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Calculation Models for Acoustic Analysis of St. Elizabeth of Hungary Church in Jaworzno Szczakowa

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In parallel with research conducted using conventional methods, a uniform index method for assessing the acoustic quality of Roman Catholic churches has been developed. The latest version of the index method has been created using the index observation matrix of 12 churches which have been rated by means of the single number global index.

Assessments of the acoustic quality of any Roman Catholic church, using two calculation models: the Global Acoustic Properties Index (GAP) and the Global Index (GI), are shown in the article. The verification was performed on the example of one church, showing the way of calculating global indices to assess the acoustic quality of a new facility. The next stages in the development of the index method for assessing the acoustic quality of churches were taking into account the audience, using simulation tests and determining the spatial distribution of the single number GAP index in an examined church. An attempt to use the GAP and GI calculation models to assess the acoustic properties of some churches is also shown in the article.

Keywords: acoustic quality; index method; church acoustics; Singular Value Decomposition (SVD); acoustic simulation tests.

1. Introduction

The acoustic parameters of worship interiors are the subject of research and analysis by many scientists (Álvarez-Morales *et al.*, 2014; Berardi *et al.*, 2009; 2015; Berardi, 2014; Engel, Kosała, 2005; Kosała, 2009; Małecki, 2014; Martellotta, 2009; Suárez *et al.*, 2015). Studies show that a large number of churches, especially modern ones, have excessive reverberation, which leads to poor speech intelligibility, poor-quality music playing and listening, and problems with the sound amplification system.

There are many newly-built churches in Poland which do not fulfill their acoustic functions in a proper way (Engel *et al.*, 2007). The problem concerns, in particular, Roman Catholic churches, which have a wide range of sound production. Ensuring adequate acoustic conditions in such spaces is a matter of compromise and a difficult task, especially as churches stand out from other public facilities due to sacred and emotional factors.

Alongside the issue of the proper acoustic design of church interiors, a significant problem is the difficulty in making a uniform assessment of acoustic parameters. Due to the fact that these parameters are correlated with each other, it is difficult to ensure a uniform overall evaluation without duplicating certain information – the interior's acoustic features. An attempt to develop an acoustic quality assessment for churches was made by Berardi (2012), when he proposed two indices separately evaluating speech and music The single speech or music indices are obtained as the weighted sum of seven partial indices, calculated from the uncorrelated acoustic parameters: EDT, BR, T_S, LF, IACC, G, and C_{50}, with respect to their preferred values for speech or music in churches, respectively. Verification of the double-index method was performed on three Italian churches with a volume range from 9000 to 19000 m^3. The proposed method of evaluating only two factors, additionally in separate ways: speech and music, does not allow the acoustic properties of the tested churches to be assessed unambiguously. Furthermore, the method does not take into account an important factor, which is the level of external disturbances, providing the possibility of uninterrupted prayer. By using the proposed method, the acoustic quality of the churches cannot be compared in a comprehensive manner.

Another approach was proposed by Engel and Kosała (2007), who presented a uniform index method based on the single-number assessment of the acoustic quality of sacral objects. The proposed index method has been modified over the years and verified on a growing number of churches. In the most recent study, in the years 2013–2014, the index method was limited to only one type of sacral object, which was Roman Catholic churches. The global index of the acoustic properties of Roman Catholic churches (GAP) was proposed by Kosała and Engel (2013) and the global index of acoustic quality of Roman Catholic churches (GI) was proposed by Kosała (2014).

The proposed index methods for assessing the acoustics of Roman Catholic churches based on GAP and GI indices are not intended to determine the exact synthesis of all information describing the sound field, but are related to the functional aspects of the church acoustically. Each global index is a single-number approximate measure of general assessment and a function of four (GAP) or five (GI) partial indices. The values of the partial indices are calculated based on acoustic parameters obtained from *in-situ* measurements in churches. The partial indices provide detailed information about the extent to which selected acoustic parameters correspond to their preferred values. The global single number GAP and GI indices averaged in frequency and in space (at measuring points) are calculated as the weighted sum of evaluation indices which are uncorrelated with one another. All indices (global and partial) assume values between 0 and 1. A value of 0 means that the acoustic properties of the church are poor and they differ greatly from the preferred values of the acoustic parameters, while a value of 1 means very good acoustic properties, corresponding to the preferred values. Using single-number global indices, it is possible to make comparisons of the acoustic properties of churches. Some churches with high rates of assessments, close to a value of 1, can perform additional functions, e.g. as a concert hall or auditorium. The interiors of churches with low values of the indices, close to 0, indicate the need to develop and perform acoustic adaptation. The index methods can also be used during the design stage of churches.

The latest version of the index method has been created using the index observation matrix of 12 churches in the range of volume from 1100 to 41000 m^3, which have been rated by means of the single number global index. Assessments of the acoustic quality of any Roman Catholic church, from the same range of volume, using two calculation models: the Global Acoustic Properties Index (GAP) and the Global Index (GI), are shown in the article. The verification was performed on the example of St. Elizabeth of Hungary Church in Jaworzno Szczakowa, showing the course of action in assessing the acoustic quality of the new facility.

The article outlines the next stages of work on developing the index methods for assessing the acoustic quality of churches, which take into account the audience, using simulations and calculating the values of partial and global single-number indices of assessments in space – at each of the measuring points.

An attempt to use GAP and GI calculation models to assess the acoustic properties in some churches is also shown in the article. The two analysed large-sized churches have a volume in excess of 41000 m^3.

2. *In-situ* measurements

2.1. Description of the church

The Roman Catholic church of St. Elizabeth of Hungary in Jaworzno Szczakowa (Fig. 1) was built between 1898 and 1903. The object, built of limestone and brick in neo-Gothic style, was based on a Latin cross plan.

a)

b)

Fig. 1. St. Elizabeth of Hungary church in Jaworzno Szczakowa: a) view from outside b) interior of the church.

The church consists of a chancel and three aisles delimited inside the columnar pillars on which cross-ribbed vaulting rests. The interior has stylish neo-Gothic uniform accessories, which include wooden altars (main and two side), a pulpit, baptismal font, confessionals, pews, and stained glass windows. The church is equipped with a pipe organ with 13 voices. There is a stoneware floor. The volume inside the church, calculated using a 3D computer model, equals 2249 m^3. The maximum height of the nave is 10 m and its width is 12.5 m.

2.2. Measurement technique

The acoustic measurements were conducted in accordance with the instructions set forth in (Martelotta *et al.*, 2009) in the unoccupied church and with its sound amplification installation switched off. An MLS measurement signal was emitted by the omnidirectional sound source controlled and synchronised with the measurement system by DIRAC v4.0 Bruel&Kjaer software installed on the laptop. The sound source was placed near the altar (Fig. 2) at a height of 1.5 m above the floor. Using an ECM BEHRIGHER 8000 measurement microphone, located at a height of 1.2 m above the floor and the EDIROL UA-5 sound card at 10 measuring points (Fig. 2), the impulse responses according to the ISO-3382 standard (ISO-3382-1, 2009) were recorded in the church. The background noise levels were measured for 1 min using a SVAN 945A sound level meter, 1.2 m above the floor at the measuring point No. 1 (Fig. 2). The temperature during the study was 15.2°C and the relative humidity was 51%.

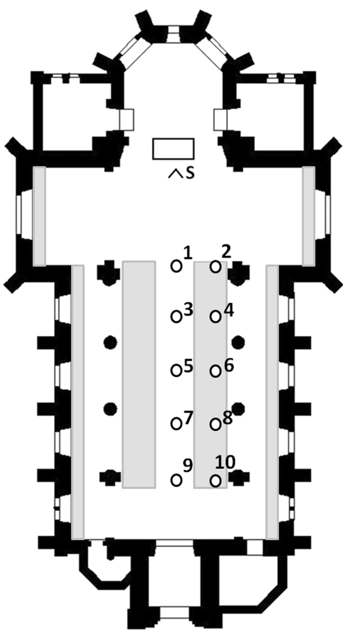

Fig. 2. Ground plan with the sound source S (>) and microphone positions (1–10) for measurements and pews zone (shaded area) for the St. Elizabeth of Hungary Church in Jaworzno Szczakowa.

