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A Cross-Vault System's Relative Periodisation Based on Geometric Analysis

The Vaulting System of the Apse of the Inner City Parish Church of Budapest

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ORIGINAL RESEARCH ARTICLE

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SUMMARY

The cross-vault system of the Inner City Parish Church of Budapest was the subject of numerous scientific works so far. In our present article, we aimed to supplement the information known about the vaults by providing exact geometric data gathered via laser scanning. Based on this data, we attempted to filter out common characteristics of the individual vaults, regarding the geometry of their ribs, their webs and the positions of their keystones. As a result, we proved that the cross vaults composing the system cannot be hallmarked as the remains of a given building period, and even within a given cross vault, more building periods can appear. Combining the results of the different geometric analyses, we concluded six distinct scenarios concerning the relative periodisation of the elements composing the cross-vault system, complemented by the evaluation of these. Thus, in the present article, we give an example of how to use point cloud-based building survey techniques to approach the questions of a given building's relative periodisations.

KEYWORDS

Inner City Parish Church of Budapest, ambulatory apse, cross-vault system, relative periodisation, geometric analysis, point cloud analysis, building scanning, laser scanning, Bauforschung

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1. INTRODUCTION

The apsis vault of the Inner City Parish Church of Budapest was the subject of numerous scientific works so far, however, based on those, the periodisation of the cross vault system of this ambulatory apse is still not unambiguous *(Figs 1–2)*. Thus, in the present article, we attempted to use laser scanning to provide as exact geometric data about the building as possible. Based on the data gathered, our aim was to filter out common characteristics in the different cross vaults, thus broadening the set of information already known about the vault system in question. This new geometric information gave the basis for our claims regarding the relative periodisation detailed in our paper.

Figure 1. Detail of the cross-vault system in the apse of the Inner City Parish Church of Budapest (Photo: the Authors)

1.1. The history of the apse's vaults

The Inner City Parish Church of Budapest has a long and rich history. Its three-nave apse with ambulatory covered by ribbed cross vaults is the remainder of the first Gothic building period: it was claimed to be from the 15th century,[1] however, according to the latest research, it most

[1] Némethy 1890. 46; Schoen 1943. 5.

Figure 2. The polygonal vault above the main altar (Photo: the Authors)

likely originated from the middle of the 14th century.[2] Even though during the second Gothic period several alterations were carried out around the apse (the rebuilding of the northern chapel, the building of the sacristy, the alteration of the nave, the building of the anterooms of the southern and northern gates), the main structure of the apse was not modified at that time.[3]

After the Ottoman occupation, when the church was used as a mosque, reconstruction works were needed. Even though the nave was more seriously injured than the apse, according to the sources, the "vault of the apse" was also rebuilt, although it is not clear, how many of the original vaults were destroyed. Most researchers claim that most likely only the polygonal vault above the altar was the subject of these works,[4] however, László Gerő[5] did not narrow the "apse

2 Horogszegi 2010. 374; Kovács 2016. 49–50.

3 Némethy 1890. 59; Schoen 1943. 5; Gerő 1956. 14; Feuerné 1958. 370; Papp 2005. 59–60; Horogszegi 2010. 374–375.

4 Lux 1933. 16; Schoen 1943. 6; Horogszegi 2010. 375; Hegedűs 2016. 57.

5 Gerő 1956. 24.

vault" to only the polygonal bay. (On the other hand, it is not fully inconceivable that Gerő meant the polygonal vault under the expression "the vault of the apse", since that is the main part of the Gothic apse with ambulatory.) These works were carried out in 1699,[6] although Gerő, after mentioning 1699 as the year of the works,[7] suggests that the year 1725 is more likely as the rebuilding time of the apse's vault.[8]

Nonetheless, other sources also mention a building period of the church in 1725, carried out by György Paur, even though according to the older sources, works on the apse or its vaults were not the subject of these,[9] however, Hegedűs[10] cites the work of Schoen from 1943 as the source about the re-vaulting of the apse. The reason why Gerő[11] thought plausible the year 1725 as the reconstruction year of the apse vault, is the person of the master, György Paur, whose work on other buildings was also of such a poor quality that in a short time, repairing was needed.[12] Gerő claimed that in the case of the church these untimely repairs were the construction works of 1775, led by Mátyás Nöpauer (Nepauer).[13] These works are mentioned in several sources, however, on their subject, the sources do not give exact information. Some write about repairs on the pillars, walls and vaults of the apse,[14] while others about the re-vaulting of it.[15]

The next significant works on the apse's vaults would have been to rebuild them "in Gothic style" by Imre Steindl in 1889–1890. Nonetheless, these parts of the plan eventually were not carried out.[16] However, it is to be noted that Steindl thought the rebuilding of the vaults is needed for presenting the Gothic picture, therefore, he did not think that the cross-vaults that existed in the 19th century were of Gothic origin.

According to several sources, in 1944 the "vaults were perforated",[17] and the main altar was hit by a bomb,[18] however, the extent of the damages is not detailed in either of them. The repair works were carried out in 1963 by László Borsos.[19] The reinforced concrete trusses visible in the attic were added at that time too.[20]

In conclusion, it is not unambiguous to which period the cross vaults of the apse of the Inner City Parish Church can be dated back. Some researchers claim that the cross vaults (with the exception of the polygonal one) are all from the 15th century,[21] however, as we detailed above,

6 Lux 1933. 16; Schoen 1943. 6; Gerő 1956. 24; Horogszegi 2010. 375; Hegedűs 2016. 57.
7 Gerő 1956. 24.
8 Gerő 1956. 29. As he mentioned the donation of György Széchenyi from the year 1689 as the resource for the construction works in both cases, he must talk about the same building period of the apse, since György Széchenyi deceased in 1695, therefore a new donation by him in the 18th century is inconceivable.
9 Némethy 1890. 268–278; Lux 1933. 17–19; Schoen 1943. 7–8.
10 Hegedűs 2016. 58.
11 Gerő 1956. 29.
12 Gerő 1956. 29.
13 Gerő 1956. 29.
14 Schoen 1943. 8; Horogszegi 2010. 376.
15 Beke 2013. 514; Hegedűs 2016. 58 (It is to be noted that both of these authors cite at this point Gerő [1956. 30], however, on the cited page, Gerő only writes about the polygonal vault of the apse, not about the whole vault-system.)
16 Horogszegi 2010. 376; Horogszegi 2016. 60–61.
17 Gerő 1956. 35; Horogszegi 2010. 377.
18 Beke 2013. 517.
19 Beke 2013. 517.
20 Horogszegi 2016. 62.
21 Lux 1933. 7; Szőke 2010. 384.

others doubt this straightforward dating. Therefore, we find it very necessary to examine the question on a new basis, by analysing and comparing the vault's exact geometry, thus making an attempt to add a new perspective for further scientific debate.

2. METHODOLOGY

Regarding the cross vault system of the apse of the Inner City Parish Church, we aimed to compare the exact geometry of the individual cross vaults, based on the laser-scanned point cloud of the church and attempted to conclude the relative periodisation of the system. To achieve this, we scanned the building with a Leica BLK 360 laser scanner.[22] Afterwards, the data collected was assembled in Leica Cyclone Register 360 software and analysed in AutoCAD *(Fig. 3)*.

