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A comparative analysis of the index assessment of church acoustics using RASTI and STI

Analiza porównawcza wskaźnikowej oceny akustycznej kościołów z użyciem RASTI i STI

Abstract

The article presents modified global assessment indices, developed in previous studies, for measuring the acoustic quality of Roman Catholic churches: the four-parameter Gap index and the Gi index based on five acoustic parameters. The replacement of *RASTI*, previously used in the acoustic assessment of churches, with *STI* has broadened the scope of church assessment and contributed to an improvement in the accuracy of the proposed method. Verification of new calculation procedures was performed on the 12 churches included in the calculation model and, additionally, on another church.

Keywords: church acoustics, index method, acoustic quality

Streszczenie

W artykule przedstawiono zmodyfikowane, opracowane w ramach wcześniejszych badań, wzory na wskaźniki globalne oceny jakości akustycznej kościołów rzymsko-katolickich: 4 parametrowy Gap oraz bazujący na 5 parametrach akustycznych wskaźnik Gi. Zamiana dotychczas używanego w akustycznej ocenie wskaźnikowej kościołów *RASTI* na *STI* poszerzyła zakres możliwości oceny kościołów oraz przyczyniła się do poprawy dokładności zaproponowanej metody. Weryfikację nowych procedur obliczeniowych przeprowadzono na 12 kościołach wchodzących w skład modelu obliczeniowego oraz dodatkowo na przykładzie jednego kościoła.

Słowa kluczowe: akustyka kościołów, metoda wskaźnikowa, jakość akustyczna

1. Introduction

Studies into the acoustic properties of worship spaces have been conducted by many researchers [4, 5, 7, 9, 15–17, 21]. Various acoustic parameters associated with the transmission of speech [4, 5] or activities outside the liturgy, such as the concert function of those interiors, have been investigated [16]. For rating the speech and music in churches, a method based on the use of two separate indices of acoustic assessment was proposed by Berardi [2]. A similar approach was shown by Álvarez-Morales *et al.* [1], where indices separately evaluating speech and music were developed for large-sized churches.

A large part of the author's research has concerned the development of a uniform method to comprehensively evaluate the acoustic properties of churches with a wide range of sound production. The proposed index method [7, 8, 13], modified in later years, is based on the global index of assessment, which is a function of several partial indices, providing more accurate information concerning reverberation, speech intelligibility, music sound quality, external noise and sound strength in the investigated churches.

Until now, the proposed version of the index method for assessing the acoustic quality of Roman Catholic churches in terms of speech intelligibility has used *RASTI*. Due to the current computing capabilities that allow the calculation of *STI* practically at the same time as *RASTI*, it is proposed to use a more accurate index (*STI*) in the index method. Therefore, it is necessary to develop new formulas for the existing GAP and GI single number global indices, as shown in the article.

2. *STI* and *RASTI* speech transmission indices

Providing a fairly good intelligibility of transmitted speech is essential in many facilities for public use, especially in places of worship. Next to the subjective methods used to assess the acoustics of interiors in terms of speech intelligibility, objective methods stand out, including *RASTI* (Rapid Speech Transmission Index) and *STI* (Speech Transmission Index) [3]. The *RASTI* method is derived from the *STI* method and is its shortened version.

Both methods, proposed by Houtgast and Steeneken [19], determine speech intelligibility by identifying and assessing the impact of the room, i.e. its internal conditions prevailing on the sound signal received by the audience [18]. Determination of the speech intelligibility is carried out by calculating the *RASTI* or *STI* ratios from the modulation transfer function (MTF), which is associated with the subjective scale of speech intelligibility [19,3].

In 1981, Schroeder showed that the MTF can be determined by the Fourier transform of the impulse response [20]:

$$m(f_m) = \int_0^\infty p^2(t)e^{-j\omega t}dt \Big/ \int_0^\infty p^2(t)dt \tag{1}$$

where:

$p(t)$ – impulse response function.

To determine the *STI*, it is necessary to calculate the MTF for seven octave frequency bands from the 125–8000 Hz range, while the *RASTI* requires two octave frequency bands of 500 Hz and 2000 Hz [22]. *RASTI* values can be determined using a Brüel & Kjaer 3361 measuring set: Rapid speech transmission index meter [19]. Currently, by using a computer and software (e.g. Dirac Room Acoustics Software from Brüel & Kjaer), *STI* and *RASTI* can be obtained from the impulse response registered in the studied interior. In most applications in room acoustics, *RASTI*, using a simplified set of modulation transfer functions, gives results similar to those obtained by using *STI*. However, due to the fact that the current technical capabilities, using fast computer calculations, allow *STI* to be obtained almost immediately, it is preferable, due to the greater accuracy of the result set, to use just *STI* instead of *RASTI*.

