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Dissertação apresentada à Universidade de Coimbra para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Biologia, realizada sob a orientação científica da Professora Doutora Cristina Nabais (Universidade de Coimbra) e sob a orientação externa de M.Sc. Marta Domínguez Delmás (Stichting RING – Netherlands Centrum Voor Dendrocronologie)

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Preamble

This work is the result of an internship at the stichting RING – Nederlands Centrum voor Dendrochronologie (RING Foundation). During this period I had the chance to learn and practice the application of the dendrochronological method to the dating of archaeological and historical timbers, as well as all the practicalities involved in the selection, collection and analysis of samples.

I would first like to thank to Prof. Dr. Esther Jansma, scientific director of the RING Foundation, for welcoming me and making this whole experience possible.

I am very grateful to M.Sc. Marta Domínguez Delmás, dendrochronologist and laboratory manager at the RING Foundation who supervised me during this period. All her patience, support and encouragement were crucial. The knowledge and orientation she transmitted were most important to me and this work would not have been possible without her guidance.

Furthermore, I want to express my gratitude to Prof. Dr. Cristina Nabais (University of Coimbra), who first introduced me to dendrochronology and whose advice, motivation, and sugestions were also indispensable for this work.

Without the logistic support of the Dutch Cultural Heritage Agency (RCE) and the Erasmus Program this work would not have been possible and for that I am very thankful.

I also must thank to Bert Tuin, Juke Dijstra and Dirk de Vries, archaeologists and building historian, for providing the background information regarding the different case studies. To Menne Kosian, from the Landscape Department of the Cultural Heritage Agency, I am equally grateful for the maps he so kindly provided.

Without mentioning any names, as it is unnecessary, I also want to thank to all of those who made my stay in the Netherlands a true pleasure by showing me what the almost untranslatable Dutch word – *gezelligheid* - means.

Abstract

Dendrochronology is based on the study of tree-ring pattern variations in relation to time and is at present the only dating technique that provides dates with annual or sub-annual resolution. Due to the climatic signal contained in these patterns, it is also possible to determine the provenance of the wood through comparison of tree-ring series derived from the objects under study with appropriate master chronologies. By allowing such a precise dating of wooden materials, dendrochronology is a fundamental tool used in archaeological and historical investigations. In this work, dendrochronology was used to date and to determine the provenance of wooden finds derived from two archaeological excavations in the Netherlands: the Martinikerkhof (St. Martin's churchyard) situated in Groningen and from Dorestad (present Wijk Bij Duurstede). With the same aim, we investigated samples from the structural timbers of historical buildings from the city of Venlo, also located in the Netherlands.

The 26 researched coffins from the Martinikerkhof had been built from oak timbers (*Quercus* sp.) derived from trees grown in different regions of Germany and France. Furthermore, the dates determined indicated that the excavated section of the churchyard was used as a burial ground since the mid 16th century until at least, the second half of the 18th century.

From the ancient town of Dorestad, 43 barrels found reused as water wells were investigated and determined to have been built either with silver fir (*Abies alba* Mill.) or with oak wood (*Quercus* sp.). The oak wood was derived from trees grown in forests of western Germany. Both kinds of barrels were contemporary and dated around the 8th century, the exception being one of the oak barrels, which dated to the 12th century.

Oak (Quercus sp.) was the only species found among the wood employed in the construction of the 12 researched buildings from the town of Venlo. The determined provenances suggest the timbers would have been harvested from Belgium forests, while in other cases it would have come from Germany, and south of The Netherlands. Only one of the buildings could not be dated. However, the dating results for the rest placed their construction in the Medieval and early Modern periods, meaning they had survived the second World War bombardments.

Resumo

A dendrocronologia baseia-se no estudo de variações nos padrões formados por anéis de crescimento de árvores ao longo do tempo e é a única técnica que, actualmente, permite a determinação de datas com resolução anual ou sub-anual. O sinal climático contido nestes padrões permite também, determinar a origem da madeira através da comparação das séries dendrocronológicas obtidas a partir dos objectos em estudo com cronologias de referência apropriadas. Por permitir tal detalhe no estudo de objectos de madeira, o método estabelece-se como uma ferramenta fundamental em investigações históricas e arqueológicas. No presente trabalho, o método dendrocronológico foi empregue na datação e determinação da origem da madeira empregue em achados recuperados de excavações arqueológicas, realizadas em dois locais nos Países Baixos: em Martinikerkhof (Cemitério de S. Martinho), situado em Groningen e na antiga cidade de Dorestad (actual Wijk Bij Duurstede). Com o mesmo fim, foram analisadas amostras derivadas das madeiras estruturais de edifícios históricos da cidade de Venlo, também nos Países Baixos.

Da excavação no Cemitério de S. Martinho, 26 caixões contruídos a partir de madeira de carvalho (*Quercus* sp.) foram analisados e determinou-se que a madeira utilizada na sua construção foi obtida de árvores crescidas em diferentes regiões da Alemanha e França. Além disso, as datas determinadas indicaram que a secção das escavações foi utilizada como cemitério desde meados do século XVI até pelo menos, a segunda metade do século XVIII.

Na antiga cidade de Dorestad, 43 barris encontrados reutilizados como suporte para poços de água foram investigados e verificou-se terem sido construídos ou com abeto (*Abies alba Mill.*) ou com madeira de carvalho (*Quercus* sp.). Determinou-se como proveniência da madeira de carvalho a região Oeste da Alemanha. Ambos os tipos de barris foram datados no século VIII, com excepção de um dos barris de carvalho, que datou no século XII.

A única espécie encontrada entre as madeiras aplicadas na construção dos 12 edifícios pesquisados da cidade de Venlo foi carvalho (*Quercus* sp.). As proveniências determinadas sugerem que as árvores teriam crescido em florestas da Bélgica, enquanto que noutros casos, teria vindo da Alemanha e do sul da Holanda. Apenas um dos edifícios não pode ser datado. No entanto, as datas determinadas para os restantes

coloca a sua construção, no período Medieval e inicio do Moderno, mostrando que sobreviveram aos bombardeamentos da Segunda Guerra Mundial.

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Chapter I

1. Introduction

1.1 Dendrochronology: brief history

Dendrochronology or tree-ring dating is an absolute dating method based on the analysis of tree-ring patterns (Baillie, 1982) and is presently the most accurate method for dating and studying wooden artifacts (Haneca et al., 2009). The name of this science has its roots in three Greek terms: *dendron* means *tree*, *khronos* means *time* and *logos* means *the study of*.

The first insights into the nature of tree growth can be found as early as in ancient Greece. Theophrastus, one of Aristoteles' students, observed a stone enclosed by the trunk of a tree and realized that trees grew on the outer circumference of the stem (Studhalter, 1956). Later, in the 15^{th} century, Leonardo da Vinci already recognized the annual character of tree-ring formation and inferred that the ring-widths would be a reflex of past seasons (Stallings, 1937). More recently, during the 19^{th} century, in Europe and America, several researchers studied independently the synchronicity of tree-ring patterns among different trees and its relation with climatic events (Studhalter, 1956). However, the first one to systematically conduct dendrochronological research and to lay the founding principles of the method was Andrew Ellicott Douglass, in 1901. Being an astronomer and studying sunspot cycles at that time, he expected that solar activity would be imprinted, into the tree's growth patterns, through its influence over climate variables such as precipitation. His assumptions were that the width of the growth-rings was a measure of the food supply, and that the food supply was mainly dependent on the available moisture. Therefore, particularly in drier areas, the ring-width would be a direct measure of precipitation, acting as the limiting factor on tree-growth (Cook and Kairiukstis, 1990). As a byproduct of the experimental verification of his theory, Douglass made possible the dating of several archaeological sites through dendrochronological methods. This accomplishment was possible after observing that similar growth patterns occurred in stumps from trees grown in different locations during the same period. By relating the patterns in the stumps with those from living trees, he succeeded to determine the calendar years of each of the rings and, later on, the date of artifacts and archaeological sites (Cook and Kairiukstis, 1990).

The general acceptance of the method as a dating technique took place soon after. Though the basic methodology devised by Douglass has prevailed, some adjustments had to be made in Europe because the climate and species-response are of a slightly different nature than those in America (Baillie, 1982). In Europe, oak provided the first long tree-ring record and both in Germany and Ireland, efforts to acquire that data were soon made. In the sixties, the first German chronologies were built by Huber and Hollstein which reached into the past as far as the 9th century AD and combined data from both living trees and historical timbers. In Ireland, by 1982, a chronology reaching the year 13 BC had been built (Baillie, 1995).

Information on the history and evolution of dendrochronology as well as on the different sub-disciplines covered by this discipline (e.g. dendroecology, dendroclimatology, etc.) can be found in detail on several publications (e.g. Baillie, 1982; Baillie,1995; Schweingruber, 1996).

1.2 Basic concepts

1.2.1 What are tree-rings?

Trees grow by adding each year and immediately under the bark successive layers of conducting vessels and supporting tissues originating from the growth and division of cambial cells (Schweingruber, 1996). Deriving from the procambium, the cambium is a secondary meristem that produces secondary phloem (bark) on the outside and secondary xylem (wood) towards the inside of the tree (Lachaud et al., 1999).

In most species of trees growing in temperate climates annual growth occurs through the seasonal accretion of different types of cells. In spring, *earlywood* is formed and is composed by large thin-walled cells with sap-conducting function while *latewood*, formed during late spring/early summer, is composed by cells with thicker walls and smaller lumina dimensions (Schweingruber, 1996) (Figure 1). Ring-width is defined as the sum of the earlywood and latewood in each ring. These concentric bands, which are macroscopically observable in the cross-section of tree trunks and branches, resemble rings, hence the designation (Kuniholm, 2001).

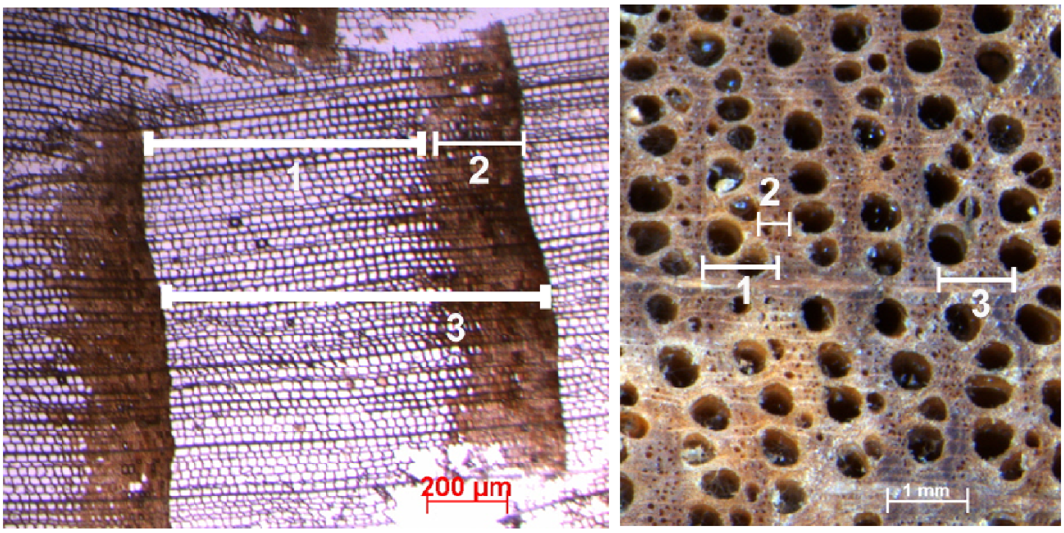

Figure 1. Transversal section of Conifer (left) and Dicotiledoneous species (right). 1- Earlywood; 2-Latewood; 3-Ring-width;

1.2.2 Tree-rings and climate

The formation of each tree-ring is triggered and conditioned by environmental and endogenous factors (Schweingruber, 1996). Concerning the latter, auxin, among several phytohormones, is known to have an exceptional role in the regulation of cambial activity, controlling cell division and wood formation (Zakrzewski, 1983; Lachaud et al., 1999). These regulatory processes are however out of the scope of the present work.

Like this, annual tree-growth results from the interaction between the tree's genetic makeup with the environmental factors (e.g. temperature, light exposure, precipitation) prevailing where the tree grows (Cook and Kairiukstis, 1990). The sequence of favorable and unfavorable years is recorded in trees as thick and thin annual increments respectively. This can be represented by a so-called *tree-ring series* or *tree-ring curve* (Figure 2) where each ring´s width is expressed as a function of time. The specific environmental variables influencing tree growth vary from site to site and differently affect different tree species, this results in characteristic tree-ring series for trees of equal species growing together under the same conditions (Schweingruber, 1996).

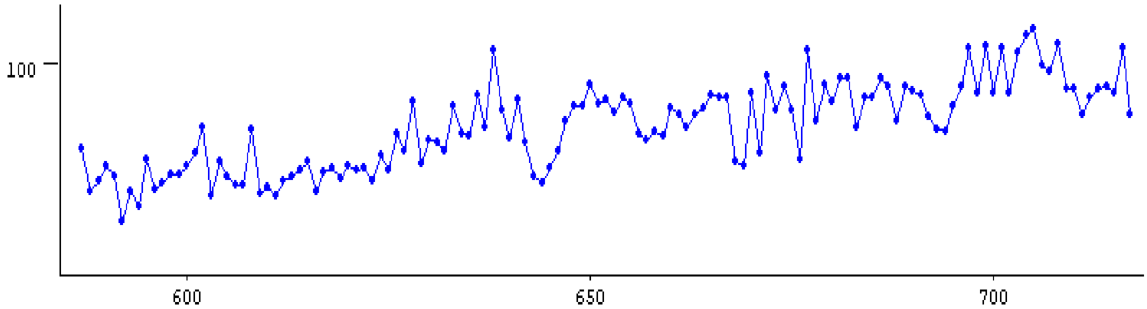

Figure 2. Tree-ring series from an oak sample (Quercus spp.); y-axis: ring-width (1/100 mm); x-axis: calendar years AD.

Several parameters can be measured from tree-rings (e.g. ring width, earlywood width, latewood width, vessel density, etc.) and different information can be derived from them (Cook and Kairiukstis, 1990). However, for dating purposes, ring-width is usually the primary data used.

To the extent of dating, high frequency variations (i.e. differences in growth from year to year) are most relevant. However, trees inherently show different growth rates throughout their lives, as they grow faster in the juvenile period and slower during old age (Cook and Kairiukstis, 1990). Besides, the environmental conditions acting during one year may also influence the growth in the following season (autocorrelation), thus the true climatic signal maybe somewhat disguised in the raw (non-standardized) ring-widths (Schweingruber, 1996). In order to extract the desired information, the data standardized by applying appropriate mathematical transformations, which are meant to remove age trends and non-climatic noise, enhancing the signal relevant for the study. These methods and their application have been extensively described in the literature (e.g. Cook and Kairiukstis, 1990) and will be briefly explained in this work.

1.2.3 The founding principle: Crossdating

The principle of *crossdating* is based on the premise that trees of the same species growing under the same conditions are similarly affected by yearly variations in the climate and this will cause them to respond in a similar way (Fritts, 1976). In long tree-ring series, the patterns caused by these random fluctuations in climate will be unique. Like this, there is only one correct matching position between each tree-ring series (Grissino-Mayer et al., 2010). Therefore, their rings can be matched, i.e.

crossdated, with one another so that any ring can only be assigned to a single calendar year (Baillie, 1982). This is the basic and most important principle of the dendrochronological method, as it allows the determination and assurance of the synchronicity of individual rings from two or more trees (Dean, 1996; Kuniholm, 2001). The crossdating process is nowadays aid by computer programs, which automatically compare tree-ring series in one year shifts, indicating for each position the resulting statistical values (set by the user). However, the dendrochronologist must always visually verify the best statistical match (Figure 3) (Kuniholm, 2002; Haneca et al., 2005; Bernabei et al., 2007; Grissino-Mayer et al., 2010). The crossdating principle also enables the relative dating of two or more floating (i.e. undated) tree-ring series between them.

The strict application of the crossdating method gives dendrochronology the highest degree of accuracy, precision and resolution of any other dating technique (Dean, 1996).

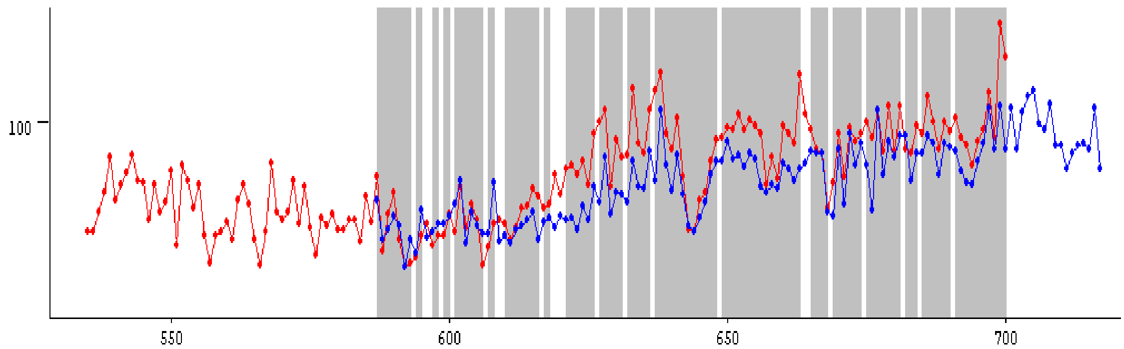

Figure 3. Crossdated tree-ring series from two oak samples (Quercus sp.); the grey area represents the same variation relative to the previous year between both series; y-axis: ring-width (1/100 mm); x-axis: years AD.

