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Two Churches, One Forest? Timber Supply for the Holy Cross Collegiate Church and St. Paul Cathedral's Roof Frames (1251–1351 CE)

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Abstract

The churches of Saint-Paul and the Holy Cross in Liège represent two important examples of medieval architecture within the Mosan region. Both have been the subject of numerous historical, archaeological, and dendrochronological studies and

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publications. The oak (*Quercus* sp.) frames of these two buildings have been dated to the 13th and 14th centuries, with relatively comparable felling phases. The comparison also extends to their construction typology and progress, suggesting that the same school of carpentry may have been responsible for both Gothic structures. Given the similarity of the construction typology and dating of these church frameworks, what can be said about the supply of wood required for both frameworks? Therefore, the analysis of tree-ring series, known as dendrochronology, contained in preserved timbers is relevant. To answer this question, we first applied a sampling protocol to (1) ensure the comparability of the two corpora and (2) assess the correlation thresholds between the annual ring series. A total of 162 timbers, dated and documented through 273 radii, revealed a new construction phase occurring between the mid-13th and mid-14th centuries. The hierarchical classification of individuals demonstrated strong correlations during tree felling in the mid-13th century, whereas correlations decreased in the subsequent phases. These findings indicate a close proximity among the forests that supplied the first felling sites. Conversely, subsequent felling suggests that the builders were sourcing resources from different forests, probably further apart.

Keywords

cluster analysis – dendroarchaeology – Middle Ages – Meuse basin – provenance – wood supply

1 Introduction

The churches of Saint-Paul and the Holy Cross in Liège are two important medieval examples of Mosan architecture (Fig. 1). Both have been examined in numerous historical, archaeological, and dendrochronological studies and publications (Hoffsummer, 1995, 2002; Piavaux *et al.* 2005; Maggi *et al.* 2012; Piavaux, 2013).

The oak (*Quercus* sp.) frameworks of these two buildings date to the 13th and 14th century, with relatively similar felling phases (Hoffsummer, 1995). The comparison extends beyond their strict dating to include their construction typology. Both roof structures utilise a rafter-frame design. The trusses of both choirs feature intersecting struts that maintain the spacing between the rafters. These similarities also apply to the construction process, leading Hoffsummer (1995) to suggest that the same carpentry school may have been responsible for both Gothic structures.

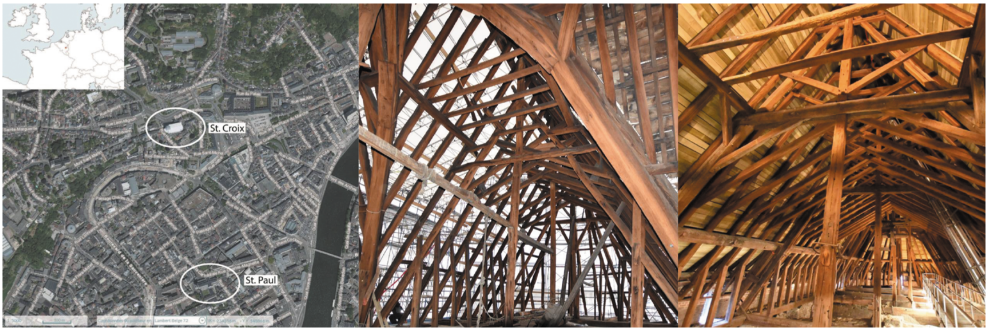

FIGURE 1 Geographical location (left). View of the choir loft at the Holy Cross Church (centre). View of the choir loft at St-Paul's church (right).

These 13–14th-century buildings are reconstructions. The two churches belonging to the diocese of Liège were established in the late 10th century and completed under the direction of Prince-Bishop Notger. Both were subsequently recognised as collegiate churches with an associated chapter of canons. Saint-Paul was designated as a cathedral in 1795 following the demolition of the former Cathedral of Saint-Lambert, while the Holy Cross retained its status as a collegiate church. Despite both chapters being under the episcopal authority of Liège, each chapter maintained distinct possessions, likely encompassing forests dating back to the Middle Ages. This was the case for Saint-Paul, which owned several hectares of forest during the latter half of the 18th century (Dury, 2018). However, the translation of this concept to the middle ages remains unclear. Although the frameworks of these churches are comparable in terms of construction typology and dating, can we draw the same conclusion regarding their wood supply?

The use of wood in constructing the frameworks of large churches has been extensively studied and examined from various perspectives in Western Europe. Numerous regional syntheses of roof truss archaeology effectively integrate the dendrochronological approach, exemplified by studies in Normandy (Epaud, 2007), Brittany (Olivier, 2020), the Paris Basin (Epaud, 2019) and, more generally, large portions of western France (Hoffsummer, 2011; Hunot, 2022), northern France, and Wallonia (Hoffsummer, 2002). Religious buildings in southern Europe have also been the subject of recent studies examining their relationship with forest resources, specifically focusing on their provenance. This is the case for the Cathedral of Jaen and the Collegiate Church of Seville in post-medieval Spain (Dominguez-Delmas *et al.*, 2018), the churches of Madeleine and Saint-Jean de Malte in Aix-en-Provence (Shindo, Claude, 2019), and the Cathedral of Florence (Macchioni *et al.*, 2023). These great religious buildings offer substantial material for study, given the considerable number of trees that have been converted into pieces of wood, leading to fossilised forests in the surviving frames. The inescapable and irreplaceable nature of these remains underscores their fragility, as evidenced by the tragic fire at Notre-Dame de Paris in 2019. However, the strong mobilisation around this burnt structure should also be emphasized (Dufraisse, 2024).

Although the provenance of wood is occasionally documented in written records (Epaud, 2017), this is rarely the case, particularly during the medieval period. The traditional ring-width dendroprovenancing method, which relies on the correlation between mean site chronologies, is often limited by the limited climatic and environmental variability present at the local scale (D'Andrea *et al.*, 2023). A dendrotypological approach at the individual scale serves as a lever to extract reproduced general climatic signals, as evidenced in average site chronology. Mean chronologies can buffer local environmental signals embedded in the ring-width series that constitute them. Consequently, an individual-series dendroprovenancing approach has been proposed to group trees more effectively by region or even specific forests of origin (Girardclos and Petit, 2011). The analysis of provenance through individual assessments has yielded promising results, applicable at various scales, including forests (Lambert, 2011), cities and their surroundings (D'Andrea *et al.*, 2024), and broader contexts (Dominguez-Delmas *et al.*, 2014; Bernabei and, Franceschi, 2024; Seim *et al.*, 2024). Hierarchical classification is particularly effective for identifying groups of trees exhibiting common growth variations and, by extension, shared local signals (Lambert, 2011). Therefore, we decided to use a cluster analysis approach to determine whether, in addition to typological similarities in construction, the two buildings previously described were also comparable in terms of wood supply. However, because the number of samples analysed for each building was uneven, we decided to conduct additional dendrochronological studies to ensure fair comparability of the two datasets. The restoration efforts undertaken at the Collegiate Church of the Holy Cross in recent years have provided an opportunity for a new sampling campaign on the roof structure of the church. Following this initial acquisition, which was added to the corpus of the tree-ring series for this building, the same protocol was implemented at Saint-Paul.

In the following section, we outline the methods used, from the sampling protocol and dating of the slaughter phases to evaluating relevant tests for cluster and growth trend analyses. This is followed by a step-by-step presentation of the results and points of discussion.

2 Material and Methods

The material used in this study was a series of tree-ring samples obtained from the roof timbers of the churches of Saint-Paul and Holy Cross in Liège (Belgium). The timber samples have been subjected to several sampling campaigns since the 1980s. The objective of these field campaigns was to date frameworks and establish the building typology. Dendrochronological analysis of the similarities and differences in wood supply indicated the standardisation of the corpora from the two frameworks and establishment of a new sampling protocol. Prior to this study, the initial corpus was relatively uneven, with 16 individuals from the Holy Cross and 66 individuals from Saint-Paul. However, in the case of Saint-Paul, it is noteworthy that out of the 66 average growth chronologies, this plan included 44 cross-sections from its restoration conducted a few years prior. The locations of some of these 44 timber pieces are still uncertain; therefore, they are not depicted in Figure 3. In addition, the method for measuring the radii differed from that specifically employed in this new study, as the two radii measured in these cross-sections were situated within the same plane. Therefore, they were omitted from analysing correlations between the radii of the same beam. However, the corresponding tree-ring series were incorporated into analysing correlations between individuals using an ascending hierarchical classification.

2.1 *Sampling*

Wood samples were taken to obtain representative correlations between the radii of individual trees and show the differences in growth along the trunk and on two opposite sides. Whenever feasible, the two cores were separated from each other, positioned on opposite radii, or aligned along the same radius for each sampled beam. They were sampled via coring using a Rinntech borer in conjunction with a power drill. Most samples were from opposite radii; however, approximately 40% were obtained from the same radius, primarily because of limited access to the opposite radius and occasionally as a result of the cutting methods (quarter or half strand). Horizontal parts, such as crossbeams, facilitate the sampling of two spokes positioned several meters apart. In the case of a vertical part, such as a punch, or an inclined part, such as a rafter, the distance between the two rays is limited by the maximum coring height based on the size of the person conducting the sampling. In the Saint-Paul framework, two superimposed metal decks in the nave and transept make it possible to walk, one over the crossbeams and the other over the false crossbeams several meters above.