3. GAP and GI single number indices in acoustics assessment of churches, the index method

Based on years of research into the uniform assessment of the acoustic quality of churches, preceded by acoustic measurements of many such interiors, in 2013, in the paper [14], the GAP (Global Acoustic Properties) single number global index for assessing the acoustic properties of Roman Catholic churches was proposed. The value of this index was calculated on the basis of acoustic parameters obtained from measurements inside the church, such as reverberation time T_{30}, clarity of music C_{80}, speech intelligibility *RASTI* and disturbing noise level L_{Aeq}. On the basis of these parameters and developed calculation procedures, shown in [14], the partial indices were determined respectively: reverberation *R*, music sound *M*, speech intelligibility S and external disturbance *D*. By using these indices, it is possible to obtain information about the extent to which acoustic parameters are consistent with their preferred values, on a scale of 1 (parameter corresponds to its preferred value) to 0 (parameter deviates significantly from a preferred value).

The development of mathematical formalism for the overall GAP single number index was possible after obtaining the acoustic parameters of a group of objects (8 churches) and required the use of appropriate analytical tools. In order to avoid the duplication of some information in the synthetic single value of overall assessment, due to the fact that certain parameters (and thus the partial indices) are correlated to each other, it is proposed to group the indices which are correlated (*R*, *M* and *S*) and uncorrelated (*D*). From correlated indices, using the SVD technique (Singular Value Decomposition) and an 8´3 matrix (8 churches, 3 partial indices) obtained a vector of values reduced to RMS single number indices. Thereafter, using Comparative Multivariate Analysis (CMA), the calculated weight of two uncorrelated variables – the RMS and D vectors, containing the values of indices of the 8 churches, is obtained.

Finally, the overall GAP single number index is presented as a weighted sum [14]:

$$GAP = 0.6RMS + 0.4D \tag{2}$$

where:

RMS – the reduced partial single number index of assessment of selected acoustic properties of the church: reverberation, the sound of music and speech intelligibility (based on *RASTI*),

D – the partial index of external disturbance.

Using the GAP single number index, the acoustic quality of 8 churches (on the basis of which the calculation model was designed) was evaluated [14]. The GAP index can assess any acoustic Roman Catholic church, as shown in [10]. Using simulation studies, the acoustic parameters of the 3D model of the church assessed with the GAP index may be carried out while taking the presence of the audience into account [12].

The approach developed in [14] for index assessing the acoustic quality of churches in 2014 proposed the extension for assessing with one uncorrelated partial index S_T as a function of the sound strength G [11]. Studies have shown that it is possible to evaluate the acoustic properties of churches using a single number based on 5 acoustic parameters (T_{30}, C_{80}, *RASTI*, L_{Aeq} and G). Based on the analysis of acoustic parameters and related partial indices, it was determined that, for a group of 12 churches, the mathematical formalism for the GI (Global Index) global single number index is given by the formula [11]:

$$GI = 0.5RMS + 0.3S_T + 0.2D \quad (3)$$

where:

S_T – the partial index of sound strength.

A uniform assessment of the acoustic quality of 12 analysed church interiors, as shown in Fig. 1 and carried out with the use of GI, more fully reflects the acoustic conditions prevailing in them. The GI global index, developed on a 12-element calculation model constituting a pattern, is applicable to the assessment of any church [10].

The two developed computational models – the GAP and GI indices used *RASTI* (S = *RASTI*) to evaluate speech intelligibility. It is possible to increase the accuracy of the index assessing the acoustic quality of the churches in terms of speech intelligibility, as signalled in [12], by using a more accurate index, which is the *STI*, the subject of this article. Inclusion of the *STI* in the global assessment requires the introduction of new weights of the partial indices, and thus the development of new formulas for the existing global indices.

12 Roman Catholic churches were studied including historical (in that number some wooden: SE, AA, JO) and modern buildings, of a cubic capacity from 1102 to 41378 m^3, with differing floor shapes and interior furnishing appropriately to the architectural style in which they were built. Different geometrical parameters were given in Table 1. The surveyed churches are built on various ground plans, among others, such as: rectangular – NS and JC, oval – PA and BM, triangular – PK or Greek cross – AP (Fig. 2). The surveyed interiors have several common features. These are wooden pews, floors made of marble or ceramic tiles, stained glass windows, and organs located on the gallery over the church main entrance (Fig. 1). Apart from three historical wooden churches, the wall finishing in churches is cement-lime plaster coated with emulsion paint. Most of these churches are described in more detail in [7].

