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Terrestrial Laser Scanning for Geometry-based Building Genealogy Research: Landshut, St. Martin's and Two Transylvanian Saxon Churches

Eszter JOBBIK*

ABSTRACT. ***Terrestrial Laser Scanning for Geometry-based Building Genealogy Research: Landshut, St. Martin's and Two Transylvanian Saxon Churches.*** Despite the abundance of literature on the construction and building methods of late Gothic net vaults, the most influential works still date back to the nineteenth and twentieth centuries. However, the use of terrestrial laser scanning enables researchers to gather precise geometric data that may challenge our current understanding of these vaults. This article presents a point-cloud-based geometric description of the nave vault in the St. Martin church of Landshut. This goes beyond the generally accepted literature on the topic of late Gothic net vaults. Based on the description, we categorise the vault into the geometric typologies of the net vaults' rib-web connections and their rib systems' global geometry, which we established during our earlier research. The literature has long discussed the guild connections between Landshut and the South-Transylvanian Saxon churches with masonry-ribbed vaults. Therefore, we present a comparative analysis of the St. Martin's vaults and those in the naves of the churches in Mediaș (Medgyes/Mediasch) and Sighișoara (Segesvár/Schäßburg), two important examples of this group, based on the same geometric typologies we set up. Through our comparative analysis, we aim to address the question of how building genealogies should be approached. This section discusses the uncertain nature of deductions based solely on plan views of rib systems, how remnants from earlier building periods influence the construction method of net vaults, and the concept of centre and periphery in net vault construction.

Keywords: *geometry-based vault analysis; late Gothic net vault; comparative vault analysis; geometric net vault typology; masonry ribbed net vault*

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1. Introduction

1.1. General introduction

The building and construction techniques used for late Gothic net vaults have long been the focus of scientific attention. However, the relevant literature on the topic was written in the nineteenth and twentieth centuries, when the original construction methods were not used anymore, and the survey techniques were not precise enough to reveal the exact geometry of these structures, especially their vertical dimensions. However, with terrestrial laser scanning, an immense amount of new geometric data can be gathered about these vaults.

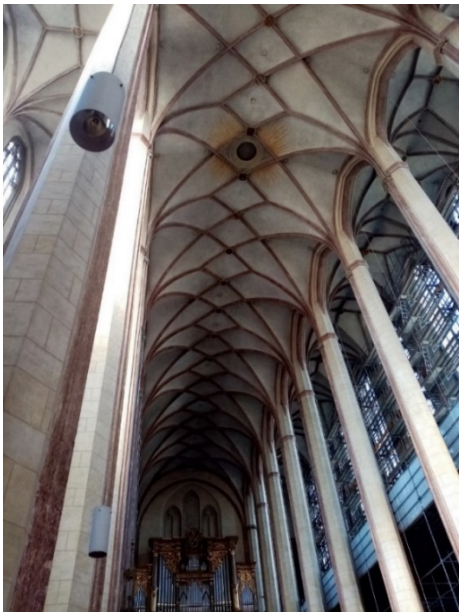

Fig. 1. Nave vault of St. Martin's in Landshut: an example of the rib pattern of 'Parleresque' vaults. (Photo: Jobbik Eszter)

The significance of the exact, three-dimensional data is that it allows for reconsidering certain generally accepted claims about late Gothic net vaults. Precise geometric descriptions of these structures could lead to the theoretical reconstruction of the underlying construction principles, which could, in turn, lead to a reevaluation of what we know about building genealogies and interconnections.

In the 'traditional' literature on the topic, such connections were most often deduced from the identical rib patterns[1] of the net vaults,[2] however, the vaults' overall geometry may prove to be a better base for such analysis.

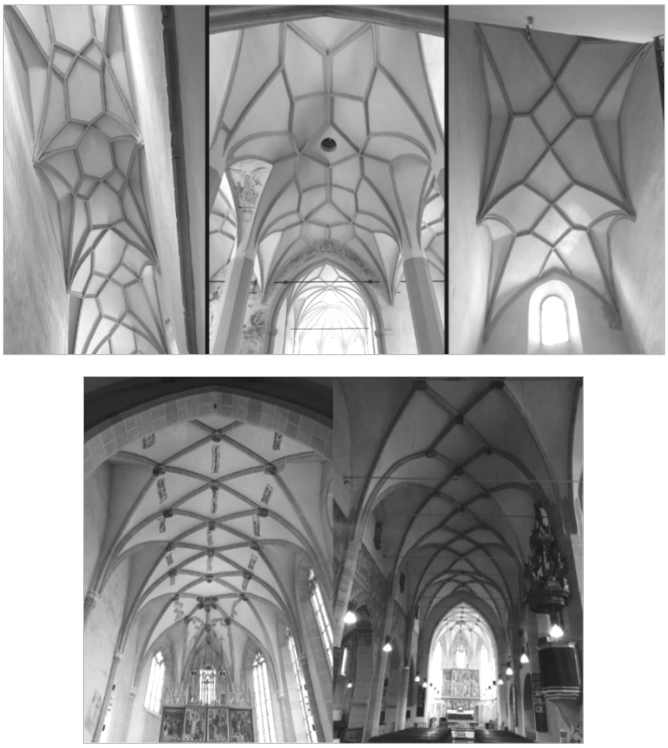

Fig. 2. The three nave vaults in the Church on the Hill in Sighişoara (upper row left to right). Apse and nave vaults in the fortified church of Mediaş (lower row left to right). (Photo: Jobbik Eszter)

The present article focuses on the example of the St. Martin's church in Landshut that has a "rib pattern" characteristic to the "Parleresque" vaults (Fig. 1). In this case study, we present the geometric analysis process of the point cloud

[1] In this context the complete accordance of two rib patterns generally means that all the junction points and ribs in a given bay of one vault have their counterpart in a given bay of the other vault and vice versa.

[2] Hermann Fabini, *Atlas der siebenbürgisch-sächsischen Kirchenburgen und Dorfkirchen,* 1–2 (Monumenta Verlag Hermannstadt and Arbeitskreis für Siebenbürgische Landeskunde, 1999); Guzsik Tamás, *A pálos rend építészete a középkori Magyarországon* (Mikes, 2003); Szőke Balázs, "A Wechselberger-Harperger motívum Délkelet-Erdély késő gótikus építészetében," in *Tanulmányok a székelység középkori és fejedelemség kori történetéből*, eds. Sófalvi András and Visy Zsolt (Pro Énlaka Alapítvány and Haáz Rezső Múzeum, 2012).

to provide a precise geometric description necessary for a comprehensive comparison of two net vault structures. Additionally, it further supports the classification of such a vault into the geometry-based typologies set up in our earlier research. The Landshut vaults, the net vaults in the apse and nave of the fortified church in Mediaş (Medgyes/Mediasch) and the nave vaults in the Church on the Hill in Sighişoara (Segesvár/Schäßburg) will be presented in a comparative analysis. The vaults in Mediaş show the same "Parleresque" pattern as the vault in Landshut, while the vaults in Sighişoara could derive from the same pattern as well (Fig. 2). Since the supposed connections between these buildings already appear in the secondary literature (see below), we try to prove how the geometry-based comparison relates to previous claims of the "classic" literature. Finally, based on our comparative analyses we claim the importance of examining the net vaults as three-dimensional structures and we discuss the varied factors that may affect the construction techniques of the late Gothic net vaults.

