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Original article

A stepwise multidisciplinary approach to determine the date and provenance of historical wooden objects ☆

Marta Domínguez-Delmás [a,aa,1,*], Hilke Schroeder [b], Margot Kuitems [c], Kristof Haneca [d], Stephanie Archangel [e], Paul van Duin [f], Hans Piena [g,gg]

[a] Amsterdam School for Historical Studies, Faculty of Humanities, University of Amsterdam, Postbus, 94551, 1090 GN, Amsterdam, the Netherlands
[aa] Conservation and Science, Rijksmuseum, Postbus, 74888, 1070 DN Amsterdam, the Netherlands
[b] Thuenen-Institute of Forest Genetics, Sieker Landstrasse 2, 22927 Grosshansdorf, Germany
[c] Centre for Isotope Research, Faculty of Science and Engineering, University of Groningen, Nijenborgh, 69747 AG, Groningen, the Netherlands
[d] Flanders Heritage Agency, Havenlaan 88 box 5, 1000 Brussels, Belgium
[e] Department of Dutch History, Rijksmuseum; Postbus 74888, 1070 DN, Amsterdam, the Netherlands
[f] Conservation and Science, Rijksmuseum; Postbus 74888, 1070 DN Amsterdam, the Netherlands
[g] Faculty of Humanities, Vrije Universiteit Amsterdam, De Boelelaan 1105, 1081 HV Amsterdam, the Netherlands
[gg] Nederlands Openluchtmuseumn, Postbus, 649, 6800 AP, Arnhem, the Netherlands

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ABSTRACT

We present a stepwise multidisciplinary approach combining woodworking expertise, dendrochronology, DNA genotyping and radiocarbon dating to determine when, where and how historical wooden objects were made. The effective implementation of this approach is demonstrated with a set of wooden stocks from the Rijksmuseum collections in Amsterdam (the Netherlands). In 2019, preceding an exhibition about slavery, stocks made of oak (*Quercus* sp.) were donated to the Rijksmuseum. The history of the object was unknown, and a stepwise approach was devised to determine the date and potential place of its manufacture, and whether they were made in the context of Dutch colonial slavery. Pencil marks and tool traces found on the surface of the wood are characteristic of traditional woodworking techniques and indicated that the stocks were processed after 1800 C.E., from fresh wood, shortly after the felling of the tree, and in one go. The tree-ring analysis revealed that the beams originate from the same tree, and that the tree grew in a dense forest. However, it failed to return an exact date for the wood and, consequently, also to determine its provenance. Therefore, we decided to employ DNA-genotyping and radiocarbon dating. The retrieval of DNA was successful, and the results placed the provenance of the wood in an area covering a broad latitudinal transect in central Europe. Radiocarbon wiggle matching, modelled with sapwood statistics for central Europe, revealed that the tree was likely cut between 1791 and 1824 C.E. These results combined suggest that the stocks were produced in the first quarter of the 19th century, using local wood, at a small rural town somewhere in Italy, the Pyrenees, eastern France, Belgium, the Netherlands, Germany or even further north (Denmark, Sweden). While their association with slavery in colonised territories seems unlikely, their production in the context of the Dutch colonial system cannot be ruled out. Therefore, they are valuable historical objects worth being curated and exhibited at a national museum. The stepwise approach here presented can be applied to other large objects at museum collections. We encourage curators, conservators and restorers to consider its implementation to maximise knowledge acquisition and appreciation of wooden cultural heritage.

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* Corresponding author.
E-mail address: m.dominguez@dendroresearch.com (M. Domínguez-Delmás).
[1] Present affiliation: Autonomous University of Barcelona; Plaça Cívica, 08193 Bellaterra, Barcelona, Spain

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1. Introduction

Wood is an abundant material in museum collections worldwide. Since ancient times this raw material has been used to make utensils, artefacts, furniture, ships, and also to produce art objects such as sculptures or paintings on panel, to name a few. The type of wood used to produce those items informs about the species available, either locally, or by means of long-distance transport or trade. Furthermore, when the date and the provenance of the wood can be determined, the wooden item becomes a direct link to the craftspeople and their technology in a specific spatiotemporal context. Consequently, studying the wood of objects in museum collections is an essential step towards their assessment and appreciation as cultural heritage.

