

CONTEMPORARY TWO-STOREY CHURCHES – ACOUSTIC INVESTIGATIONS

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Abstract. The paper discusses the idea of two-storey churches, with insight into socio-political conditions which influenced their construction. The analysis of the issue was carried out on the basis of investigations in five two-storey churches in Poznań. The churches under investigation were: Visitation of Blessed Virgin Mary Church, Christ the King Church, Our Lady of Częstochowa Church, St. Lawrence Church, and Christ the Redeemer Church. In total, ten interiors were examined. The churches were erected in the late 70s and early 80s of the 20th century. The acoustic conditions were analyzed in terms of cubature, the shape of the interior and finishes. The upper and lower churches were compared within one building; the investigation also involved comparing the churches against each other. Moreover, functionality of the buildings was analyzed, which included aspects of acoustic as well as architectural functionality.

Keywords: two-storey churches, contemporary churches, church acoustics, acoustic investigations in churches.

Introduction

The paper addresses the issue of contemporary two-storey churches in Poznań. The analysis of the issue was carried out on the basis of investigations in five two-storey churches in Poznań. The churches under investigation were: Christ the King Church (Figs 1a, b), Christ the Redeemer Church (Figs 2a, b), Our Lady of Częstochowa Church (Figs 3a, b), St. Lawrence Church (Figs 4a, b), and Visitation of Blessed Virgin Mary Church (Figs 5a, b). In total, ten interiors were examined. The churches were erected in the late 70s and early 80s of the 20th century.

The issue of acoustics in churches is complex, as church interiors must promote functions of extreme acoustic requirements. Intelligibility of speech is crucial, being the basis of the Catholic liturgy. However, the organ is inherent in the liturgy, too. For organ music, the recommended acoustic parameters are entirely different from those for speech. Two-storey churches are particularly interesting in terms of acoustics because they are composed of two interiors with different acoustic properties. As a rule, the upper church is usually bigger and more decorative.

The number of publications on the issue of acoustics in churches is not as extensive as publications on concert and opera halls. Yet, the subject is raised more and more frequently; a few of chosen publications are discussed below. In literature dealing with the issues of church acoustics, there are books like (Wróblewska, Kulowski 2007) and (Engel *et al.* 2007). The issues of religious building of different faith were discussed in (Kleiner *et al.* 2010). The study (Martellotta *et al.* 2009) presents a mode of taking acoustical measurements. The article is actually a guidebook giving instructions on taking acoustical measurements in churches. The issue was broadly discussed, including modes of measurement for buildings with longitudinal or central plan view. The article (Queiroz de Sant'Ana, Trombetta Zannin 2011) discusses an investigation of contemporary Church of Sao Carlom Borromen, it is an in-depth acoustic study of a church. The issue of reverberance was described, among others, in the papers mentioned below. The paper (Kosała, Kamisiński 2011) discusses the issue of excessive reverberance on the example of the St. Paul's

