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Singular Vectors in Acoustic Simulation Tests of St. Paul the Apostle Church in Bochnia

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A new approach to acoustic quality assessment of churches during simulation tests is proposed in the article. The numerical global index, based on four partial indices: reverberation, speech intelligibility, music sound index and a proposed new one – sound strength index, assesses the acoustic parameters of the model of the tested church in a complex manner.

The global single number index was obtained from 17 simulations of acoustic adaptation options of the investigated church's interior. The equation of the approximate global index has been obtained by means of singular vectors, obtained from Singular Value Decomposition (SVD) of the Index Observation Matrix of Simulation Variants (IOMSV). The weights of four partial indices and a universal equation of the global index have been calculated using the SVD technique to solve the problem of correlated acoustical parameters. The global index may be a helpful tool during simulation tests of acoustic quality assessment of churches. The proposed final equation of the global index does not require knowledge of the SVD technique and the values of acoustic parameters preferred for churches. Therefore the methodology proposed is easily applicable.

Keywords: acoustic quality, index method, churches, Singular Value Decomposition (SVD), acoustics adaptation.

1. Introduction

Many publications have been devoted to the acoustic quality of churches, among the others (Engel *et al.*, 2007; Martelotta, Crillo, 2006; Martelotta *et al.*, 2009; Meyer, 2003; Vodopija *et al.*, 2010). The subject of research concerns not only existing objects but also interiors in the design, building and acoustic adaptation stages. Then, simulation tests are carried out on geometric models of interiors (Gołaś, Suder–Dębska, 2009; Buratti *et al.*, 2006; Segura *et al.*, 2010; Quartieri *et al.*, 2010).

A basic, and sometimes the only, acoustic parameter which is taken into account when designing public buildings is reverberation time, which influences the other acoustic parameters such as e.g. Sound Strength G, Early Decay Time EDT and Clarity C_{80} (Skålevik, 2010). However, application of methods based only on reverberation time for assessment of church interiors does not sufficiently enclose the specification of such interiors.

The Index Method, proposed by Engel and Kosała (2007), was carried out to assess the real conditions of churches. The trial application of this method in simulation tests, as an additional tool for design, was shown in the paper. Using the Index Method for acoustic adaptation of a contemporary church was shown with the example – St. Paul the Apostle Church in Bochnia. According to acoustic research (Engel *et al.*, 2007), that particular church has poor acoustic conditions for its function.

Singular vectors obtained from Singular Value Decomposition (SVD) of the Index Observation Matrix of Simulation Variants (IOMSV) for the assessment of acoustic quality were used. The IOMSV contains acoustic parameters, obtained from calculation simulations carried out on the model of the church, as partial indices of assessment. Singular vectors are components of the single number global index, which is a function of four partial indices: reverberation, speech intelligibility, music sound quality and a new one, proposed in the article, the strength of sound index.

2. Global assessment of the acoustic quality of church interiors in simulation tests

2.1. Global index W_{GS}

The Index Method, proposed in (Engel, Kosała, 2007), was used by Carvalho and Silva (2010). The method is still being improved by using the SVD technique (Kosała, 2007; 2008a; 2008b; 2009; 2011). Singular vectors and singular values obtained from Singular Value Decomposition of the Index Observation Matrix (IOM) are used to build the global index. The single number global index allows acoustic conditions inside the interior to be approximately assessed – with reference to the preferred values of acoustic parameters. The Index Method has many assumptions, which are described in (Engel, Kosała, 2007).

At the moment, the global index, as a function of a few partial indices is expressed as follows:

$$W_G = W_1 \cdot W_2 \cdot ... \cdot W_n, \tag{1}$$

where n is the amount of uncorrelated partial indices.

One local index of the chosen acoustic parameters W_{SAP} should be created (by using the SVD technique) when partial indices are mutually correlated.

The external disturbance index W_{ed} (defined in (Engel, Kosała, 2007)) is the one which is not correlated in church acoustic assessment. Therefore, the global index

$$W_G = W_{ed} \cdot W_{SAP}, \tag{2}$$

where W_{SAP} is the local index of selected, strong mutually-correlated acoustic parameters

$$W_{SAP} = f(W_R, W_M, W_S), \tag{3}$$

where W_R is the reverberation index, W_M is the music sound index, W_S is the speech intelligibility index.

