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Timber Structures of Florence Cathedral: Wood Species Identification, Technological Implications and Their Forest Origin

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Abstract: The Cathedral of Florence is one of the largest churches in the world and is known for one of the most famous domes ever, which characterizes the skyline of the city. The dimensions of the building mean that the dimensions of the roof are equally large and so are the wooden structures that support it. The roof of the cathedral is organized on two levels: the roof of the large central nave and, at a lower level, those of the two lateral naves. The purpose of this paper is the identification of the wood species of which the structures are made. The sampling method of the 408 samples that have been identified is then described, the methods followed to reach a reliable identification and finally the results. The timbers most represented among the structural elements are those of silver fir, chestnut and elm. Other timbers are then found in the other components less directly linked to the main structural parts that make up the trusses. The paper then discusses the technological implications on the use of those woods within the wooden covering structures of the cathedral and the main sources of timber that the builders had available, in particular the Casentino forests that the Municipality of Florence had donated to the structure that managed the construction of the cathedral (Opera di Santa Maria del Fiore—OPA). OPA still exists today and is responsible for the maintenance of the cathedral and other annexed buildings.

Keywords: historic timber structures; wood identification; forest source; Florence Cathedral

Citation: Macchioni, N.; Degl'Innocenti, M.; Mannucci, F.; Stefani, I.; Lazzeri, S.; Caciagli, S. Timber Structures of Florence Cathedral: Wood Species Identification, Technological Implications and Their Forest Origin. *Forests* **2023**, *14*, 1733. https://doi.org/10.3390/f14091733

Academic Editor: Milan Gaff

Received: 1 August 2023
Revised: 22 August 2023
Accepted: 25 August 2023
Published: 27 August 2023

1. Introduction

Santa Maria del Fiore is one of the largest churches in the world. The plan consists of a triple-nave basilica with the presbytery area nested within, dominated by the large octagon of the immense dome, around which are three radial apses (or "tribunes"), each consisting of five chapels.

The cathedral is 153 m (502 feet) in length, 90 m (295 feet) wide at the transept, and 90 m high from floor to base of the dome lantern. The title "Santa Maria del Fiore" (our lady of the flower) alludes to the name of the city, "Florentia", or "city of flowers", "destined to bloom", and to its emblem, the Florentine lily.

The first stone of the new cathedral was laid on 8 September 1296, and the task of erecting it was entrusted to Arnolfo di Cambio. His project was similar in plan but smaller than the current building, which instead corresponds to the expansion developed by Francesco Talenti, beginning in the mid-14th century (Figure 1). The church was consecrated by Pope Eugene IV on 25 March 1436, when work on the dome was completed.

Over the centuries, due to the complexity and dimensions of the cathedral, challenging engineering solutions have been adopted. Among them, it is worth mentioning those adopted for building all the roofing structures, suitable for protecting the underlying vaulted structures of the three naves from weather. They, being dimensionally unique, are characterised by a wooden forest that hardly finds analogous examples in architectures of the same dimensions and characteristics (Figure 2).

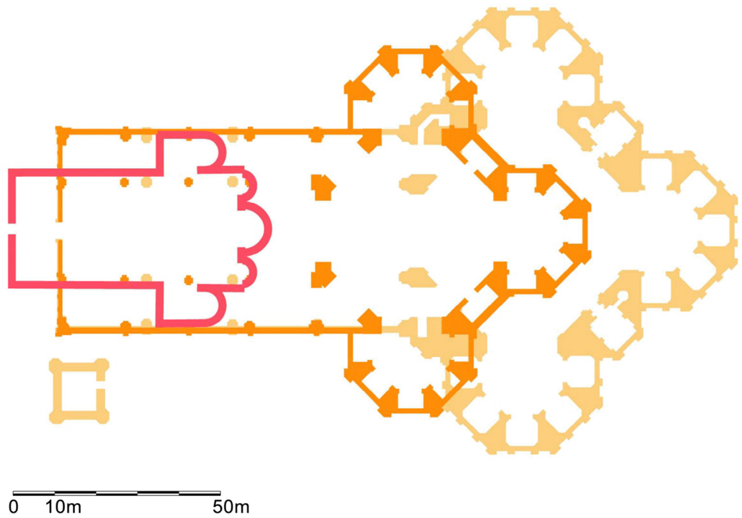


Figure 1. In red the profile of the ancient cathedral (Santa Reparata); in orange the project of Arnolfo di Cambio for the new cathedral (1296); in yellow the project by Francesco Talenti, corresponding to the adopted solution (1357).

