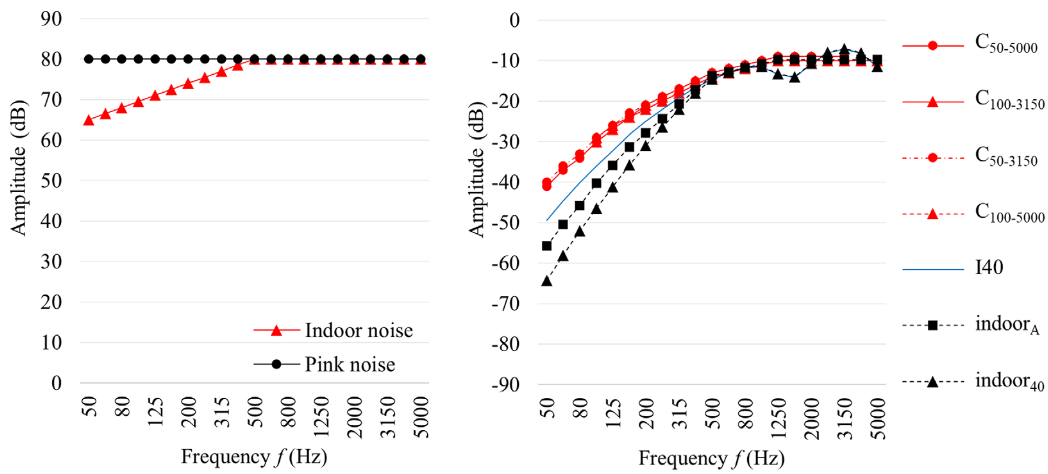

Figure 2. Left: spectrum of indoor noise used as stimulus for Zwicker's Loudness based assessments. Right: adaptation spectral terms of different SNQs.

side. Therefore, spectrum adaptation terms may be relevant to rate constructions with moderate acoustic performance mostly.

It has been shown [20] that due to differences between the weighting spectrum and the spectrum of people's hearing sensitivity the resulting single number quantity values may not adequately express the subjectively perceived insulation performance. This has inspired us to design SNQs based on potentially more adequate weighting curves and/or sending sound spectra: (i) replacing A-weighing by a function derived from the revised 40-phon equal-loudness-level contour, and (ii) replacing pink noise by an alternative sending sound spectrum more representative of indoor environments.

As mentioned above, assessing the adequacy of a SNQ is typically done by listening tests in which the insulation performance of walls as quantified by SNQs is compared with their performance as perceived by test persons. Ideally, the ranking of the insulation performance of walls based on their SNQ value should be the same as the ranking based on people's perception of the loudness of sound transmitted through those walls.

Due to the requirement of a sufficiently large, statistically representative set of tested walls and of a large number of test persons, proper assessment of SNQs by listening tests is very time consuming. In order to overcome this, in this work, we have used an alternative methodology [21], in which we replaced the subjective, listening test-based evaluation of loudness, by calculated Zwicker's Loudness (later in the text referred to also as Loudness) [22, 23]. We have applied this new approach for the assessment of the adequacy of eight different single number quantities, from which five are currently in use; R_{w}, $R_{\mathrm{w}} + C_{100\text{–}3150}$, $R_{\mathrm{w}} + C_{50\text{–}3150}$, $R_{\mathrm{w}} + C_{100\text{–}5000}$, $R_{\mathrm{w}} + C_{50\text{–}5000}$; and three new ones are put forward. One of the newly proposed SNQ is based on pink noise weighted by isophone 40 (cf. ISO 226:2003) and the other two are involving a combination of a newly proposed indoor spectrum, weighted respectively by A-weighting and by isophone 40.

In Section 2, we briefly present the newly proposed indoor spectrum. In Section 3 we elaborate on the emitted sounds that we have used for the determination of transmitted sound Loudness, on the selection of walls, and on combining those to obtain respective transmitted sounds. In Section 4 we discuss the degree of correlation between rankings of wall insulation performance based on the different SNQs and on the Zwicker's Loudness based assessment methodology. In the final section, conclusions are drawn, and perspectives for future research are given.

2 Description of a new indoor spectrum

The proposed indoor sound spectrum aims at being representative for an average household in Europe. Its calculation method is presented in [24] and was designed to use verifiable data as input. It was obtained from the energetic sum of the emission spectra of sound sources commonly found in residential buildings, each weighted by its estimated occurrence time. In total, the 71 airborne sound sources were considered, including 8 types of service equipment, 28 household appliances, 14 audiovisual devices and 21 sounds produced by human voices or human activities. For 9 of them, typical emission characteristics were found in literature [25]. For the others, calibrated audio recordings were made in real dwellings to complete the data. For each sound source category, the occurrence factor was obtained from statistical data at the European level [26], or, in case no data were available, on assumptions. Since no statistical data were available for most individual sound sources, categories were used (e.g., video equipment, cooking appliances, etc.). The occurrence factor was determined from the share of the population engaging in the considered activity on a regular basis, and on the daily time dedicated to this activity by the same share of the population. It accounts for differences between countries and a European weighted average is calculated considering the population of each

