

The geometric design of Christoph Dientzenhofer's 'radical' vaults

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Abstract

Christoph Dientzenhofer (1655–1722) is considered one of the most important Baroque master builders of Central Europe. From his extensive architectural *oeuvre*, a group of six church buildings with geometrically complex forms stands out, recognised by architectural historians as particularly innovative and influential. These churches, located in Bohemia (Czech Republic), and often collectively referred to as the 'radical', 'dynamic', 'Guarinesque', or simply 'Bohemian' group, are: St. Joseph in Obořiště (1702–11), the Castle Church in Smiřice (1702–11), St. Nicholas in the Lesser Town of Prague (1703–11), St. Clare in Cheb (1707–11), St. Margaret in Břevnov (1708–16), and the Church of the Holy Assumption in Nová Paka (1709–24). The brick vaults of these six buildings, sequences of oval domes and double-curved vault areas, are of particular interest for building research.

In this study, the geometric design of the vaults of Dientzenhofer's 'radical' churches is documented, analysed, and compared using 3D laser scans of the buildings as primary source. The 3D models generated from the scans enable a geometric analysis through the method of reverse geometric engineering, breaking down the vaults' complex three-dimensional forms into their basic two-dimensional components: segments of circles with different radii and orientations, curved in one or two directions. These forms can be found in the architectural and stereotomic treatises that were widespread at the time. By comparing the vault geometry of the six churches with each other and with the geometric concepts discussed in the treatises, general statements can be made about the architect's design choices. On the basis of this investigation, hypotheses are made about the design and underlying geometric ideas of the vaults of Dientzenhofer's 'radical group', and the results are placed in context.

Christoph Dientzenhofer's 'radical' churches

From the wide field of Baroque sacred architecture in Central Europe, a number of buildings with exceptionally complex designs is noteworthy. Curved walls, vaults seemingly based on intersecting geometrical bodies and a conceptual connection to Italian architects such as Francesco Borromini (1599–1667) and Guarino Guarini (1624–83) are the defining characteristics of this so-called 'dynamic', 'curvilinear', 'Guarinesque' or 'radical' Baroque. Among the most prominent and exemplary representatives of this current of Baroque is a group of six buildings designed and built in Bohemia in the first two decades of the 18th century, the 'radical' group. The radical, innovative nature of the churches becomes particularly clear when one looks up at their vaults. The designs of the vaults combine geometric ideas into complex sequences of intersecting oval domes and double-curved forms.

Thanks to his design of these six churches, Christoph Dientzenhofer (1655–1722) is considered one of the leading architects in early 18th century. Christoph, the middle brother of the five Dientzenhofer sons who set out from Upper Bavaria to learn the mason trade in Prague, stayed there and became the most celebrated master builder in his family. His brothers, however, left for the German regions of Franconia and Upper Palatinate, where they were successful in their own right. Christoph's son Kilian Ignaz (1689–1751) followed in his father's footsteps and left behind an *oeuvre* just as large and remarkable. A common feature of the churches designed by members of the Dientzenhofer family are their brick vaults, which combine complex geometric forms with sophisticated building techniques (Fig. 1).

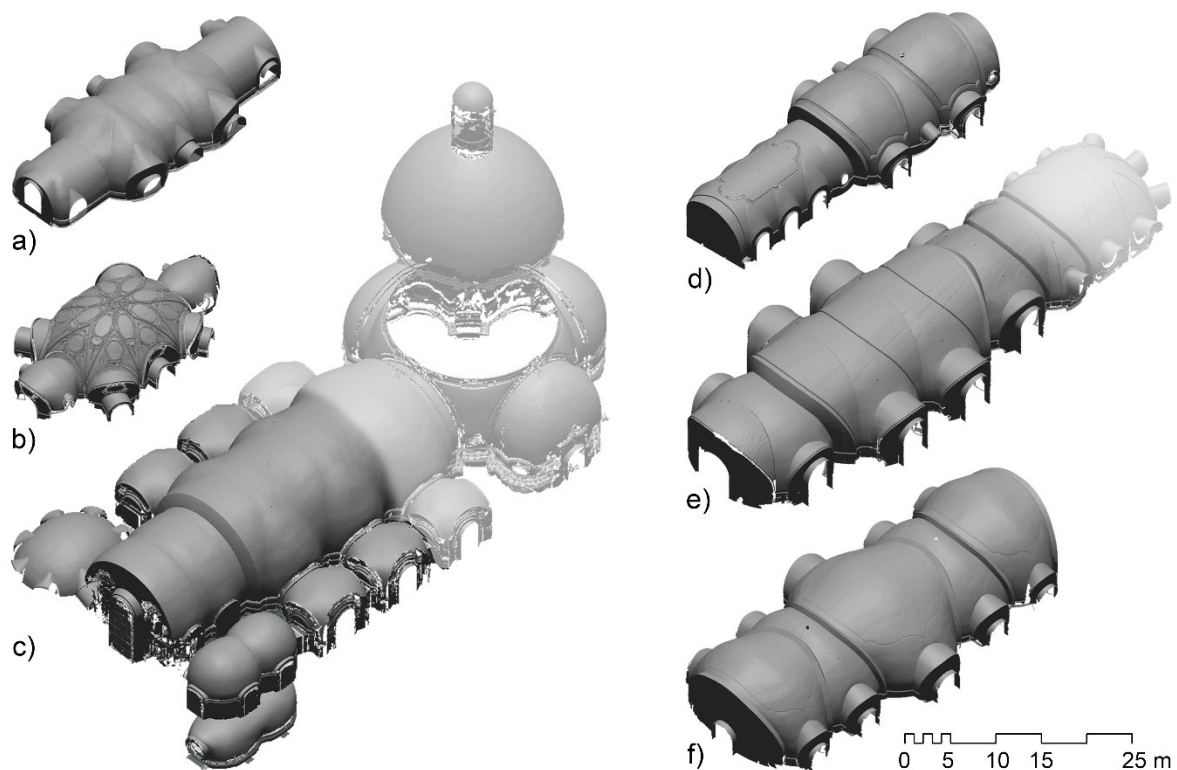


Fig. 1: The ‘radical’ group’s intrados surface models in isometric top view: a) St. Joseph, Obořiště, 1702–11; b) Castle Church, Smiřice, 1702–11; c) St. Nicholas, Prague Lesser Town, 1703–11; d) St. Clare, Cheb, 1707–11; e) St. Margaret, Břevnov, 1708–16; f) Church of the Holy Assumption, Nová Paka, 1709–24; the areas in lighter grey are later additions by Kilian Ignaz Dientzenhofer.