Calculation procedures of the partial indices W_R, W_M and W_S were described in detail for 6 churches in (Kosała, 2011).

The new global index of assessment for the acoustic quality of church interiors in simulation tests W_{GS} is a function of four strongly mutually-correlated partial indices

$$W_{GS} = f(W_R, W_M, W_S, W_{ST}), \tag{4}$$

where W_{ST} is the sound strength index.

The external disturbance index, uncorrelated with the other ones, is rejected during simulation tests because, before and after acoustic adaptation, its value is the same.

The assessment scale of the value of indices is within the range 0 to 1. The value of 0 means poor interior acoustic parameters, whereas the value of 1 represents good parameters, corresponding to the preferred values.

The W_{GS} index is defined as:

$$W_{GS} = x_1 W_R + x_2 W_M + x_3 W_S + x_4 W_{ST}, \tag{5}$$

where $x_1 \div x_4$ are the weights of partial indices.

In order to obtain the values of weights, the index W'_{GS}, based on perfectly mutually-correlated partial indices should be calculated. Perfect correlation of indices is obtained from the first approximation of the Singular Value Decomposition of IOMSV. W'_{GS} is defined as:

$$W'_{GS} = \sigma_1 \mathbf{u}_1 \mathbf{v}_{11}, \tag{6}$$

where σ_1 is the first singular value, obtained from SVD of IOMSV, $\mathbf{u}_1$ is the first left singular vector of the matrix $\mathbf{U}$, obtained from SVD of IOMSV, $\mathbf{v}_{11}$ is the first element of first right singular vector of the matrix $\mathbf{V}^{\mathrm{T}}$, obtained from SVD of IOMSV.

The procedure for calculating the weight of partial indices, described and applied in (Kosała, 2011) uses the SVD technique to solve the issue of redundant information, where the number of linear equations is greater than the number of unknowns – weights.

2.2. Sound strength index W_{ST}

According to ISO-3382 (1997), the sound strength G is defined as a logarithm of the ratio for acoustic pressure exposure of the measured impulse response to acoustic pressure exposure of impulse response, measured at the same sound source in a free-field at a distance of 10 m

$$G = 10 \log \frac{\int_0^\infty p^2(t)\,\mathrm{d}t}{\int_0^\infty p_{10}^2(t)\,\mathrm{d}t}. \tag{7}$$

Sound strength G is one of the parameters which is calculated during acoustic quality assessment of concert halls and opera houses (Beranek, 2004; Barron, 2005; Skålevik, 2010), as well as church interiors (Martelotta *et al.*, 2009).

On the basis of the preferred values of the sound strength G, given in literature (Beranek, 2004), a nomogram was prepared, from which values of the sound strength index W_{ST}, used in the index method, have been read.

According to Beranek (2004), the loudness impression is best described by the averaged value of G_{mid} for the frequency bands 500 and 1000 Hz. The preferred values of G_{mid} are within the range from 4.5 to 5.5 dB, for which the value of the index W_{ST} (Fig. 1) is maximum and equals 1.

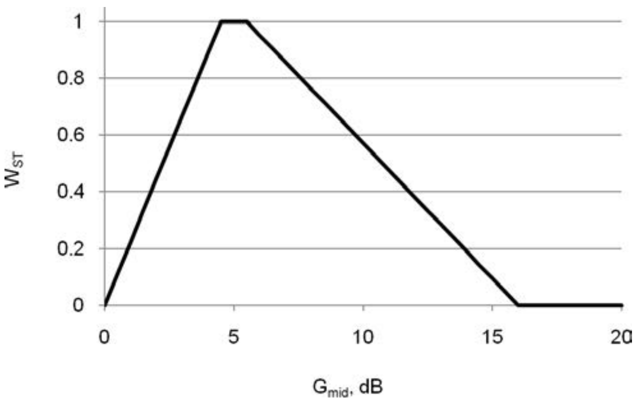

Fig. 1. The nomogram for estimation of the sound strength index W_{ST}.

3. Geometric model of the tested church

St. Paul the Apostle Church in Bochnia (Fig. 2) has already been the subject of investigations. Acoustic parameter investigations confirm the assessment of poor interior acoustic quality, which is in accordance with the opinion of the congregation. The lack of suitable acoustic conditions makes it difficult to lead religious and cultural activities. The trial for checking the options of acoustic improvement of the interior was shown in (Kosała, Kamisiński, 2011).

