Allocating Archaeological Wood Samples to a Common Source Tree and Its Use for Analyzing Wooden Settlement Structures

Vincent Mom,[1] Joachim Schultze,[2] Sigrid Wrobel,[3] Dieter Eckstein[4]

[1] Digital Preservation Projects Foundation, Dordrecht. The Netherlands.
[2] Archäologisches Landesmuseum in der Stiftung Schleswig-Holsteinische Landesmuseen Schloß Gottorf, Schleswig. Germany.
[3] Federal Research Institute for Rural Areas, Forestry and Fisheries, Institute of Wood Technology and Wood Biology, Hamburg. Germany.
[4] University of Hamburg, Dept. of Wood Science, Division of Wood Biology, Hamburg. Germany.

Abstract

Dendrochronologists, involved with the dating of wooden objects, are unavoidably confronted with the everlasting question of "which samples come from one and the same tree?" The answer can help decide whether complex structures within a settlement were built at the same time. In this paper a computational method is presented that may help to answer this question. As an example, an archaeological house structure from the Viking town Hedeby is analyzed.

Keywords: *dendrochronology, Hedeby, reconstruction of wooden structures*

1 INTRODUCTION

Dendrochronologists who are involved with the dating of archaeological, architectural, or art historical wooden objects must frequently seek to discover which samples come from one and the same tree.[1] Answers can help decide whether complex structures within a settlement were built at the same time, even if the underlying wooden samples are lacking bark or sapwood and thus their precise felling date cannot be determined. The same applies for re-used timbers or solitary timbers in an excavation stratum; by assigning them to an individual tree, it can become clear to which construction they originally belonged. Moreover, it will only be possible to assess the number of trees felled for the construction of houses, fences, roads, jetties and the like if wood samples can, as far as possible, be allocated to a common source tree.

2 ARCHAEOLOGICAL BACKGROUND

The proto-urban settlement of Hedeby in Schleswig-Holstein (Northern Germany, i.e., "Haithabu" in fig. 1) is one of the largest Viking Age trading places presently known. Of the 25.5 hectare settlement area, which is within a semi-circular rampart, about 5% has been excavated since the beginning of the 20th century. Because the remains of Hedeby lie in a wetland area, many organic finds such as wood, textile, and leather were well preserved. Examples of wooden finds are remains of buildings, trackways, fences, harbor constructions, and boats. Smaller objects were found as well.

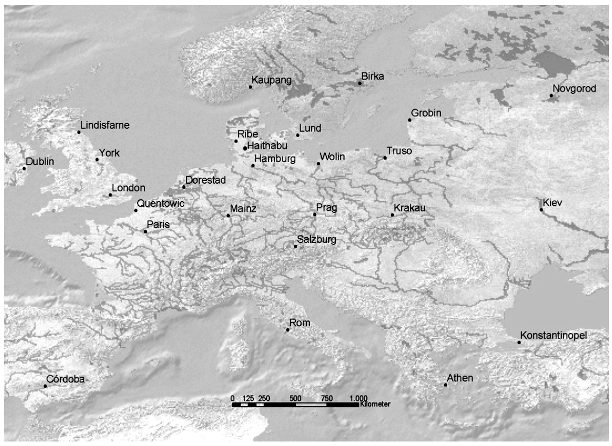


Figure 1. *Map of important places of Viking Age Europe*.

The dendrochronological analysis of more than 4,000 pieces of this waterlogged wood enables us to reconstruct the various developmental phases of the settlement. If two or more pieces of wood could be shown to be (probably) from the same tree, it would be very useful information for reconstructing infra-structural objects. Figures 2a and 2b show an example of such a reconstruction of a Viking house in Hedeby, based on the analysis of its archaeological remains.

[1] D. Eckstein and K. Schietzel, "Zur dendrochronologischen Gliederung und Datierung der Baubefunde aus Haithabu," *Ausgrabungen Haithabu* 11 (Neumünster: Wachholtz, 1977) 141–164 (archaeological objects); M. Beuting, *Holzkundliche und dendrochronologische Untersuchungen an Resonanzholz als Beitrag zur Organologie* (Ph.D. diss., Univ. of Hamburg, 2003) 219; and K. Haneca et al., "Late Gothic Altarpieces as Sources of Information on Medieval Wood Use: A Dendro-chronological and Art Historical Survey," *IAWA Journal* 26 (2005): 273–298 (for art historical objects).