Church in Bochnia. On the basis of measurements and acoustic simulations, acoustic treatment was suggested. Another study (Engel, Kosała 2005) presents a new method of acoustic assessment of religious buildings by means of the global index of the acoustic quality. The paper describes the application of the indexing method for five Roman Catholic churches. Acoustics of chapels of the Church of the Holy Trinity in Fatima were discussed in (Carvalho, Nascimento 2011). Acoustic measurements were taken and acoustic properties of the chapels were compared with typical religious buildings in Portugal. The paper (Carvalho *et al.* 2012) describes the issue of too long reverberation time and poor intelligibility of speech in two churches from the first half of the 20th century. After investigations, acoustic treatment was suggested. The article (Buenó *et al.* 2012) discusses issues of the modern church of Santa Ana in Moraltz in Madrid. The church underwent investigations and acoustic treatment was suggested to diminish the too long reverberation time. Acoustic treatment of two newly built churches in Croatia was discussed in (Horvat *et al.* 2011). Results of the investigations were presented for each stage of the applied acoustic treatment, while a study (Tavares *et al.* 2008) shows measurements taken in Old Goa's Capela do Monte, which constitutes a new approach to acoustic research in churches. The results are used to describe prayer mood of a given interior. The article (Martellotta *et al.* 2011) discusses the issue of sound absorption by worshippers in pews. The research included both laboratory and in-situ measurements in six churches. The paper (Sendra *et al.* 1999) discusses issues of acoustics in churches and describes acoustic properties of churches from early Christian times to late Baroque. Next, the study provides characteristics of the Mudejar-Gothic church, typical of the Seville area, with a timber roof. The paper also includes three rehabilitation projects in churches, in which the authors took part. The paper (Alonso 2014) presents computer simulations of the Seville Cathedral which involved examination how decoration of the interior on the occasion of various festive or commemorative events (such as canonisation of King San Fernando in 1671) changed the acoustics. The simulation was carried out by means of the CATT-Acoustic software. The article (Álvarez-Morales 2014) discusses the Cathedral of Malaga as the subject of an experimental methodology for cathedral churches. The presented issues particularly refer to spaces of big religious buildings consisting of numerous subspaces, such as a nave, a choir or a retrochoir. Also, as religious buildings are used for concert purposes, too, the publication (Magrini,

Ricciardi 2003) is an interesting work. Chosen churches in Geneva were under investigation. The interiors were examined for their acoustic adaptation for the needs of a concert.

The idea of two-storey church

The idea of the two-storey church consists in designing two interiors to hold Holy Mass within one building. The building has two storeys, with a so-called upper church and a lower church. It is assumed that the upper church is bigger and thus considered the main church, while its lower counterpart often has a size of a major chapel. It is also quite common to see a Catholic church with two interiors for religious purposes with one main hall and an additional chapel where it is possible to hold mass. However, what differentiates a two-storey church from the aforementioned building is architectural solutions and its functional layout. Namely, a two-storey church has two separate and independent entrances, often in two different elevations. This allows the interiors to be used simultaneously, and the flow of people does not disturb the course of Holy Mass. Usually, the front elevation has a door leading to the upper church, while the side or rear wall has a door leading to the lower church. It may happen that both entrances are in the main elevation but the independence of the lower and upper hall remains clear and obvious. Usually, a church with the main hall along with an additional chapel has no independent access to the chapel, that is, it either has one common entrance leading to a vestibule or the chapel can be entered from the main hall. If the chapel happens to have a separate door, it is often a small interior on the same level as the main hall of the church.

Two-storey churches are built for different purposes. One of the reasons was the socio-economical situation in Poland in the late 1970s and early 1980s, when it was difficult to obtain a permission to erect a church. In contrast, there was an urgent need for religious buildings in newly built housing estates. When the project of Visitation of Blessed Virgin Mary Church obtained such a permission, a vast building in the form of a two-storey church was erected as it was widely known that yet another permission for another church would not be feasible. For many years, the church served its purpose to dwellers of a few neighbouring housing estates.

The analyzed churches have single-space interiors. Christ the Redeemer Church has arcades on either side and in the rear, also, Our Lady of Częstochowa Church has a gallery on the side walls and on the rear wall. However, the percentage rate of the arcades and the gallery to the cubature is low in both churches.

Description of the investigations

The acoustic investigations were conducted by means of an omnidirectional sound source, a SVAN 945A Sound Level Meter and the DIRAC programme. The e-sweep signal was generated and *RT*, *Ts*, *C80* and *C50* were measured. The Brüel & Kjær ZE-0948 USB Audio Interface was used. A sound source was located in front of the altar at the height of 1.5 m. Measuring points were evenly distributed in the nave. Depending on the area of a given church, the

number of measuring points oscillated between 6 and 40. The analysis covered parameters which are regarded in literature as one of basic parameters to evaluate acoustic properties of religious interiors. The investigated acoustic parameters were compared with recommendations (Wróblewska, Kulowski, 2007); (Everest, Pohlmann, 2009). The examined churches including cubatures of upper and lower churches are shown and compared in Table 1.