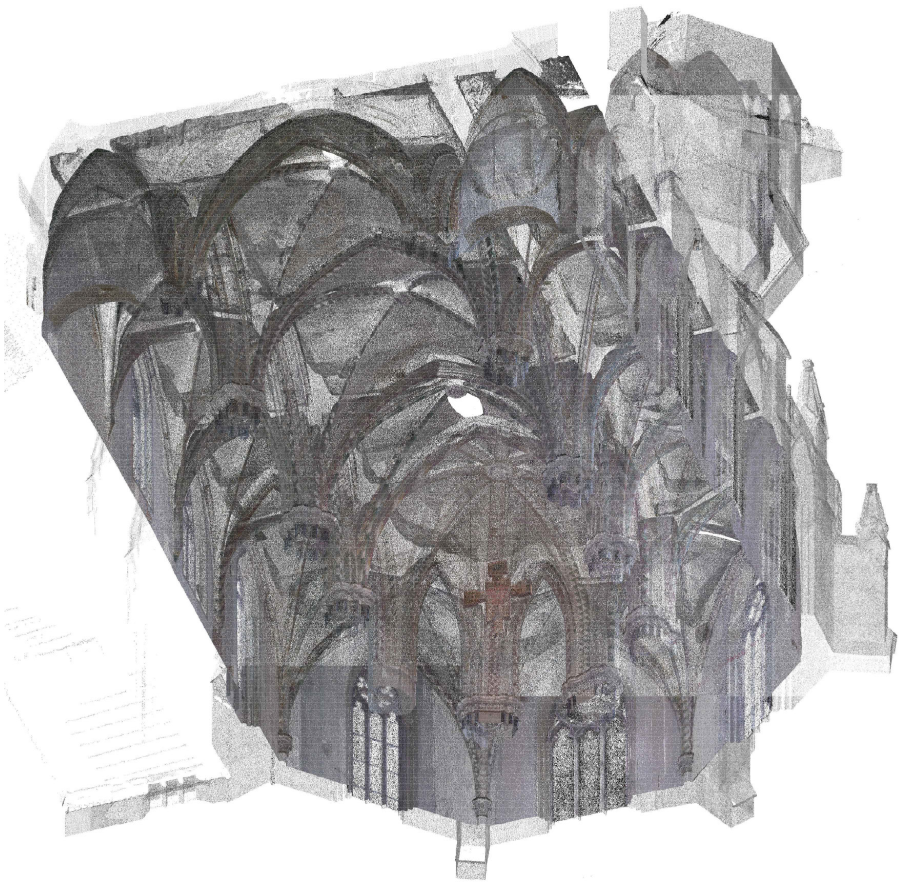

Figure 3. Picture of the point cloud

[22] Using point cloud-based survey methods for analysing vaults was carried out (with different focus than in our present research) by Olaf Huth (2020), Fuentes and Huerta (2016. 591) or Gonzalo and Talaverano (2012).

Our geometric examinations concerned three main areas. Firstly, we analysed the individual ribs of each vault, based on their curvature, chord length and arch height.[23] Then, the spatial positions of the keystones of the wall arches and transversal arches, as well as the vaults were studied in relation to each other. Finally, we compared the thickness of the cross vault's webs.

Based on these three examinations, each cross vault was associated with certain characteristics, which let us reconstruct plausible scenarios regarding the relative periodisation of the vault system.

3. ANALYSIS OF THE VAULT SYSTEM

3.1. Analysis of the individual ribs

The results of our measurements are presented in *Table 1*. For easier understanding, a Roman numeral was assigned to each cross vault of the system, and the ribs in a given vault were numbered with Arabic numerals from 1 to 4, as presented in *Fig. 4*.

Table 1. Individual rib data. The vaults represented next to each other are each other's mirror pictures on the plan to the longitudinal axis. The coloured cells show the values corresponding to each other within a group (groups stated in the text)

Sign of the rib	Radius of the curvature [m]	Arch height [m]	Chord length [m]	**Sign of the rib**	Radius of the curvature [m]	Arch height [m]	Chord length [m]
II.1.	5.73	0.86	5.76				
II.2.	5.69	0.87	5.73				
II.3.	5.45 5.11	0.98	5.82				
II.4.	5.37	0.80	5.79				
average		0.88	5.78				
dispersion		0.07	0.04				
III.1.	5.14	1.09	6.00				
III.2.	5.02	1.13	5.98				
III.3.	4.62	1.20	6.06				
III.4.	5.15	1.08	6.05				
average	4.98	1.13	6.02				
dispersion	0.25	0.05	0.04				

23 Similar analyses were carried out previously on net and stellar vaults with results proving that the measurements are precise enough to lead to conclusions: Jobbik–Krähling 2022a; Jobbik–Krähling 2022b; Jobbik–Krähling 2023.

Table 1. cont.

Sign of the rib	Radius of the curvature [m]	Arch height [m]	Chord length [m]	Sign of the rib	Radius of the curvature [m]	Arch height [m]	Chord length [m]
IV.1.	5.72	1.05	6.10				
IV.2.	5.49	1.05	6.10				
IV.3.	5.47	1.06	6.11				
IV.4.	5.34	1.15	6.07				
average	5.51	1.08	6.10				
dispersion	0.16	0.05	0.02				
V.1.	5.33 7.91	0.99	5.42	**XV.1.**	5.52	0.81	5.18
V.2.	6.22	0.75	5.27	**XV.2.**	6.16	0.84	5.19
V.3.	6.55	0.52	5.31	**XV.3.**	6.04	0.79	5.16
V.4.	6.72	0.58	5.15	**XV.4.**	6.30	0.74	5.22
average	6.50	0.71	5.29	**average**	6.01	0.80	5.19
dispersion	0.25	0.21	0.11	**dispersion**	0.34	0.04	0.02
VI.1.	5.65	0.78	4,92	**XIV.1.**	7.36	0.72	5.45
VI.2.	5.99	0.65	5,44	**XIV.2.**	5.74	0.80	5.11
VI.3.	6.08	0.60	5,27	**XIV.3.**	5.40	0.78	5.34
VI.4.	6.30	0.68	5,36	**XIV.4.**	5.83	0.81	5.30
average	6.01	0.68	5,25	**average**	6.08	0.78	5.30
dispersion	0.27	0.08	0,23	**dispersion**	0.87	0.04	0.14
VII.1.	5.48	0.46	4.12	**XIII.1.**	5.53	0.41	4.15
VII.2.	5.64	0.43	4.43	**XIII.2.**	5.51	0.43	4.20
VII.3.	5.04	0.54	4.12	**XIII.3.**	4.00	0.52	4.14
VII.4.	6.32	0.44	4.42	**XIII.4.**	4.42	0.46	4.12
average	5.62	0.47	4.27	**average**	4.87	0.45	4.15
dispersion	0.53	0.05	0.18	**dispersion**	0.78	0.05	0.04
VIII.1.	5.08	0.75	4.48	**XII.1.**	6.46	0.58	4.19
VIII.2.	4.46 5.79	1.02	4.59	**XII.2.**	4.19	1.14	4.85

Table 1. cont.