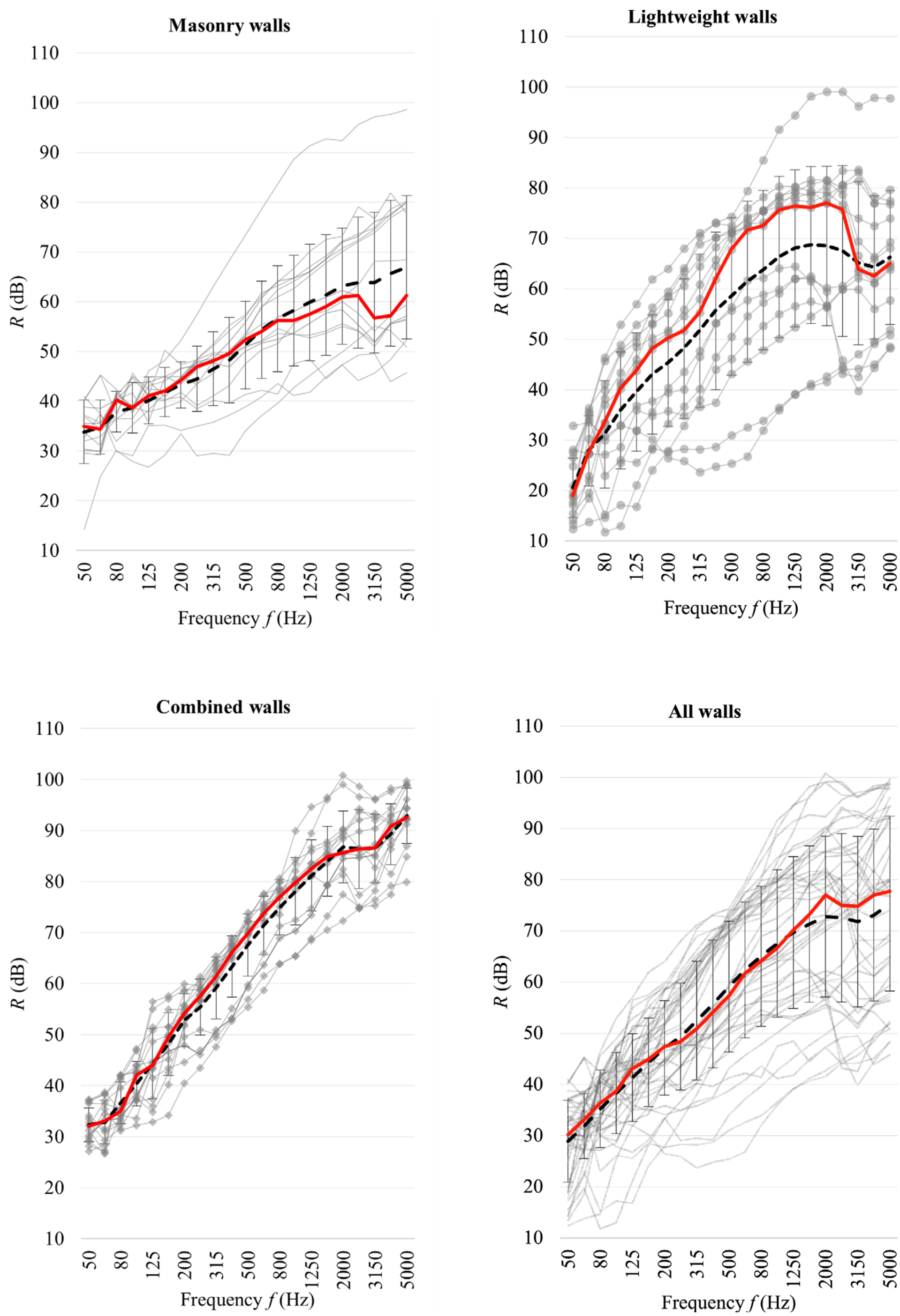

Figure 3. Sound reduction index R (dB) of all considered walls (grey curves), average spectrum (dashed black curve) with standard deviation (error bars) and median spectrum (red curve). The 4 panels show the spectra for masonry walls (top left), lightweight walls (top right), combined walls (bottom left) and all walls together (bottom right).

country. It should be noted that the input datasets cover different periods between 2000 and 2010. Therefore, some recent changes in the occupants' habits may not be accounted for, like for instance the spread of teleworking following the COVID-19 pandemic. Assumptions were also made to determine whether the considered activity is shared by the household (e.g., use of the washing machine) or repeated by each member (e.g., showering). All these assumptions are documented in [24].

The equivalent sound spectrum was calculated from the emission spectrum and occurrence factor of each category. As a simplification, the resulting spectrum was then split into two parts to produce an idealized spectrum that catches the global trend as follows: a regular increase of

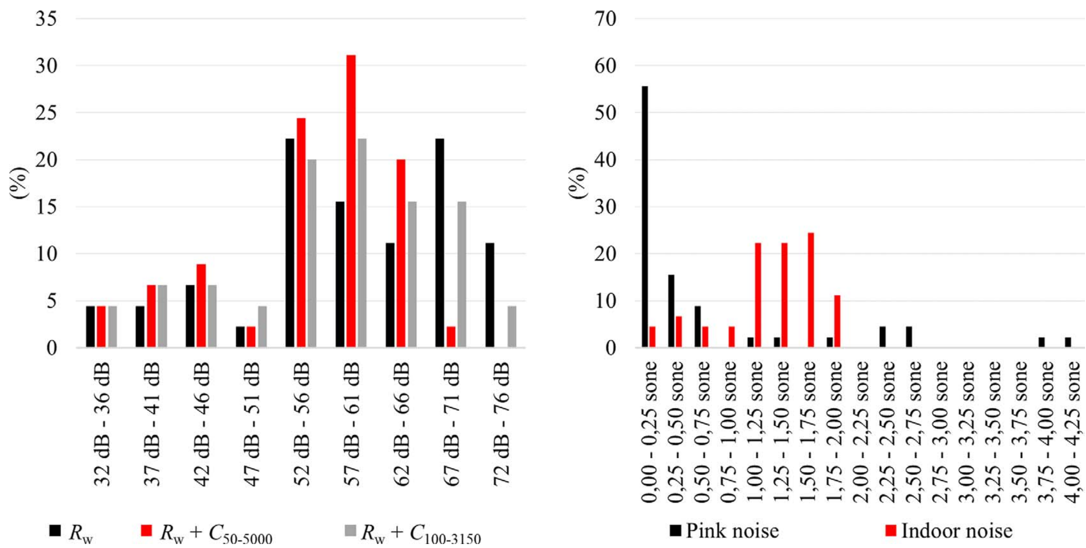

Figure 4. Histogram of the distribution of the walls over different R_w, $R_w + C_{50\text{–}5000}$ and $R_w + C_{100\text{–}3150}$ qualifiers (left), and over different Loudness values (right).

Table 1. Description of the evaluated SNQ's (see also Fig. 2 for spectrum adaptation terms). The upper five are already in use.

Symbol	Description
R_w	Weighted sound reduction index.
$R_w + C_{50\text{–}5000}$	Weighted sound reduction index modified by spectrum adaptation term, derived from A-weighted pink noise spectra 50–5000 Hz.
$R_w + C_{100\text{–}3150}$	Weighted sound reduction index modified by spectrum adaptation term, derived from A-weighted pink noise spectra 100–3150 Hz.
$R_w + C_{50\text{–}3150}$	Weighted sound reduction index modified by spectrum adaptation term, derived from A-weighted pink noise spectra 50–3150 Hz.
$R_w + C_{100\text{–}5000}$	Weighted sound reduction index modified by spectrum adaptation term, derived from A-weighted pink noise spectra 100–5000 Hz.
$R_w + I_{40}$	Weighted sound reduction index modified by spectrum adaptation term, derived from pink noise spectra 50–5000 Hz weighted by inverted 40-phon contour.
R_w + indoor$_A$	Weighted sound reduction index modified by spectrum adaptation term, derived from A-weighted indoor noise spectra 50–5000 Hz.
R_w + indoor$_{40}$	Weighted sound reduction index modified by spectrum adaptation term, derived from indoor noise spectra 50–5000 Hz weighted by inverted 40-phon contour.

4.5 dB per octave between 50 Hz and 500 Hz, then a stable level up to 5 kHz. The absolute level has no importance since an arbitrary reference was used.

This result remains uncertain due to several methodological limitations. One of them is the number and type of sound sources taken into consideration. Indeed, some source categories like musical instruments – potentially influential in the low frequency range – were neglected due to the lack of occurrence data and because of the variability of their emission characteristics, which depend on the instrument itself as well as the player's action. For other sound sources, the emission characteristics were evaluated through a small number of recordings. Plus, these recordings were made in real dwellings, with a simplified method to derive sound power and without the ability to separate airborne sound from structure-borne sound when it occurs (e.g., washing machine). Therefore, more research may be needed to challenge the assumptions made and improve the representativeness of the proposed indoor sound spectrum. It should also be noted that this approach is focused on sounds produced in residential buildings and fully based on their occurrence, without any consideration of the associated annoyance.