Table 1. Investigated churches (created by the author)



Christ the King church (Figs 1a and 1b)

1a. Upper church – cubature 4600 m³
1b. Lower church – cubature 315 m³



Christ the Redeemer Church (Figs 2a and 2b)

2a. Upper church – cubature 6700 m³
2b. Lower church – cubature 2100 m³



Our Lady of Częstochowa Church (Figs 3a and 3b)

3a. Upper church – cubature 7300 m³
3b. Lower church – cubature 3340 m³



St. Lawrence Church (Figs 4a and 4b)

4a. Upper church – cubature 7500 m³
4b. Lower church – cubature 1340 m³



Visitation of Blessed Virgin Mary Church (Figs 5a and 5b)

5a. Upper church – cubature 19000 m³
5b. Lower church – cubature 4800 m³

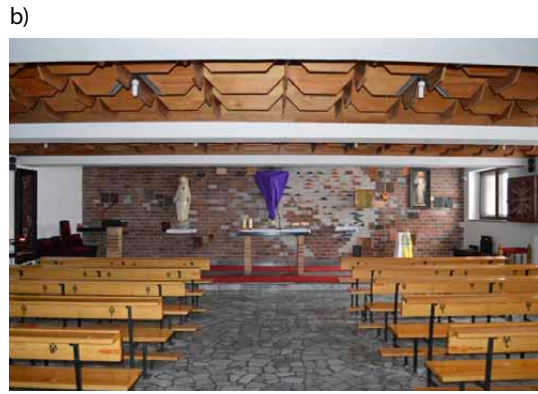


Fig. 1. Christ the King: a – upper church, b – lower church (photo by author)



Fig. 2. Christ the Redeemer Church: a – upper church, b – lower church (photo by author)



Fig. 3. Our Lady of Częstochowa Church: a – upper church, b – lower church (photo by author)



Fig. 4. St. Lawrence Church: a – upper church, b – lower church (photo by author)



Fig. 5. Visitation of Blessed Virgin Mary Church: a – upper church, b – lower church (photo by author)

Results of the investigations

Results of the investigations were compared with recommendations available in literature.

Figure 6 depicts a graph illustrating recommended reverberation time for churches depending on their cubature (Everest, Pohlmann 2009). Dark grey colour represents recommended reverberation time for churches with frequent organ music performances. Light grey colour represents reverberation time for churches where speech is dominant.

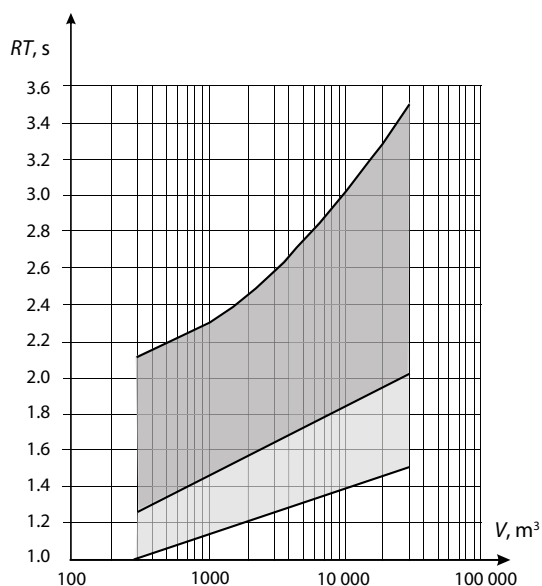


Fig. 6. Range of optimum reverberation time for churches (Everest, Pohlmann 2009)

Table 2 shows the comparison of reverberation time RT and centre time T_s . In addition, reverberation time is shown in a frequency function, separately for upper churches (Fig. 7) and separately for lower churches (Fig. 8).