Fig. 2. View of St. Paul Apostle's Church in Bochnia.

In order to make simulation tests, a geometric model of the church, consisting of 522 surfaces, was prepared (Fig. 3). The simulation tests were performed by using CATT-Acoustic v.8 software.

The values of the reverberation sound absorption coefficients of materials used in simulation tests were given in Table 1 in (Kosała, Kamisiński, 2011). The model of the interior (Fig. 3) was calibrated by using reverberation time in octave frequency bands.

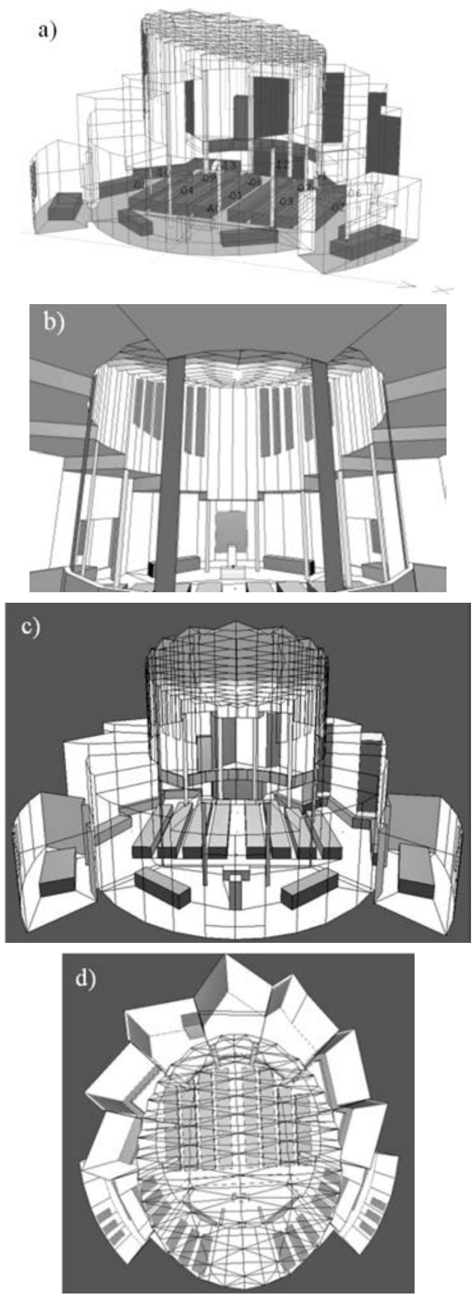

Fig. 3. The geometric model of St. Paul the Apostle Church: a) layout of sound source (A0) and measurement points (1–13), b) view from the choir, c) front view, d) top view.

4. Simulation of interior acoustic adaptation options

17 other simulation variants of interior furnishing were proposed. Particular solutions take into account the presence of the congregation and different kinds and distribution of sound absorbing materials. K13 SonaSpray cellulose plasters with different thickness were used as a sound absorbing material in acoustic adaptation of the church (Table 1). Proposed solutions, which are shown in detail in Fig. 4, are shown

Table 1. The applied acoustic adaptation simulation variants.

No.	The presence of the congregation		Thickness of K13 SonaSpray cellulose plasters			Area of sound absorbing material [m^2]	Figure
	YES	NO	16 mm	38 mm	50 mm		
1	–	x	–	–	–	–	3
2	x	–	–	–	–	–	–
3	–	x	x	–	–	587	4a
4	x	–	x	–	–	587	
5	x	–	–	x	–	587	
6	x	–	–	–	x	587	
7	x	–	–	–	x	990	4b
8	x	–	x	–	–	990	
9	–	x	x	–	–	990	
10	–	x	x	–	–	1132	4c
11	–	x	x	–	–	1571	4d
12	x	–	x	–	–	1304	4e
13	x	–	x	–	–	142	4f
14	x	–	x	–	–	385	4g
15	x	–	x	–	–	64	4h
16	x	–	x	–	–	548	4i
17	x	–	x	–	–	362	4j