Figure 2 shows the spectra used for calculation of the 8 SNQ used in this study. Note that R_w does not use an adaptation spectral term and therefore it does not appear in Figure 2. The SNQs that involve standardized spectrum adaptation terms "C" (which are based on A-weighted pink noise) and used for calculation of four existing quantities ($R_w + C_{100\text{–}3150}$, $R_w + C_{50\text{–}3150}$, $R_w + C_{100\text{–}5000}$, $R_w + C_{50\text{–}5000}$) are shown in red.

The first (i) newly proposed spectrum, indicated as I40, which is calculated as pink noise weighted by isophone 40, is shown in a blue. The other two new indoor spectra indicated as (ii) indoor$_A$ dB, and (iii) indoor$_{40}$ dB are shown in black. The "indoor$_A$ dB" SNQ is based on the A-weighted new indoor spectrum and the "indoor$_{40}$ dB" SNQ is weighted by Isophone 40.

Table 2. Overview of all initially considered walls and their properties (code name of walls is composed from order_type_ _R_w of analyzed walls). Acronyms LW stands for Lightweight walls, HW is for masonry walls and Combined means masonry walls with plaster boards lining system. Walls indicated in "**bold font**" had extreme properties (either having too poor insulation for separating dwelling apartments or having insulation so high that the transmitted sound was below hearing threshold) were discarded for the correlation analysis.

Code name	Weighted sound reduction index	Spectrum C (Pink noise weighted by A)				Pink noise weighted by isophone 40	Indoor spectrum weighted by A filter	Indoor spectrum weighted by isophone 40	Loudness	
									Pink noise	Indoor noise
	R_w	$R_w + C_{50-5000}$	$R_w + C_{100-3150}$	$R_w + C_{50-3150}$	$R_w + C_{100-5000}$	$R_w + I_{40}$	R_w + indoor$_a$	R_w + indoor$_{40}$	N	N
	dB	dB	dB	dB	dB	dB	dB	dB	Sone	Sone
1_LW_33	**33**	**33**	**32**	**32**	**33**	**34**	**34**	**34**	**4,160**	**3,830**
2_LW_36	**36**	**36**	**35**	**35**	**36**	**37**	**37**	**38**	**3,840**	**3,440**
3_HW_39	**39**	**39**	**38**	**38**	**39**	**40**	**41**	**41**	**2,700**	**2,320**
4_LW_41	**41**	**39**	**39**	**38**	**39**	**42**	**44**	**44**	**2,710**	**2,000**
5_HW_42	**42**	**42**	**42**	**42**	**43**	**43**	**43**	**44**	**2,270**	**2,030**
6_LW_43	**43**	**39**	**40**	**38**	**40**	**43**	**46**	**46**	**2,380**	**1,590**
7_HW_45	45	45	45	44	45	45	45	45	1,900	1,760
8_LW_47	47	46	46	45	46	48	48	49	1,350	1,090
9_HW_52	52	51	51	50	51	53	53	54	0,653	0,517
10_LW_53	53	45	51	44	51	51	55	58	1,140	0,513
11_HW_53	53	52	52	52	53	53	53	53	0,694	0,590
12_HW_53	53	53	52	52	53	53	54	53	0,672	0,560
13_HW_53	53	53	52	52	53	53	53	53	0,662	0,557
14_LW_55	55	53	53	52	53	56	57	59	0,472	0,291
15_combined_55	55	53	52	52	53	56	59	61	0,457	0,251
16_HW_56	56	55	55	55	55	55	56	56	0,419	0,350
17_HW_56	56	55	55	55	56	56	57	57	0,402	0,322
18_HW_56	56	55	54	54	55	57	59	60	0,359	0,237
19_HW_57	57	56	56	55	56	59	60	61	0,295	0,184
20_HW_59	59	57	57	56	58	61	63	64	0,235	0,106
21_HW_59	59	58	58	57	58	60	62	63	0,205	0,122
22_combined_59	59	59	58	58	59	61	62	64	0,185	0,107
23_HW_60	60	59	58	58	59	61	63	64	0,185	0,100
24_combined_61	61	59	59	58	60	62	64	65	0,180	0,079
25_combined_61	61	59	60	58	61	63	65	66	0,156	0,059
26_combined_63	63	58	58	57	59	63	66	70	0,195	0,059
27_combined_64	64	60	59	59	60	64	68	72	0,150	0,041
28_LW_65	65	55	63	54	64	62	66	70	0,240	0,039
29_combined_66	66	59	61	58	62	65	69	73	0,150	0,021
30_LW_66	66	58	64	57	65	65	69	73	0,111	0,006
31_combined_67	67	59	61	58	62	65	69	73	0,137	0,011
32_LW_67	67	59	65	58	66	65	69	73	0,102	0,004
33_HW_67	67	64	64	63	65	69	72	76	0,048	0,000
34_combined_68	68	62	65	61	66	68	71	75	0,070	0,002
35_combined_68	68	65	66	64	67	69	72	74	0,026	0,000
36_LW_69	69	52	66	51	65	59	64	67	0,393	0,076
37_combined_70	**70**	**62**	**67**	**61**	**67**	**68**	**72**	**76**	**0,060**	**0,000**
38_combined_70	**70**	**67**	**68**	**66**	**69**	**71**	**73**	**75**	**0,006**	**0,000**
39_LW_71	**71**	**59**	**69**	**58**	**70**	**66**	**71**	**73**	**0,062**	**0,000**
40_combined_71	**71**	**62**	**68**	**61**	**68**	**68**	**72**	**76**	**0,046**	**0,000**
41_LW_72	**72**	**57**	**68**	**56**	**66**	**63**	**66**	**66**	**0,143**	**0,000**
42_combined_72	**72**	**62**	**69**	**61**	**70**	**69**	**73**	**77**	**0,043**	**0,000**
43_combined_72	**72**	**62**	**69**	**61**	**70**	**69**	**73**	**77**	**0,036**	**0,000**
44_LW_74	**74**	**64**	**72**	**63**	**73**	**71**	**76**	**80**	**0,014**	**0,000**
45_LW_76	**76**	**65**	**73**	**65**	**71**	**69**	**72**	**71**	**0,007**	**0,000**

3 Synthesis of sound stimuli

In view of evaluating the adequacy of SNQs for a maximum number of situations that can occur in practice, 45 walls (that could be potentially chosen as partition walls in dwellings) were selected. The walls can be classified into three groups: 15 masonry walls, 15 "lightweight walls", i.e., double gypsum board walls, and 15 "combined walls", i.e., double walls based on masonry walls and gypsum boards, with an airgap filled by a porous material, such as mineral