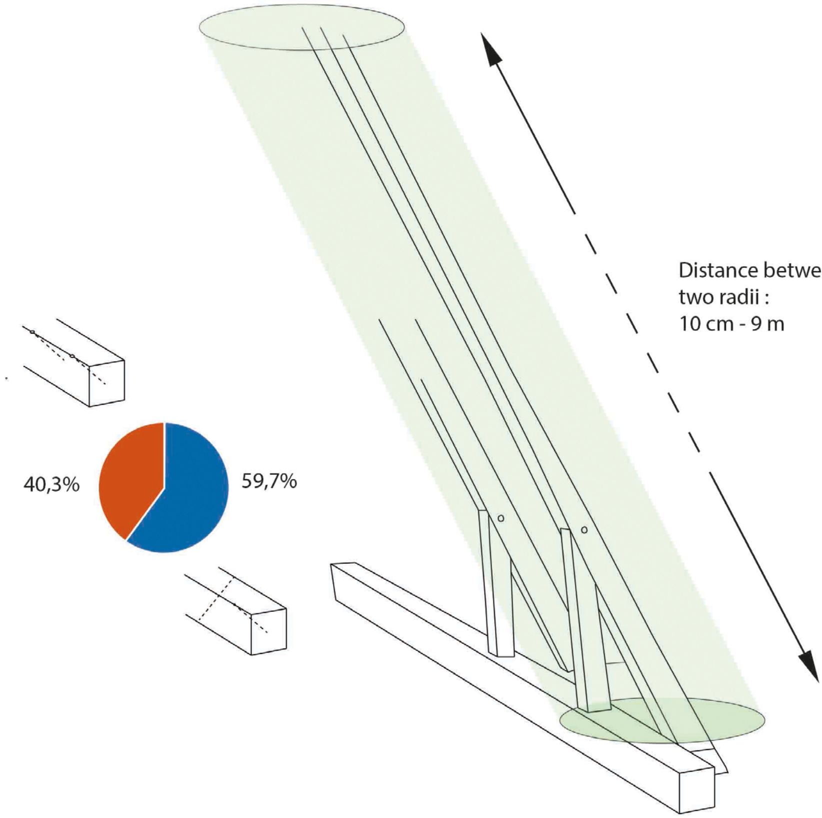

FIGURE 2 (Left) Coring repartition between samples obtained from the same (orange) and orthogonal (blue) radii. (Right) Accurate visual representation of the distance range between two samples obtained from the same beam

This configuration enabled the sampling of the radii of several vertical pieces from Saint-Paul at distances reaching up to 9 m (Fig. 2). For the Holy Cross Church, which lacked such an arrangement, the maximum sampling distance for the vertical pieces was 181 cm. Most coring distances ranged between 30 and 180 cm. Similarly, we attempted to obtain core samples with opposite radii, which were mostly achieved (Fig. 2), although approximately 40% of the cores were aligned along the same radius.

2.2 *Dating and Establishing the Phases of Construction*

Hoffsummer (1995) published the felling phases of oaks used in frame reconstructions. While the different phases were highlighted, only a few beams per phase were analysed, resulting in a potential bias. This bias, combined with the limited number of available tree-ring series (16) from the Holy Cross Collegiate and the disparity in corpus size (66 TRS from Saint-Paul were available), required careful examination. Consequently, all new samples were dated to facilitate the further development of the present study.

After the cores were cut with a cutter blade to enhance the visibility of ring limits, the averaged growth chronology (corresponding to the individual series, as defined by Kaennel and Schweingruber, 1995) was indexed and cross-dated. The accuracy of the cross-dating was determined using the Student's *t*-test, as outlined by Baillie and Pilcher (1973) and calculated using Dendron IV software (Lambert, 2006; Durost and Lambert, 2007). The radii of the same beam were averaged to obtain the individual chronology. These chronologies were subsequently detrended using the Corridor method. The chronologies were compared with the existing average chronologies for the two churches (Hoffsummer, 1995) and reference chronologies available for the Meuse Basin.

The felling phases were analysed by estimating the missing sapwood rings within a confidence interval of 4–34 annual rings, applicable in 95% of the cases (Lambert, 2006), and by comparing these findings with the archaeological evidence (assembly marks) identified by Hoffsummer (1995).

2.3 *Calculation of the Correlations between Two Radii of the Same Beam*

The correlations between the two radii of each wood were determined using four distinct calculations: natural values; logarithmic transformation; the Except de Besançon index, which is a moving window (Lambert and Lavier, 1992); and the Corridor method, a polynomial transformation based on the construction of maximum and minimum possible growth curves for each ring-width series (Shiyatov and Mazepa, 1987; Cook *et al.* 1990; Durost 2005; Lambert 2006, Lambert *et al.*, 2010). Apart from the raw value calculation, the other three methods served as detrending methods that eliminate certain (logarithmic transformation and Corridor) or all (E-Besançon) long-term trends. Additionally, the Corridor and log transformations retained some medium-frequency patterns and potentially local disturbances.

These correlations are indicated by the distance between the sampled radii and overlap of the ring-width series (as noted by Garcia-Gonzalez (2008) using the 1/*t* method). The different transformations were compared to assess their effectiveness in identifying significant value thresholds.

2.4 *Comparison of Mean Chronologies and Hierarchical Classification of Individuals*

To assess the results obtained by Hoffsummer (1995) for the mean chronologies of the two frameworks, the *t*-test values and Pearson correlation coefficients (*r*-values) calculated from the two mean chronologies were compared using the same tests (natural values, log, Corridor and E-Besançon). To examine the correlations between the two datasets, we used the averaged growth chronology to perform matrix correlations through ascending hierarchical classifications, aiming to identify both clusters and average correlations within each of the identified logging phases. This classification starts with individual observations and expresses the statistical distance, thereby indicating the similarity between two individuals. This classification iteratively groups individuals to create a classification tree (Lambert, 2019). To examine coherence or differences in supply, individuals were categorised into groups representing the main felling phases to identify clusters based on the harvesting period.

From this point of view, the objective is to group enough beams together to form clusters while simultaneously maintaining consistency regarding felling dates. Relatively close felling dates also ensure considerable overlap in the ring series. Furthermore, to ensure consistency in terms of the felling phases, sapwood was excluded from this analysis because it cannot be assigned to one phase over another. Notably, the analyses were performed over the full ring widths, ensuring a minimum overlap of 30 years. This overlap considers mid-frequency signals pertinent to similar local growth responses (Lambert, 2006; Guts, 2018). In the context of this study and in view of the data collected, the analysis conducted over a period common to all series was irrelevant due to the limited number of individuals involved.

The tests employed in this analysis proved to be the most informative and important and were derived from the calculations carried out between departments, as mentioned in the previous paragraph ('Calculation of correlations between two radii').

However, even when all four tests (natural values, log, Corridor, and E-Besançon) were considered and assessed, only the most significant results were retained.

2.5 *Growth Rates*

Growth rates or age trends were used to examine specific forest selections, highlight environmental factors (density, population, and forestry practices), and observe growth from a different perspective than that of correlations between ring series. Cumulative growth was used to obtain the overall shape of the growth curves. Additionally, the annual ring series were initially divided into functional groups and subsequently into major felling phases, facilitating examination through cluster analysis.

3 Results and Discussion

3.1 *Dating Woods and Establishing the Phases of Construction*

This study resulted in the acquisition of 111 new individuals within the ensemble, compromising 63 for Saint-Paul and 48 for the Holy Cross. These individuals supplement the 16 previously dated timbers in the Holy Cross framework and 63 from Saint-Paul. Among the 111 timber samples, 83 were dated, yielding 162 dated individual series and establishing a chronology ranging from 1034 to 1404 for the two sites (Fig. 3, top right).

3.1.1 Saint-Paul (Fig. 3, Bottom Left)

3.1.1.1 *The Choir*

The Saint-Paul choir comprises three primary trusses. From the transept square, the first two main beams are separated by five secondary beams, whereas the second and third main beams are separated by eight secondary beams. Fourteen timbers dated between 1237 and 1253 documented this area. Four timbers provided cutting dates (1242, 1251 (appears twice) and 1253). Seven timbers possessed preserved sapwood, while three timbers lacking sapwood yielded only a *post quem* date. The four timbers containing cambium had a complete endwood (felled between late summer and late winter of the following year) and revealed three closely spaced felling phases: 1242–1243, 1251–1252 and 1253–1254. The estimation of the missing sapwood from four individuals aligns with felling occurring after the 1242–1243 phase, yet it may pertain to either of the following two phases. The other three beams cannot be assigned to any of the three phases. The apparent coherence of construction is supported by Hoffsummer's (1995) numbering of farmsteads (marks and countermarks). This overall coherence means that the autumn-winter of 1252–1253 may serve as a potential *terminus post quem* for constructing the choir frame.