In recent years, well-established techniques used to determine the date and provenance of (pre)historic wood have been pushed beyond their conventional boundaries. For example, dendrochronological studies have moved from using exclusively ring-width-based chronologies to implementing proxies commonly used for climate studies, such as latewood density in conifers [1,2] and stable oxygen isotopes in broadleaves [3–5]. Radiocarbon (^{14}C) dating, typically applied to wood from archaeological sites, has also been successfully performed on art works through the wiggle matching technique [6,7]. At the same time, techniques such as geo-/biochemical fingerprinting or DNA genotyping traditionally employed in forensic sciences, geosciences and conservation studies are now being tested and implemented on wood as provenance markers (e.g. [8–13]). While all these techniques have been demonstrated to have great potential to improve our knowledge about wooden objects in museum collections, their use is not yet widespread even when they could potentially lead to significant discoveries. Here we present a stepwise approach combining woodworking expertise, dendrochronology, DNA sequencing and radiocarbon wiggle matching to unravel the production time and place of historic wooden objects. The effectiveness of this approach is demonstrated with a wooden stocks-like foot cuff of the Rijksmuseum collections (Amsterdam, the Netherlands).

Throughout history, stocks have been used around the world to punish people by restraining their movement. Generally, these objects consist of two square- or rectangular-shaped wooden beams presenting several rounded matching notches on their inner sides, which are designed to hold people by their ankles. The beams are joined at an end by a metal fitting that serves as a hinge and have another metal plate attached at the other end to which a lock can be fastened to keep the beams held together. Smaller wooden supports are either fixed to the ground on the sides of the beams, or attached to one of them to serve as a vertical or horizontal support for the stocks. Examples of such objects can currently be found in museums around the world. While some are connected to the Spanish inquisition in different countries, others are related to the history of slavery, or to illustrate punishment or imprisonment methods (Fig. 1). Despite their abundance as historical objects, information about their typology, manufacture, production and distribution is scarce in the current literature.

In 2019, preceding an exhibition about slavery, a set of stocks made of oak (*Quercus* sp.) was donated to the Rijksmuseum in Amsterdam, the Netherlands [14]. The donor's grandfather had found them in a barn in the Dutch province of Zeeland in the 1970s, but no associated information regarding their provenance was available. The wood species did not offer clues as to the potential provenance of the object, given that deciduous oaks are widely distributed in North America, Europe and Eastern Asia. The donated stocks display nine notches, and a set of chains, and were initially thought to date between 1600 and 1800 [14]. While their direct relationship with slavery in colonised territories was uncertain, their strong similarity to stocks found on former Dutch sugar plantations in Brazil made them a valuable object for the *Slavery* exhibition (12 February – 31 May 2021). They reflected the violence that had been part of the colonial system, and undeniably conveyed cruel punishment practices of an era in which the Netherlands practiced slavery and sustained it by producing and exporting instruments and other necessities such as metal cuffs, stocks, linen, glasswork, etc., to regions under its control [15]. However, the Rijksmuseum was determined to decipher the history of the object, as this national museum is actively involved in developing new methodologies and recommendations for provenance research [16].