Figure 2a. *House 2 under construction on the historical site. The characteristic wall construction can easily be identified.*

Figure 2b. *The reconstruction of House 2 is nearly finished.*

3 COMPUTATIONAL APPROACH

To tackle this problem, we are looking for computational methods to determine whether two pieces of wood are (or are not) from the same tree. Here we describe a first attempt to use an objective quantifier, based on comparing the tree-ring widths, as a measure for the (dis)similarity between wood samples. This method is then applied to one wooden structure at the Hedeby site.

The basis of our approach is the assumption that the similarity between two samples from one and the same tree, *in general*, is greater than the similarity between two samples from different trees. However, since trees encounter varying circumstances during their lifetimes that influence the growing process, the width of a tree ring may vary considerably around the circumference or in axial direction of the stem, even within one tree. In other words, our discriminating coefficient Q(x,y) (x and y indicating two wood samples) will never be so strong that its value indisputably *proves* that samples x and y are (not) from the same individual tree, but will merely give an indication. However, there are some favorable conditions to consider. First of all, there is the indisputable fact that IF samples x and y belong to the same tree, AND y and z belong to the same tree, then samples x and z also belong to this same tree. In practice this means that not only individual sample pairs should be considered, but *groups* of samples and their corresponding dissimilarity matrices. The second important factor is that the similarity analysis should be consistent with the logic of the construction process for an object. The process of felling trees, splitting them into boards, and transporting these parts to the settlement were not trivial activities, apart from the fact that the timber resources must have been limited. Therefore we may assume that a certain measure of efficiency and effectiveness was applied, resulting in construction strategies that minimized the use of "new" trees and propagated re-use and usage of waste wood from other projects.

To calculate the dissimilarity coefficient Q(x,y), the wood samples x and y must have been properly dated; undatable samples cannot be used. The dating of the samples is standard dendrochronological practice,[1] and is not further explained here. We start the computations with the regular tree-ring widths in absolute values (e.g., hundreds of millimeters). When samples x and y are compared, the overlapping time span of the two samples must be "considerable," i.e. of the same order of magnitude as required for tree-ring dating.

The first step in the calculation process is transforming the dendrochronological time series

$$x = \{ vx_1, vx_2, vx_3 \ldots vx_n \}$$

to a series of ratios as follows:

$$xr = \{ vx_2/vx_1, vx_3/vx_2 \ldots\ldots vx_n/vx_{(n-1)} \}$$

$$= \{ xr_1, xr_2 \ldots xr_n \}$$

This series is shorter than the original series by one year, but has the same end date. The dissimilarity is then calculated as:

$$SUM = 1/2\ \Sigma\ (xr_i-yr_i)(xr_i-yr_i)/xr_i*yr_i\text{, and}$$

$$Q(x,y) = 10{,}000 * \log(1 + SUM) / n$$

The constant 10,000 is chosen for pragmatic reasons, keeping the values of Q between 50 and 500; n is the number of years by which series x and y overlap.

To investigate the behavior and usability of Q, it was first of all applied to two test data sets derived from modern oak trees, where it is known from which individuals the samples come. One data set consists of 90 samples from 45 trees, each tree contributing two samples, so for each sample x there is only one other

[1]M. G. L. Baillie, *Tree-ring Dating and Archaeology* (London: Croom Helm, 1982) 274; J. Dean "Dendrochronology and the Study of Human Behavior," in *Tree Rings, Environment and Humanity,* ed. J. Dean, D. M. Meko, and T. W. Swetnam, Proceedings of the International Conference, Tucson, Arizona, 17–21 May 1994 (Tucson, 1996) 461–469; S. Wrobel and D. Eckstein, "Determining Time and Environment from Tree Rings," *PACT* 36 (1997): 33–49; A. Billamboz, "Tree Rings and Wetland Occupation in Southwest Germany between 2000 and 500 B.C.: Dendrochronology beyond Dating," *Tree-Ring Research* 59 (2003): 37–49; and K. Čufar, "Dendrochronology and Past Human Activity–A Review of Advances since 2000," *Tree-Ring Research* 63 (2007): 47–60.

sample in the remaining population of 89 samples that belongs to the same tree as x. For 90% of these samples, the minimum value of Q corresponds to the "same tree" pair.