3.1.1.2 *The Transept*

Twenty-three dated timbers documented the transepts of Saint-Paul. The northern and southern arms were each composed of three main trusses separated by five secondary trusses. At the centre, the square of the transept was formed by two strong crossbeams that intersected to form a beam with a central perforation. Six timbers from the square were dated between 1228 and 1265, including two with preserved sapwood and four with *post quem* dates. The preserved sapwood allowed us to estimate possible felling between 1251 and 1266, accompanied by a *terminus post quem* of 1269, which concerned a rafter at the

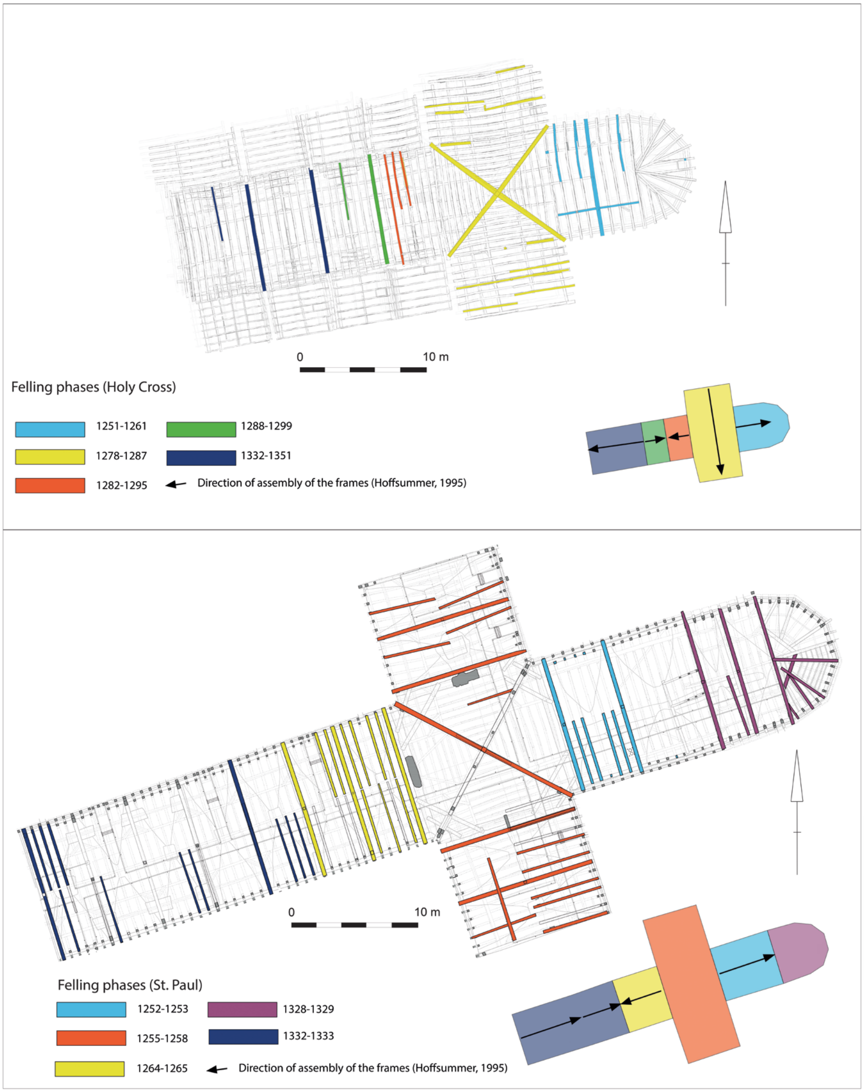

FIGURE 3 Timber felling phases superimposed on construction phases. Floor plans: AA/TGI, pHD, E.Pallot, AWAP and Uliege.

top of the roof. Given the current state of knowledge, we hypothesised that this could have been a repair performed in the second half of the 13th century.

Eleven timbers were dated between 1231 and 1261 in the southern arm of the transept, nine of which had preserved sapwood and two of which provided a *post quem* date; however, no cambium could be sampled. The range of the maximum sapwood allowed us to estimate possible felling between 1252 and 1264. To avoid misinterpretation, wood dated to 1261 and purlin from the upper parts of the roof were not included in this estimate. In this particular case, it could simply be a repair or reinforcement of a part of the roof structure, which could date between 1262 and 1281. The six dated timbers from the northern arm provided dates between 1244 and 1254. One of the timbers dated to 1247 provided a *post quem* date, while the other five, containing preserved sapwood, allowed us to estimate the felling phase between 1255 and 1258.

Assembly and countermarks were not recorded, preventing a precise construction phase proposition at this stage. The three components of the transept (square, south, and north arms) fell within the 1255–1258 period, indicating it as a possible felling phase and a *terminus post quem* for transept construction.

3.1.1.3 *The Nave*

Two sets of dates were present in the nave: the first set (n = 12) consists of a series with the last ring dated between 1248 and 1264, while the second set (n = 14) was dated between 1312 and 1332. Two pieces dated 1283 and 1404 appeared to fall outside these groups. The timbers in the first group came from the two eastern bays (from the sixth to the eighth main trusses) immediately west of the transept crossing. Of the timbers in this group, only the doorway of the sixth main truss retained a cambium dating to the autumn-winter of 1264–1265. The other timbers in the group contained preserved sapwood but no cambium. The estimation of the missing sapwood, and consequently the felling dates, indicated a felling hypothesis linked to the date of the entablature of the sixth main truss, specifically autumn-winter 1264–1265.

The timbers in the second group, dated 1312–1332, originated from the five bays next to the west. Again, only one timber, dated 1332, provided a felling date. This was a rafter from the second secondary truss. Therefore, as with the first group, the proposal to date the felling was based on this element, given the lack of contradictory or invalidating evidence. Considering the completeness of the final timber, felling in the autumn-winter of 1332–1333 appeared conceivable. However, the lack of cambium on most timbers may obscure other felling phases. The two timbers dated 1283 and 1404 were *termini post quem* and located in the five western bays, where the felling phase was proposed to have occurred in 1332.

3.1.1.4 *The Sanctuary*

The sanctuary located at the eastern end of the frame contained 11 timbers for study, dating from 1225 to 1328. Four timbers exhibited no preserved sapwood, five had preserved sapwood, and two contained cambial dates of 1327 and 1328. Three felling phases could be estimated: the first was based on two pieces of wood between 1232 and 1240; the second occurred in the autumn–winter of 1327–1328; and the third followed in the autumn–winter of 1328–1329. The two pieces of wood linked to the first felling may have originated from prior fellings and been repurposed in the construction of the sanctuary's frame, which is presumed to have been completed between 1328–1329.

3.1.2 Holy Cross (Fig. 3, Top)

3.1.2.1 *The Choir*

The choir of the Holy Cross Church contains 12 timbers dating from 1229 to 1442. No cambium was preserved, ten timbers contained preserved sapwood, and two timbers exhibited no sapwood. The sapwood rings made it possible to estimate three felling phases: the first between 1251 and 1261, the second between 1329 and 1356, and the third between 1442 and 1472. In addition, sapwood-free wood was observed, the last ring of which dated to 1283, which could possibly reflect an additional felling phase between the first two. The first phase accounted for most of the dated timbers (eight), several of which were important structural elements (beams and rafters). Therefore, we hypothesised that this could have been the first felling phase and the *terminus post quem* for constructing the choir frame. The three most likely later phases of felling individually referred to the posts and represented the repair phases.

3.1.2.2 *The Transept*

Twenty-one timbers were dated in the Holy Cross transept: five from the transept crossing, seven from the north arm, and nine from the south arm. Of the 21 timbers, 16 exhibited preserved sapwood (no cambium), while five had only a *post quem* date. The north and south arms consisted of three main trusses separated by three secondary trusses. An estimate of the maximum amount of sapwood indicated that felling occurred between 1278 and 1288 for the north arm and between 1278 and 1287 for the south arm. In the centre, the sapwood of the timber in the transept square indicated that felling occurred between 1278 and 1297. Hoffsummer's (1995) survey of assembly marks and countermarks revealed a continuous numbering system extending from the north gable wall of the north arm to the south gable wall. The felling phases of the three sets associated with these assembly marks demonstrated that the timbers were felled in the same phase between 1278 and 1287.

3.1.2.3 *The Nave*

In the nave, the 17 dated timbers provided felling dates between 1190 and 1331. Of these 17, 8 exhibited preserved sapwood samples and dated between 1254 and 1331. The remaining nine were dated *post quem*. Considering the estimated maximum amount of sapwood, we could distinguish between three felling phases: 1260–1266, 1278–1295 and 1332–1351. However, if we consider the assembly marks and numbering of the trusses identified by Hoffsummer (1995), we can observe a different phasing. This numbering was continuous from west to east and from the fifth main frame to the third secondary frame of the sixth main frame. From an archaeological perspective, this phase dated from 1288 to 1299. The numbering of frames was again continuous from the seventh to the eighth main farmstead, and this felling phase could be dated between 1282 and 1295. These two phases overlapped between 1288 and 1295. Therefore, grouping them together in a single, tighter phase may be tempting.

However, successive wood deliveries can be envisaged at different times. To date, the available data do not allow us to propose phases other than 1282–1295 and 1288–1299. To the west, from the third secondary farm, immediately before the fifth main farm, to the first main farm, two butchering phases coexisted within the same continuous number of farms: 1282–1305 and 1332–1351. The last two phases were supported by three timbers, two of which, a post (1281) and a mullion (1330), originated from the third main farm. The post of 1281 (possibly felled between 1282 and 1305) was an element from the previous felling phase that was reused or even stored until it was employed after the 1332–1351 felling phase.

3.1.3 Refining Previous Phasing

This new sampling of roof timber from the churches of Saint-Paul and the Holy Cross in Liège provided new details on the felling phases and, consequently, on the chronology of the building sites. However, this did not invalidate Hoffsummer's (1995) chronology. The new proposal for the first demolition phase of Saint-Paul's choir constituted 1252–1253 instead of 1251–1252. In the case of the transept, the cutting of which could have also been completed in 1251–1252, the new data postponed tree felling to 1255–1258. The same applies to the two eastern bays of the nave, which were previously attributed to the same phase and were now transferred to 1264–1265. However, the interpretation differed for the next two bays, which were previously confined to a felling phase at approximately 1290–1300 and now combined with the last bays to the west in a single phase of 1332–1333.

