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Research Papers

Global Index of the Acoustic Quality of Classrooms

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Acoustic quality of a classroom is a term proposed to describe acoustic properties that contribute to a subjective impression received by a human, such as speech intelligibility, external noise, or vocal effort. It is especially important in classrooms, where suitable conditions should be provided to convey verbal content to students, taking into account their age. The article presents a method for assessing the acoustic quality of classrooms based on a single number global index and taking into account a number of factors affecting the outcome of the assessment. Partial indices are presented and their weights are proposed based on an analysis of factors determining whether a room meets applicable acoustic requirements. Results of the assessment of the acoustic quality carried out with the use of the developed method in selected classrooms are also presented.

Keywords: acoustic quality index, classrooms, schools, room acoustics.

1. Introduction

The author defines acoustic quality of classrooms as a term used to describe acoustic properties that contribute to a subjective impression received by a human, including speech intelligibility, external noise, or vocal effort. Acoustic quality of classrooms indicates whether a room satisfies applicable requirements, such as ensuring the following:

- adequate speech intelligibility,
- low level of background noise,
- no need to speak in a raised voice,
- teaching and learning comfort.

Acoustic quality is particularly important for primary school rooms, where students, because of their age, should be provided with the best possible conditions for the transmission of verbal content (Sato, Bradley, 2008). Moreover, children with health problems such as hearing loss, patterns deficits, ADHD, APD, etc. need good acoustic conditions not only in terms of acquisition of knowledge, but also in terms of equalizing educational opportunities and create environment conducive to the development (Crandell, Smaldino, 2000).

Acoustic quality of rooms is affected by many factors (Mikulski, Radosz, 2010). Bad acoustic quality, which can be described for example by excessive reverberation time, deteriorates verbal communication, causes higher noise levels in rooms used for teaching and learning (Fig. 1) and, what is important for safety reasons, interferes with the reception of messages broadcast through modern warning signals (Sato, Bradley, 2008; Radosz, 2012). One option for reducing noise in classrooms and improving conditions for educational activities is to improve the acoustic quality of rooms used for teaching and learning. In order to achieve this, it is necessary to develop an unambiguous method of acoustic quality assessment of such rooms. This assessment should cover a number of important factors: room acoustic parameters, internal and external noise as well as intelligibility and clarity of speech.

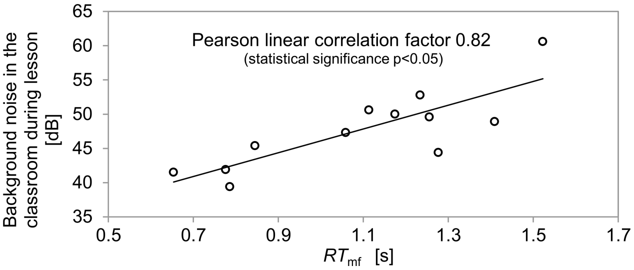


Fig. 1. Relationship between reverberation time RT_{mf} and the level of background noise during lessons (Mikulski, Radosz, 2012), where RT_{mf} is the arithmetic mean of the reverberation time from 500 Hz, 1 000 Hz and 2 000 Hz octave bands.

Room acoustics, particularly with respect to rooms used for teaching and learning, is a popular issue, which is often discussed in the literature (Rudno-Rudzińska, Czajkowska, 2010; Kotus *et al.*, 2010). Every year there are new publications in this field. In the EU, there are guidelines, criteria, and requirements to be met by such rooms, e.g. Building Bulletin 93 guidelines (United Kingdom), DIN 18041:2004-05 standard (Germany), SFS 5907:2004 standard (Finland), and ÖNORM B 8115-3 standard (Austria). However, they do not include all the relevant acoustic parameters, and most of them only provide the required insulation values of partitions, the background noise level (in empty rooms), and reverberation time.

One of the possibilities for a comprehensive assessment of classrooms, which takes into account a number of important factors affecting acoustic quality, is the index method. It involves determination of a single number-valued global index based on partial indices (Fig. 2). It has a number of applications on all aspects of vibroacoustics (Piechowicz, 2004; Pleban 1999; 2010; 2011). Index method was used in assessing the acoustic quality of church buildings and is still being developed (Engel *et al.*, 2007; Kosała, 2011; 2012) in this regard. The index method used to evaluate church buildings is also applied outside Poland (Carvalho, Silva, 2010). The index method proposed in this paper for assessing the acoustic quality of classrooms is based on similar assumptions as the method proposed by Engel (2007), but because of a different intended use, it is based on other partial indices and their weights.