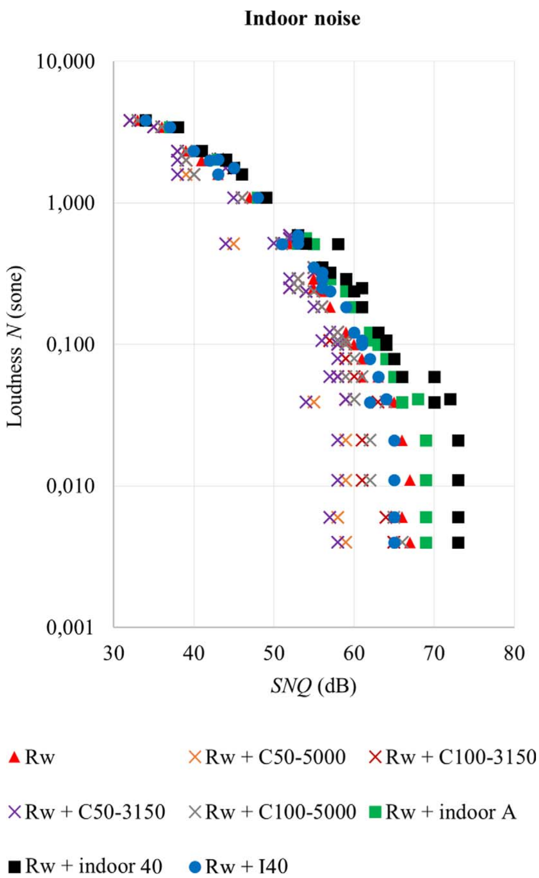

Figure 5. Correlation between the Zwicker's Loudness values of transmitted sounds (in case of indoor noise at the emitting side) and values of 8 SNQs for the tested walls.

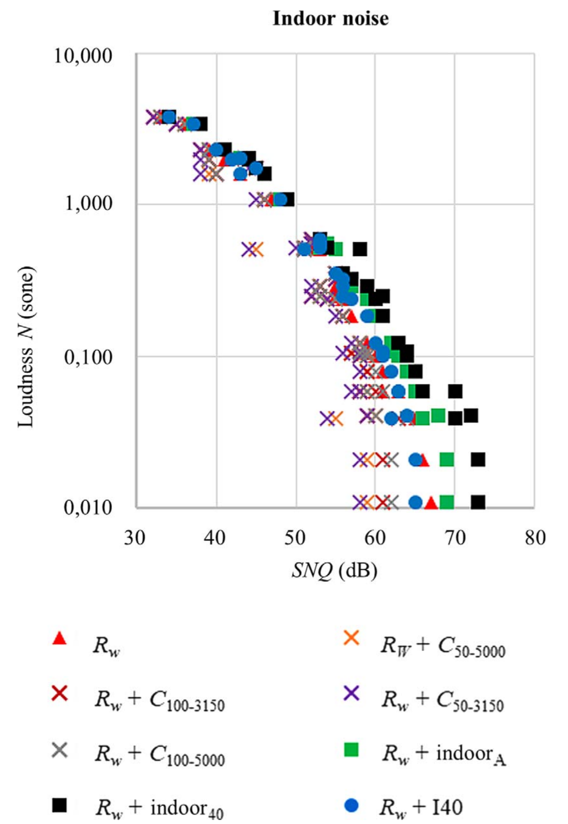

Figure 6. Correlation between the Zwicker's Loudness of transmitted sounds (in case of pink noise at the emitting side) and values of 8 SNQs for the tested walls.

wool. Figure 3 shows an overview of the sound reduction index R of these 45 walls. The eight above mentioned SNQs of each wall were calculated for sake of the later comparisons (Tab. 2).

The Loudness values of the sounds transmitted through the walls were calculated for two different types of sounds on the emitting side (e.g., expressing the sending room or a neighbours' apartment): (1) pink noise and (2) indoor noise. For the calculation of the Zwicker's Loudness, we needed calibrated sound stimuli with known absolute sound pressure level. The absolute sound pressure level of the pink noise sound (50 Hz to 5000 Hz) was 80 dB. From this pink noise, the indoor noise was created by decreasing of 1.5 dB per third octave band from 500 Hz to 50 Hz (−15 dB for third octave band 50 Hz) [24]. These rather high values of sound levels in each third-octave band represent scenarios that have a substantial probability to be disturbing on the receiving side in case of walls with somewhat poor insulation.

The two types of emitted sounds (pink noise and indoor noise) were filtered by the wall transmission spectra (50–5000 Hz) indicated in Figure 3, and the respective Loudness values N (son) were calculated. It turned out that for 5 of the walls, the obtained Loudness values (for highly insulating walls) were near to zero, indicating that the transmitted sound would not be audible. It has been therefore decided to remove these walls from the further analysis. An additional consideration that led to a further reduction of the number of walls, was to also omit the walls with very poor insulation. The limiting value was set to $R_w = 45$ dB. Together, this resulted in a selection of 40 walls to be considered for further statistical analysis.

In order to give an idea on the distribution of sound insulation quality of the 40 selected walls used in the study, Figure 4 shows histograms of the Loudness values, and the values of 3 well known SNQs: R_w, $R_w + C_{100–3150}$, and $R_w + C_{50–5000}$. Most of the walls used in this study lie in the interval of 55–60 dB, which are typical values of R_w, in most European countries [27].

Figure 4-right shows the distribution of Loudness values of the two sounds (pink noise and indoor noise) transmitted through the 40 chosen walls. For pink noise, more than half of the values are in the interval of Loudness N, between 0–0,25 sone and only very little sounds are above the value of $N > 0{,}75$ sone. The large percentage of audible pink noise audible at very low sound level (just above the threshold of hearing), in comparison with indoor noise (Fig. 4-right) is most probably caused by low frequency components in transmitted sound. In other words, the sounds transmitted through typical walls between dwellings is on the very silent side. Therefore, since in these cases the transmitted

