INDEX METHOD OF THE ACOUSTIC QUALITY ASSESSMENT OF SACRAL BUILDINGS

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Regardless of numerous references concerning investigations and creation of acoustic conditions in sacral buildings, there is a lack of a uniform, specific methods which allow to assess the acoustic quality of such interiors. The new index method of assessing acoustic properties of sacral buildings by means of a single number – the global index of an acoustic quality – is presented in the paper. The global index is a function of several partial indices. The method of the calculation of the global index as well as of five partial indices, namely: the reverberation index, the intelligibility of speech index, the uniformity of loudness index, the external disturbance index and the music sound quality index are given. The proposed scale of the tentative assessment of the acoustic quality of interiors of sacral building on the bases of the global index is shown. The index method was applied to four selected roman-catholic churches.

Keywords: acoustic quality, index method, sacral buildings.

1. Introduction

Investigations performed in many sacral buildings have shown that neither at the designing stage nor at their construction nor modernisation the need for creation of proper acoustic properties is recognised and sufficiently appreciated. It seems to be a consequence of the lack of a uniform, specific method destined for such interiors. Methods developed for the acoustic assessment of auditoriums, concert halls and opera houses have been adapted for worship spaces. Those are the methods of BERANEK [3], ANDO [1] and RASTI [30], the impulse methods [20, 21] and the method based at measuring of certain parameters (mainly the reverberation time) and comparing them with the values preferred [20, 21]. However, the analysis of those methods indicates that none of them considers to a sufficient extent the specificity and uniqueness of interiors of churches of different religions [8, 20, 21]. Thus, no single method is able to supply

complete results and must be supplemented by other methods. This situation prompted the authors to undertake a study on the index method of the acoustic assessment of interiors of sacral buildings. The method proposed can provide a complex assessment of acoustic properties by means of a single number index.

2. Global index of the acoustic quality of sacral buildings

The proposed method has been developed on the basis of the analysis of factors crucial to the acoustic properties of interiors and of the methods adapted [8, 12, 20, 21, 27]. The investigations were preceded by several acoustic measurements in a dozen or more sacral buildings [6, 7, 9–11, 14, 15, 17, 18, 21–26, 28, 29, 33].

The global index W_{AQS}, which is a function of partial indices, is given by the formula:

$$W_{AQS} = \frac{\sum\limits_{i=1}^{n} W_i \eta_i}{\sum\limits_{i=1}^{n} \eta_i}, \qquad (1)$$

where W_i – partial index, η_i – weight of the i-th partial index.

The proposed five partial indices are shown in Fig. 1. Additional partial indices are not excluded.
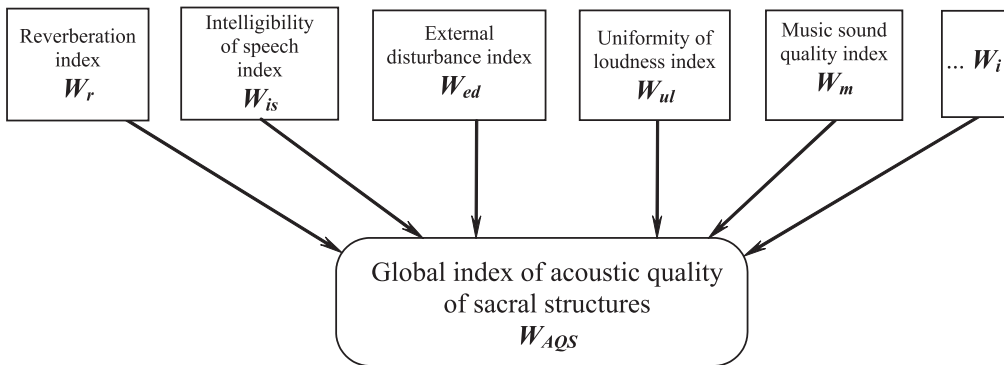

Fig. 1. Global index of the acoustic quality of sacral buildings.

The W_{AQS} index for five partial indices developed until now is given by the following equation:

$$W_{AQS} = \frac{W_r \eta_1 + W_{is} \eta_2 + W_{ed} \eta_3 + W_{ul} \eta_4 + W_m \eta_5}{\eta_1 + \eta_2 + \eta_3 + \eta_4 + \eta_5}, \qquad (2)$$

where W_r – reverberation index, W_{is} – intelligibility of speech index, W_{ed} – external disturbances index, W_{ul} – uniformity of loudness index, W_m – music sound quality index, $\eta_1 \div \eta_5$ – weights of the partial indices.

The weights of the partial indices are presented in Table 1. One must realise that their values do not result from strict dependencies. They were assumed on the basis of analyses of factors crucial for the acoustic quality of sacral buildings as well as on experimental tests performed in several buildings.

Table 1. Weights of partial indices.

η_1	η_2	η_3	η_4	η_5
1	0.5	0.3	0.3	0.2

The acoustic quality index of sacral buildings W_{AQS} takes values from 0 to 1. A building, for which $W_{AQS} = 1$ has very good acoustic properties, while $W_{AQS} = 0$ means the worst and disqualifying acoustic properties.

The calculated value of the global W_{AQS} index can be grouped tentatively into the scale shown in Fig. 2.
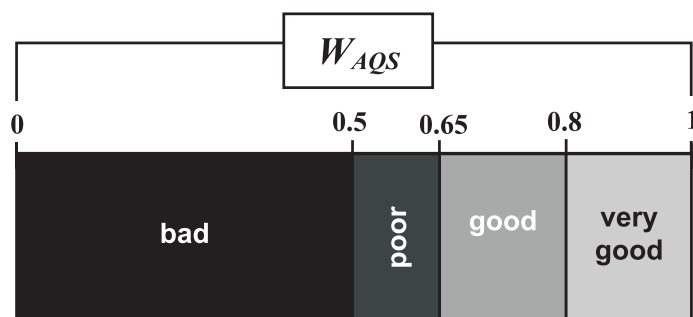
Fig. 2. The tentative scale for the estimation of the acoustic quality of interiors of sacral buildings according to the W_{AQS} index.

The tentative scale allows to classify the sacral interiors investigated into groups of buildings of certain acoustic properties. It was worked out on the basis of tests made in some sacral buildings. However, further investigations are needed to complete the scale and to make it more accurate.

