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Index assessment of the acoustics of Orthodox churches in Poland

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A B S T R A C T

This work describes the problem of acoustics in architectural objects related to Christianity in Poland, especially Orthodox churches, and to a lesser extent, Roman Catholic churches. Ensuring adequate acoustic environments in spaces of religious worship is a difficult task, especially as churches differ from other public facilities, due to sacred and emotional factors. Alongside the issue of the proper acoustic design of worship interiors, due to the wide range of acoustic production, including music and speech, a significant problem is the difficultly of making a uniform assessment of acoustic parameters.

The index method for the acoustic assessment of Orthodox churches, adapted from a method dedicated to Roman Catholic churches which was developed within the scope of earlier research, was proposed in the article. Acoustic tests conducted in Orthodox churches in Poland together with surveys and geometric measurements, as well as the architectural style along with other distinguishing features, were presented. The obtained results were compared to the subjective tests conducted in advance for the same architectural objects with the index assessment. The proposed index method for determining the single-number assessment was verified in two Orthodox churches from outside Poland in the index values for the geometric models the design stage, is featured.

1. Introduction

The problem of acoustics in places of religious worship is grounded in the history, tradition and customs of a given denomination. Verbal and musical forms accompany almost every confession and create, alongside architecture, an important element of identity. Over the centuries, distinct architectural styles have been correlated closely with musical styles. Acoustics also played a crucial role in shaping these tastes [1]. This paper addresses the problem of acoustics in architectural objects related to Christianity in Poland, especially Eastern Orthodox churches and Roman Catholic churches. Although these denominations share a number of characteristics, it does not seem obvious whether the results of research conducted on Roman Catholic churches may be projected onto Eastern Orthodox churches and vice versa and, if so, to what extent. Besides the numerous works on acoustics in Roman Catholic churches [2–7,23], there are only a few devoted to the acoustic properties of Orthodox churches [8–10].

Special attention is given to the acoustics of Roman Catholic churches in Poland in works devoted solely to this problem [11,1]. These works discuss the acoustic aspects of Roman Catholic churches in great detail. What is more, one of the authors of the present paper has developed a single-number index for the assessment of Catholic churches [12]. The suitability of this index has been confirmed by a series of experiments and calculations published in the literature on the subject [13–15].

Eastern Orthodox churches belong to a group of sacral buildings dominated undoubtedly by one form of transmission, which is singing. This applies to both large churches with professional choirs and smaller buildings where only the participants of services sing. In all Orthodox liturgies, the priest also sings out a large portion of the service. The only spoken part is the sermon and general information addressed at the congregation. Such proportions in the mode of transmission are the major determinant of the expected parameters of the church's acoustic field. Orthodox music is dominated by multi-vocal pieces. Even in local churches, songs are performed in a four-part harmony. In most cases, Orthodox liturgy is performed in the archaic Old Church Slavonic language. Orthodox churches in Poland have been poorly researched in terms of their acoustic properties. The very few works on the subject result mostly from the studies of the other co-author of the present paper [16,17]. Despite the characteristics of Orthodox churches outlined above, it must be noted that, in Poland, they are rooted in a similar cultural spectrum as Polish Roman Catholic churches. This work attempts to implement a single-number index in the assessment of Orthodox churches in Poland. The next chapters present the methods and results of acoustic tests conducted in Orthodox churches, followed by the main premises of the single-number index in the assessment of

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acoustics in Orthodox churches, as well as a detailed acoustic assessment executed with the use of the index.

2. Acoustic tests in Orthodox churches

2.1. Method of measurement

Measurements of the acoustic parameters in Orthodox churches in Poland were performed over the years 2011–2015 in over 20 diversified interiors. Surveys and geometric measurements were performed and the architectural style was analysed along with other distinguishing features. The EASERA software and scripts in the MATLAB environment were used to determine the spatial impulse response. Measurements were taken in compliance with the ISO 3382-1 standard [18], however, due to the characteristics of the interiors and technical capabilities, some simplifications were adopted. Instead of an omnidirectional source, an active JBL EON 515 column loudspeaker was used. Its parameters were examined thoroughly in advance. Its maximum level is 132 dB SPL and has a frequency response of 42 Hz–18 kHz with a ± 3 dB margin. Its horizontal and vertical coverage (−6 dB) is 100° × 60°, which is similar to human mouth directivity. It was determined that the parameters calculated were erroneous. The error margin for such buildings with a strong dispersion of the acoustic field is certainly smaller than the scatter of results that depends on the location of measurement points. Another difference in reference to the standard lies in the density of the measurement grid and the number of sound source locations. In the majority of cases, the column loudspeaker was located between the iconostasis and the exaltation altar. This is the place where most musical concerts take place and where the priest speaks or sings. In each of the buildings under examination, measurements were taken from several characteristic locations:

- behind the exaltation altar (front rows, where the concert is located),
- in the centre of the church (in no less than two spots),
- under the main dome,
- under the matroneum,
- at the back of the church,
- in aisles (in at least three spots),
- in other locations as required by the layout of the church.

In large interiors, the number of measurements was increased proportionally. In order to record the spatial properties of the acoustic field and to perform subjective listening tests, measurements were taken with the use of a Soundfield ST350 first-order ambisonic microphone. Acoustic parameters were calculated based on the pressure signal, with its frequency response being measured and characteristic linear within the acoustic range with a scatter no bigger than ± 2 dB.