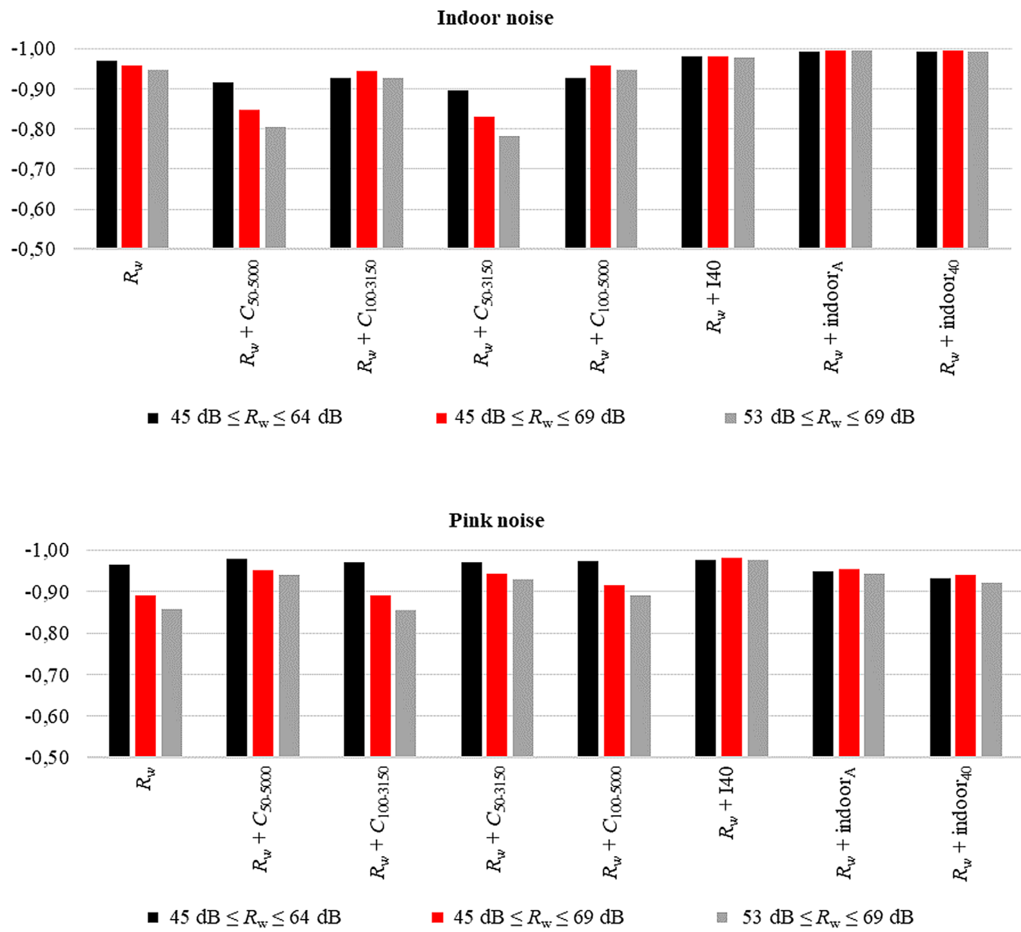

Figure 7. Degree of correlation between SNQ-ranking and transmitted loudness-based ranking, as quantified by Spearman's rank-order correlation, based indoor noise (top) and on pink noise (bottom) as emitted sound. The closer SROC is to −1, the better the correlation.

sound pressure level is substantially lower than 40 dB, A-weighting might be inappropriate for the calculation of a SNQ.

4 Assessment of SNQ adequacy

As mentioned in the introduction, the working hypothesis of this work is that the adequacy of a SNQ can be assessed by evaluating to what extent this SNQ ranks the representative set of selected walls consistently with the ranking of these walls according to the Loudness of the used pink noise or indoor noise transmitted through those walls. In other words, the adequacy of an SNQ is believed to scale with the monotonicity of the relation SNQ ($L_{\text{transmitted}}$), evaluated across the different sound-wall combinations. The exact functional dependence of this relation is of no particular importance. In view of that, we have chosen to make use of the function independent Spearman's rank-order correlation (SROC) [28] between the sorted vectors SNQ(w) and $L_{\text{transmitted}}$(w), with "w" the wall index.

As mentioned above, eight different single number quantities have been evaluated, from which five are currently in use; R_w, $R_w + C_{100–3150}$, $R_w + C_{50–3150}$, $R_w + C_{100–5000}$, $R_w + C_{50–5000}$. The nature of these SNQs is described in Table 1, and an overview of all considered walls and their properties is listed in Table 2.

The degree of (inverse) correlation between the 8 SNQ's and the transmitted Loudness can be visually assessed from Figures 5 to 6. Obviously, all relations show a decreasing trend, but there are differences in quality. The SROC values of the different SNQs are depicted in Figure 7.

5 Visual assessment of data

Comparing the results in Figures 5 and 6 visually, the following observations can be made. Using pink noise as emitting sound (Fig. 6), the eight different SNQs show a more similar trend than using indoor sound (Fig. 5). Apparently, in the latter case, different SNQs evaluate different quality features. In the case of pink noise, the steepness of the relations is quite small. There are even some clusters of cases where in spite of different SNQ values (e.g. between 54–58 dB or 56–65 dB), the Loudness values are equal. In other words, these walls have *de facto* the same insulation properties, while they are *de jure* rated with a different SNQ. This problem is most pronounced for $R_w + C_{50–5000}$ and $R_w + C_{50–3150}$. As an illustration of the

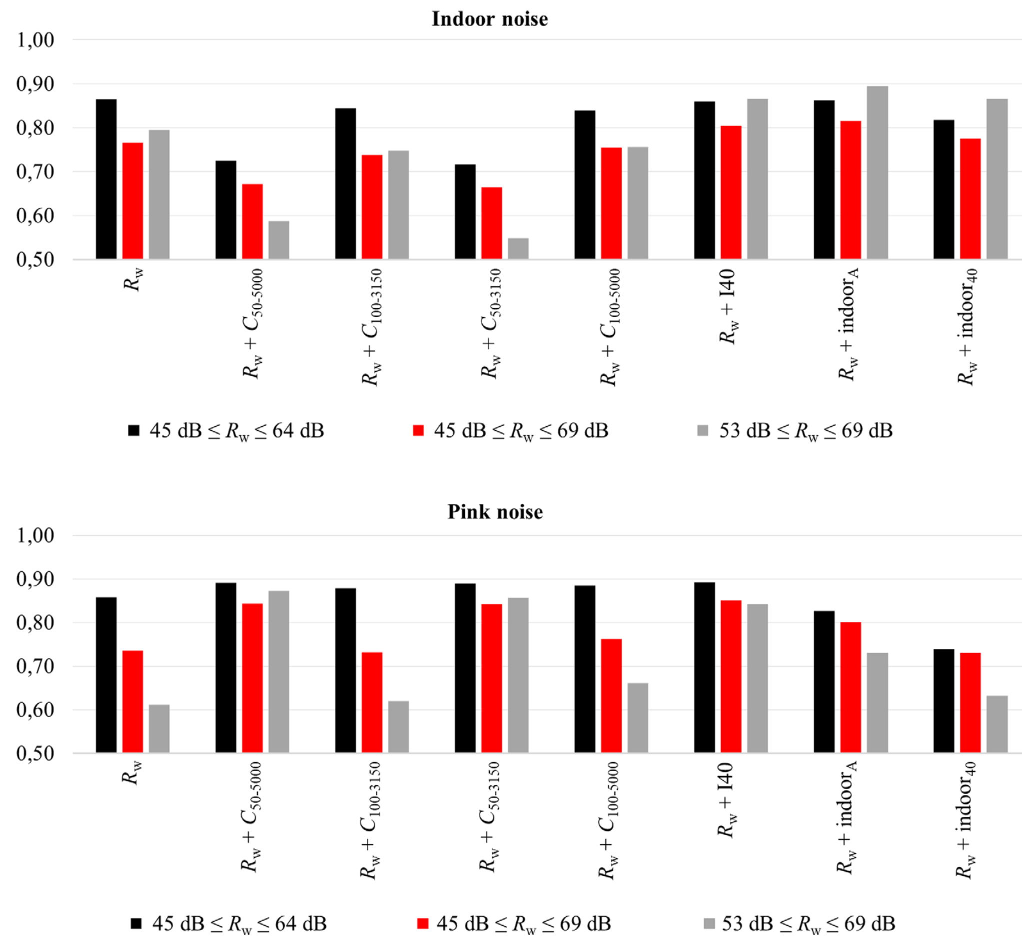

Figure 8. Degree of correlation between SNQ-ranking and transmitted loudness-based ranking, as quantified by R^2 rank-order correlation, based indoor noise (up) and on pink noise (bottom) as emitted sound.

possible consequences, the above discrepancy might imply that in some countries a wall with $R_w + C_{50-5000} = 54$ dB would be classified lower (normal acoustic comfort) than one with $R_w + C_{50-5000} = 58$ dB (increased acoustic comfort), in spite of their Loudness based performance being the same. Note that the walls with very high sound insulation and very bad sound insulation are not shown in Figures 5 and 6.