1.3 Master chronologies

The simple but crucial principle of crossdating has allowed the construction and extension of tree-ring chronologies that can reach several millennia back in time (Kuniholm, 2001). The process of chronology-building begins with the development of chronologies derived from living trees sampled across a given geographical area and representing the prevailing regional climatic signal. After standardization, the tree-ring series of several trees of the same species are crossdated and averaged into a site chronology. Because the date of the outermost ring is known (i.e. calendar year of the growing season prior to the sampling), the year of the formation of each ring is determined by counting the years with every ring towards the pith. The resulting chronology is absolutely dated and can be used as reference, earning the designation of *master chronology*. To ensure the reliability of a chronology, replication is fundamental. Not only each year's growth must be replicated by a representative number of crossdated specimens for that region (Baillie, 1982), but also the replication between the local chronologies making up the master, must be granted to ensure the quality of a chronology for dating. Tertiary replication is the ultimate test, and is verified when independent master chronologies built by different workers replicate each other (Baillie, 1995).

When a floating chronology derived from, for example, archaeological timbers or dead trees in a forest, is found to crossdate with a master chronology, it can be anchored in time. This is a dynamic process, allowing not only the dating of the floating chronology, but also the extension of the master back in time.

An extensive list of the existing European chronologies for several tree species, with reference to the areas and periods covered, can be found online at www.dendro.bf.unilj.si/first.html. The International Tree-ring Data Bank (http://hurricane.ncdc.noaa.gov/pls/paleo/fm_createpages.treering) is another useful database that contains worldwide tree-ring chronologies derived mostly from living trees. Information about the regions and periods covered by the chronologies is also provided. In Table I can be found a few examples of existing long oak European chronologies.

Table I. Examples of long oak European tree-ring chronologies

Country	Region	Period	Length (years)	Author
Germany	Hohenheim	8480 BC – present	10.429	Friedrich et al., 2004
	Göttingen	7197 BC – present	9.147	Leuschner, 1992
	Germany (south)	370 BC – 1950 AD	2.320	Becker, 1981
	Germany (west)	400 BC – 1975 AD	2.375	Hollstein, 1980
	Germany(Weserbergland)	1004 AD – 1970 AD	967	Delorme, 1972
The Netherlands	South	427 AD – 1752 AD	1.326	Jansma, 1995
	Central and north	1023 AD – 1666 AD	644	Jansma, 1995
	Coastal	2258 BC– 1141 BC	1.118	Jansma, 1995

1.4 Dendroarchaeology

The direct application of dendrochronology to archaeology or, in a broader sense, to the Humanities, consists in the absolute dating of (pre)historical wood. Since Douglass' first achievements, history and archaeology have highly profited from dendrochronological research, as dendrochronology provides data that no other technique is able to provide. The data in question goes far beyond the dates attributed to pieces of wood. Insights into previous forest management and use, as well as timber trade, for example, are added. Furthermore, the climatic record imprinted in wood from (pre)historical contexts also allows, provided the provenance of the wood is known, discerning environmental events that may have prompted past demographic changes, such as big scale migrations or disease outbreaks (e.g. Cook and Kairiukstis, 1990; Dean, 1996; Schweingruber, 1996; Kuniholm, 2001; Haneca et al., 2009; Büntgen et al., 2011).

For over 100 years, dendrochronological investigations have been conducted all over the world with different aims. These studies are today recorded in a large body of literature (over 11,700 publications in 2009, according to Grissino-Mayer et al., 2010). Here, we present a few cases that are representative of the different possible applications of dendrochronology to the field of the humanities.

Concerning pile-dwelling research, dendrochronology is of extreme utility and allows a better understanding of early human activities. In southwest Germany, the Neolithic site on the shore of lake Constance (Hornstaad-Hornle I) was investigated during 10 years within a large-scale excavation programme (Landesdenkmalamt Baden-Würtemberg). Billamboz (2006, 2008) reports the main findings of the dendrochronological research performed on a total of 20,044 samples derived from the excavations. Several species were identified and the results of his research revealed hetero-connections (i.e., crossdating between different tree species). The use of the different tree species was related to four different building phases during the 20 year occupation period around 3900 BC. In each, preference had been given to different wood species. In the early phases, ash (*Fraxinus excelsior* (L.)) was utilized and in the latest, the selected timbers for the expansion of the settlement were oak (*Quercus* sp.) and beech (*Fagus sylvatica* (L.)). Billamboz (2008) attributed this shift in resource exploitation to different intensities of construction and agricultural activities. The dates and frequency of wood applied in repairs also provided the time span of dwelling occupation.

The time in which economical activities, such as mining, were carried can be assessed through dendrochronology. Illustrative cases for this can be found, for example, in the dating of structural timbers and artifacts from the Kelchalm copper mines (Pichler et al., 2009) and Hallstatt salt mines (Grabner et al., 2007), in Austria. Pichler et al. (2009) successfully dated the copper mining activities to the year 1237 BC which proved a former established date, based on ceramics and metal artifacts typology, to be wrong.

Dendrochronological methods have been used on wooden findings from different archaeological sites and dated through standard procedures (e.g. Kulakova, 2009; Thun and Alsvik, 2009; Tarabardina, 2009). However, in some cases, the development of local master chronologies was required. In order to enable the dating of several floating chronologies derived from medieval buildings and archaeological artifacts in Norway, Thun (2005) compiled three master chronologies for *Pinus sylvestris* L. extending from the present to the years 552 AD (central Norway), 765 AD (west Norway) and 871 AD (south-east Norway). These were built from living trees and timbers from buildings allowing nowadays the dating of pine timber grown anywhere in Norway during the last millennium.

During the historical period, the conjunction of written records with dendrochronological dates provides important information concerning timber trade and the time elapsed between the cutting dates of trees and the construction of buildings. Sass-Klaassen *et al*. (2008), for example, report the investigation performed on foundation piles derived from nine buildings in the Netherlands. As the construction dates of the researched buildings were documented, once the cutting dates of the foundation piles were established, the period between tree harvest and wood implementation as foundation piles could be determined. This time was found to vary between 2 and 3 years. During this period the timbers were stored in the forest or in warehouses and transported by water either floating or inside ships. The region where the trees had grown was determined by using master chronologies from well-defined areas to date the samples (*dendroprovenancing*). In this case, the timbers were found to be derived from several regions in Europe, with Finland, Sweden and the Netherlands being the sources for pinewood, while spruce was imported from southern Germany and Norway. All these factors (i.e., provenance and time-span between harvest and use of the timber) were also helpful in the context of assessing the susceptibility of wood to biodegradation.

Another interesting application of dendrochronology is concerned with nautical archaeology. Daly (2007) dated the timbers from the Karshau ship, found in the north shore of Germany, to the early 12th century. Besides, the reasearcher was also able to accurately determine the provenance for the timbers at a local level, specifically to the town of Odense in Denmark.

Away from the mud and clay, dendrochronology has also proven its value in art-galleries and museums. Musical instruments with intrinsic cultural value can also be subjected to dendrochronological methods. A good example can be found in the work of Bernabei et al. (2010), who investigated forty-nine stringed instruments from the Cherubini Conservatory collection with the purpose of dating the timbers used in their manufacture. Thirty-seven instruments could be dated and the investigators were able to assemble, from them, a spruce chronology spanning from AD 1396 to AD 1953. Furthermore, valuable evidence can be collected which allow the correct attribution of the authorship of works of art. This can happen when a certain object is found to be made of wood derived from a tree that was still growing after their presumed makers had died (Grissino-Mayer et al., 2005; Bernabei et al., 2010). Still in the art-historical field, panel paintings have also been the object of inquiry and dendrochronology is often able to give answers by enabling the dating of the wood used in panels but also by evidencing preferences in wood from a given region for that purpose. Authorship attribution and forgery identification can also be deduced (Fraiture, 2002; Bernabei et al., 2007).

These examples give an overall idea of the accomplishments of the dendrochronological method and its potential beyond the dating. However, dendrochronology has some requirements in order to be successful (Hillam, 1979; Bernabei et al., 2007; Haneca et al, 2009):

- The tree species must produce distinct growth rings annually and have a wide natural distribution;
- The wood under research must originate from (co-) dominant trees. This means that tree growth must be regulated by regional climate rather than by competition with other trees or other local influences;
- The tree-ring pattern must manifest sensitivity, i.e. a marked year- to-year variation in ring-width, as opposed to a complacent growth pattern;
- To secure the efficacy of the crossdating method, a minimum of 30-70 overlapping rings is necessary to ensure the statistical significance of a match;
- There must be available reference chronologies for the species being investigated covering the period and region where the wood originates.

When these conditions are met, the chances of dating are high. However, when a sample is dated, the highest level of accuracy, regarding the cutting date, is attained when a sample is complete and the bark edge is present. In such cases, the completeness of the last ring will also determine the season in which a tree was cut. On the other hand, when an indefinite number of rings has been removed from the timber or was degraded, the cutting date is unknown. Nevertheless, in some species, such as oak (*Quercus* sp.), this can be estimated based on a property of trees that allows the distinction between *sapwood* and *heartwood*. While trees age, only the outermost fraction of the wood of stem and branches is kept alive with the function of conducting the sap, hence the term *sapwood*. As trees grow bigger, they need more support capacity, so the cells in the inner section of the sapwood progressively suffer autolysis and the cell lumina are infiltrated with essential oils and tylosis that will also protect the wood from fungi and insects. Once this process is completed, the ring has been turned into *heartwood*.

The observations of the number of sapwood rings in specific regions and according to tree age-classes allows the estimation of the number of sapwood rings in trees from those regions. When the sample preserves some of it, based on these regional sapwood estimates, it is still possible to indicate a minimum of missing rings until the bark and to estimate a felling date. In the absence of sapwood, an indefinite number of heartwood rings may have also been removed and the estimated date can only be expressed as a *terminus post quem* (TPQ) – the date after which an object was crafted.

Last but not least, one should bear in mind that dendrochronology dates the tree-rings but not the year in which the wood was processed and implemented in a structure or artefact. As it has been illustrated, there may be a time-span between the felling of the tree and its use. Besides, timbers from older constructions or dead trees collected in a forest could have been applied in a more recent structure or a sculpture could have been carved out of reused timbers. In such case, the dendrochronological dates could be even centuries off the date in which the structure of the artifact were made. Moreover, some timbers from buildings or ships, for example, could also have been repaired, in which case the dendrochronological dates would point at an earlier dating than the one of the original structure. This must always be kept in mind when interpreting dendrochronological dates in the context of historical and archaeological research.

1.5 Stichting RING – Nederlands centrum voor dendrochronologie

The Dutch Centre for Dendrochronology-RING Foundation was founded in 1993 by two organizations: the A.E. Giffen Institute of Pre- and Proto-Historical Archaeology (IPP, University of Amsterdam) and the National Service for Archaeological Heritage (ROB) and is currently hosted by the *Rijksdienst voor het Cultureel Erfgoed* (former ROB). The institution was created due to the growing number of researches related to wooden cultural heritage (archaeology, architecture history, etc), in the Netherlands, and the need to accurately date this kind of materials. The aim of the foundation is the promotion and encouragement of dendrochronological research for Dutch Archaeology and other disciplines.

Since then, the RING Foundation has been working, commercially, providing dendrochronological research for archaeological companies, museums, state agencies and private owners. Besides the commercial activity, it also collaborates with other institutions in national and international research projects. Current projects in progress are the Iberian Cultural Heritage and the DCCD (Digital Collaboratory for Cultural Dendrochronology), both funded by the NWO (Netherlands Organization for Scientific Research). The former aims at assessing and expanding the dendrochronological data currently available for the Iberian Peninsula within the context of Cultural Heritage studies. The DCCD project consists in the creation of an online database for storing and sharing of European dendrochronological data and metadata produced by members and contributors. The aim of the project is the creation of a standardized data network that will allow large scale investigations in the fields of wood usage, economy, climate and landscape history.

1.6 Objectives and outline of the thesis

The main objective of this work is to apply the principles of dendrochronology as a dating method and also to illustrate its potential beyond the dating. For this, the method has been applied on different wooden objects considered part of the Dutch Cultural Heritage. The acquisition of important methodological knowledge and skills required in this particular field of research was also one of the main motivations.

The methods for the selection, collection, preparation, analysis and dating of samples during dendroarchaeological investigations are described in **Chapter II – General Methods**. Following, in **Chapter III**, we present three different **Case Studies** in which dendrochronology was used to date and to determine the provenance of the wood. Wet wood samples researched in this work derived from two different archaeological excavations in two cities in the Netherlands - **Groningen (point 3.1)** and **Ancient Dorestad (point 3.2)**. The third case study comprised dry wood samples from several historical buildings in **Venlo (point 3.3)**, also in The Netherlands. These investigations were commissioned to the RING Foundation in 2010 and 2011 as part of larger, multidisciplinary research projects and for this a thorough interpretation of the results was left to the archaeologists and building historians. An **Overall Conclusion**, summarizing the potential and limitations of the method as well as the kind of information that can be extracted from its application is given at the end of this chapter in **point 4**.

Chapter II

2. General Methods

2.1 Identification of wood species

Identifying the wood species is the first step of a dendrochronological research and ideally it should be done before the samples are collected. Identifying the wood species will provide the first insight into the suitability of the samples for dendrochronology, as not all species produce distinct growth rings. Furthermore, finding out the species of the wood being researched is crucial in order to select the proper master chronologies to date the samples.

Samples from archaeological excavations may have suffered certain degree of degradation, depending on the type of soil where they were preserved. Therefore, features such as spiral thickenings (i.e. helical pattern of the secondary cell wall of tracheary elements) may have disappeared and color and odor cannot be used as distinctive features. However, most anatomical characteristics can still be recognized macro- and microscopically and, with the help of an appropriate identification key, will lead to the identification of the species. Several identification keys have been published for wood species from different natural distributions and this should be taken in consideration when selecting one (e.g. Schweingruber, 1990; Keller, 2004).

For microscopic characterization of the wood it is necessary to have the transversal, tangential and radial sections of (preferably) the stem, obtained by using either a razor blade or a microtome. If possible, the sample to be identified should have at least $1cm^3$ in order to obtain a surface big enough to observe all key characteristics in the different section. The observation of these sections under an optical microscope is usually sufficient to identify a wood sample to the genus level. Some tree species like *Quercus robur* (L.), *Quercus petraea* (Liebl) and *Quercus pubescens* (Willd.), or *Pinus sylvestris* (L.) and *Pinus mugo* (Turra), cannot be differentiated on the basis of wood anatomical characteristics (Schweingruber, 1990). Nevertheless, species such as pedunculate and sessile oak, which occupy similar geographical distributions, have been found to crossdate between them, hence for dendrochronological purposes their distinction is not so relevant (Haneca et al., 2009).

The first great division between tree species separates conifers and dicotyledonous species (dicots). Conifers present tracheids while dicots have vessels and parenchyma cells easily visible in the transversal section. This distinction can be made using a small magnification (e.g. hand lens). To narrow down to the genus, or more rarely to the species (it depends on the taxa), the presence or absence of resin canals is a crucial feature in conifers, whereas dicots can be divided according to the distribution of vessels in the ring (ring-porous or diffuse-porous), size and arrangement of the rays, etc.

2.2. Sample selection, storage and preparation

2.2.1. Sample selection

In archaeological excavations, samples are first tagged and then selected in the field by the archaeologists, according to their preservation state and relevance to date a certain structure or find. An individual number should be given to each sample and their position registered, in order to facilitate the interpretation of the results (Morgan, 1975).

Timbers used in buildings are sampled by construction phase using a dry wood borer. The person responsible for the sampling (usually a building historian or a dendrochronologist) must register what timbers were sampled and mark them on a sketch so that the dates can be matched later to the timbers. The sequence of building marks on the timbers (i.e. numbers expressed by numerals or other figures carved in the timbers to indicate their assembling order during construction) must also be noted, as well as the presence of bark or bark-edge (i.e. outermost ring located directly under the bark). These data will help interpreting the building sequence, as well as the history of repairs or the reuse of wood.

Once at the laboratory, samples are selected based on the tree-ring pattern and ring number. The size of a sample cannot be taken as an indication of the number of rings it may contain. This is only dependent on the tree's growth-rate and, for a given diameter of the stem, a fast-grown tree will present less rings than a slow-grown one.

The way the wood was processed (Figure 4) also plays a role in the suitability of samples for dendrochronological dating. Full cross-sections are preferable to planks but, often, only planks are available, either radial or tangential. The best planks are the ones that were processed through radial splitting or sawing, as they contain a section of the stem parallel to the medullar rays running straight from nearly the pith towards the bark. Tangential planks, however, usually have less rings and this number will depend on the height of the plank (Morgan, 1975).