2.3. Results of experimental studies

The values of the acoustic parameters averaged in space: reverberation time T_{30}, music clarity index C_{80}, rapid speech transmission index $RASTI$ and sound strength G, as well as the values of the sound pressure level in the octave frequency bands L_p, and equivalent sound A level of external disturbance in the church L_{Aeq}, are shown in Fig. 3. The fact that the limit

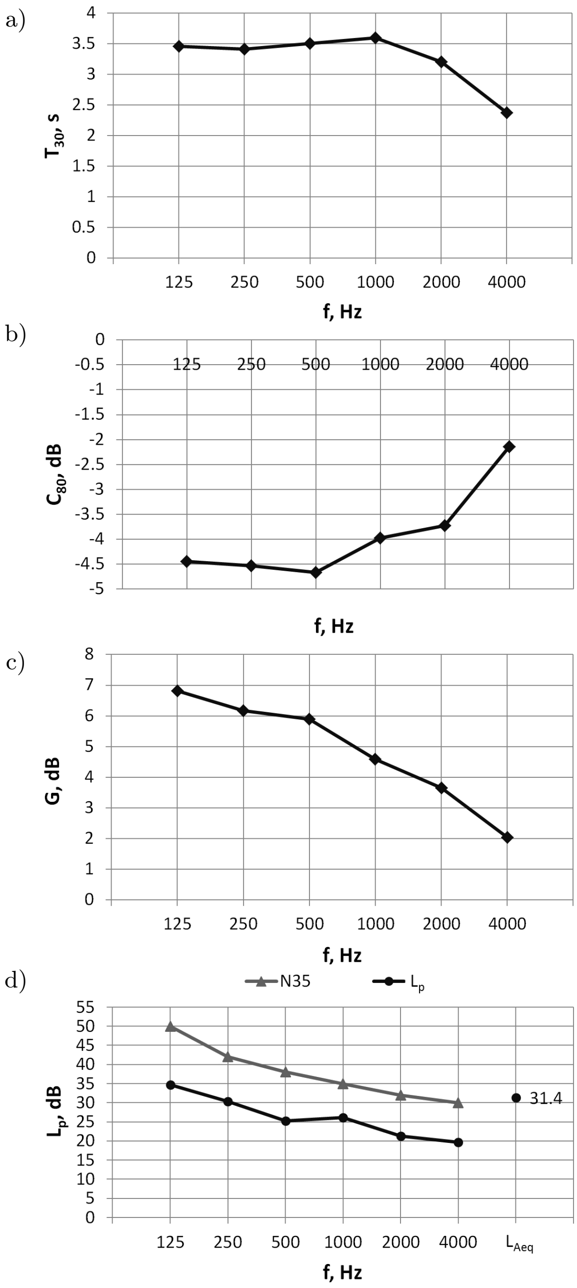

Fig. 3. Averaged in space, the acoustic parameters in octave frequency bands for the unoccupied church obtained from *in-situ* measurements: a) reverberation time T_{30}, b) music clarity index C_{80}, c) sound strength G, d) sound pressure level in the octave frequency bands L_p and the equivalent sound A level of external disturbance in the church L_{Aeq}.

value (curve N35 in Fig. 3d) of disturbing noises is not exceeded provides suitable conditions for undisturbed prayer and liturgy in the church.

Figure 4 shows the averaged in frequency bands values of the parameters T_{30}, C_{80}, G, and *RASTI* at 10 measuring points and their average from all points of the values of these parameters. The acoustic parameters obtained from *in-situ* measurements were subsequently used to develop the acoustic model of the church and to compare with the values of these parameters preferred for churches, which was held by using the index methods.

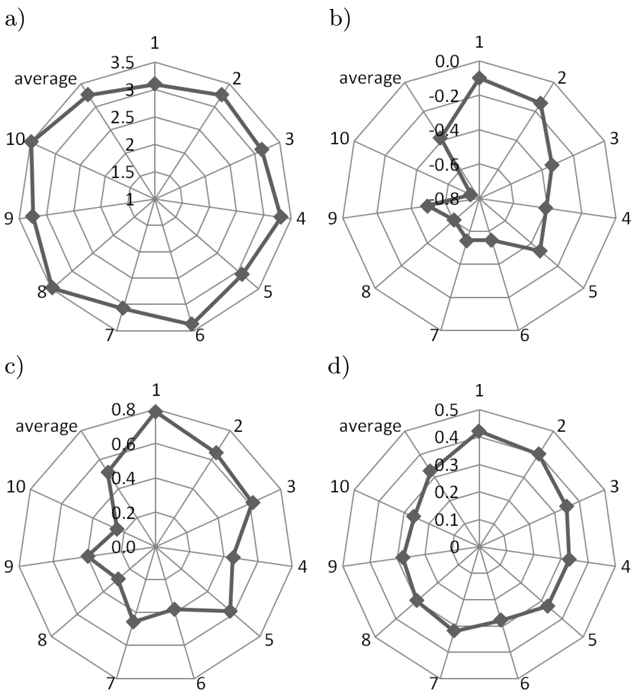

Fig. 4. Values of the parameters averaged from frequency: a) T_{30} [s], b) C_{80} [dB], c) G [dB], d) *RASTI* at 10 measuring points and the average of all the points of these parameters.

3. Simulation tests

3.1. Acoustic model of the church

An acoustic model of the church (Fig. 5) has been developed by using the CATT-Acoustic v8 computer program. The location of the sound source and 10 test points in the model were consistent with the location of the source and measuring points during *in-situ* measurements in the church. The acoustic model consists of 918 surfaces. The reverberant sound absorption coefficients α, chosen from the literature (Martellotta, 2009; Martellotta *et al.*, 2011; Vorländer, 2008; Carmona *et al.*, 2009; Meyer, 2003) and assigned to each area, correspond to the finishing materials of the church (Table 1).

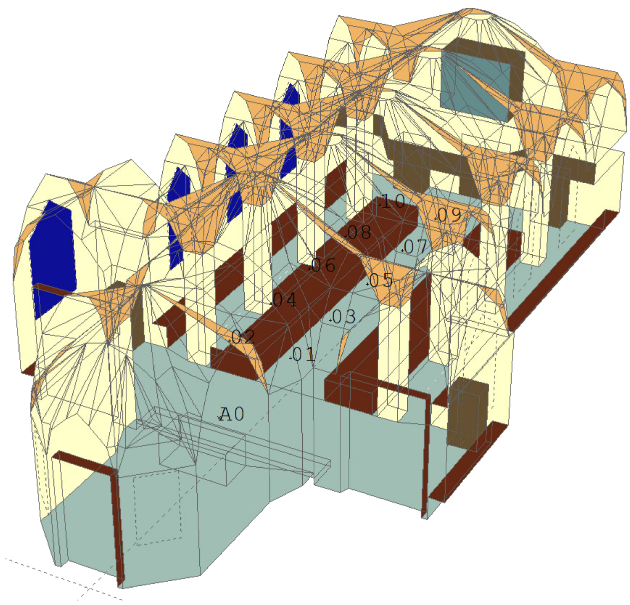

Fig. 5. Acoustic model of the church, A0 – sound source, 1–10 – test points.

Table 1. The reverberant sound absorption coefficients α and sound scattering coefficients s in octave frequency bands of materials used in simulation tests.

Material	Surface [%]	Sound absorption coefficients, α						Sound scattering coefficients, s					
		125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Walls [a)]	31.6	0.04	0.04	0.03	0.02	0.02	0.02	0.12	0.13	0.14	0.15	0.16	0.17
Domes and arches [a)]	33.4	0.05	0.05	0.05	0.04	0.04	0.03	0.2	0.25	0.3	0.35	0.4	0.45
Marble floor	14.8	0.01	0.01	0.01	0.02	0.02	0.02	0.12	0.13	0.14	0.15	0.16	0.17
Wooden altarpieces	2.8	0.12	0.12	0.15	0.15	0.18	0.18	0.3	0.4	0.5	0.6	0.7	0.8
Unoccupied wooden pews	10.0	0.1	0.15	0.18	0.2	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.8
Occupied wooden pews	–	0.23	0.37	0.83	0.99	0.98	0.98	0.3	0.4	0.5	0.6	0.7	0.8
Wooden doors	3.5	0.14	0.1	0.06	0.08	0.1	0.1	0.2	0.25	0.3	0.35	0.4	0.45
Organ	0.4	0.12	0.14	0.16	0.16	0.16	0.16	0.3	0.4	0.5	0.6	0.7	0.8
Glass	3.5	0.35	0.25	0.18	0.12	0.07	0.04	0.12	0.13	0.14	0.15	0.16	0.17

[a)] Adapted materials used for model calibration.