Lower churches have smaller cubatures, the result of which is that reverberation time meets the recommendations or is slightly exceeded. Church (5b) is an exception as its cubature is equivalent to a middle-size church. For upper churches, reverberation time fits in with the recommended values only in the case of church 2a. It is caused by the shape and construction of the ceiling, which increases sound absorption. Churches (5a) and (4a) are the most problematic as reverberation time and other parameters considerably exceed recommended values. Results of the investigations confirm subjective perception of excessive reverberation in these churches. Their interiors have such high levels of reverberation noise that the reception of Holy Mass is disturbed and speech is unintelligible. In these cases, acoustic treatment would be necessary.

To assess the clarity of music sound, centre time T_s is applied; T_s is the center of gravity along the time axis of the squared impulse response (Barron 2005). The measured parameter T_s reaches the best values in church (2a). The results show that the interior meets requirements for organ music performances. Apart from the favourable values of parameter T_s , the church has a cubature ensuring good organ sound.

Table 2. Comparison of reverberation time and centre time (created by the author)

Name of the church	RT, s			Ts, ms	
	mean	500–1000 Hz	recommended mean	mean	recommended mean
Christ the King church					
1a. Upper church	3.3	3.8	1.3–2.7	248	60–100 organ music to 180
1b. Lower church	1.6	1.6	1.0–2.1	135	60–100 organ music to 180
Christ the Redeemer Church					
2a. Upper church	2.5	2.6	1.3–2.9	175	70–120 organ music to 180
2b. Lower church	2.2	2.5	1.2–2.5	175	60–100 organ music to 180
Our Lady of Częstochowa Church					
3a. Upper church	3.6	4.2	1.3–2.9	255	70–120 organ music to 180
3b. Lower church	2.7	2.9	1.2–2.6	202	60–100 organ music to 180
St. Lawrence Church					
4a. Upper church	5.5	6.2	1.3–2.9	376	70–120 organ music to 180
4b. Lower church	3.3	3.2	1.1–2.3	216	60–100 organ music to 180
Visitation of Blessed Virgin Mary Church					
5a. Upper church	5.9	7.1	1.5–3.3	410	120–180
5b. Lower church	3.8	4.1	1.3–2.7	298	60–100 organ music to 180

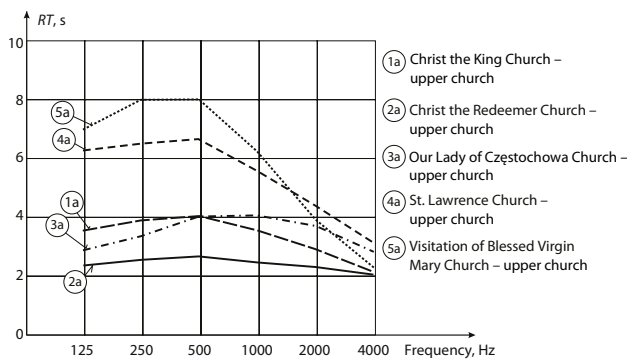


Fig. 7. Frequency characteristics of averaged reverberation time in the upper churches (created by the author)

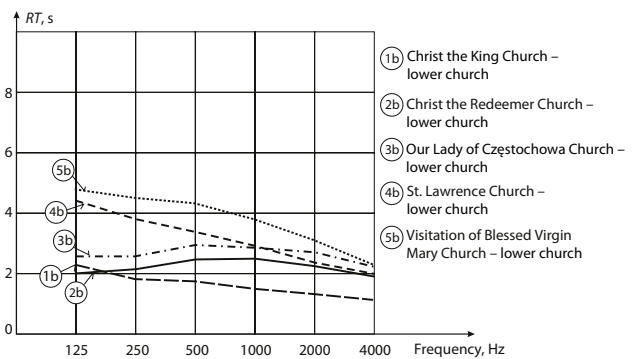


Fig. 8. Frequency characteristics of averaged reverberation time in the lower churches (created by the author)

Table 3 shows results of measurements of clarity index *C80*. This parameter is applied to determine quality of the music sound. In the logarithmic scale, it describes the ratio of the energy of the sound reaching the measuring point within first 80 ms to the energy of the sound reaching it after 80 ms (Everest, Pohlmann 2009). According to recommendations given in literature (Wróblewska, Kulowski 2007), *C80* was averaged for 0.5, 1, 2 kHz.