Figure 2. One of the trusses of the central nave.

Indeed, the wooden elements of the structures come from forests. To understand which forest, it is necessary on the one hand to identify the timbers and on the other to carefully analyse the archives relating to the period in which the roofs of the central and lateral naves were made, in the second half of the XV century [1,2].

Any type of diagnosis on wooden artifacts requires the identification of the wood species as a first step of knowledge [3]. In the case of timber structures, knowledge of the wood species allows for better estimation of the mechanical performances of the structural members, together with the characterization of defects [4]. Therefore, the wood identification is one of the first analyses to be conducted during the structural diagnosis (according to EN 17121:2019 [5]).

The "Duomo" of Florence is a building known throughout the world for Brunelleschi's dome that characterizes the skyline of the city. In the case of an ancient artwork of the importance of the cathedral of Florence, there are further implications that derive from the knowledge of the timbers.

In the past, the transport of construction timber was a non-negligible problem, due to volumes and weights in an era in which engines did not exist. Cities with a natural waterway could rely on the water to float and carry them.

In the case of Florence, following the course of the Arno River and its tributaries backwards, it is possible to identify the forests from which the construction timber came and which were the paths followed in its flow.

The important archives of the OPA (Opera del Duomo di Firenze, the still existing institution that financed and followed the construction of the building and that takes care of its continuous maintenance) are in this sense a complete source of information. The archives show the forests that OPA owned and from which most of the lumber came. The timber for the construction comes mainly from Casentino forests—donated by the Signoria to the Opera del Duomo in 1378 as a contribution to the construction of the cathedral—an enormous forest heritage located not far from the sources of the river that crosses Florence [6], where it is possible to find huge silver fir forests. The donation of the Casentino forests was not only intended to complete the cathedral, but also to ensure the OPA a perpetual source of income, such as to guarantee the self-financing of the institution even after the completion of the religious building.

In the archives, each transport is included and its volume, and the people involved in the transport are reported. The information about the timber purchased from other forests for different purposes is included as well.

But, if everything is described in the documents, why carry out the detailed identification of the timbers? Firstly, because trades are described, but not the final use of the elements. Furthermore, it is worth considering the possibility that continuous maintenance has led to the insertion, over time, of new wooden elements that could also be of a different provenance and species from the original. For example, the modern wooden elements inserted during the restorations dated 1937–1938 are clearly identifiable. Given the existence of modern means of transport at that time, it cannot be excluded a priori that the timber could also come from very far away.

It is interesting to note how the large volumes of timber floated to Florence made OPA the largest operator in the region on the timber market at the time. It should in fact be considered that much of the timber transported or purchased was not only used for the construction of structures, but also for the assembling of the scaffolding on construction sites, not only for the cathedral, but also for other buildings of great importance that were being constructed simultaneously in Florence, such as the Dominican church of Santa Maria Novella (1279–1420), the Franciscan church of Santa Croce (1294–1443), the Dominican church and the Convent of San Marco (1299–1443), and the seat of the city government, Palazzo Vecchio (1299–1314). These buildings also required large amounts of timber, not only from OPA forests, but also from surrounding forests.

In the same way, the various historical–sociological and economic aspects resulting from this trade cannot be overlooked: the involvement of local populations, the birth of market chains, from loggers in the forest to those who transported from the forest to the stream, to those who carried along the waterway to the city and, finally, the grading and selection of the single elements for the different uses.

Each wooden member of a historic building contains a story that starts from the tree in its forest, in a specific environment. Before becoming the artefact we observe, it was then a raw material within the commercial world of the time and passed through the hands of the professional who made it become what we look at.

The aim of this paper is to show the results of the anatomical identification of the wood species. From the results, other aims derive: a discussion about the technological explanation of their use within a timber structure and the connection of the obtained results with the information collected from the archives of OPA.