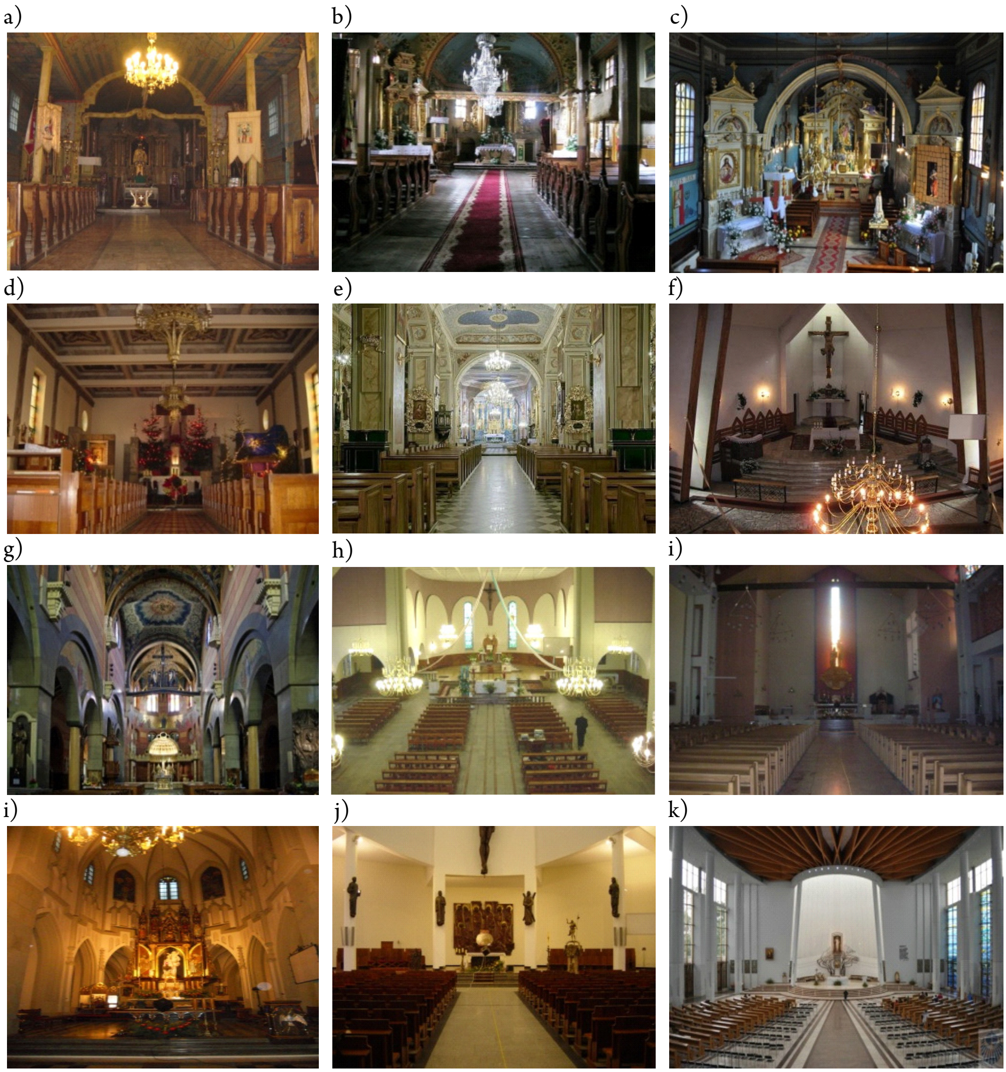

Fig. 1. Tested churches: a) St. Sebastian's Church in Strzelce Wielkie (SE), b) St. Andrew's Apostle Church in Gilowice (AA), c) St. Joachim's Church in Krzyżanowice (JO), d) The Holiest Sacred Heart's Church in Cracow (NS), e) St. Clemens Church in Wieliczka (KL), f) The Holy Cross Increase Church in Psary (PK), g) The Jesuits Fathers Church in Cracow (JE), h) St. Peter and Paul Apostles' Church in Trzebinia (AP), i) St. John the Baptist Church in Cracow (JC), j) St. Joseph's Church in Cracow (JF), k) St. Paul Apostle Church in Bochnia (PA), l) Sanctuary of the Divine Mercy in Cracow (BM)

