Assessment criterion for indoor noise disturbance in the presence of low frequency sources

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ABSTRACT

Several studies have presented the effects of environmental noise in and around buildings and communities in which people live and work. In particular, the noise introduced into a building is mostly evaluated using the A weighted sound pressure level (L_{Aeq}) as the only parameter to determine the perceived disturbance. Nevertheless, if noise is produced by activities or sources characterised by a low frequency contribution, the measurement of L_{Aeq} underestimates the real disturbance, in particular during sleeping time.

The international literature suggests methods to evaluate the low-frequency noise contribution to annoyance separately from the A weighted sound pressure level; almost all of the proposed methods are based on exceeding a threshold limit.

This paper tests international criteria, by applying them in real-life indoor noise situations, and then analysing, comparing and contrasting results.

Based on the result of the procedure above, a new criterion consisting of a single threshold is proposed, which simplifies the procedures in case of low-frequency components, but could be used for any situation.

1. Introduction

The existing and consolidated assessment methods of annoyance inside dwellings are widely based on the A-weighted sound pressure level measurement (L_{Aeq}). Nevertheless this parameter leads to an underestimation of the influence of mid (generally over 250 Hz) and low (generally below 250 Hz) frequencies [1–3].

Noise disturbance has increased hugely in the last 15–20 years. Even if traffic noise is generally considered as the first cause of disturbance, both for annoyance or sleep problems, in many cases the source is related to music, people speaking or external noisy machinery. In particular, concerning the first source, weekends have become a very difficult period for inhabitants living close to venues such as clubs, discotheques and pubs. Furthermore, these activities have usually powerful external HVAC (Heating, Ventilating, Air Conditioning), increasing the noise problems at low frequencies.

Moreover, at night the residual noise is generally lower than during the daytime and consequently the disturbance is increased. In many countries, the existing regulations do not provide an objective method able to determine whether music, HVAC or other sources create annoyance in relation to a given moment or period.

Often, the criteria used are fully based on A-weighted sound pressure levels. The A-weighting is based on the peculiar perceptions of the human ear. So using L_{Aeq} level as a mean value or as the difference with background or residual noise could lead to a misinterpretation of the results, as explained below.

The background noise is defined as the L_{90} value; on the other hand the residual noise is the result of a measurement where the noise sources are turned off.

Several measurements throughout the years have shown that the A-weighted sound pressure level was misleading in determining noise disturbance. McCullough and Hetherington [4] show how this parameter underestimates the prediction of nuisance, using a in situ based measurement technique. Jakobsen [5] described how the A-weighted filter overestimates the loudness at low levels at low frequencies. The authors stated that the L_{Aeq} parameter do not give a good estimate of the annoyance. Mirowska [6] as well as Cocchi et al. [7] using both laboratory measurement under strict

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medical protocols and real case studies demonstrated how low frequencies are less tolerated and perceived as more annoying than other frequencies and then the common L_{Aeq} single number methods could not represent the a good subjective evaluation

Though, distorted results are possible and could depend on many reasons:

a. underestimation of structural transmissions at low frequencies,
b. time of day or night when the noise appears,
c. receiver exposure time.

As a matter of fact, if the residual noise is not characterised by low frequencies, the presence of sources with these components leads to a stronger perception [8], especially at night. Therefore it is evident that the single A-weighted sound pressure level cannot be a reliable indicator, suitable to assess whether the disturbance exists or not.

Because of this reason, in this paper a selected number of noise assessment criteria (both single number and frequency analysis) are tested in order to understand and compare their methods. As a result, what was found is that all these criteria do not include many issues such as precise measurements guidelines or punctual and clear measurement spot selection; furthermore they provide very different hearing or assessment thresholds. Then, a proposal for a harmonised criterion is established by combining methods supplied in the literature with those established by the Italian legislation.

The proposed method is to be used in lawsuits, disputes or whenever an objective evaluation is needed. In this study, noise disturbance is considered both as annoyance and sleep disturbance.

2. Literature review

2.1. General studies and soundscape approach

In the last decades many authors have described the sound pressure level risks [9] both outside and inside dwellings. Miedema and Oudshoorn [10] connected annoyance with noise, focusing on transportation noise using DNL and DEN values. Even if this is a very good method, it requires very long measurements and only works for transportation sources. Indeed, it is difficult to apply it to disco pubs, people speaking, HVAC, etc.

More recently, the COST TUD action TD 0804 collected a large number of results obtained by different participants worldwide. Within the published e-book [11], many issues are presented in order to investigate noise and soundscape. The definition of soundscape, using the standard ISO 12913-1:2014 [12], is as follows: "acoustic environment as perceived or experienced and/or understood by a person or people, in context".

In particular, Kang et al. [11] report that over 30% of the EU population is exposed to noise levels above the WHO recommendation; Drever [13] studied the effect of ultra-rapid "ecological" hand dryer on vulnerable groups; Ortiz and Schulte-Fortkamp [14] focused on quite zones; Lercher et al. [15] studied the noise effects on children; Prodi et al. [16] studied the impact of noise on intelligibility in classrooms; Hiramatsu [17] connected noise and soundscape. These studies were very important in order to understand the subjective effect on receivers, but it does not supply an objective method to assess the disturbance.

Soundscape studies approach noise as a "resource" rather than "waste" [9]. In lawsuits or disputes, however, this approach is never used. In addition, it requires people to complete questionnaires regarding their positive or negative feelings towards sounds and noise. In a dispute, these results become difficult to use, as the different parties are not interested in soundscapes, but rather in winning the case.

None of these methods takes into account the façade, airborne and impact sound insulation in buildings because disturbance is measured in the context in which it takes places (noise propagation, time of day and night, etc.). Therefore, in order to evaluate the annoyance of the intruding noise, its characteristics are more important than the way in which it enters the dwelling. Clearly, the sound insulation performance of the building can affect the final perception of the intruding noise [18], even at low frequencies or in the case of impact noise [19,20]. Nevertheless, this relates only to the rating of the buildings [21,22] and not to the evaluation of the intruding noise. In order to reduce disturbance, when necessary, sound insulation can be improved or the noise level of the source can be reduced.

2.2. Single value: L_{Aeq} based techniques

2.2.1. International method: WHO guidelines

The WHO guidelines [23] are frequently used in the acoustical community. They propose health-based limits for night noise exposure stating that noise nuisance exists when the measured L_{Aeq} value inside a dwelling at night exceeds 30 dB(A), with higher limits when short-term measurements or maximum values are considered. Furthermore, it is specified that an external level below 30 dB(A) does not create negative effects on the health of the dwellers, including vulnerable groups such as children. This limit is to be considered as a long-period equivalent level. Interim levels of 40 dB(A) and 55 dB(A) were also proposed where the 30 dB(A) ultimate target cannot be achieved in a short period.

The WHO approach sets maximum thresholds for both inner and outer levels. Noise levels exceeding these thresholds are deemed to disrupt sleep. It was mainly created for traffic noise and it is based on overall levels (L_{Amax} and L_{Aeq}) only. This makes measurements and post-elaboration fairly easy, but does not take into account the mid-low frequencies contribution. The use of a single number value could lead to an underestimation of the noise disturbance since it is the average of every frequency from 20 Hz to 20,000 Hz. Then it could take into account different sources from the studied one(s) and (because it is weighted) it modifies the frequency and though the final evaluation.

2.2.2. Regional methods: Italian methods

As an example, Italian methods are presented, the first is required by the applicable legislation [24] and the second is an agreed but not codified "comparative" system adopted when the actual conditions do not allow the use of the mandatory method. It is sometimes used in court if required by the judge.