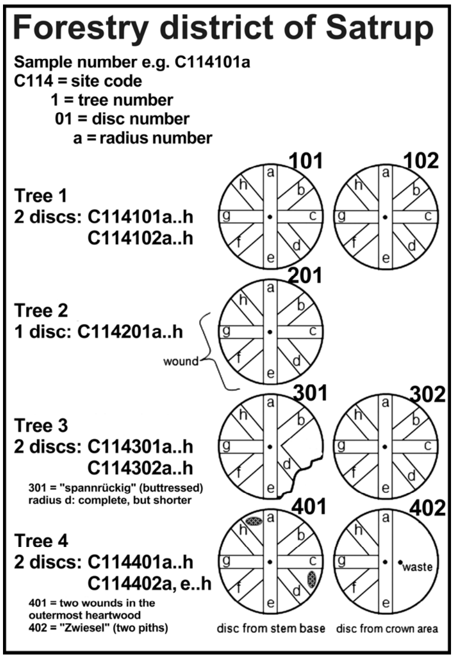
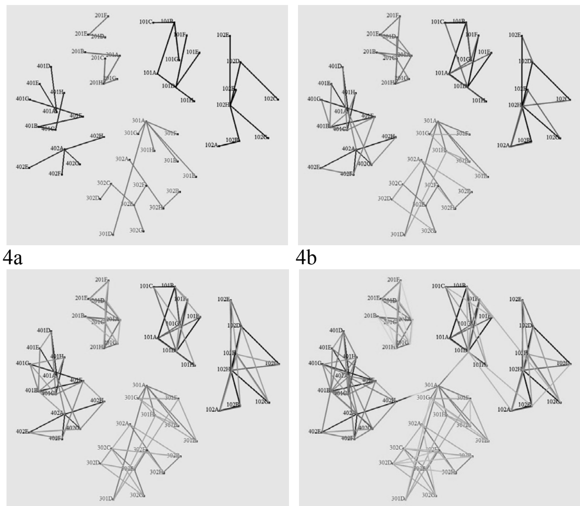


Figure 3. *Second test data set.*



4a 4b 4c 4d

Figure 4a. *Samples nearest neighbors.* **4b-d:** *next nearest neighbors, 3rd nearest neighbors and 4th nearest neighbors.*

The other data set consists of 52 samples from four trees. Trees 1, 3 and 4 contribute 16 and 13 samples, respectively, from 2 discs each (see fig. 3); from tree 2 there are 8 samples from 1 disc. For all sample pairs the value of Q is calculated resulting in a symmetrical dissimilarity matrix (as Q(x,y) == Q(y,x)). From this dissimilarity matrix, the nearest neighbor for each sample is selected (Table 1, column 1).

Figure 4a-d is a principal component analysis (PCA) representation of the data set,[1] with the nearest neighbors connected. As can be seen, all nearest neighbors are "same tree" samples, and most of them are even "same disc" samples (fig. 4a). We repeat this procedure with the "next nearest neighbors" of all samples (Table 1, column 2).