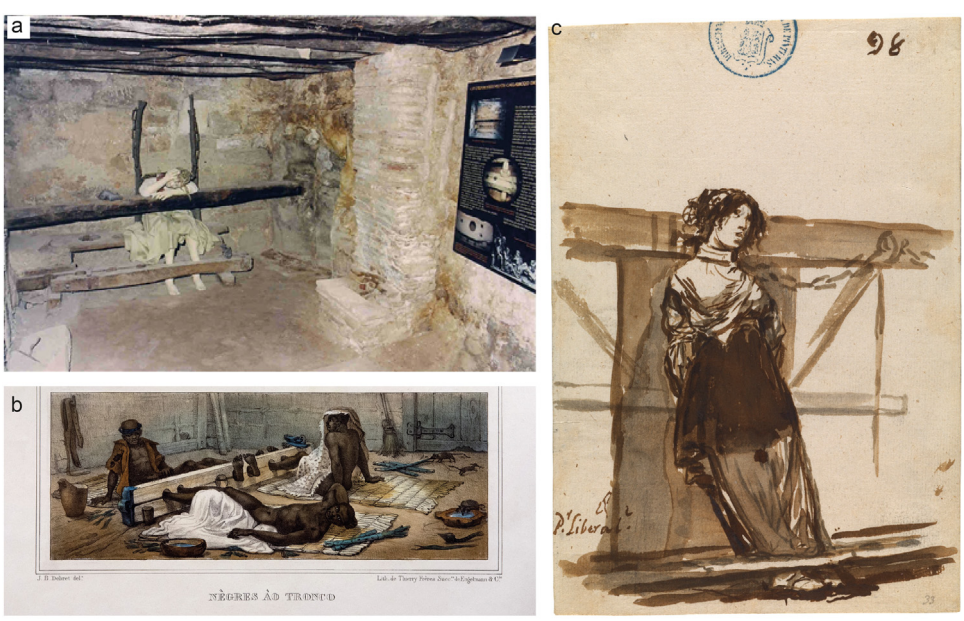

Fig. 1. Examples of stocks and their illustrated uses. a) Former dungeon at the Town Hall of Mazaleón (Spain) preserved in its original setup (source: Mazaleón town hall); b) *Enslaved Men in Brazil*, c. 1830, by Jean-Baptiste Debret (draughtsman) and Thierry frères (engraver) (source: São Paulo, Biblioteca Brasiliana Guita e José Mindlin, https://digital.bbm.usp.br/handle/bbm/3746); c) *Por liberal?*, 1814 – 1823, by Francisco de Goya y Lucientes, iron gall ink on laid paper (source: Museo del Prado).

2. Research aim

The aim of our research was to determine where and when these stocks could have been made, in order to establish whether they could have been related to the system of Dutch colonial slavery, and to contribute to the general knowledge about the production and chronology of this type of historical objects. To this end, we implemented a stepwise approach: first, we examined the tool traces and woodworking features, as they inform about the manufacturing process, and possibly reveal clues about the production time and place (Section 3). When doing so, we discovered pencil traces that provided a date for the production of the stocks after 1800 C.E. [17,18]. This finding enhanced the justification of the research, as a date in the late 19th or even the 20th century would imply that the stocks would not have been made in the context of Dutch slavery, which was abolished in all Dutch territories in 1863 C.E. Therefore, the next step consisted on carrying out dendrochronological research on the beams with a twofold purpose: i) to find out whether they belong to the same tree or to trees that grew in the same area, and ii) to determine the felling date and provenance of the trees (Section 4). When dendrochronology failed to provide the date and provenance, we decided to implement DNA genotyping to ascertain the source area of the wood (Section 5), and radiocarbon wiggle matching to obtain a narrow date range (Section 6). The findings were contrasted with written sources about the Dutch slavery system.

3. Material and methods

3.1. Step 1: object description and registration of woodworking features

The stocks at the Rijksmuseum collection (Fig. 2) are made of two beams of oak (*Quercus* sp.) of a deciduous species, processed into a rectangular shape, with a length of 265 cm, width of 37.5 cm and height of 23 cm. The nine notches have an average diameter of 10 cm. A wrought-iron hinge holds the beams together at one end, whereas a wrought-iron plate with a padlock eye is inserted at the other side of one of the beams. This plate traverses the second beam when the stocks are closed, and a lock can be fixed on the padlock eye to secure them closed. Two smaller pieces of wood (also deciduous oak) serve as support. They are attached to one of the beams with two large handwrought iron nails with T-shaped heads. The nails traverse the wooden supports and go into the beam.

Fig. 2. Stocks donated to the Rijksmuseum in 2019 (inv. nr. NG-2019–502; source: http://hdl.handle.net/10934/RM0001.COLLECT.738265; photo: Rijksmuseum). While the stocks are here presented leaning on one of the beams, their original placement would have likely been in horizontal position, resting on the smaller wooden supports.

A set of chains and metal cuffs was donated together with the wooden stocks, but their original association with them is unknown and will not be discussed in this manuscript.

Partial sapwood is present along the inner edges in several parts of Beam1 (Figs. 3a,b), but is absent on Beam2. The pith is also present on Beam1 but absent on Beam2 (Fig. 3d). The curvature and direction of the tree rings in one end of Beam2 indicate that it was cut close to a point where prominent branches were present (Fig. 3d). The beams rest on two smaller elements, also made of oak wood, and which could derive from branches or from stems of young trees, given their small dimensions and the presence of pith and partially preserved sapwood (Figs. 3e-g).