2.2. Architectural and acoustic characteristics of Orthodox churches – measurement results

Based on the measurements taken, over 20 measurement reports were compiled. Some interiors were very similar, both in terms of geometry and fittings, but also, obviously, in terms of their acoustic parameters. Therefore, a statistical analysis was performed by means of the Principal Component Analysis (PCA). The method allows the objects to be reduced by calculation of orthogonal variables, which constitute a linear combination of input parameters. The efficiency of the PCA analysis is defined by the sum of variances of input data described by subsequent orthogonal components calculated. Based on initial analyses, the 11 most diversified interiors were selected for further analysis. The reduction enables a simplification to be created, especially in the case of the subjective listening tests, to which the results of acoustic parameters are compared. In Table 1, the basic parameters of the measured buildings are compiled.

id 1: The Church of the Intercession at Fili in Zdynia (Table 1) was erected in 1786 or 1795, as a Greek Catholic parish church. It is considered to be a younger variation of the western-Lemko type. It is an oriented, three-nave, rectangular, wooden, log frame structure. From the west, it is adjacent to a pole frame structure bell tower.

id 2: St Basil the Great's Church in Konieczna was erected in the years 1903–1905. Architecturally, the building is similar to the previous one. Additionally, from the west, it is adjacent to a three-storey tower with straight walls and no protruding elements. It is topped with a large onion-shaped helm roof without a lantern. A square nave was topped with a wooden barrel vault. The reverberation time in both churches is short and comparable to the reverberation times of wooden Catholic churches built in that period [11].

id 3: St Peter and Paul's Church in Siemiatycze was erected in the years 1865–1866, based on a typical official design of an Orthodox church for small towns. It is a brick oriented church built on a rectangular plan. The interior of the church is covered with a ceiling, except for the nave, which is covered with a faux groin vault. The rich fittings of the church cause significant dispersion of the acoustic field.

id 4: Holy Trinity Khram (the Orthodox counterpart of a cathedral church) in Sanok was erected in the years 1784–1789 as a Greek Catholic church, a municipal parish church. The church is an oriented, two-part structure built of crushed stone on a rectangular plan with a dominant spacious nave. The characteristics of the reverberation time and the values of the majority of the acoustic parameters calculated are similar to medium-sized Catholic churches [11], which confirms the Latin architectural influence on buildings erected at that time.

id 5: The Dormition of the Mother of God Church in Hrubieszów was erected in the years 1873–1875 and constitutes the most monumental example of Orthodox church architecture amongst parish churches within the Kingdom of Poland. The twelve-domed church was erected on a cross plan with a separate division into three parts. The frequency characteristics of the reverberation time achieve their highest values for low frequencies (BR). The value of the sound strength G is low in comparison to the other buildings under examination.

id 6: The Nativity of Mary Church in Włodawa was erected in the years 1840–1843 as a Greek-Catholic municipal parish church and is a classical example of a Russian Revival style, which developed as an attempt to find a national Russian architectural style. It is an oriented building on a cross plan, with a square nave topped with an onion dome on a cylindrical tholobate. The church is characterised by high values of the base parameter BR and sound strength G, while the reverberation time is relatively short.

id 7: The Orthodox parish church in Tomaszów Lubelski was erected in 1890 in the Neo-Russian style. The body of the church was designed on a cross and dome plan. The acoustic parameters of the church are characterised by a very high value of the base index BR and medium reverberation time.

id 8: Hagia Sophia in Białystok was consecrated in 1998. From the architectural point of view, the church is a direct reference to the temple most important for eastern Christianity - Hagia Sophia in Istanbul. The designer's aim was to create a miniature copy (1:3). The reverberation time of Hagia Sophia in Białystok is long. The maximum of the frequency characteristics of the reverberation time is achieved for medium frequencies, which results in a low value of the base parameter BR, which may be considered untypical for such large and well reverberated buildings.

id 9: The Holy Trinity cathedral church in Hajnówka was designed by Aleksander Grygorowicz and erected in the years 1981–1983. The reverberation time of this church is relatively long for buildings of this size. The recognised acoustic advantage of the church in Hajnówka is also confirmed by the Festival of Orthodox Church Music held there annually, which is an important reference point for the analysis and interpretation of test results.

id 10: The Resurrection of Jesus Church in Siemiatycze was erected in the years 1999–2009. It is an oriented building of yellow clinker

Table 1
Acoustic parameters of selected Orthodox churches in Poland.

id	Orthodox church	Architectural parameters		Acoustic parameters									
		Floor area (m^2)	Volume (m^3)	T_{30} (s)	EDT (s)	C_{80} (dB)	C_{50} (dB)	t_s (ms)	BR	TR	LEF	STI	G (dB)
1	The Church of the Intercession at Fili in Zdynia	150	750	1.07	1.1	7.2	4.6	40	1.08	0.73	0.46	0.68	4.7
2	St Basil the Great's Church in Konieczna	140	900	1.17	1.13	7.3	4.6	40	0.75	0.88	0.4	0.67	6.6
3	St Peter and Paul's Church in Siemiatycze	200	1500	2.2	2.19	1.3	−1.2	111	1.03	0.68	0.74	0.51	9.9
4	Holy Trinity Khram in Sanok	230	1650	1.83	1.81	3.5	1.7	71	0.88	0.76	0.63	0.57	6.8
5	The Dormition of the Mother of God Church in Hrubieszów	190	1700	1.82	1.77	5.3	3.4	60	1.1	0.7	0.28	0.62	5.1
6	The Nativity of Mary Church in Włodawa	255	2400	2.09	1.92	2.1	0.2	108	1.21	0.68	0.66	0.56	9.1
7	St Nicholas Church in Tomaszów Lubelski	210	3050	2.87	2.8	0.5	−1.2	155	1.34	0.6	0.54	0.51	8.4
8	Hagia Sophia in Białystok	360	5950	6.14	5.87	0.3	−1.3	212	0.96	0.61	0.48	0.45	9.1
9	The Holy Trinity Church in Hajnówka	550	6050	4.59	4.36	−0.4	−1.6	190	1.04	0.66	0.45	0.45	8.6
10	The Resurrection of Jesus Church in Siemiatycze	450	6400	4.74	4.29	0.4	−1.2	205	1.35	0.5	0.4	0.49	8.4
11	The Holy Spirit Church in Białystok	560	9500	6.53	6.65	1	0.3	222	0.98	0.63	0.29	0.48	6.7

brick. It is outlined on a Greek cross, with all its arms closed with three side walls. The central body is topped with a large dome and a lantern based on a tholobate.