The proposed index method is destined for a certain group of sacral buildings such as Roman-catholic and evangelic churches and synagogues of a cubic capacity from 600 to 40 000 m^3 and of straight shapes.

3. Partial indices

3.1. Reverberation index

The basic parameter determining the acoustic qualities of interiors, including interiors of sacral buildings, is the reverberation index [13]. In the index method developed by the authors, the reverberation index W_r is essential. The main reverberation index con-

sists of auxiliary reverberation indices $W_{r1} \div W_{r3}$, schematically presented in Fig. 3, and is given by the following equation:

$$W_r = W_{r1} \cdot \beta_1 + W_{r2} \cdot \beta_2 + W_{r3} \cdot \beta_3, \qquad (3)$$

where W_r – reverberation index, W_{r1} – reverberation-volume index, W_{r2} – reverberation index for organ music, W_{r3} – reverberation index for speaking, $\beta_1 \div \beta_3$ – weights of auxiliary indices $W_{r1} \div W_{r3}$.
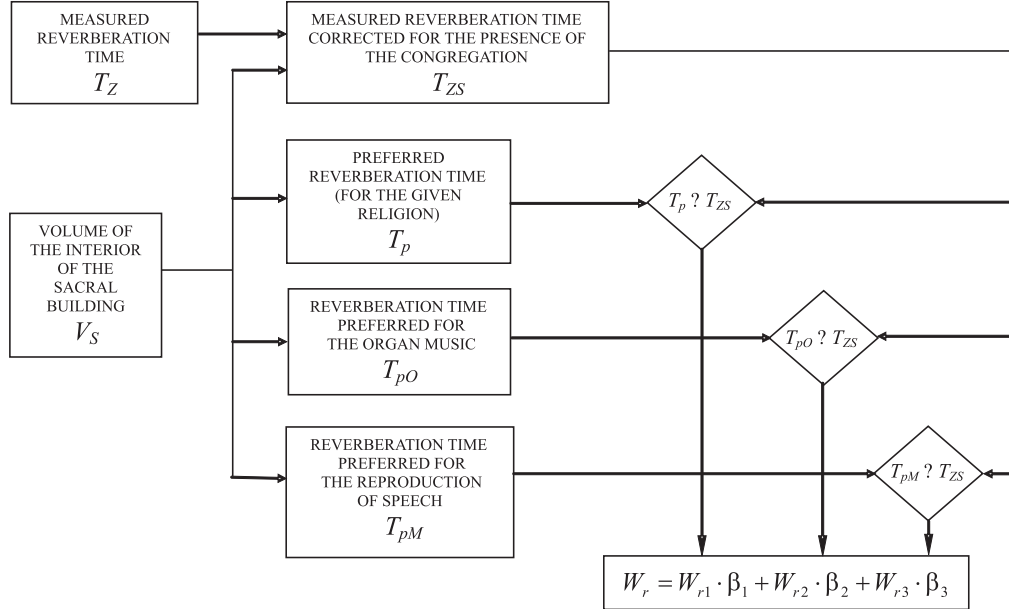

Fig. 3. Schematic diagram of the estimation of the reverberation index W_r.

The reverberation index W_r has values from 0 to 1. Taking into account the reverberation time, the conditions are most favourable when $W_r = 1$, while the worst ones when $W_r = 0$.

Each of the auxiliary indices has a determined weight (β_1, β_2, β_3). The values of these weights are given in Table 2 and discussed in [13, 21]. These values did not result from any strict dependencies but were assumed on the basis of experimental tests. The weights of the auxiliary reverberation parameters depend on the cubic capacity of the sacral building and on the religion for which the given building is destined for (since the range of sound production varies for different religions).

In order to determine the main reverberation index W_r, the cubic capacity V_s as well as the reverberation T_z, which has to be corrected for the presence of the audience, should be measured. The corrected reverberation time is compared by means of certain dependencies with the reverberation times preferred for the given sacral building due to the religion and due to the organ music and speech reproduction (according to the diagram in Fig. 3).

Table 2. Weights of auxiliary parameters for the given type of the sacral building.

Weights of auxiliary parameters			Sacral building		
	Cubic capacity V_S [m³]		$600 < V_S \leq 1500$	$1500 < V_S \leq 15000$	$15000 < V_S \leq 40000$
		Type	Small	Medium	Large
	β_1	Catholic churches, Evangelical churches, Synagogues	0.6	0.6	0.6
	β_2	Catholic churches, Evangelical churches	0.1	0.2	0.3
		Synagogues	0	0	0
	β_3	Catholic churches, Evangelical churches	0.3	0.2	0.1
		Synagogues	0.4	0.4	0.4

The reverberation-volume index W_{r1} is determined from the formula:

$$W_{r1} = 1 - \frac{|T_{ZS} - T_p|}{5},\qquad(4)$$

where T_p – reverberation time preferred for the given sacral building [s], T_{ZS} – measured time corrected by the presence of the audience [s].

The preferred reverberation time T_p depends on the cubic capacity of the sacral building V_S. The values of the preferred reverberation time can be calculated from the following formulae:

- Catholic churches:

$$T_p = 0.24 \ln(V_S) - 0.24 \ [\text{s}],\qquad(5)$$

- Evangelical churches:

$$T_p = 0.17 \ln(V_S) + 0.12 \ [\text{s}],\qquad(6)$$

- Synagogues:

$$T_p = 0.15 \ln(V_S) - 0.1 \ [\text{s}],\qquad(7)$$

where V_S – cubic capacity of the sacral interior, [m³].

The W_{r1} index (Eq. (4)) takes values from 0 to 1 on the assumption that $T_{ZS} \leq T_p + 5$. When $T_{ZS} = T_p$, the $W_{r1} = 1$, which means that the investigated sacral building has the best acoustic properties. When $T_{ZS} = T_p + 5$, the index $W_{p1} = 0$, which is tantamount to bad acoustic qualities of the building investigated.

If $T_{ZS} > T_p + 5$, Eq. (4) leads to negative values and it should be assumed that $W_{p1} = 0$. This means that the reverberation time corrected by the presence of the audience exceeds the reverberation time preferred for the given cubic capacity by more than 5 s.

The auxiliary reverberation index for organ music W_{r2} is determined from the formula:

$$W_{r2} = 1 - \frac{|T_{ZS_{500}} - T_{pO}|}{5}, \tag{8}$$

where T_{pO} – preferred reverberation time for organ music for the octave band of medium frequency 500 Hz [s], $T_{ZS_{500}}$ – measured, corrected reverberation time for the octave band of medium frequency 500 Hz [s].