Sound scattering coefficients s (Table 1) were matched to the type of materials with smooth surfaces (for example: walls or marble floor), moderately irregular (for example, domes and arches) and irregular (for example, the altar) (Alonso *et al.*, 2014).

Calibration of the acoustic model was carried out using the reverberation time. In the case of this church the calibration process relied on adjusting the values of the sound absorption coefficients α of the two materials with the largest percentage among all the finishing materials, which were wall surfaces (31.6%) and domes and arches (33.4%). The values of the sound absorption coefficients α of walls and domes and arches (Table 1) are similar to those given in (Vorländer, 2008) and (Martellotta, 2009), respectively. Such adjustments ensured that satisfactory values of the simulated reverberation time were obtained.

The comparison of the reverberation time in octave frequency bands for the church without an audience derived from T_{30} *in-situ* measurements and $T_{30-unocc}$ obtained from simulation tests carried out on the model, are shown in Table 2, along with the relative errors δ.

Table 2. Averaged, in space, values of the reverberation time in octave frequency bands for the church without an audience derived from *in-situ* measurements T_{30} and obtained from simulation tests $T_{30-\text{unocc}}$ carried out on the model, along with the relative errors δ.

	f [Hz]						average
	125	250	500	1k	2k	4k	
T_{30} [s]	3.5	3.4	3.5	3.6	3.2	2.4	3.3
$T_{30-\text{unocc}}$ [s]	3.4	3.4	3.5	3.6	3.2	2.3	3.2
δ [%]	1.6	1.6	0.7	0.8	0.0	3.2	1.3

The values of T_{30} and $T_{30-\text{unocc}}$ varied less than 5% in each octave frequency band, which corresponds to the Just Noticeable Difference (JND) threshold. Hence, it was assumed that the calibration of the church's acoustic model was performed with sufficient accuracy (Vorländer, 2008; Bueno *et al.*, 2012). The temperature and humidity used in the calibration of the model and in the simulation tests were the same as during *in-situ* measurements in the church.

3.2. The results of acoustic parameter tests and taking the audience into account

The CATT-Acoustic v8 acoustic simulation software, in which the model of the church was analysed, is based on Randomized Tail-corrected Cone-tracing (RTC-II), which is a hybrid cone-tracing and image-source approach (Dalenbäck, 2008). In the simulation calculations, 30000 rays were applied while the length of the impulse response was truncated to 3300 ms. The main purpose of the simulations was to determine the effect of the audience's presence on the acoustic parameters of the church. This was performed by changing the values of sound absorption and sound scattering coefficients of unoccupied pews on the right for the occupied pews in the acoustic model of the church (Table 1).

The values of the reverberation time $T_{30-\text{unocc}}$, music clarity index $C_{80-\text{unocc}}$, and $RASTI_{-\text{unocc}}$ were calculated with simulations. Comparisons of the values of the reverberation time averaged in space without ($T_{30-\text{unocc}}$) and with the audience ($T_{30-\text{occ}}$), as well as the values of the music clarity index without ($C_{80-\text{unocc}}$) and with the audience ($C_{80-\text{occ}}$) obtained from the simulations, are shown in Fig. 6. The biggest decrease in the reverberation time of 1.5 s can be observed for frequencies from 500 to 2000 Hz. For the 125 and 250 Hz octave frequency bands, the reduction in the values of reverberation time was from 0.5 to 0.8 s. Taking the audience into account resulted in a much higher value of the music clarity index being obtained in comparison with the unoccupied church. The smallest differences of C_{80} (≈1 dB) can be observed for the 125 and 250 Hz octave bands.

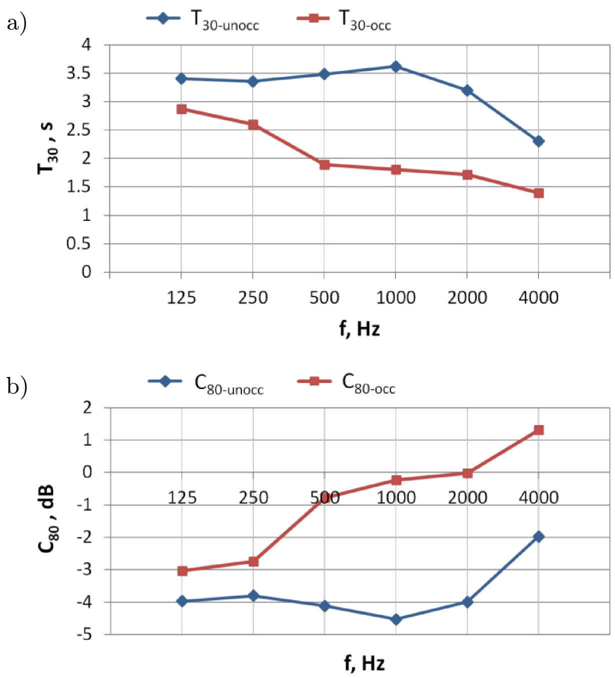

Fig. 6. Reverberation time (a) and music clarity index (b) in octave frequency bands, obtained from simulations for the unoccupied ($T_{30-\text{unocc}}$, $C_{80-\text{unocc}}$) and occupied church ($T_{30-\text{occ}}$, $C_{80-\text{occ}}$).

Frequency averaged values of parameters: reverberation time, music clarity index, and $RASTI$ at each of the 10 test points and the average values of these parameters are shown in the radar graphs in Fig. 7.

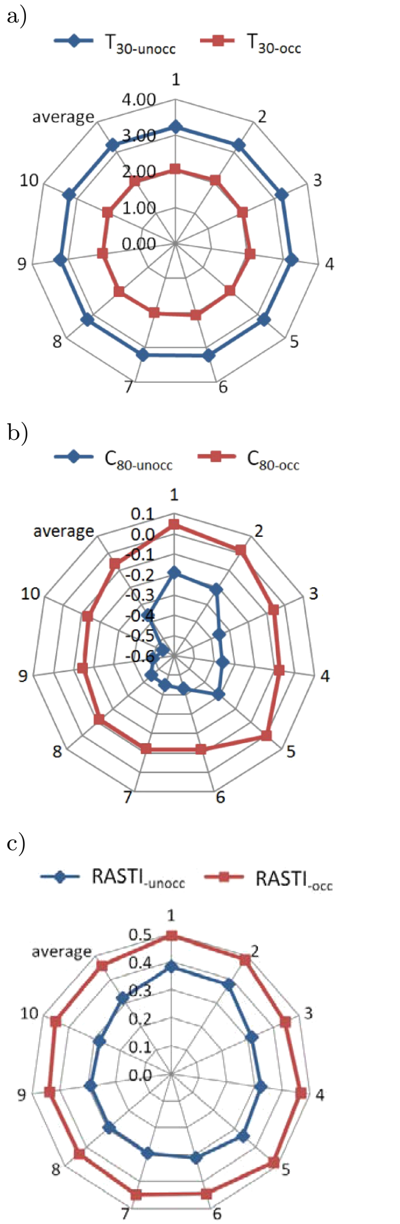

Fig. 7. Averaged, in frequency, values of the reverberation time T_{30} (a), music clarity index C_{80} (b), and *RASTI* (c), obtained from simulation tests for the unoccupied (unocc) and occupied church (occ) at 10 test points.

The simulation tests revealed that, similarly to the case of experimental studies, the reverberation time has virtually the same value regardless of the location of the test point. Taking the audience into account gave the effect of reducing reverberation time from 3.2 s to 2 s, which corresponds to better conditions for playing and listening to music, especially symphonic music, than in the interior without an audience. One can observe an improvement in speech intelligibility from poor in the unoccupied church ($RASTI_{\text{avr}} = 32.1\%$) to fair ($RASTI_{\text{avr}} = 45.9\%$) for the church with an audience. The results of the simulation showed that the greatest variability among the three examined parameters, depending on the location of the test points, was for the values of C_{80} (Fig. 7b).