Apart from church (4a), the value of clarity index *C80* is suitable for organ music in upper churches. As for lower churches with a smaller cubature, it is assumed that the electronic organ will be used. For this type of instrument, the value of the index *C80* is exceeded in comparison with the recommendations. The case of church (5b) is particularly problematic as the values of the index *C80* considerably exceed

Table 3. Comparison of clarity index *C80* (created by the author)

Name of the church	<i>C80</i> , dB				general recommendations
	first row	recommended	last row	recommended	
Christ the King church					
1a. Upper church	-2.0 -4.8 -6.2	>0	-5.3 -6.0 -5.3	>2	symphonic and oratorio music -3 to 6 organ music < -3
1b. Lower church	-0.7 0.3	3 to 8	-1.7 -1.6	-	> 6 electronic organ
Christ the Redeemer Church					
2a. Upper church	-0.4 -0.5 -2.6 -3.3	>0	-4.1 -2.5 -3.5 -4.7	>2	symphonic and oratorio music -3 to 6
2b. Lower church	-2.2 -2.4	3 to 8	-5.1 -6.1	-	> 6 electronic organ
Our Lady of Częstochowa Church					
3a. Upper church	-1.4 -1.3	>0	-6.5 -5.8 -6.6 -7.7	>2	symphonic and oratorio music -3 to 6
3b. Lower church	-0.6 -1.2	3 to 8	-5.7 -6.1	-	> 6 electronic organ
St. Lawrence Church					
4a. Upper church	-2.5 -4.4 -5.5 -6.3	>0	-6.4 -7.5 -8.2 -8.3	>2	symphonic and oratorio music -3 to 6
4b. Lower church	-0.36 -0.68 -0.65	3 to 8	-3.1 -2.8 -2.3 -3.2	-	> 6 electronic organ
Visitation of Blessed Virgin Mary Church					
5a. Upper church	-2.6 -4.5 -8.2	>0	-5.9 -7.3 -8	-1 to 1	organ music -8 to -3 oratorio music -3 to 6
5b. Lower church	-1.8 -2.3 -3.3	>0	-17.3 -18.6 -17.9	>2	symphonic and oratorio music -3 to 6

recommended values in the rear pews. It is caused by the shape of the interior, because the height abruptly decreases in the rear pews.

Table 4 presents results of measurements of clarity index *C50*. By analogy, the index is defined like *C80*. The measurements allow to calculate the weighted value of clarity index *C50*. Octave bands 0.5, 1, 2, 4 kHz are multiplied by the weighting factor equal to 0.15, 0.25, 0.35 and 0.25 for each band respectively; thus obtained results are added. The index *C50*, like index *C80*, is particularly unfavorable in church (5b). The values which considerably vary from the recommendations occur in the rear pews.

Conclusions

In the analyzed buildings, contemporary construction solutions were applied. Load bearing elements of the ceiling and roof construction were made either of monolithic reinforced concrete or by means of steel trusses. Such solutions enable covering of considerable spans without application of intermediate supports. This has a large influence on the acoustics of the interior as the lack of subspaces affects excessive reverberation.