The preferred reverberation time for organ music T_{pO} depends on the cubic capacity according to the following relationship:

$$T_{pO} = 0.73 V_S^{0.15} \, [\text{s}], \tag{9}$$

where V_S – cubic capacity of the interior of the sacral building, [m^3].

The values of the preferred reverberation time for organ music T_{pO} (Eq. (9)) are related to the octave band of medium frequency 500 Hz. The index W_{r2} (Eq. (8)) ranges from $0 \div$ to1 on the assumption that $T_{ZS_{500}} \leq T_{pO} + 5$. When $T_{ZS_{500}} = T_{pO}$, then the index $W_{r2} = 1$, which means very good properties for organ music resounding. When $T_{ZS_{500}} = T_p + 5$, then the index $W_{r2} = 0$, which means that the difference between the measured, corrected reverberation time and the time preferred equals 5 s which is tantamount to bad acoustic properties of the building tested.

If $T_{ZS_{500}} > T_p + 5$, Eq. (8) produces negative values, thus the assumption $W_{r2} = 0$ should be made. This means that the reverberation time corrected by the presence of an audience exceeds the time preferred for organ music by more than 5 s.

The auxiliary reverberation index for the intelligibility of speech W_{r3} is determined from the formula:

$$W_{r3} = 1 - \frac{|T_{ZS} - T_{pM}|}{5}, \tag{10}$$

where T_{pM} – permissible reverberation time for interiors destined for a speech reproduction [s], T_{ZS} – measured, corrected reverberation time, s.

The permissible values of the reverberation time for a speech reproduction, T_{pM}, can be estimated from the equation:

$$T_{pM} = 0.17 \ln(V_S) - 0.43 \, [\text{s}], \tag{11}$$

where V_S – cubic capacity of the sacral building interior [m^3].

Equation (10) assumes values from 0 to 1 on the assumption that $T_{ZS} \leq T_{pM} + 5$. When $T_{ZS} = T_{pM}$, the index $W_{r3} = 1$. When $T_{ZS} < T_p$, it is assumed that $W_{r3} = 1$. The index $W_{r3} = 0$ when $T_{ZS} = T_{pM} + 5$, which means that the difference between T_{ZS} and T_{pM} equals 5 seconds. When $T_{ZS} > T_{pM} + 5$, it should be assumed that $W_{r3} = 0$.

The measured reverberation time corrected by the presence of the audience T_{ZS} is determined from the following formula:

$$T_{ZS} = \frac{0.16 V_S}{(S - S_1 - S_2)\,\alpha_p + S_1 \alpha_1 + S_2 \alpha_2}, \tag{12}$$

where α_p – average reverberation absorption coefficient, V_S – cubic capacity of the sacral building interior [m^3], S – area of the boundary surfaces [m^2], S_1 – surface area

of sitting down persons [m^2], S_2 – surface area of standing persons [m^2], α_1 – absorption coefficient of the area of sitting down persons, α_2 – absorption coefficient of the area of standing person, 0.16 is a numerical coefficient, which value results from the reverberation time definition and the assumptions of the Sabin's or Eyring's theory [s/m].

The average reverberation absorption coefficient is estimated from the following equation:

$$\alpha_p = \frac{0.16 V_S}{T_Z S},\qquad(13)$$

where V_S – cubic capacity of the sacral building interior [m^3], T_Z – averaged measured reverberation time [s].

Equation (12) is an approximate equation based at that of Sabine. The accuracy of the estimation of the reverberation time corrected by the presence of the audience depends, among other things, on the assessment of the cubic capacity of the interior of a sacral building. In some churches due to their complicated shape ("sculpturing") or the arrangement of the interior, this estimation might be sometimes rather difficult. Absorption coefficients for a sitting person α_1, and for a standing person α_2 are given in the references [20, 21, 31, 32].

3.2. External disturbance index

A high level of disturbing sounds masks and distorts the useful sound. Noise can also distort the tone quality. External disturbances of sacral buildings are mainly caused by traffic noises.
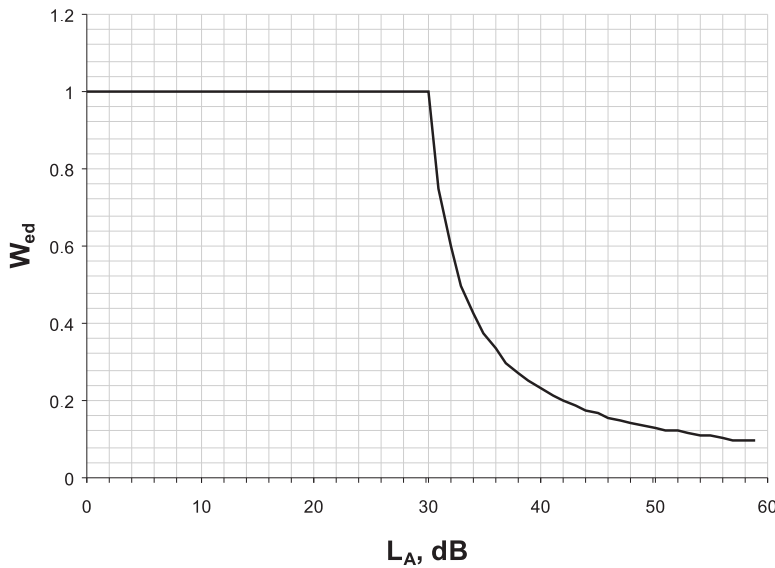

Fig. 4. Nomogram for the estimation of the external disturbance index W_{ed}.

When $L_A > 30$ dB, the external disturbance index of the sacral building is given by the formula:

$$W_{ed} = \frac{3}{L_A - 27},$$
(14)

where L_A – sound A level of external disturbance inside the church, dB.

The external disturbance index can be found also from the graph presented in Fig. 4.

The sound A level of 30 dB was assumed as the permissible level of disturbing noises. When the sound A level $L_A \leq 30$ dB, the permissible level of external disturbances is not exceeded and $W_{ed} = 1$.

3.3. Music sound quality index

In Poland churches and temples are places where, apart from the liturgical ceremonies, certain cultural events are organized, e.g. various kinds of concerts. Thus, the acoustic quality of such places should be assessed not only when organ music determined by the auxiliary reverberation time for organ music is taken into account, but also when classic music is considered.