The first method consists of the L_{Aeq} measurement and third octave bands analysis with a minimum sampling rate of 125 ms. This is necessary for the investigation of tonal or impulsive events in the measured signal (frequency range 20–20,000 Hz).

The final values need to comply with the mandatory requirements specifying separate limits for daytime and night time. These limits take into account both external and internal acoustic conditions. The outer (*absolute*) values are not to be exceeded and are based on equivalent levels over the whole day or night periods. The inner values (*differential*) are evaluated considering the difference between the environmental and the residual noise (noise source switched off). If the measured L_{Aeq} is greater than the residual noise by 5 dB during the day (6–22) and 3 dB during the night (22–6), then the measured noise is regarded as disturbance. The measurements are based on short-term periods (about 1–20 min for example), with the disturbing source on and off.

There are lower minimum limits for the applicability of this method: the disturbing noise has to be greater than 50 dB(A) during daytime and 40 dB(A) during night time within the dwelling with open windows and 35 dB(A) and 25 dB(A) within the dwelling with closed windows. The differential limits do not apply to any type of traffic sources.

The mid-low frequency effect is taken into account only for tonal phenomena (a noise in which a frequency is predominant) but not for broadband. The very high sampling definition requires the acquisition of a lot of data. As a consequence, measurements and post processing are difficult, and expensive sound level meters are needed.

The "comparative method", is sometime used in lawsuits, but it has no scientific bases. As a consequence no robust results are supplied.

2.3. Frequency analysis based methods

2.3.1. Polish criterion

The Polish criterion is robust and detailed [6] and its use was made a legal requirement (see for application Section 3). It establishes two control conditions for the definition of indoor noise disturbance: the 1/3 octave band L_{eq} spectrum needs to exceed the given threshold and the measured value needs to exceed the background noise by 6 dB. Background noise is defined as the noise measured when no disturbing and thus measurable source is active (i.e. residual noise). The noise constitutes a nuisance if both of the above conditions are met in any 1/3 octave band between 10 Hz and 250 Hz. No measurement guidelines are given and no sampling criterion is included.

This method is based on both clinical and acoustical evidence and it is the only method taking into account residual noise and considering a wide frequency range (up to 250 Hz).

2.3.2. Danish criterion

This method [5] focuses on the 10–160 Hz bandwidth and uses a logarithmic summation of these 1/3 octave bands but no sampling criterion is included. Its application is required by the law. The obtained value, named $L_{pA,LF}$, must not be greater than $L_{pA,LF}$ = 25 dB during day time and $L_{pA,LF}$ = 20 dB during night time inside dwellings. A maximum value of L_{pG} = 85 dB(G) (using G-weighting) is required for infrasound, splitting the low frequency domain.

The measurements must be performed in three different positions and the final value is obtained by averaging the measurements. This method combines measuring guidelines and an assessment of vibration and refers to the background noise measured when the noise source is turned off (residual noise).

2.3.3. Australian criterion (I)

This method [25] is almost equal to the Danish method, but the limit is reduced by 5 dB in the event that the source is disco music.

2.3.4. German criterion

This is the only standardised method within DIN 45680:1997 [26]. This German standard was reviewed in 2011 and 2013 [27] and two unapproved drafts are currently being discussed.

A first check is made on the measured noise: if L_{Ceq} is 20 dB (15 dB in the 2011 and 2013 drafts) higher than L_{Aeq}, then the disturbance can be evaluated. No time range in indicated as reference period. To do so, the exposition period and the rating time must be assessed; no sampling criterion is included. The residual noise must be 6 dB below the disturbing noise. The standard requires measurement with linear weighting.

Once the above steps have been completed, the linear L_{eq} is weighted with high penalising k_{ai} coefficients derived from the EN 60651 standard [28]. The final value is compared with daytime, evening and night time limits. Then, a logarithmic summation of 8–100 Hz 1/3 octave bands is required, but only for those that are higher than the threshold indicated for the disturbance. The 2011 and 2013 DIN 45680 drafts use the ISO 226 [29] threshold, while the DIN 45680:1997 version is based on the threshold provided by the same standard.

2.4. External noise criterion

This criterion is used in the Australian method II [30]. According to this system, the noise is measured outside the building using a C weighting curve. The measurement procedure is simple (no need to access the dwellings by night, no need to arrange measurement time and day etc.).

Nevertheless, neither the noise source within the same receiver building nor structural transmission (through substructures etc.) are taken into account.

Other methods using only external noise exist, but they contain almost the same issues of the presented one.

3. Application in real-life cases

In recent years, several measurements were carried out by the authors with different types of sources and different situations for the receiver.

For discotheques, pubs etc. the noise disturbance can be divided in two categories:

(1) People speaking outside;
(2) Music source from live concerts, disc-jockeys, karaoke, HVAC etc.

The first case has already been discussed in [31] and other similar cases where presented in [32], with both environmental health officers and researchers/engineers arriving to the same conclusions while using different methods. In the second case, different assessment methods lead to different results.

In the following paragraphs, the results of the application of different methods for any of the different types of sources, are shown. In the following figures, the general definition of "level (dB)" reported in *y* axes, refers to what the specific paragraph is concerning about.

3.1. Live concerts

In the following example, the indoor noise disturbance in a residential apartment came from the live concert inside a music pub (blues/jazz/pop music). The disturbed room was located on the second floor of the building and the pub was located on ground floor of the same building.

3.1.1. German criterion

The first step is to verify the 20 dB (or 15 in the drafts) threshold between L_{Ceq} and L_{Aeq}. Fig. 1 shows the comparison between 100 ms sampling and 1 s sampling rate. In the standard there is no indication on the time gap usable for this comparison and so it was chosen the worst case providing the higher sound pressure level. The change of sampling clearly affects the assessment method. It is evident how the 1 s sampling hardly met the 20 dB threshold and the general sound pressure level is quite lower than the 100 ms sample one. Furthermore, the 20 dB threshold is very difficult to reach. No indication is given of whether a single excess in an individual sample is enough to move on to the next steps, or

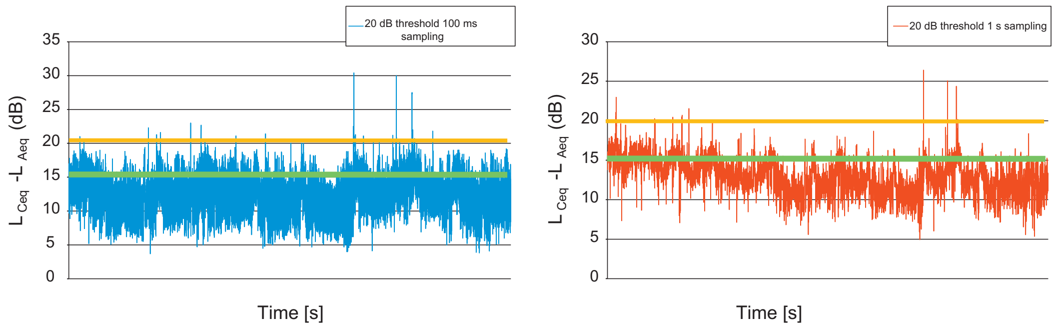

Fig. 1. Operability threshold (20 dB yellow line, 15 dB green line) according to DIN 45680 (time range 22.15–23.37). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

whether the whole measurement has to exceed the threshold to continue the assessment.

The second step provides a comparison between the 1/3 A weighted octave bands ($L_{terz,r}$) and the DIN 45680 threshold (Fig. 2).