Sign of the rib	Radius of the curvature [m]	Arch height [m]	Chord length [m]	**Sign of the rib**	Radius of the curvature [m]	Arch height [m]	Chord length [m]
VIII.3.	4.14 3.76	0.76	4.86	**XII.3.**	4.38	0.95	4.60
VIII.4.	7.48	0.30	4.21	**XII.4.**	4.71	0.81	4.52
average	6.28	0.71	4.54	**average**	4.94	0.87	4.54
dispersion	1.70	0.30	0.27	**dispersion**	1.04	0.24	0.27
IX.1.	3.98	0.43	4.18	**XI.1.**	6.13	0.67	4.18
IX.2.	5.10	0.82	5.43	**XI.2.**	6.07	0.75	5.41
IX.3.	4.68	0.99	5.38	**XI.3.**	5.28	0.99	5.49
IX.4.	4.78	0.42	3.81	**XI.4.**	4.98	1.06	4.02
average	4.64	0.67	4.70	**average**	5.62	0.87	4.78
dispersion	0.47	0.29	0.83	**dispersion**	0.57	0.19	0.78
X.1.	6.30	0.74	3.93				
X.2.	4.45	0.78	4.16				
X.3.	3.74	1.10	5.38				
X.4.	4.30	1.13	5.47				
average	4.70	0.94	4.74				
dispersion	1.11	0.21	0.80				

Regarding the geometry of the individual ribs of the vault system, first, we measured the curvature's radius of each rib. According to the sources, in the case of the ribbed cross vaults (likewise the "Prinzipalbogen" theory in the case of the net vaults), a plausible solution would be to construct every rib with the same curvature,[24] to accelerate the building process.[25] In the case of cross vaults with pointed arches, after the 12th century,[26] a widespread practice could be to use two or three different arches within the run of one rib.[27] However, the values measured in the case of the vault system in the apse of the Inner City Parish Church of Budapest showed a great dispersion, even within one vault, and although not unprecedented, the use of several different arches within one rib was not a commonly used technique in this case.[28]

24 Ungewitter 1901. 27.
25 Renn et al. 2014. 71; Vidal 2017. 1007.
26 Ungewitter 1901. 28.
27 Willis 1842. 15–16.
28 Based on the research of Vidal (2017. 1009), it is proven that even though displacements and settlings occur after the building of a vault, despite these deformations, the curvature of the ribs usually remains appointable.

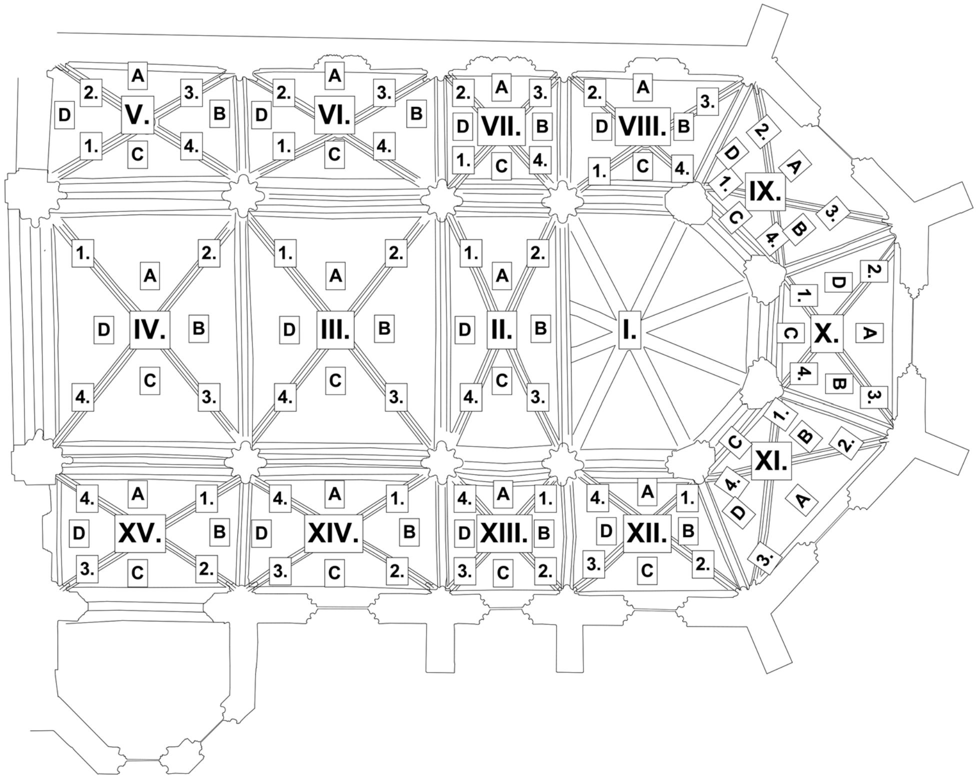

Figure 4. Legend. The Roman numerals refer to the individual cross-vaults, the Arabic numerals refer to the individual ribs and the capital letters refer to the individual webs

As for the chord length,[29] our measurements showed a more systematic result. (While contemplating the results, it must not be forgotten that in the case of the trapezoid cross vaults, any degree of uniformity can only be expected between the corresponding ribs of the vaults of the same plan.) As the values presented in *Table 1* show, two different types of logic can be differentiated regarding the chord lengths. As regards the vaults of rectangular plan, regarding vaults II, III, IV, XIII and XV, the chord lengths of the four ribs are virtually the same (with 2–4 cm dispersions), while in vaults V, VI and XIV we detected another idea. Although the chord lengths in vaults V, VI and XIV have a significantly bigger dispersion than in the previous case, we found that the very same four chord length values appear in the case of all three vaults. We deduced, that this potentially signifies the use of the same (or coinciding) temporary supporting structure during the construction works.

In the case of the vaults above of different trapezoid plans, we found that vaults IX, X and XI, which have approximately coincident plans, also have ribs of the same relation to each other as

[29] Within this article we defined the chord length of a rib as the straight line connecting the lowest point where the rib deviates from the vertical direction and the point where the rib connects to the keystone.

the ribs of vaults V, VI and XIV to one another. The same connection was found in vaults VIII and XII, which are also vaults of the same plan.

In the case of vault VII, the chord lengths of the two-two ribs of the same diagonal are the same, but these values on the two diagonals significantly differ from each other, although the plan of the cross vault is a square. Thus, in the case of this vault, only the second idea is feasible, however, since the only other vault of the same plan (vault XIII) belongs to the first group, we cannot without a doubt accept it as the example of the second group.

To conclude the question of the ribs' chord lengths, we want to highlight that although all the vaults of a trapezoid plan belong to one group, the differentiation cannot be concluded from the shape of the cross vaults' plan since both distinguished groups have examples of the same rectangular plan. It is also to be noted that regarding the second group, even in the case of the trapezoid vaults, where the ribs' length on the plan view can clearly be grouped into two long and two shorter ribs, the chord length values do not belong to one or the other, they are mixed between the two kinds, and the difference in the length on the plan is masked by starting the rib from a lower point. To summarise, we represented the two groups on the plan of the vault system *(Fig. 5)*.