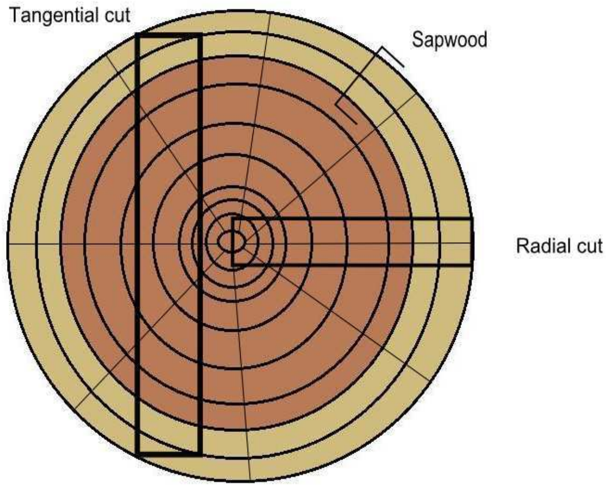

Figure 4. Wood conversion types : tangential and radial cuts

Quality timber for dating is described as knot free and having many rings which are usually sensitive i.e., show great variation in width (Hillam, 1979). Samples showing distorted ring patterns caused by reaction wood, knots, wounds and complacent growth-patterns are less likely to date and should be excluded from further analysis.

The ring number is estimated during the selection by rough counting. The more rings, the higher the chances of getting significant values in a single match that will identify it as the date. In general, 70 rings are necessary to obtain unique statistical and visual matches. However, if a high number of samples from the same context is available, samples containing less rings can also be considered (Bernabei et al, 2007). When possible, all available samples should be collected, tagged and measured (Hillam, 1979).

When researching art-historical wooden objects, the dendrochronologists must inform the owner or curator about the best place to clean a ray to observe the tree-rings and a compromise must be made, given the invasiveness of the cleaning process. Usually a ray may be cleaned in a section that is hidden from sight (e.g. the back of drawers or planks in a cabinet, the upper section of the legs of a table, etc.), and preferably, where there is sapwood present. The tree-ring pattern of overlapping sections will be photographed using a scale and the tree-rings will be measured with adequate software.

2.2.2. Storage of samples

The storage and preservation of samples will be determined by their moisture content. Wood found in waterlogged environments underground is generally described as *wet wood*, whereas wood from archaeological sites in dry areas and wood from buildings and art-historical objects (panel-paintings, sculptures, furniture, etc) is described as *dry wood*. In waterlogged wood, water has replaced what used to be cellulose in the cell walls, hence the drying out will lead to its structural deformation. This may preclude any clear observation and measurement of the tree-rings (Jordan, 2001; Jiachang et al., 2009). To safeguard the preservation of the samples, they must be protected from oxygen and moisture loss immediately after collection. This can be achieved by wrapping them in plastic or self-sealing bag, depending on the sample size. Adding a bit of water to the bag can help keeping the moisture level (Morgan, 1975). This prevents further degradation caused by bacteria and fungi in aerobic conditions and impedes the desiccation of the samples.

Dry wood cores obtained from construction timbers do not require any special care regarding preservation, as the wood is dry and still maintains its structural integrity. They may be stored in paper envelopes and kept in a low moisture environment.

2.2.3. Sample Preparation

For microscopic observation and ring width measurement of wet wood samples, the surface of the transversal section, after collection, is prepared with razor blades until a clear, smooth surface is obtained. The use of razor blades is hard to master at first but it proves to be very effective after some practice is acquired. Given the soft texture of the wood the use of sand paper is not appropriate.

The dry-wood cores are fixed with a vice and can be prepared using a Stanley knife to smoothen the transversal surface and expose the tree-rings for observation. This method works quite well, especially because it allows clearing the sapwood section without applying much pressure on it and makes the tree-rings perfectly clear. The diameter of the samples will determine the need to mount them on wooden supports, given that thinner cores may break during their manipulation if they are not supported. If necessary, cores can also be polished using sandpaper. This must be done carefully to prevent the destruction of sapwood, which might be partially eaten by insects.

Rubbing chalk powder on the cleaned surface of both wet and dry samples will highlight tree-ring structure and boundaries (Cook and Kairiukstis, 1990).

2.3. Acquisition of tree-ring data

2.3.1. Acquiring data from wood samples

Ring-width measurements are usually made using a measuring table, with a 1/100 mm or 1/1000 resolution and with the aid of a stereomicroscope. The measuring table is connected to a computer which has specific software used to record the ring-width series in measurement files and perform statistical analysis. Several programs are available nowadays as for example PAST 4 (Knibbe, 2008) and TSAP (Rinn, 1996).

2.3.2. Acquiring data from digital images

When the piece of wood to be analyzed is too big, or cannot be sampled, the measurement of tree-rings is made using digital images. A thin line (< 0,5 cm) has to be cleaned and for this several methods exist (e.g. micro-sanding, surgical scalpels, etc.) as different authors illustrate (Fraiture, 2002; Hanecka,2005b).

After the surface is smooth and the tree-rings are visible, photographs are taken. Usually, tape (or a ruler) is used to mark the ring sequence and to provide a calibration scale. After taking the pictures these are loaded into specific software for tree-ring measurement in digital images (e.g. CooRecorder by Larsson, 2007). The ring-widths are marked on the screen by the analyst after setting the right scale. A standard measurement file is obtained for analysis.

2.4. Crossdating

Once tree-ring series are obtained from a set of samples, they are compared between them (internal crossdating) and against the master chronologies (external crossdating). Crossdating must be confirmed not only by statistical parameters but also by the dendrochronologist through the visual inspection of the agreement between tree-ring series (Baillie, 1995; Kuniholm, 2002).

Two main statistical tests are used when crossdating: the Coefficient of Parallel Variation (%PV) and the Student's t-test. The %PV is a non-parametric test and is used to compare the annual common variation between two raw ring-width series for a certain overlapping position. It expresses the fraction of synchronous rings that show the same variation (increase or decrease in width), relative to the previous year (Bernabei and Bontadi, 2011). The Student t test is a parametric test and assesses the certainty of a given crossdating position by indicating if the correlation between both series is significantly different from zero (Sass-Klaassen et al., 2008). However, the Student t test can only be employed if the data follow a normal distribution, which is not usually the case of tree-ring series. The normalization is therefore accomplished by applying logarithmic transformations to the data. Two algorithms are commonly used: the one proposed by Hollstein (1980) and the one developed by Baillie and Pilcher (1973) (Haneca, 2005b). Besides normalizing the data, these transformations also remove the age trends present in the series. Both are usually integrates in some dendrochronology-specific software and are automatically computed. In this work only t-values calculated according to Holstein are reported, however the t-values after the Baillie and Pilcher transformation were also taken into consideration during the analysis.

The Hollstein (1980) algorithm removes the age trend by dividing the value of the current year (Yi) for the value of the following (Yi + 1). After this, the logarithm is applied for normalization resulting in tree-ring indices ($Yi\ (Holl)$) at each year being compared (Haneca, 2005b):

$$Yi\ (Holl) = \log\left(\frac{Yi}{Yi+1}\right)$$

After both series being tested have been transformed the t-value is calculated as follows:

$$t_{\text{HO}} = \frac{r \times \sqrt{n-2}}{(1-r^2)}$$

Where r is the correlation coefficient between sample and reference and n is the number of overlapping years between both.

Usually, a t-value value of 4 is the minimum considered to be indicative of a match when dating a tree-ring series. Regarding internal crossdate, the degree of correlation between two series allows to infer the affinity between them. The treshold values are arbitrarily set based on experience or on experimental evidence, but usually, t-values above 6 may suggest a common geographical origin. While, in general, matches between individual series resulting in t-values above 10 indicate that both are derived from the same tree (Wazny, 2009). However, the visual verification of the growth pattern agreement between series is indispensible to make such conclusions. Furthermore, the t_{HO}-value is also dependent on the number of overlapping years between two series being compared. A short overlap (<40) may result in a t value of 4, for example, even though the series come from the same tree. The inverse also applies, as a long overlap (>150) may produce values higher than 10 for series that derive from different trees. The ultimate decision falls into the dendrochronologist's judgment and experience (Kuniholm, 2001).

When possible, more than one radius per sample are measured and averaged into mean curves in order to eliminate intra-tree variability. If different samples can also be crossdated they are averaged to enhance the common environmental signal and increase the chances of successful crossdating with the master chronologies (Hillam, 1979).

2.5 Determination of timber provenance

When the comparison of a time series against several master chronologies results in a date, this may be replicated by several independent chronologies with different levels of correlation. Besides confirming the date, these replications also provide an indication about the region where the wood came from. The premise is that the master chronology showing the highest correlation does so because the tree-ring series in comparison is derived from the same region and expresses the same climatic signal (Haneca et al., 2005a; Sass-Klaassen et al., 2008; Haneca et al., 2009). If the master chronologies cover extensive areas, further refinement is necessary to accurately determine the area of provenance. The tree-ring curve in question is then compared to local chronologies, covering smaller areas, within the suspected area of provenance. The strength of the calculated correlations is compared and the same principle as before is applied (i.e. the higher the correlation is, the higher the geographical proximity). There are, however, two limitations for this procedure. Firstly, the climatic signal contained in a single sample might not be very representative of that of the area of origin, as noise caused by individual factors may disguise it. This can be overcome by averaging highly correlated tree-ring series derived from the same context to produce a mean curve. This reduces the noise and enhances the common variations caused by climate. Secondly, local chronologies for the period of interest and covering the whole range of ecological conditions on a given area must be available (Bernabei and Bontadi, 2011).

2.6 Sapwood estimations

In oak species, the sapwood is susceptible to insects and fungi attacks. It degrades quickly and was often removed from the timbers before they were utilized, being rarely found in archaeological and art-historical artifacts (Hughes et al, 1981). TPQ dates are calculated within a 95% confidence interval The lower limit of the 95% confidence interval from regional sapwood estimates (Table II) is added to the date of the last measured ring (Haneca *et al.* 2009). When these are lacking, estimates from a nearby region can be used.

Table II. Sapwood statistics for Germany (Hollstein, 1965, 1980), after Haneca *et al.* (2009)*, n.s = not specified*

Tree age-class	Average no. of sapwood rings	Standard deviation	Median	Range (min-max)	95% conf. interval	Sample depth
<100	16.0	4.50	–	–	–	–
100–200	20.40	6.20	–	–	–	–
>200	25.90	7.50	–	–	–	–
n.s.	19.00	7.54	–	7–66	8.22–37.95	446

Chapter III

3. Case studies

3.1. Martinikerkhof (St. Martin's Churchyard), Groningen

3.1.1. Introduction

The town of Groningen is situated in the northeast of the Netherlands (Figure 5) and originated from a small early medieval agricultural settlement, donated by the German emperor Henry II to the Church of Utrecht in AD 1040. Around the 13th century the administration of the city shifted from religious to secular and by the 15th century it held the major political force and economical influence in the northern region of the Netherlands. In 1594 the town was taken over by the Protestant Rebellion of the Dutch Republic and the political and economic situation stabilized thereafter. Following the Industrial Revolution in the late 19th century and during the first half of the 20th century, the city grew so rapidly that by the 1960s, the town had earned the name of "metropolis of the North" (Bert P. Tuin, pers.com.).

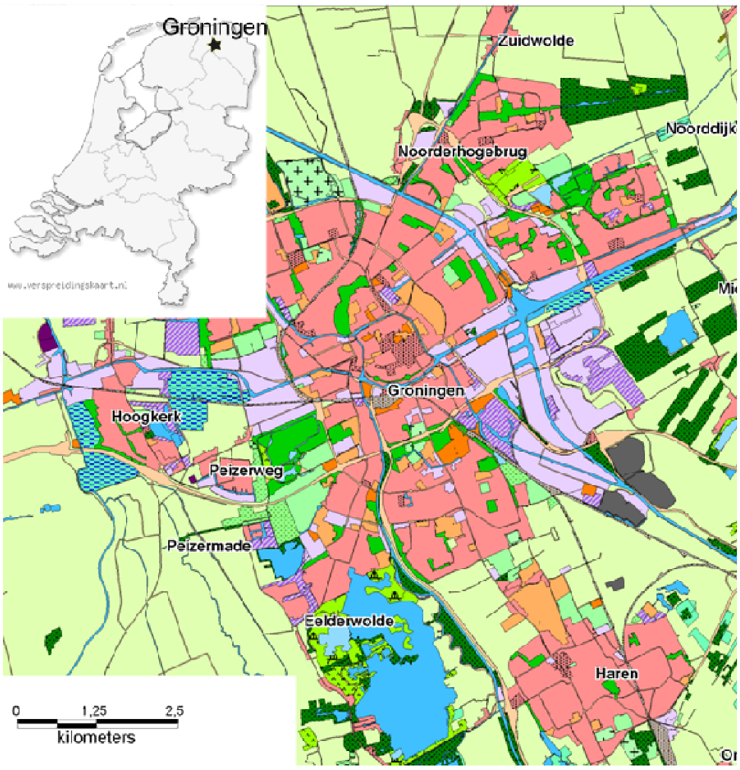

Figure 5. City of Groningen located in the northeast of the Netherlands

Built in the 9th century, the Martinikerk was the most important church in Groningen. The churchyard around it (Martinikerkhof) has therefore an intrinsic value as a repository of information concerning part of the city's history and development. The grounds inside the Martinikerk were excavated in sixties and seventies during a restoration action and graves were found (B.P. Tuin, pers.com.). These were radicarbon dated to the period between the 8th and 10th centuries (Lanting J.N., 1990a, 1990b). Despite this and the existence of some historical written records, questions remained about the use and expansion of the Martinikerkhof (burial grounds). Dendrochronological methods had never been systematically applied to the finds (B.P. Tuin, pers.com.). Therefore, the excavation carried out in 2009 in the southeastern section of the church, provided a unique opportunity to perform dendrochronological analysis to all the coffins recovered.

3.1.2. Materials and Methods

The area of the excavation is shown in Figure 6. The coffins had been preserved on the ground in a waterlogged environment. The archaeologists documented them and extracted them from the ground, selecting the planks from each coffin based on the degree of preservation. Though a coffin is composed of six planks (Figure 7), only a maximum of five planks per coffin could be retrieved in most cases.

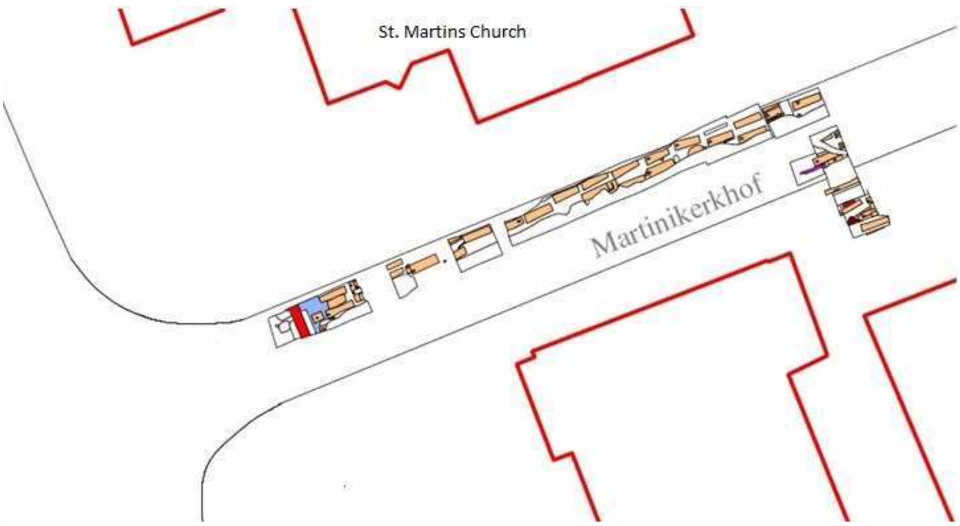

Figure 6.Extract plan of the 2009excavations. Graves in trenches.

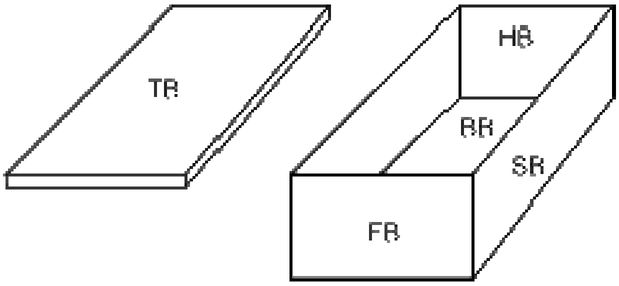

Figure 7. Scheme of the coffins. TB=Topboard; HB=Headboard; BB=Bottom board; SB=Sideboard; FB=Footboard.

Figure 8 – Coffin photographed during the excavation before their removal. The coffins were found in a waterlogged environment.

At the Ring Foundation laboratory, we used a band-saw to cut an approximately 3 cm thick transversal section of each plank (Figure 9). The subsequent selection and preparation of the samples for dendrochronological research, as well as the data acquisition and crossdating followed the approach described in point 2.

Figure 9. Sample sawn with a band-saw to obtain the transversal section of the plank (scale bar = 20 cm).

When possible, more than one radius per sample was measured. Crossdating between all the elements belonging to each coffin was systematically tested and averages were made when sound matches were found. Planks from different coffins were compared between them in the same way.

In order to determine dates and wood provenances, individual measurements were checked against the master chronologies available at the RING Foundation laboratory for the respective species.