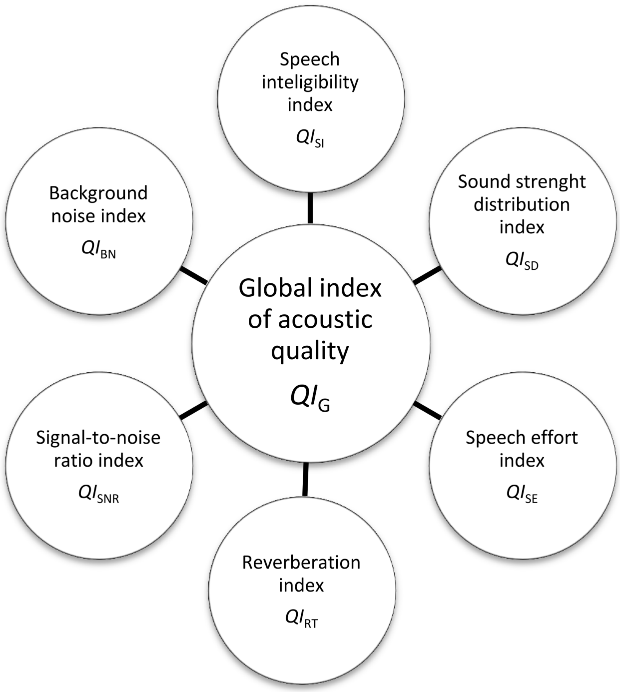


Fig. 2. The global index of classroom acoustic quality.

2. Assumptions for the index method of classroom acoustic quality assessment

Assumptions for the proposed classroom acoustic quality assessment method are based on the following:

- commonly used measurement methods (ISO 3382-1:2009, EN 60268-16:2011),
- results of measurements of acoustic properties of more than 100 classrooms (Mikulski, Radosz, 2011),
- analysis of factors affecting the intelligibility of content, low level of background noise, teacher's speech effort, and the comfort of teaching and learning (Sato *et al.*, 2008; Radosz, 2012; Mikulski, 2012),
- experimental tests in selected classrooms.

To complete a global classroom assessment with the use of the index method, it is necessary to carry out the following measurements:

- room impulse response (reverberation time RT, speech transmission index STI, clarity C_{50}, relative sound strength G_{rel}) in empty but furnished classrooms,
- sound level identifying teacher's speech effort during classes,
- signal-to-noise ratio (SNR) for the duration of classes,
- background noise level in empty but furnished classrooms.

Based on the measured acoustic parameters, values of the individual partial indices are determined and then, after taking into account their respective weights, the global index QI_G is determined according to the following formula:

$$QI_G = \frac{\sum_{i=1}^{n} QI_i \eta_i}{\sum_{i=1}^{n} \eta_i}, \tag{1}$$

where QI_i is the i-th partial index, η_i is the weight of the i-th partial index, and n is the total number of partial indices.

To determine the global acoustic quality index of classrooms, 6 partial indices are proposed, which are presented in Fig. 2.

For the proposed partial indices, the global index of classroom acoustic quality is expressed by the following formula:

$$QI_G = \Big(QI_{RT}\eta_{RT} + QI_{SI}\eta_{SI} + QI_{SE}\eta_{SE} + QI_{SD}\eta_{SD} + QI_{BN}\eta_{BN} + QI_{SNR}\eta_{SNR}\Big) \Big/ \Big(\eta_{RT} + \eta_{SI} + \eta_{SE} + \eta_{SD} + \eta_{BN} + \eta_{SNR}\Big), \tag{2}$$

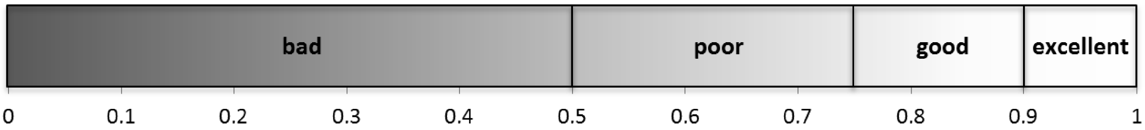


Fig. 3. Assessment scale of the global index of classroom acoustic quality.

where QI_{RT} is the reverberation index, QI_{SI} is the speech intelligibility index, QI_{SE} is the speech effort index, QI_{SD} is the sound strength distribution index, QI_{BN} is the background noise index, QI_{SNR} is the signal-to-noise ratio index, η_{RT} is the reverberation index weight, η_{SI} is the speech intelligibility index weight, η_{SE} is the speech effort index weight, η_{SD} is the sound strength distribution index weight, η_{BN} is the background noise index weight, and η_{SNR} is the signal-to-noise ratio weight.