The surfaces of the beams were carefully inspected under raking light to allow the observation and registration of tool traces and annotations.

3.2. Step 2: dendrochronological research

Dendrochronology is usually implemented to determine the date and provenance of the wood, but it can also serve to identify wooden elements derived from the same tree. While taking a core from each beam with a dry-wood borer would have provided suitable samples for dendrochronological research, it was decided to proceed with a less invasive method, whereby tree rings are photographed in the surface at the end of the beams (Fig. S1 in Supplementary Material).

To improve the visualisation of the tree rings, some portions of the end grain of the beams were cleaned with brushes and slightly prepared with sharp scalpel blades. The tree-ring patterns were photographed with a macro lens, and ring widths were measured on screen with CooRecorder [19]. The photographs included a ruler to allow the calibration of the measurements. Crossdating was done in PAST4 v. 4.3.102 [20].

3.3. Step 3: provenance of the wood based on DNA genotyping

When dendrochronology does not provide a date for the wood, the source area cannot be identified by tree-ring-based methods either. Therefore, to ascertain the provenance of the wood, we resorted to genetic analyses. While DNA in wood starts decaying as soon as the wood becomes heartwood in the tree, recent studies have demonstrated the possibility to retrieve and amplify strands of DNA from historic and ancient wood (e.g. [9,21,22]). Furthermore, molecular markers to identify the continental origin of deciduous oaks have already been developed [23], providing the necessary reference to which oak DNA from unknown origin can be compared. Then, once the continental origin is known, haplotype differentiation can be attempted to determine the source of the wood within the continent [9,24].

3.3.1. DNA sampling, extraction and genotyping methods

Three samples were taken for DNA analysis (Fig. S2 in Supplementary Material). Two samples were taken at the underside of Beam1 near the holes, one containing sapwood and the other one containing sapwood and some heartwood. The third sample was taken from the Beam2, and consisted of heartwood taken at the transverse end. First, the surface layer of the targeted sample area was stripped off using a scalpel. Then, thin wood slices were taken and collected in a 20 ml glass container. Each sample yielded about 8 ml of wood.

3.3.2. DNA extraction

All processes of DNA extraction were carried out in sterile, UV decontaminated clean benches, following a protocol patented in 2015 [25] in combination with the innuPREP Plant DNA Kit from Analytik Jena (Germany), which was used for the last purification

Fig. 3. Wooden elements of the stocks and macro-anatomical characteristics. a) Partial sapwood on the inner side of Beam1; b) part of the surface researched in one end of Beam1 (the dash line runs along the heartwood/sapwood boundary); c) the pith is present on Beam1 but absent on Beam2, which also has a large knot from a thick branch. The curvature and direction of the tree rings in Beam 2 (indicated by the arrows) suggest that the beam was cut at this end close to a splitting point of the stem; d,e) small wooden elements atop which the beams rest. Their small dimensions, together with the presence of pith and sapwood, suggest that they could originate from branches; f) each of the small wooden elements is attached to Beam1 by two metal nails. Photos: M. Domínguez-Delmás.

step. The protocol is optimized for the use on timber, as some compounds must be separated from the DNA which inhibit the further DNA amplification. Due to the small amount of total DNA extracted from timber, the DNA quantity was not measured; rather, standard dilutions of 1:15 and 1:7.5 (DNA:water) were used for all PCR reactions.

3.3.3. Molecular markers for determination of the continental origin

The markers used for the determination of the continental origin of oak wood samples were the ones identified by [23]. These are a bundle of five markers based on plastid specific DNA sequences. The DNA markers “trnCD” and “trnLF” differentiate between oaks originating from either Northern America or Eurasia, while the markers “psaI-ycf4” and “psbE-petL” differentiate between oaks originating from either Asia or Northern America/Europe. The marker “trnDT” differentiates between all three continents mentioned before. These markers and the PCR conditions for amplification are described in detail in [23] (see also Supplementary Material_Extended methods).

All PCR amplified marker fragments were run on a Beckmann capillary sequencer, the individual genotypes of the samples were analysed using the software GeneMarker (version 3.0.0) (SoftGenetics LLC, Pennsylvania, USA).