These changes are similar to those seen in the Holy Cross Church. The first phase, previously proposed as 1255–1256, was re-estimated to a wider interval between 1251 and 1261. The transept and two eastern bays of the nave have also been dated to a narrower range of 1283–1284. The three new phases proposed in 1278–1287 (transept), 1282–1295 (1st bay of the nave) and 1288–1299 (2nd bay of the nave) complicated the chronology of construction as they overlapped in time. These phases of construction closely followed each other. However, the lack of timber with cambium prevented us from further analysing this new chronology.

These dates provide a *terminus post quem* for construction. We know that in *Ancien Régime* societies, timber was squared shortly after felling, and in many cases, construction followed shortly afterwards (Hoffsummer, 2002). The timber may have been stored. This was the case at Bourges Cathedral (France), where work on the nave began around 1256 and continued around 1263, with timber being cut and stored from 1230 onwards (Epaud, 2017). However, this prolonged period between the two construction phases can also be found at sites geographically closer to Liège, albeit later. This is the case, for example, with Notre Dame du Sablon in Brussels, where the eastern part of the nave was constructed at the end of the 15th century, approximately 30 years after the transept frame and approximately 45 years before the western part of the nave (Weitz *et al.*, 2015). A similar pattern can be observed in constructing the frame of the Mechelen Cathedral, with construction phases separated by 50 and up to 100 years (Eeckhout and Houbrechts, 2002; Cremer and Maggi, 2018).

3.2 *Comparing Radii and Assessing Correlation Thresholds*

A comparison between the radii from the same wood was performed on 86 of the 162 dated individuals, specifically 172 radii (Table A1 in the Appendix). The 76 individuals excluded from this analysis showed disturbances or irregularities in growth (e.g., branches leaving the area close to the core) in one of the two radii. The first result (Fig. 4A) shows the r-values in relation to the overlap. Although relative dispersion of the overlaps existed, the majority appeared to be concentrated in the 60–110 interval, with extreme values between 21 and 110 tree-rings. The results obtained for the raw, logarithmic, and Corridor values demonstrated that overall, the *r*-value was stable, although a slight decrease was observed as the overlap increased. However, the results obtained by E-Besançon showed a sharp decrease in the *r*-value as the overlap increased. This result excluded the E-Besançon, whereas the other three calculations exhibited the relative stability of *r* as a function of overlap.

Regarding the coring distance between the two radii in terms of the *r*-value, the four calculations showed a drop of approximately 0.2 between the minimum (30 cm) and maximum (9 m) distances (Fig. 4B). In the case of raw value and log, *r*-values varied from 0.8 to 0.6 overall and was slightly less (from 0.62/0.63 to 0.5/0.55) for the Corridor and E-Besançon transformations.

Although this variation seems understandable as the distance between the two radii along the trunk increases, these results suggest that lower average *r*-values should be considered when identifying beams from the same trunk. Indeed, the common origin of the two logs from the same tree indicates that they most likely originated from two distant locations on the trunk.

Considering the *r*-values obtained by the four calculations, we can observe that they vary over an extensive range, from 0.21 to 0.92. Most *r*-values were obtained by transformation with E-Besançon and Corridor between 0.45 and 0.75/0.8. Both tendencies are somewhat constant but do not show a significant range of values or thresholds owing to the high dispersion of *r*. However, a threshold can be determined using raw values and log transformations. As can be seen in Fig. 5, the *r*-values are far more represented (16–19%) between 0.8 and 0.9 than those obtained for the other two transformations. If we look at the shape of the log and raw curves, we see that they rise more sharply around 0.6 and 0.7, respectively. In the scope of this demonstration, the logarithmic transformation appears to be the most relevant.

The thresholds for attributing two timbers to the same tree are the subject of several publications in dendrochronological literature. Bernabei (2022), who provides a summary of the issue, concludes that Student's *t*-test alone is inadequate to confirm this common origin. For example, while Hillam and Groves (1996) suggested $t > 10$ (for oceanic oak in the UK), Klein *et al.* (2014) suggested $t > 14$ for continental oak, which tended to indicate strong differences in correlation depending on the geographical area of observation (Bernabei, 2022).

Overall, the intra-individual data available (in raw and logarithmic form) indicates a *t*-test between 4 and 12 for an *r*-value between 0.6 and 0.7, between 8 and 17 for an *r*-value between 0.7 and 0.8, and between 7 and 47 for $r > 0.8$ (Table A1 in the Appendix). These results suggest that $r > 0.85$ is required to exclude all $t < 11$.

Girardclos and Petit (2011) propose a minimum *r*-value of 0.8 in addition to a visual similarity of the curves for two logs originating from the same tree. Girardclos and Petit (2011) also used this exclusive indicator to provide a finer approximation of local factors influencing tree growth for dendrotypological purposes. In addition, the analysis of the radii of the two collegiate churches assisted in proposing a new interpretation of the correlation thresholds within the same oak (from the Meuse Basin), enabling us to use these calculations and values in the inter-individual analysis. Given the current statistical tools available in dendrochronology, precise characterisation and modelling of the local factors influencing growth, whether due to site conditions or human activity, remain two major research challenges.

TABLE A1

SMP	Raw	L1	L2	OVL	Ttest	rMoy	Corrido	L1	L2	OVL	Ttest	rMoy
91-01-006		159	133	128	13.08	0.66		159	133	128	10.26	0.59
91-01-008		151	156	147	13.14	0.64		151	156	147	12.25	0.62
91-01-009		185	102	99	23.78	0.81		185	102	96	10.31	0.63
91-01-011		98	86	84	22.07	0.82		98	86	84	8.66	0.61
91-01-014		153	117	116	5.02	0.4		153	117	116	6.49	0.47
91-01-016		66	69	64	14.91	0.77		66	69	61	12.43	0.74
91-01-022		149	148	145	47.09	0.88		149	148	142	32.28	0.83
91-01-023		123	143	108	6.88	0.5		123	143	107	6.68	0.49
91-01-025		98	87	81	15.91	0.76		98	87	80	7.97	0.59
91-01-029		59	86	58	5.45	0.53		59	86	55	5.98	0.56
91-01-034		111	109	107	34.35	0.86		111	109	102	20.55	0.79
91-01-035		138	162	134	8.65	0.64		138	162	129	10.3	0.59
91-01-036		94	107	83	5.05	0.45		94	107	81	4.31	0.41
91-01-037		120	41	40	10.72	0.75		120	41	40	4.93	0.55
91-01-038		109	153	108	8.28	0.56		109	153	105	4	0.35
91-02-001		129	114	112	35.39	0.86		129	114	108	4.28	0.36
91-02-004		84	90	81	20.59	0.81		84	90	76	10.14	0.66
91-02-005		167	176	166	26.36	0.79		167	176	159	7.29	0.46
91-02-006		139	118	83	16.85	0.77		139	118	83	8.32	0.6
91-03-003		46	244	45	12.56	0.77		46	244	45	8.28	0.68
91-03-004		192	201	191	36.25	0.83		192	201	189	21.26	0.73
91-03-009		23	35	22	12.22	0.83		23	35	22	10.58	0.81
91-04-003		84	82	76	9.36	0.64		84	82	73	5.52	0.49
91-04-004		66	68	64	14.49	0.76		66	68	64	7.75	0.61
91-04-005		80	68	67	4.2	0.43		80	68	66	4.65	0.46
91-04-006		69	86	67	13.18	0.74		69	86	67	3.67	0.39
91-04-007		79	87	78	4.11	0.4		79	87	73	6.83	0.56
91-04-009		78	87	77	19.09	0.8		78	87	72	2.74	0.3
91-04-010		42	50	38	21.92	0.87		42	50	36	11.57	0.78
91-04-011		97	147	96	6.41	0.5		97	147	94	4.5	0.4
91-04-012		83	58	57	10.33	0.7		83	58	54	3.06	0.37
91-04-013		34	55	33	7.58	0.7		34	55	33	6.86	0.67
91-04-014		84	75	73	15.42	0.76		84	75	71	4.63	0.45
91-04-016		106	94	93	11.42	0.67		106	94	89	6.38	0.51

E_Bes	L1	L2	OVL	Ttest	rMoy	Log	L1	L2	OVL	Ttest	rMoy	Dist (cm)	CrossSMP
	159	133	128	8.31	0.53		159	133	128	13.71	0.67	441	–
	151	156	147	8.62	0.52		151	156	147	15.92	0.69	337	–
	185	102	99	8.92	0.59		185	102	99	21.45	0.8	265	–
	98	86	84	22.67	0.82		98	86	84	30.96	0.86	78	+
	153	117	116	5.43	0.42		153	117	116	5.34	0.41	200	+
	66	69	64	12.4	0.73		66	69	64	21.09	0.83	65	+
	149	148	145	24.98	0.79		149	148	145	46.4	0.88	720	+
	123	143	108	7.99	0.55		123	143	108	6.99	0.51	840	+
	98	87	81	4.32	0.41		98	87	81	15.42	0.75	850	+
	59	86	58	2.35	0.41		59	86	56	6.17	0.57	800	+
	111	109	107	15.53	0.72		111	109	107	26.31	0.82	70	+
	138	162	134	6.13	0.43		138	162	134	13.31	0.66	800	+
	94	107	81	4.38	0.41		94	107	81	5.05	0.45	800	+
	120	41	40	4.31	0.51		120	41	40	9.2	0.72	800	+
	109	153	108	4.01	0.34		109	153	108	8.98	0.58	800	+
	129	114	112	2.74	0.25		129	114	112	18.41	0.75	69	+
	84	90	81	9.95	0.65		84	90	81	23.34	0.83	30	+
	167	176	166	6.83	0.43		167	176	166	24.08	0.77	225	+
	139	118	83	10.29	0.65		139	118	83	15.76	0.75	89	+
	46	244	45	7.18	0.64		46	244	45	10.99	0.75	30	–
	192	201	191	10.9	0.55		192	201	191	29.7	0.79	32	–
	23	35	22	11.86	0.83		23	35	22	12.89	0.84	340	+
	84	82	76	4.72	0.44		84	82	76	8.58	0.62	116	+
	66	68	64	9.01	0.65		66	68	64	18.9	0.81	110	+
	80	68	67	2.17	0.25		80	68	67	2.93	0.33	115	–
	69	86	67	7.72	0.61		69	86	67	13.61	0.75	600	+
	79	87	78	9.02	0.63		79	87	78	7.64	0.58	113	–
	78	87	77	10.6	0.67		78	87	77	20.29	0.81	140	+
	42	50	38	16.64	0.84		42	50	38	24.51	0.89	161	–
	97	147	96	4.67	0.4		97	147	96	5.77	0.47	60	+
	83	58	57	4.88	0.5		83	58	57	8.01	0.64	80	–
	34	55	33	5.49	0.61		34	55	33	6.78	0.67	124	+
	84	75	73	6.14	0.53		84	75	73	13.13	0.73	121	–
	106	94	85	3.54	0.34		106	94	91	14.49	0.73	95	+