In this case, the 80 Hz and 100 Hz bands exceed the limit. Using the corrections of k_{ai} coefficients provided in Annex 1 of the DIN 45680, the obtained overall value of the noise inside the room is 18.9 dB(A). According to the night time limits provided (25 dB (A)), no disturbance is found.

3.1.2. Polish method

Fig. 3(a) shows a comparison between the noise level L_{Aeq} and A weighted background noise; the threshold curve L_{A10} is also reported. Fig. 3(b) shows the difference between L_{Aeq} and the threshold values (ΔL_1) and between L_{Aeq} and background level (ΔL_2). In the first case the disturbance is verified for $\Delta L_1 > 0$; in the second one the disturbance is verified for $\Delta L_2 > 6$ dB.

The presence of disturbance between 80 Hz and 250 Hz is evident, as it is when applying the German method (before k_{ai} weighting).

3.1.3. Danish method

Here the comparison between A-weighted sound pressure level for low frequencies ($L_{pA,LF}$) within 1/3 octave bands 10 –160 Hz range and G-weighted for infrasound (L_{pG}) and given daytime and night time limits is reported. For the latter period these are $L_{pA,LF}$ = 20 dB(A) maximum and L_{pG} = 85 dB(G) maximum. Table 1 shows the final measured values.

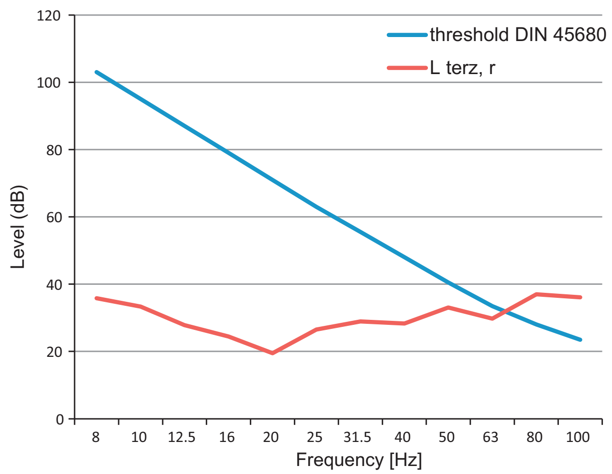

Fig. 2. Comparison between the 1/3 A weighted octave bands ($L_{terz,r}$) and the DIN 45680 threshold.

3.1.4. Australian method (I)

This method is very similar to the Danish method, but for impulsive sources like disco music the given limit is 5 dB(A) lower. This penalisation has not been applied in the case analysed here (live music). Noise assessment with the Australian method produced exactly the same results as with the Danish method.

3.2. Karaoke and piano bar

In this case the measurements were carried out inside a dwelling during a piano bar and karaoke night; the disturbance came from both inside and outside the pub.

3.2.1. German method

Fig. 4 shows the difference between L_{Ceq} and L_{Aeq} represented with 100 ms sampling; both thresholds (15 and 20 dB(A)) are exceeded. The comparison between the 1/3 A weighted octave bands ($L_{terz,r}$) and the DIN 45680 threshold is then provided.

The noise disturbance is found from 80 Hz. Nevertheless, if k_{ai}-weighting is applied the final value is 16.2 dB(A). Since the night limit is 25 dB(A), no disturbance can be ascertained.

3.2.2. Polish method

Fig. 5 shows a comparison between the noise level L_{Aeq} and residual noise and the difference between L_{Aeq} and the threshold values (ΔL_1) and between L_{Aeq} and residual level (ΔL_2). This method shows a wider noise disturbance range (from 80–250 Hz).

3.2.3. Danish method

Here for the night time period these are $L_{pA,LF}$ = 33.9 dB(A) maximum and L_{pG} = 58 dB(G) maximum. Table 2 shows the final measured values.

3.2.4. Australian method (I)

This method is very similar to the Danish method, but for impulsive sources like disco music the given limit is 5 dB(A) lower. This penalisation has not been applied in the case analysed here (live music). Noise assessment with the Australian method produced exactly the same results as with the Danish method.

3.3. Distant disco music

Here, the indoor noise disturbance comes from a club 70 m away. The sources are both disco music and a live concert, often playing with open windows and doors.

3.3.1. German method

Fig. 6 shows the difference between L_{Ceq} and L_{Aeq} represented with 100 ms sampling; both thresholds (15 and 20 dB(A)) are

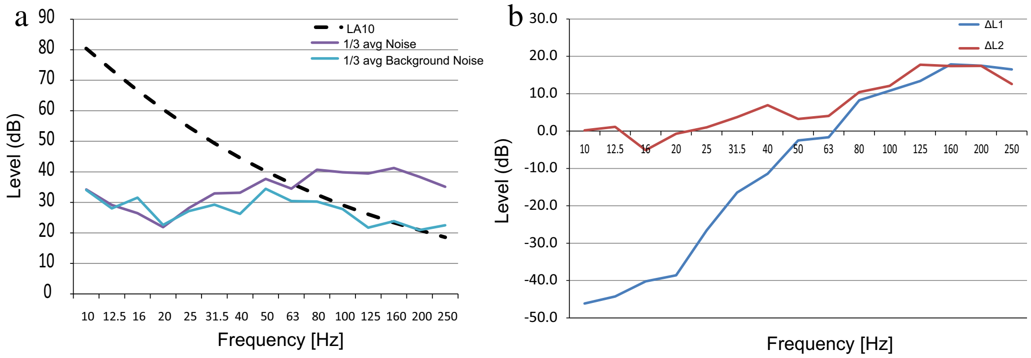

Fig. 3. Polish method trends, (a) noise and threshold; (b) defined parameters.

Table 1
Noise trends $L_{pA,LF}$ and L_{pG} parameters.

Frequency (Hz)	$L_{pA,LF}$ (dB(A))	L_{pG} (dB(G))
10.0	−36.2	34.2
12.5	−34.2	33.2
16.0	−30.4	34.0
20.0	−28.6	30.9
25.0	−16.5	31.9
31.5	−6.4	29.0
40.0	−1.4	21.2
50.0	7.5	17.7
63.0	8.3	6.5
80.0	18.2	4.7
100.0	20.8	−4.1
125.0	23.4	−12.5
160.0	27.9	−18.7
Overall	30.2	40.4

The noise disturbance is present at low frequencies but not in the infrasound range.

exceeded. The comparison between the 1/3 A weighted octave bands ($L_{terz,r}$) and the DIN 45680 threshold is then provided.

The noise disturbance is found from 100 Hz. This is due to the absence of structural transmissions. Nevertheless, applying the k_{ai}-weighting, the final value is 16.2 dB(A). Since the night limit is 25 dB(A), no disturbance is confirmed.

3.3.2. Polish method

Fig. 7 shows a comparison between the noise level L_{Aeq} and residual noise and the difference between L_{Aeq} and the threshold values (ΔL_1) and between L_{Aeq} and residual level (ΔL_2). This method evidences a noise disturbance range from 100 Hz.

3.3.3. Danish method

Here for the night time period these are $L_{pA,LF}$ = 24.9 dB(A) maximum and L_{pG} = 45.3 dB(G) maximum. Table 3 shows the final measured values.

3.3.4. Australian method (I)

This method is very similar to the Danish method, but for impulsive sources like disco music the given limit is 5 dB(A) lower. This penalisation has not been applied in the case analysed here (live music). Noise assessment with the Australian method produced exactly the same results as with the Danish method.

3.4. Disco music coming from the same building

The measurements were carried out inside a block of flats, in the apartment belonging to a family who complained about the noise from a disco club.