2. Materials and Methods

2.1. Description of the Timber Structures

Visiting the cathedral from the outside and inside, the tourist cannot observe wooden elements, because the building is finished in masonry, covered by plaster and marble. In reality, the tile roofs are supported by a wooden structure: in the attics there are wooden structural elements for a total of 360 m^3 and a weight of about 150 tons.

The central nave of the Cathedral of Santa Maria del Fiore has a double pitched roof. The main framework is formed by nineteen timber trusses, articulated according to the scheme called "*all'italiana*" [7], or king post with struts (Figure 3). This typology consists of two principal rafters, tie beam, king post and struts. The king post is shaped to enable the housing of the rafters and struts. Similar indentations are prepared on the rafters to contain the struts. King post and rafters are connected to each other by a simple notch, reinforced with heel straps. The nodes between each constitutive element are strengthened by metal fittings such as straps and nails.

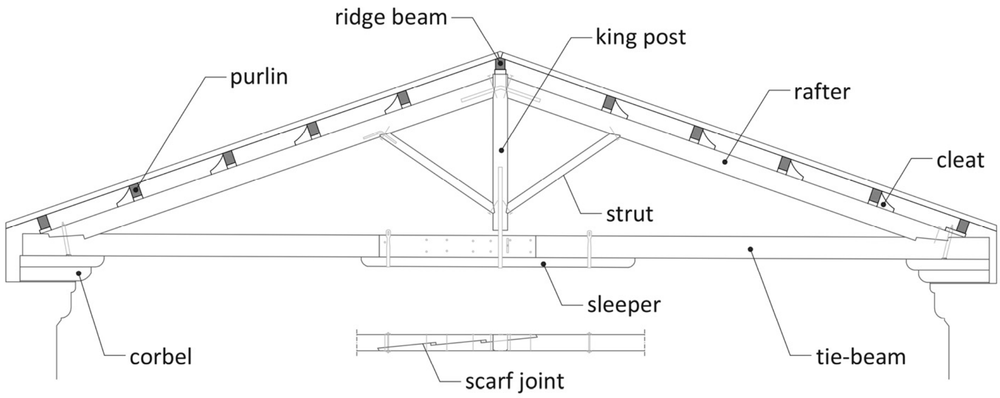


Figure 3. Scheme of the trusses of the central nave.

Covering a free span of around 19m, the tie beams are composed of two elements, normally jointed in the centre line by a scarf joint (also called "bolt of lightning") reinforced with bolts. The tie beams replaced in 1938 are a combination of four elements, probably due to the fact that, at the time, trees with appropriate size were not easily available.

An additional constitutive element of the central nave trusses is the sleeper, located under the middle of the tie beam and connected to it and to the king post through a strap and heel straps.

The truss rests at both ends of the tie beam on wooden corbels.

The secondary framework is composed of purlins laying on the rafters and the ridge beam that lays directly on the king post. Cleats retain purlins from sliding. Above the purlins stands a warping of common rafters, on which rests a layer of tiles and the rest of the covering bundle.

The aisles are composed of four bays divided by three flying buttresses, hidden by the single pitched roof. Being located at the same level as the trusses, the *arcs-boutants* replace them in the structure layout. The sixteen asymmetrical trusses are surmounted by purlins parallel to the line of the eaves, with a false rafter (Figure 4). In this case too, king post, rafters and struts are connected with indentations. The joint between tie beam and rafters includes a simple notch, occasionally bolted and strapped. Here, the tie beam lays directly on the supporting wall. Due to a smaller free span (around 8.5 m) compared to the central nave, the tie beam is formed by a single element. The rafter and false rafter are often topped by an additional wooden element that reduces the roof inclination. The secondary framework is again composed of purlins that support the covering bundle.