The global index has a value of 0 to 1. The better the acoustic quality of a classroom, the higher the value of the global index. This assumption results from the analogy to other applications of the index method (Engel *et al.*, 2007) and objective evaluation methods of acoustic parameters (EN ISO 9921:2003). In order to facilitate the assessment of the acoustic quality of a classroom, assessment intervals were adopted to classify unambiguously the tested room depending on the value of the global index (Fig. 3). The classification is the result of the analysis of acoustic parameters of tested classrooms and recommendations and standards for this type of rooms.

A vast majority of classrooms (about 95%) in Polish schools have volumes between 155 m^3 and 200 m^3 (Mikulski, Radosz, 2011). Therefore, it was assumed that the proposed assessment method applies only to rooms within the above volume range, with the exception of special-purpose rooms, such as music rooms or speech therapy rooms. However, the author does not preclude future expansion of the scope of the proposed assessment method.

Weights of partial indices are shown in Table 1. Weight values do not the result from close relationships. They have been adopted on the basis of analysis of the factors affecting the acoustic quality of classrooms and based on the results of experimental tests conducted in selected rooms. Justification of the adopted weights is provided in the discussion of individual partial indices.

Table 1. Weights of partial indices.

η_{RT} – the reverberation index weight	0.8
η_{SI} – the speech intelligibility index weight	1
η_{SE} – the speech effort index weight	0.3
η_{SD} – the sound strength distribution index weight	0.5
η_{BN} – the background noise index weight	1
η_{SNR} – the signal-to-noise ratio weight	0.5

3. Methods for determining partial indices

3.1. Reverberation index

Reverberation time, because of a strong correlation of the reverberation time and auditory impressions, is one of the most important criteria for assessing acoustic quality of a room. This parameter is usually determined in octave frequency bands. Studies (Sato *et al.*, 2008) show that the difficulty in understanding speech is affected by the reverberation effect in the frequency range of 1–4 kHz. These studies also show a strong correlation between reverberation time in the octave band with a centre frequency of 2 kHz and subjective speech intelligibility tests. This is also confirmed by research carried out by CIOP-PIB (Mikulski, 2012). Therefore, to determine the reverberation index, reverberation time in the octave band with a centre frequency of 2 kHz was adopted. A reverberation index curve (Fig. 4) was determined empirically, based on the results of research carried out in Poland and other countries (Sato, Bradley, 2008; Leśna, Skrodzka, 2010; Mikulski, Radosz, 2011; Mikulski, 2012) and the criteria and requirements for this type of rooms (Building Bulletin B93, ANSI S.12.60, SFS 5907:EN). To plot the curve, students' acoustic absorption was taken into account and its value was adopted as 0.41 m^2 per person for a frequency of 2 kHz (Sato, Bradley, 2008). The reverberation index takes the value 1 for the reverberation time $RT_{2\,\mathrm{kHz}}$ in the range 0.45–0.55 s. It is the optimal value of the reverberation time for classrooms with a capacity of less than 200 m^3 according to many studies in this field (Bradley, 1986; Sato, Bradley, 2008; Sato *et al.*, 2008; Leśna, Skrodzka, 2010). The curve is also corresponding to the criteria and requirements of the above mentioned standards. The reverberation index value QI_{RT} can be determined from the curve presented below or by using the formula:

$$QI_{RT} = -0.48\{RT_{2\,\mathrm{kHz}}\}^4 + 2.55\{RT_{2\,\mathrm{kHz}}\}^3 - 4.77\{RT_{2\,\mathrm{kHz}}\}^2 + 3.13\{RT_{2\,\mathrm{kHz}}\} + 0.34, \quad (3)$$

where $\{RT_{2\,\mathrm{kHz}}\}$ is the numerical value of the reverberation time in the octave band with a centre frequency of 2 kHz, in seconds.

Based on the analysis of the results of studies by Sato and Bradley (2008) and the results of own experimental research, the value of the weight of the reverberation index $\eta_{RT} = 0.8$ was adopted.

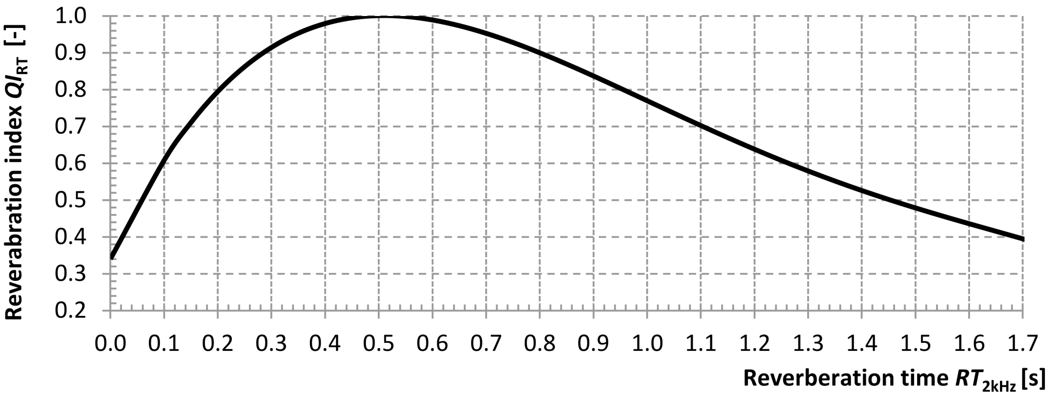


Fig. 4. Relationship between the reverberation time $RT_{2\,\mathrm{kHz}}$ and the reverberation index QI_{RT}.