3.3.4. Molecular markers for the determination of the origin within Europe

Within Europe, a more detailed determination of the origin is possible using a second marker set. These markers relate to known geographic genetic structure of haplotypes of the chloroplast DNA [26]. The cpDNA haplotypes of white oaks from different regions within Europe show a typical distribution pattern based on the recolonization routes after the last ice age [24]. Considering this information, wood specific markers have been developed. By comparing the analysed haplotypes of the wood samples with known haplotypes in the corresponding continent, a plausible origin of the sample can be provided. Two different DNA fragments of the intergenic spacer trnD_trnT within the chloroplast genome have been amplified and sequenced by an external company (StarSeq GmbH, Mainz, Germany). Analysis of the sequences was performed using the software Sequencher (version 5.4.6) (GeneCodes, Michigan, USA). The primer combination dt72F_R was developed by [27], the other one, QT7F_R, was developed at the Thuenen Institute of Forests Genetics. For both primer combinations, a detailed description is given in [9].

Since wood is a difficult material for DNA extraction, the quality of the isolated wood DNA varies between different samples, depending on the age and quality of the sample material and only a certain percentage of the markers will deliver results.

Table 1
Results of the DNA marker analysis. EuAm = origin is Europe or America; Eurasia = origin is Europe or Asia as described in detail in 5.3; „/“: no result for this marker.

Sample_ID	trnCD	trnLF	psaI-ycf4	psbA-petL	trnDT	Continental origin
DNA_1	/	/	/	/	/	/
DNA_2	Eurasia	/	EuAm	EuAm	/	Europe
DNA_3	Eurasia	/	EuAm	/	/	Europe

3.4. Step 4: radiocarbon wiggle matching

Radiocarbon dating is commonly used in archaeology to estimate the age of organic materials. Nowadays, small samples of barely 5 mg of wood can be analysed by accelerator mass spectrometry (AMS) to obtain a radiocarbon date that is subsequently converted into a range of calendar years by means of a calibration curve [28]. Radiocarbon dates are expressed as ranges of years that are associated to a certain probability, which implies that they represent an absolute but imprecise dating method. To increase the precision of this method to date wood, it is sometimes possible to implement wiggle matching [29]. This technique relies on a sequence of ^{14}C-dated tree rings separated by a known number of years. The resulting ^{14}C dates for the individual rings are then calibrated considering the known number of years between them, which results in their more precise placement on the calibration curve. While radiocarbon wiggle matching is not as precise as dendrochronology, it provides a narrower date range than just one single radiocarbon date, and is often used to obtain date ranges for wood from archaeological sites [30–33]. However, despite the potential of this technique to date wooden art objects (see [6,7]), it is seldom used in such contexts.

Four samples were taken at the transverse end of Beam1 with a surgical scalpel. One of the samples was taken from the first growth ring surrounding the pith (sample nr. 4). The other three represent the 13th, 30th-32nd and 78th-79th growth rings from the pith (samples nr. 1, 2 and 3 respectively) (Fig. S4 in Supplementary Material). After the 79th growth ring, there are 70 more growth rings up until the outermost one (including 14 rings of sapwood). Each sample consisted of 10 mg of wood and yielded part of a single growth ring or a few growth rings with a maximum of three.

The four samples were chemically pretreated and analysed at Beta Analytics (see details in Supplementary Material_Extended methods). The ^{14}C measurements were done with an in-house NEC accelerator mass spectrometer. The Conventional Radiocarbon Age was calculated using the Libby half-life (5568 years) and corrected for total isotopic fractionation. Calibration relied on the IntCal20 calibration curve [34].

4. Results

4.1. Manufacturing process

Tool traces and other marks present on the surface inform about the manufacturing process (Fig. 4). One of the beams has traces that result from splitting a stem in half (Fig. 4a). The halves must have been squared with a single-bevel broad axe, as these marks are present in several parts of the beams (Fig. 4b). Shaping timbers with this type of axe is most efficient when the wood is still fresh. Therefore, such traces demonstrate that the stem was processed shortly after felling. Saw marks on the outer faces of both beams (corresponding to the inner part of the stem) (Figs. 4c,d) suggest that the split and squared half stems were sawn into two quarters with a frame saw, while supporting them on trestles. Trestle sawing can leave the marks observed on the Beam2 (Fig. 4c), as well as the characteristic triangular saw-kerf-scar observed on Beam1(Fig. 4d), which results from sawing from opposite directions [35,36].