Probably the earliest representative of the ‘radical’ group is the Pauline monastery church St. Joseph in Obořiště, built from 1702–11. The design of the vault already contains conceptual ideas that Christoph Dientzenhofer later developed further (Fig. 1 a). The Sternberg family’s Castle Church in Smiřice was built around the same time from 1702–11. The vault of this ‘radical’ building is decorated with the star of the Sternberg family coat of arms, but otherwise bears many similarities to the other members of the group (Fig. 1 b). The Jesuit church St. Nicholas in the Lesser Town of Prague, built from 1703–11, is one of Dientzenhofer’s major works, not only because of its size and prominent location. His original design was heavily altered, when a much bigger choir with a huge drum and dome were added by his son Kilian Ignaz in 1737, and the vault’s original arches were removed in 1760 (Fig. 1 c). The Clarisse Church of St. Clare in Cheb was built in 1707–11. The nave, which has a ‘radical’ vault design based on circle segments, is adjoined by the nuns’ choir with a simple barrel vault (Fig. 1 d).

St. Margaret in Břevnov, 1708–16 is another *magnum opus*. The imposing building replaced the destroyed Romanesque church of the renowned Benedictine monastery outside Prague. The choir was completed by Kilian Ignaz (Fig. 1 e). The last church belonging to the group is the Pauline monastery Church of the Holy Assumption in Nová Paka, built in 1709–24. The vault design, based on ovals, recalls all the defining elements of the radical group (Fig. 1 f).

Research on the ‘radical’ vaults

Although researchers have long been unanimous in recognising the architectural significance of the ‘radical’ group, the lack of written sources has led to decades of debate about its authorship and exact composition, resulting in the development of two strands of research: one doubting the attribution to Dientzenhofer and suggesting Johann Lucas von Hildebrandt (1668–1745) or Jan Blažej Santini Aichel (1677–1723) as the originator of the group [1] and one defending Dientzenhofer’s authorship [2]. While the attribution of the radical group to Christoph Dientzenhofer is shared by the majority of researchers today, the buildings in Obořiště, Smiřice and Nová Paka are still controversial members of the group [3]. In addition to discussions about the architect, the geometric basis of the designs, especially with regard to the vaults, is usually discussed by scholars [4]. Until now, geometrical considerations have mostly been based on simplified schematic drawings or, if available, historical building plans, which often differ greatly from the actual buildings.

Although photogrammetric surveys of the buildings in question have already been carried out [5], modern surveying methods still offer a great deal of potential for new research questions, especially when focusing on historical vaults, as the spatially curved forms are notoriously difficult to measure and describe. To discuss the geometry of the radical vaults based on the actual buildings, the six churches were scanned with a 3D laser scanner [6]. Not only the interior, but also the facades and roof areas were scanned to document the intrados and extrados of the vaults together with adjacent building elements [7]. The resulting point clouds were used to generate orthophotos, drawings and triangulated mesh models (Fig. 1). The 3D models of the intrados form the basis for geometric analysis using reverse geometric engineering.

The first step in the analysis is to split the triangulated mesh model into individual areas (e.g. oval domes, arches, etc.). The software can then automatically fit geometrically defined curves

that fit the edges with the least deviation [8]. These fitted curves act as hypotheses about the underlying geometric design. To verify the hypotheses, colour coded needle diagrams visualise the deviation between the scanned model and the ideal curve (Figs 5-9). All dimensions and geometric features mentioned in the analyses are derived from the measured data of the built object, by optimisation and with reasonably small margins of error. This information can be correlated with possible design decisions, taking into account deviations such as deformations during construction and lifetime of the vault, plastering on the brick structure, imperfect execution and measurement inaccuracies [9]. The measured dimensions are not identical to the dimensions used during construction, but are approximations that suggest ratios.

Theoretical context of vault design

The geometric design of Dientzenhofer's 'radical' vaults must be seen in the context of vault construction at the turn of the 18th century, a time when established Late Gothic building practices were still familiar to building professionals, but when theoretical architectural treatises dealing with stereotomic problems such as projections and sections of cylinders, spheres, and cones, were also influencing design decisions. Christoph Dientzenhofer, a master mason by trade who managed to educate himself and improve his skills to the point of becoming a leading architect who transformed or 'radicalised' the architectural concepts of his time, is an embodiment of this combination of practical and theoretical knowledge.

The basic geometric shapes that can be used to describe the vaulted areas discussed in the following chapter can be found in treatises such as Sebastiano Serlio's *Il primo libro d'Architettura* (1545), Philibert de l'Orme's *Le premier tome de l'architecture* (1567), or Guarino Guarini's *Architettura Civile* (1737) [10]. These treatises, written by authors who were both architects and theorists, were aimed at mathematically proficient building professionals. They provide an overview of the geometric knowledge available at the time, describing intersecting geometric bodies, explaining methods of geometric construction, or providing inspiration by suggesting particular design ideas. The study of the treatises thus allows us to gain an insight into the design process that led to the creation of the radical vaults [11].

The oval

Ovals are two-dimensional curves with two axes of symmetry, made up of at least four circle

segments with different radii, which continuously merge into each other. Their use in architectural designs became increasingly popular from the 15th century onwards, until they became a central element of Baroque architecture, especially in the architecture of sacral buildings [12]. One of the reasons for the spread of the oval was Serlio's *Il primo libro d'Architettura*, which became immensely popular and influential [13]. In his treatise, Serlio shows the reader four methods for constructing an oval (Fig. 2) [14].