4. Index assessment of the acoustic quality of churches – two calculation models

4.1. The global index of acoustic properties of Roman Catholic churches, GAP, and taking the audience into account

The global single-number index of acoustic properties of Roman Catholic churches, developed in (Kosała, Engel, 2013), is given by the formula:

$$GAP = 0.6RMS + 0.4D, \tag{1}$$

where *RMS* is the reduced partial single number index of assessment of selected acoustic properties of the church: reverberation, the sound of music and speech intelligibility; D is the partial index of external disturbance.

The calculations of the values of the indices: reverberation R, the music sound M, and speech intelligibility S were necessary in order to obtain the value of the *RMS* index afterwards. The values of the R, M, S indices, as well as the D index, calculated from acoustic parameters, such as T_{30}, C_{80}, *RASTI*, L_{Aeq}, according to (Kosała, Engel, 2013), for the St. Elizabeth of Hungary Church, are given in Table 3.

Table 3. Acoustic parameters averaged in space and frequency obtained from the measurements in the St. Elizabeth of Hungary church and the calculated values of partial indices.

Acoustic parameters				Partial indices of assessment			
T_{30} [s]	C_{80} [dB]	*RASTI*	L_{Aeq} [dB]	R	M	S	D
3.3	−4.33	0.33	31.4	0.63	0.57	0.33	0.68

In order to determine the value of the *RMS* index, the Index Observation Matrix, which is the reference calculation model with correlated indices, $\mathbf{A}_0$: 12×3, was extended by the calculated indices R, M, and S, according to the scheme shown in Fig. 8.

In the matrix $\mathbf{A}_0$ (Fig. 8) the R, M, and S indices calculated for the following 12 churches appear: St. Sebastian's Church in Strzelce Wielkie (SE), St. Andrew's Apostle Church in Gilowice (AA), St. Joachim's Church in Krzyżanowice (JO), The Holiest Sacred Heart's Church in Cracow (NS), St. Clemens Church in Wieliczka (KL), The Holy Cross Increase Church in Psary (PK), The Jesuits Fathers Church in Cracow (JE), St. Peter and Paul Apostles' Church in Trzebinia

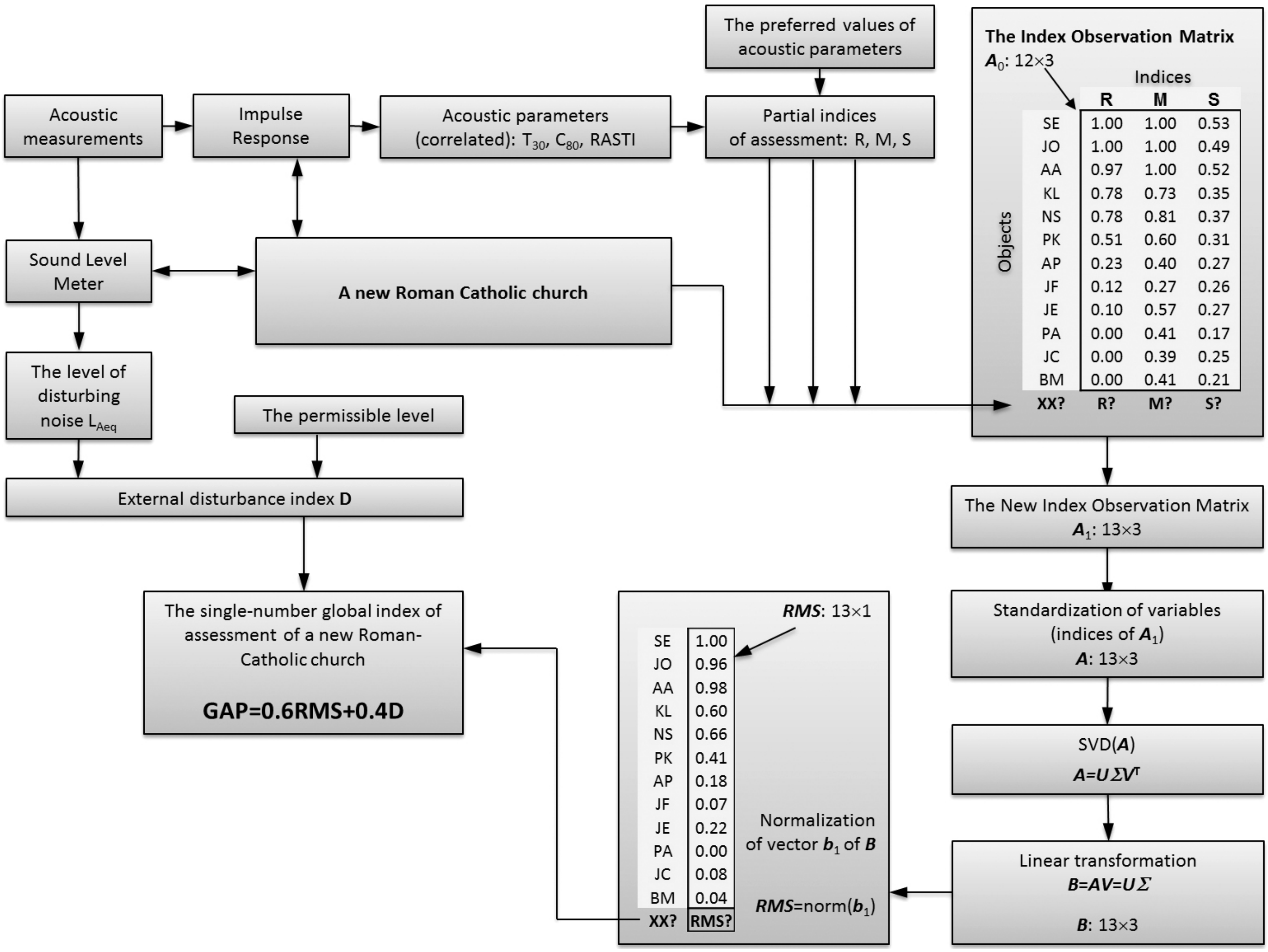

Fig. 8. Procedure for determining the GAP global index of acoustic properties of Roman Catholic churches for a new object.

(AP), St. John the Baptist Church in Cracow (JC), St. Joseph's Church in Cracow (JF), St. Paul Apostle Church in Bochnia (PA), and Sanctuary of the Divine Mercy in Cracow (BM).

Indices in the newly-created matrix $\mathbf{A}_1$: 13×3 after standardisation constituted the components of matrix $\mathbf{A}$. Matrix $\mathbf{A}$ was decomposed into three matrices $\mathbf{U}$, $\mathbf{\Sigma}$ and $\mathbf{V}^{\mathrm{T}}$ using the Singular Value Decomposition function in MATLAB. Matrix $\mathbf{B}$: 13×3 was obtained by performing a linear transformation by multiplication of matrices $\mathbf{AV} = \mathbf{U\Sigma}$. Ultimately, the value of the single number index $RMS = 0.45$ for the tested unoccupied church was obtained from the column vector $\mathbf{b}_1$ normalised to the range: 0–1, according to Formula 9 in (Kosała, Engel, 2013).

In order to automate the calculations, a computationally-diagnostic program was implemented in MATLAB. The results of these calculations in the form of a screenshot are shown in Fig. 9. This program calculates the *RMS* indices, including the 13th church tested, on the basis of the input data stored in the matrix 13×3.

Using the calculation procedure shown above to determine the value of the *RMS* index, which concerned the case of the unoccupied church, the value of the RMS_{occ} index was calculated, which corresponded to the occupied church. The values of acoustic parameters, averaged in space and frequency, such as: $T_{30-\mathrm{occ}}$, $C_{80-\mathrm{occ}}$, $RASTI_{\mathrm{occ}}$, obtained from the simulation tests, as well as the calculated values of the partial R_{occ}, M_{occ}, S_{occ}, and RMS_{occ}, are shown in Table 4.

Table 4. Acoustic parameters averaged in space and frequency obtained from the simulations taking into account occupied the St. Elizabeth of Hungary church and the calculated values of partial indices.