Both ends of the two beams have a 45° angle so that they can fold open (Figs. 4a,b). At the hinge end, the beams show chop marks as if they were cut to length with an axe. The opposite ends are straight and smooth, which may be a later alteration. Lastly, all surfaces were levelled and smoothed with an adze (Figs. 4e,f). The adze had a chipped cutting edge leaving the same pattern on all parts, including the two feet. This suggests that the stocks were likely made in one go, probably by one person.

On the inner side, nine semi-circular holes were cut into each of the two beams. The outline of these holes was marked out with scratch lines, probably from a compass, and with thin grey lines, possibly from a pencil (Figs. 4g,h). This pencil lines seem to be original from the time of the manufacture of the stocks, which suggests a production date after 1800 C.E. [17,18]. The centre lines of the semicircles were cut with a hand saw. Then the semicircles were carved out with a gouge. These original semicircles are now semi-ellipses in shape, indicating that the beams must have shrunk considerably while drying after being processed. Furthermore, the beams have warped, so they no longer run parallel. This is an indication that the wood used for the beams was fresh when processed. Moreover, signs of drilling holes prior to inserting the nails are absent, and no cracks have been observed around the points where the iron enters the wood. This further supports that the wood was fresh when the iron work was hammered into it.

4.2. Results dendrochronological research

A measurement series containing 149 tree rings (including 14 sapwood rings) was obtained from the Beam1, whereas the Beam2 provided a shorter series with 120 rings. The comparison of the tree-ring series obtained from each beam with each other revealed an outstanding match (almost identical growth pattern) in the first decades (Fig. 5), and a larger amplitude on the series from the Beam2, which is the result of measuring the tree rings on an oblique angle. Despite that difference, the good match between both series suggests that they originate from the same tree. The series of both beams were merged into a mean curve. Crossdating with reference chronologies from central, western, eastern and northern Europe and eastern North America did not result in a match. Therefore, both the date and the provenance of the wood remained unknown.

4.3. Results DNA marker and haplotype analyses for determination of the origin

The quality of the DNA extracted from the stocks was not optimal, given the dried-out condition of the wood. Nevertheless, up to three markers for determination of continental origin could be successfully amplified, revealing a European provenance for two of the samples (Table 1).

In a next step, the identified haplotypes of the wood samples were compared to the distribution areas of the known haplotypes in Europe (Fig. S3 in Supplementary Material). The sequence analysis was performed for all three samples despite the fact that the analysis of the continental origin gave no result for sample DNA_1.

Fig. 4. Tool and manufacture traces. a) Traces of splitting the stem on Beam2; b) single-bevel broad axe marks on Beam2; c) saw marks resulting from multiple-trestle sawing on the outer face of Beam2; d) triangular saw-kerf-scar on the outer face of Beam1 resulting from trestle sawing; e,f) adze marks on the surface of Beam2 (e) and on the underside of one of the supports (f) that indicate that the edge of the blade had a notch (they are consistent throughout the surface of all the elements of the stocks, suggesting that they were all processed with the same tool, possibly by the same person); g,h) the holes were drawn as aligned semicircles on the inner part of both beams, as demonstrated by the pencil lines indicated by arrows; h) indentations on the edges of the central part of the semicircles suggest that a handsaw was used to cut a line as a way to mark the centre line of the semicircles. Photos a,b,e,f: Rijksmuseum; photos c,d,g,h: M. Domínguez-Delmás.