3.1.3. Results

A total of 64 samples were collected from planks of 26 coffins. All the planks were identified as oak (*Quercus sp.*) macroscopically due to conspicuous characteristics in the transversal section (Figure 10): ring porous with large vessels in earlywood and large aggregate rays perpendicular to the growth-rings (Morgan, 1975; Baillie, 1982). The planks had been processed through tangential sawing of tree trunks and their width ranged between 12 and 59 cm. Seven samples had sapwood but none of them had the bark edge preserved. The average tree ring number was 105 (range 35-292), with 70% of the samples presenting more than 70 tree-rings.

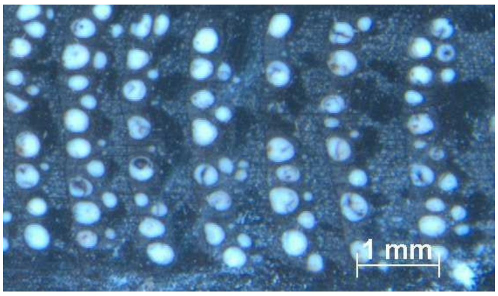

Figure 10. Transversal section of an oak wet wood sample after preparation (growth direction towards the right).

From the 64 samples, 43 (67%) were successfully dated including five with sapwood. The number of rings in the dated samples ranged between 53 and 292 rings. The dates of the last measured ring span from the year AD 1489 to AD 1757. TPQ dates, based on Hollstein's (1980) sapwood estimates, ranged from AD 1503 to AD 1768 (Appendix 1). The statistical parameters (%PV, t_{HO}) associated with the comparison between each of the samples and the matching master chronology varied between 58.7 and 84.7 (%PV) and 3.28 and 10.7 (t_{HO}) (Table III). The t_{HO} value of 3.27 was accepted as indicative of a match for a particular sample, because the same date was replicated by other chronologies. The visual comparison was also taken into account.

Table III. Dating results for all samples collected per coffin. Dates of the last ring and estimated TPQ dates represented for the dated samples as well as the dating master chronologies for each of those. The two letter code after the find number indicates the relative position of the sample in its original context: TB=Topboard ; HB=Headboard ; BB=Bottom board ; SB=Sideboard ; FB=Footboard ; LP=Loose plank ; n = number of rings ;SW Rings = Present sapwood rings ; t_{HO} = t -value according to Holstein ; %PV = Coefficient of parallel variation ; p = the probability of the determined %PV value occurring by chance (expressed as a fraction of 1).

Object	Find Number and relative position	Dendrocode	n	SW rings	Date Last Ring (AD)	Estimated felling date	t_{HO}	%PV	p	Master Chronology
Coffin1	340BB	GMK00110	167	0	1690	after AD 1703	12.3	78,7	0,0001	FRLOTH02
Coffin2	358HB	GMK00121	150	0	1550	after AD1562	7,49	72,7	0,0001	DEOFRI01L
Coffin3	578 BB	GMK00131	70	0	-	-	-	-	-	-
Coffin4	360SB	GMK00141	67	0	1540	after AD1551	4,46	65,7	0,02	BEBELG01
	361HB	GMK00150	129	0	1624	after AD1638	5,98	71,7	0,0001	NLMIZU01
	362FB	GMK00160	57	0	-	-	-	-	-	-
	363SB	GMK00171	70	0	1563	after AD 1575	5,27	71,4	0,0005	FRNOORD01
	364BB	GMK00180	62	0	1555	after AD 1566	8,09	84,7	0,0001	NLTWWF01
Coffin5	372SB	GMK00191	114	0	-	-	-	-	-	-
	421FB	GMK00201	91	0	1622	after AD 1634	6,41	68,1	0,001	DEOFRI011
	422BB	GMK00210	77	2	1626	AD 1640 ±4	3,28	63	0,025	NLTWWF01
Coffin6	400BB	GMK00220	40	0	-	-	-	-	-	-
Coffin7	487HB	GMK00230	107	0	1587	after AD 1599	5,46	64	0,005	DENIKU01
Coffin8	471BB	GMK00240	101	9	1644	AD 1654 ±6	7,15	73,3	0,0001	DENSA701
	470SB	GMK00250	63	0	1621	after AD 1632	6,28	77	0,0001	DENSA701
Coffin9	544SB	GMK00260	72	0	-	-	-	-	-	-
	545HB	GMK00270	59	0	-	-	-	-	-	-
Coffin10	238SB	GMK00280	86	0	1599	after AD 1612	5,79	69,2	0,0005	NLTWWF01
	221HB	GMK00290	79	0	1590	after AD 1602	5,42	62,7	0,025	NLTWEN02
Coffin11	210LP	GMK00301	56	0	-	-	-	-	-	-
Coffin12	160LP	GMK00311	56	0	-	-	-	-	-	-
	177HB	GMK00321	98	0	-	-	-	-	-	-
	178HB	GMK00331	35	0	-	-	-	-	-	-
	179SB	GMK00341	63	0	-	-	-	-	-	-
	222BB	GMK00351	71	0	-	-	-	-	-	-
Coffin13	166TB	GMK00361	126	0	1517	after AD 1529	5,46	58,7	0,1	DENSA601
	167SB	GMK00370	124	ST	1645	AD 1667±9	7,6	73	0,0001	DENSA601
	215BB	GMK00380	100	0	1618	after AD 1629	8,6	66,5	0,001	DENISA01

Coffin14	119LP	GMK00390	114	0	-	-	-	-	-	-
Coffin15	410BB	GMK00400	167	0	1535	after AD 1548	7,76	72,5	0,0001	DENSA701
	411HB	GMK00411	148	0	1594	after AD 1608	8,17	69,3	0,0001	NLTWWF01
	413SB	GMK00420	111	0	1607	after AD 1618	4,57	68	0,0002	DENSA701
	412FB	GMK00431	100	0	1567	after AD 1578	6,62	71,5	0,0001	DEOFRI01L
	414SB	GMK00440	40	5	-	-	-	-	-	-
Coffin16	252SB	GMK00450	105	0	1617	after AD 1642	7,74	71,9	0,0001	DEOFRI01L
	223TB	GMK00460	110	0	1631	after AD 1642	7,64	71,8	0,0001	DEOFRI01L
	260BB	GMK00470	87	0	1652	after AD 1664	5,68	71,8	0,0001	DENSA701
	253HB	GMK00480	136	0	1649	after AD 1661	4,26	61,4	0,01	DEOFRI01L
	259FB	GMK00490	133	0	1649	after AD 1661	5,79	64,7	0,001	DENSA701
Coffin17	182BB	GMK00500	216	0	1726	after AD 1740	10,7	73,4	0,0001	DECENT01
	176SB	GMK00510	102	0	1757	after AD 1768	5,2	64,7	0,005	FRQUSP_moselle
	169TB	GMK00521	58	0	-	-	-	-	-	-
Coffin18	143SB	GMK00531	55	0	-	-	-	-	-	-
Coffin19	496SB	GMK00541	159	0	1559	after AD 1577	6,69	63,2	0,001	NLTWWF01
	495HB	GMK00551	71	0	1554	after AD 1567	6,6	68,3	0,005	NLTWWF01
Coffin20	378BB	GMK00560	55	4	-	-	-	-	-	-
	376TB	GMK00570	92	0	1619	after AD 1630	7,1	68,5	0,0005	DENSA701
Coffin21	600BB	GMK00581	111	0	-	-	-	-	-	-
	601SB	GMK00591	44	0	-	-	-	-	-	-
Coffin22	158SB	GMK00600	189	0	1527	after AD 1541	6,26	64	0,0002	DENSA701
	156TB	GMK00611	77	0	1489	after AD 1503	5,41	69,5	0,001	NLTWEN02
	157HB	GMK00621	77	7	1625	1637 ± 6	5,48	71,4	0,0002	DENIKU01
	159BB	GMK00630	108	7	1624	1640 ± 7	7,14	71,3	0,0001	NLTWEN02
Coffin23	165BB	GMK00640	53	13	1677	1683 ± 6	6,02	75,5	0,0002	DEOFRI01L
	164HB	GMK00651	240	0	1635	after AD 1651	9,39	67,3	0,0001	EUDLIM01
	163SB	GMK00661	104	0	1583	after AD 1596	6,92	74	0,0001	DENSA701
	161SB	GMK00670	140	0	1629	after AD 1644	7,29	64,6	0,001	NLTWWF01
	162HB	GMK00680	143	0	1563	after AD 1651	6,54	65	0,0005	EUDLIM01
Coffin24	399LP	GMK00690	154	0	1541	after AD 1556	6,03	58,8	0,03	NLNSA501
Coffin25	524BB	GMK00700	52	0	-	-	-	-	-	-
Coffin26	515SB	GMK00710	208	0	1742	after AD 1756	9,71	73,1	0,0001	DESUDE01
	516SB	GMK00720	74	0	-	-	-	-	-	-
	519BB	GMK00730	292	0	1675	after AD 1691	10	66,8	0,0001	EUDLIM01
	541HB	GMK00740	203	0	1744	after AD 1759	6,91	64	0,0002	FRQUSP_moselle

Most of the samples presented higher correlations with master chronologies representing the regions of Lower and Central Saxony and Westphalia (in Germany). These results indicate that most of the trees grew in northwest Germany and adjacent areas. A smaller group of samples dated with French chronologies covering the areas adjacent to the Mosel river and the region of Lotharingen (Figure 11), what suggests that the wood was imported from that area to the Netherlands. Some of the master chronologies used to date the samples have been developed from timbers derived from archaeo-historical contexts, hence their exact origin is unknown. These chronologies serve the purpose of dating but cannot be used for provenancing.

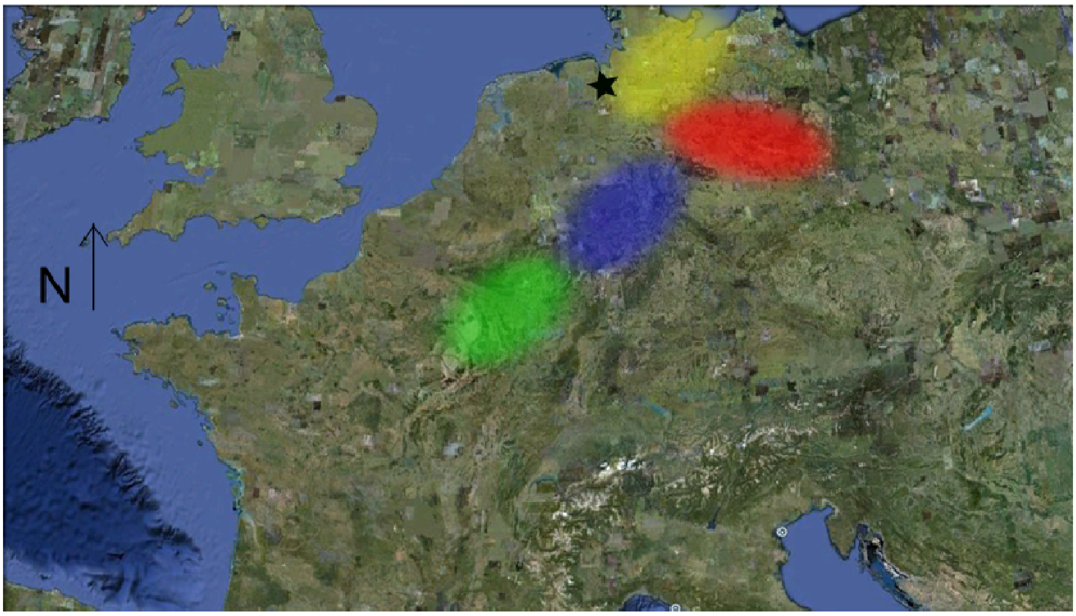

Figure 11. Region of provenance of the samples from the Martinikerkhof (black star). The trees grew in Central Saxony (red), Lower Saxony (yellow),Westphalia (blue) and Moselle and Lotharingen regions (green)(Google maps).

A TPQ date was determined for each of the coffins as a whole, based on the most recent date of the planks (Table IV). The undated coffins had only one or two planks, except coffin 12 which had four.

Table IV. Estimated dates for the trees felled most recently to make each coffin.

Coffin #	Date
coffin1	after AD 1703
coffin2	after AD 1562
coffin3	undated
coffin4	after AD 1638
coffin5	**AD 1640.±4**
coffin6	undated
coffin7	after AD 1599
coffin8	**AD1654±6**
coffin9	undated
coffin10	after AD 1612
coffin11	undated
coffin12	undated
coffin13	**AD1667 ±9**
coffin14	undated
coffin15	after AD 1618
coffin16	after AD 1664
coffin17	after AD 1768
coffin18	undated
coffin19	after AD 1577
coffin20	after AD 1630
coffin21	undated
coffin22	**AD 1640± 7**
coffin23	**AD 1683±6**
coffin24	after AD 1556
coffin25	undated
coffin26	after AD 1759

The estimated felling dates for the trees of coffins 5, 8, 13, 22 and 23 spread from the 1630s to the 1680s, whereas for the rest only a TPQ could be estimated.

Two planks, out of the five analyzed from coffin 16 (the side board GMK00450, and the top board GMK00460), were found to originate from the same tree given the degree of correlation (Table V). The head and foot planks used in coffin 23 (GMK00650 and GMK00680, respectively) also derived from a single tree.

Table V – Statistical crossdating values between samples considered to be derived from a single tree.

Tree	Sample Code		t_{HO}	%PV
1	GMK00460	GMK00450	10,2	70,3
2	GMK00650	GMK00680	16.60	76,9

3.1.4. Discussion

The construction date of the coffins can only be presented as a TPQ date also for the coffins containing planks with sapwood, because the period between felling and the making of the coffins could vary with many factors (e.g. transport of the timber, seasoning of the wood, drying time, etc.). In any case, the dates show that this particular section of the terrain served as burial ground probably since the second half of the 16th century until, at least, the second half of the 18th century (Figure 12).

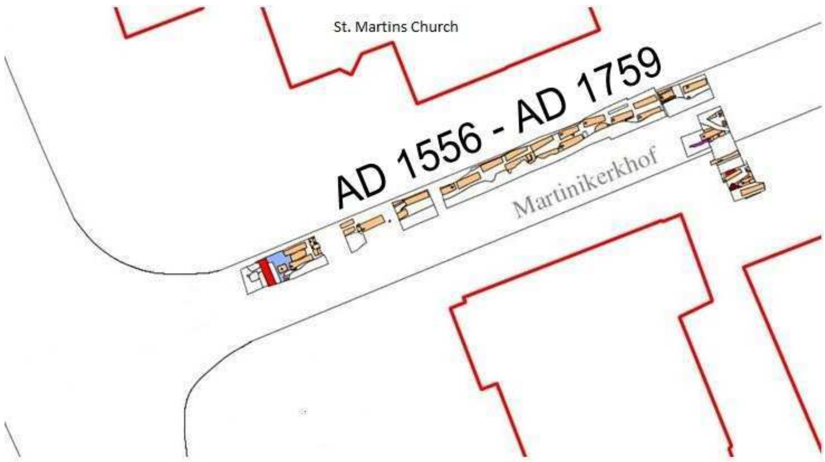

Figure 12. Estimated period of utilisation of this section of the Martinikerkhof. Estimation based on the interval between the TPQ dates of the oldest and most recent coffins.

Periods of high mortality rates caused by epidemics or other factors would be associated with conspicuous clusters of burial dates which were not observed. Furthermore, this would require finding felling dates for the trees of all the coffins, which was not the case.

Within the planks of several coffins there are differences between the dates of the last ring, the most pronounced in coffin 13. In this case the date of the last ring of the top board and the side board (GMK000361 and GMK000370, respectively) differ in 124 years. This can be explained by the fact that the planks, after being obtained by tangential cut, were further processed longitudinally, to use the materials more efficiently. The curvature of the rings in sample GMK000361 indicated that maybe 10 to 15 rings were missing towards the pith. In turn, sample GMK000371 presented no ring curvature in the oldest of the rings and presented the initial discoloration of the sapwood transition. By observing both raw ring-width curves (Figure 13), one represents the juvenile period of fast growth while the other shows the slower growth rate of old trees. This may suggest the planks belonged to the same tree but four tree-rings were lost during the conversion of the first plank into two smaller ones, hence there was no overlapping period. Both samples were dated separately and the master chronology giving the highest correlation values was the same, which further reinforces this assumption.

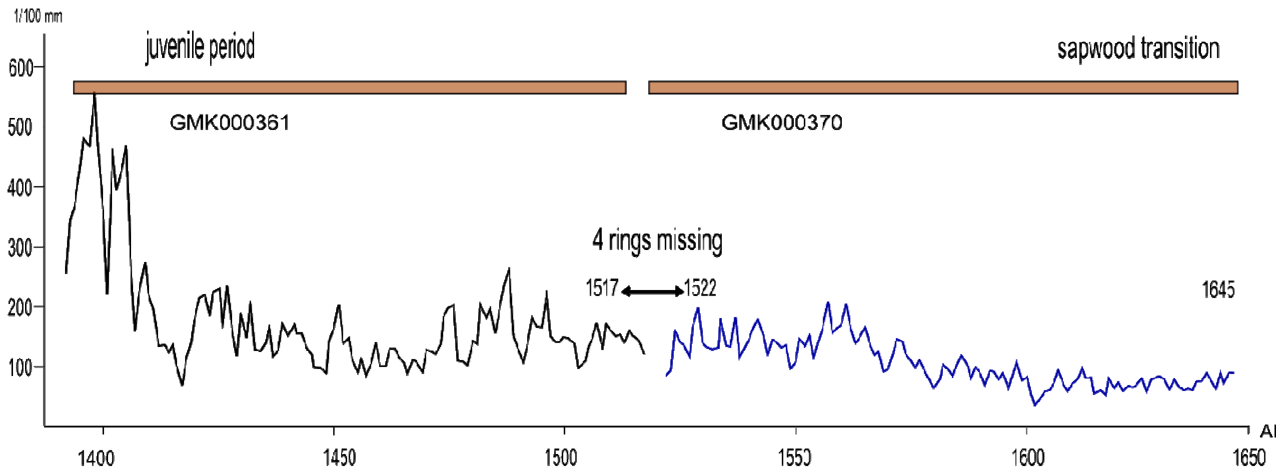

Figure 13. Two non-overlapping ring-width-series derived from two different planks from coffin 13 may represent one single tree, in which case, four tree- rings were lost during conversion of the plank.