The first oval is a general method for constructing parallel ovals with angles of 60° and 120° between their radii, based on two central equilateral triangles (Fig. 2 a). The other three ovals have fixed proportions for their angles, axis lengths, arc lengths and radii: the second oval has axis lengths in the ratio 1 to $\sqrt{2}$ and radius and arc lengths in the ratios 1 to $1+\sqrt{2}$. The angles are 90° (Fig. 2 b). Serlio's third and fourth oval have axial ratios of 3 to 4 and radius and arc length ratios of 1 to 2, but differ in their angles: the third oval has 90° angles (Fig. 2 c), while the fourth oval has 60° and 120° angles between the radii (Fig. 2 d), proving that ovals can look very similar in proportion even though they are constructed differently [15]. Serlio's fourth oval was particularly popular with Early Modern architects because of its simple construction and clear proportions [16]. Serlio himself described it as “very pleasing to the eye and serene to many things because of its ease of making and its gentleness”. [17]

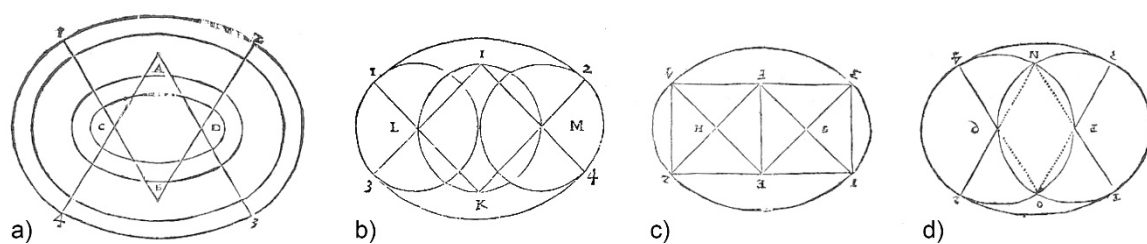


Fig. 2: Serlio's four methods for the construction of ovals. Sebastiano Serlio: Il primo libro d'architettura, Paris 1545, p. 14, edited.

The double-curved arch

Double-curved arches, that is, arches with a spatial curvature in the horizontal plane as well as in the vertical plane, were described in de l'Orme's treatise *Le premier tome de l'architecture*. This treatise, giving practical instructions on precision stone carving for building professionals,

was very influential on many subsequent treatises. The treatise describes the basic exercise of the *tour ronde* [18]: the design of an arched doorway in a round tower, based on the intersection of two cylindrical surfaces (Fig. 3, left). Double-curved arches are also found in Guarini's *Architettura Civile*, a book of five separate treatises that is more concerned with theoretical questions of geometry than with being a practical manual. In the third treatise, devoted to stereotomic problems, he describes the projection of various arches onto a cylinder [19]. The corresponding figures (Fig. 3, centre and right) are very reminiscent of de l'Orme's *tour ronde* [20].

The spatially curved elements depicted in contemporary treatises, which could be replicated using more conventional building techniques, were not only adapted for the 'radical' vaults. Double-curved arches are a central feature of the vault architecture of the entire Dientzenhofer family: Christoph's brother Johann and son Kilian Ignaz also used these forms, as did Balthasar Neumann, another contemporary architect famous for his complex sacral vaults [21].

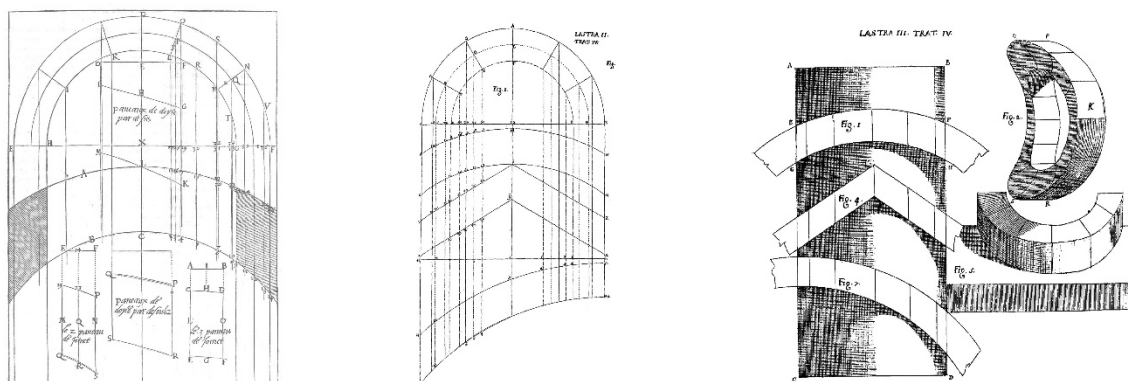


Fig. 3: Double-curved arches in Early Modern architectural treatises. Philibert de l'Orme: *Le premier tome de l'architecture*, Paris 1567, fol. 77 r. (left); Guarino Guarini: *Architettura civile*, Turin 1737, *Treatise IV*, Plate II Fig. 1 and Plate III Fig. 1,2,4,5,7 (centre and right), edited.

The lunette (vault)

In the third treatise of his *Architettura Civile*, Guarini devoted a chapter to “The vaults and the different ways of making them”. One of the six possible types of vaults he mentions is the lunette vault, which is made by cutting into a main vault of any shape. These cuts, seen from above, leave either a triangular or a circular imprint on the main vault, which is then filled with a half-cylinder: these are the two types of lunette vaults (Fig. 4) [22]. Guarini discusses the

issue as a geometrical problem and describes the shapes as intersections of geometrical bodies [23]. Although the complete edition of Guarini's treatise was not published until 1737, the plates with his church designs and parts of his books were already well known in Prague at the end of the 17th century [24], and might have contributed to Dientzenhofer's interest in lunette vaults.