TABLE A1 (*cont.*)

SMP	Raw	L1	L2	OVL	Ttest	rMoy	Corrido	L1	L2	OVL	Ttest	rMoy
91-04-017		79	68	51	11.26	0.74		79	68	46	7.77	0.66
91-04-018		179	178	172	21	0.74		179	178	167	8.36	0.49
91-04-020		103	73	51	3.34	0.4		103	73	51	4.44	0.48
91-04-021		184	140	135	13.93	0.67		184	140	135	8.58	0.53
91-04-022		135	169	123	10.73	0.61		135	169	118	9.45	0.58
91-04-023		78	61	60	6.51	0.57		78	61	58	4.84	0.49
91-04-024		121	45	44	4.63	0.52		121	45	44	2.85	0.38
98-01-001		150	111	110	17.14	0.74		150	111	107	8.6	0.57
98-01-004		135	118	117	9.24	0.58		135	118	108	10.19	0.62
98-01-006		82	68	67	10.8	0.69		82	68	66	5.48	0.51
98-01-007		77	65	61	29.53	0.88		77	65	61	37.68	0.9
98-01-008		63	86	61	6.69	0.58		63	86	61	5.41	0.52
98-01-009		59	64	54	30.25	0.89		59	64	54	13.09	0.76
98-01-010		63	71	59	9.21	0.67		63	71	56	11.91	0.74
98-01-012		70	83	63	6.99	0.59		70	83	63	8.78	0.65
98-01-013		61	70	60	4.25	0.45		61	70	60	7.34	0.61
98-01-015		76	111	67	18.19	0.8		76	111	67	6.67	0.56
98-01-017		94	133	92	15.56	0.74		94	133	90	7.05	0.54
98-01-018		217	209	202	9.19	0.49		217	209	196	5.94	0.37
98-01-019		95	79	76	12.1	0.71		95	79	74	7.35	0.58
98-01-021		120	131	119	7.09	0.49		120	131	115	8.28	0.55
98-01-023		93	90	82	6.34	0.52		93	90	82	4.63	0.42
98-01-025		67	49	46	11.59	0.75		67	49	46	10.2	0.73
98-02-001		74	74	69	11.51	0.71		74	74	67	6.69	0.56
98-02-002		145	146	142	37.91	0.86		145	146	135	10.06	0.58
98-02-003		127	116	113	11.42	0.64		127	116	113	14.76	0.7
98-02-004		108	116	101	8.41	0.57		108	116	99	9.53	0.61
98-02-008		98	101	96	14.02	0.71		98	101	94	13.05	0.7
98-02-011		79	93	74	22.99	0.83		79	93	74	12.82	0.72
98-02-012		129	138	119	27.62	0.82		129	138	107	5.63	0.44
98-02-013		92	121	91	24.29	0.82		92	121	91	18.88	0.78
98-02-014		117	85	76	10.71	0.68		117	85	76	8.34	0.61
98-02-015		123	138	119	13.56	0.68		123	138	119	10.03	0.6
98-02-016		169	171	167	15.25	0.66		169	171	164	10.21	0.55

E_Bes	L1	L2	OVL	Ttest	rMoy	Log	L1	L2	OVL	Ttest	rMoy	Dist (cm)	CrossSMP
	79	68	51	9.33	0.69		79	68	51	10.52	0.72	77	+
	179	178	172	5.17	0.35		179	178	170	8.53	0.5	350	+
	103	73	51	5.13	0.53		103	73	51	3.79	0.44	300	+
	184	140	135	5.93	0.42		184	140	135	10.81	0.6	910	–
	135	169	123	7.3	0.5		135	169	123	14.76	0.69	455	+
	78	61	60	4.81	0.48		78	61	60	5.32	0.51	45	+
	121	45	44	3.09	0.4		121	45	44	3.68	0.45	317	+
	150	111	110	10.72	0.63		150	111	110	17.03	0.74	69	+
	135	118	117	5.7	0.43		135	118	117	9.92	0.6	58	+
	82	68	67	5.7	0.52		82	68	67	12.87	0.73	97	+
	77	65	61	28.78	0.88		77	65	61	25.75	0.86	75	–
	63	86	61	2.39	0.29		63	86	61	5.52	0.52	114	–
	59	64	54	18.28	0.82		59	64	54	23.37	0.86	37	+
	63	71	60	13.5	0.76		63	71	60	37.77	0.9	126	–
	70	83	63	10.73	0.7		70	83	63	6.65	0.57	83	–
	61	70	60	3.6	0.4		61	70	60	5.9	0.54	120	+
	76	111	67	5.57	0.51		76	111	67	14.38	0.76	87	+
	94	133	92	17.33	0.76		94	133	92	15.22	0.74	47	–
	217	209	204	4.62	0.3		217	209	202	8.58	0.47	67	–
	95	79	76	6.44	0.53		95	79	76	10.93	0.68	181	+
	120	131	119	5.11	0.4		120	131	119	9.67	0.59	115	–
	93	90	82	7.45	0.57		93	90	82	5.86	0.49	570	+
	67	49	46	16.66	0.82		67	49	46	15.88	0.81	46	–
	74	74	69	5.12	0.48		74	74	69	7.81	0.61	79	+
	145	146	142	10.22	0.58		145	146	142	25.04	0.79	56	+
	127	116	113	6.13	0.46		127	116	113	11.36	0.64	46	+
	108	116	101	11.09	0.65		108	116	101	11.71	0.66	60	+
	98	101	96	11.11	0.65		98	101	96	12.45	0.68	59	+
	79	93	74	8.18	0.61		79	93	74	18.75	0.8	84	–
	129	138	119	9.13	0.57		129	138	119	17.71	0.74	162	+
	92	121	91	16.44	0.75		92	121	91	22.9	0.81	???	+
	117	85	76	7.84	0.59		117	85	76	10.46	0.67	78	+
	123	138	119	7.75	0.52		123	138	119	15.12	0.7	94	–
	169	171	167	4.56	0.32		169	171	165	17.66	0.7	30	+

TABLE A1 (*cont.*)

SMP	Raw	L1	L2	OVL	Ttest	rMoy	Corrido	L1	L2	OVL	Ttest	rMoy
98-02-017		169	182	168	9	0.51		169	182	161	9.57	0.54
98-02-020		105	108	101	11.07	0.65		105	108	99	16.98	0.75
98-02-021		126	86	85	16.69	0.76		126	86	81	14.19	0.73
98-02-022		127	150	126	5.56	0.41		127	150	126	7.64	0.51
98-02-023		91	95	83	8.72	0.61		91	95	78	6.17	0.52
98-02-025		134	54	53	16.06	0.8		134	54	53	6.61	0.6
98-02-026		180	166	165	9.62	0.54		180	166	160	7.39	0.46
98-03-01		49	48	40	19.63	0.86		49	48	40	14.62	0.81
98-03-03		117	114	103	24.65	0.82		117	114	103	19.64	0.78
98-03-06		49	46	42	17.45	0.71		49	46	40	4.75	0.54
98-03-08		76	75	72	20.38	0.82		76	75	72	15.92	0.77
98-03-09		46	28	26	9.65	0.78		46	28	26	4.09	0.57
98-03-10		25	40	24	11.37	0.81		25	40	24	6.65	0.71
98-03-12		56	42	40	10.77	0.75		56	42	40	8.88	0.71
98-03-14		111	73	72	6.05	0.52		111	73	72	4.41	0.43
98-03-15		59	34	31	13.5	0.82		59	34	27	8.89	0.76
98-03-16		94	58	57	3.31	0.38		94	58	57	3.73	0.42
98-03-17		51	22	21	8.01	0.76		51	22	21	5.36	0.67