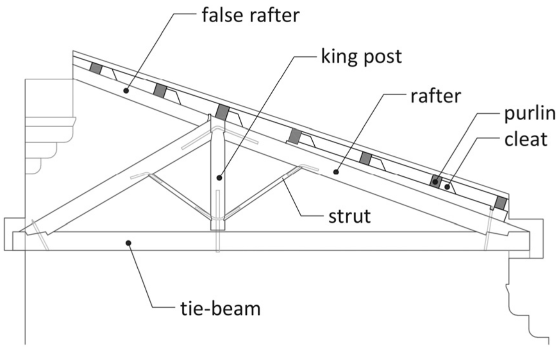


Figure 4. Scheme of the trusses of the side naves.

2.2. Sampling and Wood Identification

The sampling to identify the wood species has been made in accordance with standard UNI 11118:2004 [8]. It was decided to sample only the structural elements of the trusses safely reachable, so excluding purlins. From every element under investigation has been taken a three-dimensional sample, from which was obtained the three anatomical sections necessary to identify the species, ideally a small cube of 0.5 cm. To alter the artefact as little as possible, the samples were taken from areas where sampling was barely visible. Every sample has been stored in a box named after a recognizable code. A total of 408 samples were collected and analysed.

The microscopic identification has been made at the laboratory of wood anatomical characterisation of CNR-IBE. At first, every sample has been boiled in water, until the sinking of the sample, to soften wood. Once softened, the samples have been shaped along the transversal, radial and tangential longitudinal directions. With the aid of a Peltier cooler, for every anatomical direction has been cut a thin section that thereafter has been placed on a microscope slide covered with glycerol. Observing the slides under a microscope, it is possible to recognize the distinctive anatomical features and to identify the timbers. The identification is based on the observation of specific atlases (such as [9,10]) and on the comparison with the anatomical slides collection of CNR-IBE.

The anatomical characterization of wood actually goes as far as the identification of the genus. It is, however, possible to infer the species in many cases starting from historical and/or logical considerations. For example, if you find in a historic building in central Italy wood identified as *Castanea*, you can deduce that it is *Castanea sativa* Mill. The same is true for the genus *Abies*, for which we deduce that it is *Abies alba* Mill. For other identifications, instead, the number of possible species is such as to stop at the genus, as in the case of *Ulmus*, for which the possible species are about three different ones. In these cases, the identification stops at *Ulmus* sp.

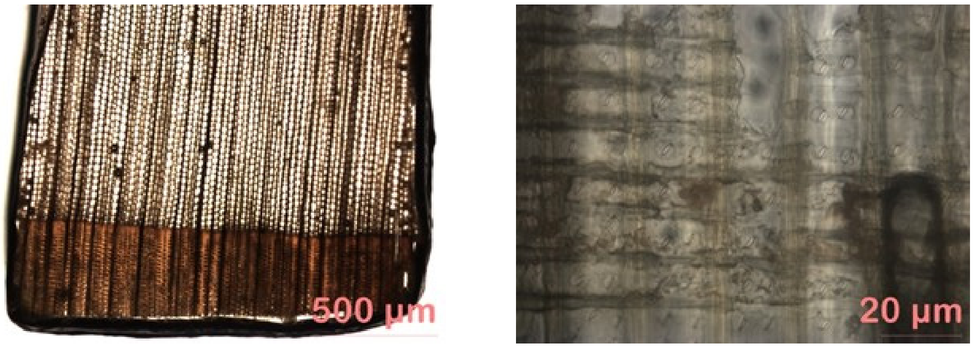
3. Results

From the central nave, 237 samples were brought. The timbers resulting from wood identification are listed in Table 1.

Table 1. Number of identified samples drawn from the structural members of the central nave.

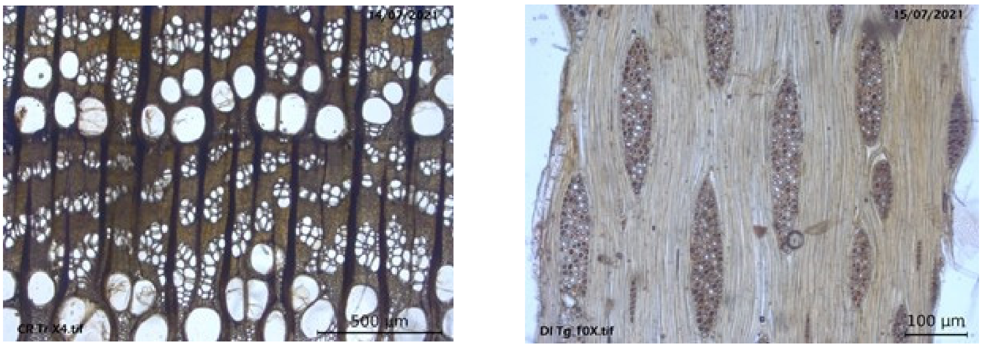
Timber	Identified Samples
Abies alba Mill.	178
Ulmus sp.	27
Robinia pseudoacacia L.	11
Castanea sativa Mill.	10
Picea abies Karst.	7
Quercus sp.	2
Juglans regia L.	2