The last examination regarding the individual ribs was that of their arch height. We found that in the case of those vaults where the ribs' chord length is of the same value, that is the first

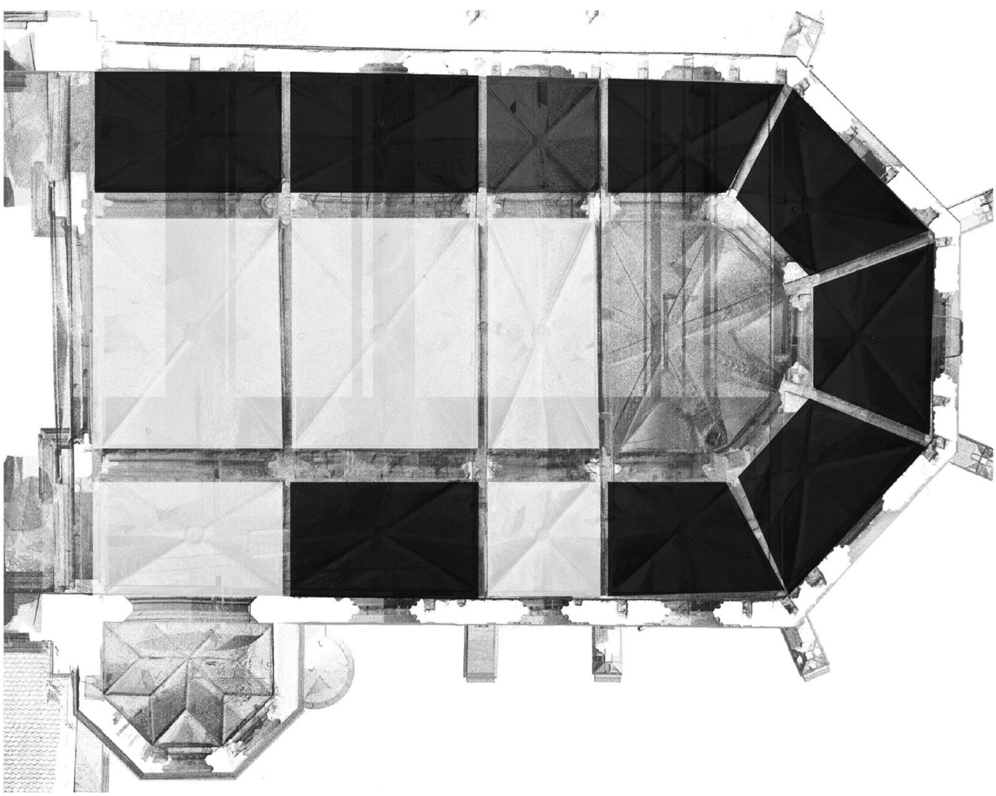

Figure 5. The distribution of the two rib-construction logic within the vault system

Figure 6. The remains of the wall arches above the present polygonal vault (Photo: the Authors)

group described, the values of the arch height also show a low dispersion, whereas, in the case of the other vaults, the dispersion is significant. Thus, this dataset supports our theory about the differentiation of the above-detailed two groups.

3.2. Analysis of the spatial positions of the keystones

The basis of the analysis of the spatial positions of the vault system's keystones is the structural remains of the wall arches above the present vault, formerly observed, and dated to the Gothic period by numerous researchers *(Fig. 6)*.[30] However, by using space scanning, we are able to very accurately compare the remains' positions to the wall arches, transversal arches and keystones of the present vault system of the apse *(Fig. 7)*. (At this point we must accentuate that in the case of this vault system, uneven sinking is not likely since the ribs do not show any sign of congestion to each other or diverging from each other, thus the examined points' relative positions to each other are likely their original positions.) The analysis is highly relevant since when constructing pointed-arched cross vaults, the keystone's height position has a crucial importance.[31]

30 Lux 1933. 7; Gerő 1956. 29; Szőke 2010. 384.
31 Gonzalo–Talaverano 2013. 190.

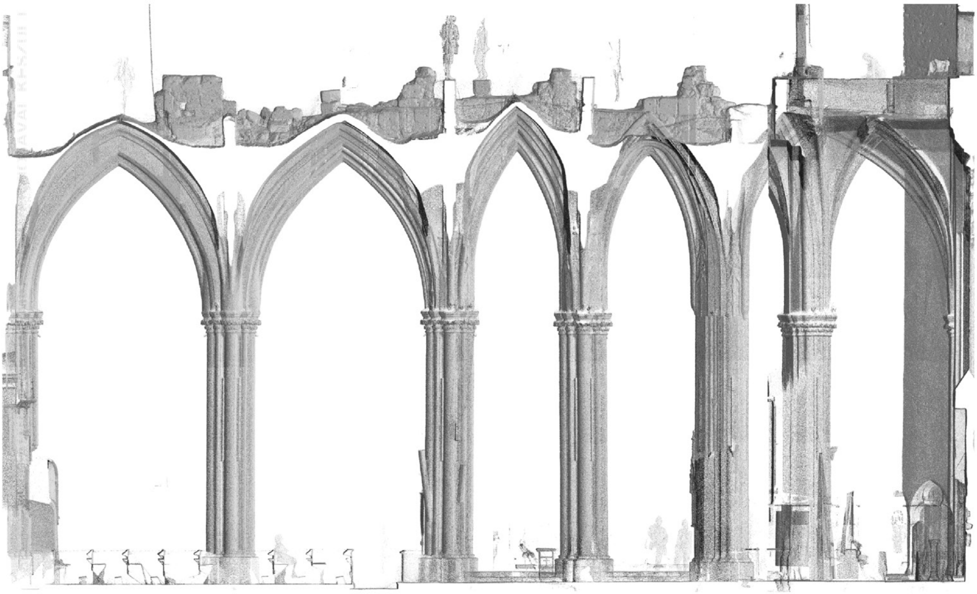

Figure 7. The longitudinal section of the point cloud

While contemplating the results of this examination, we must be aware that even if a certain keystone in the system is at the same height as the ones accepted to be of Gothic origin, it does not necessarily mean that the given vault or rib-arch is also originated from the Medieval building periods since conforming to the remaining parts of a damaged building is a very plausible scenario.

For presenting our results, we assigned capital letters X, Y, Z, A and B to each possible height position for the examined keystones. Regarding the result of this analysis, first, we must state that one of these arches is positioned lower (B) than the other three (X) – it proves that even the original structure's heights were not uniform *(Fig. 8).* The height positions in question are presented in *Fig. 9*.

To conclude this analysis, we found that the results of this examination do not correspond unequivocally to the analysis of the individual ribs. According to our measurements, no two corresponding vaults of the same plan ratios have every keystone at the same position. Therefore, we claim that considering that even the remains of the gothic wall arches show irregular deviations from each other and that (especially in the case of cross vaults of trapezoid plan) the uniform height of the bordering arches and the crown point of the vault is not at all essential,[32] based on this analysis, the "originality" of given arches or vaults cannot be stated for sure.