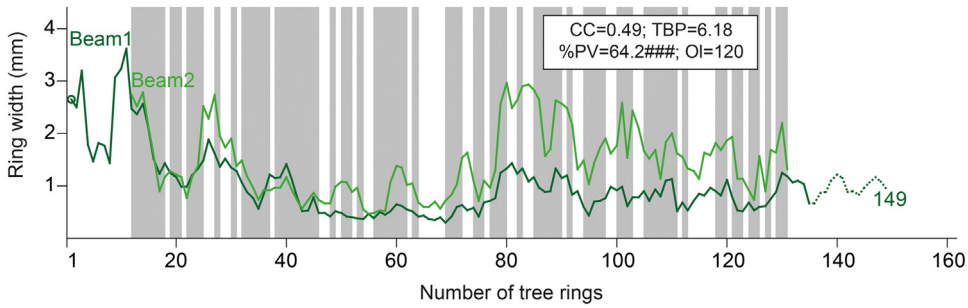

Fig. 5. Visual and statistical match between the tree-ring series obtained from both beams. The tree-ring series from the Beam2 was measured along an oblique edge and therefore, it shows an increased amplitude towards the outer rings. The circle indicates that the pith is present in the beam, and the dash line represents the sapwood rings. CC: correlation coefficient; TBP: Student's *t*-value according to [37]; %PV: percentage parallel variation [38]; ###: significance level of%PV at $p<0.001$; Ol: overlap. The shaded area is a visual representation of the%PV, highlighting where the tree-ring width varies synchronously in both series.

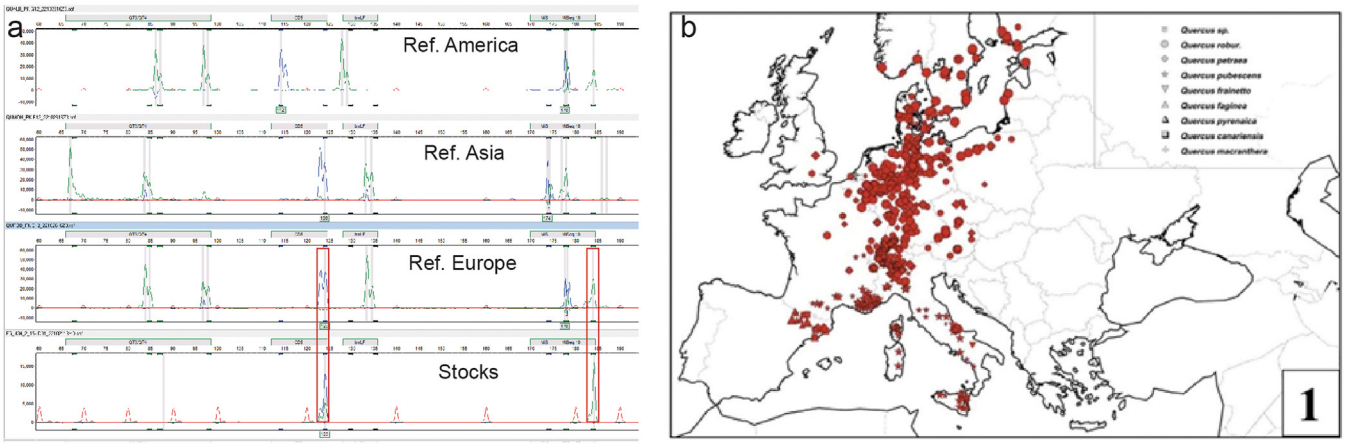

Fig. 6. Results DNA genotyping. a) Results of the provenance determination through DNA markers, which place the continental origin of the wood in Europe; b) Distribution within Europe of the haplotype1 identified in two of the samples (reprinted from [24], Copyright (2002), with permission from Elsevier).

The sequence for the fragment QT7 was of a quite good quality, thus, an analysis was possible. For the other sequenced fragment (dt72) no result was obtained (Table 2). However, the sequence analysis resulted in the haplotype 1 for two of the samples (DNA_2 and DNA_3). This haplotype has a distribution area in Central and Northern Europe (Fig. 6). Since the dendrochronological study has revealed that the beams belong to the same tree, the results of the DNA analysis apply to both beams.

4.4. Wiggle-matching results and estimated felling date of the tree

The radiocarbon analyses returned results for the individual samples with different probability ranges (Table 3). The calibrated age range of the individual samples spans more than 200 calendar years, as a result of the relatively unfavourable shape of the IntCal20 calibration curve for this time period.

To narrow down the date of the last ring present in Beam1, the results of the individual samples were wiggle-matched against the IntCal20 calibration curve in the program OxCal [39,40] using the D Sequence function. Given that the relative positions of the ^{14}C samples within the beam were known (i.e. the exact number of calendar years between each sample had been counted), as well as the remaining number of rings from the last ^{14}C sample until the outer ring present in the beam (70 rings), it was possible to model the date of the outermost sapwood ring (the code used in OxCal is available in Supplementary Material_ Extended methods). In this way, the modelled results narrowed down the date range of the last ring present in the wood to 1789–1813 C.E. (94.8% confidence interval) (Fig. 7a).