In the case of single-interior churches, with big curvatures (about 5000 m³ and more) and finished with

Table 4. Comparison of clarity index *C50* (created by the author)

Name of the church	<i>C50</i> , dB		
	mean	range of variation	recommended
Christ the King church			
1a. Upper church	-7.9	-2.9 to -12	> -2
1b. Lower church	-3.7	-2.7 to -5.5	> -2
Christ the Redeemer Church			
2a. Upper church	-5	-2.6 to -6.9	> -2
2b. Lower church	-5.6	-4.2 to -8.1	> -2
Our Lady of Częstochowa Church			
3a. Upper church	-7.1	-2.4 to -11	> -2
3b. Lower church	-5.8	-2.3 to -7.9	> -2
St. Lawrence Church			
4a. Upper church	-7.86	-2.8 to -9.8	> -2
4b. Lower church	-3.4	-1.3 to -4.6	> -2
Visitation of Blessed Virgin Mary Church			
5a. Upper church	-8.6	-2 to -13	> -2
5b. Lower church	-15.4	-3.8 to -41	> -2

materials with a low absorption coefficient, too long reverberation time can be expected and, in result, unfavourable acoustic conditions may occur. In the examined churches, the finishes are typical of contemporary religious architecture, i.e. smooth walls covered in lime-cement plaster or clinker bricks, along with numerous glazing windows.

In the majority of cases, the examined lower churches have the recommended reverberation time despite application of sound reflective finishes. The interiors have fairly small cubature, so omission of the acoustic aspect does not cause major problems.

The investigations showed that upper churches i.e. St. Lawrence Church (4a) and Visitation of Blessed Virgin Mary Church (5a) are particularly problematic. The shape of the church (4a) is a regular octagon. The floor is covered with marble, which is a solid material and the absorption coefficient is close to zero. Most of the interior is made of reinforced concrete, which has low acoustic absorption properties. In the wall behind the altar there is a vast stained glass window. The remaining walls have glazings in the form of narrow strips. The reinforced concrete coffered ceiling is massive and solid. Both the walls and the ceiling are textured, which promotes sound diffusion in the interior. However, the applied materials and the vast space result in considerably exceeded reverberation time amounting to about 6 s, while the recommended value should not exceed 3 s. Our Lady of Częstochowa Church (3a) is similar to the church (4a) in terms of the

cubature, but it has far better acoustic properties, which is the result of substantially bigger spatial variation. The interior is rectangular, with subspaces in the form of galleries on the side walls and the rear wall. In addition, the range of the applied material is wider: there are carton-gypsum boards constituting the ceiling, which is fixed to the load-bearing structure of the roof. Also, wooden panelling was applied; it was fixed to the side parts of the ceiling and on a few parts of the side walls. Reverberation time in the church amounts to about 4 s.

The church (5a) is considerably bigger from the other churches. The roof has a steel load-bearing structure. The surface of the ceiling is finished with gypsum lime plaster. The ceiling is concave; its area exceeds the area of the plan view of the church. The walls are made of brick. Brick pilasters are evenly distributed on the wall of the presbytery and the side walls. There are glazings inside, especially on the rear wall. The applied pilasters and zigzag shape of the ceiling affect sound diffusion in the interior. In terms of its cubature, the church belongs to the category of the biggest churches (Wróblewska, Kulowski 2007). Such churches often have a high-class organ, and their interiors are often used for concerts. Currently, the discussed church does not have a concert organ. The reverberation time is big and amounts to about 7 s.

When designing a church with a big cubature, it is necessary to design the interior with acoustic requirements in mind. Otherwise, the interior will not properly serve its liturgical purpose, i.e. speech. Besides, reverbe-

ration noise occurring in such interiors creates unfavourable acoustic atmosphere. Correction of acoustic defects after the erection of the church causes problems and it is difficult to realize because of high costs.

When erecting a new big church, it is advisable to opt for a two-storey one. The upper church is then designed to hold liturgy on Sundays and holidays when a high number of participants is expected. The lower church is used to hold Holy Mass on weekdays with a small number of participants. In addition, with the climate in this part of Europe in mind, maintenance costs of a two-storey church in winter are lower.

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