Some samples presenting sufficient rings for dendrochronological research remain undated. These samples probably contained a growth pattern that was unrelated to a climatic influence and therefore no correlation was found with the master chronologies.

3.2 Ancient Dorestad

3.2.1. Introduction

The town of Dorestad (present Wijk bij Duurstede, figure 14) was located at the meeting point of the rivers Rhine and Lek at the border of the Frankish Empire and the Frisian area. Under Frankish rule the city developed as the most important trading center of the Empire, especially during the first half of the 9th century. Not much is known about the origins of the ancient city but, in previous investigations, coins have been found to be mint there as early as 630 AD. The existence of a mint expresses the economical importance of the city. In fact, Dorestad acted as the main distribution center in north-west Europe (Dijkstra and Williams, 2009).

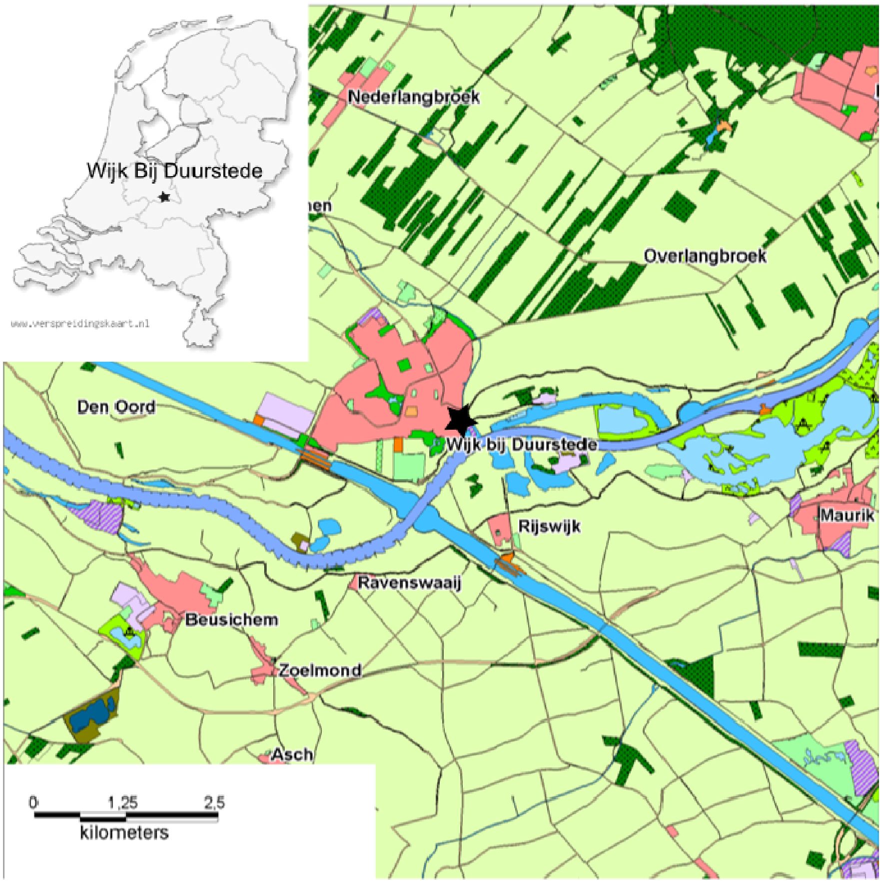

Figure 14. Map of the Netherlands and location of Wijk Bij Duurstede (ancient Dorestad).

Excavations in different areas of the ancient city have been carried out in the past (Van Es, 1969). Wooden barrels built for the transport of wine were found across the excavated area, secondarily used as enclosures for wells, and therefore remained fairly preserved underground. Eckstein et al. (1975) researched through dendrochronology a number of these excavated barrels and dated them to the period around the 8th century AD. The wood was determined to be derived from West Germany.

In 2010, the archaeology company ADC ArcheoProjecten, excavated a different area (Figure 15) corresponding to the center of the northern part of ancient Dorestad. More wells enclosed by barrels were discovered. To interpret the meaning of the finds, by placing them in the temporal scale, these were subjected to dendrochronological analysis.

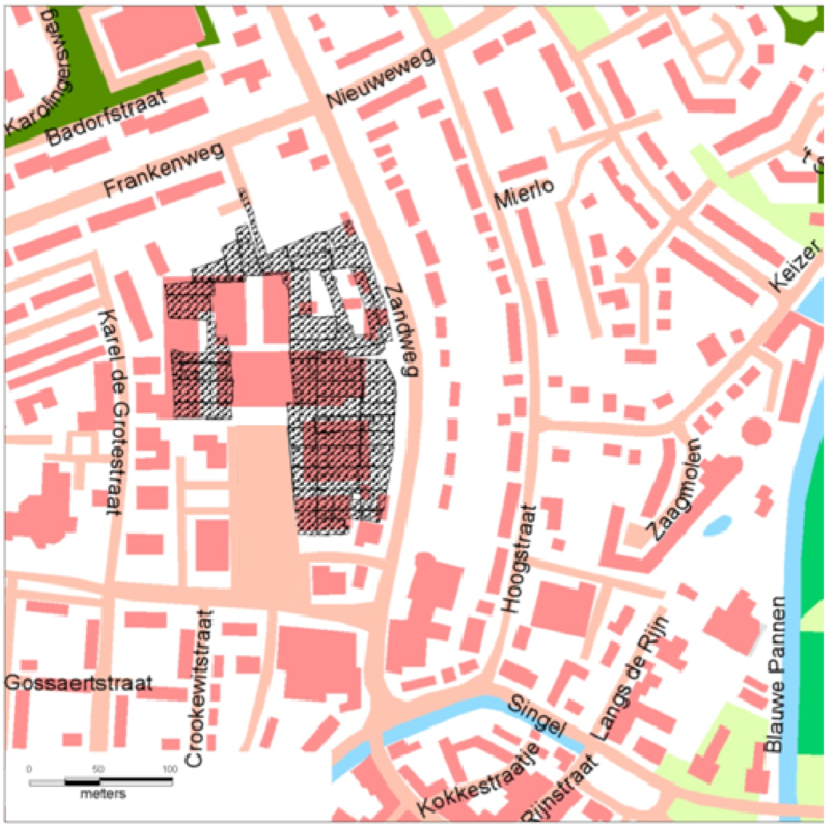

Figure 15. Area of the excavation in the ancient town of Dorestad, where the barrels had been found reused in water wells.

3.2.2. Materials and Methods

Each barrel (Figure 16a) consisted of several staves (Figure 16b). The staves were first selected by the archeologists, in the field. Samples were collected from as much staves as possible (1 to 10) at the laboratory of the Ring Foundation. Some of them arrived in pieces and could not be used for dendrochronological analysis. The selected planks were sawn and transversal sections were obtained for tree-ring width measurement. Tree-ring series representing samples of the same species were compared. In order to determine dates and wood provenances these were then compared with the master chronologies available at the RING laboratory for each of the identified species.

Figure 16. A) Barrel *in situ* during the excavation. The artifacts were found in a waterlogged environment (scale bar = 1m) (photo:ADC ArcheoProjecten). B) Staves received at the laboratory (scale bar = 20 cm).

3.2.3. Results

A total of 124 barrel-staves from 43 barrels were sampled. Among these, 76 (61%) belonged to the genus *Quercus* (oak) and were identified macroscopically thanks to the characteristics observed in the transversal section: ring porous with large vessels in earlywood and large rays perpendicular to the growth-rings (Morgan, 1975; Baillie, 1982). Forty-eight samples (39%) were identified as *Abies alba* Mill. (silver fir). These were identified using optical microscope to observe the wood anatomical characteristics in the transversal, radial and tangential sections (Figure 17) and following the identification key by Schweingruber (1990). In the transversal section, we observed the abrupt transition between latewood and earlywood and the overall absence of resin canals. Some samples presented, in some rings, traumatic resin canals, arranged in tangential rows across the latewood (Figure 18). Such arrangement of the resin canals is typical of this species. In the radial section we could observe the absence of tracheids in rays, which is also a key characteristic for the identification of this species. Ray height (15-25 cells) was observed in the tangential section.

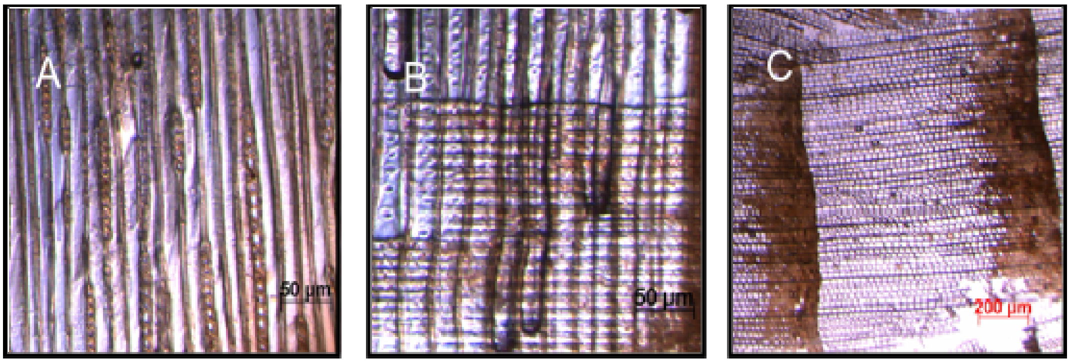

Figure 17. Section planes of *A.Alba* specimens using optical microscope: a) tangential, b) radial, c) transversal.

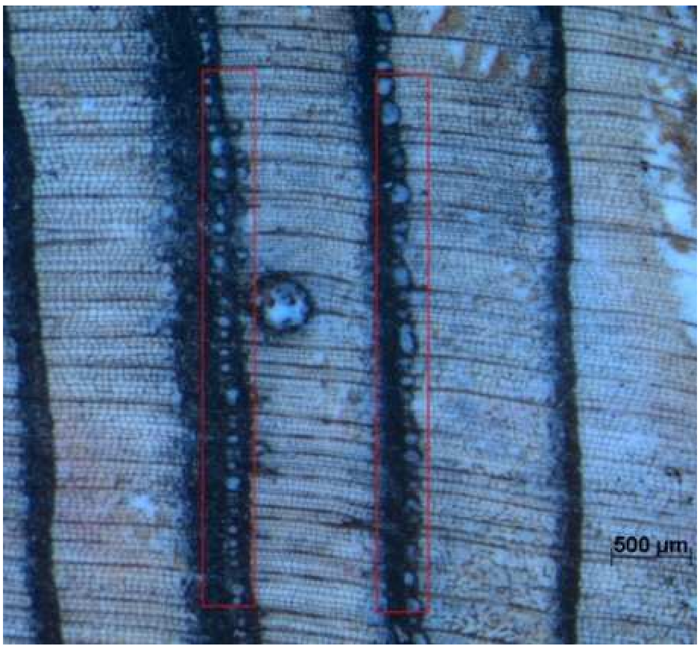

Figure 18. Latewood with resin canals clustered in tangential rows, are indicative of a traumatic event and are characteristic of the species *Abies alba* Mill.

Each barrel had been built either with silver fir or with oak timbers, as we did not find both species employed in the same object. Planks had been obtained through radial processing of tree-trunks and the width of the samples varied between 5 and 16 cm.

The oak samples presented 106 rings on average (range: 25 - 238) and four samples had sapwood, although it was incomplete. After comparing the measurements between them and averaging tree-ring series representing the same tree, these were compared with the master chronologies. After visually inspecting the best matches (t_{HO} > 4), dates were determined for 48 (63%) of the samples. The average ring number of the dated samples was 138 (range 54-238). The dates of the most recent tree-ring ranged from the years AD 639 to AD 1123. Based on regional sapwood statistics (Hollstein, 1980) TPQ and approximate felling dates were estimated, spanning from the year AD 649 to the year AD 1135 (Table VI).

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Table VI. Dating results for the oak samples derived from the barrels excavated in Wijk Bij Duurstede.. Dates of the last ring and estimated TPQ dates represented for the dated samples as well as the dating master chronologies for each of those. n = number of rings; SW Rings = Present sapwood rings; t_{HO} = t-value according to Holstein ; %PV = Percentage of parallel variation ; p = the probability of the determined %PV value occurring by chance (expressed as a fraction of 1).

Barrel	Find Number	Wood species code	Sample code	n	SW rings	Date Last Ring	TPQ	t_{HO}	%PV	p	Master chronology
1	5252A	QUSP	WDS00611	232	-	735	after AD 776	7.63	62.3	0.005	DECENT01
	5252B	QUSP	WDS00621	205	-	760	after AD 776	8.1	65.4	0.0001	DECENT02
	5252C	QUSP	WDS00630	238	-	759	after AD 776	8.41	70.4	0.0001	NLZUID01
5	5589	QUSP	WDS00761	40	-	-	-	-	-	-	-
6	742	QUSP	WDS00770	47	-	-	-	-	-	-	-
7	744	QUSP	WDS00780	33	-	-	-	-	-	-	-
8	746	QUSP	WDS00790	42	-	-	-	-	-	-	-
9	745	QUSP	WDS00800	38	-	-	-	-	-	-	-
10	741	QUSP	WDS00810	54	21	-	-	-	-	-	-
11	768	QUSP	WDS00820	36	-	-	-	-	-	-	-
13	807A	QUSP	WDS00861	40	-	-	-	-	-	-	-
	807B	QUSP	WDS00871	38	-	-	-	-	-	-	-
	807C	QUSP	WDS00881	42	-	-	-	-	-	-	-
	807D	QUSP	WDS00891	44	-	-	-	-	-	-	-
	807E	QUSP	WDS00901	42	-	-	-	-	-	-	-
14	403A	QUSP	WDS00911	122	-	696	after AD 708	8.6	69.7	0.0001	NLZUID01
	403B	QUSP	WDS00921	136	-	717	after AD 729	6.64	69.1	0.0002	NLMIZU01
	403C	QUSP	WDS00931	166	-	700	after AD 713	7.46	69.1	0.0001	NLZUID01
	403D	QUSP	WDS00941	90	-	-	-	-	-	-	-
	403E	QUSP	WDS00951	87	-	687	after AD 698	6.67	71.8	0.0001	DECENT01L
	403F	QUSP	WDS00961	143	-	657	after AD 670	7.68	70.6	0.0001	DECENT01
	403G	QUSP	WDS00971	155	-	686	after AD 713	10.2	72.9	0.0001	DECENT02
	403H	QUSP	WDS00981	131	17	717	after AD 726 ± 5	5.9	67.9	0.0001	DECENT01
	403I	QUSP	WDS00991	42	-	-	-	-	-	-	-
	403J	QUSP	WDS01001	54	-	639	after AD 649	6.4	70.4	0.005	NLBOUW02
15	5274	QUSP	WDS01011	159	-	674	after AD 687	10.4	76.9	0.0001	DECENT01