3.4.1. German method

Fig. 8 shows the difference between L_{Ceq} and L_{Aeq} represented with 100 ms sampling; both thresholds (15 and 20 dB(A)) are exceeded. The comparison between the 1/3 A weighted octave bands ($L_{terz,r}$) and the DIN 45680 threshold is then provided.

The noise disturbance is found from 50 Hz, highlighting the structural path as predominant. Nevertheless, applying the k_{ai}-weighting, the final value is 24.4 dB(A). Since the night limit is 25 dB(A), no disturbance is confirmed.

3.4.2. Polish method

In Fig. 9 a comparison between the noise level L_{Aeq} and residual noise and the difference between L_{Aeq} and the threshold values (ΔL_1) and between L_{Aeq} and residual level (ΔL_2) is shown. This method evidences a noise disturbance range from 80 Hz.

3.4.3. Danish method

Here for the night time period these are $L_{pA,LF}$ = 19.5 dB(A) maximum and L_{pG} = 57.8 dB(G) maximum. Table 4 shows the final measured values.

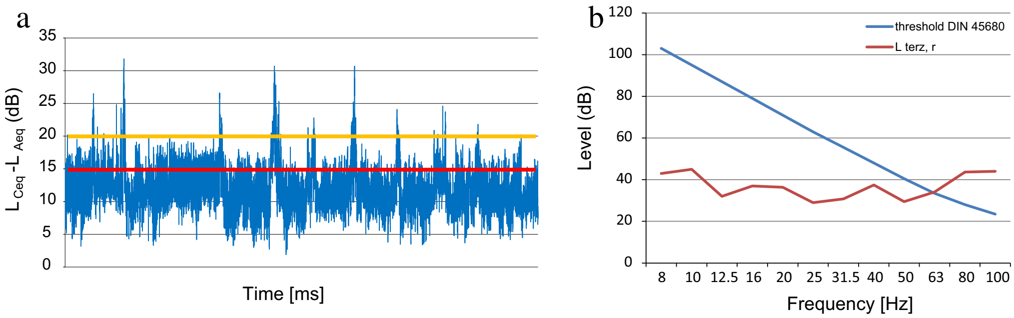

Fig. 4. (a) First step (time range 22.06–23.01) and (b) 1/3 octave band assessment.

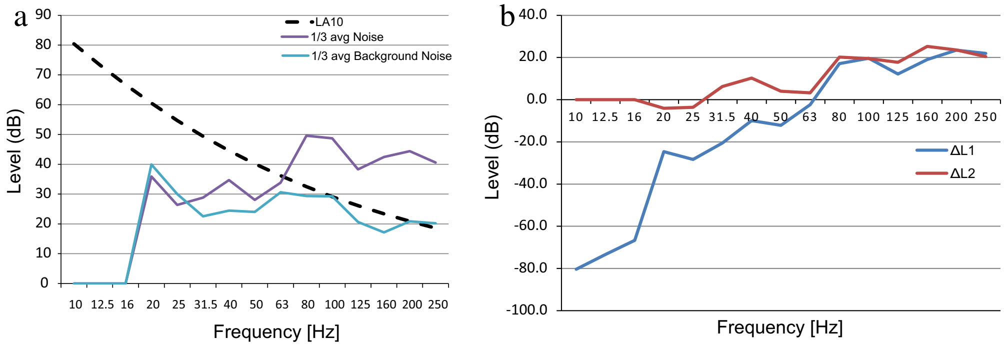

Fig. 5. Polish method trends, (a) noise and threshold; (b) defined parameters.

Table 2
Noise trends $L_{pA,LF}$ and L_{pG} parameters.

Frequency (Hz)	$L_{pA,LF}$ (dB(A))	L_{pG} (dB(G))
10.0	−13.4	57.0
12.5	−19.4	48.0
16.0	−18.7	45.7
20.0	−14.7	44.8
25.0	−18.4	30.0
31.5	−10.5	24.9
40.0	0.2	22.8
50.0	−2.1	8.1
63.0	7.7	5.9
80.0	27.1	13.6
100.0	29.7	4.8
125.0	22.3	−13.6
160.0	29.1	−17.5
Overall	33.9	58.0

The noise disturbance is present at low frequencies but not in the infrasound range.

3.4.4. Australian method (I)

This method is very similar to the Danish method, but for impulsive sources like disco music the given limit is 5 dB(A) lower. This penalisation was applied in the case analysed here (Disco music) and so the disturbance was assessed.

3.5. Large HVAC

In this case, the noise came from a large (4 × 2 × 2 m) HVAC system for winter and summer air and water conditioning unit located at a distance of 1 m from the receiver windows. It had in-built silencers and noise barriers. The measurements were carried out during daytime.

3.5.1. German method

Fig. 10 shows the difference between L_{Ceq} and L_{Aeq} acquired with a 100 ms sampling rate, where only the 20 dB(A) threshold is exceeded. The comparison between the 1/3 A weighted octave bands ($L_{terz,r}$) and the DIN 45680 threshold is then provided.

The disturbance cannot be assessed as the L_{Aeq}–L_{Ceq} check never exceeds 15 dB. Nevertheless, if the standard method is used, the output values exceed the threshold starting from 50 Hz and by applying the k_{ai}-weighting the final value is 29.5 dB(A), which confirms the disturbance.

3.5.2. Polish method

Fig. 11 shows a comparison between the noise level L_{Aeq} and residual noise and the difference between L_{Aeq} and the threshold values (ΔL_1) and between L_{Aeq} and residual level (ΔL_2). This confirms a disturbance at 50 Hz and from 100 Hz.

3.5.3. Danish method

Here for the night time period these are $L_{pA,LF}$ = 24.6 dB(A) maximum and L_{pG} = 51.3 dB(G) maximum. Table 5 shows the final measured values.

3.5.4. Australian method (I)

This method is very similar to the Danish method, but for impulsive sources like disco music the given limit is 5 dB(A) lower. This penalisation has not been applied in the case analysed here (HVAC). Noise assessment with the Australian method produced exactly the same results as with the Danish method.

3.6. Traditional HVAC

The measurements are carried out inside an apartment located on the 4th floor of a building; the indoor noise disturbance comes from a traditional (air cooling 1 × 0.8 × 0.4 m) HVAC system located in the courtyard. The measurements were carried out during daytime.

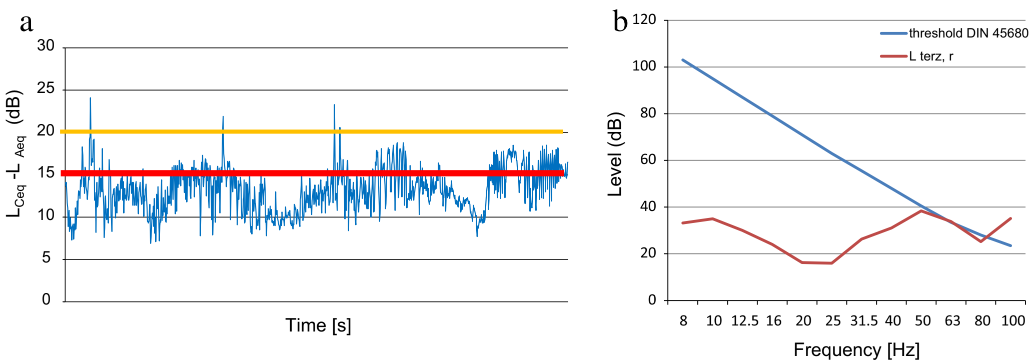

Fig. 6. (a) First step (time range 23.45–00.15) and (b) 1/3 octave band assessment.