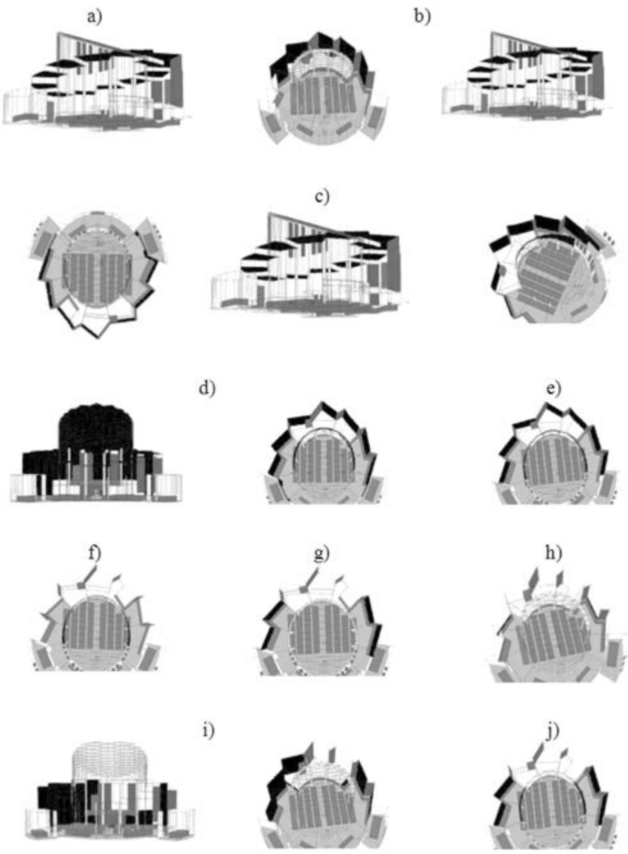

Fig. 4. Simulation variants of sound absorbing material distribution.

in Table 1. Sound absorbing material should be distributed mainly on large surfaces, which reflect the sound. Such surfaces are: the stepped ceiling (simulation variants 3–11), back and side walls (simulation variants 7–12, 16 and 17) and upper ceiling (simulation variant 11). In order to get information on the values of acoustic parameters, changed by using small amount of sound absorbing material, its locations on part of side walls (Fig. 4g, Fig. 4h and Fig. 4j) and part of elliptical cylinder walls (Fig. 4f and Fig. 4j) were proposed in simulation variants 13–15 and 17.

The characteristics of reverberation times for simulation variants 1–17, as a result of simulation tests, were obtained (Fig. 5).

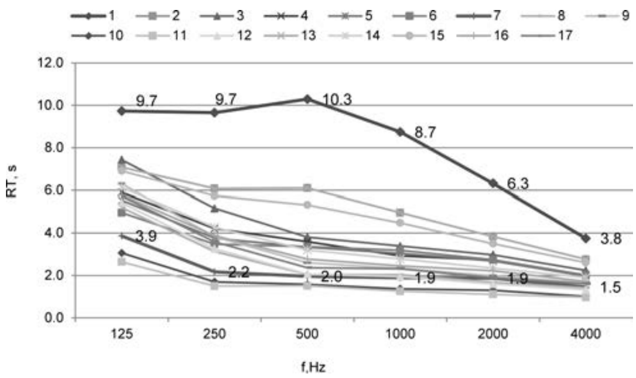

Fig. 5. Frequency characteristics of reverberation time for simulation variants 1–17 of the church model.

The characteristic of reverberation time obtained from Simulation 7 is in accordance with the preferred one, given in literature (Kosała, Kamisiński, 2011). It is practically flat in all the octave frequency bands.

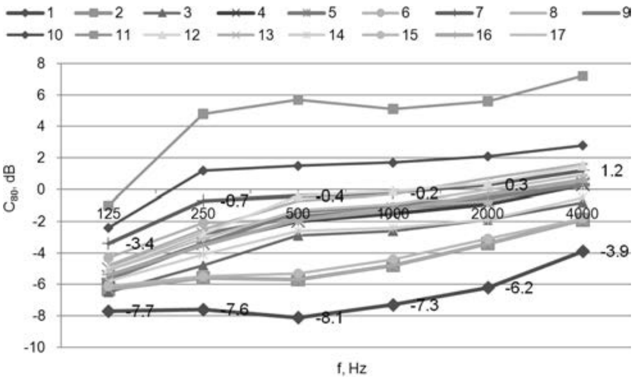

Fig. 6. Frequency characteristics of the music clarity index C_{80} for simulation variants 1–17 of the church model.