European fir (*Abies alba* Mill., Figure 5) is the most represented timber, then elm (*Ulmus* sp. Figure 6) follows, but much less represented. The woods that amaze in Table 1 are that of black locust (*Robinia pseudoacacia* L.) and spruce (*Picea abies* Karst.), the first because it was not present in Europe at the time of the construction of the cathedral, the second because it is found very rarely in historical Florentine structures: despite being present in the Italian flora, the typical origins of spruce are Alpine, very far from Florence.



(**a**) (**b**)

Figure 5. Microscopic pictures from *Abies alba* Mill. samples: (**a**) a cross section showing the aspect of a softwood without resin ducts; (**b**) a longitudinal radial section showing a cross-field with taxodioid pits and without radial tracheids.



(**a**) (**b**)

Figure 6. Microscopic pictures from *Ulmus* sp. samples: (**a**) a cross section showing the earlywood typically ring porous and the latewood in tangential bands of vessels and axial parenchyma; (**b**) a longitudinal tangential section showing the parenchymatic rays homogenous and 4–6 seriates.

It becomes interesting to observe the division of the timbers for the different structural elements that make up the trusses (Table 2).

The samples that are not listed are those with which the wedges to tension the scarf joints of the tie-beams were made of: nineteen of elm wood, eleven of black locust, two of deciduous oak (*Quercus* sp.), two of walnut (*Juglans regia* L.) and one of spruce wood. They are not listed in Table 2 because of not really having a structural function.

Finally, it is possible to note a marked differentiation according to the function of the element within the triangular frame of each truss. The longer elements are almost always in silver fir, and only in the king posts is the presence of elm wood important. For the production of corbels and wedges, the composition varies greatly. Note the presence of black locust wood wedges to stretch the tie-beams made from scratch during the restoration carried out in the two-year period 1937–1938.

Less samples were taken from the two lateral nave timber structures, for various reasons. There are 16 trusses instead of 19, there are no corbels and no composite elements and, finally, the safe accessibility to all the elements of half of the 16 trusses was practically impossible.

Table 2. Identified timber and their use in the central nave structures.

Structural Member	Timber	Identified Samples
Tie-beam	*Abies alba* Mill.	38
Sleeper	*Abies alba* Mill.	38
Rafter	*Abies alba* Mill. *Picea abies* Karst.	38 2
King post	*Abies alba* Mill. *Ulmus* sp.	13 6
Strut	*Abies alba* Mill. *Ulmus* sp.	37 1
Corbel	*Abies alba* Mill. *Castanea sativa* Mill. *Picea abies* Karst. *Ulmus* sp.	33 10 3 1

The general appearance of the lateral nave structures is less well-finished and is limited to the presence of structural elements only, as the corbels are not present, and generally they have a hint of carved decoration. Even the supporting niches in the walls often have the appearance of chiselled breaches in already-completed masonry. In the central nave, however, the supports were shaped during the construction of the walls.

From the northern lateral nave, 80 samples were drawn. The timbers resulting from wood identification are listed in Table 3.

Table 3. Number of identified samples drawn from the structural members of the northern lateral nave.

Timber	Identified Samples
Abies alba Mill.	52
Castanea sativa Mill.	26
Picea abies Karst.	1
Fagus sylvatica L.	1

Even in these wooden structures, fir is the prevailing timber, but the presence of chestnut structural elements is one third of the total. Clearly of replacement are the single member, a king post, of beech wood (*Fagus sylvatica* L.) and a spruce rafter.