id 11: The Holy Spirit Orthodox Church in Białystok was consecrated in 1999 and is the largest Orthodox church in Poland in terms of cubic capacity. A central plan was used for the layout of the church. An octagonal nave (side length: 10 m) was covered with a dome, which, at 2/3 of its height (7 m), turns into a lantern topped with a flat dome. In the tholobate, there are 8 windows. The significant size of the church and sparse sound-absorbing materials used in its interiors determine the long reverberation time, with the highest values of frequency characteristics being obtained for low and medium frequencies. Despite the high dispersion of the acoustic field, the value of sound strength G is low and, surprisingly, similar to small buildings. A more detailed acoustic and architectural design was presented, among others, in [17].

3. Index assessment of acoustic properties of Orthodox churches

3.1. Premises of the index assessment

The index method for the acoustic assessment of Orthodox churches was adapted from a method dedicated to Roman Catholic churches [12], which was developed within the scope of earlier research. Due to the simplifications adopted that consist of, among others, the application of approximation in the function of frequency and within the area resulting from measurement points, index assessments must be considered as tentative. The application of these indices does not aim at a thorough synthesis of all information describing the acoustic field, but is related to the functional aspects of places of religious worship. Index methods inform us about the extent to which the selected acoustic parameters of the interiors under study respond to their preferred values.

The approximate acoustic assessment of Orthodox churches is determined by the single-number index of selected parameters as mentioned above, OA (Orthodox Church Acoustics Index), which serves as a general measurement tool and a function of several selected partial indices, which provide more specific information on the acoustic properties of these interiors. All partial indices, as well as the global one, are normalized within the range of 0 through 1. The value of 1 represents very good acoustic properties, that is, such that allow a given parameter to reflect its preferred value. The value of 0, on the other hand, means that a given parameter falls far away from its recommended value. By using the global index, we may compile a ranking list of Orthodox churches according to their acoustic properties. It is possible to select interiors that possess especially favourable acoustics and thus may be used for additional purposes beyond liturgy, such as concerts, as well as to identify buildings whose acoustic parameters require correction.

In index methods for the acoustic assessment of church interiors, at the present state of advancement, the loudspeaker installation existing within such buildings is not taken into consideration. The proposed index method dedicated to Orthodox churches is based on acoustic studies conducted for empty interiors, that is, when the congregation was absent. The presence of the congregation may be taken into consideration in the assessment after simulation tests have been carried out on a pre-developed acoustic model of the building under examination, which happened for Roman Catholic churches [14].

Due to the fact that the scope of acoustic productions in Orthodox churches is similar to the one in Roman Catholic churches, it was proposed that the single-number assessment index of selected OA acoustic parameters, dependent on 3 partial indices, also assessed such basic acoustic conditions in sacral buildings: reverberation (index R), music sound (M), and intelligibility of speech (S). The partial indices R, M and S correspond to the acoustic parameters determined in the interiors, respectively: T_{30}, C_{80} and STI. The selection of partial indices was connected with the acoustic requirements for places of religious worship. Ensuring suitable reverberation conditions – when it comes to simultaneous reproduction and listening to music and voice signals, good comprehensibility of speech of the priest and the congregation, as well as music quality, reaching a compromise is not an easy thing to achieve both at the design stage and in the everyday use of such objects as places of religious worship.

As presented in the paper, the current stage of research into the index assessment of acoustic properties of Orthodox churches does not include the impact of external disturbances on peaceful prayer or meditation inside Orthodox churches. To develop a new partial index uncorrelated with the existing ones, that is a function of disturbing noise level L_{Aeq}, further research must be carried out within the buildings under analysis. Emphasis was placed on acoustic parameters and their corresponding assessment indices, which are, in the opinion of the authors of this paper, the most important for assessing acoustic parameters and those whose synthetic assessment, in the form of the single-number OA index proposed here, may be compared to a survey of subjective preference assessment conducted by two groups of listeners.

Developing a procedure for the single-number OA index was preceded by acoustic tests conducted in Orthodox churches, calculations of assessment partial indices – according to the procedures presented below, and analyses performed on the index observation matrix of Orthodox church interiors. The procedure for determining the OA index is described in Section 3.3.