Figure 5 shows that there are also clusters of walls, which, in spite of the transmitted Loudness being very different, according to their equal SNQ, would be ranked as equally isolating. This discrepancy occurs for $R_w + C_{50-3150}$ and $R_w + C_{50-5000}$ for walls in the 50 dB – 60 dB range, which covers values that are quite common for partitions between dwellings. For the newly proposed SNQs this happens only for some walls with superior insulation, so that the involved consequences are less critical (the levels of the transmitted sound is so low that in daily life circumstances it is masked by background noise). Nevertheless, this indicates that it is not feasible to conceive an SNQ that is perfectly adequate (in terms of being consistent with Loudness) without any exception. This is not surprising, given the non-uniformity of many of the insulation spectra.

Figure 5 (indoor noise at emitting side) shows a very good correlation slope for the three newly proposed quantities, especially in the range 45–64 dB. These SNQs are thus good descriptors in the given range. In case of the newly proposed parameter R_w + indoor$_{40,}$ the performance is actually quite good over the full Loudness range (SNQ value range 45–70 dB), including highly insulating walls. For only about 3 of the 45 walls the Loudness values can be considered as outliers that strongly deviate from the rather monotonic N(SNQ) trend. The detailed and individual data of Figures 5 and 6 are shown in Table A2 in the annexes of this article.

6 Statistical analysis

Figures 7 and 8 depict the results of statistical analysis performed on the data shown in Figures 5 and 6. Two statistical models were used and listed in Table 3: Spearman's correlation (Fig. 7) and logarithmic R^2 rank-order correlation (Fig. 8). The statistical analysis was performed for three different sound insulation intervals in terms of R_w (which is at the moment the mostly used quantity): (i) 45–64 dB, (ii) 45–69 dB, and (iii) 53–69 dB. This *ad hoc* classification was made on the basis of clearly different

Table 3. R^2 SROC coefficients between SNQs and Loudness values based on pink noise and indoor noise, for wall categorized in different R_w classes.

SNQ	R^2						Spearman's correlation (SROC)					
	Pink noise			Indoor noise			Pink noise			Indoor noise		
	45 dB $\leq R_w \leq$ 64 dB	45 dB $\leq R_w \leq$ 69 dB	53 dB $\leq R_w \leq$ 69 dB	45 dB $\leq R_w \leq$ 64 dB	45 dB $\leq R_w \leq$ 69 dB	53 dB $\leq R_w \leq$ 69 dB	45 dB $\leq R_w \leq$ 64 dB	45 dB $\leq R_w \leq$ 69 dB	53 dB $\leq R_w \leq$ 69 dB	45 dB $\leq R_w \leq$ 64 dB	45 dB $\leq R_w \leq$ 69 dB	53 dB $\leq R_w \leq$ 69 dB
R_w	0,8579	0,7358	0,6115	0,8646	0,7662	0,7952	−0,9650	−0,8919	−0,8576	−0,9699	−0,9567	−0,9451
$R_w + C_{50-5000}$	0,8908	0,8430	0,8723	0,7245	0,6712	0,5868	−0,9794	−0,9509	−0,9399	−0,9159	−0,8482	−0,8048
$R_w + C_{100-3150}$	0,8792	0,7312	0,6193	0,8439	0,7374	0,7472	−0,9719	−0,8901	−0,8547	−0,9271	−0,9426	−0,9278
$R_w + C_{50-3150}$	0,8901	0,8426	0,8569	0,7163	0,6643	0,5481	−0,9695	−0,9421	−0,9288	−0,8965	−0,8309	−0,7818
$R_w + C_{100-5000}$	0,8844	0,7622	0,6613	0,8397	0,7547	0,7559	−0,9725	−0,9152	−0,8901	−0,9259	−0,9566	−0,9478
$R_w + I_{40}$	0,8926	0,8512	0,8423	0,8598	0,8047	0,8656	−0,9752	−0,9825	−0,9769	−0,9811	−0,9808	−0,9770
$R_w + \text{indoor}_A$	0,8268	0,8007	0,7299	0,8618	0,8147	0,8943	−0,9482	−0,9547	−0,9423	−0,9919	−0,9951	−0,9953
$R_w + \text{indoor}_{40}$	0,7396	0,7300	0,6326	0,8172	0,7757	0,8665	−0,9316	−0,9408	−0,9224	−0,9909	−0,9934	−0,9910

trends in difference in performance of some SNQs between the latter intervals.

Spearman's correlations in Figure 7 confirm the observations made visually in Figures 5 and 6. The best correlation (SROC close to −1) is in general observed for the three newly proposed quantities, especially $R_w + \text{indoor}_A$ and $R_w + \text{indoor}_{40}$, when indoor noise is used as emitting source. The worse performance is offered by $R_w + C_{50–3150}$ and $R_w + C_{50–5000}$. The most "consistent" SNQ, i.e. the one that is least dependent on the choice of emitted noise (pink or indoor) is $R_w + I_{40}$ and $R_w + \text{indoor}_{40}$, which is scoring well in all cases. $R_w + C_{50–3150}$ and $R_w + C_{50–5000}$ are also least consistent between the two types of emitted noise. In the Appendix, a series of wall pairs are discussed, with the goal to give some insight in the reasons why some wall pairs yield an equal Loudness but different SNQ or vice versa.

In Figure 8, the logarithmic R^2 rank-order correlations are shown. Care should be taken to analyse these data together with the results in Figures 5–7 (which visualize the monotonicity). Some parameters might reach good R^2 rank-order, but if the data is not monotonic and the slope of correlation is not steep enough, then the SNQ does not represent the quality of sound insulation well. Figure 8 shows that $R_w + \text{indoor}_A$ has the highest R^2 rank order for indoor noise. $R_w + C_{50–5000}$ and $R_w + C_{100–3150}$ have the highest R^2 rank order for pink noise.

7 Conclusions

Based on earlier reports [14, 15] that Zwickers' Loudness is an adequate quantity to be used for the perceived loudness of sound transmitted through walls in the framework of airborne sound insulation assessments, this quantity has here been used to compare the adequacy of existing and newly conceived single number quantities for airborne sound insulation. Two different emitting sounds (pink noise and newly proposed indoor noise) were filtered through 40 different lightweight, heavyweight and combined walls, and the Zwicker's Loudness values of the transmitted sounds were calculated.

Based on the correlations between the Loudness values and the eight SNQs, the following conclusions can be made. Compared to the use of pink noise as stimulus on the sending side of the walls to be assessed, use of the newly proposed indoor noise leads to more monotonic correlations between transmitted Loudness and SNQ value, and thus a clearer differentiation between walls with different insulation quality.