1.2. History of St. Martin's in Landshut

Construction of the Gothic masonry church started around 1385,[3] prompted by spatial limitations of the earlier church, as documented in mid-fourteenth century sources.[4] The new church was built with a floor level of approximately four meters higher than of its predecessor.[5] According to a document issued in 1389[6] and confirmed by a 1392 inscription on the choir's façade,[7] "maister Hanns pawmeister zw sand martein" worked on the church. The sources refer most likely to the master builder of the choir: Hanns der Krumnauer.[8] (Previous studies have suggested that "maister Hanns" refers to Hanns von Burghausen as master of the building works from start to finish.[9]) Nonetheless, the architect of the nave was beyond doubt Hanns von Burghausen, one of the best-known

[3] John W. Cook, "A New Chronology of Hanns von Burghausen's late Gothic Architecture," *Gesta* 15, no. 1/2 (1976): 97, https://doi.org/10.2307/766755.

[4] Jos Werner, *Geschichte der Pfarrei St. Martin in Landshut mit XXVI. Tafeln Abbildungen* (Reitsch, 1854), 9; Friedrich Haack, *Die gotischen Architektur und Plastik der Stadt Landshut* (Wolf &Sohn, 1894), 23.

[5] Haas, Walter, "The Presentation of Research in and Under Existing Buildings," *Conservation and Management of Archaeological Sites* 3, no. 1–2 (1999): 77. https://doi.org/10.1179/135050399793138635.

[6] Cook, "A New Chronology," 97.

[7] Spörl claims 1392 as the commencement of the building works. Johann Spörl, "Der Bau und die Erbauer des Chors zu Sct. Martin in Landshut," *Verhandlungen des Historischen Vereins für Niederbayern* 5, (1857): 263–279.

[8] Cook, "A New Chronology," 97.

[9] Haack, *Die gotischen Architektur*, 21–22.

masters of Bavarian and Austrian hall churches. A 1432 plaque commemorates his involvement in this building site.[10] Based on archival and structural evidence, it is known that he only became active in Landshut at the beginning of the fifteenth century.[11] His works showed a close connection to the Parler school.[12] By the time Burghausen started his work on this church, the choir had already been vaulted. The proportions and geometry of the nave and tower relate to those of the earlier building parts. The width of the nave and aisles equals the length of the choir, and the width of the main nave equals that of the choir.[13] The western portal was finished in 1432.[14] In the same year, Burghausen passed away, leaving the vaulting of the nave and the tower still incomplete.[15] Hans Stethaimer, Burghausen's nephew,[16] and the latter's son, Stefan Purghauser, further led the construction works. The addition of a musical gallery to the choir was Stettheimer's contribution.[17] According to dendrochronological evidence, the tower's foundation dates around 1445 – thus, it can't be attributed to Burghausen.[18] The nave was completed around 1475 and the tower around 1500.[19]

In 1945, the church was damaged by bullets, requiring structural reinforcement of the walls and inner pillars. Thus, the pillar foundations were fortified, and wires were installed above the vaults for support.

1.3. History of the fortified church in Mediaș

The construction of the present parish church in Mediaș began in the fourteenth century, replacing an earlier one.[20] Significant alterations were carried out during the Gothic period, including the demolition of the northern wall and the addition of a northern aisle in the late fourteenth century.[21] A new

[10] Werner, *Geschichte der Pfarrei*, 13; Cook, "A New Chronology," 97.
[11] Cook, "A New Chronology," 97.
[12] Cook, "A New Chronology," 98.
[13] Cook, "A New Chronology," 99.
[14] Haack, *Die gotischen Architektur*, 24.
[15] Cook, "A New Chronology," 104, endnote 19.
[16] Achim Timmermann, "Frau Venus, the Eucharist, and the Jews of Landshut," in *Judaism and Christian Art*, eds. Herbert L. Kessler and David Nirenberg (University of Pennsylvania Press, 2011), 186.
[17] Norbert Nussbaum, "Hybrid Design Strategies around 1300: Indications of a "Post-Classical" Gothic Architecture?" in *The Year 1300 and the Creation of a New European Architecture*, eds. Alexandra Gajewski and Zoe Opacic (Brepols, 2007), 145, https://doi.org/10.1484/M.AMA-EB.3.12.
[18] Timmermann, "Frau Venus", 186.
[19] Haack, *Die gotischen Architektur*, 24–25.
[20] Fabini, *Atlas*, 1, 467.
[21] Fabini, *Atlas, 1,* 468.

apse was built in 1440, the choir and the main nave were rebuilt in the late fifteenth century, when a southern aisle was also added.[22] The southern aisle and the main nave together form a hall church; however, the earlier northern aisle and the main nave together form a basilical space. Some researchers explain these changes with plan alterations and not different building phases.[23] First mentioned in 1452 as "fortified", the church was completed in 1488.[24] The net vaults of the nave and apse date to the late fifteenth century. They are adorned with coats of arms featuring painted apostles and saints.[25]

1.4. History of the Church on the Hill in Sighişoara

The nave's net vault system in the Church on the Hill in Sighişoara originates from the Gothic rebuilding of the church's western part between 1429 and 1525.[26] These works did not change the asymmetric, irregular wall contours of the Romanesque period.[27] The inner space was altered by building only three pairs of columns instead of the four Romanesque ones and creating a hall church instead of a basilica.[28] Following an earthquake in 1838, reconstruction was necessary.[29] Written sources do not clarify which part of the vault system was affected. Based on our geometric research, the overall geometry of the rib system is highly consequent, despite its seemingly haphazard appearance.[30] Therefore, we claim that the earthquake could not have significantly affected the nave's vault system (additionally, neither source refers to a significant rebuilding phase).

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22 Fabini, *Atlas, 1,* 468.

23 Karl Werner, *Die Mediascher Kirche* (Druk von Theodor Steinhaußen, 1872), 25–26.

24 Fabini, *Atlas*, 1, 468.

25 George Oprescu, *Die Wehrkirchen in Siebenbürgen* (Sachsenverlag, 1961), 34.

26 Victor Roth, *Geschichte der deutschen Baukunst in Siebenbürgen* (Heitz&Mündel, 1905), 66.

27 Daniela Marcu Istrate, "Voraussetzungen und Vorbedingungen für den Bau der Bergkirche in Schäßburg," *Zeitschrift für Siebenbürgische Landeskunde* 41, (2018): 13; Daniela Marcu Istrate, "Entstehung und Entwicklung der siebenbürgischen Stadtkirchen im 12–15. Jahrhundert," in *Sachsgeschichte(n). Beiträge zu einer interdisziplinär verstandenen Archäologie des Mittelalters und der Neuzeit. Festschrift für Barbara Scholkmann zu ihrem 80. Geburtstag*, eds. Dorothee Ade et alii (Tübingen Library Publishing, 2021), 457.

28 Istrate, "Voraussetzungen", 14.

29 Friedrich Müller, "Die Schässburger Bergkirche in Siebenbürgen," *Mitteilungen der K. K. Central-Commission* 1, (1856): 172.

30 Eszter Jobbik and János Krähling, "Approaching Building Connections Based on Net Vaults' Geometric Analysis. The Vaults of the Church on the Hill of Sighişoara and the Church of Băgaciu," *Brukenthal. Acta Musei* 18, no. 1 (2023): 49–68; Eszter Jobbik and János Krähling, "The Geometric System of the Nave Vault of the Church on the Hill of Sighişoara," *Studia UBB Historia Artium* 68, (2023): 7–43, https://doi.org/10.24193/subbhistart.2023.01.

1.5. Building connections

The late fifteenth–early sixteenth century period of the Mediaş church was likely influenced by the guild of Sibiu (Nagyszeben/Hermannstadt), which was primarily connected to the guild of Vienna.[31] In the broader context, late Gothic building techniques, including masonry ribbed net vaults, first appeared in Transylvanian Saxon architecture during the late Gothic building phase of the Church on the Hill in Sighişoara, spreading afterwards in the Sighişoara and Mediaş Seats.[32] This building connects to the guild of Landshut directly via its master builder, Jacob Kendlinger.[33] Additionally, the pattern of the rib systems indicates a presumed connection with the St. Martin's church,[34] which was reconstructed by Hans Stethaimer after a conflagration.