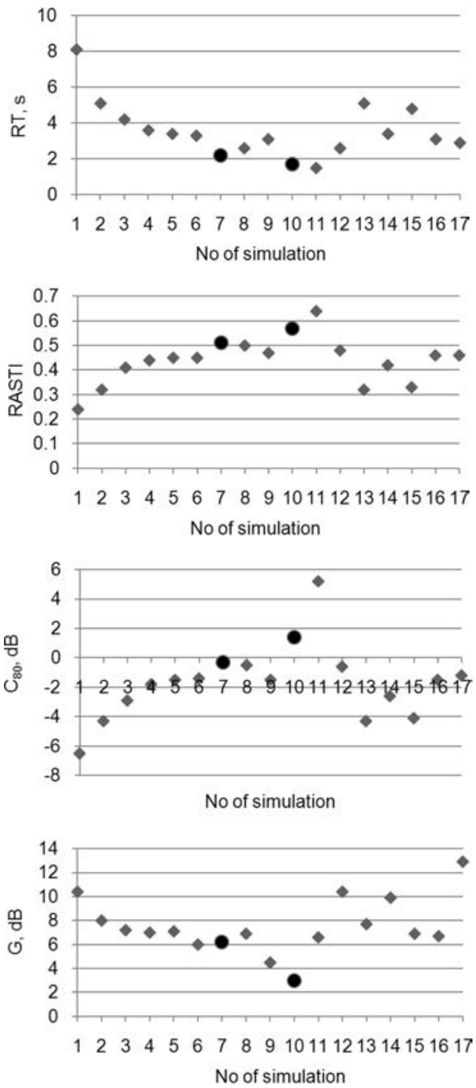

Fig. 7. Values of acoustic parameters for particular simulation variants.

Frequency characteristics of the music clarity index C_{80} for simulation variants 1–17 are shown in Fig. 6. Obtained values are close to the preferred ones (Simulation 7 in Fig. 6).

Calculated, averaged from measurement points, values of acoustic parameters for particular simulation variants (1–17): reverberation time RT, indices: music clarity index C_{80}, speech intelligibility $RASTI$ and sound strength G, are shown in Fig. 7.

Simulation variants 7 and 10 are marked in Fig. 7 as ones for which the values of acoustic parameters are simultaneously in accordance with preferred ones.

5. Global index assessment

5.1. Index observation matrix of simulation variants IOMSV

In order to obtain a global assessment of acoustic quality for the proposed simulation variant acoustic adaptation by using the index W_{GS} (Eq. (5)), the IOMSV from calculated partial indices was created. Next, the rows of the matrix were ordered according to decreasing values of reverberation indices. The content of IOMSV is shown in Fig. 8.

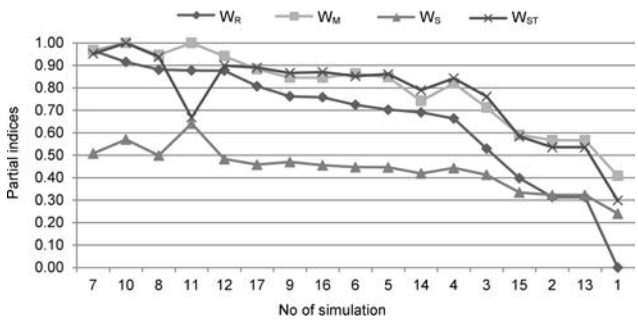

Fig. 8. Content of Index Observation Matrix of Simulation Variants – IOMSV.

All four partial indices of assessment are strongly mutually correlated. Linear correlation coefficients between indices are given in Table 2.

Table 2. Linear correlation coefficients between partial indices.

$W_R \leftrightarrow W_M$	0.9823
$W_S \leftrightarrow W_R$	0.9188
$W_M \leftrightarrow W_S$	0.9551
$W_{ST} \leftrightarrow W_R$	0.9207
$W_M \leftrightarrow W_{ST}$	0.8855
$W_{ST} \leftrightarrow W_S$	0.7475

5.2. Singular Value Decomposition of IOMSV

Decomposition of the IOMSV was performed by means of the SVD technique. As a result, three matrices $\mathbf{U}$, $\mathbf{\Sigma}$ and $\mathbf{V}^{\mathrm{T}}$, containing left and right singular vectors and singular values were obtained. The percentage shares of the explanation of information concerning the independent variables by following singular components, obtained from singular values, are shown in Fig. 9.