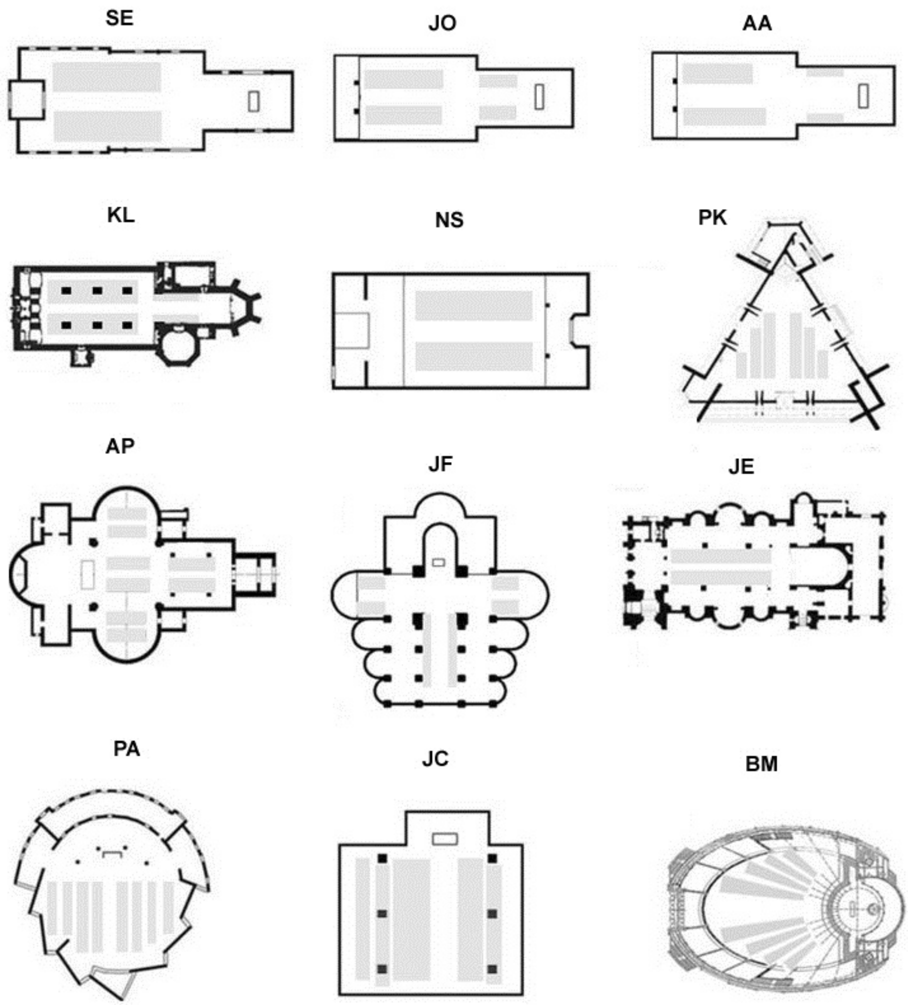

Fig. 2. Ground plan with pew zone (shaded area) for the 12 churches surveyed

Table 1. Geometric data of the 12 churches surveyed

Church ID	Style/year of build	Volume [m³]	Floor area [m²]	Length [m]	Height [m]
SE	Neoclassical/1785	1102	121	16.5	7.4
JO	Neoclassical/1794	1770	230	17.4	7.7
AA	Neoclassical/unknown	1215	188	23	7.3
KL	Neoclassical/1806	6380	712	55	13
NS	Modern/1928	2750	275	25	10
PK	Modern/1986	6800	589	31	12.6

AP	Modern/1927	12000	1187	55	10.2
JF	Neo-gothic/1909	16962	1223	44	22
JE	Modern/1921	9120	550	52	19
PA	Modern/1985	14000	812	35	25
JC	Modern/1989	14360	977	33	22
BM	Modern/2002	41378	1973	65	24

4. Speech intelligibility in churches, index *s*

To determine speech intelligibility in churches, both *RASTI* and *STI* are used. Evaluation of speech intelligibility in Catholic churches using *RASTI* has been the subject of many studies conducted by Carvalho [4, 5] and Lencastre [5]. Research showed the extent to which sound amplification systems improve speech intelligibility. The results of acoustic research conducted by Desarnaulds *et al.* [6] in 6 churches showed that the audience increases the speech intelligibility of *STI* = 0.050 when the sound amplification system is on and the *STI* = 0.035 when the sound amplification system is off.

In [14], the values of *RASTI* were shown versus the distance between the receiver and sound source for the 8 surveyed, unoccupied churches. In 7 churches, not taking into account the receivers placed nearest to the sound source, the speech intelligibility was bad and poor. Only one church, a historic wooden one, SE, had good or fair speech intelligibility.

In the current version of the index method assessment of the acoustic quality of Roman Catholic churches [14, 11], the partial index of speech intelligibility S corresponding to *RASTI* adopts the values of the same range, at each of the evaluation indices (partial and global), in line with the assumptions of the proposed method [8], i.e. from 0 to 1. According to these assumptions, all acoustic parameters, including *RASTI*, are calculated without taking into account the sound amplification system in the tested church interiors and in the conditions of unoccupied churches.

As part of further research into the improvement of the index method, proposed modifications concerned the new partial index of speech intelligibility *s* = *STI*, instead of the previously used *S* = *RASTI*, meaning that the assessment using the index method is more accurate.

Fig. 3 shows the averaged, from the measuring points, values of *RASTI* and *STI* obtained from the impulse responses recorded during the *in-situ* measurements in 12 churches.