2. Methodology

2.1. Survey method

To carry out the net vault analysis presented in this article, we used the data from a Leica BLK 360 terrestrial laser scanner. The point cloud data was processed in Leica 360 Cyclon Register.

It is important to consider the accuracy of the scanner when addressing the exact geometry of the vaults. Leica BLK 360 has a precision of 8mm at a distance of 20m.[35] Given the dimensions of the churches' spaces under investigation, potential inaccuracies of approximately 1–3 cm are anticipated. Considering the expected precision in the buildings' geometry, primarily influenced by the building technologies of the Late Gothic period,[36] we claim that these point clouds are well-suited for the intended analyses.[37]

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31 Hermann and Alida Fabini, *Kirchenburgen in Siebenbürgen* (Koehler&Amelang, 1985), 83.

32 Szőke, "A Wechselberger-Harperger motívum," 204.

33 Fabini and Fabini, *Kirchenburgen*, 83; Szőke, "A Wechselberger-Harperger motívum," 204.

34 Szőke, "A Wechselberger-Harperger motívum," 204.

35 „BLK360 Frequently Asked Questions. 8. How accurate is the BLK360?" Leica Geosystem BLK, accessed 30 October 2023, https://shop.leica-geosystems.com/leica-blk/blk360/blog/blk360-frequently-asked-questions.

36 Fehér and Halmos identify discrepancies in the geometry of vault rib elements, attributing some to the inherent inaccuracy in the original construction. These inconsistencies are presumed to extend beyond individual elements to impact the global geometry of the vault. Krisztina Fehér and Balázs Halmos, "Problems of Surveying Profile Shapes of Gothic Architectural Fragments," *Pollack Periodica* 13, (2017): 222.

37 Not only our own experiences but also other research support this claim: e.g. Vidal proved by the experiential method, regardless of the deterioration, the curvature of the ribs can be found

It is important to acknowledge that inaccuracies may occur when we carry out measurements on the point cloud. However, similar inexactness may have been present in the original construction of these structures. Therefore, if such variability is considered acceptable during construction, it should also be accepted in the measurements.

2.2. Analysis method

2.2.1. Mapping

Our analysis method is based on the premise that the geometry of the vaults is determined by the original construction and building techniques, such as the geometry of the temporary supporting structure. Therefore, "reverse engineering" may be applied, and the geometry may be traced back. Another indication of the initial premise is that the more irregular the geometry of the vault, the more precisely the original methods can be deduced. This is because regular geometry can be achieved in several ways. However, "regular irregularities" limit the possibilities when trying to determine the original construction steps. It is important to note that examining net vaults using this principle requires an initial assessment of whether any geometric changes that may have occurred in the structures since their construction, thus involving studying the history of the buildings.

The analysis of net vaults includes two main steps: examination of the connection between the rib system and the webbing, and the overall geometry of the rib system. In practice, we analyse the "mapping" of the vaults and the geometry of their plan projections, cross-sections, and longitudinal sections.

By "mapping" we mean sectioning the vault with horizontal planes (Fig. 3). This provides information about the connection between the rib system and the webbing, as well as preliminary observations about the global geometry of the rib system. Regarding the former, three main theoretical outcomes can be expected.

Firstly, according to the literature, some net vaults can be classified as "pseudo net vaults" as some researchers argue that certain net vaults are structurally barrel vaults, with their rib system serving a purely decorative function and constructed after the webbing. Despite the existence of opposing

with a high probability. R. Maira Vidal, "The Evolution of the Knowledge of Geometry in Early Gothic Construction: the Development of the Sexpartite Vault in Europe," *International Journal of Architectural Heritage* 11, no. 7 (2017): 1005–1025, DOI:10.1080/15583058.2017.1332254.

viewpoints,[38] this theory is quite common in the literature concerning masonry ribbed vaults[39] Secondly and thirdly, the more widespread theory suggests that most net vaults are "real net vaults", with their rib system built first and the webbing built on the rib system.[40] The webs of the latter may be constructed with or without formworks. The former means that full-surface formworks were placed on the ribs, on which the webs were built,[41] resulting quite flat web surfaces[42] and the occasional sagging of the formwork may cause the introflexion of the webs.[43] The latter implies that either only a centring[44] was used or not even that.[45] Thus, each course of the web worked as a self-supporting arch after completion.[46] Voigts[47] also pointed out, that occasionally a combination of the two main methods was used, with each web using the more suitable method.

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38 Elena Pliego, "Georg Gottlob Ungewitters Lehrbuch der gotischen Constructionen," in *Bautechnik des Historismus. Von den Theorien über gotische Konstruktionen bis zu den Baustellen des 19. Jahrhunderts*, eds. Uta Hassler and Christoph Rauhut (Hirmer, 2012), 220; Szőke, "A Wechselberger-Harperger motívum," 207–208.

39 E.g. Roth, *Geschichte*, 36; Fabini, *Atlas*, 1999; Harsányi István, "A szeged-alsóvárosi ferences templom gótikus szentélye csillagboltozatának helyreállítása," *Műemlékvédelem* 45, no. 5 (2001): 302.

40 As described first by Saunders in 1814 and specified later by Willis in 1842 (as quoted by Wendland [David Wendland, "Traditional Vault Construction without Formwork: Masonry Pattern and Vault Shape in the Historical Technical Literature and in Experimental Studies," *International Journal of Architectural Heritage: Conservation, Analysis, and Restoration* 1, no. 4 (2007): 342, https://doi.org/10.1080/15583050701373803] and mentioned by Ungewitter [Georg Gottlob Ungewitter, *Lehrbuch der gotischen Konstruktionen. Neue bearbeitet von K. Mohrmann* (Chr. Herm. Tauchnitz, 1901) 37].

41 Clemens Voigts, "Vaults, Centring, and Formwork of the Late Gothic Period in Southern Germany," in *History of Construction* Cultures, eds. João Mascarenhas-Mateus and Ana Paula Pires (CRC Press, 2021), 78.

42 Voigts, "Vaults, Centring, and Formwork", 78; David Wendland, "Traditional Vault Construction without Formwork: Masonry Pattern and Vault Shape in the Historical Technical Literature and in Experimental Studies," *International Journal of Architectural Heritage: Conservation, Analysis, and Restoration* 1, no. 4 (2007): 342, https://doi.org/10.1080/15583050701373803.

43 Manfred Schuller, "Bautechnik," in *Der Dom zu Regensburg 7/3*, eds. Achim Hubel and Manfred Schuller (Pustet, 2016), 474.

44 Such a device is pictured e.g. in Viollet-le-Duc [Eugène Viollet-le-Duc, *Dictionnaire raisonné de l'architecture française du XIe au XVIe siècle,* 1–9, (Morel, 1854–1868), Tome 4, 106, Fig. 58]; Ungewitter, *Lehrbuch,* 117; Fitchen [John Fitchen, *Construction of Gothic Cathedrals. A Study of Medieval Vault Erection* (University of Chicago Press, 1961), 101, Fig. 40].

45 E.g. Fitchen (*Construction of Gothic Cathedrals,* 69) – based on Lassaulx (1831) – pictures how a stone-weighted rope device can stabilise the unfinished courses.

46 Voigts, "Vaults, Centring, and Formwork," 79.

47 Clemens Voigts, "Spätgotische figurierte Gewölbe in Bayern: Konstruktion und Herstellungsweise." In *Koldewey-Gesellschaft Vereinigung für Baugeschichte Forschung e.v. Bericht über die 48. Tagung für Ausgrabungswissenschaft und Bauforschung vom 28. Mai bis 1. Juni 2014 in Erfurt*, eds. K. Tragbar and N-M. Bauers (Thelem, 2014), 250; Voigts, "Vaults, Centring, and Formwork," 80–81.