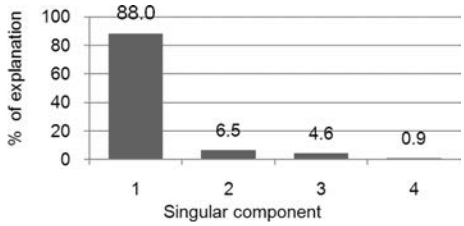

Fig. 9. The percentage shares of explanation of information concerning the independent variables by following singular components.

By using approximation of the first rank i.e. first singular value, which is far bigger than the other ones (Fig. 9), and the first left and right singular vectors (Eq. (6)), the PIOM (Perfectly correlated Index Observation Matrix) with indices similar to the original ones, however perfectly mutually-correlated, was obtained. Content of the PIOM with new indices is shown in Fig. 10.

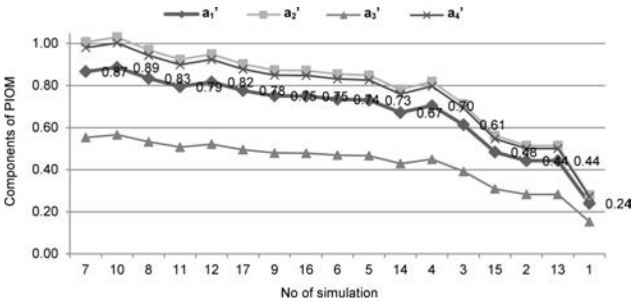

Fig. 10. Content of PIOM.

Vector $\mathbf{a}_1'$ (Fig. 10) contains the global indices W_{GS}', data of simulation variants and is related to the original reverberation index W_R, which is the best correlated with the other partial indices. The correlation coefficient between the indices W_R and $\mathbf{a}_1'$ equals 0.99, and between the matrices IOMSV and PIOM: 0.96.

5.3. Universal global assessment of simulation variants with weights – problem of redundant information

By using the global index W_{GS}', it is possible to assess only the simulation variants which were taken into account in IOMSV. A much more useful tool for quick single number assessment of the state of any object would be a universal equation, which is easy to apply and does not require knowledge of the SVD technique. The way to obtain such a universal equation for real objects, based on three partial indices, was shown in the article (Kosała, 2011). In this way (like in (Kosała, 2011)), weights necessary for the application of Eq. (5) (with four partial indices) for objects in the design stage or acoustic adaptation were calculated. Weights obtained from Matlab software are shown in Fig. 11.

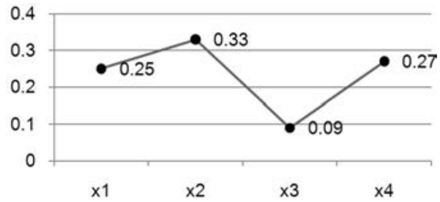

Fig. 11. Weights of partial indices.

Finally, Eq. (5) is given as:

$$W_{GS} = 0.26W_R + 0.33W_M + 0.09W_S + 0.27W_{ST}. \quad (8)$$

Application of Eq. (8) gives the same results, in comparison to Eq. (6), however, it is a universal one and, by using it, it is possible to assess any simulation variant of the simulation of acoustic parameters of other church interiors.

The obtained result – the assessment of the church's acoustic adaptation by using the global index W_{GS}, calculated from Eq. (8) is shown in Fig. 12. The best simulation variants for adaptation are variants 10 and 7. Simulation variant 10 ($W_{GS} = 0.9$) does not take into account the presence of the congregation and requires the application of sound absorbing material on a surface which equals: 1132 m^2. Whereas simulation variant 7 ($W_{GS} = 0.9$), taking into consideration the congregation in all pews, and the surface of sound absorbing material placed on the rear walls and staircase ceiling (Fig. 4b) equals: 990 m^2.