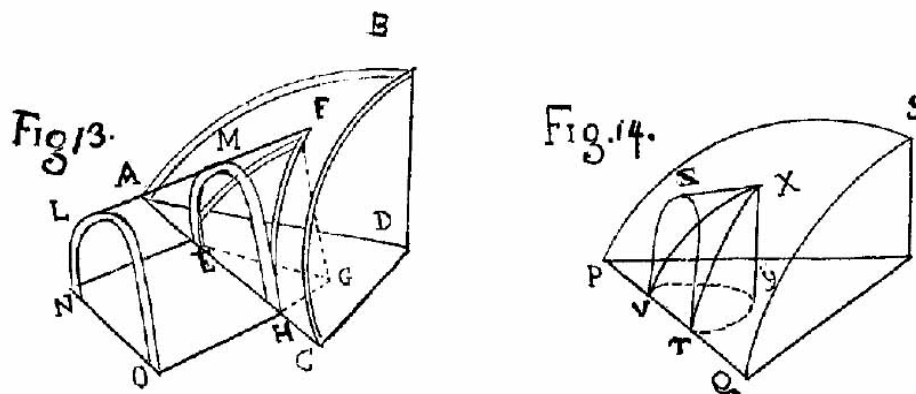


Fig. 4: Guarini describes lunette vaults cutting into the main barrel vault, with triangular (left) and semi-cylindrical (right) projections. Guarino Guarini: Architettura civile, Turin 1737, Treatise III, Plate XIX Fig. 13, 14, edited.

Geometric design of the vaults

The geometric design of the vaults in Christoph Dientzenhofer's 'radical' buildings can be studied by comparing basic vault areas of similar design [25]. For this purpose, three vault areas that are a prominent feature of the radical vaults were selected: vault segments based on ovals, vault segments based on double-curved arches, and lunette vaults.

The oval vaults

Vaults with an oval shape in their horizontal projection are a central feature of the dynamic, curvilinear Baroque. Many of Christoph Dientzenhofer's vaults are sequences or combinations of individual oval domes. However, trying to work out exactly which of the oval designs popular at the time were used in the geometric construction of the oval vaults actually built is a challenging task. It is a typical difficulty that ovals, even when constructed by different methods using different centres, can be very similar or even indistinguishable from each other [26], regardless of the accuracy of the measurements on which the study is based [27]. In order

to make a plausible assumption about the oval that the architect originally drew in his design, scholars have proposed some guidelines for the analysis of oval forms. The ratio between the two axes (1:2, 2:3, $\sqrt{1}$, etc.), the opening angle of the circle segments (30°, 45° or 60°), the position of the centres of the circle segments (placed on the vertices of a central triangle), or the measured values (multiples of the historical unit of measurement), can all be indicators of special ovals used in the design [28]. It is also important to consider whether the architect had a free hand or was restricted by the existing structures on site when designing, resulting in the use of unrestrained or restrained ovals, the latter deviating more from the ideal forms.

The Castle Church in Smiřice has two vault areas with an oval-shaped horizontal projection (Fig. 5 a). The vault in the entrance area of the church can be approximated by two small circles with a radius of 2.18 metres and two large circles with a radius of 4.29 and 3.99 metres respectively, since the oval is not perfectly symmetrical and is slightly deformed at its northern edge (about 90 millimetres deviation from a perfect circular arch). Aside from this locally limited deviation, the oval shares many characteristics with Serlio's fourth oval: the axial length has a ratio of 3 to 4 (Smiřice: 0.76), the larger radii are twice as long as the smaller radii (Smiřice: 0.52 for the southern edge), the arch lengths are identical (Smiřice: 0.94), and the angles are 60° and 120°.

The 'Chapel of the Dead' (Fig. 5 b) is located to the north of the entrance area of St. Nicholas in the Lesser Town of Prague [29]. Eight window openings cut into the oval vault and make it difficult to define its precise shape. It can best be described by two small circles with a radius of 4.55 metres and 4.60 metres and two large circles with a radius of 9.22 metres and 9.15 metres. This relatively rounded shape does not bear a strong resemblance to any of Serlio's ovals, but the dimensions of the oval still reveal some proportions on which the design was probably based: the ratio of the radii is very close to 1 to 2, and the angles have proportions of 1 to 5 (30°/150°).

The central vault of the Church of the Holy Assumption in Nová Paka can be approximated by small circles with radii of 5.52 and 5.60 metres and two large circles with radii of 12.92 and 12.80 metres respectively (Fig. 5 c). The proportions come close to an oval construction using two equilateral triangles, which Serlio also describes for his first oval, with opening angles of 60° and 120° degrees between the radii of the individual circle sections. The deviation analysis

shows that the curves between the four vertices of the oval are flatter than the ideal circle sections of the radii mentioned (with deviations of max. 60 millimetres).