Beside several parameters describing the properties of interiors for music perception, four factors have been chosen hereby for the assessment of interiors of sacral buildings: two subjective factors introduced by L. L. Beranek (1962) i.e. the liveness T_{mid} and sound warmth BR *(Bass Ratio)*, the clarity index C_{80} introduced by Reichardt and the centre of gravity time T_S proposed by Kürer (1969) and developed by Cremer (1982).

The acoustic liveness means the perceived reverberation level inside a room and is connected with the reinforcement of medium and high tones. The reverberation time related to liveness concerns the interior fully occupied by the audience. The liveness is given by the equation [3]:

$$T_{\text{mid}} = \frac{T_{500} + T_{1000}}{2}, \text{ s} \qquad 0.8 \leq T_{\text{mid}} \leq 2.1\,\text{s}.$$
(15)

The sound warmth or tone quality indicates the response of the room to low frequencies (below 250 Hz) determining the fullness of bass resounding and softness of music. The warmth of sound is given by [3]:

$$BR = \frac{T_{125} + T_{250}}{T_{500} + T_{1000}}, \qquad 0.85 \leq BR \leq 1.45.$$
(16)

The clarity index, C_{80} is 10 times the logarithm of the ratio of energy in the first 80 ms to the remaining energy [16]:

$$C_{80} = 10 \log \left(\frac{\int_0^{80\,\text{ms}} p^2(t)\mathrm{d}t}{\int_{80\,\text{ms}}^{\infty} p^2(t)\mathrm{d}t} \right), \text{ dB}$$
(17)

where $p(t)$ – pressure function of the impulse response.

The clarity index allows to assess how the given interior, including that of a sacral building, influences the possibility of distinguishing sounds, which are generated immediately one after another.

The centre of gravity time is also used for the assessment of the music clarity index T_S. It is given by the following equation [33]:

$$T_S = \frac{\int\limits_0^\infty tp^2(t)\mathrm{d}t}{\int\limits_0^\infty p^2(t)\mathrm{d}t}, \text{ s,} \tag{18}$$

where $p(t)$ – pressure function of the impulse response.

The music sound quality index W_m is a function of four auxiliary indices W_{m1}, W_{m2}, W_{m3} and W_{m4}.

$$W_m = f(W_{m1}, W_{m2}, W_{m3}, W_{m4}), \tag{19}$$

where W_{m1} – auxiliary sound index determining the acoustic liveness, T_{mid}, inside the sacral building, $0 < W_{m1} \leq 1$; W_{m2} – auxiliary sound index concerning the sound warmth BR inside the sacral building, $0 < W_{m2} \leq 1$; W_{m3} – auxiliary sound index – the clarity index C_{80} inside the sacral building, $0 < W_{m3} \leq 1$; W_{m4} – auxiliary sound index concerning the centre of gravity time T_S inside the sacral building, $0 < W_{m4} \leq 1$.

Like the auxiliary indices, the music sound quality index assumes values $0 < W_m \leq 1$. The index W_m is given by the formula:

$$W_m = \sqrt{\frac{W_{m1}^2 + W_{m2}^2 + W_{m3}^2 + W_{m4}^2}{4}}. \tag{20}$$

Nomograms, from which the auxiliary sound indices W_{m1} and W_{m2} can be estimated, were prepared on the basis of the analysis of parameters applied by L. L. Beranek for the assessment of music perception in various rooms. To determine the value of the W_{m1} index, it is necessary to calculate the acoustic liveness of the interior of the sacral building. L. L. Beranek defined the rating, which describes the acoustic liveness of opera rooms (Italian operas, Wagner's operas) and concert halls (romantic music, typical orchestra, classic music, baroque music). Due to the specificity of sacral interiors, two scales of acoustic liveness T_{mid}, the scale for classic music and that one for baroque music, have been averaged. The scoring was also changed. In the Beranek's scale, the number of points for the acoustic liveness ranges from 0 to 15. According to the assumption that the music sound quality index assumes values from 0 to 1 and in order to satisfy equation (20), the value of the auxiliary sound index concerning the acoustic liveness should also be within the range $0 \leq W_{m1} \leq 1$. The values of W_{m1} can be found from the nomogram presented in Fig. 5. The auxiliary index W_{m1} assumes the maximum value equal to 1 for $T_{\mathrm{mid}} = 1.6$ s, while $W_{m1} = 0$ when $T_{\mathrm{mid}} \leq 0.8$ or $T_{\mathrm{mid}} > 2.1$.
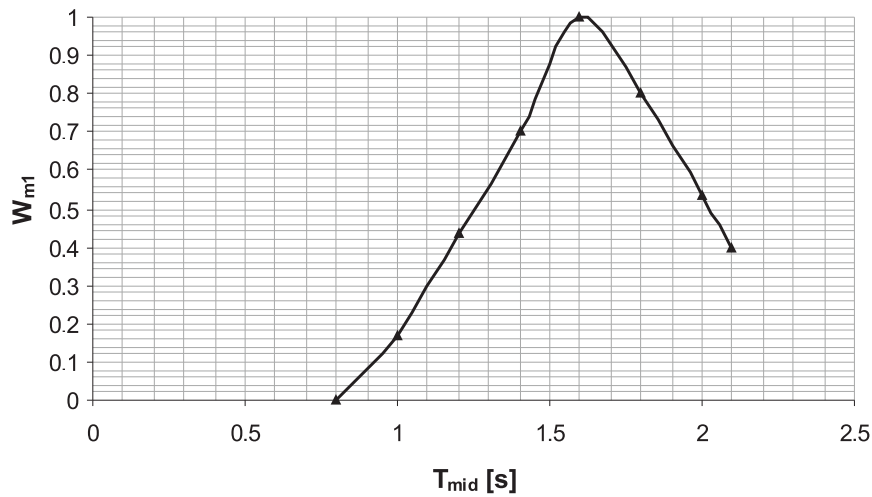
Fig. 5. Nomogram for the estimation of the auxiliary sound index W_{m1}.

In a similar fashion as in case of W_{m1}, to adapt the second Beranek's parameter – the sound warmth BR – to the index method, like in the event of W_{m1}, the scale has been changed from the range $0 \div 15$ to $0 \div 1$.