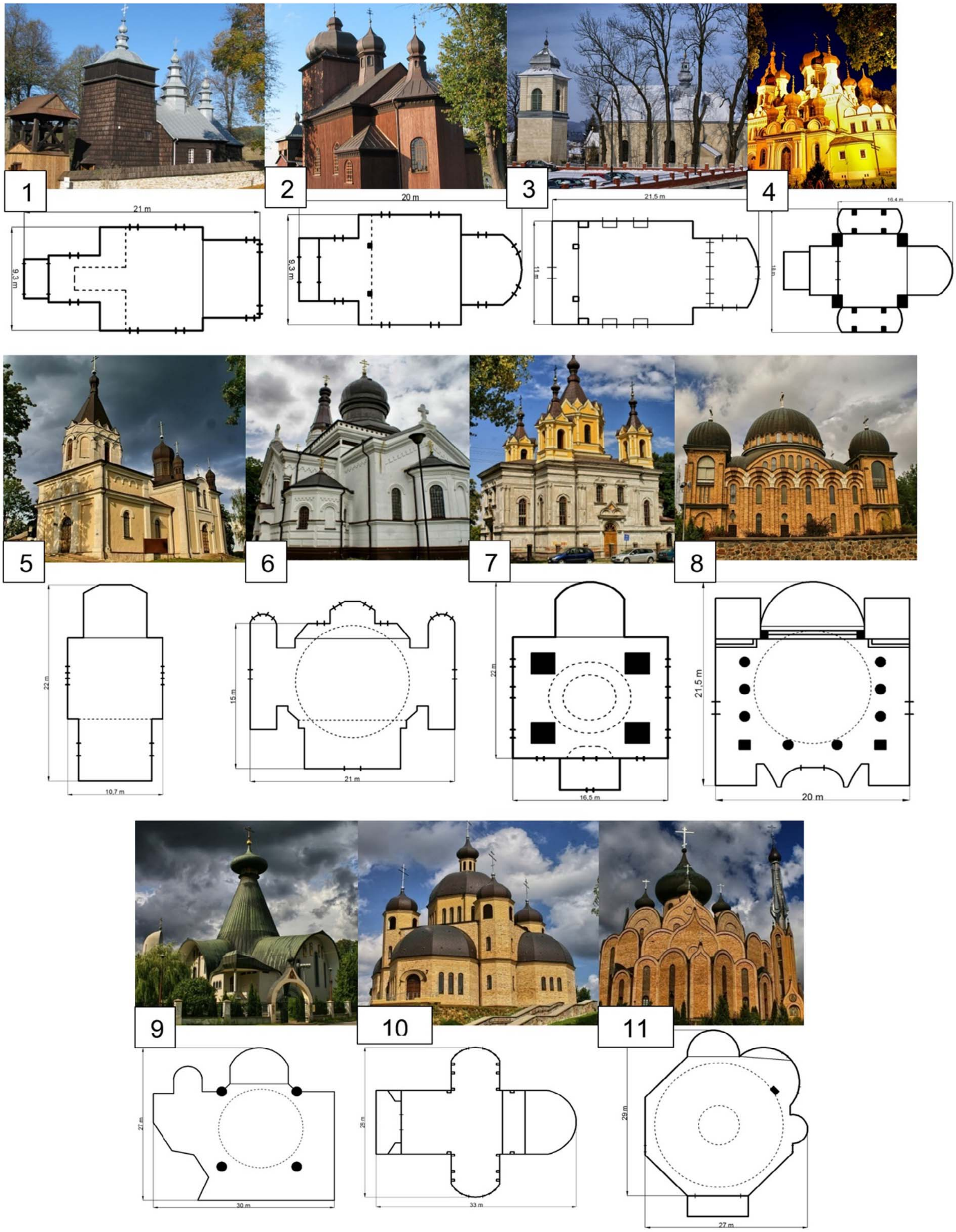

Fig. 1. Photographs and plans of selected Orthodox churches in Poland. The numbering of churches is in accordance with Table 1.

3.2. Partial indices

3.2.1. Reverberation index R

The reverberation index R, like all the partial indices, assumes values from within the range of 0–1. The value $R = 1$ means that the reverberation time of T_{30}, measured and approximated, within the frequency range of 125–4000 Hz, corresponds to the preferred value of T_p. For Orthodox churches, T_p is calculated from the formula below [19]:

$$T_p = 0.28\ln(V)-0.31, s \tag{1}$$

where V – Orthodox church cubic capacity, m^3.

It is assumed that unfavourable reverberation conditions occur when the reverberation time T_{30} exceeds the preferred value T_p by