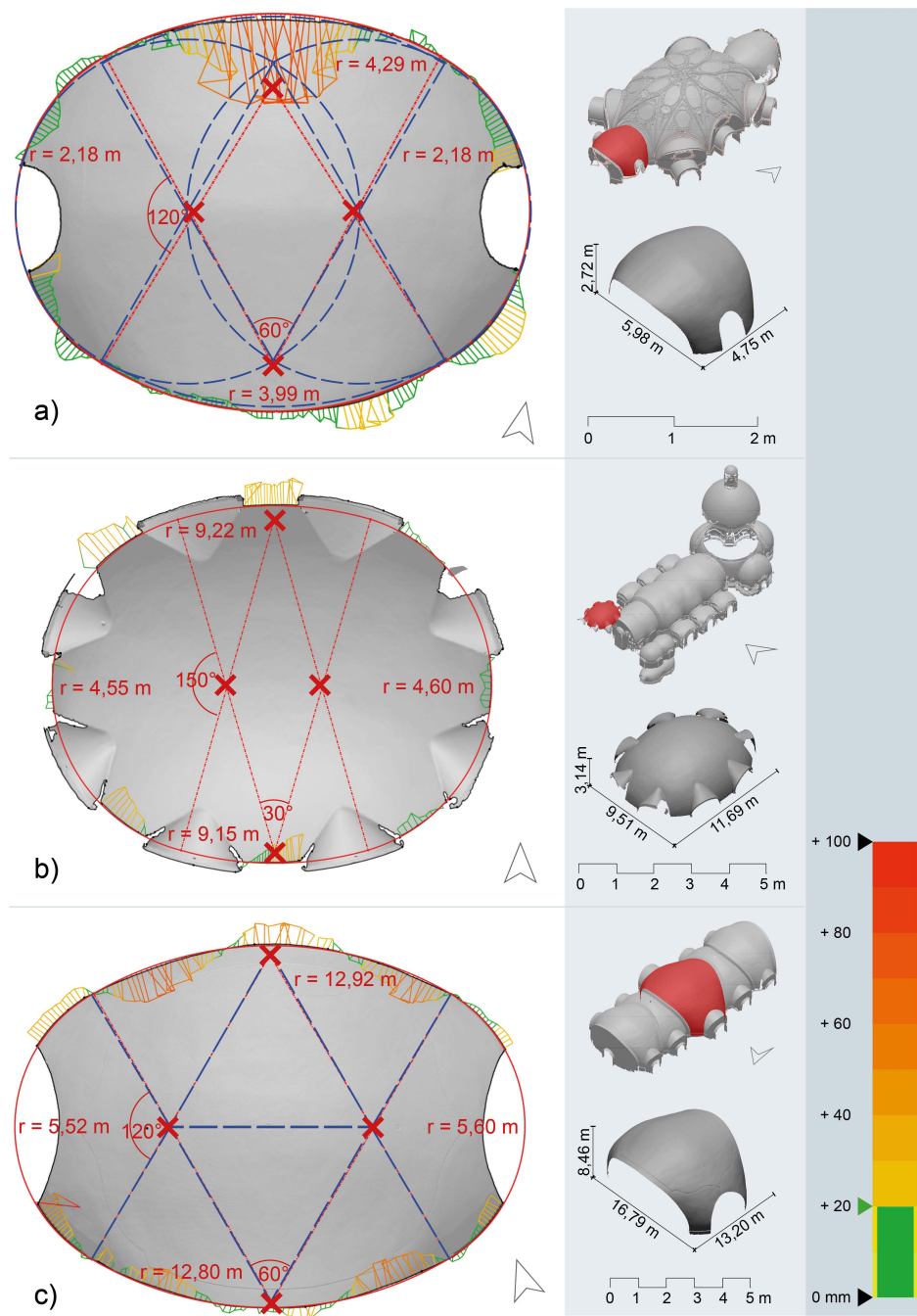


Fig. 5: Geometric design of the oval vaults in horizontal projections: a) Castle Church, Smiřice, 1702–11, overlaid with Serlio's third oval; b) St. Nicholas, Prague Lesser Town, 1703–11; c) Church of the Holy Assumption, Nová Paka, 1709–24, overlaid with Serlio's first oval. Measured points in black, proposed geometric design in red (radii with dotted line), Serlio's ideal ovals in blue (dashed line). The deviation between the proposed design and the measured points is shown on a colour scale.

There is more to analyse about oval vaults than just the horizontal projection. The vault area above the organ in the Church of the Holy Assumption in Nová Paka, despite its asymmetric horizontal projection (Fig. 6 a), is exemplary for the geometric description of the vertical sections of Dientzenhofer's oval vaults. Vertical sections of oval vaults usually result in either semi-circles or straight lines rising to the apex. In the case of the Nová Paka oval vault, the longitudinal section shows a segment of a circle with a radius of 7.67 metres (max. deviation 30 millimetres, Fig. 6 b), and the transverse section through the short side of the oval vault shows rising lines for the ridge curves (Fig. 6 c). The sections highlight the asymmetry, which is difficult to see with the naked eye when visiting the building. The longitudinal and transverse sections give an insight into the construction process of oval vaults. For the longitudinal section, a semi-circular centering was used, while for the transverse section simple straight planks rising to the centering were sufficient [30].