The values of *RASTI* in the investigated churches are from 0.17 to 0.53, while the *STI* values range from 0.27 to 0.57 (Fig. 3). In all churches, the *STI* values are from 2 to 10% greater than *RASTI*. Only three historic wooden churches (SE, JO, AA), have sufficient speech intelligibility, in which the values of *STI* (or *RASTI*) of 0.5–0.6 in the interiors without sound amplification systems are considered as satisfactory conditions.

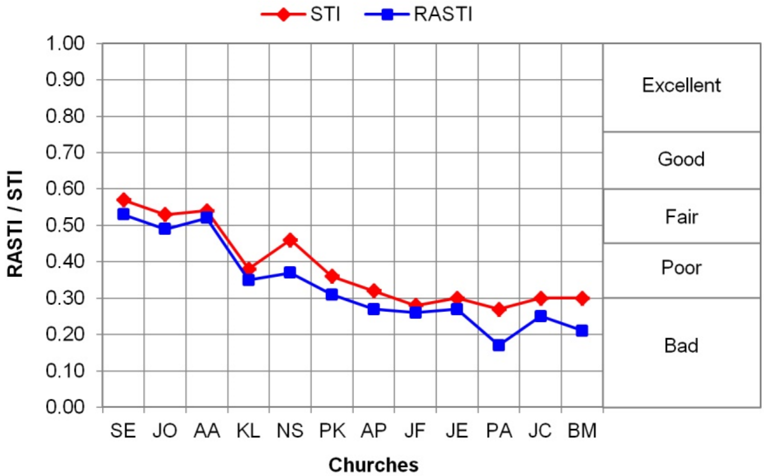

Fig. 3. Speech intelligibility, *RASTI* and *STI* in 12 investigated churches

5. The proposal of the new Gap and Gi single number indices of assessment

The introduction of *STI* instead of *RASTI* in the index calculation procedures entails the need to develop new formulas for the GAP and GI global indices, which will be replaced respectively by Gap and Gi.

Table 2 shows the acoustic parameters and partial indices, calculated for the 12 analysed churches.

Table 2. Acoustic parameters and partial indicies calculated for 12 churches

Church ID	Acoustic parameters					Partial indices of assessment					
	T_{30} [s]	C_{80} [dB]	STI	L_{Aeq} [dB]	G_{mid} [dB]	*R*	*M*	*s*	*D*	RMs	S_T
SE	1.4	2.5	0.57	27.3	5.2	1.00	1.00	0.57	1.00	1.00	1.00
JO	1.6	0.8	0.53	22.9	2.4	1.00	1.00	0.53	1.00	0.95	0.53
AA	1.6	1.3	0.54	35.1	3.8	0.97	1.00	0.54	0.37	0.95	0.85
KL	2.8	–2.7	0.38	32.2	2.8	0.78	0.73	0.38	0.58	0.56	0.62
NS	2.6	–1.9	0.46	34.6	5.8	0.78	0.81	0.46	0.39	0.70	0.97
PK	4.1	–4.0	0.36	33.4	4.3	0.51	0.60	0.36	0.47	0.39	0.96
AP	5.5	–6.6	0.32	39.6	0.3	0.23	0.40	0.32	0.24	0.15	0.07
JF	6.1	–8.8	0.28	29.6	1.0	0.12	0.27	0.28	1.00	0.00	0.22
JE	6.0	–4.3	0.30	32.3	9.3	0.10	0.57	0.30	0.57	0.17	0.63
PA	8.1	–6.5	0.27	26.3	4.9	0.00	0.41	0.27	1.00	0.02	1.00
JC	7.4	–6.8	0.30	32.1	2.3	0.00	0.39	0.30	0.59	0.05	0.51
BM	7.6	–6.5	0.30	28.8	–0.5	0.00	0.41	0.30	1.00	0.06	0.00

The calculation model based on the Gap single number index was determined on the basis of the procedure described in [14]. Based on research conducted in 12 churches, the index observation matrix **A1**:12×3 was developed. In MATLAB (Fig. 4), the matrix **A1** containing the correlated indices R, M and, based on *STI*, the new index s (Tab. 1) was decomposed of Singular Values (by using SVD) to generate a vector with reduced partial single number indices of assessment for selected acoustic properties of the church RMs, analogously as described in [14]. The RMs index is strongly correlated with the partial indices *R*, *M* and *s*. The coefficients of linear correlation *r* are equal to 0.98, 0.99 and 0.99, respectively (Fig. 4).

Uncorrelated with each other, the indices RMs and D ($r = 0.07$) are constituents of the weighted sum, which is the Gap single number global index. Weights assigned to the two indices were calculated according to the procedure shown in [14], using Comparative Multivariate Analysis (CMA).