The reverberation index provides also a basis for the approximate evaluation of acoustic quality with use of the singular value decomposition (SVD) method (Kosała, 2012).

3.2. The speech intelligibility index

Speech intelligibility is very important in the process of teaching and learning. For an objective assessment of speech intelligibility, the speech transmission index STI is used, which is highly correlated with subjectively perceived speech intelligibility. The values of the indicator are adopted in the range between 0 and 1, where 1 indicates perfect intelligibility (EN ISO 9921).

For objective assessment of speech intelligibility in classrooms, clarity C_{50} can also be used which is the ratio of the signal energy received by listener during the first 50 ms to its total energy (a value of 50 ms is related to the time constant of the ear). Clarity C_{50} is an important measure of classroom acoustics because it determines the perception of sounds occurring in quick succession. As in the case of the reverberation time, it is provided in octave frequency bands. Due to a strong correlation with the subjective speech intelligibility (Bradley, 1986), to determine the speech intelligibility index the octave band with centre frequency of 1 kHz was adopted. To determine the value of the speech intelligibility index QI_{SI}, it is necessary to determine the value of an auxiliary index, conventionally adopted as the clarity index CI. It is determined on the basis of clarity $C_{50(1\,\mathrm{kHz})}$, assuming that above $C_{50(1\,\mathrm{kHz})} = 4$ dB, the value the auxiliary clarity index CI will be 1. The auxiliary clarity index curve (Fig. 5) is based on the research by Bradley and Bistafa (2002). The auxiliary clarity index CI can be determined from the curve presented below or by using the formula

$$CI = -0.00616\{C_{50(1\,\mathrm{kHz})}\}^2 + 0.0615\{C_{50(1\,\mathrm{kHz})}\} + 0.85, \tag{4}$$

where $\{C_{50(1\,\mathrm{kHz})}\}$ is the numerical value of the clarity in the octave band with a centre frequency of 1 kHz.

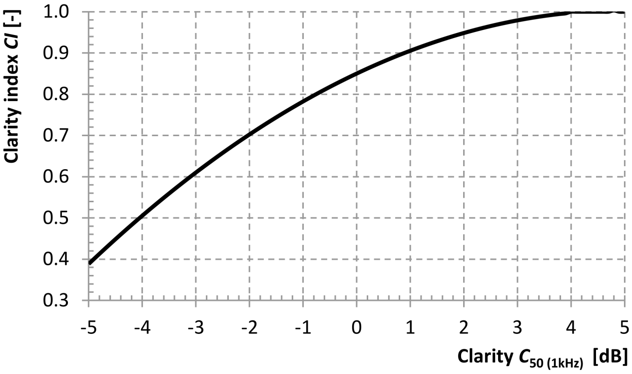


Fig. 5. Relationship between the clarity $C_{50(1\,\mathrm{kHz})}$ and the auxiliary clarity index CI.

On the basis of the research by Bradley (1986) and the results of our own research (Mikulski, Radosz, 2010) it was assumed that speech intelligibility will depend on the speech transmission index and the clarity, therefore it was assumed that it will be determined with the use of the formula:

$$QI_{SI} = 0.55STI + 0.44CI, \tag{5}$$

where STI is the speech transmission index and CI is the auxiliary clarity index.

Due to the intended purpose of classrooms, speech intelligibility is very important, therefore, it was assumed that the weight of the speech intelligibility index η_{SI} will be equal to 1.

3.3. The speech effort index

According to studies conducted by various research centres (Koszarny, 1992; Bronder, 2003; Augustyńska *et al.*, 2010) teachers, especially primary school teachers, complain about a need to speak in a raised voice during lessons. This leads not only to an increased speech effort, but also to a fast growth of fatigue. A significant percentage of teachers who find it necessary to speak in a raised voice during lessons, negatively assesses the conditions of their work and physical well-being.