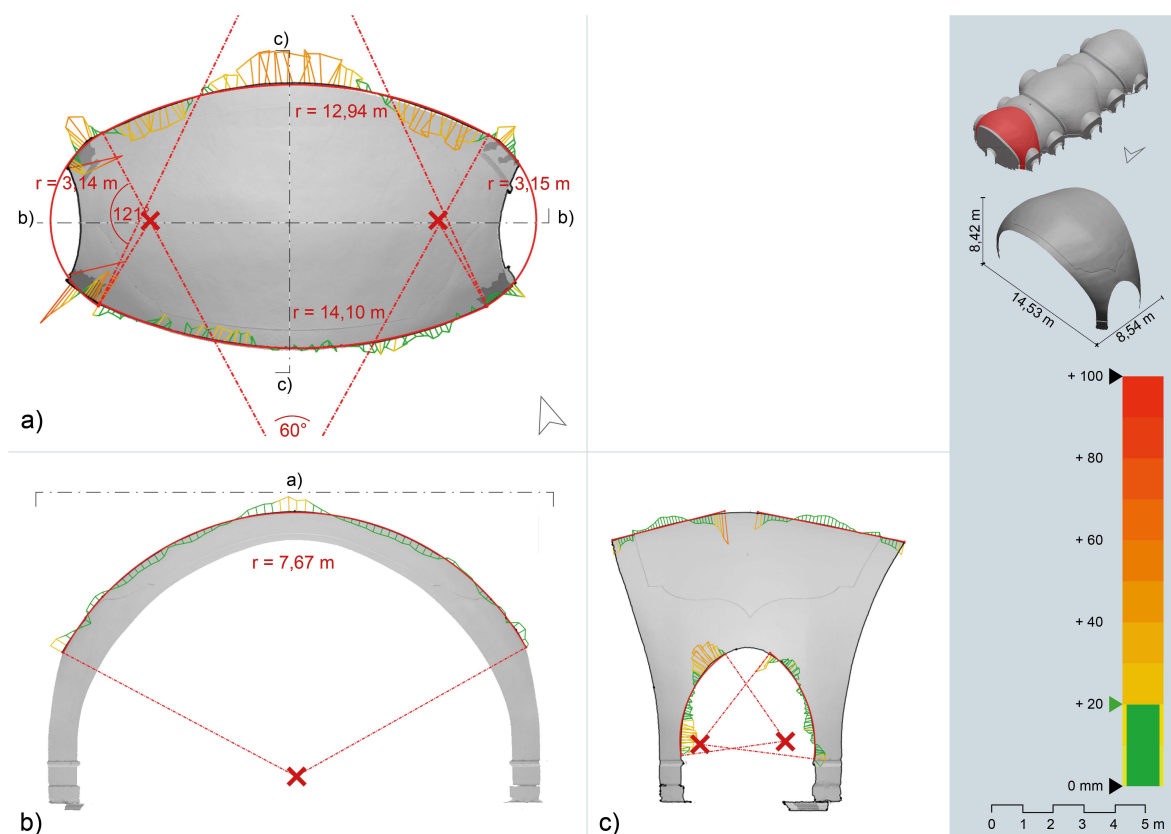


Fig. 6: Geometric design of the oval vault above the organ of the Church of the Holy Assumption, Nová Paka, 1709–24; a) horizontal projection, b) longitudinal section, c) transverse section. Measured points in black, proposed geometric design in red (radii with dotted line). The deviation between the proposed design and the measured points is shown on

a colour scale.

The double-curved arches and related forms

Another characteristic element of Dientzenhofer's vaults are the double-curved arches. They usually appear in pairs, while in Smiřice we find single arches. Another special case is the Church of St. Nicholas in the Lesser Town of Prague, where the double-curved arches were removed from the main vault after a few decades [31]. A surviving example of double-curved arches can be found in the choir of St. Margaret's in Břevnov. It is not entirely clear to what extent Kilian Ignaz Dientzenhofer, who was responsible for the construction of the choir, altered his father's plans, which at one point included a different choir design [32].

The pair of Břevnov's double-curved arches follow simple circular arcs in their horizontal and vertical projections. For the horizontal projection (Fig. 7 a), a circle segment with a radius of 10.01 metres can be assumed for the outer edge of the western arch and a segment with a radius of 10.53 metres can be assumed for the outer edge of the eastern arch, with a maximum deviation of 30 millimetres. The outer curve of the vertical projection (Fig. 7 c) fits best to a circle segment with a radius of 7.03 metres, with an asymmetric deviation of up to 80 millimetres on one side. The inner curve of the vertical projection (Fig. 7 d) is closest to a circle segment with a radius of 6.25 metres (max. deviation 40 millimetres). The different radii of the inner and outer curves result in the twisted effect of the arches. In general, the particular shape of the pair of arches is geometrically defined by the spatial curves describing their edges. The surface area of the arch is just the connection between the edges and is not geometrically defined in itself.

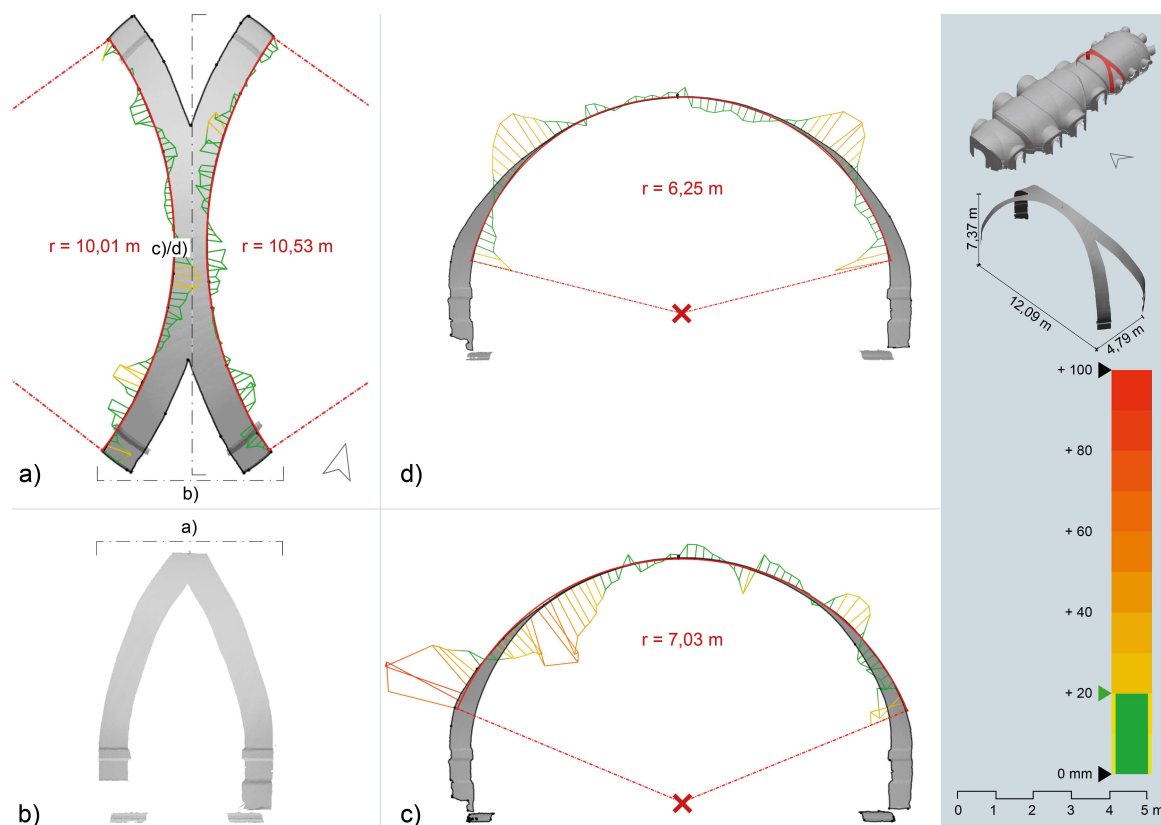


Fig. 7: Geometric design of the double-curved arches of St. Margaret, Břevnov, 1708–16; a) horizontal projection, b) transverse projection, c) longitudinal projection (outer edge), d) longitudinal projection (inner edge). Measured points in black, proposed geometric design in red (radii with dotted line). The deviation between the proposed design and the measured points is shown on a colour scale.