Regarding the global geometry of the rib system in real net vaults, they may be either "linear net vaults"[48] or "centralising net vaults".[49]

These various geometric and structural solutions produce mapping projections of different natures. Pseudo net vaults have straight horizontal section lines of the webbing that do not reflect the position of the ribs. Real net vaults, on the other hand, have webs and rib systems that are interdependent, that is also reflected in the mapping. If a real net vault's webs were built with formworks, the horizontal sections of the webs would be almost straight, slightly convex or concave. However, if formworks were not used, the horizontal section lines of the webs would be curved.

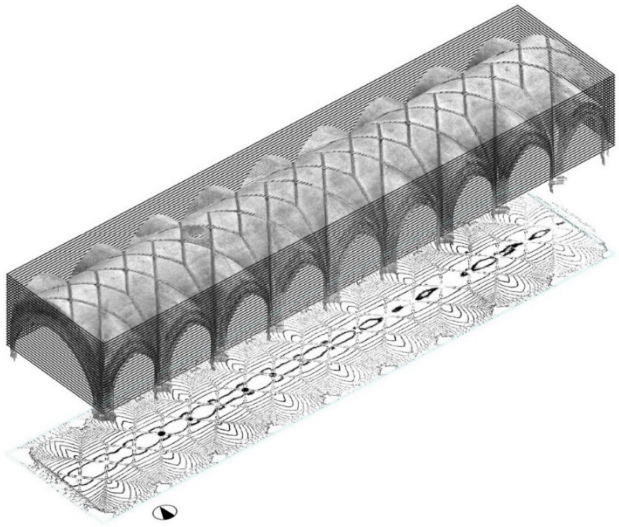

Fig. 3. Theoretical outcomes of the "mapping" of a net vault.

In the case of linear net vaults, the webs' horizontal sections (or the lines connecting the crossing points, in the case of webs built without formworks) do not change directions when crossing the ribs. In the case of centralising net vaults, they do.

[48] In this article, we define linear net vaults as net vaults where the vertical disposition of the rib system and their junction points do not reflect the boundaries of the bays. It must be pointed out that our definition does not concern the pattern of the rib system, as we found that with the same pattern and in the same vault both of these characters may appear. (These geometric necessities may be seen as connected to the problem of distinguishing net vaults and stellar-net vaults. However, the difference between these two and their definitions is quite ambiguous in the literature and is not independent of the pattern of the rib system.)

[49] In this article, we define centralising net vaults as net vaults, where the vertical disposition of the rib system and their junction points reflect the boundaries of the bays.

2.2.2. Analysing the ribs' spatial positions

After analysing the "mapping" of the vaults, the next step is to examine the spatial positioning of the rib junction points. We do this in a Cartesian coordinate system fitted along the longitudinal, cross, and vertical directions of the vault (Fig. 4). While the older literature on the topic generally assumes that the construction of a rib system starts with its plan[50] our previous research showed that exceptions do exist.[51] Therefore, our analysis aims to find the two coordinates defining the plane, where the projected picture of the vault was first constructed. Based on our earlier results and the geometric necessities of these structures, this examination may result in four different theoretical outcomes.

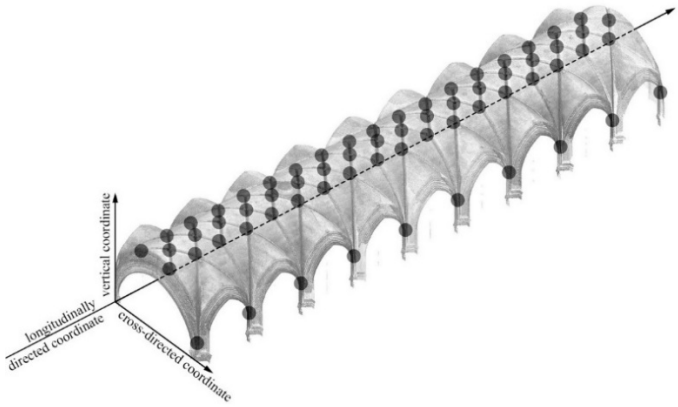

Fig. 4. Theoretical Cartesian coordinate system for analysing the global geometry of a net vault's rib system.

In the first case, the three coordinates of the junction point's spatial positions can be constructed independently of each other. In other words, a construction method can be reconstructed for any one of them without knowing the other coordinates. Consequently, these vaults are of a very regular

[50] Bartel Ranisch, *Beschreibung aller Kirchengebäude der Stadt Dantzig…* (Raths und Gymnasii Buchdruckern, 1695); Friedrich Hoffstadt, *Gothisches ABC-Buch: Vorlegeblätter zum gothischen A-B-C-Buche…* (Frankfurt a. M., 1840); Warth, *Die Konstruktionen*; Ungewitter, *Lehrbuch*.

[51] Eszter Jobbik and János Krähling, "Late Mediaeval Net Vault Construction Method Rediscovered by Geometric Analysis. A Case Study of the Fortified Church of Băgaciu (Bogeschdorf)," *Brukenthal. Acta Musei* 17, no. 2 (2022): 179–202; Jobbik and Krähling, "Approaching Building Connections"; Jobbik and Krähling, "The Geometric System"; Eszter Jobbik and János Krähling, "A Methodological Approach and Geometry-Based Typology of Late-Gothic Net Vaults' Rib Systems. Presented on Case Studies from Historic Hungary," *Nexus Network Journal* 27, (2024): 95–117, https://doi.org/10.1007/s00004-024-00780-1.

geometry. As a result, only vague statements can be made about them (as explained in section 2.2.1.). One should note that in such cases, although any plane of the visionary coordinate system could have theoretically been primary during construction, the primacy of the plan is the most plausible and simplest method of execution.

The second theoretical outcome occurs when the geometry of the rib system shows that the plan view must precede the vertical dimensions. In other words, to determine the vertical coordinate of a rib junction point, one must first know its projected position on the plan. Previous literature points out several principles that may characterise the underlying construction principles of such a plan view. These are methods based on quadrate nets (e.g. Schulze's method as quoted by Müller[52]), rotated inscribable quadrats,[53] triangulation, and circle-based constructions.[54] Adding the vertical dimension to these systems, multiple geometric solutions are described in the literature: projection-based approaches, such as net vaults deduced from cross-vaults[55], from fan vaults[56] and barrel vault-like net vaults[57] (the junction points fit on a cylindrical surface) or "linear approaches" such as the "principle of the longest route."[58]

The third theoretic outcome on the construction sequence of the different planes on the visionary Cartesian coordinate system is when the cross section was first constructed, and the longitudinal dimension was added subsequently. We first described this possibility when examining the nave vaults in Băgaciu (Szászbogács/Bogeschdorf) and Sighişoara.[59] In these cases, the plan

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52 Werner Müller, "Die Zeichnungsvorlagen für Friedrich Hoffstadts 'Gotisches A.B.C.-Buch' und der Nachlass des Nürnberger Ratsbaumeisters Wolf Jacob Stromer (1561–1614)," *Wiener Jahrbuch für Kunstgechichte* 28, (1975): 45, https://doi.org/10.7767/wjk.1975.28.1.39.

53 Hoffstadt, *Gothisches ABC-Buch*, XIV. A. board, as quoted in Müller, "Die Zeichnungsvorlagen", 52; Jean-Marie Guillouët, *Flamboyant Architecture and Medieval Technicality (c. 1400–c. 1530)*, (Brepols, 2019), 63.

54 Arnold Pacey, *Medieval Architectural Drawing: Geometry and Medieval Drawing*, (Tempus, 2007), 73–74.

55 Otto Warth, *Die Konstruktionen in Stein*, (J. M. Gebhardt, 1896), 254–55; Ungewitter, *Lehrbuch*, 63.

56 Warth, *Die Konstruktionen*, 257; Philibert De l'Orme, *Le quatrieme livre de l'architecture de Philibert de l'Orme…* (Paris: Morel, 1567), 108.