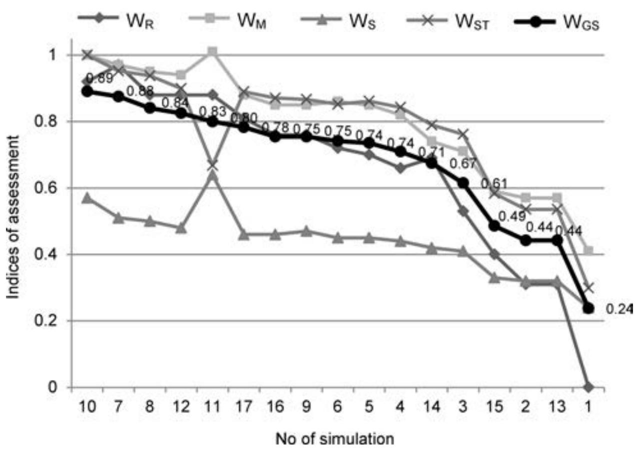

Fig. 12. The global index of assessment for acoustic adaptation of the church.

A comparison of values of partial and global indices of simulation variants: the best (7 and 10), the worst (13 and 15), without adaptation (1) and without adaptation but with the congregation (2), is shown in Fig. 13.

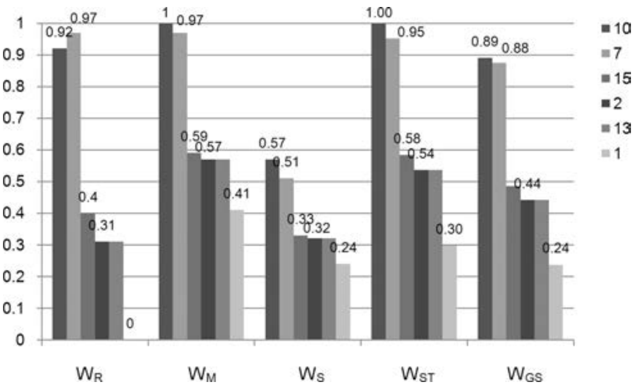

Fig. 13. Values of partial and global indices for simulation variants 1, 2, 7, 10, 13 and 15.

The global index (Fig. 13) is the number within the range 0.2 (simulation variant 1 – without adaptation) to 0.9 (simulation variants 7 and 10), for which adaptation is the best. Taking into account only the congregation (simulation variant 2, $W_{GS} = 0.44$), does not provide many improvements to the acoustic parameters of the interior, as well as the application of simulation variants 13 and 15, with too little sound absorbing material surface.

6. Conclusions

An innovative approach for the assessment of the acoustic quality of church interiors in the design stage or acoustic adaptation of the object is shown in the paper. It is proposed to assess simulation variants using a single number global index, which is the function of four partial indices: reverberation, sound of music, speech intelligibility and a new one, introduced in the article – sound strength index. Application of a single number index can be useful during the design, modernization or simulation tests of acoustic adaptation of interiors. A numerical index of acoustic quality determines, in an approximate way, how acoustical parameters do or do not differ from preferred ones. More accurate pieces of information are characterized by partial indices. The people who conduct assessments need not know the preferred values of acoustic parameters, which makes the global index easy to use. The variation of global index values for 17 cases of acoustic adaptation in a selected church are shown. By using the SVD technique to solve the problem of redundant information, the weights of four partial indices and a universal equation of the global index were calculated. The universal equation is easy in use, because knowledge of the SVD technique is then not required.

According to simulation tests carried out on a model of the church, the application of sound absorbing material (K13 SonaSpray cellulose plasters) will have a beneficial influence on the improvement of the church interior's acoustic quality. Practically, a flat characteristic of reverberation time, in accordance with the preferred values, in one case (simulation variant 7) was obtained. For this case, the interior will have good acoustic conditions for music and speech performances.

Application of the index method confirms that simulation variant 7 is among the best results obtained in simulation tests (there are high values of partial indices and the global one ($W_{GS} = 0.9$)). The second good simulation variant, variant 9 ($W_{GS} = 0.9$), does not take into account the presence of the audience and requires the application of more sound absorbing materials. By using the single number index, acoustically the best solutions of acoustic adaptations, which forecast suitable conditions of reverberation to perform a liturgical function with good speech intelligibility and sound quality of music, are indicated. The simulation variants of adaptation with low global index values ($W_{GS} < 0.5$) should be rejected due to weak acoustic parameter improvement.

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