The sound pressure level of the speech is one of objective parameters determining the speech effort. According to EN ISO 9921:2003, normal speech effort is equivalent to A-weighted sound pressure level of 60 dB at 1 metre from the mouth of the speaker (Table 2). The above-mentioned standard does not specify the methodology for measurement in real conditions such as conducting classes. However, for the purpose of the proposed index method, a noise dosimeter was used with appropriate correction due to distance from the mouth. The speech effort was deduced from time history of A-weighted sound pressure levels during several classes.

Table 2. Speech effort of a male speaker and associated A-weighted sound pressure level at a distance of 1 m from the mouth (EN ISO 9921:2003).

Speech effort	A-weighted sound pressure level (in dB)
Very loud speech	78
Loud speech	72
Raised voice	66
Normal speech	60

Based on the above data, a curve (Fig. 6) was plotted to determine the speech effort index QI_{SE} based on the teacher's A sound level at a distance of 1 m. Assuming that for the level of the teacher's voice $L_{Aeq,1\,\mathrm{m}} = 60$ dB and below, the value of $QI_{SE} = 1$ for the speech effort index is adopted, the following formula can also be used:

$$QI_{SE} = -0.041\,\{L_{Aeq,1\,\mathrm{m}}\} + 3.46, \tag{6}$$

where $L_{Aeq,1\,\mathrm{m}}$ is the numerical value of A-weighted sound pressure level of the teacher's voice at a distance of 1 m.

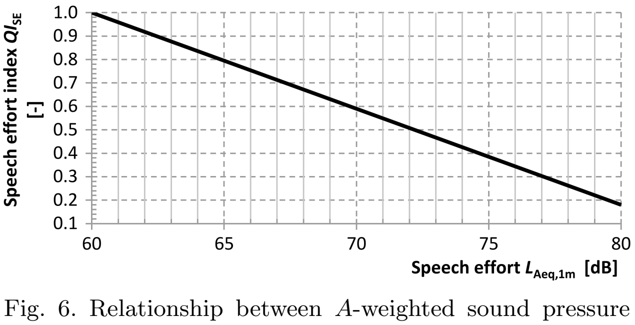


Fig. 6. Relationship between A-weighted sound pressure level of teacher's voice at a distance of 1 m and the speech effort index QI_{SE}.

Excessive speech effort lasting for an extended period of time is a cause of chronic diseases of the voice organ, but it is largely dependent on the teacher, therefore the value of the weight of the speech effort index $\eta_{SE} = 0.3$ was adopted.

3.4. The sound strength distribution index

An important criterion for assessing the classroom is the sound (teacher's voice) level distribution in the room. The more uniform the distribution, the better the classroom acoustic quality. For this purpose, the parameter of relative sound strength was used the due to a possibility of determining it from the room impulse response. It is usually determined in octave frequency bands. In the case of the distribution of sound pressure in the room, the most informative parameter is the difference between extreme values of the relative sound strength ΔG_{rel}.

To determine the values of sound strength distribution index in a given octave frequency band $QI_{SD,f}$, the following relationship was empirically adopted:

$$QI_{SD,f} = -0.08\,\{\Delta G_{\mathrm{rel},f}\} + 1, \tag{7}$$

where $\{\Delta G_{\mathrm{rel},f}\}$ is the numerical value of the difference between extreme values of the relative sound strength ΔG_{rel} for the frequency band f. The above relationship is also shown in Fig. 7.

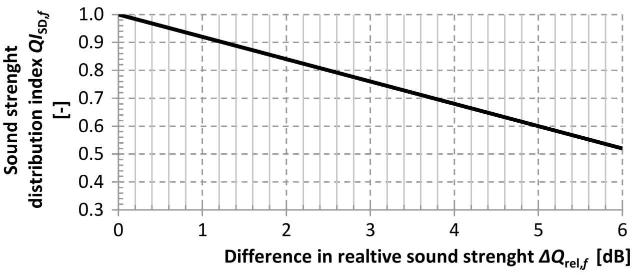


Fig. 7. Relationship between difference in relative sound strength $\Delta G_{\mathrm{rel},f}$ and the value of sound level distribution index $QI_{SD,f}$ for a given frequency.

To determine the values of sound strength distribution QI_{SD}, relevant frequency bands and their weights should be taken into account. It was assumed that frequency bands of 1 kHz, 2 kHz and 4 kHz will be taken into account because of their importance for verbal communication (Sato *et al.*, 2008), and the relationship will be expressed by the formula:

$$\begin{aligned} QI_{SD} = {} & 0.296 QI_{SD,1\,\mathrm{kHz}} + 0.37 QI_{SD,2\,\mathrm{kHz}} \\ & + 0.333 QI_{SD,4\,\mathrm{kHz}}\,, \end{aligned} \tag{8}$$

where $QI_{SD,1\,\mathrm{kHz}}$ is the sound strength distribution index in the octave band with a centre frequency of 1 kHz, $QI_{SD,2\,\mathrm{kHz}}$ is the sound strength distribution index in the octave band with a centre frequency of 2 kHz, and $QI_{SD,4\,\mathrm{kHz}}$ is the sound strength distribution index in the octave band with a centre frequency of 4 kHz.