The determination of the sound warmth BR given by the relation (16) is necessary to estimate the auxiliary sound index W_{m2}. One can read the values of W_{m2} from the nomogram presented in Fig. 6 on the basis of the estimated sound warmth BR. The
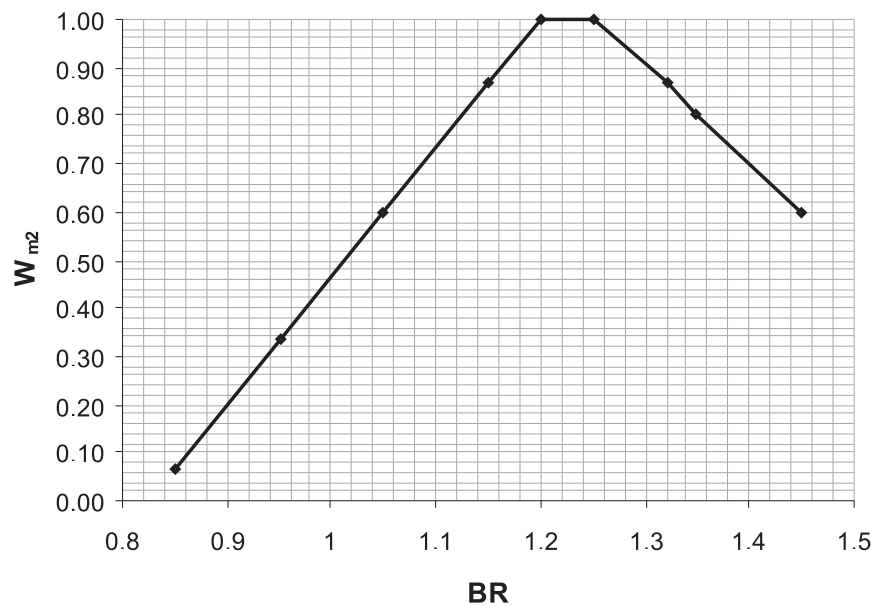

Fig. 6. Nomogram for the estimation of the auxiliary sound index W_{m2}.

auxiliary sound index W_{m2} assumes the maximum value equal 1 for $1.2 \leq BR \leq 1.25$, while $W_{m2} = 0$ when $BR < 0.85$ or $BR > 1.45$.

The auxiliary sound index W_{m3} depends on the clarity index C_{80} determined by Eq. (17). The values of C_{80} recommended (according to Kraak) for concert halls are given in [33]. The nomogram presented in Fig. 7, prepared on the basis of the preferred values, is to be used for the determination of the auxiliary sound index W_{m3} being in the range from 0 to 1.
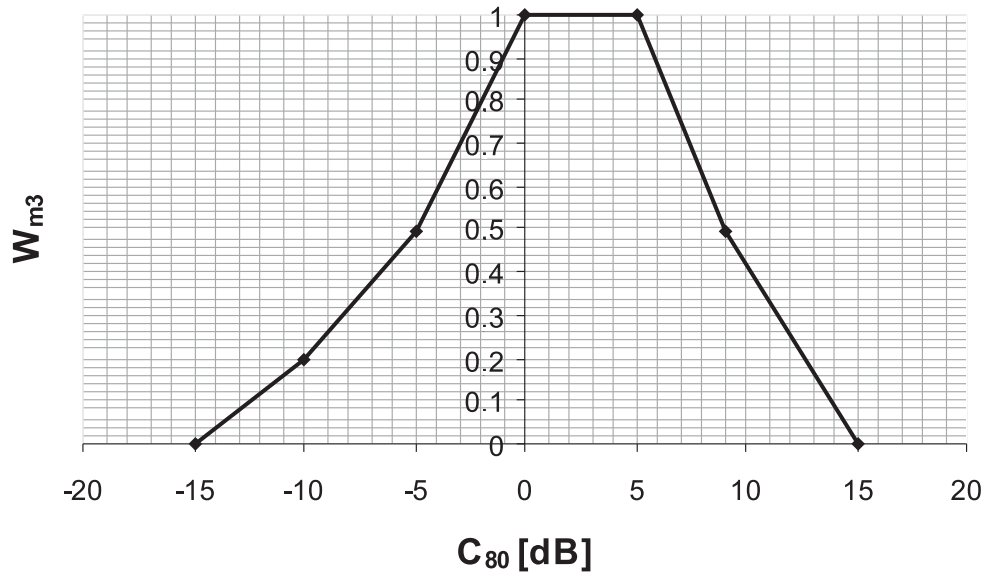

Fig. 7. Nomogram for the estimation of the auxiliary sound index W_{m3}.

The auxiliary sound index W_{m3} achieves its maximum (equal to 1) for $0 \leq C_{80} \leq 5$. $W_{m3} = 0$ when $C_{80} < -15$ or $C_{80} > 15$.

In order to determine the auxiliary sound index W_{m4}, it is necessary to find the value of the centre of gravity time of the echogram T_S, given by the formula (18). The T_S value can be found from the impulse response of the sacral building interior. The nomogram presented in Fig. 8 was prepared on the basis of the preferred T_S values recommended in the reference [33]. The value of the auxiliary sound index W_{m4} can be determined from the centre of gravity time.

Since the music sound quality index W_m is considered from the point of view of performing concerts of classical music in sacral buildings, the auxiliary sound index W_{m4} assumes the maximum value ($W_{m4} = 1$) for the range of T_S values recommended for symphonic orchestras, i.e. for $100 \leq T_S \leq 150$ ms. The values $T_S < 80$ ms and $T_S > 180$ ms are not recommended for music reproduction and therefore W_m equals 0 in such cases.
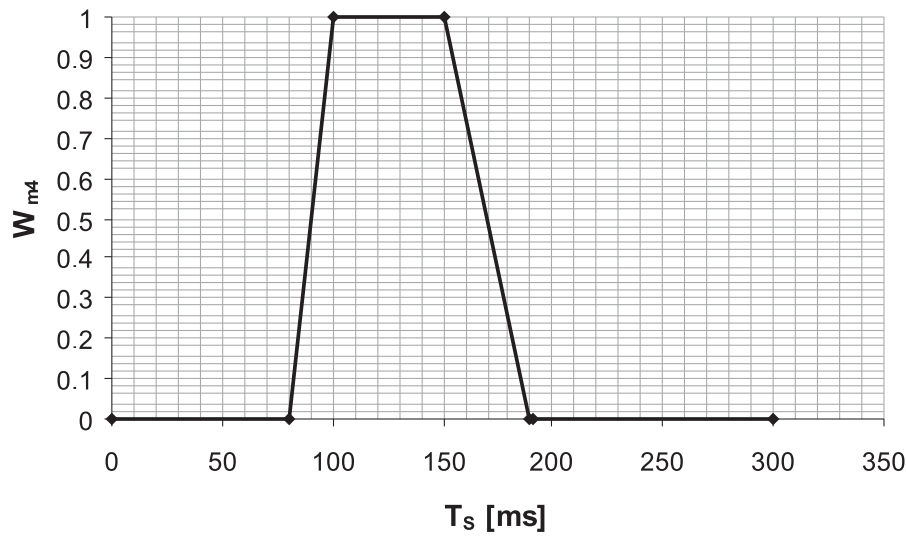
Fig. 8. Nomogram for the estimation of the auxiliary sound index W_{m4}.