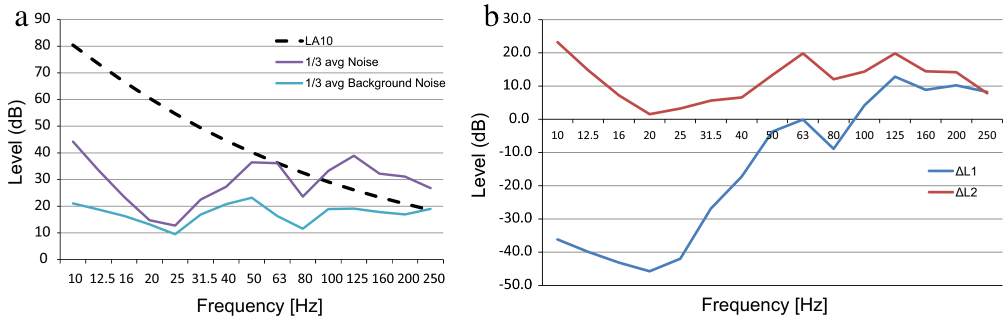

Fig. 7. Polish method trends, (a) noise and threshold; (b) defined parameters.

Table 3
Noise trends $L_{pA,LF}$ and L_{pG} parameters.

Frequency (Hz)	$L_{pA,LF}$ (dB(A))	L_{pG} (dB(G))
10.0	−26.2	44.2
12.5	−29.9	37.5
16.0	−33.2	31.2
20.0	−35.7	23.8
25.0	−32.0	16.4
31.5	−16.9	18.5
40.0	−7.3	15.3
50.0	6.3	16.5
63.0	9.9	8.1
80.0	1.1	−12.4
100.0	14.2	−10.7
125.0	22.8	−13.1
160.0	18.8	−27.8
Overall	24.9	45.3

The noise disturbance is present at low frequencies but not in the infrasound range.

3.6.1. German method

Fig. 12 shows the difference between L_{Ceq} and L_{Aeq} acquired with a 100 ms sampling rate; both thresholds (15 and 20 dB(A)) are exceeded. The comparison between the 1/3 A weighted octave bands ($L_{terz,r}$) and DIN 45680 threshold is then provided.

The noise disturbance is found starting from 50 Hz. Nevertheless, if the k_{ai}-weighting is applied, the final value is 16.4 dB(A). Since the night limit is 25 dB(A), no disturbance is ascertained.

3.6.2. Polish method

Fig. 13 shows a comparison between the noise level L_{Aeq} and residual noise and the difference between L_{Aeq} and the threshold values (ΔL_1) and between L_{Aeq} and residual level (ΔL_2). No disturbance is ascertained.

3.6.3. Danish method

Here for the night time period these are $L_{pA,LF}$ = 23.0 dB(A) maximum and L_{pG} = 59.3 dB(G) maximum. Table 6 shows the final measured values.

3.6.4. Australian method (I)

This method is very similar to the Danish method, but for impulsive sources like disco music the given limit is 5 dB(A) lower. This penalisation has not been applied in the case analysed here (HVAC). Noise assessment with the Australian method produced exactly the same results as with the Danish method.

3.7. Discussions of results

All methods require the 1/3 octave band frequency analyses and provide specifications on background noise conditions. Some of them contain measurement specifications and only one introduces a penalty depending on the disturbance occurring by day or by night.

The German method does not confirm the existence of the disturbance at any time while the Danish/Australian methods, in most cases, do. No method considers the frequency trend of the source, nor the influence of multiple sources, nor the sampling measurement step.

Some processes require multiple measurements and supply hearing or disturbance thresholds. Finally, the different frequency ranges are investigated and no importance is attached to the windows being open or closed.

If the measure is slightly over the threshold changing receiver positions, sampling, etc. can affect the final result regardless of the chosen method.

If no strict rules are imposed on the measurement and parameters methodology, the results cannot be compared and disturbance cannot be clearly and objectively assessed.

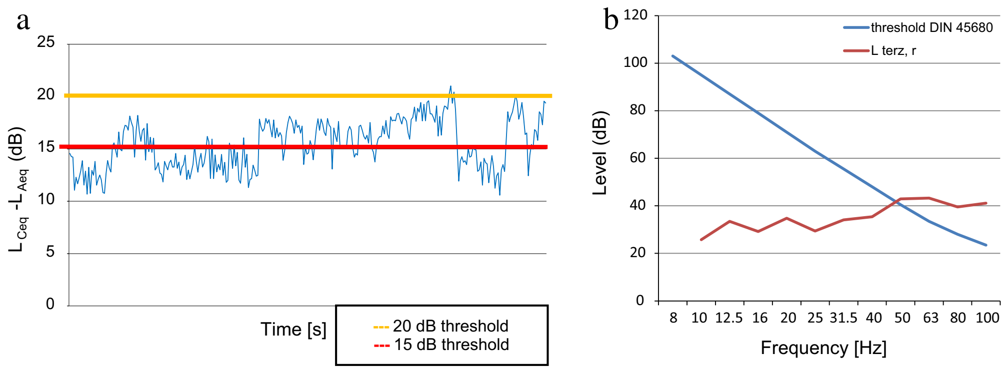

Fig. 8. (a) First step (time range 01.38–02.15) and (b) 1/3 octave band assessment.

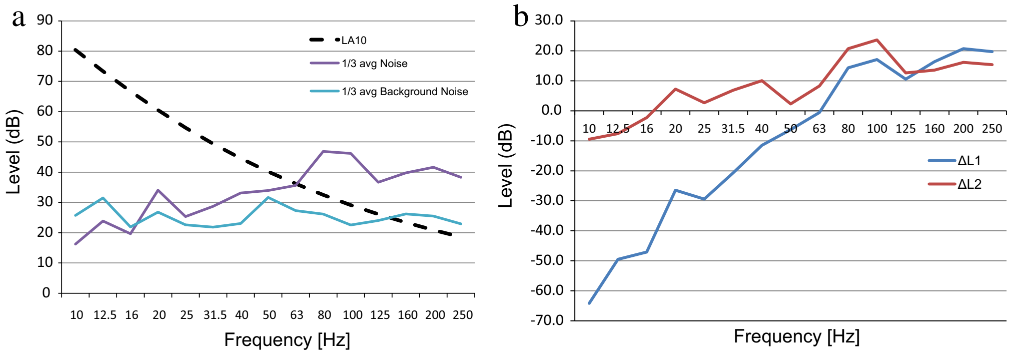

Fig. 9. Polish method trends, (a) noise and threshold; (b) defined parameters.

Table 4
Noise trends $L_{pA,LF}$ and L_{pG} parameters.

Frequency (Hz)	$L_{pA,LF}$ (dB(A))	L_{pG} (dB(G))
10.0	−13.4	57.0
12.5	−19.4	48.0
16.0	−18.7	45.7
20.0	−23.4	36.1
25.0	−22.9	25.5
31.5	−12.9	22.5
40.0	−6.9	15.7
50.0	4.5	15.2
63.0	8.4	7.6
80.0	9.4	−4.1
100.0	14.3	−10.6
125.0	12.6	−20.3
160.0	14.1	−32.0
Overall	19.5	57.8

The noise disturbance is not present at low frequencies as well as in the infrasound range.

4. Proposal for a harmonised assessment criterion

Since measuring subjective disturbance is impossible as each individual has is sensitive to noise in a different way, no universal threshold can and will ever be established. Despite the use of subjective interviews for example in soundscapes [11], in the cases described here the noise is considered a disturbing source and never a positive contribution. Subjective evaluations, particularly in the case of legal disputes, are not a reliable form of measurement.

Nevertheless, several studies have been carried out over the years in many different countries using laboratory subjective tests in order to obtain a hearing/disturbance threshold [2,3,5,6,11]. Determining a new threshold using subjective tests therefore makes little sense.