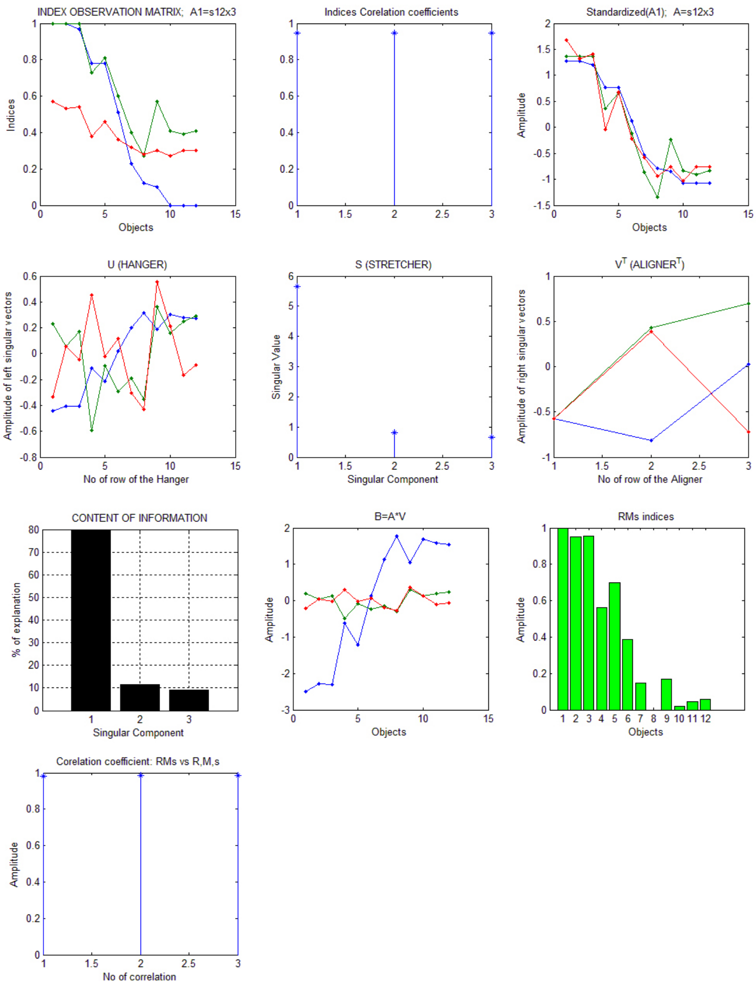

Fig. 4. Reduced indices RMs of 12 investigated churches

Modified Gap global index of the acoustic properties of Roman Catholic churches expressed by the formula:

$$Gap = 0.68RMs + 0.32D \quad (4)$$

where:

RMs – the reduced partial single number index of assessment of selected acoustic properties of the church: reverberation, the sound of music and speech intelligibility (based on *STI*).

In a similar way, also using CMA, weights were obtained for the three uncorrelated indices RMs, D and S_T (r < RMs, S_T > = 0.51; r < D, S_T > = – 0.09) needed to obtain the formula for the Gi global index.

The modified *Gi* global index of acoustic quality of Roman Catholic churches was defined as:

$$Gi = 0.48RMs + 0.3S_T + 0.22D \quad (5)$$

6. Application of modified global indices in assessment of surveyed churches

Fig. 5 shows the comparison lists of 12 surveyed churches using global acoustic assessment of traditional (GAP) and modified (Gap) indices, based on 4 acoustic parameters and Fig. 6. – the global assessment of traditional (GI) and modified (Gi) indices, based on 5 acoustic parameters.