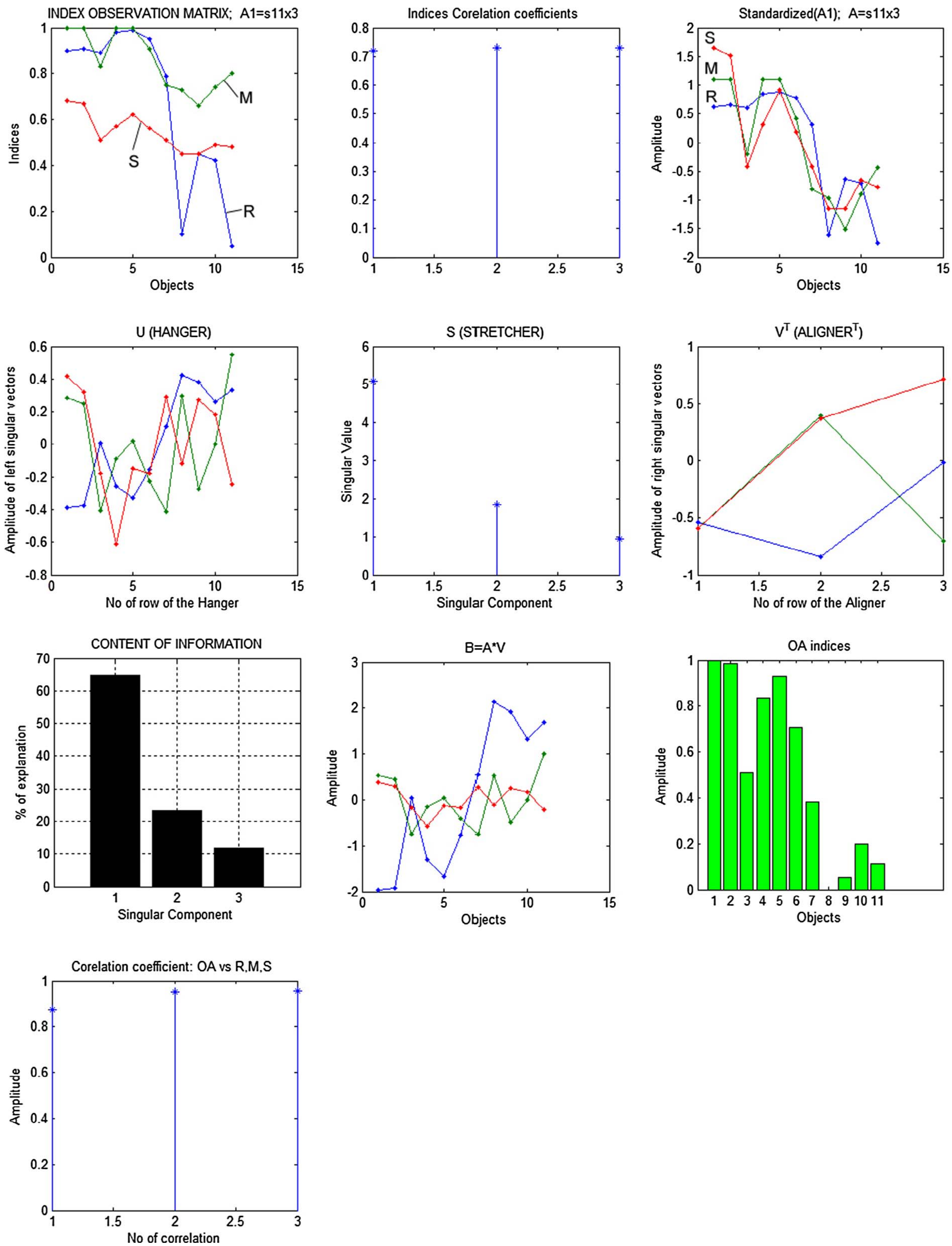

Fig. 2. Results of the calculations of single-number OA indices for 11 Orthodox churches.

4.5 s. The reverberation index equals 0 in such a case. The reverberation index R is calculated from the formula below:

$$R = \begin{cases} 0 \quad for \quad T_{30} > T_p + 4.5\ s, \\ -0.22|T_{30} - 0.28\ln(V) + 0.31| + 1 \quad for \quad T_{30} \leqslant T_p + 4.5\ \ s. \end{cases} \tag{2}$$

3.2.2. Music sound index M

The music sound index M, as the function of clarity C_{80}, is calculated from an equation developed on the basis of the preferred values of this parameter, as stated in [20,1]

Table 2
Acoustic parameters, partial indices and reduced indices of selected acoustic parameters of 11 Orthodox churches.

id	T_{30} (s)	C_{80} (dB)	STI	R	M	S	OA
1	1.07	7.2	0.68	0.90	1	0.68	1.00
2	1.17	7.3	0.67	0.91	1	0.67	0.99
3	2.2	1.3	0.51	0.89	0.83	0.51	0.51
4	1.83	3.5	0.57	0.98	1	0.57	0.84
5	1.82	5.3	0.62	0.99	1	0.62	0.93
6	2.09	2.1	0.56	0.95	0.91	0.56	0.71
7	2.87	0.5	0.51	0.79	0.75	0.51	0.38
8	6.14	0.3	0.45	0.10	0.73	0.45	0.00
9	4.59	-0.4	0.45	0.45	0.66	0.45	0.05
10	4.74	0.4	0.49	0.42	0.74	0.49	0.20
11	6.53	1	0.48	0.05	0.8	0.48	0.11

$$M=\begin{cases}0 \quad for \quad -12\,dB>C_{80}\\ 0.04C_{80}+0.3 \quad for \quad -12\leqslant C_{80}<-7 \;\; dB\\ 0.06C_{80}+0.5 \quad for \quad -7\leqslant C_{80}<-2\,dB\\ 0.1C_{80}+0.7 \quad for \quad -2\leqslant C_{80}<3 \;\; dB\\ 1 \quad for \quad 3\leqslant C_{80}<8 \;\; dB\\ -0.12C_{80}+1.325 \quad for \quad 8\leqslant C_{80}<12 \;\; dB\\ 0.5 \quad for \quad 12\,dB\leqslant C_{80}\end{cases} \tag{3}$$

The minimum value of the M index is 0 (unfavourable conditions for listening to music), while the maximum value is 1 (the most desired conditions for listening to music) (see Fig. 1).

3.2.3. Speech intelligibility index S

It is assumed that the speech intelligibility partial index S corresponds to the Speech Transmission Index (STI). S = STI takes values from the same range as each of the assessment indices (partial and global), according to the assumptions of the index method proposed here, that is, from 0 to 1. According to these premises, all acoustic parameters, including STI, are determined without sound amplification systems in the Orthodox church and for empty interiors.

3.3. Global OA index of acoustic properties of Orthodox churches

The calculation procedure for determining the single-number OA of the acoustic properties of Orthodox churches was adapted from a procedure developed for Roman Catholic churches presented in [11]. Based on acoustic tests conducted in 11 Orthodox churches in Poland, an index observation matrix **IOM**:11 × 3 (11 churches, 3 indices) was developed. From the **IOM** that contains the inter-correlated indices R, M and S, upon proper transformations presented in [12] with the use of singular value decomposition (SVD), a vector with single-number reduced indices of assessment of acoustic parameters, OA, is obtained. Fig. 2 shows a print screen of the results – the values of OA indices obtained with the MATLAB application.

Table 2 shows the values of acoustic parameters and the determined partial indices, as well as the reduced single-number OA indices for 11 Orthodox churches.

Fig. 3 shows linear correlation coefficients between acoustic parameters and the partial indices.

4. Use of index assessment for the interiors of Orthodox churches

4.1. Assessment of the interiors of Orthodox churches under study

Fig. 4 shows a comparative compilation of the single-number assessment of selected acoustic properties with the use of the reduced OA index and partial indices, reverberation index R, music sound index M, and intelligibility of speech index S. Churches with numbers respective to the interiors presented in Table 1 were listed from the best to the worst acoustic properties, as assessed by the OA index.