57 Warth, *Die Konstruktionen*, 258; Ungewitter, *Lehrbuch*, 64–65.

58 Bucher, François, "Medieval Architectural Design Methods, 800–1560," *Gesta* 11, no. 2 (1972): 47, https://doi.org/10.2307/766593; the treatise of Lorenz Lechler - as quoted by Leon. R. Shelby and R. Mark, "Late Gothic Structural Design in the 'Instructions' of Lorenz Lechler," *Architectura* 9, no. 2 (1979): 125; Hoffstadt, *Gothisches ABC-Buch*, XIV.A/5; Ungewitter, *Lehrbuch*, 67–68; Carl Anton Meckel, "Figurierte Gewölbe der deutschen Spätgotik," *Architectura: Jahrbuch für Geschichte der Baukunst* 1, (1933): 107–121. https://doi.org/10.11588/diglit.19241#0011.

59 Jobbik and Krähling, "Late Mediaeval Net Vault"; Jobbik and Krähling, "Approaching Building Connections"; Jobbik and Krähling, "The Geometric System".

view of the vault appears irregular, as rib junctions of the same type and located on the same side of the vault align along straight lines. While these lines may not appear parallel in the plan view, they do run parallel in the longitudinal sections. Based on the case studies examined, it is likely that the longitudinal positions of the junctions were determined by the lengths of the rib chords. The fourth theoretical outcome refers to the primacy of the longitudinal section over the cross-direction coordinate. Thus far, there are no known real examples or descriptions in the literature of this possible case.

One should note that theoretical figures in the literature usually only show rib systems (and net vaults in general) with outlines. The construction steps described in the literature lead to a single point as the "position" of a given rib junction element. This point is presumed to be on the lower surface of the rib system, as it can be positioned most easily with the help of temporary supporting structures. Hontañon's drawing[60] also supports this idea.

3. Results

3.1. Mapping of the nave vault in St. Martin's in Landshut

The mapping of the nave vault of St. Martin's Church in Landshut displays very regular features. Most horizontal section lines of the webs are close to straight or slightly convex. Occasional introflexed lines occur. The web section lines do not change directions at the ribs. It is worth noting that the "lunettes" are not vaulted as those of a regular barrel vault, as the higher junction points of the lunettes' ribs are not at the same height as the transverse arches between the main nave and the aisles (Fig. 5).

Based on the geometric description, we concluded that the nave vault of St. Martin's in Landshut was probably built as a real net vault, with webs built using formworks. Regarding the overall geometry of the rib system, the vault seems to be a linear net vault, according to the definition given above.

[60] As presented in Pablo Moreno Dopazo, "Rodrigo Gil de Hontañón and 16th-Century Building Techniques: The Cimborio Vault of Archbishop Fonseca College Chapel in Salamanca (Spain)," *International Journal of Architectural Heritage* 10, no. 8 (2016): 1110–1124, doi.org/10.1080/15583058.2016.1187778.

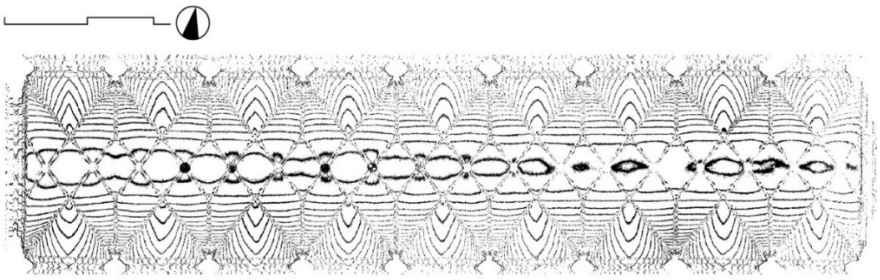

Fig. 5. Mapping of the main nave vault of St. Martin's.

3.2. Global geometry of the rib system of the nave vault in St. Martin's in Landshut

The rib system of the nave vault has very regular features. The preliminary examinations of the point clouds resulted in the following observations: the diagonally directed ribs fit on an even surface; however, the cross-directed ribs don't. On the individual geometry of the ribs, we found that both the curvatures of the diagonally directed ribs and the cross directed ribs are uniform, although the values of the curvatures of the two groups differ.

An important feature of the analysed space is that the length of the bays is equal to half of the width of the main nave. Analysing the coordinates of the rib junction points, we noted the following results: firstly, the diagonally directed ribs on the plan view fit on lines that connect the opposite corners of rectangles, which have a width equal to that of the main nave and a length of 1.5 times the bays' length. Let the length of such a line be "D". Based on these pieces of information, the plan projection of the vault (longitudinal and cross-directed coordinates of the rib junction points) can be reconstructed (Fig. 6).

Secondly, the same D value is the radius of the circle the curvature of which equals to the inner curvature of the diagonal ribs (Fig. 7). Therefore, the vertical coordinates of the junction points can also be constructed in the same underlying geometric system as the coordinates of the plan view. As the diagonal section of this part of the rib system fits on a circle segment, the cross section must be elliptic.

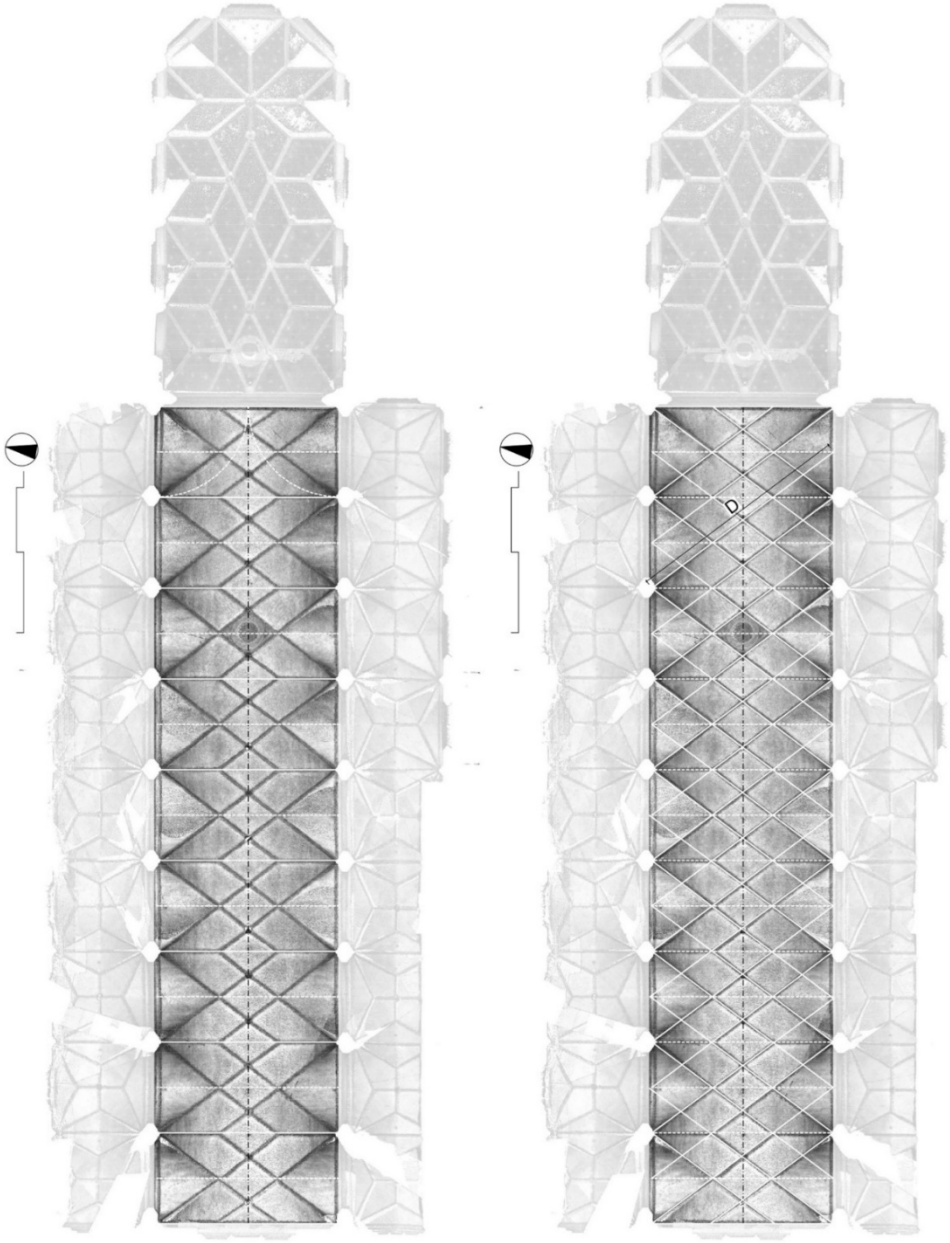

Fig. 6. Theoretical construction principles of the plan layout of the main nave vault of St. Martin's.