Acoustic parameters			Partial indices of assessment			
$T_{30-\mathrm{occ}}$ [s]	$C_{80-\mathrm{occ}}$ [dB]	$RASTI_{\mathrm{occ}}$	R_{occ}	M_{occ}	S_{occ}	RMS_{occ}
2.05	−0.65	0.46	0.90	0.93	0.46	0.86

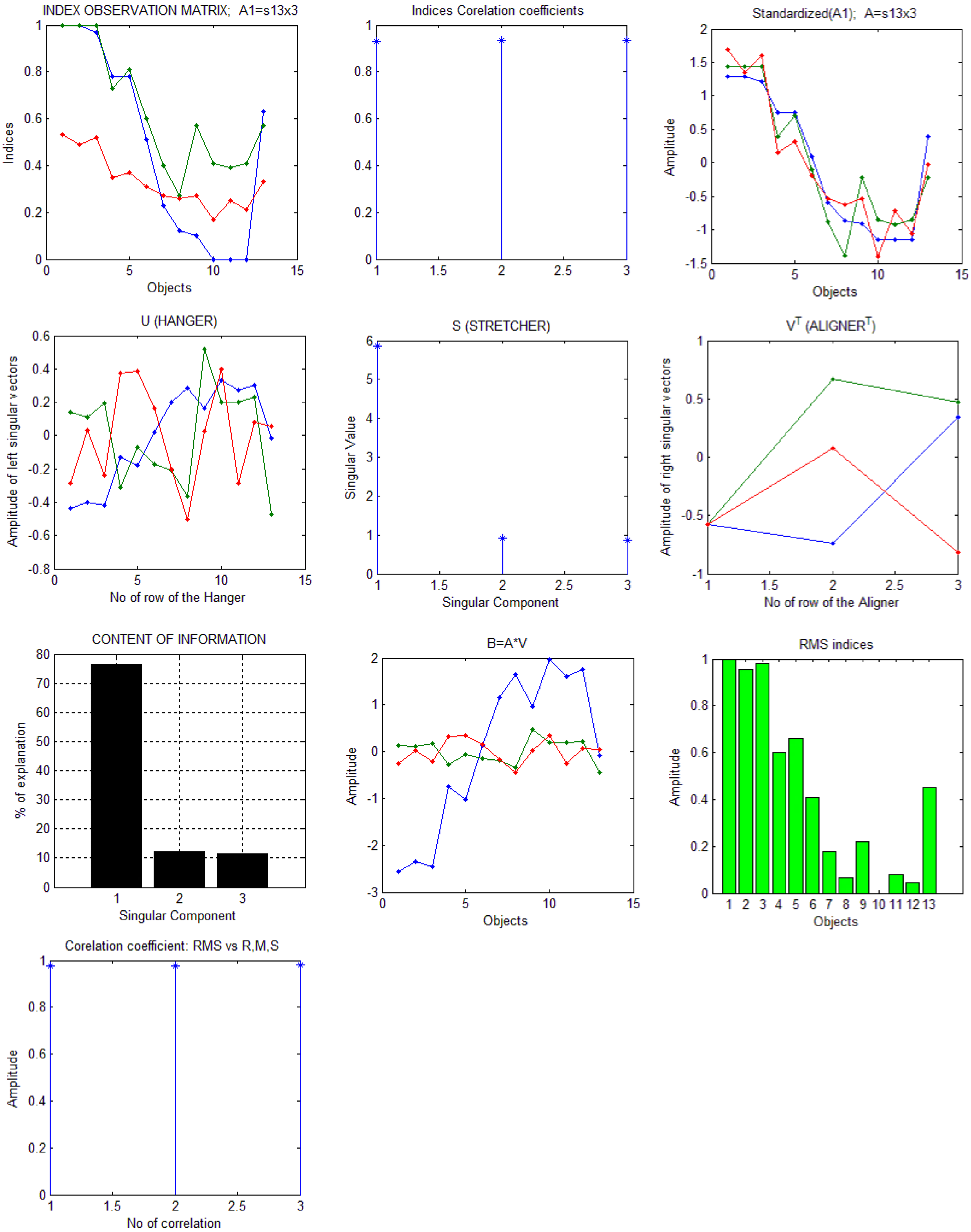

Fig. 9. Reduced index *RMS* of the new tested church, obtained in MATLAB.

After putting the partial indices *RMS* (RMS_{occ}) and *D* into Formula (1), the values of GAP = 0.54 for the unoccupied church and GAP_{occ} = 0.79 for the church with the audience were obtained. The calculated values of the four partial indices and the single-number global index of acoustic properties of the St. Elizabeth of Hungary Church for unoccupied and occupied cases are shown in Fig. 10.

In addition, the values of the GAP global indices at each of the 10 measuring points were determined (Fig. 11). The curves defining the value of the partial and global indices in the space (at test points) after taking the public into account have a flatter characteristic than in a church without an audience, where the values of the indices are sometimes, depending on the index, widely varied.

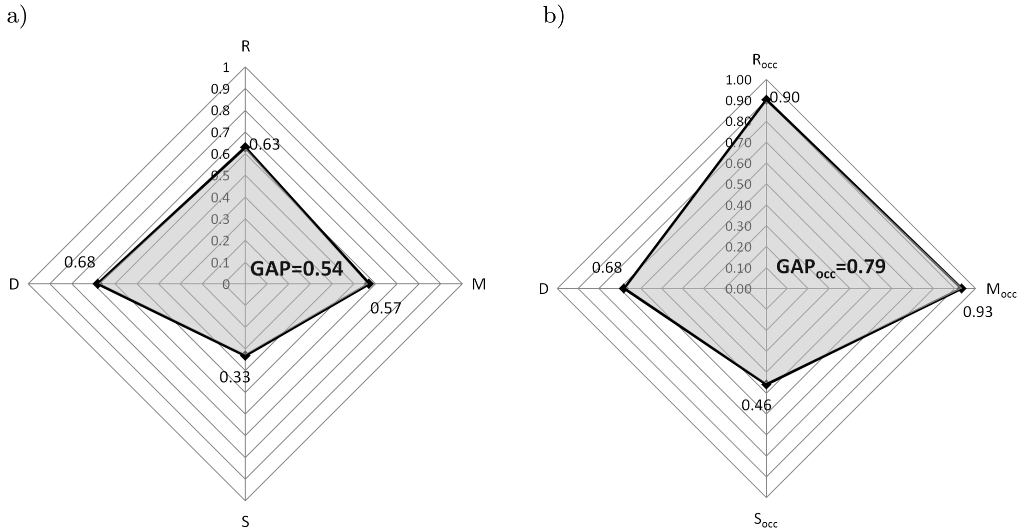

Fig. 10. Assessment of the acoustic properties of the St. Elizabeth of Hungary Church by using the single-number, four-parameter GAP index: a) for *in-situ* measurements (object without an audience), b) simulation tests, taking the audience into account.

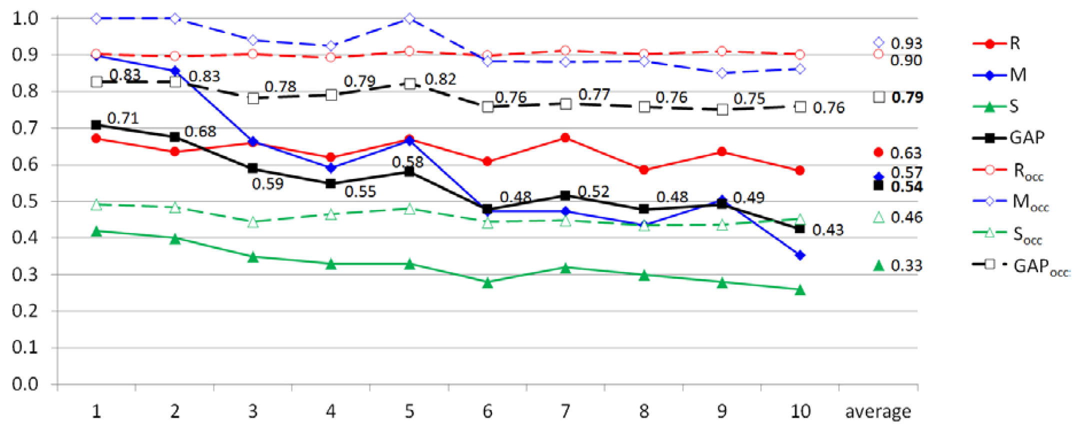

Fig. 11. Comparison of calculated and averaged in 10 test points values of the partial indices: reverberation R, music sound M, speech intelligibility S, and the global index of acoustic properties GAP of the St. Elizabeth of Hungry Church, obtained from *in-situ* measurements (church unoccupied) and from simulation tests (church occupied, indices: R_{occ}, M_{occ}, S_{occ}, GAP_{occ}).