The aim of this work is to determine an objective method to assess the noise disturbance (considered both as annoyance and sleep disturbance) in the usual conditions and for the average individual, taken for granted that this is the only way to include as many people as possible. So it makes sense to calculate the average of the hearing thresholds included in standards/literature as presented in Fig. 14 and Table 7, since they come from different authors who have used different techniques and operate in different part of the world and since these thresholds are average themselves. In a way, this represents the "average of the averages".

After all this case history, the present study suggests the following steps in order to assess disturbance:

(1) Noise should be measured both inside the dwelling where the disturbance is higher and at the source. If the source signal is stable enough, then this measurement can be carried out separately. If the 1/3 octave bands trend of the former is comparable with the latter (also a composition of frequencies due to many sources), then this method can be used, according to [7].

The source(s) measurements have to be carried out at a distance of 1 m from the highest emitting point. If the noise source is composite (industrial plant) then the receiver should be placed in a spot equally distant from the different sources in a normal direction starting from the focal point of the overall surface. If this is not possible (close walls, irregular shape) the instrument needs to be placed closer to the surface, remaining in a normal direction starting from the focal point.

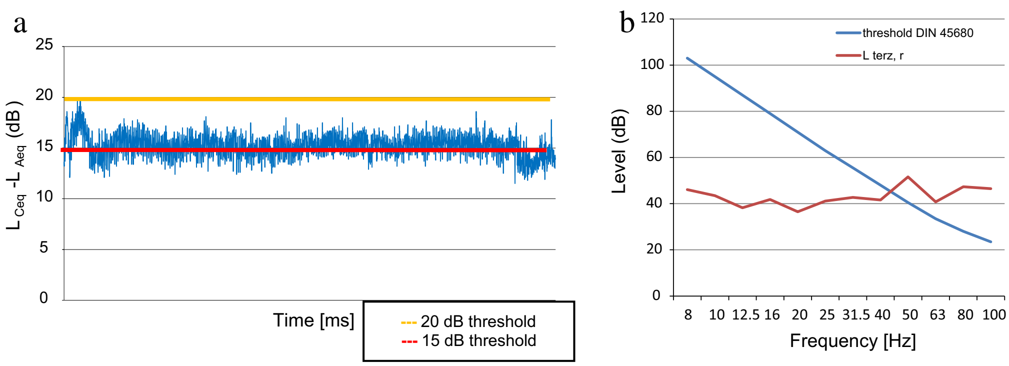

Fig. 10. (a) First step (time range 17.30–18.30) and (b) 1/3 octave band assessment.

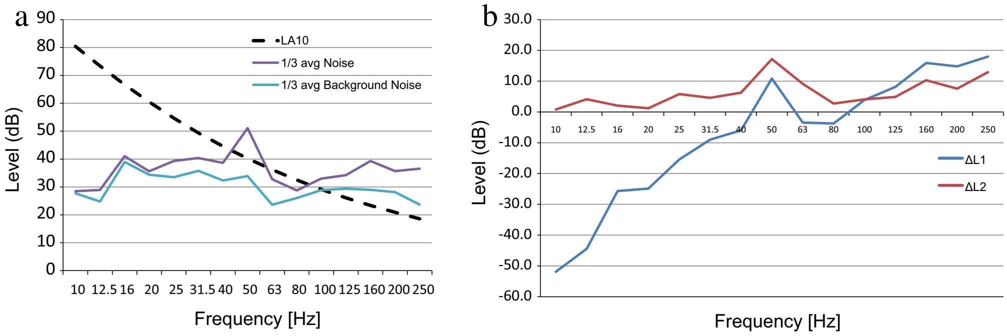

Fig. 11. Polish method trends, (a) noise and threshold; (b) defined parameters.

Table 5
Noise trends $L_{pA,LF}$ and L_{pG} parameters.

Frequency (Hz)	$L_{pA,LF}$ (dB(A))	L_{pG} (dB(G))
10.0	−42.0	28.4
12.5	−34.5	32.9
16.0	−15.6	48.8
20.0	−14.8	44.7
25.0	−5.4	43.0
31.5	1.0	36.4
40.0	4.1	26.7
50.0	19.1	31.1
63.0	6.6	4.8
80.0	6.0	−7.5
100.0	12.8	−11.1
125.0	17.2	−17.7
160.0	20.9	−20.7
Overall	24.6	51.3

The noise disturbance isn't present at both at low frequencies and in the infrasound range.

(2) The residual noise (source(s) off) should be measured in the same period of the day and week before or after the noise source is used.
(3) The residual noise should be compared and contrasted with the disturbing noise. If the difference (in 1/3 octave band analysis) is higher than 6 dB according to [6], the disturbance can be evaluated using following steps.
(4) The measured disturbing noise within the dwellings should be compared and contrasted with the average threshold. If the former exceeds the latter two different scenarios must be considered:
   a. If it is night time (from 22 to 7 h); if the receivers are children up to the age of 3 or people with serious illnesses (all day long); if the receivers are in hospitals or schools or buildings where silence is needed (all day long), then the excess of the threshold confirms the existence of the disturbance. Night time period (22–7) represents the typical and average sleeping time of children and workers.
   b. If none of the above conditions applies, the excess has to be equal to or higher than 3 dB according to [23] in any 1/3 octave band.

Measurement guidelines:

(1) A minimum of three different 15 min measurements are to be averaged. If the noise is shorter, then the use of multiple receivers is needed (3 minimum) with at least 1 min measurement time each. The microphone(s) need to be 50 cm away from each other.

If the noise source(s) is not constant (e.g. concert, short and repeated HVAC cycle etc.) and the related residual noise is shorter than 2 min, then the measures have to be post-processed in order to compute the disturbing noise only and exclude the residual noise. The minimum sampling step is set to 1 s, based on authors experience realizing this study. The described time ranges are based on the authors' measurement experience related to the development of this study and concern the minimum time lapse within whom the sound event could be considered robust and reliable.

(2) At the same time an instrument must be placed near the source(s) in order to acquire the frequency trend. If the signal is stable enough, then this measurement can be carried out separately (before or after those in the dwelling).

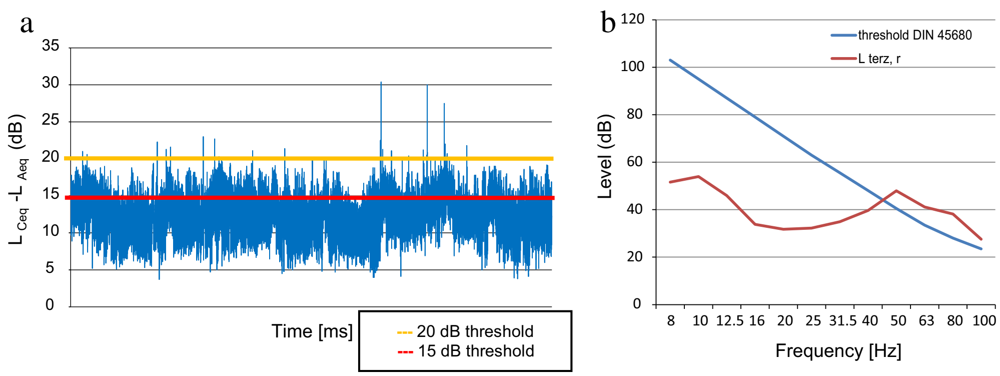

Fig. 12. (a) First step (time range: 20.30–22.00) and (b) 1/3 octave band assessment.