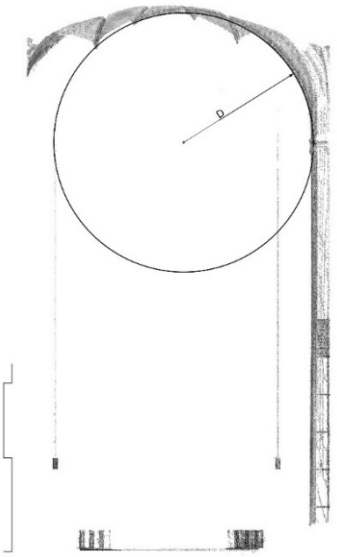

Fig. 7. Diagonal section of the main nave vault of St. Martin's.

Projecting the plan's hypothetic construction net on the cross-section, we found that the geometric interdependence of the building's rations seems to be present in the height of the space (the distance of the lower surface of the junction points composing the crown line and the floor level) and even in the height of the ribs as well (Fig. 8). Based on this construction net, further height values are constructible as well, such as the crown point of the transverse arches between the nave and the aisles.

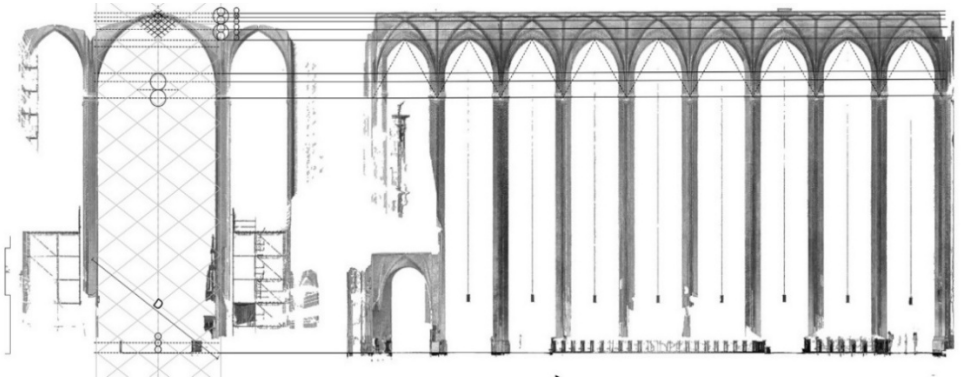

Fig. 8. Theoretical construction principles of the cross- and longitudinal sections of the main nave vault of St. Martin's.

However, due to the highly regular spatial positions of the rib junction points, it is impossible to figure out the exact underlying construction idea followed by the original builders. The presented construction sequence is just one of the possibilities.

Nonetheless, it has been proven that the spatial positions of the junction points were indeed constructed. Additionally, it is quite likely that the longitudinal and cross-directed coordinates of the rib system were constructed prior to the vertical coordinates, as the value D depends on the plan layout.

Similarly, the original building techniques are probably not identifiable either. We would like to add that, although a surface-like temporary supporting structure could be conceivable in this case, such a solution is less beneficial economically and in terms of workload. Thus, we claim that linear supporting structures are more plausible (Fig. 9).

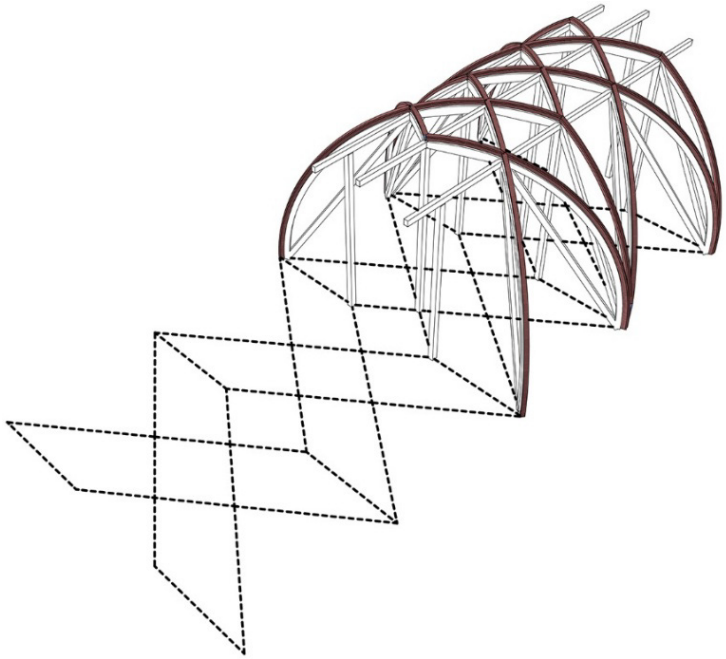

Fig. 9. Theoretical reconstruction of the Landshut vault's building technique.
The figure focuses on the logic and nature of the supporting structure and does not aim to reconstruct the exact structural solutions of the wooden elements.

4. Discussion

As already mentioned, when discussing the net vault genealogies in the literature, the "pattern" of the rib system frequently played a central role. The presented vault from the St. Martin's church in Landshut has the same "pattern" as the nave and apse of the fortified church of Mediaş, according to the above definition.