Sample	Nearest neighbour	2nd Nearest neighbour	3rd Nearest neighbour	4th Nearest neighbour
101A	101H (108)	101D (121)	101E (121)	101B (123)
101B	101A (123)	101G (123)	101E (124)	101D (127)
101C	101B (129)	101D (130)	101G (131)	101E (138)
101D	101E (118)	101A (121)	101F (125)	301A (125)
101E	101D (118)	101A (121)	101B (124)	101F (131)
101F	101D (125)	101G (126)	101B (130)	101E (131)
101G	101B (123)	101A (124)	101D (126)	101F (126)
101H	101A (108)	101D (128)	101G (130)	101B (131)
102A	102B (118)	102H (118)	102F (132)	101D (137)
102B	102H (103)	102A (118)	102F (142)	101D (145)
102C	102D (138)	102H (141)	102F (144)	102B (160)
102D	102H (131)	102E (132)	102F (136)	102C (138)
102E	102H (120)	102D (132)	102F (141)	102B (151)
102F	102H (130)	102A (132)	102G (135)	102D (136)
102G	102H (134)	102F (135)	102D (145)	101F (162)
102H	102B (103)	102A (118)	102E (120)	102F (130)
201A	201H (67)	201E (73)	201D (75)	201G (76)
201B	201A (78)	201C (79)	201G (79)	201H (82)
201C	201H (73)	201D (75)	201G (75)	201B (79)
201D	201E (67)	201A (75)	201C (75)	201H (75)
201E	201D (67)	201A (73)	201F (73)	201H (76)
201F	201E (73)	201C (82)	201D (84)	201A (85)
201G	201H (62)	201C (75)	201A (76)	201D (77)
201H	201G (62)	201A (67)	201C (73)	201D (75)
301A	301H (64)	301G (71)	301F (74)	301B (86)
301B	301A (86)	301H (122)	301G (124)	301F (130)
301D	301A (136)	301H (157)	301F (176)	301G (176)
301E	301A (91)	301H (126)	301F (129)	301G (132)
301F	301A (74)	301G (100)	301E (129)	301B (130)
301G	301A (71)	301F (100)	301H (105)	301B (124)
301H	301A (64)	301G (105)	301B (122)	301E (126)
302A	302H (96)	302D (116)	302C (117)	301A (123)
302B	302H (109)	302A (126)	302C (130)	302D (136)
302C	302D (109)	302E (111)	302A (117)	302F (124)
302D	302C (109)	302A (116)	302E (119)	302F (124)
302E	302C (111)	302G (115)	302D (119)	302H (119)
302F	302E (120)	302H (123)	302C (124)	302D (124)
302G	302E (115)	302D (148)	302C (150)	302A (156)
302H	302A (96)	302B (109)	302E (119)	302F (123)
401A	401E (99)	401B (103)	401D (104)	402F (106)
401B	401F (98)	401C (100)	401A (103)	401G (106)
401C	401B (100)	401F (105)	401H (106)	401A (107)
401D	401A (104)	401C (112)	401E (113)	401H (118)
401E	401A (99)	401B (113)	401D (113)	401F (115)
401F	401B (98)	401G (99)	401C (105)	401A (111)
401G	401F (99)	401B (106)	401C (110)	401A (112)
401H	401C (106)	401A (111)	401G (115)	401B (118)
402A	402G (112)	401A (118)	401B (126)	401C (126)
402E	401A (123)	402F (128)	402G (132)	401D (135)
402F	401A (106)	401F (121)	401E (124)	402G (125)
402G	402A (112)	401A (113)	402H (115)	401B (118)
402H	401A (114)	402G (115)	401F (117)	301A (123)

Table 1. *Sample nearest neighbors.*

These relations have been plotted in fig. 4b on top of the "nearest neighbor" relations. All "next nearest neighbors" are also "same tree" samples. This pattern repeats itself for the next "next nearest neighbors" (fig. 4c) and it is not until the fourth "nearest neighbor" that sample pairs from different trees come into view (fig. 4d, sample pairs 301A -101D and 301A-402H). This data set probably looks more like the data sets that one may derive from archaeological excavations than the aforementioned data set. Therefore, we think that introducing the Q coefficient in the analysis of archaeological wooden structures, with caution of course, may help us to obtain additional insight into the construction history of wooden remains found at Hedeby (or elsewhere).

[1]V. Mom, "Where Did I See You Before... A Holistic Method to Compare and Find Archaeological Artifacts," in *Advances in Data Analysis. Studies in Classification, Data Analysis and Knowledge Organization*, ed. R. Decker and H.-J. Lenz (Berlin: Springer, 2007): 671–680.

4 AN EXAMPLE: HOUSE 2 IN HEDEBY

House 2 in Hedeby was chosen as a first "real" object to test whether the results are meaningful for the archaeological interpretation (fig. 5).[1] Although only two-thirds of the structure survived, 50 timbers were sampled and from 39 of them dendrochronological data could be incorporated in the study (fig. 6). This seemed to be an adequate number for a first test.