A total of 81 samples were taken from the southern lateral nave structures. The resulting identifications are listed in Table 4.

Table 4. Number of identified samples drawn from the structural members of the southern lateral nave.

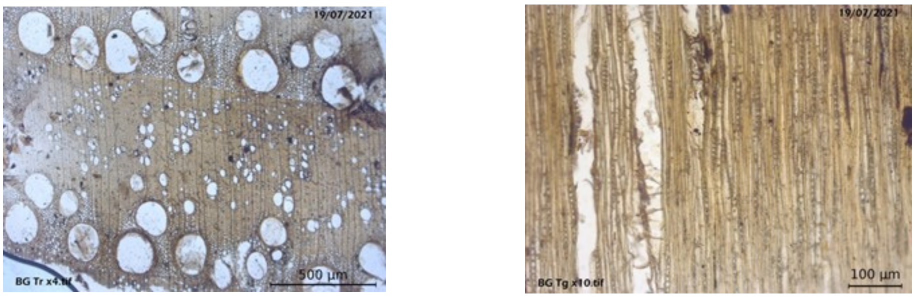
Timber	Identified Samples
Abies alba Mill.	43
Castanea sativa Mill.	24
Pinus nigra Arn./*sylvestris* L.	13
Picea abies Karst.	1

The distribution of timbers in the southern lateral nave reflects that found in the north nave, in particular as regards the ratio between fir and chestnut. However, the presence of pine wood appears in an important way. It should be remembered that the anatomical differences between the woods of *Pinus nigra* Arn. (black pine) and *P. sylvestris* L. (Scots pine) do not allow a reliable distinction between the two woods [9]. It is worth noting that there are no Scots pine forests along the Apennine chain of the Italian peninsula, while there are plantations of black pine, and the Corsican pine, a variety of *P. nigra* Arn., is spontaneously present.

Table 5 shows the use of the different timbers in the trusses of both the lateral naves. It is worth underlining that the two main timbers are fir and chestnut (Figure 7) and that the important presence of pine wood is mainly in struts (of the southern nave).

Table 5. Identified timber and their use in lateral naves structures.

Structural Member	Timber	Identified Samples
Tie-beam	*Abies alba* Mill.	33
	Castanea sativa Mill.	3
	Pinus nigra Arn./*sylvestris* L.	1
Rafter	*Abies alba* Mill.	33
	Castanea sativa Mill.	27
	Picea abies Karst.	1
King post	*Abies alba* Mill.	5
	Castanea sativa Mill.	11
	Fagus sylvatica L.	1
Strut	*Abies alba* Mill.	15
	Pinus nigra Arn./*sylvestris* L.	12
	Castanea sativa Mill.	3



(**a**) (**b**)

Figure 7. Microscopic pictures from *Castanea sativa* Mill. samples: (**a**) a cross section showing the earlywood ring porous wood and the latewood's small vessels organized in a radial dendritic pattern; (**b**) a longitudinal tangential section showing vessels containing tyloses and uniseriate parenchymatic rays.

4. Discussion

Producing long, slender structural members has generally drawn attention to softwood rather than hardwood lumber. This is mainly due to the shape of the conifer stems, with mainly monocormic branching, while broad-leaved trees generally have dendritic branching. The monocormic habit implies main stems from which branch off almost horizontal branches and a much smaller diameter than that of the stem. It therefore becomes easier to obtain relatively long beams of constant section, with relatively small defects, principally knots [11].

Even in the case described in this paper, coniferous wood elements clearly prevail, more particularly silver fir. The silver fir is present almost exclusively to compose the trusses of the central nave, where the structural elements are very long. For example, consider that each element that makes up the tie-beams is 12–13 m long, and for that length it maintains a section of 30 × 45 cm. This means that such beams were obtained from silver fir trunks, which at about 14 m in height, were more than 50 cm in diameter. The rafters in the central nave are also very long: about 9 m, with sections similar to those of the tie-beams.