20	4606A	QUSP	WDS01070	25	-	-	-	-	-	-	-
	4606B	QUSP	WDS01081	25	-	-	-	-	-	-	-
22	4312A	QUSP	WDS01121	150	-	745	after AD 759	8.48	72.5	0.0001	EUDLIM01
	4312B	QUSP	WDS01130	171	-	744	after AD 757	8.73	72.4	0.0001	NLZUID01
23	5951A	QUSP	WDS01141	204	-	757	after AD 773	7.27	68.9	0.0001	NLZUID02
	5951B	QUSP	WDS01151	207	-	724	after AD 773	8.96	73.6	0.0001	DECENT01
25	4155A	QUSP	WDS01181	116	-	729	after AD 746	6.39	76.3	0.0001	EUDLIM01
	4155B	QUSP	WDS01191	119	-	734	after AD 746	5.93	66.8	0.0005	DECENT01
26	4555A	QUSP	WDS01201	131	-	709	after AD 721	7.71	69.8	0.0001	DECENT01
	4555B	QUSP	WDS01211	138	-	689	after AD 701	7.38	71.6	0.0001	DECENT01
27	4607A	QUSP	WDS01220	94	-	-	-	-	-	-	-
	4607B	QUSP	WDS01231	130	-	-	-	-	-	-	-
30	6173A	QUSP	WDS01291	93	-	673	after AD 684	6.29	70.4	0.0002	NLZUID01
	6173B	QUSP	WDS01301	151	-	677	after AD 690	5.91	65	0.0002	DECENT01
	6173C	QUSP	WDS01310	105	-	674	after AD 686	6.52	75.2	0.0001	NLZUID01
31	405	QUSP	WDS01321	194	8	705	after AD 726 ± 11	11.5	74	0.0001	DECENT01
32	5047A	QUSP	WDS01331	29	-	-	-	-	-	-	-
	5047B	QUSP	WDS01341	31	-	-	-	-	-	-	-
33	4945A	QUSP	WDS01351	34	-	-	-	-	-	-	-
	4945B	QUSP	WDS01361	48	-	-	-	-	-	-	-
	4945C	QUSP	WDS01371	45	-	-	-	-	-	-	-
34	2936A	QUSP	WDS01381	150	-	713	after AD 741	8.26	73.3	0.0001	EUDLIM01
	2936B	QUSP	WDS01391	183	-	727	after AD 741	6.97	69.4	0.0001	EUDLIM01
	2936C	QUSP	WDS01401	167	-	719	after AD 741	7.9	70.7	0.0001	EUDLIM01
36	2461A	QUSP	WDS01471	152	-	730	after AD 744	9.43	69.1	0.0001	DECENT01
	2461B	QUSP	WDS01481	166	-	721	after AD 744	8.71	73.1	0.0001	EUDLIM01
	2461C	QUSP	WDS01491	125	-	709	after AD 744	8.34	73.2	0.0001	DECENT01
37	4167A	QUSP	WDS01501	112	-	1106	after AD 1118	8.48	70.5	0.0001	DECENT01
	4167B	QUSP	WDS01511	148	-	1123	after AD 1135	7.77	65.5	0.0002	DECENT01
	4167C	QUSP	WDS01521	136	-	1120	after AD 1135	6.56	64	0.005	EUDLIM01
38	2828A	QUSP	WDS01541	97	-	-	-	-	-	-	-
	2828B	QUSP	WDS01551	98	-	-	-	-	-	-	-

39	5245	QUSP	WDS01561	84	-	665	after AD 676	5.54	70.8	0.0002	DECENT01L
41	6418A	QUSP	WDS01581	115	-	737	after AD 749	5.9	72.2	0.0001	NLROMR02
	6418B	QUSP	WDS01591	108	-	692	after AD 703	8.89	79.2	0.0001	NLBOUW02
	6418C	QUSP	WDS01601	83	-	703	after AD 714	5.24	67.5	0.005	DECENT01L
	6418D	QUSP	WDS01611	103	-	714	after AD 725	5.9	67	0.001	NLBOUW02
	6418E	QUSP	WDS01621	99	-	713	after AD 725	6.52	74.7	0.0001	NLBOUW02
	2891A	QUSP	WDS01630	67	-	-	-	-	-	-	-
42	2891B	QUSP	WDS01641	131	-	698	after AD 712	10.1	70.7	0.0001	NLBOUW02
	2891C	QUSP	WDS01651	146	-	675	after AD 712	6.49	68.8	0.0001	DECENT01L
44	6655A	QUSP	WDS01730	56	-	-	-	-	-	-	-
	6655B	QUSP	WDS01741	45	-	-	-	-	-	-	-
45	0755A	QUSP	WDS01751	119	-	688	after AD 704	5.06	66.8	0.0005	DECENT01
	0755B	QUSP	WDS01761	99	-	681	after AD 692	6.43	72.7	0.0001	DECENT01
	0755C	QUSP	WDS01771	84	-	691	after AD 704	5.15	69	0.001	DECENT01
	0755D	QUSP	WDS01781	117	-	692	after AD 704	5.46	64.3	0.005	DECENT01
46	3708A	QUSP	WDS01800	124	-	712	after AD 749	7.31	69.4	0.0001	NLZUID01
	3708B	QUSP	WDS01811	150	-	736	after AD 749	8	70.7	0.0001	NLZUID01
	3708C	QUSP	WDS01821	149	-	717	after AD 749	8.49	75.2	0.0001	NLZUID01

After this, all the measurements representing individual trees were compared in dated position. In total, 20 tree-ring series (representing 37 samples from 20 trees), were inter-correlated with an average t_{HO}-value of 10.60 which suggested a common origin. These series were averaged into the site mean curve WDSQUSP1 (Figure 19). The level of correlation between this curve and the master chronology DECENT01 (Hollstein, 1980) (t_{HO}=16.30; %PV=77.00) indicates western Germany as the region of provenance for this group of samples (Figure 20). A second site mean curve, WDSQUSP2, representing five trees (five samples) was created based on their internal correlation level (t_{HO} = 7.92). These were not included in the first group because they presented a faster-grown tree-ring pattern. These were dated with a chronology built from archaeological material (NLBOUW02). This mean-curve presented a high correlation (t_{HO} = 8.09) with the site chronology WDSQUSP1.

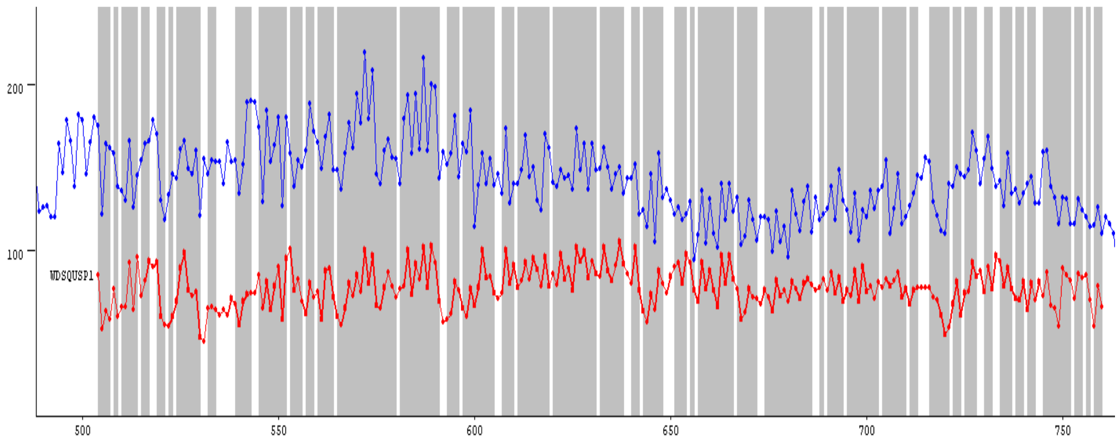

Figure 19. Crossdating between the site mean curve WDSQUSP1 and the German master chronology by Holstein (1980). y-axis: ring-width (1/100 mm) ; x-axis: years AD. The series are derived from *Quercus* sp. Grey area represents the parallel variation between both curves. Overlap = 257; t_{HO} = 16.30 ; %PV= 77.00 ; $p < 0.0001$.

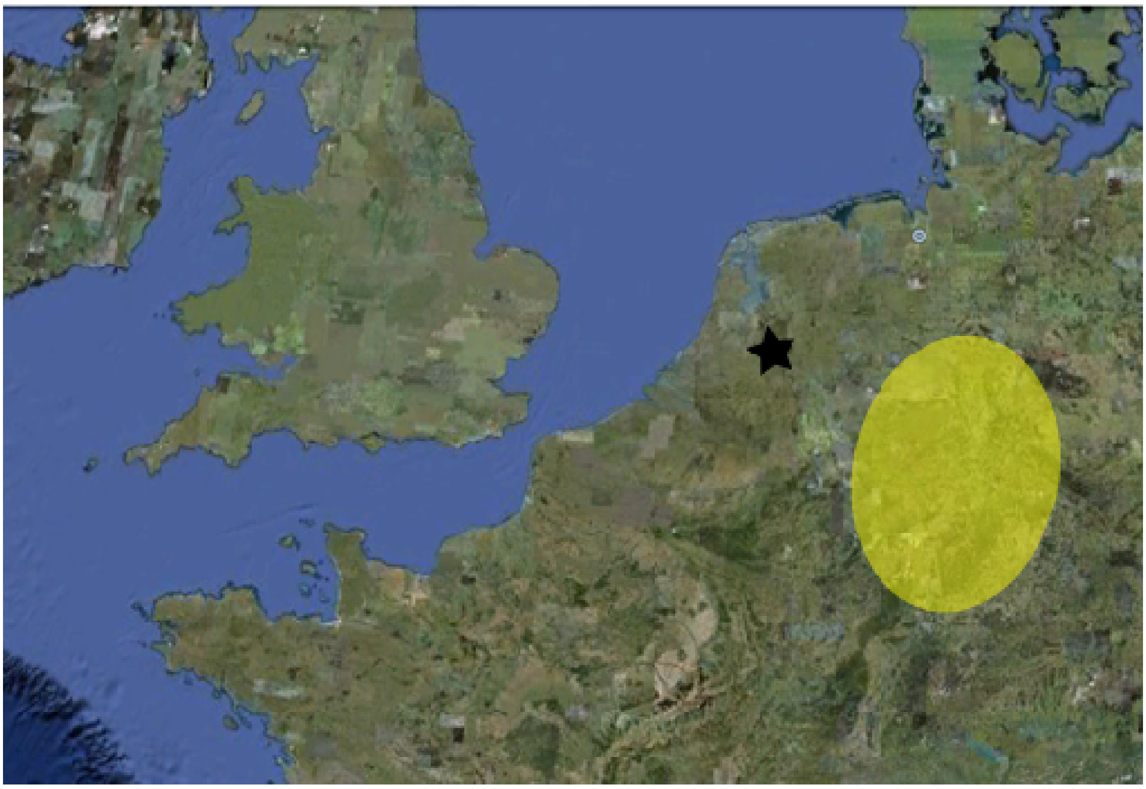

Figure 20. Map of Central Europe. Dorestad (star), region of wood provenance in yellow (west Germany).

The average ring number of the silver fir samples was 43 (range 20-113) and 90% of the samples contained less than 70 tree-rings. Despite the low number of rings, more than half of the samples (54%) could be dated (Table VII).

The average ring number of the dated samples was 48 (range 20-113). The dating of these samples was only possible after comparing and crossdating the individual measurements between them. The internal crossdating resulted in the construction of two site mean curves: WDSABAL2 (179 rings) and WDSABAL3 (47 rings). These were then successfully crossdated (t_{HO} = 13.00 and t_{HO} = 5.21, respectively) with an *A. alba* master chronology (Ring foundation, unpublished) to the end years 776 AD and 718 AD (Figures 21 and 22 respectively). We sent the shorter site mean curve to W. Tegel (Dendronet; University of Freiburg) who confirmed the dating with independent chronologies.

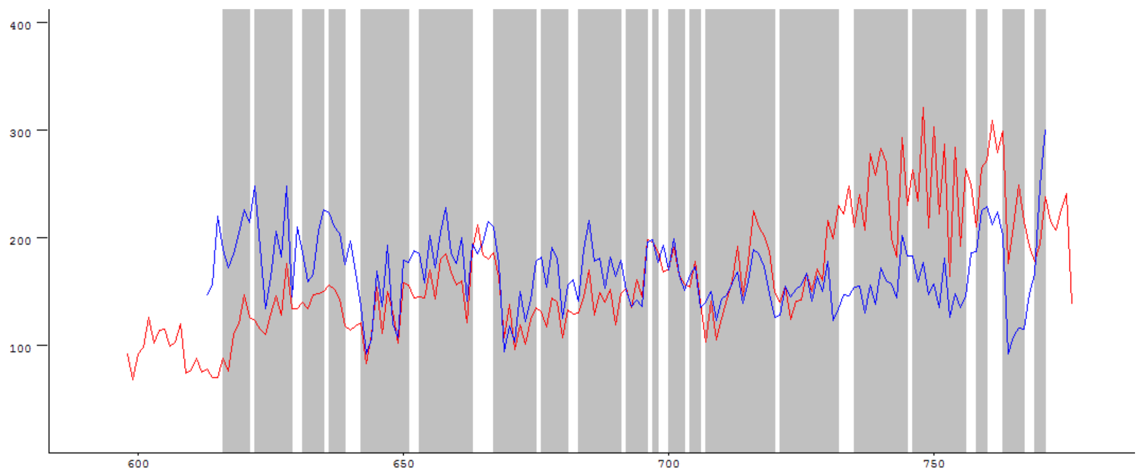

Figure 21. Crossdating between the site mean curve WDSABAL2 and the master chronology WDSABAL01 (silver fir), (RING, unpublished). Grey area represents the parallel variation between both series. Overlap = 159; t_{HO} = 13,0 ; %PV= 77,7 ; p < 0,0001. yy: ring-witdth (1/100 mm) ; xx: years AD.

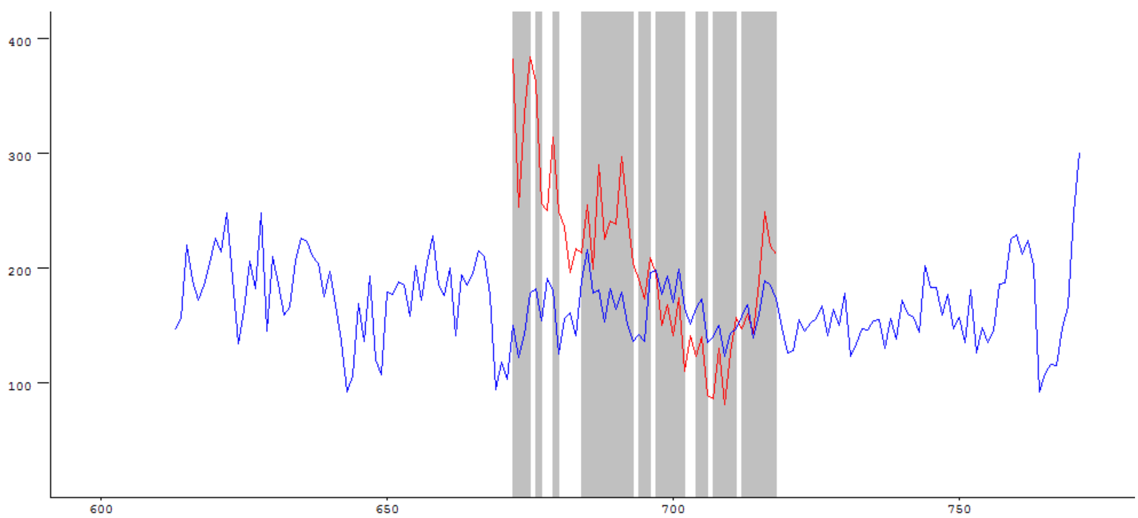

Figure 22. Crossdating between the site mean curve WDSABAL3 and the master chronology WDSABAL01 (silver fir), (RING, unpublished). Grey area represents the parallel variation between both series. Overlap = 47 ; t_{HO} = 5.21 ; %PV= 69,1 ; p < 0,01. yy: ring-witdth (1/100 mm) ; xx: years AD

Table VII. Dating results for the samples of *Abies alba* Mill. derived from the barrels excavated in Wijk bij Duurstede.

Barrel	Find number	Species code	Sample code	n	Date last ring	Master chronology
2	1400A	ABAL	WDS00641	56	728	Via WDSABAL2
	1400B	ABAL	WDS00651	92	725	Via WDSABAL2
	1400C	ABAL	WDS00661	55	-	-
	1400D	ABAL	WDS00671	65	711	Via WDSABAL2
	1400E	ABAL	WDS00681	55	728	Via WDSABAL2
3	5590A	ABAL	WDS00691	37	-	-
	5590B	ABAL	WDS00701	31	-	-
4	1179A	ABAL	WDS00711	43	760	Via WDSABAL2
	1179B	ABAL	WDS00721	25	759	Via WDSABAL2
	1179C	ABAL	WDS00731	20	755	Via WDSABAL2
	1179D	ABAL	WDS00741	28	758	Via WDSABAL2
	1179E	ABAL	WDS00751	22	760	Via WDSABAL2
12	5443A	ABAL	WDS00831	32	775	Via WDSABAL2
	5443B	ABAL	WDS00841	46	776	Via WDSABAL2
	5443C	ABAL	WDS00851	37	770	Via WDSABAL2
16	3332	ABAL	WDS01021	72	732	Via WDSABAL2
17	3330	ABAL	WDS01031	67	-	-
18	3331	ABAL	WDS01041	93	737	Via WDSABAL2
19	5961A	ABAL	WDS01051	30	-	-
	5961B	ABAL	WDS01061	27	-	-
21	4654A	ABAL	WDS01091	28	738	Via WDSABAL3
	4654B	ABAL	WDS01101	20	-	-
	4654C	ABAL	WDS01110	20	738	Via WDSABAL3
24	5932A	ABAL	WDS01161	20	-	-
	5932B	ABAL	WDS01171	42	-	-
28	4601A	ABAL	WDS01241	113	710	Via WDSABAL2
	4601B	ABAL	WDS01251	60	-	-
	4601C	ABAL	WDS01261	55	693	Via WDSABAL2
29	2860A	ABAL	WDS01271	41	-	-
	2860B	ABAL	WDS01281	28	-	-
35	2740D	ABAL	WDS01411	38	-	-
	2740E	ABAL	WDS01421	34	-	-
	2740F	ABAL	WDS01431	64	-	-
	2740A	ABAL	WDS01441	27	-	-
	2740B	ABAL	WDS01451	30	-	-
	2740C	ABAL	WDS01461	57	-	-
40	6279	ABAL	WDS01571	74	692	Via WDSABAL2
43	3681A	ABAL	WDS01661	41	718	Via WDSABAL3
	3681B	ABAL	WDS01671	45	717	Via WDSABAL3
	3681C	ABAL	WDS01681	28	713	Via WDSABAL3
	3681D	ABAL	WDS01691	39	715	Via WDSABAL3
	3681E	ABAL	WDS01701	40	718	Via WDSABAL3
	3681F	ABAL	WDS01711	45	716	Via WDSABAL3
	3681G	ABAL	WDS01721	38	718	Via WDSABAL3
47	6423	ABAL	WDS01831	20	-	-
48	5964A	ABAL	WDS01841	38	-	-
	5964B	ABAL	WDS01851	35	-	-
	5964C	ABAL	WDS01861	31	-	-

After all the samples had been dated, the date of the barrels was estimated by the date of the most recent stave (Table VIII).