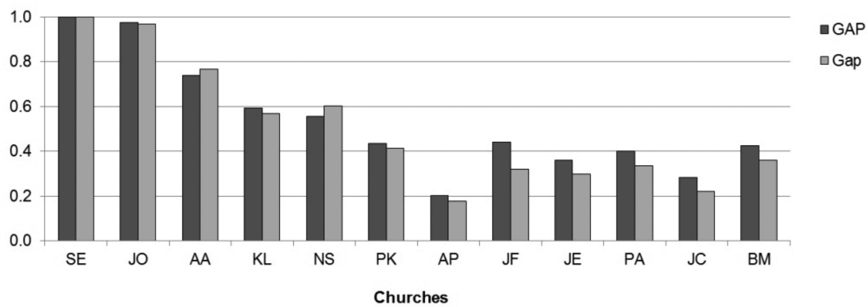

Fig. 5. Global assessment of 12 churches using GAP and Gap indices

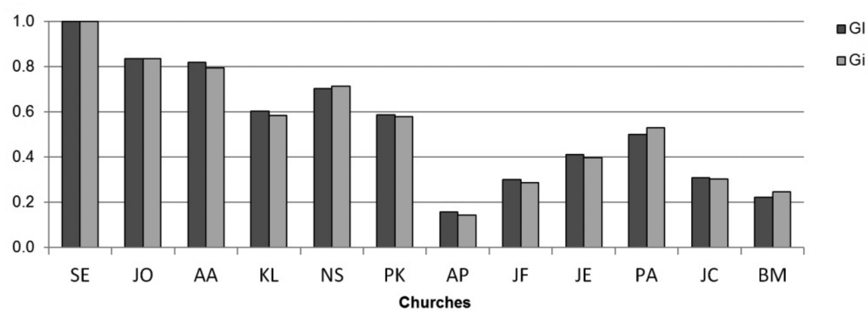

Fig. 6. Global assessment of 12 churches using GI and Gi indices

From the graphs shown in Fig. 5 and 6, it can be seen that modification of the formulas of the global indices, resulting from the replacement of *RASTI* by the more accurate *STI*, contributed to the values of global indices to a greater extent on the assessments of 4 parameters (Fig. 5) than on the assessments of 5 parameters (Fig. 6).

Fig. 7 shows a comparison of global assessments of 12 churches by modified Gi and Gap global indices. Assessments of these indices are based on *STI*.

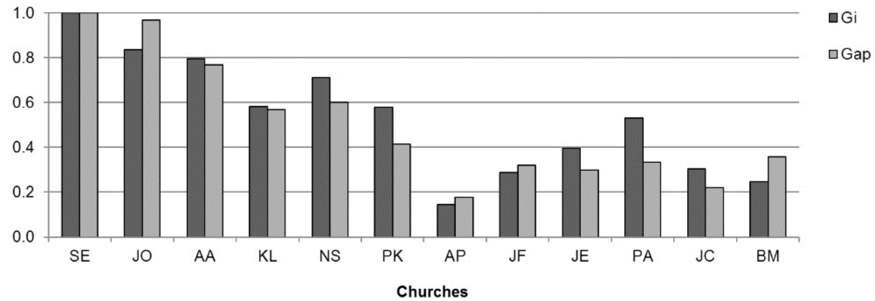

Fig. 7. Global assessment of 12 churches using Gi and Gap indices

The proposed new Gi and Gap global indices take a wide range of values from close to 0 (poor acoustic quality of the church) Gi = 0.15, Gap = 0.18, to equal the value of 1 (very good acoustic quality of the church).

Table 3 shows a comparison of the coefficients of linear correlation between global indices (traditional and modified) and acoustic parameters as well as partial indices. Modified global indices are more strongly correlated with the new partial index of speech intelligibility s (*STI*) than traditional global indices with the old index S (*RASTI*).

Table 3. Coefficients of a linear correlation between global indices, acoustic parameters and partial indices

	T_{30} [s]	C_{80} [dB]	RASTI (STI)	L_{Aeq} [dB]	G_{mid} [dB]	R	M	S (s)	RMS (RMs)	D	S_T
GAP	–0.81	0.88	0.88	–0.55	–	0.85	0.88	0.88	0.89	0.38	–
Gap	–0.87	0.93	(0.94)	–0.46	–	0.91	0.93	(0.94)	(0.94)	0.27	–
GI	–0.85	0.93	0.87	–0.35	0.44	0.89	0.93	0.87	0.91	0.12	0.75
Gi	–0.82	0.92	(0.89)	–0.39	0.43	0.87	0.92	(0.89)	(0.91)	0.15	0.75

Index assessment can be conducted for any of the Roman Catholic churches, as shown in the example of St. Elizabeth of Hungary Church in Jaworzno Szczakowa [10], where the GAP and GI indices and GAP_{occ}, taking into account the presence of the audience, were used. The assessment of acoustic conditions in the occupied church was possible after a testing simulation on the developed acoustic model of the church (Fig. 8).

The use of the modified global index to assess this church is shown. Table 4 shows the acoustic parameters of the church derived from the acoustic measurements, taking into account the presence of the audience using simulation tests.

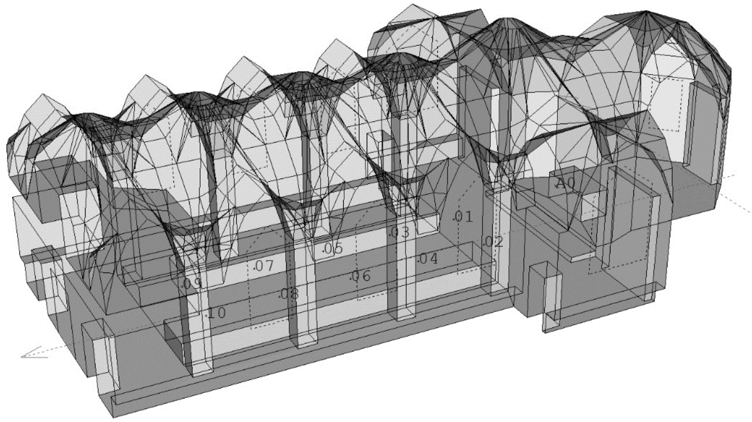

Fig. 8. Acoustic model of St. Elizabeth of Hungary Church in Jaworzno Szczakowa

Table 4. Acoustic parameters of the unoccupied and occupied St. Elizabeth of Hungary Church