Studies conducted with the use of index assessment (Fig. 4) showed that in 7 (Churches 1, 2, 5, 4, 6, 3 and 7) out of the 11 analysed churches, the reverberation conditions are very good ($R = <0.8, 1>$). However, taking into consideration two further acoustic parameters and the reduction of 3 partial indices to a single-number OA allowed us to obtain a ranking list of Orthodox churches in terms of their acoustics, which is more diversified in comparison to comparative assessments performed with the same reverberation time (reverberation index). According to the OA index, determined based on the acoustic studies conducted, only 4 churches (1, 2, 5 and 4) deserve to be considered as having very good acoustic quality. Assessment with the OA index proved that 4 churches (8, 9, 11 and 10) have poor acoustic conditions for their liturgical function (OA = $<0, 0.2>$). Such low values of the OA index of these buildings were influenced by low values of the reverberation index R.

Based on the index analysis (Fig. 4), it may be concluded that all the Orthodox churches under examination exhibit high values of the music quality index ($M = <0.7, 1>$). In addition, the average values of speech intelligibility ($S = <0.45, 0.68>$) for the measurement points are high, if we take note of the fact that sound amplification systems in these interiors were not taken into consideration during the research. 8 churches, according to the subjective scale [21], exhibit sufficient speech comprehensibility, while 3 churches (1, 2 and 5) are good.

Fig. 5 shows linear correlation coefficients between the reduced single-number index of the selected OA acoustic parameters and acoustic parameters and partial indices. The reduced OA index, obtained through SVD, is closely correlated with the partial indices R, M and S ($r = <0.8730; 0.9538>$).

4.2. Verification of single-number assessments obtained with subjective tests

Measurements of the acoustic parameters in selected Orthodox churches in Poland, which were described in the present paper, were extended to listening tests. The main objective of the psychophysical procedure adopted was to assess the interiors measured in terms of their

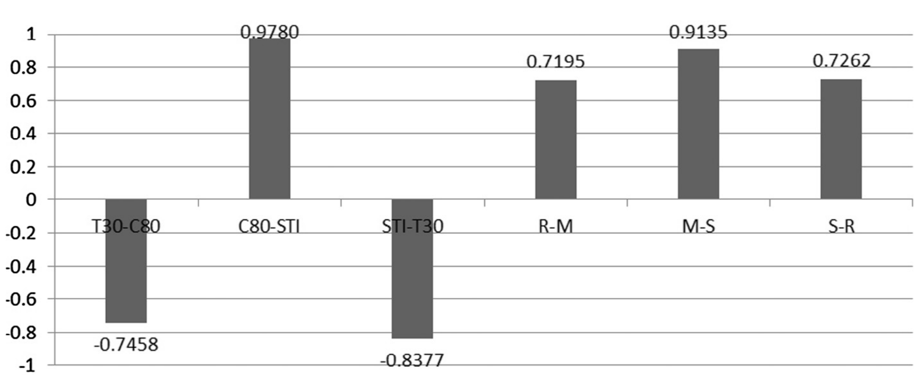

Fig. 3. Linear correlation coefficients r between acoustic parameters and the partial indices.

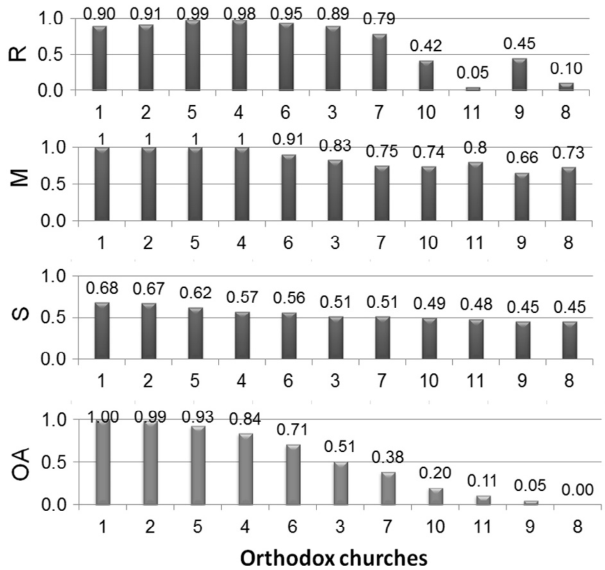

Fig. 4. Evaluation of selected acoustic properties of 11 Orthodox churches using partial indices and the reduced single-number index.

suitability for listening to choir music. Such a criterion cannot be interpreted unambiguously. Therefore, an interdisciplinary method of multidimensional scaling (MDS) [22] was used. The group of listeners contained 20 people aged 20–35, including 6 women. The listeners varied in terms of education, religion and their professional experience in sound technology. All the listeners exhibited normal hearing capabilities. Based on statistical analysis of the results, two groups of listeners were selected with significant correlations between preference test results of particular listeners. Therefore, separate analyses were executed for each of these groups, marked as 1 and 2 with different preferences. The detailed course of the listening tests was described in [17], while the results were compared with the OA indices determined (Figs. 5 and 6).

For the first group of listeners, the linear correlation coefficient between the values of the OA index and the subjective test scores is high and equals $r = 0.7601$. Based on Fig. 6, it may be concluded that high assessment values with the OA index obtained by four churches (1, 2, 5 and 4) with very good acoustic properties according to the index assessment confirm the subjective impressions of the 1st group of listeners.

The linear correlation coefficient between the values of the OA index and the subjective test scores for the 2nd group of listeners is $r = -0.2034$. Based on Fig. 7, it can be concluded that the results of the subjective survey in relation to the OA index are correlated only for Churches 3–6. For both groups of preferences, Churches 6 and 7 have been rated much better than OA index. This is probably because the listening test was conducted for the same distance of sound source and receiver. For both Churches the capture of spatial impulse response was directly under the dome so their parameters differed from averaged that was listed in Table 1.