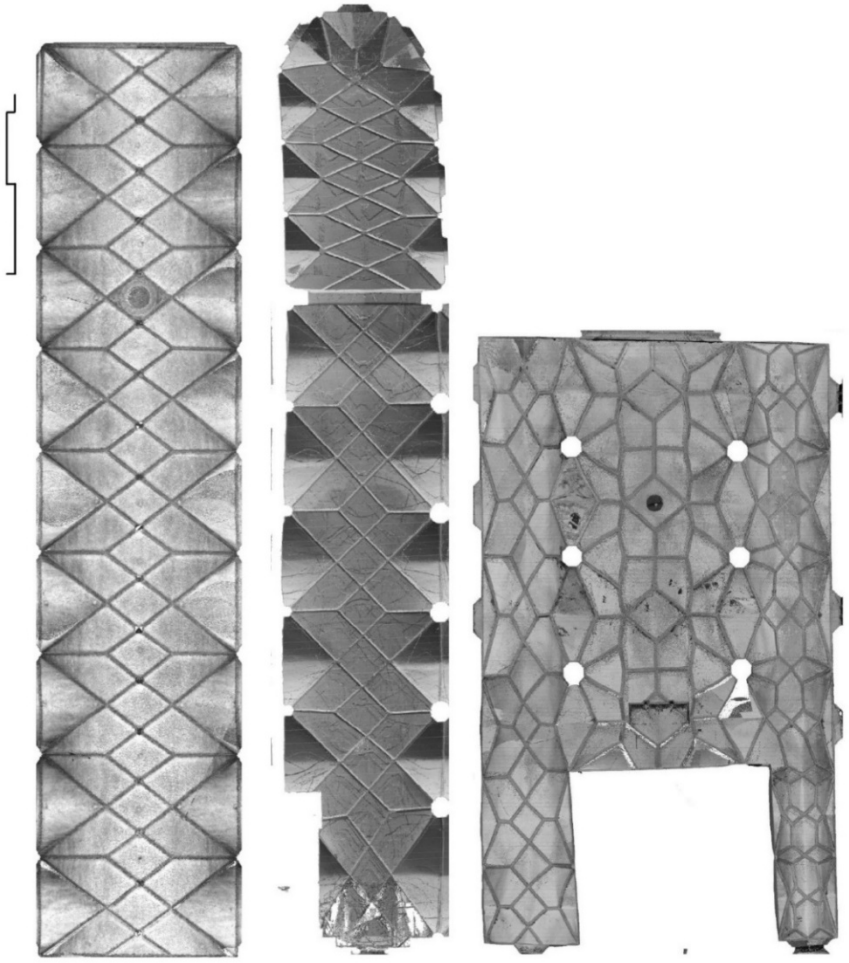

Fig. 10. Rib patterns of the analysed buildings: nave in St. Martin's in Landshut, apse and nave in the fortified church of Mediaş, nave vaults in the Church on the Hill in Sighişoara (left to right).

Secondary literature suggests that the two vaults could have a genealogical connection as well. The same is true of the nave vaults of the Church on the Hill in Sighişoara. The pattern of its northern aisle vault is very similar to the examined vaults in Landshut and Mediaş. The only difference is the presence of "additional" cross-directed ribs between the lunettes' ribs and the ribs of the crown line (Fig. 10). Therefore, it could be interesting to compare the geometric descriptions and presumed building methods of these structures.

4.1. Comparative analysis: Landshut–Mediaş

As already mentioned, the Landshut vault displays highly regular features. Despite its slightly distorted outlines, the apse vault of Mediaş is also very orderly.

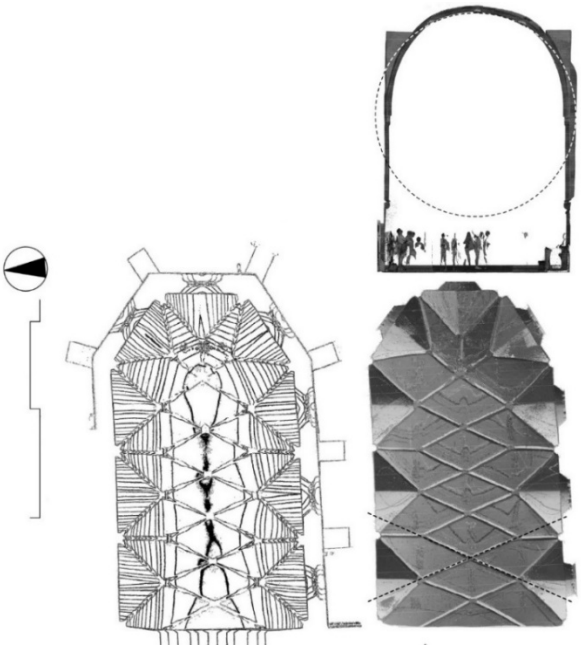

Fig. 11. Plan and cross-section of the apse vault in the fortified church of Mediaş.

Based on the mapping, this structure is also a real net vault with webs built using formworks. The linear net vault features also apply.[61] The spatial arrangement of the rib junction points in this case also appears to be regularly

[61] Eszter Jobbik, "Linear and Centralised Net Vaults: Geometry-based Building Archaeology Presented on the Net Vaults of the Fortified Church of Mediaş," *Építés-Építészettudomány* 52, no. 1–2 (2024): 32, https://doi.org/10.1556/096.2024.00118.

constructible. However, unlike in Landshut, the positions of the ribs in the plan view do not align along straight diagonal lines. While the vertical coordinates of the rib junctions can be constructed using the same fundamental dimensions as those used for the plan, they are not arranged along a cylindrical surface based on a regular circle segment (either on the diagonal or on the cross-section[62]), as in the case of the St. Martin's (Fig. 11).

On the other hand, the nave vault in Mediaş depicts an even more irregular picture. Nevertheless, it exhibits characteristics of real net vaults with webs constructed using formwork.[63] For the present comparison we only discuss its easternmost four bays, as the westernmost bays are quite distorted because of the tower's position.

The cross and longitudinally directed coordinates (plan view) of the vault are very regular, and in this case, the diagonal-dominant feature of the Landshut vault also appears. However, an obvious change in geometry appears in the mapping in the second bay from the east: the easternmost part displays features of centralized net vaults, while the westernmost parts seem closer to linear net vaults (Fig. 12).[64] Additionally, the vertical coordinates of the nave vault's junction points are not uniform, similarly to the above-discussed vaults, but they show a tendency to adjust to the neighbouring spaces: the vertical coordinates of the apse on the eastern side and those of the southern nave's westernmost bays on the western side. Between the two "endpoints", they follow a sloping line connecting them (Fig. 13).

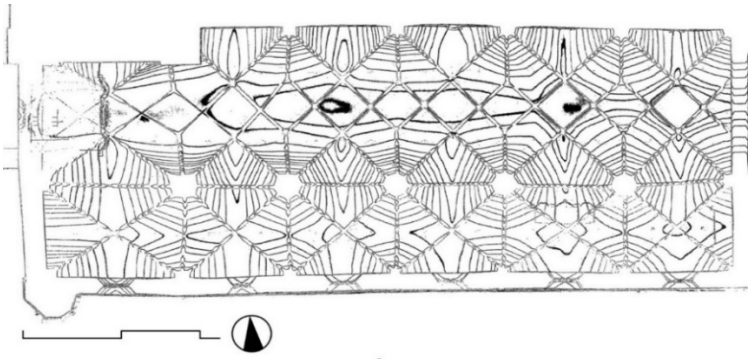

Fig. 12. Mapping of the main nave vault in Mediaş.

[62] Jobbik, "Linear and Centralised Net Vaults," 33–35.
[63] Jobbik, "Linear and Centralised Net Vaults," 35.
[64] Jobbik, "Linear and Centralised Net Vaults," 36–38.

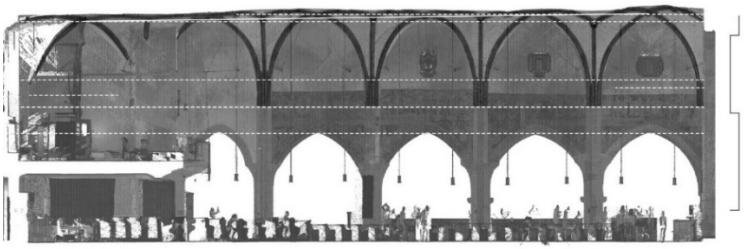

Fig. 13. Longitudinal section of the main nave vault in Mediaş.

Overall, despite the identical rib patterns, the overall geometry of the rib systems in the nave of St. Martin's in Landshut and the apse and nave of the fortified church in Mediaş differ significantly. The very regular and clear system of Landshut is not reproduced in Mediaş.

4.2. Comparative analysis: Landshut–Sighişoara

In the case of Sighişoara, the rib patterns are not identical to the above-discussed vaults. However, existing literature indicates that this church is directly analogous to Landshut due to guild connections. Therefore, the underlying logic of the structures may be worth analysing.

The connection between the ribs and webbing may also be described as a real net vault with webs built using formworks. However, the centralising and linear net vault features are mixed: the lower parts of the vaults are centralising, while the upper parts are linear[65] (Fig. 14). Additionally, the identified underlying construction technique of the rib system in these vaults displayed sharply different features than in former cases. Based on the global geometry of their rib systems, these vaults can be classified as examples of the third theoretical outcome. Thus, the construction of the cross-directed and vertical coordinates (cross-section view) preceded the construction of the longitudinal coordinates. The latter were likely added using the chord length of the individual ribs—as those are very regular within a given rib type[66] (Fig. 15). Since the nave vaults in St. Martin's and in Mediaş can be regarded as examples of the second theoretical outcome, and the apse in Mediaş may be classified as the first theoretical outcome, the nave vault in Sighişoara is very distinct in this respect.