In Cheb, Břevnov and Nová Paka we can find vault areas that are very similar to the double-curved arches. These areas, referred to by different names in the literature, have the basic shape of short barrel vaults with a curved apex and concave edges. They connect two oval or convex vault areas and are a central element of the vault designs. A historical building plan of St. Clare's in Cheb proves that this vault was planned at an earlier stage with double-curved arches instead of the concave vault area that was finally built [33].

The geometrical analysis of the vault area between the main vault and the organ vault of the Church of the Holy Assumption in Nová Paka shows that the geometrical design consists of circular segments. In the horizontal projection (Fig. 8 a), the vault area comes closest to two large circle segments with a radius of 12.11 metres and 12.09 metres, respectively, and two small segments with a radius of 4.58 metres and 4.93 metres, respectively (max. deviation 40

millimetres). The corners of the vault area are straight lines set at an angle according to the pilasters on which they stand. The transverse section through the short side of the vault area reveals a curved apex line (Fig. 8 b). The longitudinal section is a segment of a circle that corresponds to an ideal segment with a radius of 7.81 metres (max. deviation 30 millimetres, Fig. 8 c).

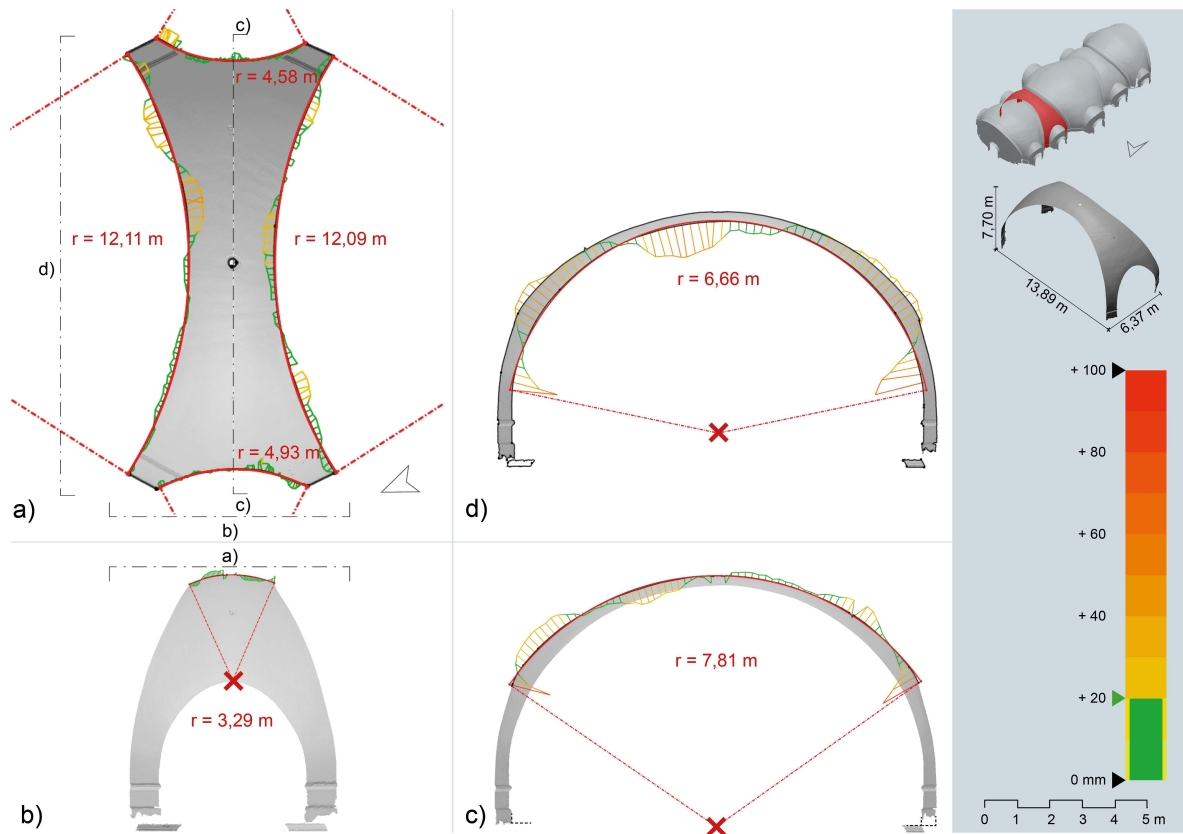


Fig. 8: Geometric design of a double-curved vault area of the Church of the Holy Assumption, Nová Paka, 1709–24; a) horizontal projection, b) transverse section, c) longitudinal section, d) longitudinal projection. Measured points in black, proposed geometric design in red (radii with dotted line). The deviation between the proposed design and the measured points is shown on a colour scale.

The lunette vaults

In his vault designs, Dientzenhofer often used lunettes to incorporate window openings into the main vault. In their horizontal projections, these lunettes can be triangular incisions in the main vault, as in Cheb (Fig. 9 a, top) and Obořiště (Fig. 9 b, top), or they can follow a segment of a circle, as in Břevnov (Fig. 9 c, top). Their edge towards the exterior wall of the buildings can also be straight or rounded. Their vertical projections correspond to stilted semicircles (Fig. 9, centre). Vault areas with a lenticular horizontal projection, as in the Břevnov window

lunettes (Fig. 9 c, top), also appear in the main vault area above the nave at Břevnov, again with a semi-circular longitudinal section.