5. Verification of the single-number OA index for selected churches

If we consider **IOM**:11 × 3 as a template (reference calculation model), we may calculate the single-number index for selected OA acoustic parameters for any given Orthodox church. In order to do so, the size of the **IOM** must be enlarged with a new line containing the new indices *R*, *M* and *S*, calculated for the new building and again, using SVD in the MATLAB application, reducing partial indices to a single-number OA index.

The proposed method for determining the single-number assessment

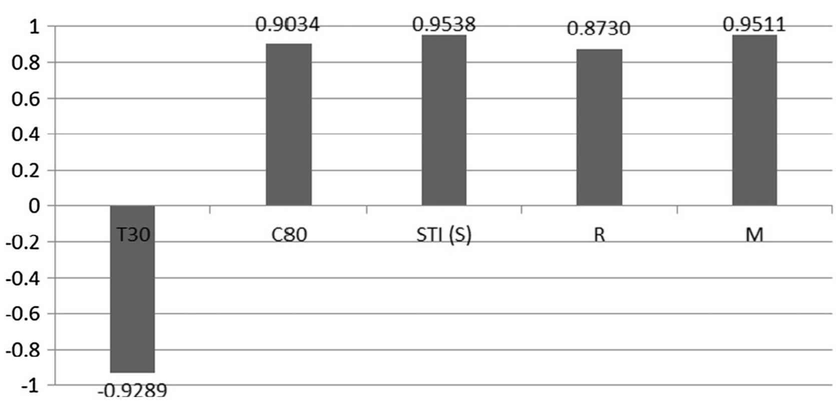

Fig. 5. Linear correlation coefficients between the single-number OA index and acoustic parameters and partial indices.

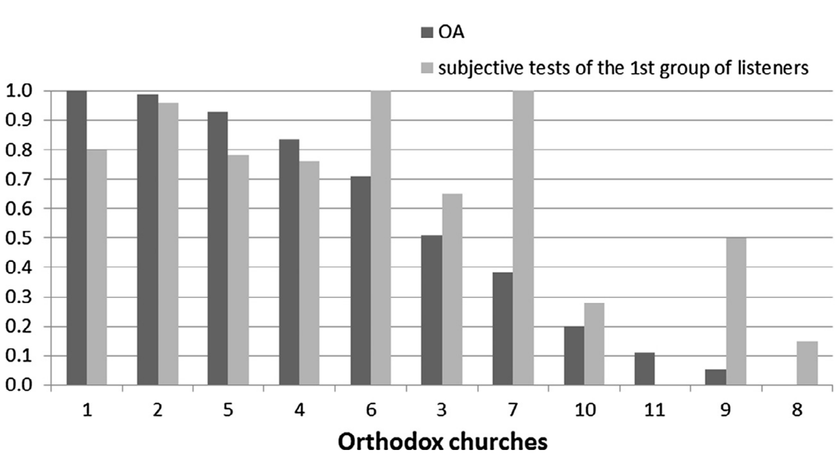

Fig. 6. Comparison of the results of the assessments by single-number OA index and the subjective tests of the 1st group of listeners.

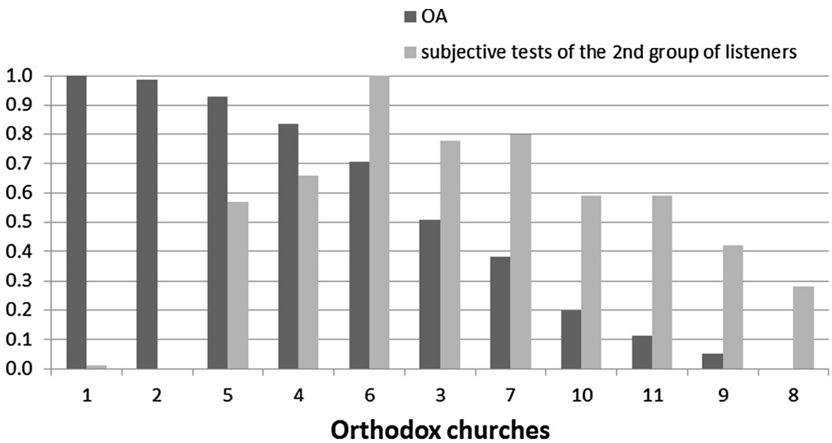

Fig. 7. Comparison of the results of the assessments by single-number OA index and the subjective tests of the 2nd group of listeners.

Table 3
Acoustic parameters of the Orthodox churches: San Nicola [9] and St. George [10] and their indices of acoustic assessment.

No.	Orthodox church	Volume, (m^3)	Occupancy	Acoustic parameters			Partial indices of assessment			Single number index
				T_{30} (s)	C_{80} (dB)	STI	R	M	S	OA
1	San Nicola, Bari, Italy	1500	Empty	2.56	−0.73	0.45	0.81	0.63	0.45	0.16
2	St. George, Žitni Potok, Serbia	2163	Empty	2.3	−1.13	0.43	0.89	0.59	0.43	0.10
			Full	1.74	0.6	0.58	0.98	0.76	0.58	0.59

(OA index) was verified for two Orthodox churches (from outside Poland): San Nicola in Bari [9] and St. George in Žitni Potok [10]. Based on the acoustic parameters T_{30}, C_{80} and STI, the values of the partial indices R, M and S, as well as the single-number OA index, were determined for empty churches and, in the case of St. George, with the congregation present inside, as shown in Table 3.

Index assessment of selected acoustic parameters conducted for these two Orthodox churches showed poor acoustic properties of their interiors. The single-number OA index takes values close to 0 (Church 1: OA ≈ 0.2, Church 2: OA = 0.1), despite high values of reverberation indices in both cases.

Comparing the acoustic properties of Orthodox churches with the same volume of 1500 m^3, San Nicola and St Peter and Paul's in Siemiatycze (Table 1), we may conclude that, according to the proposed index assessment, the Polish church exhibits better properties (OA = 0.51), which was influenced by a higher value of the music quality index (M = 0.83) for this church, with the values of the two other indices, R and S, being very similar for both churches.