The GAP global index determined at each test point takes values from the range $\langle 0.43,\ 0.71\rangle$ for a church without an audience. After taking the audience into account the acoustic properties of the church improved substantially and it can be said that they are distributed more evenly as a function of distance from the sound source ($\text{GAP}_{\text{occ}} = \langle 0.75,\ 0.83\rangle$).

4.2. The global index of the acoustic quality of Roman Catholic churches, GI

The global index of the acoustic quality of Roman Catholic churches, GI, introduced and implemented in the assessment of 12 churches in (Kosała, 2014), is defined by the formula:

$$GI = 0.5RMS + 0.2D + 0.3S_T, \tag{2}$$

where S_T is the sound strength index.

In order to determine the value of the GI index, the acoustic parameters obtained from *in-situ* measurements, as well as the values of the partial indices *RMS* and *D*, described and calculated in Subsec. 4.1 of the article, were used.

The value of the sound strength index S_T in the St. Elizabeth of Hungary Church was determined using the nomogram proposed in (Kosała, 2012). For the averaged, from the octave frequency bands 500 and 1000 Hz, values of $G_{\text{mid}} = 5.29$ dB the $S_T = 1$.

The value of the global index of the acoustic quality of the St. Elizabeth of Hungary Church, calculated using Eq. (2), equals GI = 0.66. A summary assessment using five partial indices and the single-number GI global index of the St. Elizabeth of Hungary Church is shown in Fig. 12.

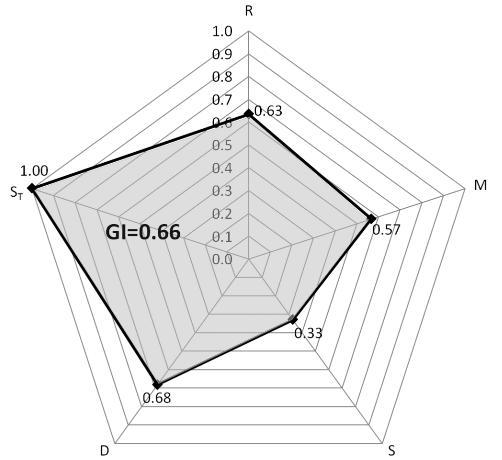

Fig. 12. Assessment of the acoustic quality of the St. Elizabeth of Hungary Church by means of the single-number index GI, based on the five partial indices R, M, S, D, and S_T.

5. Verification of the calculation models in some churches

In this section, three churches: the Holy Trinity Church in Fatima (Carvalho, Silva, 2010) – church FA, the Cathedral of Malaga (Álvarez-Morales *et al.*, 2014) – church MA, and the church of Santa Ana in Moratalaz in Madrid (Bueno *et al.*, 2012) – church SA, were assessed by using two calculation models based on the GAP and GI global indices. On the basis of the acoustic parameters of the three churches T_{30}, C_{80}, $RASTI$, L_{Aeq}, and G_{mid}, the values of partial indices R, M, S, D, and S_T were calculated and are shown in Table 5.

Both the GAP and GI indices are functions of a reduced RMS index. In order to determine the value of the RMS indices for the new tested churches, the Index Observation Matrix, which is the reference calculation model with correlated indices, $\mathbf{A}_0$: 12×3 (Fig. 8), was extended by the calculated indices R, M, and S of the three churches. Using the Singular Value Decomposition of the newly-created Index Observation Matrix A_1: 15×3 and the calculation procedure as described in Subsec. 4.1, the RMS indices were calculated (Table 5). The values of the GAP and GI indices, shown in Table 5, were calculated on the basis of Eqs. (1) and (2), and shown with the values of the partial indices in Figs. 13 and 14, respectively.

Two tested churches of large-sized FA and MA of a comparable volume have significantly different acoustic properties (Fig. 13). Single number assessment by using the GAP global index, based on four parameters, showed very good acoustic properties of the Holy

Table 5. Acoustic parameters of the churches: FA (Carvalho, Silva, 2010), MA (Álvarez-Morales *et al.*, 2014) and SA (Bueno *et al.*, 2012) and their indices of acoustic assessment.

Church ID	Volume [m^3]	Acoustic parameters					Partial indices of assessment						Global indices	
		T_{30} [s]	C_{80} [dB]	$RASTI$	L_{Aeq} [dB]	G_{mid} [dB]	R	M	S	RMS	D	S_T	GAP	GI
FA	130000	2.1	2.5	0.57	23.0	–	0.89	1.00	0.57	1.00	1.00	–	1.00	–
MA	118000	7	−6.2*	0.38	37.4	0.09	0.01	0.43	0.38	0.23	0.29	0.02	0.25	0.18
SA	3674	5.7	−6.6	0.33	34.3	18.1	0.11	0.4	0.33	0.20	0.41	0.00	0.28	0.18

* averaged from 500–1000 Hz frequency octave bands

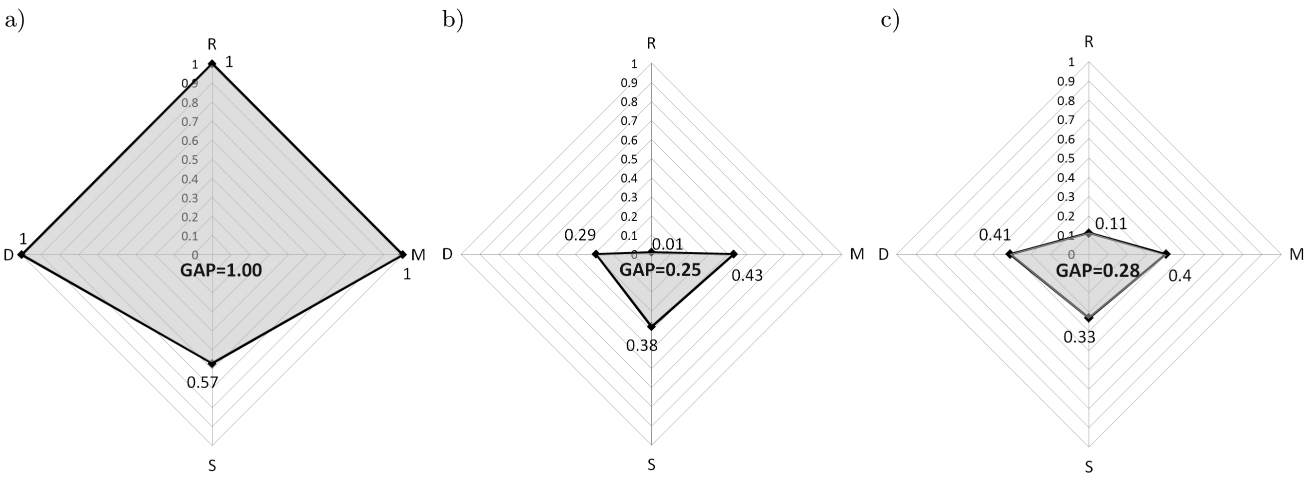

Fig. 13. Assessment of the acoustic properties of the churches: FA (a), MA (b), and SA (c) by using a single-number, four-parameter GAP index.

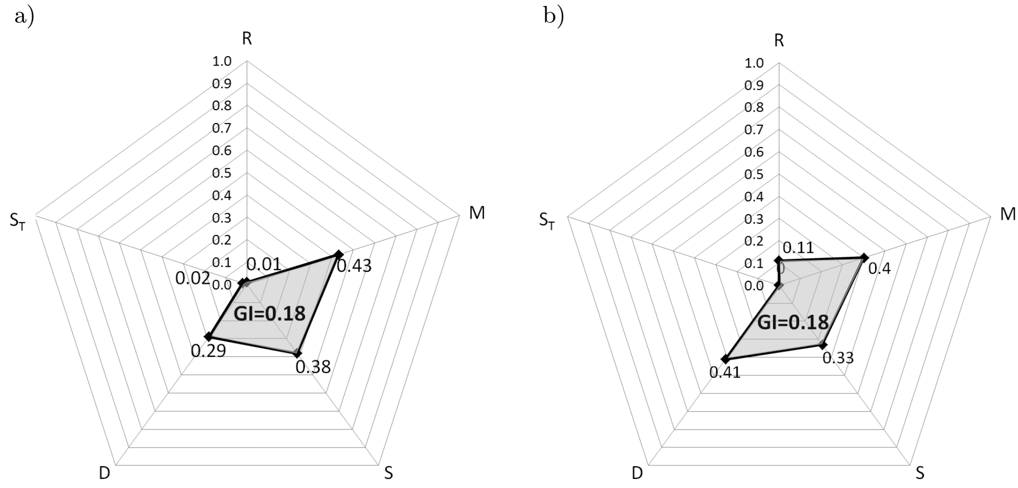

Fig. 14. Assessment of the acoustic quality of the churches: MA (a) and SA (b) by means of a single-number GI index (based on 5 indices).