The value of the sound strength distribution index weight is adopted as $\eta_{SD} = 0.5$. The sound strength distribution in a room is a very important parameter that takes into account the distance of the speaker from the listener; however, in the case of the classrooms under consideration (method assumptions), because of their volume, it is less important for assessing acoustic quality.

3.5. The background noise index

In Poland, background noise can be estimated on the basis of the PN-B02151-02 standard. According to this standard, the equivalent A-weighted sound pressure level of noise penetrating into classrooms and school rooms (except school workshop rooms) must not exceed the following values:

- total noise from all sources $L_{Aeq} = 40$ dB,
- from the building plant and other equipment inside or outside the building $L_{Aeq} = 35$ dB.

The value of background noise level permitted in classrooms acceptable in Poland ($L_{Aeq} = 40$ dB) is therefore within the limits of values adopted in most countries. Also the acceptable level of noise penetrating into school rooms from building equipment corresponds to the levels adopted in other countries.

Based on the above data, a curve (Fig. 8) was plotted to determine the background noise level QI_{BN} based on A-weighted background noise level in an empty classroom during classes in other classrooms (taking into account all sources of noise). Assuming that for the background noise level $L_{Aeq} = 40$ dB and below, the background noise level index is $QI_{BN} = 1$, and above 60 dB this value is $QI_{BN} = 0$, the following formula can be used:

$$QI_{BN} = 0.002\,\{L_{Aeq}\}^2 - 0.246\{L_{Aeq}\} + 7.64, \qquad (9)$$

where $\{L_{Aeq}\}$ is the numerical value of A-weighted background noise level in an empty classroom.

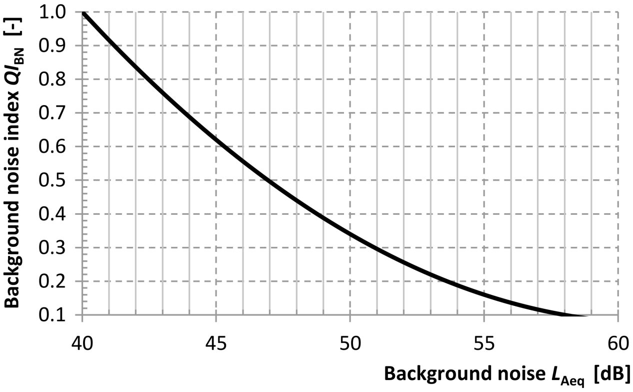
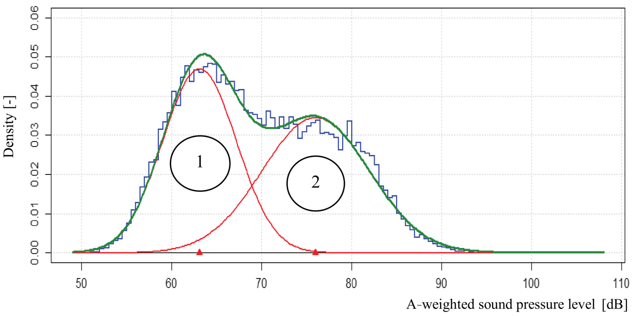


Fig. 8. Relationship between A-weighted background noise level in an empty classroom and the background noise index QI_{BN}.

Background noise has a significant impact on reception of messages in the process of speech understanding. Furthermore, limit values acceptable for the background noise level are defined by standards. Therefore, the value of weight of the background noise level index was assumed as $\eta_{BN} = 1$.

3.6. The signal-to-noise ratio index

The signal-to-noise ratio (SNR) is a parameter determining the distance of the speech signal from the background noise level at the place of the recipient at the time of the actual teaching/learning conditions (during classes/lectures). To measure this parameter, a sound meter/analyser is used that can record sound pressure level over time. Histograms (Fig. 9) are analysed to determine difference between medians of the distributions which correspond to the level of teacher's/lecturer's speech and the background noise level related to students' activity (Hodgson *et al.*, 1999). For this purpose, R software can be used with the Mixtools add-on. A measuring point is determined in the room based on the relative value of the sound strength G_{rel} where the difference of this parameter with respect to the reference value is the greatest.



Component of the distribution		Observation belonging to the component [%]	Distribution [dB]	
			Median	Standard deviation
1	Backround noise during classes (in fixed measurement point)	49	63.1	4.1
2	A-weighted sound pressure level of teacher's speech (in fixed measurement point)	51	76.0	5.9

Fig. 9. Example of histogram of the A-weighted sound pressure level in classroom during a lecture.