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65 Eszter Jobbik and János Krähling, "Mapping Rib-Webbing Connections in Late Gothic Net Vaults: A Geometry-Based Typology," *Digital Applications in Archaeology and Cultural Heritage* 35, (2024). https://doi.org/10.1016/j.daach.2024.e00388.

66 Jobbik and Krähling, "Late Mediaeval Net Vault," 186–187; Jobbik and Krähling, "The Geometric System," 29.

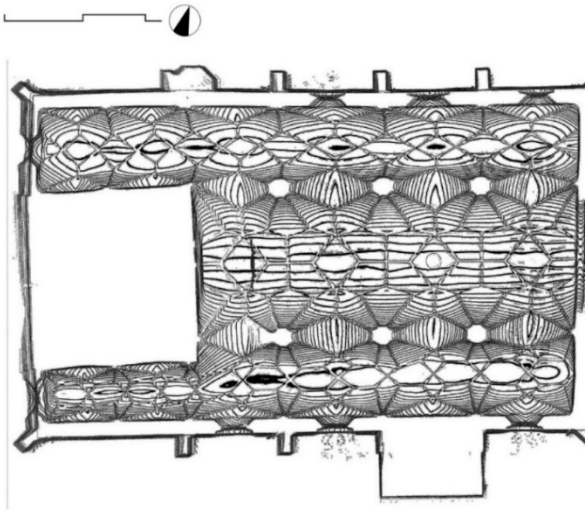

Fig. 14. Mapping of the main nave vaults in Sighişoara.

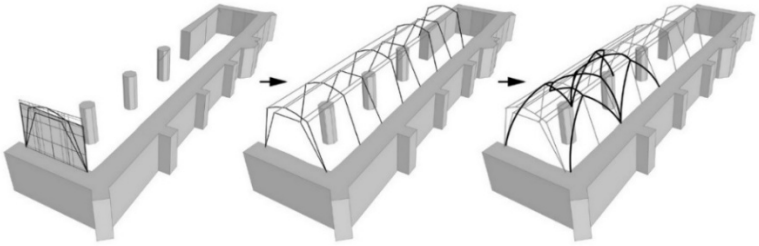

Fig. 15. Theoretical reconstruction of the Sighişoara vaults' building technique. The figure solely shows the logic and nature of the supporting structure and does not aim to reconstruct the exact structural solutions of the wooden structures.

4.3. Evaluation

Based on the findings of the comparative analyses, we argue that the rib pattern, which has traditionally been considered the primary basis for establishing genealogical relationships among net vaults, is insufficient for identifying two structures as identical. Laser scanning allows us to examine underlying construction methods and design principles in unprecedented detail. Therefore, the global geometry of net vault structures should not be overlooked when researching architectural interconnections during the Late Gothic period in Europe. To further emphasize the importance of the vertical coordinate and the global geometry in

this regard, we would like to point out that no measuring device is needed to sketch the rib pattern of a net vault. Any master visiting foreign churches must have been able to do that. In other words, rib patterns are quite easy to copy. Nonetheless, the production of the same global geometry or even of the same underlying construction principles required a deeper knowledge of the sample structure. This kind of knowledge may have been transferred when a guild or a master builder moved to a new building site. However, when a less experienced participant in the original construction—or even an external observer—attempted to replicate it at a new site, the resulting details were unlikely to align precisely.

Another issue pertaining to the discussed question concerns the circumstances of each construction project. In Landshut, for example, the nave was built "from scratch," and, although multiple masters worked on it, no previous building phases restricted the geometry of the vaults. In the case of Mediaş, the position of the tower clearly affects the ground plan of the nave, and the distortion of the apse's layout might have been caused by the adaptation to a previous apse. Nonetheless, these slight distortions did not necessarily imply significant changes in the construction methods. The case of Sighişoara is different due to the distorted outline of the Romanesque church, which was influenced by the position of a former rotunda and the load-bearing characteristics of the hill.[67] The Gothic phase followed the outline of the Romanesque one,[68] resulting in a highly irregular plan to vault. The peculiar vault construction strategy identified in this case presumably served to mask the irregularities in the church's space.[69] This suggests that the given circumstances (former construction phases) may have had a considerable effect on the construction and building strategies, therefore even the global geometry of the vaults is to be considered carefully when discussing building genealogies. The case studies presented in this article naturally prompt reflection on the relationship between center and periphery. The comparative analyses reveal that the construction strategy employed at St. Martin's represents a far more coherent and self-contained system than those observed in the two Transylvanian churches. Of these, Sighişoara—long regarded as the Transylvanian "place of origin"—exhibits the most irregular structural system. The concept of center and periphery can be interpreted in terms of the expertise of the involved craftsmen and guilds involved, as well as the financial resources available to communities undertaking construction projects. These factors may also intersect with the existence of previous building phases.

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[67] Istrate, "Voraussetzungen", 9.

[68] Istrate, "Voraussetzungen", 13; Istrate, "Entstehung und Entwicklung," 457.

[69] Jobbik and Krähling, "The Geometric System," 29; Jobbik and Krähling, "A Methodological Approach," 109.

Ultimately, we believe that examining additional case studies from both central and peripheral contexts is necessary to determine the significance of this issue.

5. Conclusion

This article discussed the new possibilities offered by terrestrial laser scanning in building archaeology. Through the presented case studies, the scope of the discussion was extended to include the analysis of building connections.

First, we had to summarize the geometry-based typologies established during our previous research on construction strategies for connecting rib systems and net vault webs, as well as the global geometry of rib systems in such vaults. This was a necessary methodological prerequisite. The scanning provided a geometric description of the main nave vault of St. Martin's Church in Landshut. Furthermore, we identified the categories within the presented typologies to which this structure may belong. We also examined the potential temporary supporting structures that could have been employed during the construction process. The analyzed net vault was found to be highly regular in its construction, a characteristic that extends not only to the vault itself but to the other architectural elements of the main nave as well.

Another step in the present inquiry was conducting comparative analyses of the net vaults in St. Martin's Church and two South Transylvanian churches: the apse and main nave vaults in Mediaș and the three nave vaults in Sighișoara. Of the Transylvanian examples, the construction principles of the apse vault in Mediaș were found to be the most regular. However, this structure still exhibits less self-consistency than the vault in Landshut. The nave vault in Mediaș displays distinct and varied characteristics. The nave vaults in Sighișoara, on the other hand, exemplify a particularly unique construction principle, especially in relation to the overall geometry of the rib systems. This feature distinguishes them from the other case studies discussed here. Overall, the comparative analysis primarily highlighted significant differences in the underlying construction principles and strategies. Based on the results of the comparative analyses, we discussed two key aspects of using global vault geometry as the foundation for discussing vault genealogy and building interconnections, rather than focusing solely on the plan layout or rib pattern. First, we considered how specialized knowledge was required to "replicate" the global geometry, particularly the vertical dimensions of a net vault, in contrast to simply "duplicating" the rib pattern. Second, we considered the site-specific circumstances that might influence decisions during the construction of net vaults. We argue that the presence of previous building periods can significantly limit available options or necessitate

unique solutions. Our three case studies support this conclusion. Additionally, we explored how a building's location in the center or periphery in a given era might impact the outcome of the construction process.

Overall, the accurate data and geometric analysis of late Gothic net vaults offer valuable insights into their structural design and geometry-based typology. When examined across multiple buildings, the geometric relationships among their net vaults can significantly enhance our understanding of architectural genealogies and interconnections in late Gothic Europe.

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