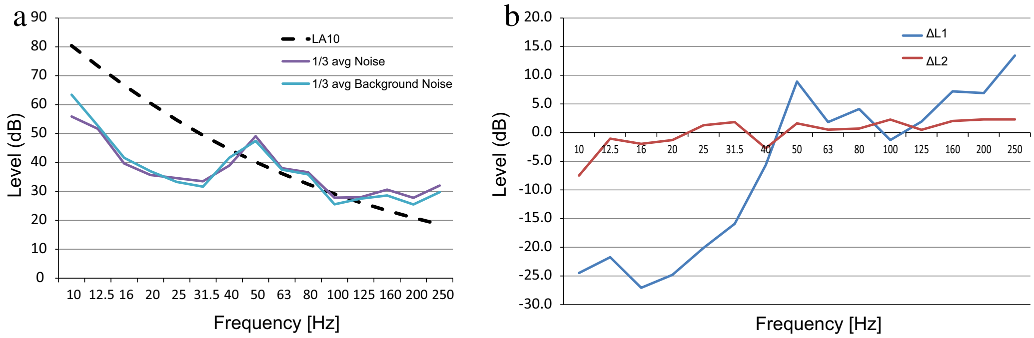

Fig. 13. Polish method trends, (a) noise and threshold; (b) defined parameters.

Table 6
Noise trends $L_{pA,LF}$ and L_{pG} parameters.

Frequency (Hz)	$L_{pA,LF}$ (dB(A))	L_{pG} (dB(G))
10.0	−14.5	55.9
12.5	−11.7	55.7
16.0	−17.1	47.3
20.0	−14.8	44.7
25.0	−10.1	38.3
31.5	−5.9	29.5
40.0	4.4	27.0
50.0	18.9	29.1
63.0	11.8	10.0
80.0	14.1	0.6
100.0	8.7	−16.2
125.0	11.9	−24.0
160.0	17.2	−29.4
Overall	23.0	59.3

The noise disturbance isn't present at both at low frequencies and in the infrasound range.

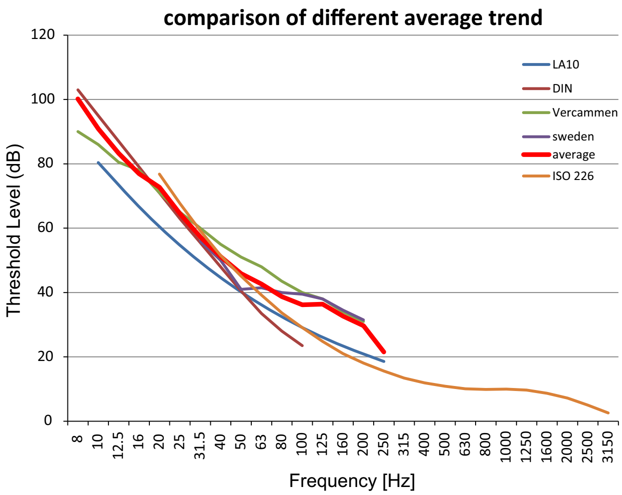

Fig. 14. Literature standard and average of the averages trends.

(3) No other person except the engineer(s) must be present during the measurements. All the external acoustic events are to be taken into account and post-processed to avoid any outer interference.
(4) All doors and windows must be closed.
(5) The measurements must be carried out in closed rooms such as dining room, living room, bedroom, etc. No corridors, storerooms, bathrooms smaller than 8 square meters (minimum area for repeatable measurements, taking into account furniture, room shape etc.) should be considered.

Table 7
Average of the averages.

Hz	dB
8	100.2
10	90.9
12.5	83.3
16	76.9
20	72.7
25	64.5
31.5	57.3
40	51.1
50	45.9
63	42.6
80	38.7
100	36.2
125	35.2
160	31.5
200	28.5
250	21.5

When providing results:

(1) Report measurement methodology.
(2) Identify irrelevant acoustic events during occurring during measurement operation and do not factor them in while assessing the disturbance.
(3) Report name, type and certification of the instrumentation.
(4) Describe the source type and report the frequency and trend.
(5) Attach pictures of the measurements and of the sources.
(6) Report the 1/3 octave band assessment trend and indicate if and where the presence of a noise disturbance is confirmed.
(7) Propose possible solutions.

5. New method application

The 6 cases discussed above were used to test, analyse and assess the methods proposed in the literature, to understand their rationale and identify potential issues. Lessons were in this way learned and translated into a new method meant to provide an objective assessment of noise disturbance, which was obviously not available when the 6 cases above were initially assessed and could therefore not be applied.

Following its creation, chances arose to apply the new method in just two of the six above discussed:

(1) Disco music coming from the same building (Section 3.4). Here the noise was measured by night and no receivers listed in (4) sub (a) with no receivers as described in point (4) sub (a) in the building.

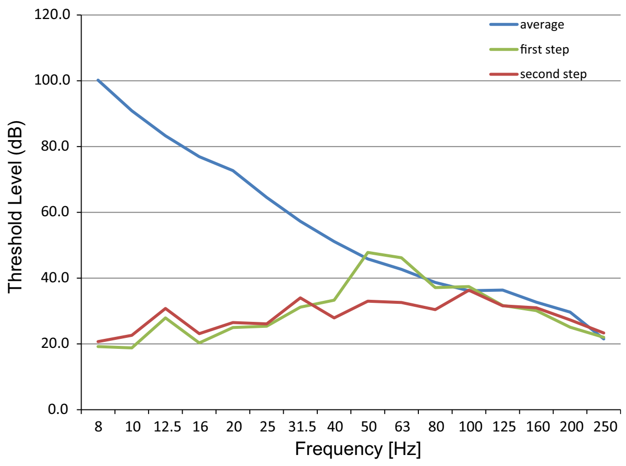

Fig. 15. The new method applied in real-life circumstances (see Section 3.4).

(2) Large HVAC (Section 3.5). Here the noise was measured by night and no receivers listed in (4) sub (a) with no receivers as described in point (4) sub (a) in the building.

The comparison with the described literature methods could not be reported since the new criterion obtained results could not be compared with other results. This fact is caused by the different measurement guidelines approach (sampling, time rate, frequency range, thresholds, weighting, and measurements number). So final results would be sensibly affected by these differences.

In (1) the methods provided in the literature produced very diverging results. Those who dwelt inside the building while the measures were in progress nevertheless unanimously reported the presence of a noise disturbance (first step, Fig. 15). The proposed approach also confirmed the existence of the disturbance. The source was subsequently modified (by means of a limiter and a DSP analyser) and the disturbance was measured by 2 different teams. The new method was used in addition to the old method in order to contrast results.

By using the methods proposed in the literature, the 2 teams once again obtained diverging results, owing to unspecific measurement procedures and uncertainty as to which threshold should be applied in which case.

By using the new method, the 2 teams obtained comparable results and concluded that there was no disturbance (second step, Fig. 15), which was in line with the subjective perception of the police, present in the building, and the owners of the building

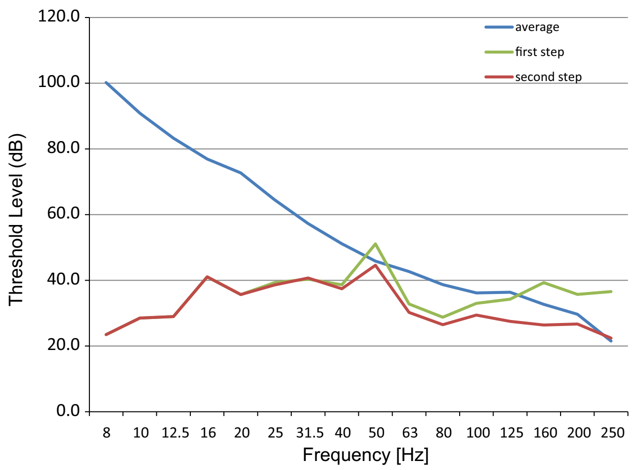

Fig. 16. The new method applied in real-life circumstances (see Section 3.5).