Among the structural elements, the king posts are shorter, while retaining the sections of the other elements, i.e., about 3 m. Silver fir also prevails among the king posts, but those made of elm wood are not uncommon (Figure 8). Macchioni and Mannucci [12] already reported about the use of fir wood in Florence area for rafters and tie-beams, while elm wood was common in king posts and corbels. Why the elm wood for those purposes? Giving an answer is not simple: it is true that elm wood is hard and therefore it can be useful for making joints between rafters and king posts, near the ridge of the roof, but it is certainly not the only hard wood available at the time for that purpose. There is also the possibility that the use of elm wood, for that specific structural use, could have had a traditional or ritual meaning at the time that we are no longer able to interpret today.

Figure 8. One of the elm wood king posts of the central nave shows a graved possible dating (MCCII). In this case, the graved year would be more than two centuries before the assembling of the roof, marking a possible reuse from a previous structure.

In the lateral naves, although silver fir wood continues to be prevalent, hardwood, such as chestnut, takes on a more important role.

Chestnut wood is very suitable for structural uses because the heartwood has a high natural durability and the sapwood is always very thin; furthermore, the mechanical performances are high [13]. In fact, it is a wood widely used in historical structures in Rome and Naples [14–16]. It has two important limitations, i.e., major flaws, particularly ring shake and large knots, and the stems are tapered, so they do not maintain the required sections for large lengths.

In accordance with the characteristics described, chestnut wood is well represented among the structural elements in the lateral naves, where the longest elements are the tie-beams (about 9 m) and the rafters (about 5 m).

Hardwood timbers have found wide use in these structures where a high hardness was required of wood. We find them, in fact, in the corbels and in the wedges of the central nave. As mentioned previously, timber reached Florence by floating from the Casentino forests (Figure 9), through the Arno/Sieve basins. The Casentino forests mainly produced silver fir timber.

From the Campigna plateau, the trunks were pulled by pairs of oxen to Pratovecchio, signed with the mark of OPA, transported in "rafts", formed by logs tied together, along the Arno River in Florence at the port of Porticciola d'Arno (a small port destroyed in 1862) [17].

The purchase of other kinds of timber comes from the surroundings of Florence: elm, beech and chestnut are generally bought at the local market and oak from the Apennines of Pistoia. To obtain chestnut wood, OPA acquired specific forests in the Pistoia area a few centuries later.

Among the timbers identified in this work, there are several others, in addition to the three mentioned here. Two in particular, walnut and deciduous oak, appear as hardwoods for making the tensioning wedges, as does elm. These are woods that are part of the local flora and very common at the time.

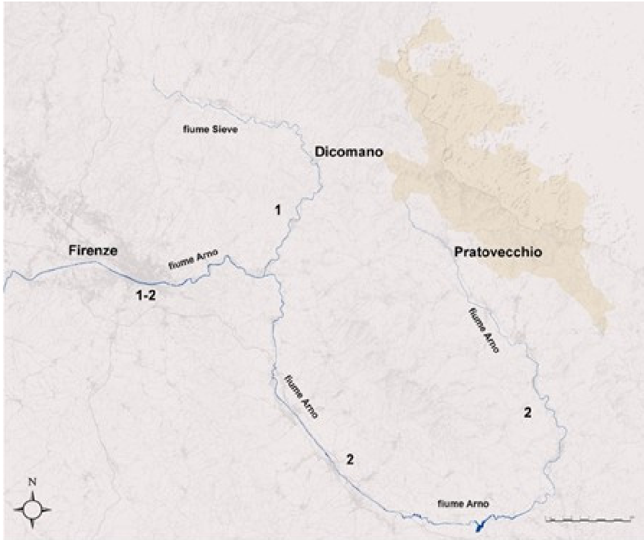


Figure 9. The two principal floating directions to Florence from the Casentino forests (the yellow area): 1—from Dicomano by the Sieve River then Arno following a 30 km path; 2—from Pratovecchio only by Arno River, following a 130 km path [6].

Two others, spruce and black/Scots pine, are part of the Italian flora, but not of the local one. Therefore, it is very likely that these are recent introductions within the trusses, due to restorations carried out in the post-unification period, probably during the great works carried out in 1937–1938. In those restorations, the most used timber continued to be silver fir; however, in the trusses dating back to those years, there are also some elements of spruce. The pine, as we have seen, is found in only one of the two aisles, mainly, but not exclusively, in the form of new struts.