The optimum SNR value to ensure the proper reception of content should not be less than 15 dB (Sato, Bradley, 2008). Therefore, to determine the signal-to-noise ratio index QI_{SNR}, the relationship shown below was empirically adopted, assuming that the value of $SNR = 15$ dB and above, the signal-to-noise ratio index has a value of $QI_{SNR} = 1$.

$$QI_{SNR} = 0.058e^{0.18\{SNR\}+0.14}, \qquad (10)$$

where SNR – is the numerical value of the signal-to-noise ratio in actual teaching/learning conditions. The above relationship is also shown in Fig. 10.

The signal-to-noise ratio has a significant impact on the received content in the process of understanding speech. Low values of this parameter virtually prevent communication. However, the SNR value depends

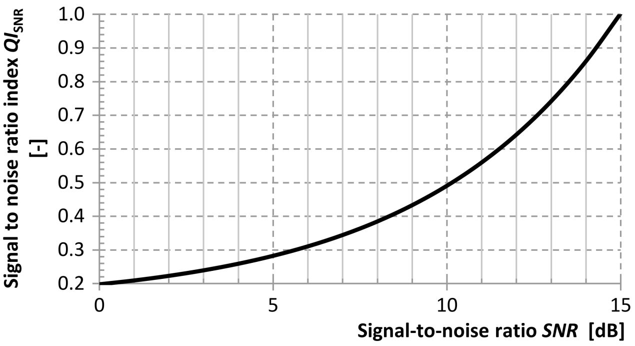


Fig. 10. Relationship between the signal-to-noise ratio SNR and the signal-to-noise ratio index QI_{SNR}.

in part on the teacher and his control over the class, therefore the value of the weight of the signal-to-noise ratio was adopted as $\eta_{SNR} = 0.5$.

4. Acoustic quality assessment of selected classrooms

Nine classrooms were selected (Table 3) to evaluate the acoustic quality in locations with diverse environmental noise. Selection was based on results of previous research (Mikulski, Radosz, 2010). The classrooms concerned had no acoustic adaptation.

Table 3. The tested classrooms.

No	Type of school	Classroom	Volume [m^3]	Number of students	Traffic noise L_{DWN} [dB]
1	Primary	A	160	24	55–60
2		B	160	22	55–60
3		C	157	28	< 50
4		D	157	32	< 50
5		E	158	30	50–55
6		F	158	32	50–55
7	Secondary	G	157	34	< 50
8		H	157	34	< 50
9.		I	157	38	< 50

L_{DWN} – A-weighted long-term average sound pressure level (reference interval equal to all days of the year).

The following measuring equipment was used for testing purposes:

- omnidirectional sound source B&K 4296 with an amplifier meeting the requirements of ISO 3382 and the directional sound source ADAM A5X,
- measuring microphone DPA 4007,
- measuring card RME UFX,
- a portable computer,
- B&K Dirac software,
- class 1 sound meter/analyser SVAN 945.

Measurement results (Table 4) confirmed previous study (Mikulski, Radosz, 2011) – in most cases values of parameters obtained from impulse response (reverberation time $RT_{2\,\mathrm{kHz}}$, speech transmission index STI, clarity $C_{50(1\,\mathrm{kHz})}$ and relative sound strength $\Delta G_{(\mathrm{rel},f)}$ are similar between classrooms. It results from the volume and the shape of classrooms. There are also similar equipment and furnishing which influence acoustics.

Measurement of A-weighted sound pressure level of the teacher's voice indicates that in most cases the speech effort correspond to raised voice (according to EN ISO 9921:2003).

The results of background noise obtained from measurements in classrooms were the result of:

- traffic noise around the schools not exceeding 60 dB,
- sound insulation of external partitions with windows (R'_{A1} from 30 to 36 dB),
- sound insulation of internal partitions (R'_{A1} from 49 to 56 dB),
- sound insulation of internal partitions with doors (R'_{A1} from 23 to 29 dB),
- the lack of activity in corridors,

where R'_{A1} – sound insulation index (airborne sound insulation).

Only one classroom meets the requirements for the SNR parameter. High levels of teachers' voice and low

Table 4. The results of measurements in tested classrooms.