In (2), the results obtained using the methods provided in the literature are at utter variance, although all those who dwelt inside the building while the measures were in progress agreed that the disturbance was there (first step, Fig. 16). The disturbance could also be identified using the new method. The source was then modified by applying the appropriate silencer and the new method was used along the old method to assess the disturbance, so that the results could be contrasted.

And again, using the methods proposed in the literature, the team obtained diverging results, owing to unspecific measurement procedures and uncertainty as to which threshold should be applied in which case

By using the new method, the team concluded that there was no disturbance (second step, Fig. 16), which was in line with the subjective perception of the police, present in the building, and the owners of the building

6. Conclusions

Sound measurements inside dwellings are commonly used to understand noise and sleep disturbance. As a consequence, many researchers worldwide have tried to determine objective methods to assess whether a disturbance is present or not. Some countries use the discussed criteria and have made their use compulsory. Each method focuses on some features, leaving possible interpretations to the engineers, which may cause misunderstandings. The goal of this paper is to inform stakeholders in the drafting of new standards or legislation, or in the integration of existing legal requirements by proposing an objective method built on robust and scientific criteria that should replace the current, unreliable but widely used procedures and their subjective interpretation.

To this end, an in-depth analysis of different disturbance assessment methods was carried out. Six different traditional sources were analysed and measured and results were compared and contrasted. Pros and cons were highlighted and a new assessment criterion was proposed and successfully tested combining, were possible, the different approaches and standards discussed in the literature. A new average threshold is supplied which simplifies the procedures in case of low-frequency components, but which could be used for any situation. This is complemented with new and well defined measurement steps and guidelines.

Author contributions

All the authors contributed equally to the conception of this study.

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References

[1] Persson K, Björkman M, Rylander R. Loudness, annoyance and dBA in evaluating low frequency sounds. J Low Freq Noise and Vib 1990;9(1).

[2] Vercammen MLS. Low-frequency noise limits. J Low Freq Noise Vib 1992;11:7–13.

[3] Vercammen MLS. Setting limits for low frequency noise. J Low Freq Noise Vib 1989;8:105–8.

[4] McCullough P, Hetherington JO. A practical evaluation of objective noise criteria used for the assessment of disturbance due to entertainment music. J Environ Health Res 2005;4:69–74.

[5] Jakobsen J. Danish guidelines on environmental low frequency noise, infrasound and vibration. J Low Freq Noise, Vib Act Control 2001;20(3):141–8.
[6] Mirowska MJ. Evaluation of low-frequency noise in dwellings. New Polish recommendations. J Low Freq Noise, Vib Act Control 2001;20(2):69–74.
[7] Cocchi A, Fausti P, Piva S. Experimental characterisation on the low frequency noise annoyance arising from industrial plants. J Low Freq Noise Vib 1992;11(4):124–32.
[8] Drexl M, Otto L, Wiegrebe L, Marquardt T, Gürkov R, Krause E. Low-frequency sound exposure causes reversible long-term changes of cochlear transfer characteristics. Hear Res 2016;332(01):87–94.
[9] Babisch W. The noise/stress concept, risk assessment and research needs. Noise Health 2002;4:1–11.
[10] Miedema HME, Oudshoorn CGM. Annoyance from transportation noise: relationships with exposure metrics DNL and DENL and their confidence intervals. Environ Health Perspect 2001;109(4).
[11] Kang J, Chourmouziadou K, Sakantamis K, Wang B, Hao Y, editors. Soundscape of European cities and landscape. Oxford: Soundscape-COST; 2013.
[12] ISO 12913-1:2014. Acoustics – soundscape – part 1: definition and conceptual framework.
[13] Drever J. Sanitary soundscapes: the noise effects from ultra-rapid ecological hand dryers on vulnerable subgroups in publicly accessible toilets. In: Proceedings of AIA-DAGA congress, Meran (Italy) 18–21 march 2013.
[14] Ortiz NM, Schulte-Fortkamp B. Quiet-zones, is "quiet" the correct identifier? In: Proceedings of AIA-DAGA congress, Meran (Italy) 18–21 march 2013.
[15] Lercher P, Eisenmann A, Dekoninck L, Botteldooren D, Widmann U, Evans G. Noise exposure and health effect in children: results from a contextual soundscape perspective. In: Proceedings of AIA-DAGA congress, Meran (Italy) 18–21 March 2013.
[16] Prodi N, Farnetani A, Visentin C, Fausti P. Efficiency of communication in auralized classrooms. In: Proceedings of EURONOISE 2009, Edinburgh 26–28 October 2009. ISBN 1901656985.
[17] Hiramatsu K. Soundscape concept in association with noise control. In: Kang J, Chourmouziadou K, Sakantamis K, Wang B, Hao Y, editors. Soundscape of European cities and landscape. Oxfords: Soundscape-COST; 2013. p. 128–31.
[18] Ordonez R, Visentin C, Markovic M, Fausti P. Objective and subjective evaluation of façade sound insulation. In: Proceedings of internoise 2013 noise control for quality of life, Innsbruck 15–18 September 2013. ISBN 978-16-32662-67-5.
[19] Bettarello F, Fausti P, Baccan V, Caniato M. Impact sound pressure level performances of basic beam floor structures. J Build Acoust 2010;17(4):305–16. http://dx.doi.org/10.1260/1351-010X.17.4.30. ISSN 1351-010X.
[20] Caniato M, Bettarello F, Marsich L, Ferluga A, Sbaizero O, Schmid C. Time-depending performance of resilient layers under floating floors. Constr Build Mater 2016;102:226–32. 131.
[21] Di Bella A, Fausti P, Scamoni F, Secchi S. Italian experiences on acoustic classification of buildings. In: Proceedings of inter noise 2012, New York, USA, August 19–22, 2012. ISSN 0736-2935.
[22] Cremonini R, Fausti P. Considerations on low frequencies results of in situ sound insulation measurements. In: Proceedings of AIA-DAGA 2013 conference, Merano, Italy, 2013. ISBN 978-3-939296-05-8.
[23] World Health Organisation. Guidelines for community noise. Geneva: World Health Organisation; 1999.
[24] National Italian Law D.P.C.M. 14-11-97. Determination of the limit values of noise sources, G.U. n. 280, 1-12-97.
[25] Roberts C. Ecoaccess guideline for assessment of low frequency noise. In: Proceedings of acoustics 2004, Gold Coast, Australia, November 2004.
[26] DIN 45680 – Measurement and evaluation of low-frequency noise immissions in the neighbourhood; 1997.
[27] Draft DIN 45680. Measurement and evaluation of low-frequency noise immissions; 2013.
[28] EN 60651– Specification for sound level meters; 1994.
[29] ISO 226 – Acoustics – Normal equal-loudness-level contours; 2003.
[30] Broner NJ. A simple criterion for low frequency noise emission assessment. J Low Freq Noise, Vib Act Control 2010;29(1):1–13.
[31] Caniato M, Bettarello F, Taffarel M. Sound power level of speaking people. Proceedings of meetings on acoustics, vol. 19 040026.
[32] Caniato M, Bettarello F, Patrizio F, Marsich L, Ferluga A, Schmid C. Low frequency noise and assessment methods: a brief literature overview. In: 22st International congress on acoustics, ICA.