Taking into consideration the presence of the congregation in St. George, the values of the partial indices R, M and S, increased by 8.7%, 17.3%, and 15%, respectively, while the single-number OA index increased from 0.1 (empty interiors) to ≈0.6 (congregation present inside). Taking the presence of the congregation into consideration improved the acoustic properties of the church to a large degree. Further research in other Orthodox churches within this scope is recommended.

6. Conclusions

The present work contains an analysis of acoustics in Orthodox churches in Poland in relation to acoustics in Roman Catholic churches. A single-number index for the assessment of acoustics in Orthodox churches was presented. The index was designed originally for the assessment of Roman Catholic churches, however, it was modified in order to take recommendations on studies of Orthodox churches found in literary sources into consideration. Due to their cultural and geographical similarity, a hypothesis was proposed that the index designed for Roman Catholic churches would be useful for the assessment of acoustics in Orthodox churches as well. Thorough acoustic measurements taken in advance in selected Orthodox churches in Poland allowed the OA index to be implemented and the examined churches to be ranked according to their acoustics. Detailed statistical analyses confirm the validity of the assumptions and important correlations between the partial indices used in the analyses.

Additionally, the obtained results were compared to the subjective tests conducted in advance for the same architectural objects as the index assessment. A close correlation of listening preferences with the values of the single-number index was obtained for one of the listener groups (approximately half of the surveyed population). The preferences of the other surveyed group of listeners are strongly non-linear in reverberation time, because neither churches with very long reverberation times nor churches with relatively short reverberation times are preferred. Such a state of affairs may not be interpreted unambiguously and any attempts to do so have not been satisfactory. This suggests a need to modify the index so that it reflects the listeners' preferences within the scope of the main transmission type in Orthodox churches, that is, choir music. This requires additional listening tests to be carried out with a larger population sample and diversified audio content.

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References

[1] Wróblewska D, Kulowski A. Acoustics in church design [in Polish]. Gdańsk: Wydawnictwo Politechniki Gdańskiej978-83-7348-198-5; 2007.
[2] Cirillo E, Martellotta F. Worship, acoustic, and architecture. Essex (UK): Multi-Science Publishing0906522447; 2006.
[3] Carvalho APO, Morgado AEJ, Henrique L. Relationship between subjective and objective acoustical measures in churches. Build Acoust 1997;4:1–20.
[4] Berardi U. A double synthetic index to evaluate the acoustics of churches. Arch Acoust 2012;37:521–8.
[5] Cirillo E, Martellotta F. An improved model to predict energy-based acoustic parameters in Apulian-Romanesque churches. Appl Acoust 2003;64:1–23.
[6] Martellotta F. Understanding the acoustics of Papal Basilicas in Rome by means of a coupled-volumes approach. J Sound Vib 2016;382:413–27.

[7] Engel Z, Kosała K. Acoustic properties of the selected churches in Poland. Mechanics 2005;24(3):173–81.
[8] Mijic M. Serbian orthodox church – an acoustical view. In: Proc of 17th ICA, Italy, Rome; 2001.
[9] Elicio L, Martellotta F. Acoustics as a cultural heritage: the case of Orthodox churches and of the "Russian church" in Bari. J Cult Herit 2015;6:912–7.
[10] Stojanović V, Milivojević Z. The evaluation of certain acoustic parameters of the Orthodox Church, evaluation. Int J Innov Res Advan Eng 2014;10:27–36.
[11] Engel Z, Engel J, Kosała K, Sadowski J. The bases of acoustics of sacral objects [in Polish]. Kraków-Radom: ITE978-83-7204-622-2; 2007.
[12] Kosała K, Engel ZW. Assessing the acoustic properties of Roman Catholic churches: a new approach. Appl Acoust 2013;74:1144–52.
[13] Kosała K. The comparative analysis of acoustic properties of Roman Catholic churches using the index method. Act Phys Pol A 2014;125:99–102.
[14] Kosała K. Calculation models for acoustic analysis of St. Elizabeth of Hungary Church in Jaworzno Szczakowa. Arch Acoust 2016;41:485–98.
[15] Kosała K. Index assessment of the influence of occupancy on the acoustic quality of selected churches [in Polish]. In: Proc of LXIII Open Seminar on Acoustics OSA, Poland, Białowieża; 2016. p. 401–12.
[16] Małecki P. Acoustics desired for choral music-using virtual acoustics and MDS methods. In: Proc. of Iberian Acoustics Congress, Spanish Congress on Acoustics TECNIACUSTICA 2016, EuroRegio 2016, Portugal, Porto; 2016.
[17] Małecki P. Evaluation of objective and subjective factors of highly reverberant acoustic field [in Polish]. Ph.D. thesis. Kraków (Poland): AGH UST; 2013.
[18] ISO 3382-1. Acoustics – measurement of the reverberation time of rooms with reference to other acoustical parameters. Geneva: ISO; 2009.
[19] Malecki I. Building acoustics [in Polish]. Warszawa: Instytut Badawczy Budownictwa; 1949.
[20] Kraak W. Criteria for the acoustical design of rooms. In: Proc of the international symposium on subjective and objective evaluation of sound, Poland, Poznań; 1990. p. 138–50.
[21] RASTI. Technical review, vol. 3. Brüel & Kjaer Naerum; 1995.
[22] Borg I, Groenen PJF. Modern multidimensional scaling: theory and applications. Springer Science & Business Media; 2005. ISBN-13: 978–0387-25150-9.
[23] Carvalho APO. Relation between rapid speech transmission index (RASTI) and other acoustical and architectural measures in churches. Appl Acoust 1999;58(1):33–49.