Table VIII. Estimated felling dates for the most recent trees used in each of the barrels. *ABAL =Abies alba* Mill.*, QUSP = Quercus sp.*

Barrel	Species	Date	Barrel	Species	Date
1	QUSP	after AD 776	23	ABAL	after AD 710
2	ABAL	after AD 728	24	ABAL	Undated
3	ABAL	Undated	25	QUSP	after AD. 690
4	ABAL	after AD 760	26	QUSP	**AD 726 ± 11**
5	QUSP	Undated	27	QUSP	Undated
6	QUSP	Undated	28	QUSP	undated
7	ABAL	after AD 775	29	QUSP	after AD 741
8	QUSP	Undated	30	ABAL	undated
9	QUSP	after AD 729	31	QUSP	after AD 744
10	QUSP	after AD 687	32	QUSP	after AD 1135
11	ABAL	after AD 732	33	QUSP	undated
12	ABAL	undated	34	QUSP	after AD 676
13	ABAL	after AD 737	35	ABAL	undated
14	ABAL	undated	36	QUSP	after AD 725
15	QUSP	undated	37	QUSP	after AD 712
16	ABAL	after AD 738	38	ABAL	after AD 718
17	QUSP	after AD 759	39	QUSP	undated
18	QUSP	after AD 773	40	QUSP	after AD 704
19	ABAL	undated	41	QUSP	after AD 749
20	QUSP	after AD. 746	42	ABAL	undated
21	QUSP	after AD 721	43	ABAL	undated
22	QUSP	undated			

A number of staves were found to derive from single trees (Table IX). Most of them were used in the same barrel, but in some cases wood from the same tree was found in different objects. However, no barrel was made from a single tree.

Table IX. Staves derived from the same tree and barrels in which they were applied.

Tree #	No. Of staves	Sample code	t_{HO}	Barrel #
1	2	WDS01511, WDS01521	15.50	32
2	2	WDS01651, WDS01641	10.30	37
3	2	WDS01181, WDS01191	16.20	20
4	2	WDS01141, WDS01151	10.80	18
5	2	WDS00971, WDS01321	18.10	9 and 26
6	3	WDS01381, WDS01401, WDS01391	15.70*	29
7	3	WDS01471, WDS01481, WDS01491	14.60*	31
8	2	WDS01201, WDS01211	11.70	21
9	3	WDS01291, WDS01301, WDS01310	11.70*	35
10	3	WDS01800, WDS01811, WDS01821	16.30*	41
11	3	WDS00611, WDS00621, WDS00630	14.40*	1
12	3	WDS00721, WDS00731, WDS00751	14.30*	4
13	2	WDS01021, WDS01041	16.50	11 and 13

* Mean group t_{HO} value, calculated after comparison of each individual tree-ring series with the mean curve created with the remaining series of the group being tested.

3.2.4. Discussion

Given that the barrels under study were reused for a secondary purpose the interpretation of the results has an intrinsic *post quem* character. Although the date after which some of the barrels were made was determined, the time span before they were re-used as enclosures for water wells is unknown. Nevertheless, the dates provide a valuable reference for the archaeologists investigating the ancient city.

The dates of the oak barrels coherently fall within the same range as the silver fir samples and by comparing our dating results with the ones obtained by Eckstein et al. (1975), both lots of samples seem to be contemporary (8^{th} century) with the exception of barrel 32 which dated to the early 12^{th} century. Besides, the chronology that dated the samples indicated as provenance the region of western Germany, which further replicates our results. Eckstein and colleagues compared the barrel's mean curves with a total of 25 regional chronologies covering several localities within the area covered by the master chronology which dated the samples.

Following a similar dendroprovenancing approach, we decomposed the Hollstein master chronology into the local ones composing it. We selected the ones that approximated the most of the period covered by the dated tree-ring series. These chronologies were downloaded from the web site http://www.cybis.se/forfun/dendro/hollstein/merging/index.htm. Then the individual tree-ring series from the WDSQUSP1 group were compared in dated position with the regional chronologies and the correlation values (t_{HO}) were calculated. There was however an obstacle to this approach. The chronologies, restricted to certain geographical areas, do not span the entire period of interest (Figure 22). Therefore the best match between a sample and a given chronology could be due not to the geographical proximity but rather due to the inexistence of other chronologies for the same period but covering a different and possibly correct area. Besides, the overlap between the sample curves and some regional chronologies was not sufficient to make conclusions. For this we abandoned this exercise, remaining the general region of provenance West Germany.

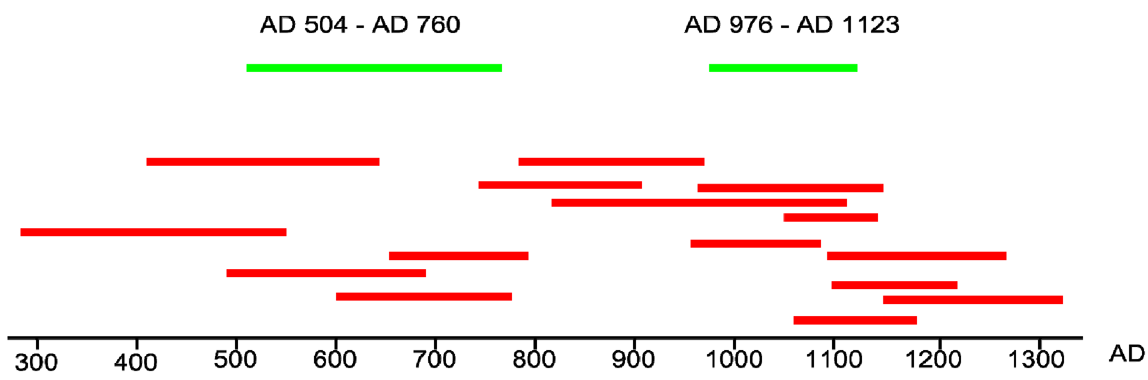

Figure 22. Periods covered by the Hollstein local chronologies (red bars) used for determining sample provenances. Chronologies from different sites do not span the whole period of interest (green bars).

The correlation between the mean curves WDSQUSP1 and WDSQUSP 2 (t_{HO} = 8.09), suggests a similar provenance, though the trees composing the latter probably grew within an area where different ecological conditions prevailed, which was reflected by the difference in growth-rate.

The number of samples collected per object was essential in raising the chances of successful dating. For the silver fir specimens it is important to note that despite 90% of the samples contained less than 70 rings, the majority could be dated. This was accomplished because all of them derived from the same context and were successfully crossdated. Individually it would have been impossible to do so, but after building a site mean curve the match was found and independently verified. Measurement series with few rings that could not be crossdated with other samples remained undated because they did not yield unambiguous statistical values. The main obstacle to the dating of some of the samples with more than 70 tree-rings was the level of local influences during tree growth. Individual reactions (growth depression, growth release) to within-stand disturbances may have overwhelmed the regional climate imprint, preventing crossdating with the master chronologies.

3.3 Venlo, historical buildings

3.3.1. Introduction

The town of Venlo is located in the north of the province of Limburg (south of the Netherlands). The city was bombarded during the Second World War and it was generally assumed, by the cultural heritage scholars, that few original houses from the Middle Ages had remained (Dukers, 2004). Inventories to assess the quality and quantity of existing buildings were a concern of the local entities and a survey was initiated together with local researchers (B.Klück and B.Dukers) and the Cultural Heritage Agency (RCE). Numerous buildings were inspected in the town center and based on architectural features (e.g. façade style, roof framing), a group of those were selected for research.

The provision of absolute dates by dendrochronology would also be important in establishing local building typologies. Dendrochronological dates can serve as a mean of calibrating these typologies by anchoring in time certain trends and construction techniques as well as the use of a certain species of timber. Obtaining such a system of reference, per locality and period, allows an easier and more effective evaluation and characterization of undated historical buildings (D. de Vries, personal communication). Through dendroprovenancing, information about the availability and local preference of timber, as well as timber trade, can be inferred.

For this, the Ring Foundation was commissioned to perform dendrochronological research on samples from 12 historical buildings located in the town center (Figure 23).

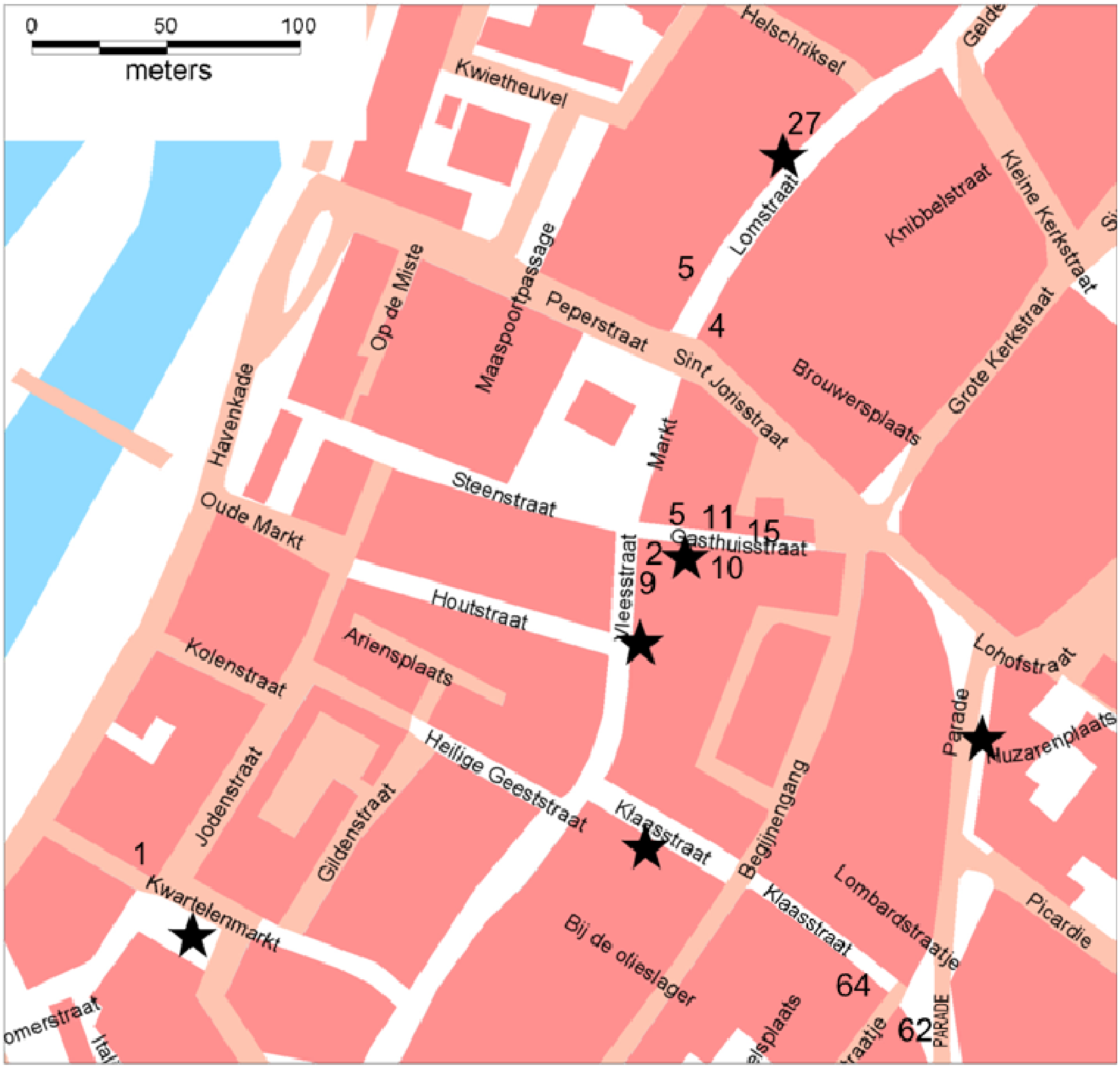

Figure 23**.** Venlo historical center. Stars represent the streets where the investigated buildings were located: Lomstraat no. 4, 5 and 27; Gasthuisstraat no. 2, 5, 11, 10 and 15; Vleesstraat no. 9; Klaasstraat no. 64; Parade no. 62; Kwartelenmarkt no.1.

3.3.2. Material and Methods

The sampling was carried out in January 2011 by Dirk de Vries in the presence of the local specialists. The number of samples per building varied from three to seven, and these were collected from the main construction frame, related to one or two constructing phases.

A selection of the suitable cores was done at the laboratory of the Ring Foundation. Then they were prepared and analyzed according to the procedures described in point 2 (Figure 24). In order to determine dates and wood provenances, individual measurements were compared with the oak master chronologies available at the Ring Foundation. Each building was assigned a code for identification of tree-ring measurements (Table X).

Figure 24.Two dry wood cores before (top) and after preparation (bottom).The lighter color on the right corresponds to the sapwood.

Table X. Investigated buildings and respective codes

Building	Code
Gasthuisstraat 2	VGA
Gasthuisstraat 5	VGB
Gasthuisstraat 10	VGC
Gasthuisstraat 11	VGD
Gasthuisstraat 15	VGE
Klaasstraat 64	VKL
Kwartelenmarkt 1	VKW
Lomstraat 4	VLL
Lomstraat 5	VLT
Lomstraat 27	VNL
Parade 62	VPR
Vleesstraat 9	VVS

3.3.3. Results

A total of 44 samples from structural timbers of 12 buildings were analyzed. They all were identified as oak by the key features observable by naked eye on the transversal section (ring porous with large vessels in earlywood and large rays perpendicular to the growth-rings) (Morgan, 1975; Baillie, 1982). Thirty-six samples presented sapwood and 21 presented the bark edge. Some samples presented earlywood vessels in the bark edge, implying that the tree was cut in spring, in the beginning of the growing season (Figure 25). Other samples presented the last ring fully formed, indicating that the tree was felled either in late summer or in winter of the next year, before the beginning of the growing season (Figure 26).

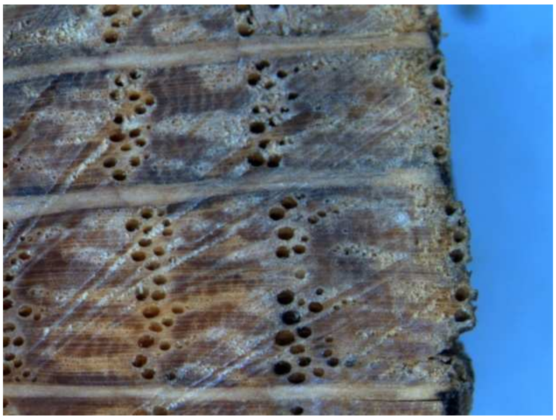

Figure 25. The presence of earlywood vessels in the bark edge indicates that the tree was felled in spring (growth direction towards the right) (magnification: 60x).

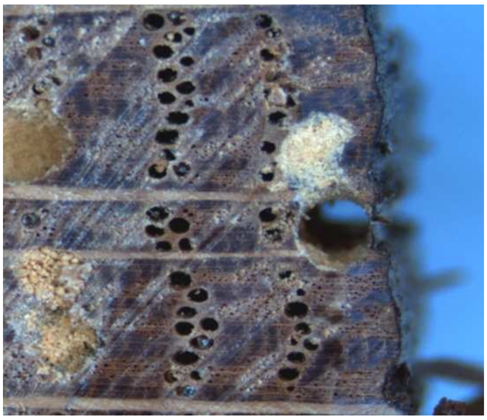

Figure 26. Last ring is fully formed, indicating the tree was felled during late summer or winter, before the next growing season (magnification:40x)

Thirty-four samples (80%) representing 11 buildings were successfully dated (Table XI), from which 17 still preserved the bark edge. The average ring number was 86 (range 41-189). The dates of the last growth-ring ranged from AD 1264 to AD 1709. Only one of the buildings remained undated and the determined dates for the remaining place their building in the Middle Ages and Early Modern periods. The wood originated mainly from the catchment area of the river Meuse, in Belgium, but also from south of the Netherlands and the south and west of Germany.

Table XI. Dating results for the samples collected from the buildings located at Venlo historical center. . n = number of rings; SW Rings = Present sapwood rings; t_{HO} = t value according to Holstein ; %PV = Percentage of parallel variation ; p = the probability of the determined %PV value occurring by chance (expressed as a fraction of 1).