Church	Acoustic parameters				
	T_{30} [s]	C_{80} [dB]	RASTI (STI)	L_{Aeq} [dB]	G_{mid} [dB]
unoccupied	3.3	–4.33	0.33 (0.37)	31.4	5.29
occupied	2.05	–0.65	0.46 (0.47)	31.4	–

Based on the acoustic parameters, the partial as well as the global indices of acoustic properties of the church were determined, as shown in Table 5. Global assessment for the church using the modified Gap and Gi global indices, based on *STI*, practically does not differ from the values of the traditional GAP and GI indices, based on *RASTI*.

Table 5. Partial and global indices of assessment of acoustic properties of St. Elizabeth of Hungary Church

Church	Partial indices						Global indices			
	R	*M*	*S* (s)	RMS (RMs)	*D*	S_T	GAP	GI	Gap	Gi
unoccupied	0.63	0.57	0.33 (0.37)	0.45 (0.42)	0.68	1	0.54	0.66	0.5	0.65
occupied	0.90	0.93	0.46 (0.47)	0.86 (0.81)	0.68	–	0.79	–	0.77	–

Comparison of the acoustic properties of the unoccupied and occupied St. Elizabeth of Hungary Church using the modified index method with the Gap and Gap_{occ} indices shown in Fig. 9.

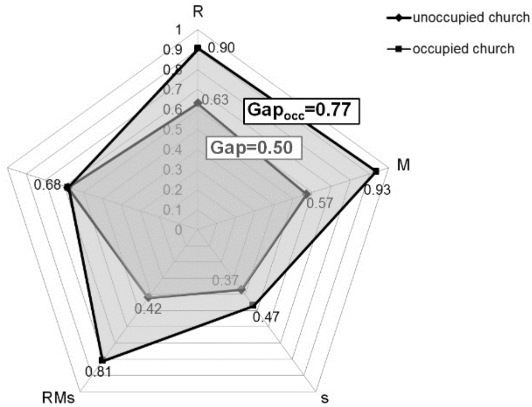

Fig. 9. Assessment of acoustic properties of the unoccupied and occupied the St. Elizabeth of Hungary Church using the modified index method with the Gap and Gap_{occ} indices

Assessment of the acoustic properties of St. Elizabeth of Hungary Church using the modified index method with the Gi index shown in Fig. 10.

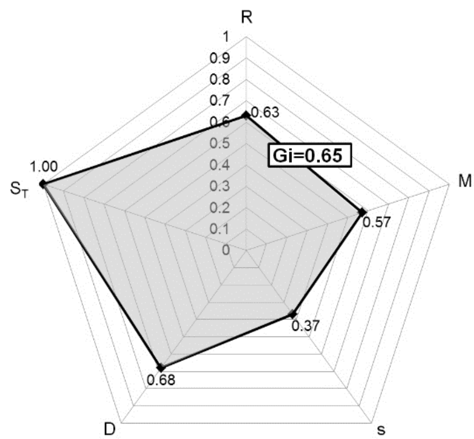

Fig. 10. Assessment of the acoustic properties of the unoccupied St. Elizabeth of Hungary Church using modified index method with Gi index

7. Conclusions

Analysis of the acoustic parameters of the data set consisting of 12 Roman Catholic churches, with a capacity from about 1100 to 41000 m^3, of different interior designs and different geometries, enabled the development of computational models as global assessment indices of the acoustic quality of churches. After the acoustic measurements in churches by using global indices, which were general measures and functions of *RASTI*, it was possible to make the assessment based on 4 acoustic parameters (GAP) and a more accurate one, based on 5 acoustic parameters (GI). Re-using the model with the data structure – acoustic parameters of 12 churches but containing acoustic measurement values of *STI* in these churches – has enabled the development of new formulas for the global indices: Gap, as a function of acoustic parameters, such as: T_{30}, C_{80}, *STI* and L_{Aeq}, and Gi, which is a function of T_{30}, C_{80}, *STI*, L_{Aeq} and *G*.

New formulas for the global indices have widened the scope of the proposed index method of objects, in which, instead of *RASTI, STI* is measured. Currently, *STI* can be calculated from the impulse response registered in the church interior as quickly as *RASTI*. Assessments of the acoustic quality of the churches made using the new global indices, which are functions of the *STI*, can be considered as more accurate in comparison with traditional global indices, based on *RASTI*.

The new global indices may be applied for the assessment of any Roman Catholic church, not only to the 12 objects in the index observation matrix. Verification of new indices were shown to assess St. Elizabeth of Hungary Church, where the acoustic model, developed in earlier studies, also allowed the audience presence to be taken into account.

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