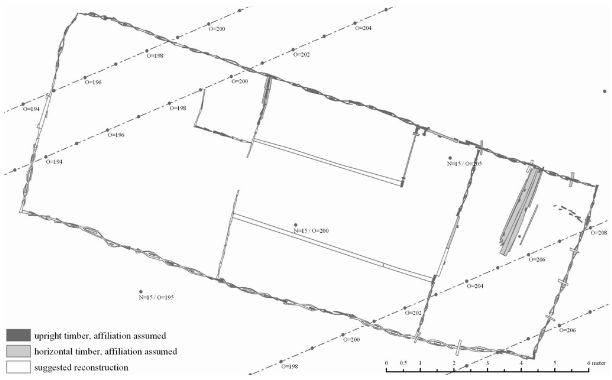


Figure 5. *Suggested reconstruction of the ground plan of House 2.*

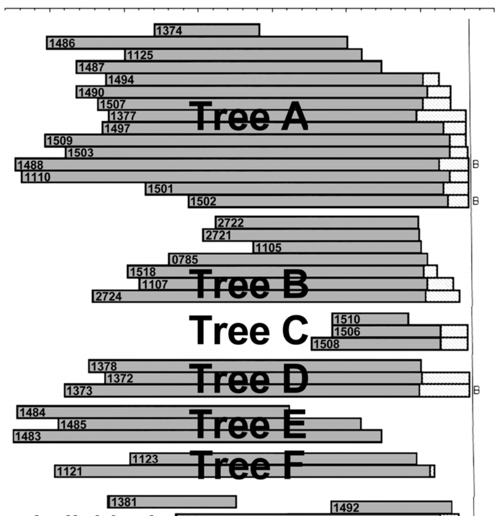


Figure 6. *Dendrochronological dating of 39 timbers of House 2 and their assignment to individual trees: horizontal bars, length of tree-ring series and their placement on the time axis; hatched areas, existent sapwood; B, bark.*

The building measures 16.3 m by 6.2 m (max.) and consists of three main rooms, a small cubicle and a small anteroom of the middle room created by a windbreak (figs. 5, 7, and 8). While the eastern room might possibly have been used as a stable, the middle room with a fireplace in the center seems to have been the main living room. The function of the western room is so far unknown, as is the function of the small cubicle partitioned off the western room. While the northern and eastern parts of the house, which were built on comparatively soft ground, were well preserved, only a few timbers of the southern wall remained and from the western wall hardly any traces survived. Moreover, it is uncertain whether the middle room was separated from the western room by a partition wall. This might well have been the case, as several rows of timbers crossed this section of the building in a north-south direction; however, at least some of them were of later date, although most of them are not dated yet.

House 2 was constructed in 833 AD, replacing a burnt-down building that had been erected earlier in the same year. But it did not last for a long time either, as it also burned down and was succeeded by a new building in 834 AD. That house burned down too, and in 840 AD a fourth building was erected nearly on the same spot. Because of the frequent rebuilding, considerable parts of the older structures were destroyed, especially the southern walls of these houses. The northern walls, on the other hand, were erected parallel to each other and could be distinguished from the preserved wattle work. For the southern wall, however, it was difficult to assign the timbers to the different construction phases.

The main frame posts of House 2 were incorporated in the outer wattle walls. As supporting posts, 30 to 40 cm wide planks were used, while the panels consisted of daubed wattle woven around small planks, only 10 to 20 cm wide. The two lateral wattle walls, which separated the stable part from the living area, were built in a similar way. For the end posts of these short wattle walls robust planks were used and the wattle itself was woven around smaller planks. In contrast to this partition wall and the outer wall, the windbreak and the walls of the small cubicle were constructed differently. While the windbreak was constructed by shoving horizontal planks into the grooves of two upright posts, the walls of the small cubicle were built of planks whose sharp sides were placed into the grooves of the blunt sides of the adjoining planks.