Based on the newly proposed indoor noise, the best SROC correlations were found for the three newly proposed quantities, especially $R_w + \text{indoor}_A$, $R_w + \text{indoor}_{40}$, and R_w + I40, while the poorest consistency was found for $R_w + C_{50–3150}$ and $R_w + C_{50–5000}$. The latter two SNQs severely fail when it comes to assessment of well insulating walls, which in some cases would be classified in different acoustic comfort classes (normal and enhanced) in spite of equal transmitted Loudness. This could be expected, as they both are based on A-weighting, which is not adequate for well-isolated sounds with low intensities, especially at low frequencies. For pink noise, the best correlation was found for R_w + I40.

The most consistent quantity in terms of independence of the emitted sound type is the newly proposed $R_w + I_{40}$. According to all performed quality assessments, this SNQ is among the best three parameters.

The work shows that the use of Zwicker's Loudness in the assessment of transmitted sound is a useful tool for research for the conception, adaptation or validation of single number quantities that are aimed to quantify airborne sound isolation.

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Appendix

The left panel in Figure A1 shows the insulation spectra of 2 walls with equal $R_w + C_{50-5000}$ value (58 dB). In spite of their equal value, the spectra of walls "21_HW_59" and "30_LW_66" are quite different. Moreover, the Loudness of pink noise transmitted through the LW ($N = 0.111$ sone), and HW ($N = 0.205$ sone) walls are different by almost a factor 2, or 3 dB in terms of L_N value. The HW wall is less isolating than the LW wall over almost the whole spectrum. Nevertheless, due to its better insulation below 100 Hz, its $R_w + C_{50-5000}$ value is equally good. Frequencies below 100 Hz are much less audible than higher frequencies, explaining why the insulation of the LW wall is judged significantly based on the Loudness of the transmitted sound. SNQ $R_w + I_{40}$ (based on pink noise weighted by isophone 40) of the LW wall (65 dB) is 5 dB higher than the one of the HW wall (60 dB), which is qualitatively consistent with their Loudness based ranking. According to SNQ R_w, the LW wall scores even 66–59 = 7dB higher than the HW wall.

The right panel in Figure A1 shows the insulation spectra of two walls, LW wall "36_LW_69" and HW wall "17_HW_56". In spite of their almost equal Loudness value for transmitted pink noise sound, respectively $N = 0.393$ sone and $N = 0.402$ sone, their $R_w + C_{50–5000}$ values are 3 dB different, respectively 52 dB and 55 dB. The difference in qualification is again related to the relative weight of the frequencies below 100 Hz in the assessment. $R_w + C_{50-5000}$ is qualifying the HW wall 3 dB better than the LW wall, in spite of the HW wall having a substantially poorer insulation for frequencies above 100 Hz. According to SNQs $R_w + I_{40}$ and R_w, the HW wall is qualified respectively 59–56 = 3 dB and 69–56 = 13 dB better than the LW wall, as a consequence of these SNQs, in particular R_w, giving higher importance to high frequency insulation in their weighting.

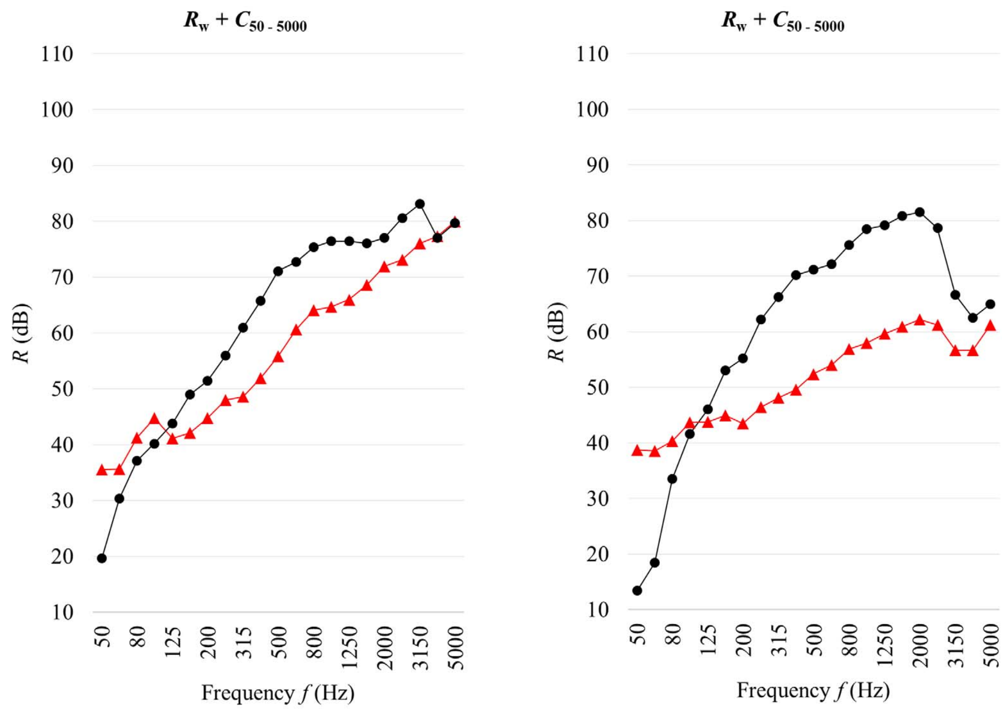


Figure A1. *Left*: spectra of 2 walls with equal $R_w + C_{50–5000}$ SNQ value (58 dB): wall "21_HW_59" $N = 0.205$ sone (red curve with triangles), wall "30_LW_66", $N = 0.111$ sone (black curve with dots). *Right*: spectra of 2 walls with very similar transmitted Loudness values: wall "36_LW_69", $R_w + C_{50–5000} = 52$ dB, $N = 0.393$ sone (black curve with dots), wall "17_HW_56", $R_w + C_{50–5000} = 55$ dB, $N = 0.402$ sone (red curve with triangles). The mentioned Loudness values (N) are based on emitted pink noise on the sending side.

Table A1. Selection of the walls of which the spectra are depicted in Figure A1, and their properties.

Code name	Weighted sound reduction index	Spectrum C (Pink noise weighted by A)				Pink noise weighted by isophone 40	Indoor spectrum weighted by A filter	Indoor spectrum weighted by isophone 40	Loudness	
									Pink noise	Indoor noise
	R_w	$R_w + C_{50–5000}$	$R_w + C_{100–3150}$	$R_w + C_{50–3150}$	$R_w + C_{100–5000}$	$R_w + I_{40}$	R_w + indoor$_A$	R_w + indoor$_{40}$	N	N
	dB	dB	dB	dB	dB	dB	dB	dB	Sone	Sone
21_HW_59	59	58	58	57	58	60	62	63	0,205	0,122
30_LW_66	66	58	64	57	65	65	69	73	0,111	0,006
17_HW_56	56	55	55	55	56	56	57	57	0,402	0,322
36_LW_69	69	52	66	51	65	59	64	67	0,393	0,076

Table A2. Individual data used for summary graphs Figures 5 and 6. Correlation between the Zwicker's Loudness values of transmitted sounds (in case of indoor noise and pink noise at the emitting side) and values of 8 SNQs for the tested walls. Each correlation is given in an individual graph.