32 Ungewitter 1901. 17.

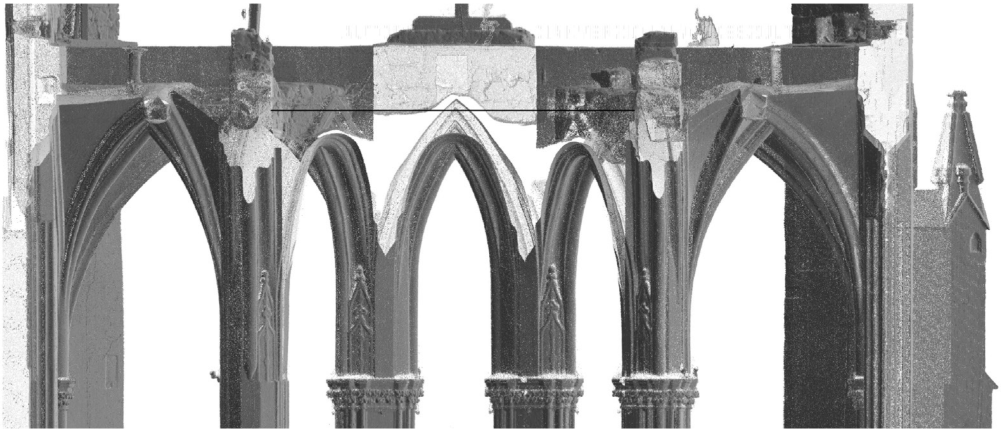

Figure 8. The cross-section of the point cloud through the polygonal vault.
The black line signs the apex point of the wall arch, which is of a different height than the others
(out of the wall arches above the polygonal vault)

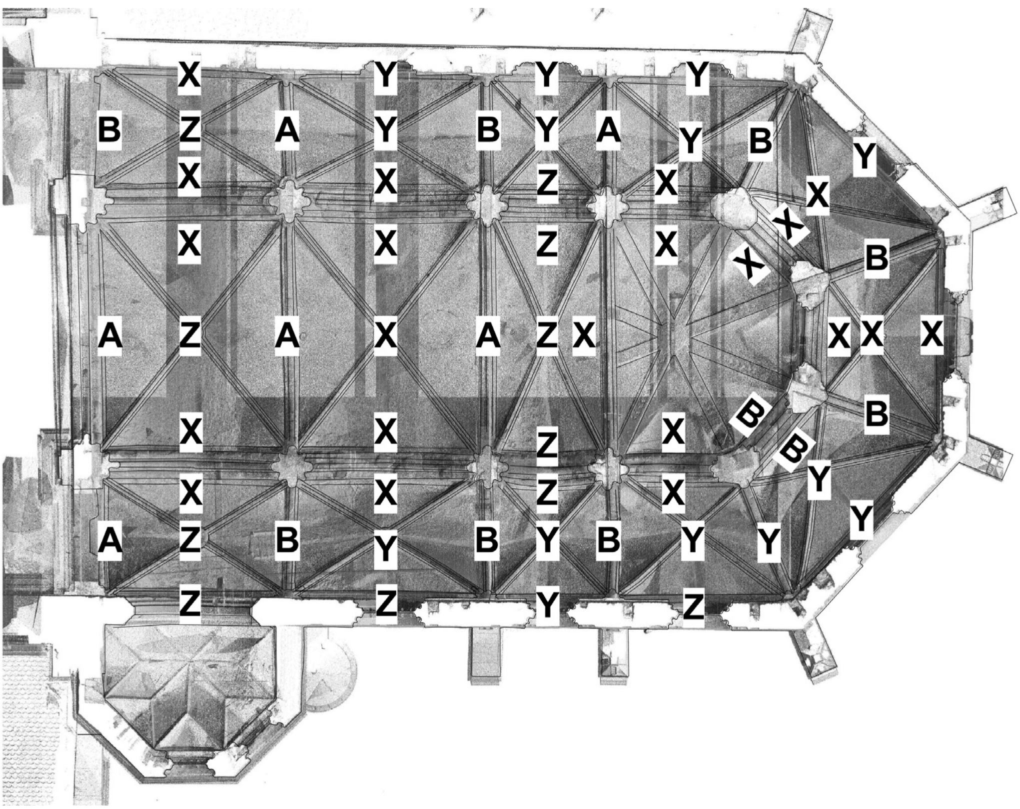

Figure 9. The distribution of the different keystone heights represented on the plan of the vault system

3.3. Analysis of the thickness of the webs

Our last analysis was measuring the thickness of each individual web in the vault system. The measured values are presented in *Table 2.* The "Sign of the web" data in the table corresponds to the Roman numerals of the vaults, and the letters A to D assigned to the four webs in each vault, as presented in *Fig. 4.*

Based on our measurements, three different thickness groups were found. Vaults X, XI, and XIII have only webs of the thinnest group, whereas vaults III and IX consist of only the thickest group of webs. In the case of the remaining vaults (II, IV, V, VI, VII, VIII, XII, XIV and XV) the different groups appear to be mixed *(Fig. 10).*

To contemplate the results, we must be aware that in the case of ribbed vaults, the ribs can be stable without the webs (for a period of time), since masonry structures have multiple equilibri-

Table 2. The measured thickness of the webs.
The colours refer to the groups of the values (defined in the text)

Sign of the web	Thickness of the web [cm]
II.A	22
II.B	14.2
II.C	20.5
II.D	21
III.A	20,8
III.B	21.1
III.C	20.5
III.D	20.8
IV.A	15.4
IV.B	21.1
IV.C	20.5
IV.D	19
V.A	21.8
V.B	15.9
V.C	17.1
V.D	17.9
VI.A	23.5
VI.B	21.2
VI.C	16.1
VI.D	17.5
VII.A	19.3

Sign of the web	Thickness of the web [cm]
VII.B	18.5
VII.C	19.2
VII.D	16.8
VIII.A	22.5
VIII.B	20.1
VIII.C	18.8
VIII.D	18
IX.A	19.1
IX.B	21.5
IX.C	20.8
IX.D	21
X.A	14.2
X.B	12.2
X.C	11.9
X.D	14.4
XI.A	11.5
XI.B	12
XI.C	13
XI.D	12
XII.A	13.8
XII.B	16

Sign of the web	Thickness of the web [cm]
XII.C	17.6
XII.D	16.4
XIII.A	14.2
XIII.B	14.2
XIII.C	14.8
XIII.D	12.7
XIV.A	18.7
XIV.B	17.6
XIV.C	20.2
XIV.D	18.5
XV.A	19.2
XV.B	16.2
XV.C	15.8
XV.D	15.1
average	20.73
deviation	1.13
average	17.16
deviation	1.11
average	13.475
deviation	1.27