3.4. Intelligibility of speech index

There are several indices applied in the acoustics of interiors for the assessment of the intelligibility of speech. This indices are, among other things: STI *(Speech Transmission Index),* RASTI *(Rapid Speech Transmission Index),* SII *(Speech Intelligibility Index),* ALCONS *(Percentage Articulation Loss of Consonants),* C_{50} *(Clarity Index),* D_{50} *(Definition, Deutlichkeit).*

The use of three indices: the ALCONS, RASTI and C_{50} has been hereby proposed for the assessment of the intelligibility of speech inside sacral buildings. The auxiliary indices as well as the general index of intelligibility of speech, W_{is}, are determined on the basis of these three indices. All the three indices can be assessed from the impulse response of the sacral building interior.

On the basis of the dependencies between the measured subjective and objective indices of the intelligibility of speech given in [5], the nomograms presented in Fig. 9 have been used for the estimation of the auxiliary indices W_{s1}, W_{s2} and W_{s3} from the ALCONS, RASTI and C_{50} coefficients. The presented nomograms allow also to find the subjective assessment of the intelligibility of speech.

The intelligibility of speech index W_{is}, being the partial index of the global index of the acoustic assessment of sacral buildings W_{AQS}, is a function of the auxiliary indices of the intelligibility of speech W_{s1}, W_{s2} and W_{s3} and is expressed as:

$$W_{is} = \sqrt{\frac{W_{s1}^2 + W_{s2}^2 + W_{s3}^2}{3}}, \tag{21}$$

where W_{s1}, W_{s2}, W_{s3} – auxiliary indices of the intelligibility of speech, which assume values in the range from 0.1 to 1.
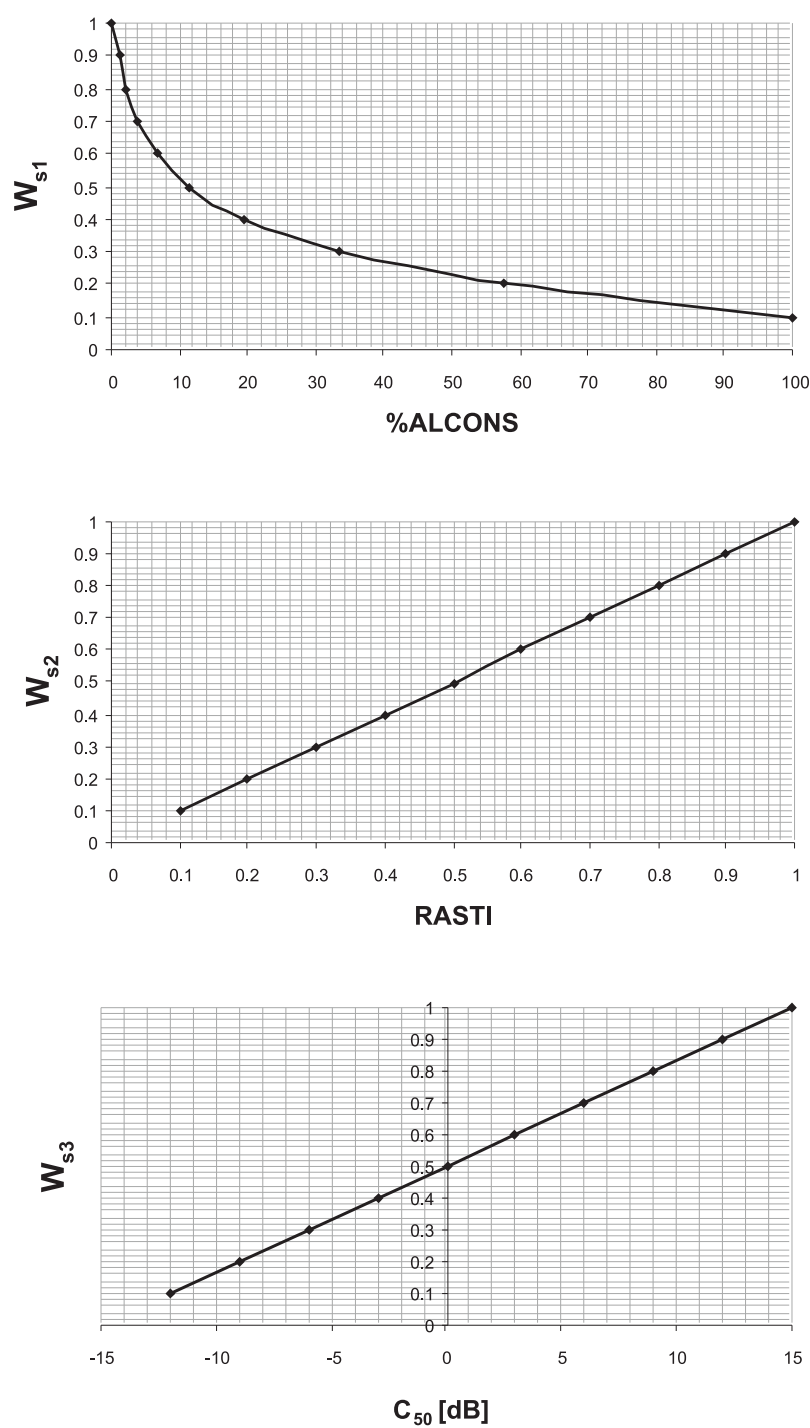
Fig. 9. Nomograms for the estimation of the auxiliary indices W_{s1}, W_{s2}, W_{s3}.