E_Bes	L1	L2	OVL	Ttest	rMoy	Log	L1	L2	OVL	Ttest	rMoy	Dist (cm)	CrossSMP
	169	182	168	4.95	0.34		169	182	168	11.45	0.58	78	+
	105	108	101	13.18	0.69		105	108	101	13.5	0.7	165	+
	126	86	85	15.15	0.74		126	86	85	17.13	0.77	107	–
	127	150	126	7.97	0.52		127	150	126	5.64	0.42	703	+
	91	95	83	5.86	0.49		91	95	83	10.6	0.66	727	+
	134	54	53	10.69	0.72		134	54	53	19.75	0.84	30	+
	180	166	165	3.32	0.24		180	166	165	11.35	0.58	62	+
	49	48	40	19.41	0.85		49	48	40	21.32	0.87	116	–
	117	114	103	17.15	0.75		117	114	103	29.13	0.84	58	–
	49	46	42	4.86	0.54		49	46	42	12.75	0.78	49	–
	76	75	72	13.41	0.74		76	75	72	17.61	0.79	82	–
	46	28	26	2.07	0.37		46	28	26	7.35	0.72	81	–
	25	40	24	5.51	0.66		25	40	24	11.85	0.82	57	–
	56	42	40	6.43	0.63		56	42	40	9.01	0.71	89	–
	111	73	72	4.73	0.45		111	73	72	5.86	0.51	148	–
	59	34	31	8.66	0.74		59	34	31	13.99	0.83	177	+
	94	58	57	3.73	0.42		94	58	57	4.13	0.45	320	+
	51	22	21	21.99	0.91		51	22	21	13.06	0.85	164	+

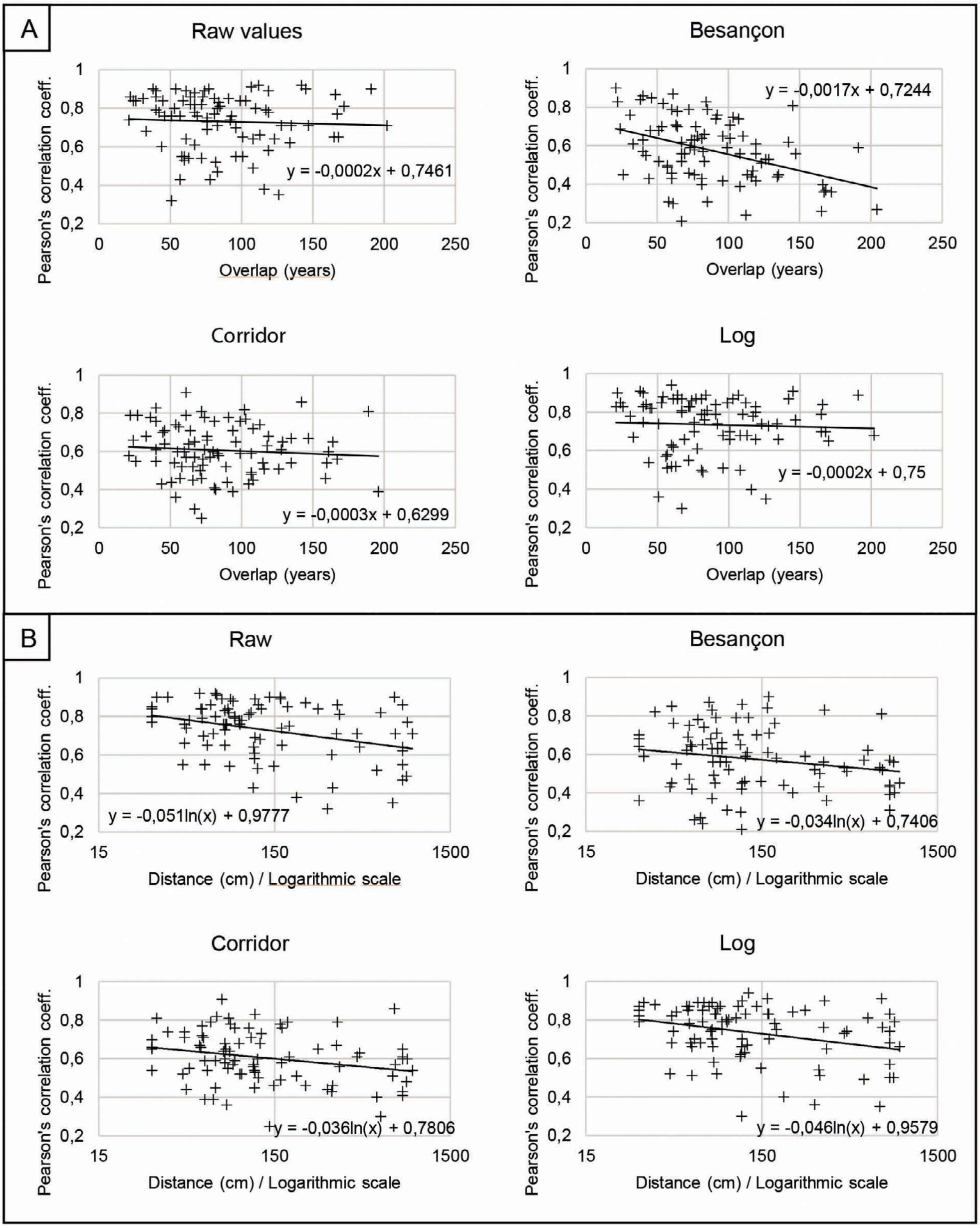

FIGURE 4 (A) Correlation coefficients (*r*-value) between radii from the same piece of wood compared to the overlap between these two radii and (B) the distance between the two radii within the piece of wood

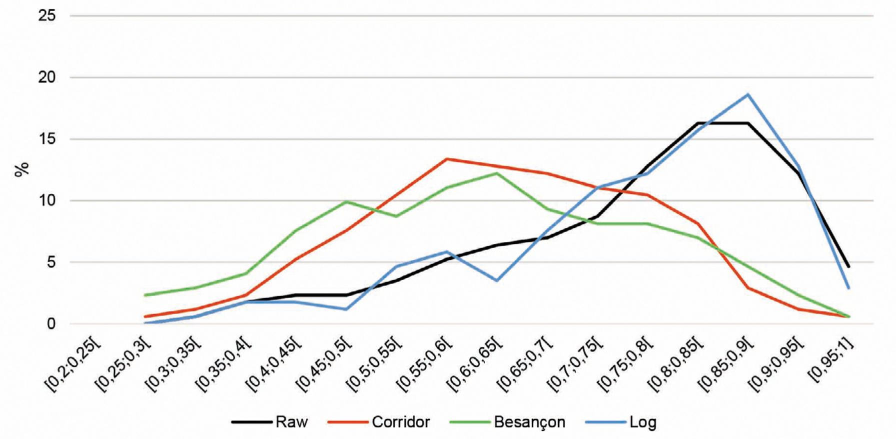

FIGURE 5 Intra-individual Pearson's correlation coefficient normalised repartition by class (smoothed).

3.3 *Cluster Analysis*

The two mean chronologies for Saint-Paul and the Holy Cross exhibited strong similarities (Fig. 6, top right). The visual correlation between the two curves was statistically verified, with a *t*-value of 13 ($r = 0.53$). With this simple comparison and similar values, it might be tempting to suggest a similar provenance. However, comparing the two chronologies with the chronologies available for the Meuse Basin and for this period mainly provides results from other sites in Liège and Namur, corresponding to the medieval sites documented and studied, without indicating possible provenance. Although the average chronology reproduces a common climatic signal, individual chronologies record a stationary signal carrying information regarding the dendrological terroir in which the tree grows (Girardclos, Petit, 2011).

The hierarchical classification we used to observe clusters of individuals was supported by the results obtained in the previous section (Fig. 6); therefore, we used the *r*-values obtained from the radius analysis. We considered values above 0.6, calculated from correlations after logarithmic transformations, as well as natural values. We observed the following: (1) the number of values above this threshold (highlighted in the correlation matrices) and (2) the median correlation coefficient (*r*) in each matrix. Additionally, the data contained in the various correlation matrices originated from the results provided in the section on the dating and establishing construction phases. As mentioned above (cf. Section 2.4), we divided the annual ring series into three groups:

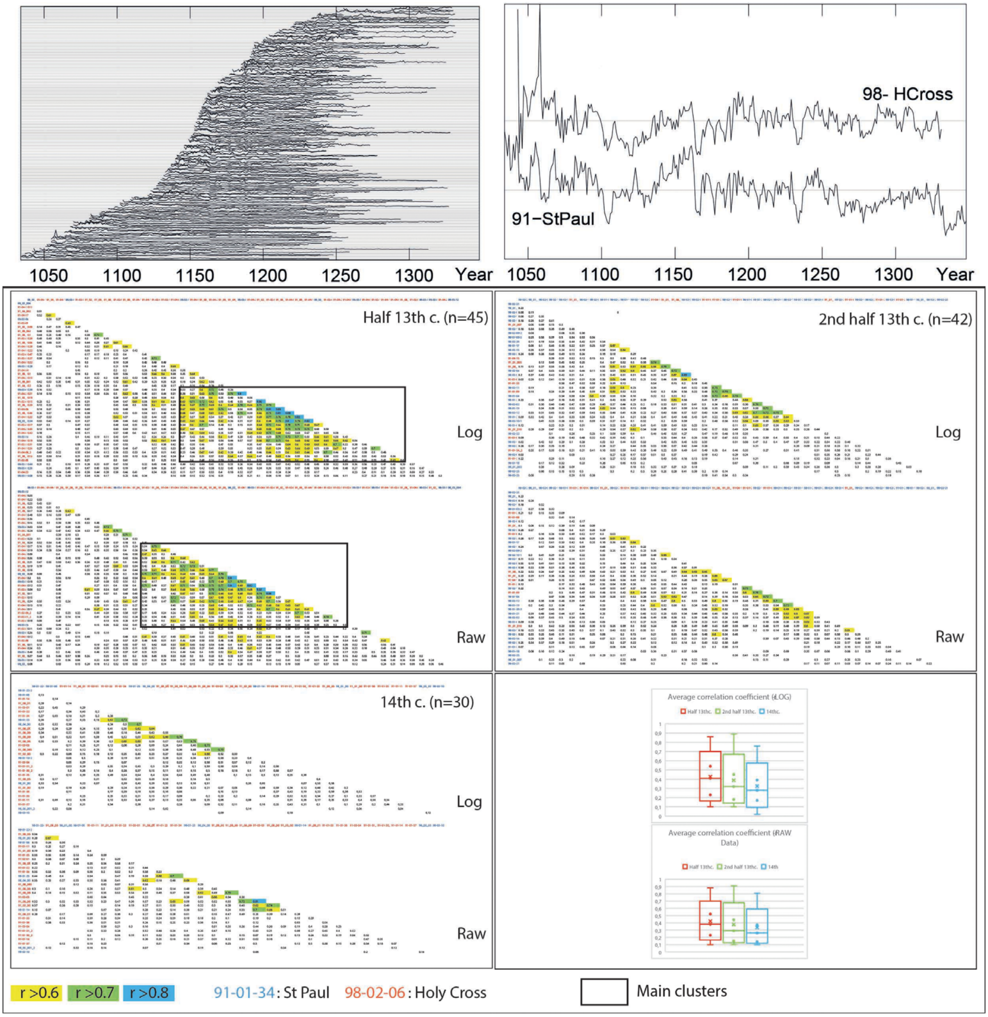

FIGURE 6 Growth patterns of dated individual series (top left) and two average chronologies represented in natural values (top right) produced with the R studio dplR package (Bunn, 2008). (Middle and lower left) Hierarchical classification of correlation matrices using Dendron IV (Lambert, 2006) and Microsoft Excel®. (Bottom right) Box plot of mean correlation coefficients

The first group (*n* = 45) consisted of timbers felled during the first phases of construction of the two frames (mid-13th century), and we included timbers felled between 1240 and 1265. Most of the wood in this group came from St-Paul Church, and it was also the group with the largest number of individuals.

The second group (*n* = 42) encompassed timber felled in the second half of the 13th century, after 1265, and up to the end of the 13th century. This group included timbers from the Holy Cross Church.

The third group ($n = 30$) comprised the woods of the 14th century (1st third of the 14th century). Although Saint-Paul timbers predominate in this group, they appear to be more balanced than the two previous groups.

The two matrices calculated for wood in the first group exhibited a cluster of individuals that correlated with each other with particularly high values. In particular, a group of 14 individuals was identified for which the correlation coefficients were between 0.26 and 0.84, with a high proportion of $r > 0.6$. This group included individuals from Saint-Paul ($n = 11$) and three individuals from the Holy Cross. The latter synchronised with high r-values among themselves but also with individuals from Saint-Paul, with r-values > 0.8 in two cases. These correlations were found in both raw and logarithmic value correlation matrices. However, the logarithmic transformation resulted in stronger correlations than the natural values. The second group, which includes individuals shot during the subsequent phases in the second half of the 13th century, showed fewer strong correlations. Individuals shot in the 14th century followed the same trend. In the latter two cases, clusters of individuals had r-values greater than 0.6 can be identified, albeit in much smaller numbers than those in the first phase.

In parallel with identifying clusters of individuals, we observed an overall decrease in the median value of the correlation coefficient over time.

Felling in the second half of the 13th century, supplying the choir and transept of St-Paul's and the choir of the Holy Cross, indicated a comparable dendrological terroir for a group of timbers common to both collegiate churches. In this group, which included 45 individuals, 14 individuals exhibited correlations greater than 0.6, with some exceeding 0.7 or even 0.8. These results do not mean that some wood, including those demonstrating a strong correlation between the two churches, originate from the same tree. However, it suggests that this wood may originate from similar forests up to the same forest plot. However, these 14 timbers should not obscure the 31 others that synchronise with r-values of less than 0.6. If we consider that a high correlation coefficient between wood harvested at broadly comparable times could indicate a similar dendrological terroir, the opposite might be considered: the felling in the mid-13th century could have originated from a common forest source for the two frameworks and from other forests that might be church-specific. This was not the case for fellings in the second half of the 13th century and the first half of the 14th century. The median correlations decreased, with fewer high r-values. However, fewer did not mean that they were nonexistent. Indeed, the correlation matrices for these later felling phases still included some high correlations (> 0.6, 0.7), including those between the timbers from the two frames. However, the decreased amount of high correlations indicated more diverse supply sites. However, this analysis had no geographical resolution and could not estimate the distance between the felling sites nor the distribution of the different sites across the Meuse Basin.

3.4 *Growth Trends*

The growth trends were calculated by summing the ring widths. Individuals with no pith or sapwood rings were excluded. Therefore, 142 individuals were included. Two breakdowns occurred. The first is the function of the pieces of wood (Fig. 7A), and the second is the function of the felling period (utilising the same repartition as in the previous section). It appears that growth trends do not discriminate between timber from one building and that from another. From a functional perspective, bollards followed a relatively similar trend. To a lesser extent, this observation also applies to crossbeams. In both cases, this can indicate forest selection for a particular use — in this case, to produce posts and crossbeams for the two structures. Apart from these two specific cases, the other trends did not indicate a particular selection process, either chronologically or functionally.

In terms of the calibres of the timbers, we observed that they were slightly larger in the Saint-Paul structure than those in the Holy Cross structure. The larger size of Saint-Paul Church may explain this difference, which is reflected in the different wood requirements. However, if we consider the age of the trees harvested, we could deduce that the trees providing timber for the Saint-Paul framework (median = 119 tree-rings) were overall older than those for the Holy Cross (median = 100.5 tree-rings), thereby suggesting a relatively logical relationship between age and calibre. However, this relationship did not hold for all periods, as in the second half of the 13th century, the relationship was reversed, and the trees used in the Holy Cross frame were slightly older than those used in the Saint-Paul frame.

Overall, trees were harvested from the middle of the 13th century to the first third of the 14th century. At Saint Paul, the median age was 171 years in the 14th century. This gradual increase in the age of harvested stands was detected in the southern Alps during the late Middle Ages (Labbas *et al.*, 2022). Population growth would have increased pressure on forest resources, thereby leading to the exploitation of older stands that had previously remained intact. However, if we compare the ages of the trees felled in the mid-13th century for Bourges Cathedral (Epaud, 2017), the forests of the churches of Liège appear to have been felled at an older age. Additionally, more diversity exists in the ages of the felled stands. This observation broadly applies when comparing the medieval frameworks from the Paris Basin to those of the Meuse Basin (Epaud, 2019).

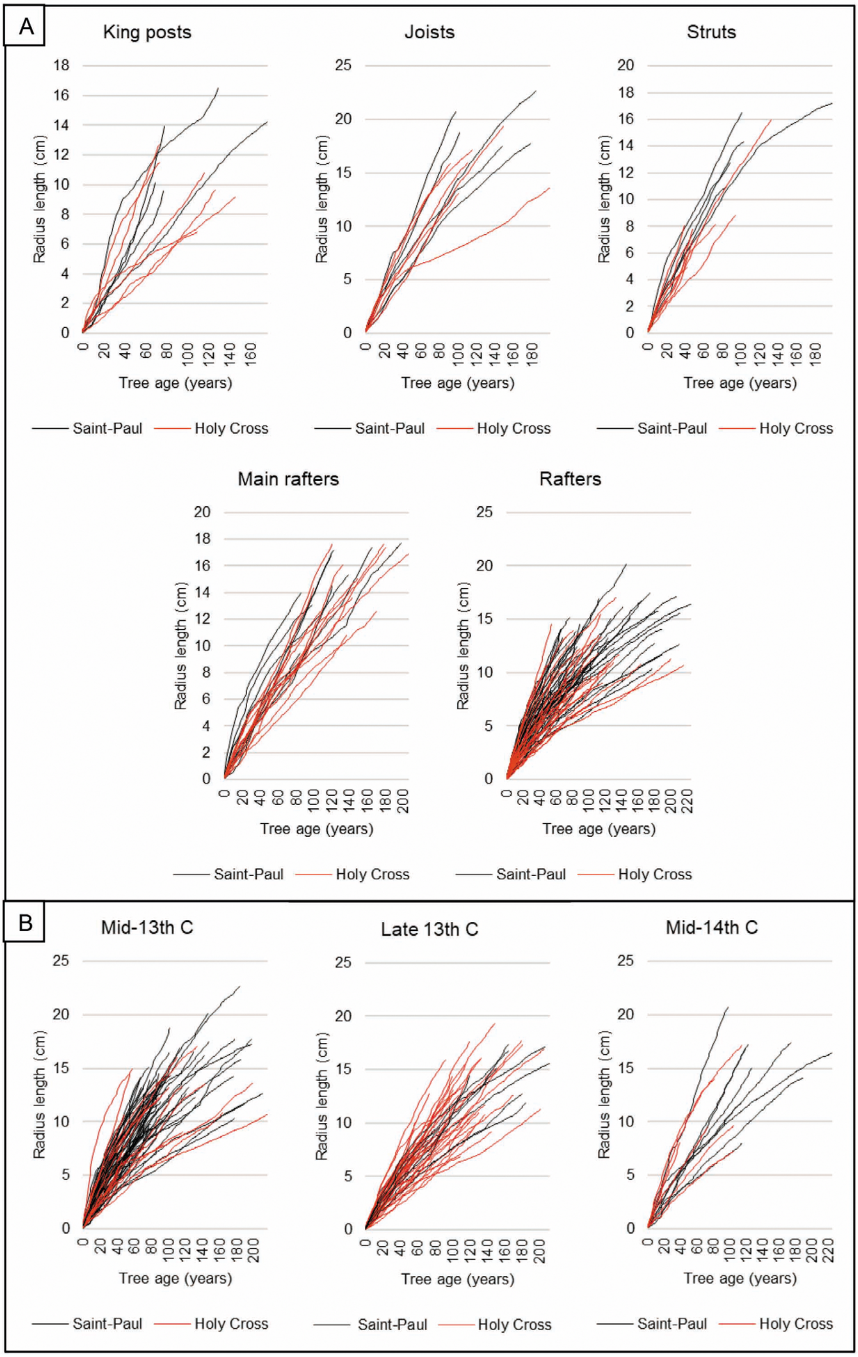

FIGURE 7 Growth trend of individual woods classified by (A) wood function and (B) felling periods

3.5 *Frameworks of Saint-Paul and Holy Cross: Mosan Forests in Perspective*

The correlation matrices show high correlations for the mid-13th century, which tend to decrease over time, and very high correlations could reflect similar dendrological terroirs and, by extension, trees coming from common or neighbouring forests or even plots. In the Middle Ages, the chapters of these two collegiate churches probably owned their own land, including forests.