The distribution of the dendrochronological samples, which probably originate from the same tree, generates interesting and assuring results (figs. 6–8). The 15 planks of tree A can be found throughout the whole building. Obviously, the massive trunk of an oak tree at least 307 years old (see sample 1488) was split up into robust planks. These were primarily used as the main supporting posts of the frame construction, as can well be recognized in the northern wall. Interestingly enough, one plank of this tree was used in the southern wall as well (sample 1110), which supports the earlier assignment of this row of timbers to House 2. Apart from planks used as supporting posts within the outer walls, timbers of tree A were used in all three internal

[1] J. Schultze, "Haithabu–Die Siedlungsgrabungen. I. Methoden und Möglichkeiten der Auswertung," *Ausgrabungen Haithabu* 13 (Neumünster: Wachholtz, 2008) 201–216.

walls showing different constructions. If the allocation of these timbers to tree A is correct, this clearly indicates that these partitions cannot be interpreted as later additions.

Tree B seems to have been a big tree as well, being at least 249 years old (sample 2724). As with the timbers of tree A, the robust planks of tree B were used as supporting posts within the outer wall. Timbers of this tree seem to have been primarily used as corner posts (samples 785, 1518, 2721, 2722). In addition, the fact that three samples (1105, 1107, 2724) in the southern wall were related to this tree supports, once again, the assignment of the southern wall to House 2, which was previously based exclusively on archaeological and constructional arguments.

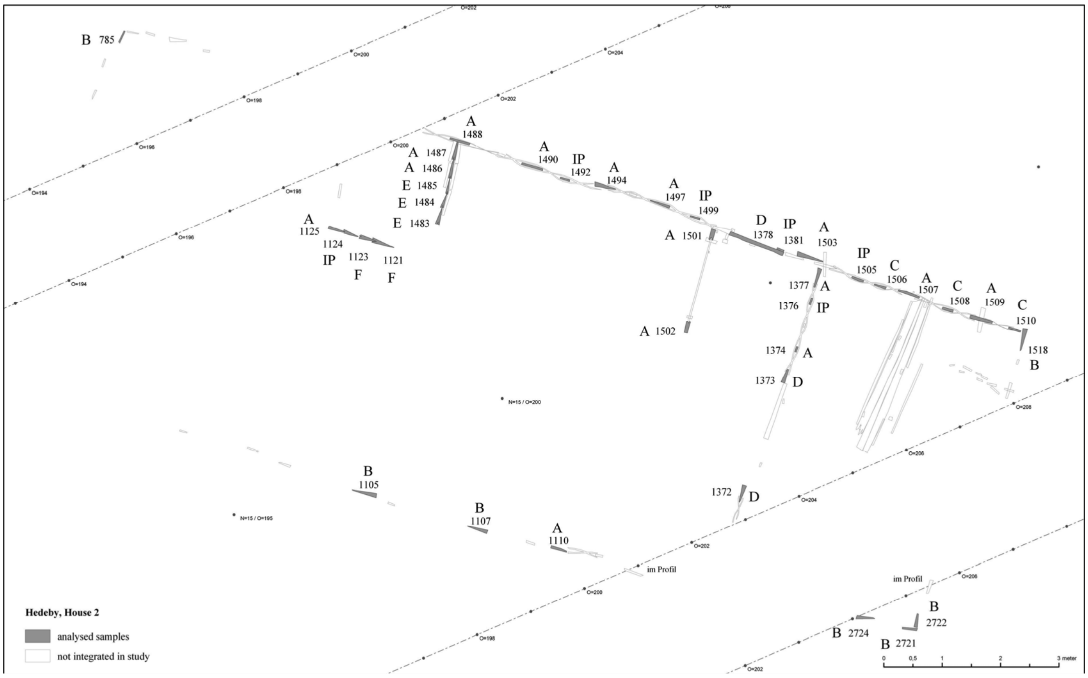


Figure 7. *Ground plan of House 2 showing all timbers preserved. The tree individuals are indicated (A-F, IP) and the numbers give the number of the dendrochronological sample.*