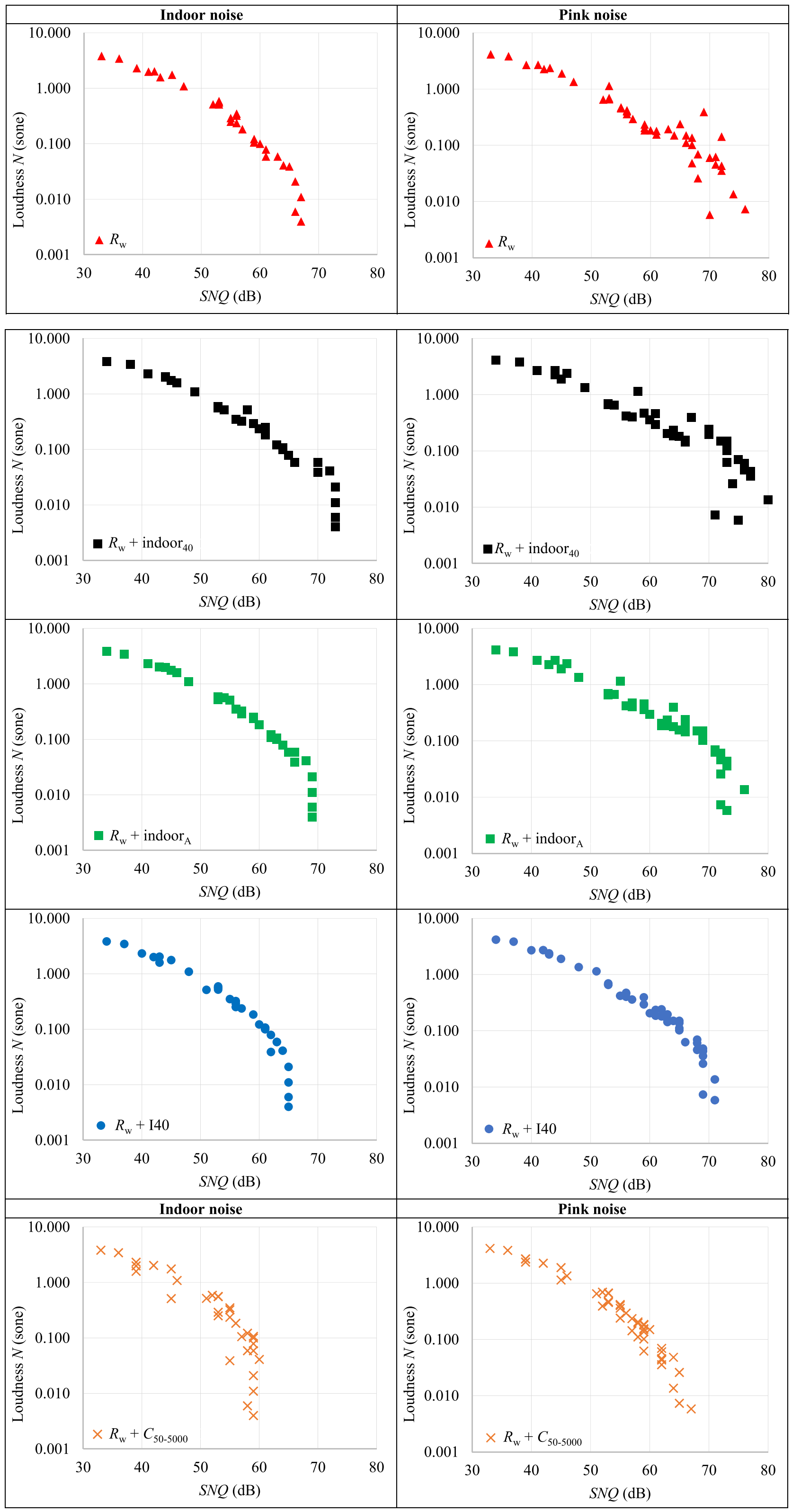
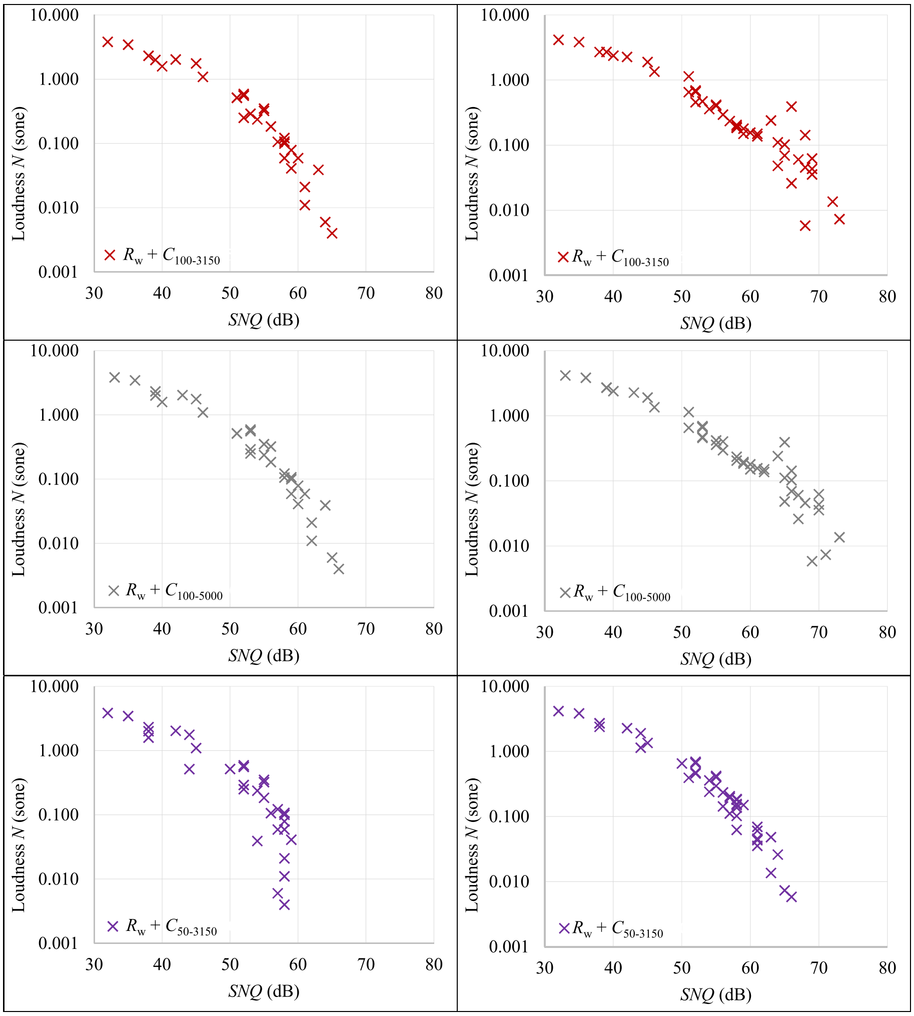


Table A2. Continued



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