The same forest might have been shared between different owners, as was the case for Saint-Palais Forest (near Bourges, France) in the 13th century. Shared owners include the archbishop, cathedral chapter, abbey, and castellany (Epaud, 2017). Plots from the same forest can exhibit significant correlation values, as shown by a dendrochronological study of the Chaux Forest (Jura, France), initially conducted by hierarchical classification between the average chronologies of the plots (Lambert, 2019). In this study, examination of the individual series indicated that r-values > 0.8 were mostly obtained between individuals from the same plot and, to a lesser extent, between individuals from adjacent plots. Moreover, r-values > 0.7 were very rarely (only two cases identified out of 129 individuals) obtained between individuals more than 10 km apart. Based on these results, it can be hypothesised that, at the very least, some of the forest plots exploited for felling and supply belonging to Saint-Paul and the Holy Cross were in close proximity during the mid-13th century. However, no source can either confirm nor deny that the two chapters obtained their supplies strictly from their own forest areas or whether there were any commercial exchanges.

Some correlations (> 0.8) could even lead to the belief that some trees were common to both frameworks. While this cannot be proven, several concordant factors exist: high correlation ($r > 0.8/t > 15$), close start and end dates, overlap > 70 years, and criteria which correspond to some of those given by Beuting (2011). To develop this hypothesis, according to which a single tree may have provided wood for two frames, we must consider very long timbers, as the beams range from 8 to 12 m long. Indeed, useful timber lengths ranging from 16 m to more than 24 m must be considered to supply two beams (apart from struts) from the same tree.

Epaud (2017) identified oaks with a useful length of 21 m exceeding 130 years in age, suggesting that our hypothesis remains viable. Consider the example of king post 04–20 in the transept of Saint-Paul's and the rafter 03–03 in the apse of the Holy Cross. The king post, dated 1147–1249, is made of heavy (34×32) sawn timber, with some sapwood preserved but no pith damage. The rafter from the Holy Cross, dated 1122–1238, is half stranded and half its size (17×16). The two timbers were synchronised with high values ($t = 21$, $r = 0.81$) and an overlap of 91 years. Although formal proof was lacking, nothing prevented the same tree, approximately 20-m long and with a diameter greater than 40–45 cm, from supplying the wood for these two large pieces. This is not an isolated case, as Seim *et al.* (2024) suggest that the wood used in various works by Anthony Van Dick originated from the same tree. This hypothesis may lead to two additional hypotheses: the first pertains the re-reading of the felling phases for the two frames, while the second concerns the routing of wood and its provenance. In terms of the felling phases, the king post of St-Paul originates from the transept square, with the felling estimated to have occurred between 1255 and 1258. The rafter originating from the collapse of the Holy Cross is dated to a felling phase between 1251 and 1261. If one tree supplied two timbers for the construction of both churches, this could refine the *terminus post quem* for the apse of the Holy Cross to the years 1255–1258, contingent upon the verification of this common tree beyond mere hypothesis.

3.6 *From Transport to Origin*

When transporting wood, whether it is two long pieces of 8–12 m or a single piece of approximately 20 m, it is difficult to imagine it being transported over any substantial distance by land. Therefore, it seems more likely that they employed floating. The fact that timber floated down the Meuse in the Middle Ages is attested to by written records dating back to the 14th century (Bruwier, 1958) and archaeological evidence dating back to the 12th century, particularly by traces of raft assembly (Hoffsummer, 2002; Houbrechts, 2008). These characteristic traces have also been identified in the timbers of the structures at Saint-Paul and the Holy Cross. Therefore, the floating of 10-m long timbers on the Meuse or one of its tributaries in the 13th century is a proven fact. However, what about trees 20 m or more in length? According to the current research, nothing suggests that such timber lengths were floating on the Meuse, especially during the 13th and 14th century. From the end of the 15th century, and more generally during the 16th and 17th century, rafts assembled in trains, probably several dozen meters long, were recorded on the Meuse (Suttor, 2000). In more remote contexts, such as the southern Alps and torrential rivers, archaeological experiments have demonstrated that rafts assembled from timber over 20 m long may float and navigate (Furestier, 2023). Furthermore, nothing prevents this timber from floating on the Meuse River, which has a classic rainy-oceanic regime. No known written record has reported the origin of the wood used for the two Gothic structures. Moreover, from a strictly dendrochronological perspective, a large part of the tree-ring chronologies in the Meuse

Basin for the Middle Ages (especially during the 12th–14th century) came from elite religious buildings, mainly in Liège and Namur. Dendroprovenance studies frequently refer to a large Rhine-Meuse area, reflecting low spatial resolution (Weitz and Fraiture, 2019). Forests belonging to the Saint-Paul chapter are indicated in planimetric documents from the second half of the 18th century (Dury, 2015). These maps demonstrate that the forests belonging to Saint-Paul are in close proximity to Meuse on an axis running from Liège to Dinant. On one hand, it is evidently difficult to transpose this information to the 13th century, and on the other hand, to associate any forests belonging to the Chapter of the Holy Cross with these locations, for which information is lacking. Written references have been made to timber supplies from the Ardennes dating from the 14th century (Schroeder, 2016). Before this period, the extent of timber trade in the Meuse Basin was not measurable. It is worth considering whether the economy and urbanisation at the turn of the 13th century resulted in timber imports from the Ardennes owing to the scarcity of timber in the forests bordering the Meuse. The 13th century appears to have been a period of urban transition marked by heightened pressure on forest resources (Hoffsummer *et al.* 2019; Haneca *et al.* 2020). This question could be addressed through the results of the correlation matrices: we would gradually transition from a mainly coherent supply with relatively high intercorrelations to a more dispersed supply characterised by weaker correlations and greater diversity in dendrological territories.

Recent research has indicated that the stone required for the 13th-century church of Saint-Paul may have come from quarries near Sedan, located further south but still in close proximity to Meuse (Lecuit *et al.* 2018). The distance covered by this heavy material raises the question of whether the stones were transported by rivers, rafts, or boats. More broadly, in such cases, could the stone and wood have originated from the same source?

Therefore, several avenues need to be explored to address the question of wood provenance. In the context of the Middle Ages, specifically regarding the timber from the 13th and 14th centuries associated with the two churches of Liège, there are no precise archival sources to identify resource forests. Furthermore, no oak stands of sufficient age to allow for chronological reconstruction. Geochemical analysis, particularly the examination of stable isotopes that can provide geological signatures, such as strontium and neodymium (Stulc *et al.*, 2023), may elucidate the provenance of the timber. The isotopic composition comparison between wood from the two churches and the potential supply areas mentioned by Dury (2015) and Lecuit *et al.* (2018) can also provide a basis for further research. In addition, examining more recent periods for other corpora (*e.g.* 16th–18th century) may facilitate comparisons between these different geochemical, dendroarchaeological, and historical methodologies. This approach proposes a pertinent provenance and transport model for earlier periods where archival sources may be lacking.

4 Conclusion

The frameworks of the churches of Saint-Paul and the Holy Cross in Liège reveal connections to forestry that extend beyond their construction typology. The question addressed in this article was whether a connection exists in the wood supply of the Gothic building sites of these two collegiate churches.

To answer this question, the identification of clusters of individuals using a hierarchical classification was proposed. The average chronologies for each of the two frameworks exhibited high correlations; however, they still obscured certain local information.

A specific sampling protocol was applied (involving two radii and different coring distances), with the objectives of 1) obtaining two corpuses comparable in terms of size and 2) evaluating the correlation thresholds and necessary transformations.

The 162 individuals dated for the two buildings broadly confirmed and simultaneously refined the felling phases previously proposed by Hoffsummer (1995). These phases could be categorised into three main felling periods common to both structures: 1251–1265, 1278–1299 and 1328–1351.

The hierarchical classification and analysis of correlation coefficients indicated numerous high correlations in the first phase, including those among beams from different churches. These results suggest that the two sites had similar wood supply at the onset of reconstruction, as evidenced by the correlation calculation protocol applied to living trees. The gradual decrease in the values obtained during the subsequent two major phases may reflect distinct dendrological terroirs and, by extension, potentially more remote felling sites.

In addition to the previously proposed research topics, these findings suggest the potential for extending the method (sampling protocol, cluster analysis, and analysis of growth rates) to other comparable sites (e.g., high-profile buildings) and different socioeconomic contexts.

Further characterisation of dendrological terroirs is warranted, for which the identification of local forest disturbances (%GC) should be integrated with the geographical precision of resource forests, as determined by strontium isotopes.

Several of these sites present new research opportunities, wherein a large corpus of time series should be acquired on the scale of a large Mosan basin to encompass a longer chronological period and represent the diverse components of past societies.

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