Classroom	$RT_{2\,\mathrm{kHz}}$ [s]	STI	$C_{50(1\,\mathrm{kHz})}$ [dB])	$L_{Aeq,1\,\mathrm{m}}$ [dB]	$\Delta G_{\mathrm{rel},1\,\mathrm{kHz}}$ [dB]	$\Delta G_{\mathrm{rel},2\,\mathrm{kHz}}$ [dB]	$\Delta G_{\mathrm{rel},4\,\mathrm{kHz}}$ [dB]	L_{Aeq} [dB]	SNR [dB]
A	1.22	0.54	−2.3	66.0	2.8	1.2	1.8	23.9	11.1
B	1.00	0.59	−1.0	63.8	2.2	1.3	1.4	24.0	13.5
C	1.08	0.56	−1.5	62.8	3.3	2.4	2.0	25.9	11.2
D	1.18	0.63	−3.1	69.1	2.5	2.2	1.6	25.7	16.3
E	1.46	0.51	−3.7	68.3	1.4	2.1	2.6	24.6	7.7
F	1.12	0.56	−1.8	62.4	1.9	2.0	2.8	23.6	12.4
G	0.65	0.65	0.8	60.6	3.5	2.9	3.6	27.2	13.2
H	1.18	0.54	−3.3	65.8	3.1	2.5	2.3	27.8	12.4
I	1.14	0.64	−2.4	61.7	3.0	2.2	2.1	26.9	12.1

See text for explanation of symbols.

Table 5. Partial indices and the global index of acoustic quality of the tested classrooms.

Classroom	QI_{RT}	QI_{SI}	QI_{SE}	QI_{SD}	QI_{BN}	QI_{SNR}	QI_{G}	Scale of assessment
A	0.63	0.60	0.75	0.85	1	0.49	**0.73**	Poor
B	0.77	0.68	0.84	0.87	1	0.76	**0.82**	Good
C	0.72	0.64	0.89	0.80	1	0.50	**0.76**	Good
D	0.65	0.62	0.63	0.83	1	1.00	**0.79**	Good
E	0.50	0.52	0.66	0.84	1	0.27	**0.65**	Poor
F	0.69	0.63	0.90	0.82	1	0.62	**0.77**	Good
G	0.97	0.76	0.98	0.74	1	0.72	**0.87**	Good
H	0.65	0.56	0.76	0.79	1	0.62	**0.73**	Poor
I	0.68	0.65	0.93	0.81	1	0.59	**0.77**	Good

See text for explanation of symbols.

levels of background noise in classrooms indicate high levels of noise coming from the activity of the students in most of the classrooms.

Based on the results of the measurements, partial indices were determined and then the global index of acoustic quality of classrooms taking into account the weights (Table 5).

Test obtained for 9 selected classrooms have shown differences both in the individual partial indices and the global index of acoustic quality. An exception was the background noise index, because in none of the tested classroom the value of acceptable A-weighted sound pressure level of noise penetrating into classrooms and school rooms from all sources combined was exceeded (according to PN-B02151-02). The values of the global index of acoustic quality ranged between 0.65 and 0.87 (three classrooms with poor quality and six classrooms with good quality). All classrooms failed to meet the requirements to qualify as a room with excellent sound quality.

5. Summary

The paper presents a possibility of using the index method in the evaluation of acoustic quality of classrooms. The method is based on a set of objective acoustic parameters such as reverberation time RT, speech transmission index STI, clarity C_{50}, relative sound strength G_{rel}, pressure of a teacher's voice, and the background noise. Thanks to the proposed weights of partial indices, the global index of acoustic quality includes the assessment of the following: speech intelligibility, external noise level (background noise), teacher's speech effort, and the comfort of teaching and learning. Values assigned to the weights of the partial indices are arbitrary, however they correspond to various research and requirements in the field of classroom acoustics.

The proposed method has been verified on a sample of several selected classrooms. The results showed that some of the rooms required an appropriate adjustment of acoustic conditions. These conditions can be improved by increasing the acoustic absorption of rooms (including the appropriate design of wall and ceiling covered with sound-absorbing materials and the use of room equipment with high sound absorption). In particular, this is true for the rooms of the youngest students where the global index of acoustic quality to be aimed at should be above 0.9, which corresponds to excellent acoustic quality.

Due to the complexity of measurements, taking into account all the factors in the acoustic assessment is a difficult task. For this reason, the author intends to use the singular value decomposition (SVD) method to assess the acoustic quality which will allow for completing the assessment in the absence of complete information on all factors affecting this assessment (Kosała, 2011).

Next stage of research concerns experimental studies with different kind of linguistic material (isolated words, sequences of numbers and sentences) for developing subjective intelligibility tests to ensure the reliability and repeatability of tests. The results of subjective and objective (index method) assessment of classrooms will be statistically analyzed to verify both methods of acoustic quality assessment.

It is assumed that utilisation of unambiguous assessment of acoustic quality of classrooms using the index method will increase the awareness of architects, designers, school personnel and occupational health and safety specialists of the impact of room acoustic properties on noise pollution. It is also envisaged that proposed index method will affect acoustic requirements in the construction of new school buildings as well as in the expansion and upgrading of the existing ones.

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