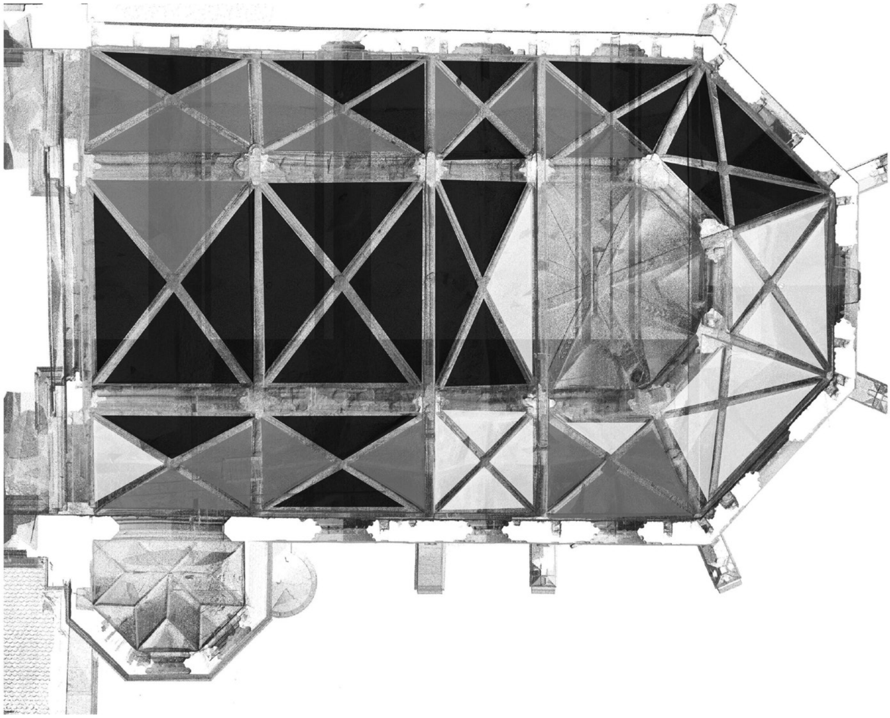

Figure 10. The distribution of the different web thicknesses represented on the plan of the vault system

um states,[33] meaning a dynamic equilibrium held by the ribs and webbing of a ribbed vault, which is capable of rearranging if the circumstances change.[34] Therefore it is acceptable that in certain cases only certain webs were rebuilt in a given vault due to partial destruction.

To conclude this part, we found that the results do not correspond unequivocally either with the results based on the analysis of individual ribs or with the analysis based on the spatial positions of keystones and imposts.

Regarding the analysis of the webbing, we carried out the mapping of it (meaning we "sliced it up" with horizontal planes). Although the mapping showed the diverse characters of the webs, the reason behind the seemingly different characteristics is rather the difference in the general geometry (the height relations of the keystones) than the building technique itself *(Fig. 11)*.

4. DISCUSSION

As our above-presented examinations clearly show, certain characteristics of the individual vaults can unequivocally be detected, however, the different characteristics based on different kinds of analysis do not fully correspond with each other. We claim that this indicates that the

33 Heyman 1995. 20–22; Huerta 2012. 183.

34 Lengyel–Bagi 2015. 58.

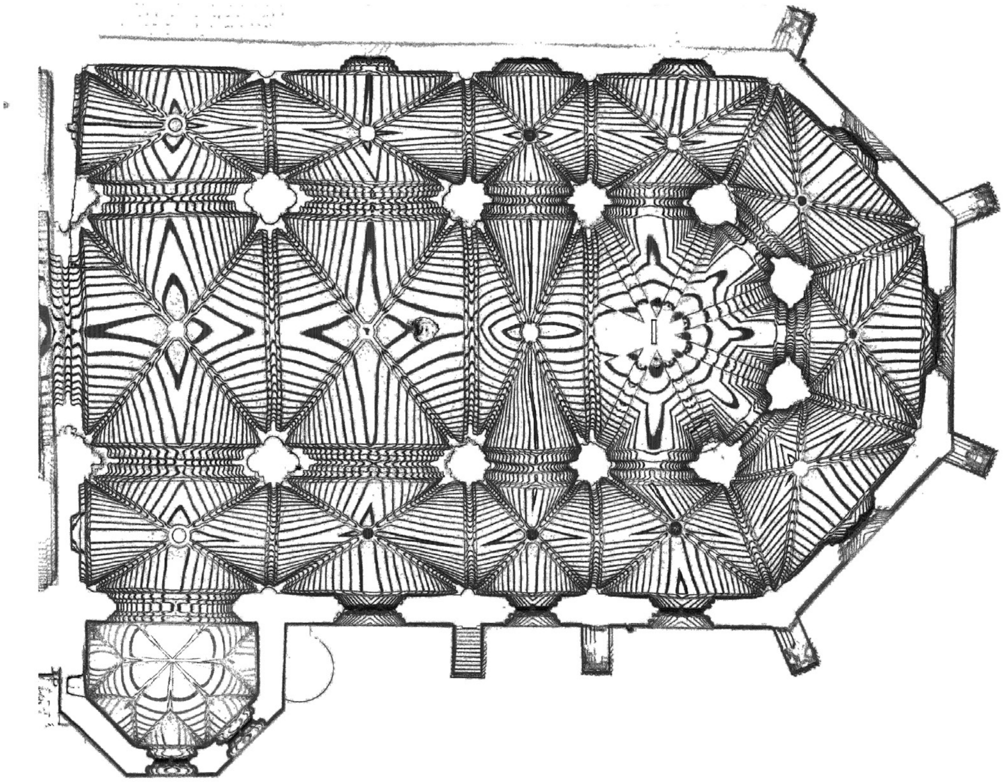

Figure 11. The mapping of the vault system

vault system of the apse of the Inner City Parish Church is not the result of one specific building period, thus the sources claiming the total rebuilding of the vault system at a given time or that all the cross vaults are from a Gothic building period are refuted. However, given the many uncertainties, it does not seem possible to point out a set of characteristics that undoubtedly belong to a given building period (except perhaps the remains of the wall arches above the polygonal vault).

Based on the data we collected, each cross vault can be defined as a combination of the three types of characteristics from the three main analyses. Derived from these, we found that by using logical deductions, several plausible scenarios regarding the relative periodisation of the vault system can be reconstructed.

4.1. Scenario 1

Assuming that the thickest webbings are the most ancient out of the three groups, either vault IX or vault III must have been the earliest remains of the vault system.

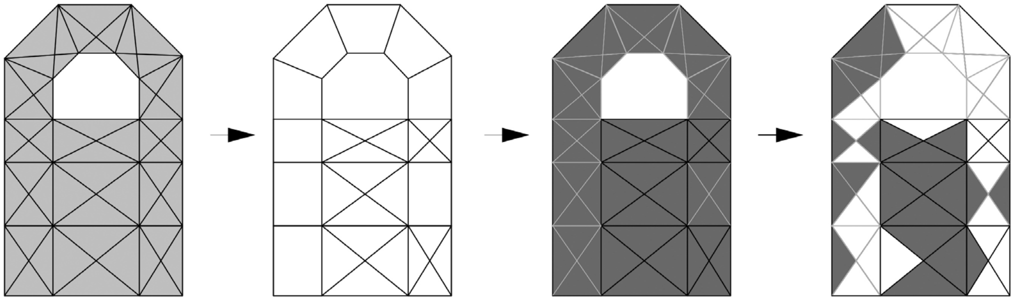

Figure 12. Scenario 1.1.