The reconstruction of some trusses in 1937–1938 also introduced a timber of North American origin, which became part of the Italian flora from the 18th–19th century, that of black locust. The durability of locust wood against fungi and insects and its hardness make it a great choice for wedges.

A final part of the discussion regards the relationships between the timber structure durability and wood natural durability. Of the structural elements of the trusses of the central nave, 95% are made of silver fir. According to EN 350:2016 [18], the wood of silver fir is in class 4 to fungal rot (not durable) and to the principal degrading insects. Even elm wood is not durable, and its heartwood is largely attacked by beetles (performing the diagnostic survey, elm wood was frequently recognised at first sight due to the massive insect attacks, even before microscopic identification).

The only durable wood is the sweet chestnut found in lateral naves. Its natural durability is somehow increased by a very limited sapwood, normally 2–4 growth rings thick. Similar characteristics are also found for the wood of black locust, but it has been seen that in reality its use in duomo timber structures is recently introduced (for historical reasons) and is mainly due to its high hardness.

The carpenters who assembled the structures described here knew that the durability of a wooden structure was due more to the construction details and maintenance than to the natural durability of used timbers. The carpenters also knew that the most harmful and dangerous attacks are those from fungal rot and that when the conditions for a fungal decay exist, even the most durable woods undergo decay, only slower than the less durable ones.

Taking into account the wood used for the construction of the trusses elements, 80% of the elements are of silver fir, a not-durable wood. Those who built the structures knew that the points of greatest risk of fungal attack are the connections between masonry and wood, which in the case of the Duomo of Florence, are always very large and ventilated. The attics in general are also well ventilated.

A further important aspect for the durability of the wooden structures is that they are accessible and checked frequently, in particular during rainy events, to assess the tightness of the roof covering.

5. Conclusions

Meiggs [19] rightly argues that no large commercial empire existed in the past that did not have large forests at its disposal. A trade empire needed forests to build ships and to be able to caulk them with the pitch produced from the resin.

At the end of this paper, we think we can add that the forests were also used to demonstrate power through the construction of large buildings, both religious and civil.

Buildings could not be built without timber, and large buildings could not be built without large quantities of timber. Important cities had to have large forests at their disposal, preferably if forests and cities were connected by rivers. In Italy, the link between forests and the expansion of political power is palpable by observing Venice. But it is known that the Florentine Signoria had decided to build a new cathedral to demonstrate the achieved economic wealth and the resulting political weight [20].

From the point of view of the structural diagnostic analysis, wood identification is a basic knowledge. This work aimed to show that identifying the timbers in a large historic roofing structure can have further meanings and, with the help of archival sources, allow discussion of the possible origins of the timber and the possibility of studying the history of maintenance.

A series of possible further studies of dendrochronology [1] and dendroprovenance on the roof structures of Santa Maria del Fiore will allow us to deepen our knowledge on the construction and maintenance of the cathedral of Florence.

Author Contributions: Conceptualisation: N.M., S.C. and M.D.; methodology: N.M., F.M. and S.L.; formal analysis: N.M., S.L. and I.S.; investigation: S.L., I.S. and M.D.; writing—original draft: N.M., I.S. and F.M.; writing—review and editing: F.M., I.S., MD., S.C. and N.M.; project administration: S.C. and N.M.; funding acquisition: N.M. and S.C. All authors have read and agreed to the published version of the manuscript.

Funding: The work was financed by the Tuscany Region, funds POR-FSE 2014–2020, Action A.2.1.7. Intervention program: CNR4C; Project: DiaManTE.

Data Availability Statement: Not applicable.

Acknowledgments: Authors want to thank: Carlo Tacconi and Paolo Lombardini of OPA for their assistance for the on-site safety work organisation during the sampling; Nils Lefeuvre, Logan Bellet and Thomas Lemaire students of École Supérieure du Bois (ESB) in Nantes (F) for the technical support in sampling and identifying, during their summer internships at CNR-IBE.

Conflicts of Interest: The authors declare no conflict of interest.

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