Trinity Church in Fatima (GAP = 1), in spite of its large volume, whereas the two other tested churches have poor acoustic properties. Confirmation of this was a more accurate assessment performed by means of the GI indices (Fig. 14), based on five parameters (partial indices), which are also close to the value 0: GI = 0.18 (MA) and GI = 018 (SA). Due to the lack of data on the sound strength G in the church FA, comparing the acoustic quality with the other tested churches by using the GI index was not possible.

6. Comparison of the acoustic properties of analysed Roman Catholic churches by using GAP and GI indices

Figure 15 shows a comparison of the acoustic properties of Roman Catholic churches by using a single number GAP and GI indices. Additionally, the index GAP_{occ} for the examined church (EW), in which the audience presence was taken into account, is given in the graph.

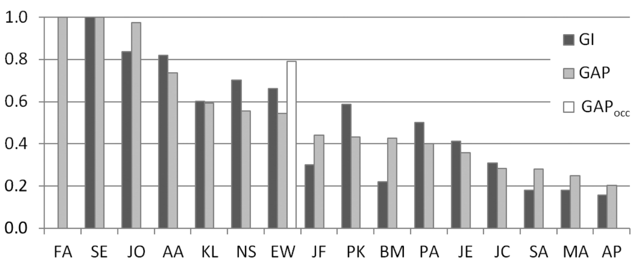

Fig. 15. Comparison of the acoustic properties of Roman Catholic churches by using a single-number GAP and GI indices (GAP_{occ} means that the assessment takes into account the audience's presence).

The GAP index, as the weighted sum of two uncorrelated components: RMS and D indices, may, as shown in the article, be used for the assessment and prediction of the acoustic parameters in churches' simulation studies. The research and analysis for the St. Elizabeth of Hungary Church showed that, after taking the audience into account, the acoustic properties of the object improved (Fig. 15). The single-number global index has improved by 25% to the value of GAP = 0.79.

A single-number assessment by using the GI index is the result of the synthesis obtained from the *in-situ* measurements of the acoustic parameters: T_{30}, C_{80}, $RASTI$, L_{Aeq}, and G with respect to their preferred values. Assessments by using the GI index (Fig. 15) have a large range of results, from a value close to 0 (poor quality acoustic), e.g. GI = 0.16, to GI = 1 (churches with very good acoustic quality). Overall assessment enables preparation of the ranking of churches and information to be obtained as to what extent the Roman Catholic churches, of various volume, architectural style, form of interiors and equipment, fulfill their utilitarian function acoustically. The information contained in partial indices of the global assessment by using the GI index is not duplicated, which was obtained from the weighted sum of uncorrelated components: the RMS index, G, and S_T. The RMS index is obtained by reduction of the partial indices R, M, and S, which are correlated with each other.

7. Sensitivity of the calculation model required to obtain reduced *RMS* indices

The proposed computational procedure in the evaluation of a new church (EW) or the new churches (FA, MA, and SA) involves adding an additional object (line) or objects (lines) to matrix A_0 and execution of SVD could cause slight changes in the resulting new values of the *RMS* indices of the 12 former churches. Hence, an analysis of errors was calculated using the following formula:

$$e = \frac{\left| RMS_{x(i)} - RMS_{m(i)} \right|}{RMS_{m(i)}} \cdot 100\%, \tag{3}$$

where $RMS_{m(i)}$ is the i-th ($i = 1, \ldots, 12$) reduced partial single number index of assessment of selected acoustic properties of the church *RMS*, obtained from the SVD of the reference Index Observation Matrix A_0: 12×3; $RMS_{x(i)}$ is the i-th ($i = 1, \ldots, 12$) reduced partial single number index of assessment of selected acoustic properties of the church *RMS*, obtained from the SVD of the new extended Index Observation Matrix A_1 (13×3) or (15×3).

Figure 16 shows the error values: e_1 – where the additional 13-th object was the St. Elizabeth of Hungary Church (EW), and its values of the partial indices, calculated on the basis of the acoustic parameters obtained from *in-situ* measurements and e_2 – where the additional 13-th object was the same church and its values of the partial indices, calculated on the basis of acoustic parameters obtained from simulations, taking into account the presence of the audience. Analysis of the errors e_1 and e_2 shows that the maximum error has a value of 1.1%.

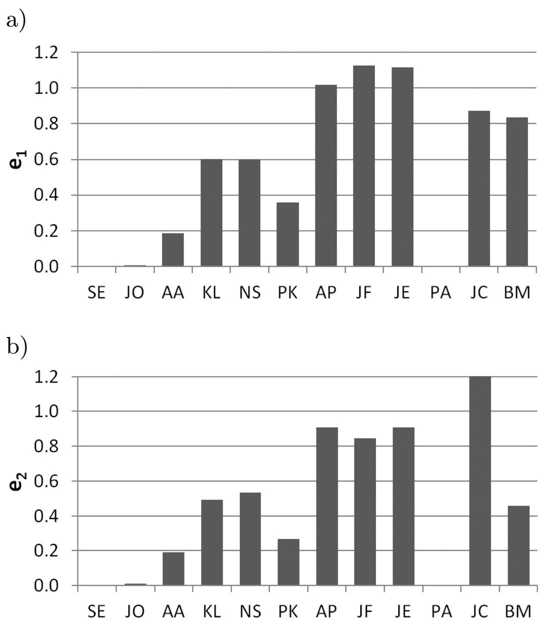

Fig. 16. Values of errors of the new 12 *RMS* indices of churches obtained after SVD of the matrix A_1: 13×3 in the case a) of unoccupied additional (EW) church, b) of occupied additional (EW) church.

Hence, the addition of the next line with the values of the partial indices R, M, and S of the new object (the church) to matrix A_0 and execution of the SVD of matrix A_1 does not cause a significant influence either on the *RMS* values of the former tested churches or on the structure of the data in the Index Observation Matrix A_0: 12×3.

The percentage shares of clarification of information about independent variables by successive singular components σ_1, σ_2, and σ_3 were equal to 77.8%, 11.5%, and 10.7% for the matrix A_0: 12×3 and for the new matrix A_1: 13×3: 76.5%, 12.1%, and 11.4% for the unoccupied church, and 78.6%, 11.1%, and 10.3% for the occupied church. The singular components σ_2 and σ_3 give the values of the shares close to 10%, which is considered as a limit value of the information noise. Meanwhile, the most informative singular component σ_1 has values from 76 to 79% of the general information.

To evaluate the sensitivity of the calculation model required to reduce the correlated indices R, M, and S, and obtain a single number reduced *RMS* index for three additional tested churches, described in the Sec. 5, the error analysis shown in Fig. 17 was carried out.

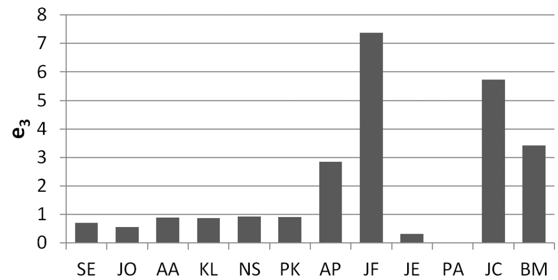

Fig. 17. Values of errors of the new 12 *RMS* indices, obtained after SVD of the matrix A_1: 15×3: with FA, MA, and SA as additional three tested churches.

The maximum values of errors for the new churches FA, MA, and SA are greater than they were for the examined EW church, but they are still acceptable. In the case of calculation of the *RMS* index, the maximum error was equal to 7.4% for the church JF (Fig. 17).