3.5. Uniformity of loudness index

The scattering of the acoustic energy, which, among other things, determines the uniformity of loudness inside the sacral building, is a significant factor influencing the acoustic quality. A non uniform field, which means a not satisfactory scatter of the acoustic energy, causes worsening of the intelligibility of speech as well as of the tone and sound quality. In order to obtain a good energy dissipation, an adequate shape and acoustic proportions of the interior should be provided as well as proper arrangements of the sound absorbing and sound scattering systems should be accomplished.

The investigations of the uniformity of loudness by means of the index method have been made in sacral buildings where the electro-acoustic installations were switched off, since the measurements concerned the acoustic properties of the interiors themselves but not the acoustic performance of the equipment which improved those properties.

The distribution of the sound pressure level, which are crucial for the uniformity of loudness, can be determined from measurements of the sound pressure level at the measuring points.

The conversion of the measured sound pressure levels into their decrease Δ_L, in dB, from the maximum measured sound pressure level $L_{p_{\max}}$, is more advantageous for the application of the index method. This is expressed by the formula:

$$\Delta_L = \left| L_{p_{\max}} - L_{p_i} \right|, \text{ dB}, \tag{22}$$

where $L_{p_{\max}}$ – maximum sound pressure level, [dB], L_{p_i} – sound pressure level at the given measuring point, [dB].

Isophone lines of the decrease of the pressure level plotted in the distribution diagram will show the value, by which the sound pressure level decreased in the given surface area.

The uniformity of loudness index is determined for each j-th frequency octave band from the following formula:

$$W_{U_j} = \frac{\displaystyle\sum_{j=1}^{n} \kappa_j \cdot S_{\Delta L}}{S_c}, \tag{23}$$

where κ_j – coefficient of the decrease of the sound pressure level for the j-th frequency octave band, ($j = 125; 250; 500; 1000; 2000; 4000$ Hz), S_c – surface area on which the uniformity of loudness is investigated, [m^2], $S_{\Delta L}$ – surface area between two neighbouring loudness contours in which the decrease Δ_L, [m^2] occurs.

The values of the uniformity of loudness index for separate octave bands are within the range: $0 < W_{U_j} \leq 1$. When the acoustic scattering is sufficient, the sound pressure level does not exceed, depending on the frequency, the following values: ± 3 dB up to 500 Hz; ± 2 dB for the frequency range 500 Hz $\div$ 2000 Hz and ± 1 dB above 2000 Hz.

The nomogram presented in Fig. 10 was prepared in accordance with the deviations of the sound pressure level given above. The values of κ for octave bands of medium
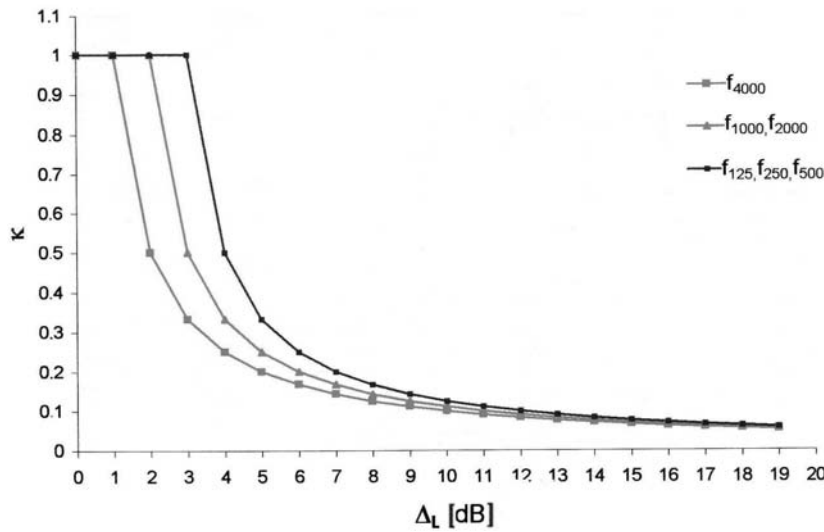
Fig. 10. Nomogram for the determination of the coefficient of the decrease of the sound pressure level κ, for the j-th octave band for the decrease of the sound pressure level, Δ_L determined by the i-th loudness contour.

frequencies $f_{125} \div f_{4000}$ can be found from this nomogram. They are in the range $0 < \kappa \leq 1$ and can be calculated as follows:

$$\kappa = \frac{1}{\Delta_L} \qquad \text{for} \quad f_{4000}, \tag{24}$$

$$\kappa = \frac{1}{\Delta_L - 1} \quad \text{for} \quad f_{1000}, f_{2000}, \tag{25}$$

$$\kappa = \frac{1}{\Delta_L - 2} \quad \text{for} \quad f_{125}, f_{250}, f_{500}, \tag{26}$$

where Δ_L – decrease of the sound pressure level, [dB], $f_{125} \div f_{4000}$ – medium frequencies of the octave bands.

When the uniformity of loudness indices in the frequency octave bands $W_{U125} \div W_{U4000}$ are determined, the averaged uniformity of the loudness index can be calculated from the formula:

$$W_{ul} = \frac{\sum\limits_{j=1}^{6} W_{Uj}}{6}, \tag{27}$$

where $W_{U_j} W_{Uj}$ – the uniformity of loudness index for the j-th frequency octave band.

The values of the averaged uniformity index, like in case of the W_{U_j} values, are contained within the range $0 < W_{ul} \leq 1$. The best acoustic properties are tantamount to the uniform loudness of the sacral building, i.e. the sound pressure level not exceeding the permissible values occur when $W_{ul} = 1$. Thus, the acoustic properties are the worst ones when W_{ul} approaches 0.