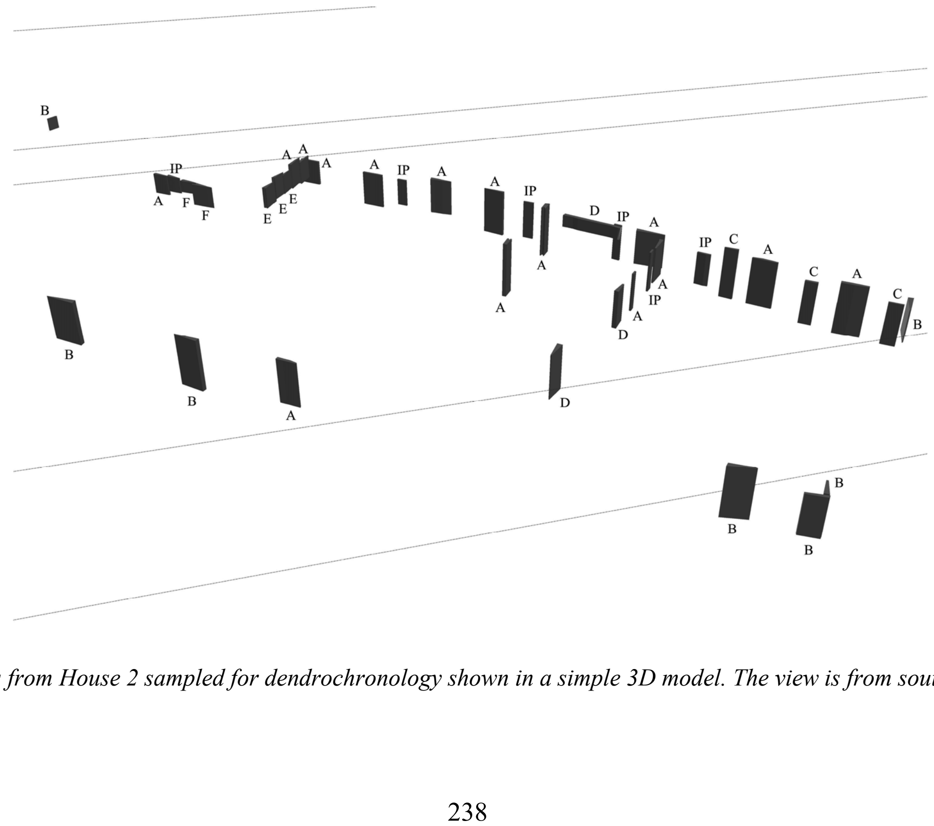


Figure 8. *Timbers from House 2 sampled for dendrochronology shown in a simple 3D model. The view is from south to north.*

Compared to the trees A and B, tree C might have been a minor trunk, as only a maximum of 106 year rings was recorded (sample 1508). Accordingly, the allocated planks were much smaller and were not used as supporting posts. Their function was to hold the wattle of the panels of the northern wall of the stable part.

The timbers assigned to tree D, obviously an older oak again (sample 1373 contains 274 tree rings), show a very specific distribution. The three planks of this trunk are found exclusively within the context of entrances. One timber was used as the door sill of the northern entrance and two planks were used as door posts of the passageway to the stable. Although one has to assume that more planks were originally split from this one trunk, the use within the context of entrances is still conspicuous. One might wonder whether the main frame construction was built first and the entrances were constructed afterward.

Only a few planks could be allocated to trees E and F. Both trees seem to have been quite old, however, and therefore a lot more timbers should be expected. The planks allocated to these trees have so far been found within the walls of the small cubicle. As with the construction of the entrances, it might be discussed whether the internal partitions were built at a later stage of the building process and additional wood was used for that. But with this interpretation one must remember that we do not know anything of the timbers used within the roof truss.

Six samples were not allocated to individual trees as their minimum Q value was rather high. These individual pieces were primarily used within the wall panels and did not have any supporting function.

5 CONCLUSION

The assignment of timbers to different individual trees, achieved by computational means, seems to make sense when it is considered in the archaeological context.
First, the tree identities seem to confirm the ground plan of House 2, which was originally identified by means of archaeological and constructional arguments only; in particular, the correct row of timbers was obviously assigned to the southern wall. Second, the distribution of timbers derived from individual trees within House 2 seems to be consistent with the building process. While the robust planks split from the big trees A and B were primarily used for supporting posts, the smaller tree C, as well as smaller individual pieces, seems to have been used for non-supporting posts of the wall panels that were holding the wattle wall. It seems of special interest that the timbers of tree D were used for entrances and the wood of the trees E and F for the construction of the small cubicle. Trees C, D, E, and F were apparently not used at all for the frame construction.

The method appears to be promising for (re)analyzing the settlement structure and the house constructions of Hedeby.

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