4.1.1. Scenario 1.1

Presuming the primacy of vault III, the reconstructed scenario starts with a cross-vault system with ribs of uniform chord lengths within each given vault, and webs of an unknown thickness. Afterwards, the vaults get destroyed, with the exception of the ribs of vaults II, III, IV, XIII and XV, the arches found above the polygonal vault[35] (and presumably several wall and transversal arches). Then, the system gets rebuilt in a way that the new ribs have the same chord length in every corresponding vault and the webs have the greatest thickness found in the system. After another destruction, only those webs remained that have the greatest thickness in today's vault system *(Fig. 12)*. Then, the missing webs got substituted with either of the two thinner thicknesses. A last period, when some of the webs are damaged and replaced by the third webbing group, can be assumed.

4.1.2. Scenario 1.2

If we presume the primacy of vault IX, the original system's vaults had ribs, where the ribs within a given vault were not uniform, however, the vaults of the same plan shape had corresponding ribs, and the webs were of an unknown thickness. After a period of destruction, only the ribs of vaults V, VI, VII, VIII, IX, X, XI, XII and XIV (and perchance several wall and transversal arches of other vaults) remained, thus the system was substituted with vaults, where the ribs were of the same length within each vault, and webs of the thickest kind among the today known ones. Then, the webbing was partially destroyed again and was rebuilt with either of the two thinner thicknesses *(Fig. 13)*. Finally, some webs were replaced with the third kind.

4.2. Scenario 2

Assuming that the thinnest webbings are the oldest ones, vaults X and XI, or vault XIII must be the most ancient remains in the system. Even though the logic of the individual ribs, the thick-

[35] Naturally, depending on the time of the destruction, it is possible that the late polygonal vault also survived. Since there is no way to claim either its survival or its destruction at this point, henceforth we do not mention it in this relation.

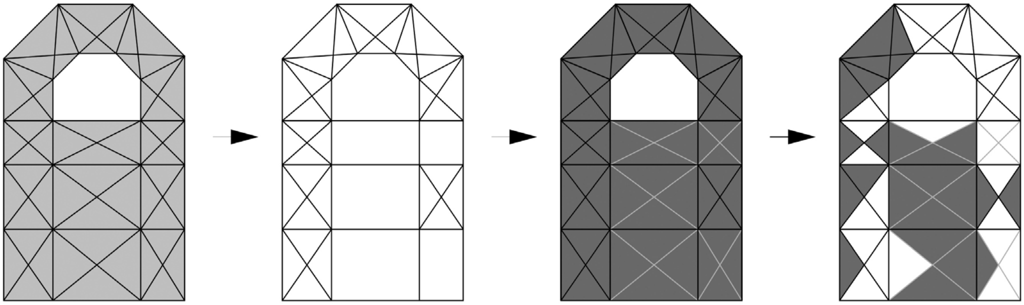

Figure 13. Scenario 1.2.

ness of the webs, and the shape of their plans are uniform in the case of vaults X and XI, their keystones are not in every case positioned likewise. This can be either a conceptual difference in design or a given circumstance.[36]

4.2.1. Scenario 2.1

Presuming the primacy of vault XIII, the primary system was built with vaults, which had ribs of the same length within each vault. When this vault system got partially destructed, only the ribs of vaults II, III, IV, XIII and XV remained (as well as perchance several wall and transversal arches of other vaults). Afterwards, the missing vaults were rebuilt in a way that the vaults of the same plan shape had corresponding rib chord lengths, and every web was of the smallest thickness in today's system *(Fig. 14)*. After the ensuing partial destruction of the webbing, it was rebuilt with either of the thicker kind of webs, and the next partial destruction resulted in the third thickness.

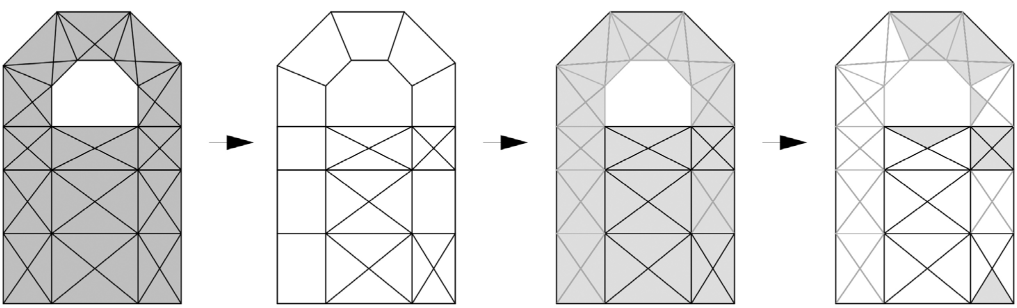

Figure 14. Scenario 2.1.

[36] In theory, a wall arch can be a given circumstance since it is not unimaginable that a vault collapsed, but the adjacent wall remained and later was used for the next vault's construction.

4.2.2. Scenario 2.2

Presuming the primacy of vaults X and XI, the vaults of the scenario's original system had ribs, where the ribs within a given vault were not uniform, however, the vaults of the same plan shape had corresponding rib chord lengths, and the webs were of an unknown thickness. When it got destroyed, only the ribs of vaults V, VI, VII, VIII, IX, X XI, XII and XIV remained (and perchance several wall and transversal arches of other vaults). Then, the missing vaults' ribs got rebuilt with ribs of the same chord length within a vault and the thinnest kind of webs. Then the system's webbing got destroyed again, with the exceptions indicated in *Fig. 15,* and was rebuilt with either of the thicker kind of webs. Following another partial destruction, the third kind of web appeared.

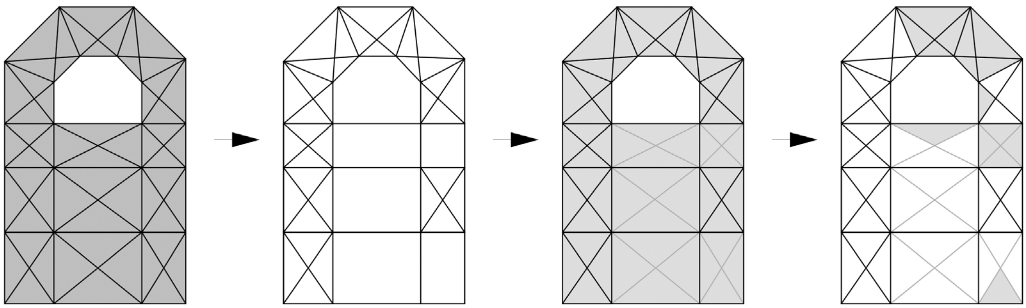

Figure 15. Scenario 2.2.

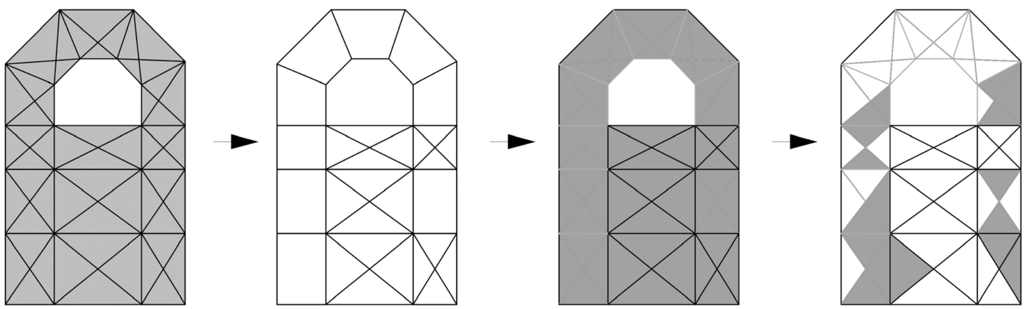

Figure 16. Scenario 3.1.