4. Application of the proposed index method for the acoustic assessment of sacral buildings

A verification of the proposed method was performed in four Roman-catholic churches of the general lay-out presented in Fig. 11. The church presented in Fig. 11c is not rectangular shaped in contrast to the assumption of the index method. This was a trial of verification of the method to non-rectangle lay-out interiors. The trial was successful and will be the object of further investigations.
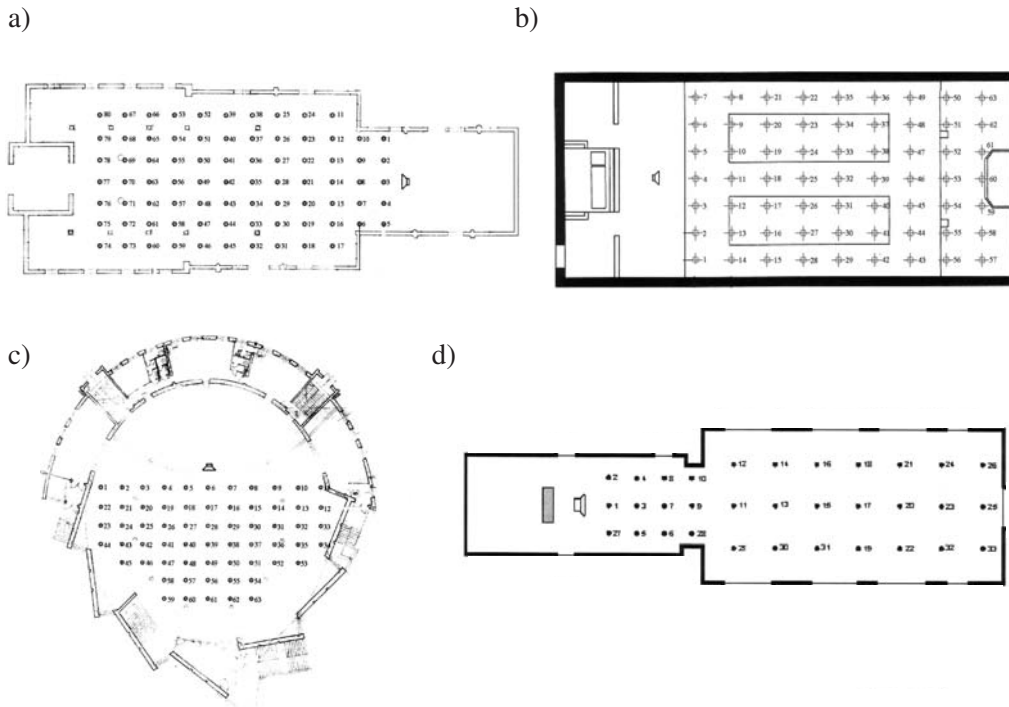
a)

b)

c)

d)

Fig. 11. General lay-outs of: a) the St. Sebastian's Church in Strzelce Wielkie b) the Holiest Sacred Heart's Church in Kraków; c) the St. Paul Apostle's Church in Bochnia; d) the Reformati Fathers Church in Wieliczka.

The measurements of the impulse responses were performed at the measuring points of the tested interiors [21]. Measurements of the external disturbance levels as well as those of the sound pressure levels for a sound source placed near the altar were also accomplished. The acoustic parameters were calculated from the impulse response. Thus, in this way the values of individual partial parameters for each church were assessed (see Sec. 3) and presented in Table 3.

According to the index method, the best acoustic performance among the tested churches characterise – the Holiest Sacred Heart's Church in Kraków and the wooden, antique St. Sebastian's Church in Strzelce Wielkie, while the worst – one charcterise the modern St. Paul Apostle's Church in Bochnia built on an ellipse lay-out.

Table 3. Comparison of acoustic properties of sacral building by means of partial indices and the global index.

Sacral building	$V\ [\mathrm{m}^3]$	W_r	W_{is}	W_{ed}	W_{ul}	W_m	W_{AQS}	assessment
The Reformati Fathers Church in Wieliczka	4450	0.88	0.33	0.37	0.26	0.48	**0.56**	Poor
The Holiest Sacred Heart's Church in Kraków	2750	0.94	0.34	0.4	0.53	0.6	**0.66**	Good
The St. Sebastian's Church in Strzelce Wielkie	1650	0.88	0.49	1	0.2	0.67	**0.71**	Good
The St. Paul Apostle's Church in Bochnia	22000	0.39	0.21	1	0.78	0.21	**0.47**	Bad

5. Conclusions

The new method of the acoustic assessment of sacral buildings interiors – the index method – was presented in this paper. The suggested index method builds hope that, after further improvements, it may be successfully applied for approximate assessments of the acoustic quality of sacral interiors. The index method is destined for a certain group of sacral buildings such as Roman-catholic and evangelic churches and synagogues of a cubic capacity ranging from 600 to 40 000 m^3 and of straight shapes. The shape of the interior has basically influence on its acoustic conditions. The usage of interior shapes of based on a circular or semicircular lay-out and with various domes are definitely unfavorable in point of the acoustic quality [29]. The straight shaped interiors are rectangular prism interiors. The index method proposed includes also near-rectangular prism interiors. At present the method cannot be applied for interiors having acoustically coupled spaces. Such applications require further research.

The assessment using the index method has been done when the sound-reinforcement system of the sacral object was turned off. The sound-reinforcement system problem will be considered in further investigations.

The tentative assessment is performed by a complex method by means of a single number index. In addition, the partial indices allow to estimate the individual acoustic properties of the sacral building, such as: the reverberation time, intelligibility of speech, music sound qualities, external disturbance levels and the uniformity of loudness level. The index method proposed allows a better estimating of the acoustic properties, than the presently used methods adapted for sacral buildings. The analysis of those methods indicates that none of them considers sufficiently the specificity of interiors of churches of different religions. Thus, no single method is able to supply complete results and must be supplemented by other methods. This should not be surprising since those methods were developed either for the acoustic assessment of concert and opera halls or for auditoriums.

The measurement of the impulse responses at the measuring points inside a given building as well as the sound pressure level and external disturbance levels are needed for the global assessment. On the basis of those measurements, the values of individual acoustic parameters, e.g. reverberation time, C_{80}, C_{50}, ALCONS and RASTI indices, and the centre of gravity time are calculated. Those parameters are then used for the calculation of the partial indices as well as the global index of the acoustic qualities of sacral buildings.

The verification of the proposed method has been performed in four selected Roman-catholic churches, which were classified into groups of sacral buildings of certain acoustic properties, by means of a proposed tentative scale.

The application of the index method will allow to create a data base of sacral buildings of similar acoustic properties, which might contribute to the development of designing, building and the proper equipment and arrangement of sacral buildings.

The index method proposed includes a lot of assumptions and simplifications because of the complexity of the acoustic assessment of sacral buildings. This influences the range of applications of this method. The authors are doing research on the application the Singular Value Decomposition (SVD) method for solving those problems.

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