Building (street, no.)	**Samplecode**	**n**	**SW rings**	**Date last ring**	**Felling date**	t_{HO}	**%PV**	**p**	**Master chronology**
Gasthuisstraat no. 2	VGA00011	189	27	1343	spring AD 1344	5,97	62,2	0,001	NLNOOR1(E)
	VGA00021	58	17	-	-	-	-	-	-
Gasthuisstraat no.5	VGB00011	58	18	1428	summer/winter AD 1428-9	4,21	72,3	0,001	VGB2MMMM
	VGB00021	56	18	1428	summer/winter AD 1428-9	6,36	75	0,0002	NLZUID01
	VGB00031	53	19	1428	summer/winter AD 1428-9	8,33	69,8	0,005	NLZUID01
Gasthuisstraat no. 10	VGC00011	79	24	1600	summer/winter AD 1600-1	4	70,9	0,0002	NLMIDD01
	VGC00021	94	6	1580	AD 1593 ±6	6,44	76,9	0,0001	NLNSA501
	VGC00031	56	-	1468	after AD 1478	5,6	73,2	0,001	BEMAAS01
Gasthuisstraat no. 11	VGD00011	94	21	1556	spring AD 1557	8,65	74,7	0,0001	NLZUID01
	VGD00021	117	-	1264	after AD 1276	6,02	74,4	0,0001	DECENT01
Gasthuisstraat no. 15	VGE00011	127	11	1483	AD1493±7	6,79	70,1	0,0001	NLZUID01
	VGE00021	104	10	1491	spring AD 1492	5,83	69,9	0,0001	DEAREI02
	VGE00031	88	15	1491	spring AD 1492	7,76	75,9	0,0001	NLMIZU01
	VGE00041	78	9	1483	AD 1492±5	6,77	70,4	0,0005	BELIEGE1
Klaasstraat no.64	VKL00011	98	21	1709	summer/winter AD 1709-1	4,68	64,4	0,005	DEWEBE01
	VKL00021	88	20	1495	summer/winter AD 1495-6	4,63	69,3	0,0005	DENSA501
	VKL00031	90	14	1497	AD 1502± 5	6,52	64,6	0,01	BEARDEN2
	VKL00041	96	20	1502	summer/winter AD 1502-3	6,52	74	0,0001	NLMIZU01
Kwartelenmarkt no. 1	VKW00011	94	9	1484	AD 1494 ± 5	7,34	67,7	0,001	BENAMUR1end
	VKW00021	107	24	1483	AD 1485 ± 1	7,75	75,9	0,0001	NLMIZU01
	VKW00031	122	14	1471	AD 1479 ± 7	7,93	67,1	0,0005	BEMAAS01
Lomstraat no. 4	VLL00011	86	23	-	-	-	-	-	-
	VLL00021	60	16	-	-	-	-	-	-

	VLL00031	41	20	-	-	-	-	-	-
	VLL00041	73	13	-	-	-	-	-	-
Lomstraat no. 5	VLT00011	142	25	1542	spring AD 1543	6,02	72,7	0,0001	FRLOTH02
	VLT00021	61	9	1545	summer/winter AD 1545-6	7,41	75,4	0,0002	NLBOUW02
	VLT00031	67	10	-	spring	-	-	-	-
	VLT00041	102	36	1528	AD 1546± 1	-	-	-	via VLT2-4M
	VLT00051	53	-	1512	after AD 1522	7,81	73,1	0,001	BEARDEN2
	VLT00061	43	-	1503	after AD 1513	5,89	70,9	0,01	NLBOUW01
	VLT00071	65	-	1509	after AD 1520	6,14	78,9	0,0001	FRQUSP_meuselle
Lomstraat no. 27	VNL00011	76	13	1495	AD 1501± 5	6,14	73,3	0,0001	FRQUSP_meuselle
	VNL00021	55	18	1498	summer/winter AD 1498	7,2	72,7	0,001	FRQUSP_meuselle
	VNL00031	76	12	-	-	-	-	-	-
	VNL00041	58	15	-	-	-	-	-	-
	VNL00051	116	-	1474	after AD 1486	4,45	64,8	0,005	NLARTD01
Parade no. 62	VPR00011	61	24	1542	summer/winter AD 1542-3	5,02	75,4	0,0002	BEMAAS01
	VPR00021	109	17	1535	AD 1548±4	5,8	73,8	0,0001	BEARDEN2
	VPR00031	125	-	1533	after AD 1543	5,49	65,6	0,001	FRQUSP_meuselle
Vleesstraat no. 9	VVS00011	138	12	1430	summer/winter AD 1430-1	5,57	62,7	0,005	BEMAAS01
	VVS00021	62	8	-	-	-	-	-	-
	VVS00031	116	23	1434	summer/winter AD 1434-5	4,74	67,2	0,0002	NLBOUW02
	VVS00041	60	12	-	-	-	-	-	-

3.3.4 Discussion

It is worth mentioning the quality of the samples. Such a high proportion of samples presenting sapwood (69%), and including the bark edge (57% of those) is not the most frequent scenario in dendrochronological research (M. Dominguez-Delmás, pers. comm.).

Although we could determine the felling dates of most of the trees used for construction, some time elapsed before their implementation in the buildings. The comparison of the cutting dates with historical records about the construction dates would help inferring the time invested in the transport, seasoning and processing of the wood (not necessarily in this order).

In the building in Gasthuisstraat 5 (VGB) we can observe that the three beams derived from trees felled in the same year (AD 1488) during a harvesting campaign in spring. This was the only building where a common provenance was found for all the trees employed in the construction (mean group t_{HO}-value of 5.45).This allowed the dating of sample VGB00031 ($t_{HO} = 6.94$) through the mean curve created with the other two samples.

In the construction at Gasthuistraat 15 (VGE), the agreement between actual felling dates (AD 1492, samples VGE00021 and VGE00031) and the estimated ones (AD 1493±7 and AD 1492±5, respectively samples VGE00031 and VGE00041), suggests they were both felled within one year, between AD 1492 and AD 1493.

In the building in Klaasstraat 64 (VKL), one of the beams is dated to two centuries later than the rest of the beams from the same context. This suggests that a repair or extension phase took place 206 years after the initial structure was built.

Only one or two samples preserved the bark edge in each of the buildings Lomstraat no. 27 (VNL), Lomstraat no.5 (VLT), Gaasthuisstraat no.10 (VGC) and Parade no.62 (VPR). Thereby, interpretation must be cautious since the samples that presented no sapwood may indeed be more recent than the ones that did.

About the building in Vleesstraat 9 (VVS) there is a difference of four years between the cutting dates (AD 1430 and AD 1434) which may indicate that if they were in fact used at the same time, the oldest one (sample VVS00011) was acquired together with the most recent (sample VVS00031) 3-4 years after being felled.

Regarding the building Kwartelenmartkt no.1 (VKW), no cutting dates were determined and, as with the buildings Gaasthuisstraat no. 2 (VGA) and Gaasthuisstraat no. 11 (VGD) no other conclusions can be drawn by us. None of the four samples received from the building at Lomstraat no. 4 could be dated.

The determined provenances suggest the timbers would have been harvested from Belgium forests (Ardennes), while in other cases it would have come from Germany, and south of The Netherlands (Figure 27).

4. Overall Conclusions

The dendrochronological method was applied to date wooden artifacts derived from three different sites and historical contexts. The main goal of dating and provenance determination of the timbers was achieved. This provided useful information for the different researchers (building historians and archeologists) and we can state that depending on the nature of the research and of the objects in question, different kinds of information can be extracted.

Concerning the dating of the timbers, besides placing them in a temporal scale with annual or intra-annual resolution, the relative placement of these is also of utmost importance as in the case of historical buildings. Construction periods and structure repairs can be pinpointed with extreme accuracy. Besides, the determined dates will provide a mean of placing in time the correspondent building techniques and arquitechtural styles. The timber preparation and use can also be made available if it is possible to combine dendrochronological data with historical information. We also demonstrate that the number of trees used in the manufacture of a certain object, as well as the region where they have grown, is a story that can be read from the tree-rings. The processing of timbers applied in the production of a given object can also be deducted.

The dendrochronologist, supported by statistical tools, relies solely on the tree-ring patterns and their attributes for dating. Nonetheless, one must keep in mind that the determined dates are for the rings and that the objects or archaeological features under study may have been produced some time after the felling of the tree from which the wood was obtained. The opposite may also occur when wood is reused in a more recent date that the one indicated by the tree-rings.

Singlehandedly, dendrochronology may not provide answers to all the questions posed to the artifact as the witnesses of human behavior but, together with other disciplines, may provide invaluable data for the understanding of Human past.

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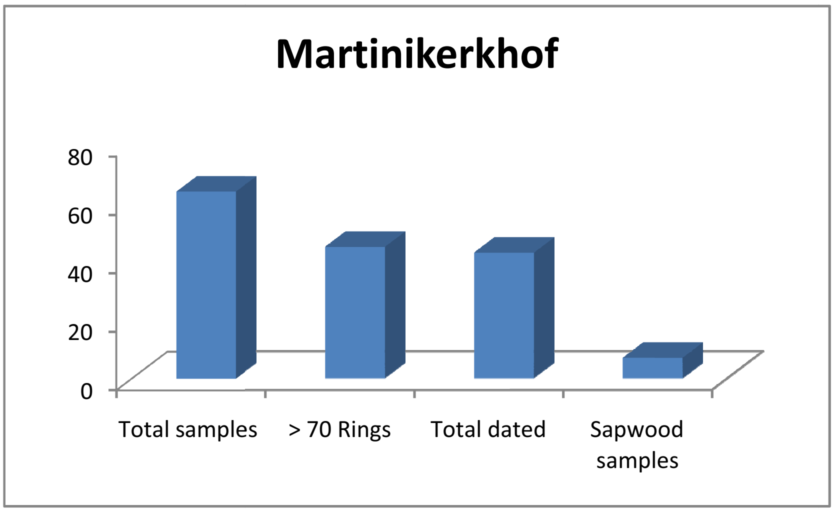
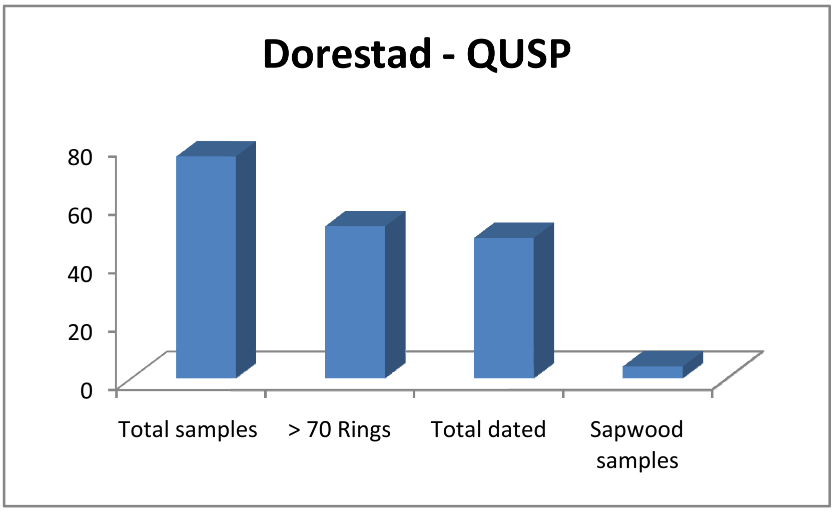
Appendix

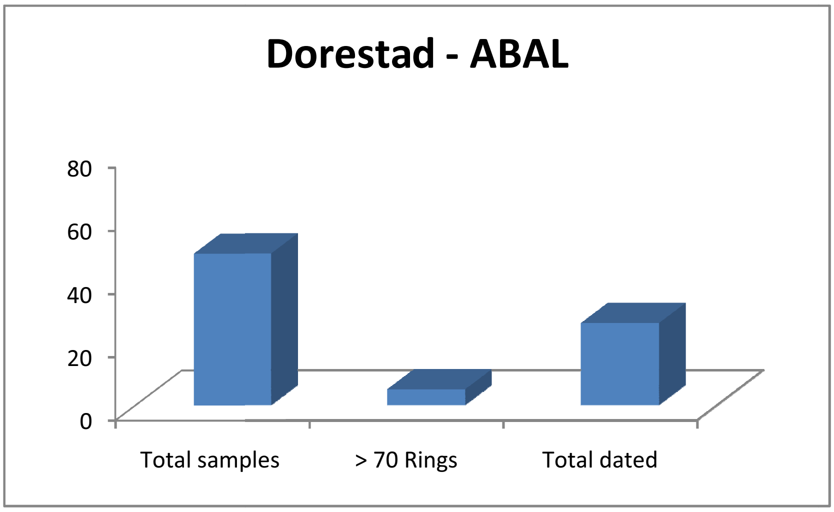
List of chronologies used to date the samples researched in this work

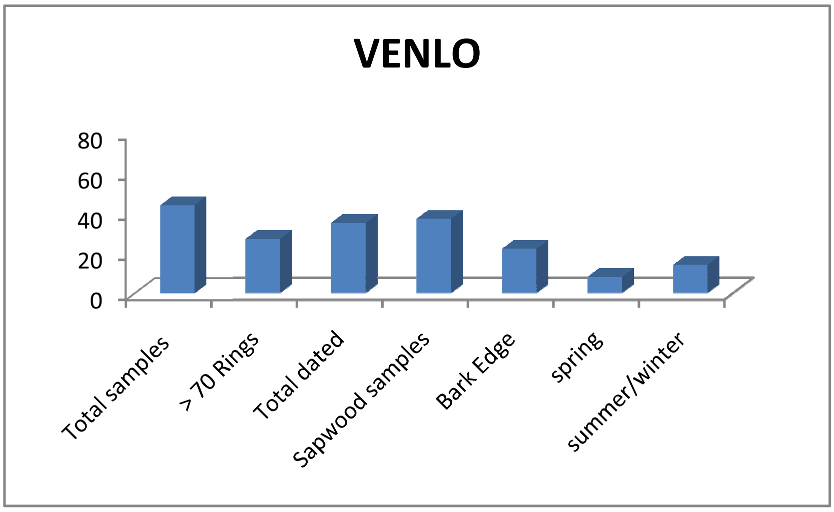
RINGCode	Species	Author(s)	First Year	Last Year	Area
BEARDEN2	QUSP	Hoffsummer, 1989	1144	1986	Ardennes
BEBELG01	QUSP	Hoffsummer, 1989	1408	1566	Central Belgium
BELIEGE1	QUSP	Hoffsummer, 1989	672	1112	East Belgium
BEMAAS01	QUSP	Hoffsummer, 1989	672	1986	East Belgium
BENAMUR1.	QUSP	Hoffsummer, 1989	919	1252	East Belgium
DEAREI02	QUSP	Hollstein, 1980	1300	1598	Ardennes, Eifel .
DECENT01	QUSP	Hollstein, 1980	-690	1975	West Germany
DENIKU01	QUSP	Leuschner, n.p.	1082	1972	German coastal area
DENISA01	QUSP	Leuschner, n.p.	915	1873	Lower saxony
DENSA501	QUSP	Leuschner, n.p.			Eastern lower Saxony
DENSA601	QUSP	Leuschner, n.p.	881	1992	Central lower saxony
DENSA701	QUSP	Leuschner, n.p.	865	1992	Lower saxony
DEOFRI01	QUSP	Leuschner n.p.	-441	1992	Eastfriesland
DESUDE01	QUSP	Hollstein 1965; Hollstein, n.p.	631	1950	South Germany
DEWEBE01	QUSP	Delorme, 1972			Lower Saxony (Germany)
EUDLIM01	QUSP	EU Contractnr. ENV4-CT95-0127	-681	1994	n.s
EUDLIM01	QUSP	EU Contractnr. ENV4-CT95-0127	-681	1994	n.s.
FRLOTH02	QUSP	Tegel, n.p.	1016	1988	Lotharingen
FRNORD01	QUSP	divers, n.p.	1274	1979	North France
FRQUSP_MEUSE	QUSP	Willy Tegel, IAWVF, Universität Frankfurt			Meuse river
FRQUSP_MOSELLE	QUSP	Willy Tegel, IAWVF, Universität Frankfurt	671	1969	Moselle
NLARTD01	QUSP	Jansma et al. 2004			South-Germany
NLBOUW01 .	QUSP	Eckstein et al. 1975			Germany
NLBOUW02	QUSP	Buisman, 2000.	427	1752	n.s.
NLBOUW02	QUSP	Jansma, 2000			The Netherlands, Belgium and Germany
NLMIDD01	QUSP	Jansma, 1995			n.s
NLMIZU01	QUSP	Jansma 1995c, 1995d, 1998, 2000	624	1749	no provenance
NLMIZU01	QUSP	Jansma 1995c, 1995d, 1998, 2000	624	1749	n.s.

NLNOORD1	QUSP	Jansma 1995; 2006 n.p.			n.s
NLNSA501	QUSP	Van Daalen, Jansma, 2003	1372	1721	
NLNSA501	QUSP	Van Daalen, 2003			n.s.
NLROMR02	QUSP	Jansma 1995a, (RING n.p.)	-1027	826	n.s.
NLTWWF01	QUSP	Tisje, n.p.	1040	1972	Twente/westfalen
NLZUID01	QUSP	Jansma 1995a	427	1752	n.s.
NLZUID01	QUSP	Jansma, 1995			n.s
NLZUID02	QUSP	Van Daalen, Jansma, 2003	790	1021	n.s.
	QUSP	Tisje, n.p.	1357	1724	Twente






Dorestad - ABAL
80
60
40
20
0
Total samples
> 70 Rings
Total dated


VENLO
80
60
40
20
0
Total samples
> 70 Rings
Total dated
Sapwood samples
Bark Edge
spring
summer/winter