4.3. Scenario 3

Assuming that the webbings of the middle thickness are the most ancient out of the three groups, we find that there is no vault in the system which is the remainder of less than three building periods.

4.3.1. Scenario 3.1

Presuming that the ribs of vaults II, III, IV, XIII and XV are antecedent to the other one, the reconstructed scenario starts with a cross-vault system with ribs of uniform chord lengths within each given vault, and webs of an unknown thickness. Then, all the webs and the ribs of vaults V, VI, VII, VIII, IX, X, XI, XII and XIV got destroyed. Afterwards, the missing ribs were built with the other rib logic and the new webs were of the middle thickness of today. As for the last two building periods, the webbing got partially destroyed, then rebuilt with either the thickest or the thinnest of the present kinds, and finally, after another partial destruction, the last thickness was installed *(Fig. 16).*

4.3.2. Scenario 3.2

If the ribs of vaults II, III, IV, XIII and XV are posterior to the others, the scenario must start with a system where the vaults of the same plan shape had corresponding rib chord lengths, and the webs were of an unknown thickness. When the webbing and the ribs of vaults II, III, IV, XIII and XV were destroyed, the reconstruction works resulted in the application of the other rib logic and the webs of the present middle thickness. Then the webbing's partial destruction required its rebuilding, with either of the other two web thicknesses. The last step, like in the previous scenario, was the application of the third thickness following a subsequent partial collapse *(Fig. 17).*

Although in these scenarios, the multiple different positions of the different keystones are not addressed, however, it is not unimaginable that their coordination was not utterly precise in the first place. (As we accentuated above, even the wall arches above the present polygonal vault are not of the same height.)

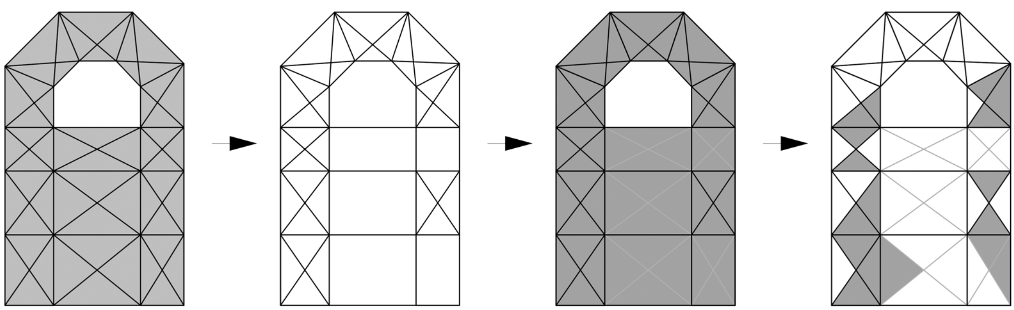

Figure 17. Scenario 3.2.

5. CONCLUSIONS

We consider the primary result of our research that based on the data collected from the laser-scanned point cloud we proved that the cross vault system of the apse of the Inner City Parish Church of Budapest holds the remains of multiple different building periods. Our measurements allowed us to differentiate a set of characteristics indicating these different periods. As the different characteristics based on different elements of the vault system were not clearly coincident in any of the individual vaults, we found that presumably none of the cross vaults represents only one building period, thus on this basis it is not possible to pinpoint any of the characteristics as the remnants of a given building period.

- Even though the wall arches above the polygonal vault could mean a point of reference regarding the Gothic vaults, we must be aware that even among those arches two different heights appear, although their positions do not explain this kind of deviance. Furthermore, even though the wall arches of the outer walls and the transverse arches of the system often adjust to one or the other of these heights, their distribution is not consistent regarding their functions in the whole vault system. It is also not inconceivable that later building periods conform to the remains of the preceding ones.
- Since the most obvious link of the vault system with the Gothic period (namely the wall arches above the polygonal vault) is therefore not enough to give a base for further deductions, neither are the results from individual rib data and web thickness, as their temporal relationship with these arches (or with each other) is not unequivocal.

However, combining the results, which individually did not give enough information to form conclusions, we were able to deduce six different scenarios about the relative periodisation of the cross-vault system.

We believe that the scenarios outlined as a result of the research definitely cast light upon a complex and multi-period construction history, they lay the foundation for further research, which can be refined by applying the complex methodology and tools of building archaeology, historical, natural science and restoration research – destructive and non-destructive methods.

Even though the established scenarios do not explicitly deal with the problem of the different heights of the keystones, they are not to be rejected on that basis, since the inconsistency in the keystones' heights may be explained by the idea that the original design of the system used different construction principles depending on the given cross vault's location in the system (e.g. rectangular plan in the aisles, square plan, right trapezoid plan, isosceles trapezoid plan).

In addition to the primary results, we gave an example of how to use point cloud-based building survey techniques to approach the questions of a given building's relative periodisations.

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Conflict of interest

The 2nd author, János Krähling is a member of the Editorial Board of the journal. Therefore, the submission was handled by a different member of the editorial board, and he did not take part in the review process in any capacity.

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Egy keresztboltozat-rendszer relatív periodizációja

A Budapest-Belvárosi Nagyboldogasszony Főplébánia-templom szentélyboltozat-rendszere

ÖSSZEFOGLALÓ

A Budapest-Belvárosi Nagyboldogasszony Főplébánia-templom már számos tudományos munka tárgyát képezte. E cikk keretein belül célunk a korábbi munkák kiegészítése a szentély boltozatrendszerének lézerszkennerrel felmért pontos geometriai adataival, melyek alapján az egyes keresztboltozatok közös tulajdonságait – a bordák geometriája, a boltsüvegek, és a zárókövek pozíciója tekintetében – feltérképeztük. Ennek eredményeként bebizonyítottuk, hogy a boltozati rendszert alkotó keresztboltozatok nem tarthatók egy adott építési periódus maradványának, sőt az egyes boltozatokon belül is több periódus nyoma tűnik fel. A különféle geometriai vizsgálataink eredményeit összevetve hat eltérő „forgatókönyvet" állítottunk fel a boltozati rendszer elemeinek relatív periodizációjáról, és munkánkat kiegészítettük e lehetőségek értékelésével is. Így az itt bemutatott kutatás a pontfelhő alapú felmérések épületek relatív periodizációjának felállítására való felhasználását is példázza.

KULCSSZAVAK

Budapest-Belvárosi Nagyboldogasszony Főplébánia-templom, szentélykörüljáró, keresztboltozat-rendszer, relatív épületperiodizáció, geometriai elemzés, pontfelhőelemzés, épületszkennelés, lézerszkenner, Bauforschung