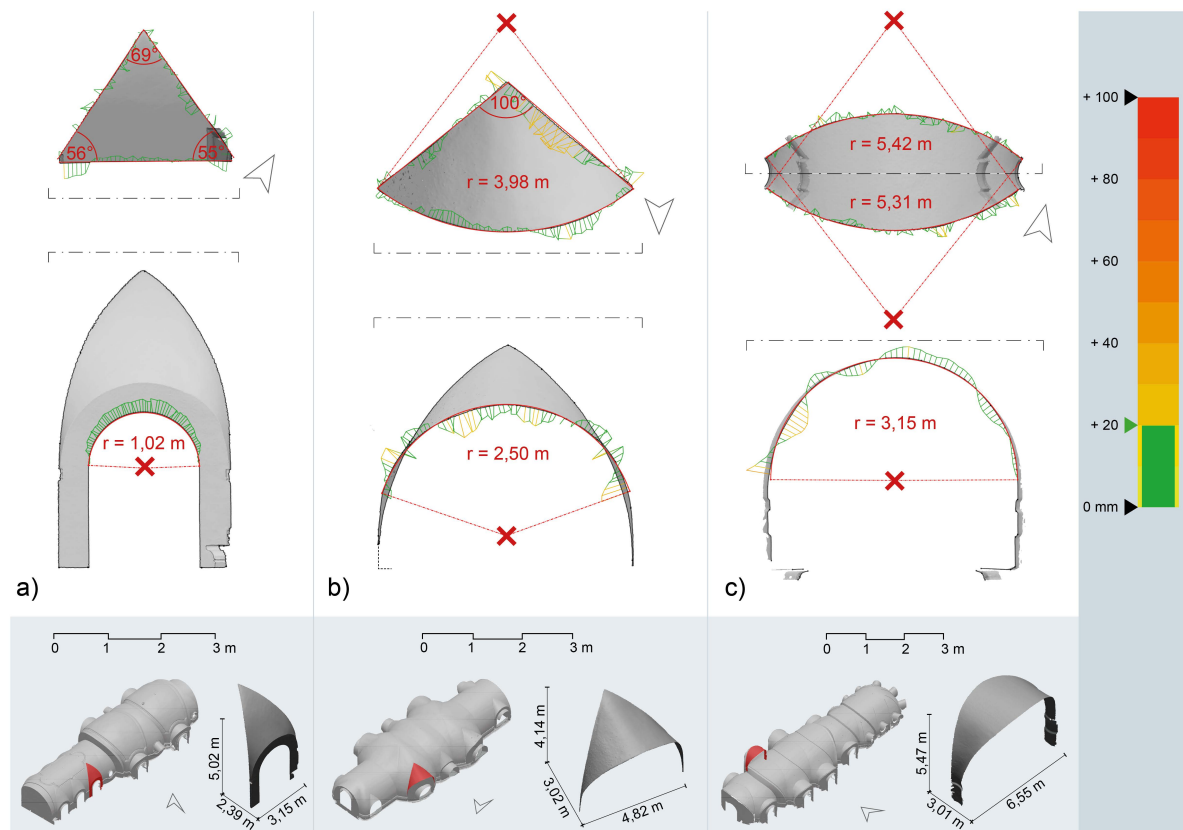


Fig. 9: Geometric design of the lunette vaults, horizontal (top) and vertical (centre) projections: a) Ct. Clare, Cheb, 1707–11; b) St. Joseph, Obořiště, 1702–11; c) St. Margaret, Břevnov, 1708–16. Measured points in black, proposed geometric design in red (radii with dotted line). The deviation between the proposed design and the measured points is shown on a colour scale.

Conclusion

The vaults of Christoph Dientzenhofer's 'radical' group are characterised by their geometrically complex forms. The vaults of the group of six churches all share similar basic forms and geometric design elements, such as vaults created from ovals, double-curved arches and lunette vaults. These basic forms also appear in contemporary architectural and stereotomic treatises, which may have served as inspiration or instructions for the geometric constructions used in the design of the 'radical' vaults.

This study, which employed reverse geometric engineering of 3D laser scans, has shown that the basic design elements are mostly composed of segments of circles, both in their horizontal and vertical projections. The oval vaults have proportions corresponding to the ovals described in Serlio's treatise. The double-curved arches, other double-curved vault areas as well as the lunette vaults for the window openings in the main vault can all be found in the treatises available at the time. As well as revealing the basic geometric concept of spatial curvature at play, these analyses also indicate where wooden centering arches might have been placed during construction.

The 'radical' vaults appear at first glance to have complex geometric designs created by intersecting bodies, but when broken down into basic elements and vertical and horizontal projections, simple circular arcs are the only necessary components of the designs that can be correlated with contemporary treatises.

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- [7] The extrados of the church in Smiřice is covered with insulation, which made scanning impossible.
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- [14] Serlio (Note 10) p. 14.
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- [16] Duvernoy, (Note 12) p. 447.
- [17] Serlio, (Note 10) p. 14. Translation by author.
- [18] de l'Orme, (Note 10) Book III, Chapter XIII, p. 75, left.
- [19] Guarini, (Note 10) p. 196.
- [20] Schmitt and Wendland, (Note 11).
- [21] Schmitt and Wendland (Note 9); R.E. Schmitt, 'Geometric design and construction of a Late Baroque brick vault: Kilian Ignaz Dientzenhofer's Benedictine Church of the Holy Cross and St. Hedwig at Legnickie Pole', in Construction History Society (Ed.), *Timber and Building Construction: The Proceedings of the Ninth Annual Conference of the Construction History Society*, 1-3 April 2022. Cambridge: University of Cambridge, 2022, pp. 143–155.
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- [28] A.A. Mazzotti and A. Ilchmann, 'A method for recognising oval forms: The case study of a copperplate engraving of the Bibliotheca Wolfenbüttel 1705/23'. Submitted for publication to *Nexus Network Journal*, 2022, p. 13.
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- [30] A publication on the 'radical' vaults' building and construction techniques is in preparation by the author.
- [31] H.G. Franz, *Bauten und Baumeister der Barockzeit in Böhmen: Entstehung und Ausstrahlungen der böhmischen Barockbaukunst*, Leipzig: Seemann, 1962, p. 65.
- [32] Franz attributes the double-curved arches to Kilian Ignaz's alterations, while Vilímková considers them to be part of Christoph's later alterations to his own original design: H.G. Franz, *Die Dientzenhofer: Ein bayerisches Baumeistergeschlecht in Böhmen und Franken*, München: Haus der Bayerischen Geschichte, 1991, p. 26.; Vilímková, (Note 29) p. 95.
- [33] Roidl, (Note 4) p. 72.