The percentage shares of clarification of information about independent variables by successive singular components σ_1, σ_2, and σ_3 were equal to 73.1%, 17.5%, and 9.4%. Hence, in the case of the three tested church, the value of the first singular component, used for the construction of a reduced *RMS* index by using the SVD method, is still high and its correlation with the partial indices R, M, and S, is respectively: 0.969, 0.980, 0.945. This means that the *RMS* values of each of the 12 former churches were changed, however, not significantly, which is shown in Fig. 18.

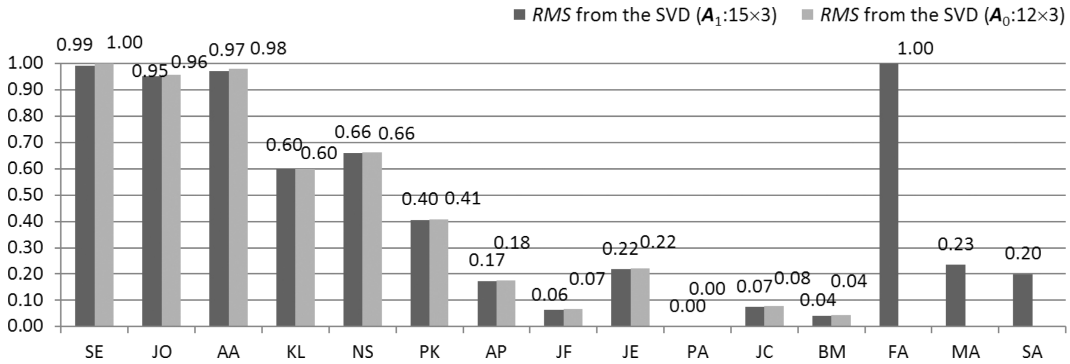

Fig. 18. Comparison of the values of *RMS* indices for 15 tested churches, obtained after SVD of the matrix A_1: 15×3: with FA, MA, and SA as additional objects and the values of *RMS* indices for 12 former churches, obtained after SVD of the reference matrix A_0: 12×3.

8. Conclusions

The article shows that for the index assessment of church acoustics, two methods, based on GAP and GI calculation models and proposed in earlier research, may be applied for the assessment of any Roman Catholic Church. Confirmation of this is the St. Elizabeth of Hungary church, for which studies into the acoustic parameters by means of *in-situ* measurements have been extended by using simulation tests and taking into account an important factor in shaping the acoustic climate of this type of interior – the presence of the audience. The analysis showed that the audience definitely improves the acoustic properties of the church, which is indicated by higher by 23%, the averaged value of the global index GAP = 0.8 and the distribution of GAP index values in the space defined by test points, which is more uniform, compared with the church without an audience.

For a more accurate analysis of the acoustic quality of the church, the GI global index was used. The GI index proposed in earlier studies takes into account an additional uncorrelated parameter – the sound strength. A single number comparative analysis, being the result of synthesis of the acoustic parameters obtained from *in-situ* measurements, showed a large range of GI results from 0.16 to 1, which has helped draw up a ranking of the acoustic quality of the 16 Roman Catholic churches in the criteria of the range of values: 1 – very good acoustic properties, corresponding to the preferred values of acoustic parameters in churches, 0 – poor properties, significantly different from the preferred values.

Additionally, an attempt performed and shown in the article to apply the GAP and GI indices to assess the acoustics of three additional churches (FA, MA, and SA) was successful. Two large-sized objects of comparable volume, but of varied style and interior equipments have, according to the index assessment, the acoustic properties: very good – the Holy Trinity Church in Fatima (GAP = 1), and poor – the Cathedral of Malaga (GAP = 0.25, GI = 0.18). The same low value of GI = 0.18 and poor acoustic properties were observed in the third analysed church – Santa Ana in Moratalaz, with a volume 30 times smaller than the one in Malaga. However, more detailed differences in the acoustic properties of these two churches are provided by the five partial indices.

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References

1. Alonso A., Sendra J. J., Suárez R., Zamarreño T. (2014), *Acoustic evaluation of the cathedral of Seville as a concert hall and proposals for improving the acoustic quality perceived by listeners*, Journal of Building Performance Simulation, **7**, 5, 360–378.
2. Álvarez-Morales L., Zamarreño T., Girón S., Galindo S. (2014), *A methodology for the study of the acoustic environment of Catholic cathedrals: Application to the Cathedral of Malaga*, Building and Environment, **72**, 102–115.
3. Berardi U. (2012), *A double synthetic index to evaluate the acoustics of churches*, Archives of Acoustics, **37**, 4, 521–528.
4. Berardi U. (2014), *Simulation of acoustical parameters in rectangular churches*, Journal of Building Performance Simulation, **7**, 1, 1–16.
5. Berardi U., Cirillo E., Martellotta F. (2009), *A comparative analysis of acoustic energy models for*

churches, The Journal of the Acoustical Society of America, **126**, 4, 1838–1849.

6. Berardi U., Iannace G., Ianniello C. (2015), *Acoustic Intervention in a Cultural Heritage: The Chapel of the Royal Palace in Caserta, Italy*, Buildings, **6**, 1, 1–14.
7. Bueno A.M., León A.L., Galindo M. (2012), *Acoustic rehabilitation of the church of Santa Ana in Moratalaz, Madrid*, Archives of Acoustics, **37**, 4, 435–446.
8. Carmona C., Zamarreño T., Girón S., Galindo M. (2009), *Acústica virtual de la iglesia san Lorenzo de Sevilla*, Revista de Acústica, **40**, 3–4, 7–12.
9. Carvalho A.P.O., Silva P.M.A. (2010), *Sound, Noise and Speech at the 9000-Seat Holy Trinity Church in Fatima, Portugal*, Archives of Acoustics, **35**, 2, 145–156.
10. Dalenbäck B.I. (2008), *CATT-Acoustic v8 user's manual*, CATT, Mariagatan A, 16, 41471, Gothenburg, Sweden.
11. Engel Z., Engel J., Kosała K., Sadowski J. (2007), *The bases of acoustics of sacral objects*, [in Polish: *Podstawy akustyki obiektów sakralnych*], ITE, Kraków – Radom.
12. Engel Z., Kosała K. (2005), *Acoustic properties of the selected churches in Poland*, Mechanics, **24**, 173–181.
13. Engel Z., Kosała K. (2007), *Index method of the acoustic quality assessment of sacral building*, Archives of Acoustics, **32**, 3, 3–22.
14. ISO-3382-1 (2009), *Acoustics – Measurement of room acoustic parameters, part 1: performance spaces*, Geneva, Switzerland: ISO.
15. Kosała K. (2009), *Calculation Models for Acoustic Analysis of Sacral Objects*, Archives of Acoustics, **34**, 1, 3–11.
16. Kosała K. (2012), *Singular Vectors in Acoustic Simulation Tests of St. Paul the Apostle Church in Bochnia*, Archives of Acoustics, **37**, 1, 23–30.
17. Kosała K. (2014), *The comparative analysis of acoustic properties of Roman Catholic churches using the index method*, Acta Physica Polonica A, **125**, 99–102.
18. Kosała K., Engel Z.W. (2013), *Assessing the acoustic properties of Roman Catholic churches: A new approach*, Applied Acoustics, **74**, 1144–1152.
19. Małecki P. (2014), *Auralization of Several Churches and Listening Comparison Using Multidimensional Scaling Approach*, Proceedings of the EAA Joint Symposium on Auralization and Ambisonics, pp. 151–155, Berlin.
20. Martellotta F. (2009), *Identifying acoustical coupling by measurements and prediction-models for St. Peter's Basilica in Rome*, J. Acoust. Soc. Am., **126**, 1175–1186.
21. Martellotta F., Della Crociata S., D'Alba M. (2011), *On Site Validation of Sound Absorption Measurements of Occupied Pews*, Applied Acoustics, **72**, 12, 923–933.
22. Martelotta F., Crillo E., Carbonari A., Ricciardi P. (2009), *Guidelines for acoustical measurements in churches*, Applied Acoustics, **70**, 378–388.
23. Meyer J. (2003), *Kirchenakustik*, Frankfurt am Main, Verlag Erwin Bochinsky.
24. Suárez R., Alonso A., Sendra J. (2015), *Intangible cultural heritage: The sound of the Romanesque cathedral of Santiago de Compostela*, Journal of Cultural Heritage, **16**, 239–243.
25. Vorländer M. (2008), *Auralization, fundamentals of acoustics, modeling, simulation, algorithms and acoustic virtual reality*, Berlin, Springer-Verlag.