Given that partial sapwood (14 rings) is present in the Beam1, sapwood estimations available for deciduous oaks in Europe can be used to estimate the number of sapwood rings still missing to the waney edge (outermost portion of wood under the bark, corresponding to the felling date). The number of sapwood rings in European deciduous oaks has been found to vary decreasingly along a longitudinal gradient from west to east [41]. Therefore, the sapwood model to apply should be the one representing the region of provenance of the wood. Based on the DNA results, we decided to use the sapwood estimates available for Germany [42,43], which have been compiled and modelled by [44] to produce felling-date intervals with a 95.4% credibility. The choice of the sapwood statistics from Germany instead of the Baltic is based on i) the representativity of the area covered by the Haplotype 1 (the sapwood statistics from Germany can also be valid for eastern France and

Table 2
Result of the sequence analysis of two fragments within the intergenic spacer trnD_trnT of the chloroplast genome. „/“: no result for this marker. The five rows of *Q. robur* indicate the genetic pattern of the corresponding reference haplotypes [24,26]. The last three rows (DNA_1, DNA_2 and DNA_3) show the results of the samples collected from the stocks. “QT7” and “dt72” are the markers used for the analysis, and the numbers in the row below are the positions within the sequence of the intergenic spacer.

Haplotype (HT)	QT7			dt72		Identified
	45	58	109	1510	1511	haplotype
Q. robur, HT1	C	C	A	T	G	
Q. robur, HT4,5y	A	C	A	A	G	
Q. robur, HT5x,6	A	C	A	T	G	
Q. robur, HT7	A	C	C	T	G	
Q. robur, Ht10,11,12	A	T	A	T	T	
DNA_1	/	C	A	/	/	/
DNA_2	C	C	A	/	/	HT1
DNA_3	C	C	A	/	/	HT1

Table 3
Results of the radiocarbon analyses for each individual sample (source: Beta Analytics reports).

Sample Name	Laboratory Reference	^{14}C age (yr BP)	Calibrated dates (yrs C.E.)
Sample 4 (1st growth ring)	Beta-643,769	259 ± 16	(82.8%) 1634 - 1665 (8.1%) 1783 - 1795 (4.5%) 1528 - 1540
Sample 1 (13th growth ring)	Beta-643,770	255 ± 16	(82.0%) 1636 - 1666 (11.5%) 1782 - 1795 (2.0%) 1530 - 1538
Sample 2 (31st growth ring)	Beta-643,771	158 ± 16	(37.2%) 1724 - 1782 (21.7%) 1915 - 1948 (16.4%) 1668 - 1696 (10.8%) 1796 - 1813 (9.4%) 1837 - 1878
Sample 3 (79th growth ring)	Beta-643,772	200 ± 16	(55.8%) 1735 - 1804 (24.2%) 1656 - 1684 (15.4%) 1929 - Post 1950

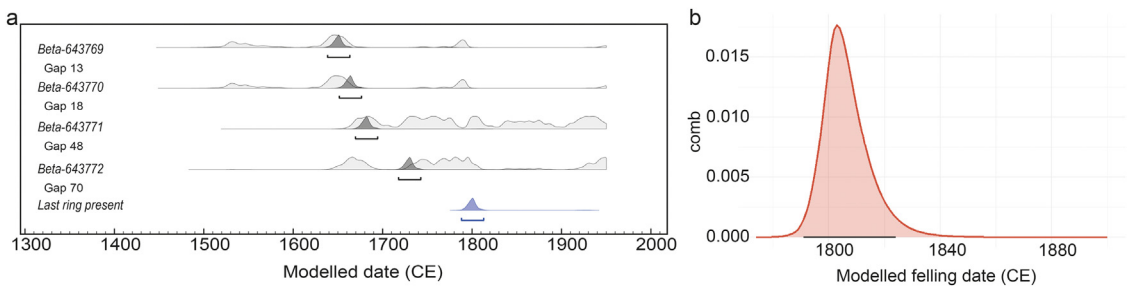

Fig. 7. Results radiocarbon wiggle matching and modelled felling date of the tree. a) Modelled date of the outermost ring present on Beam1 based on the ^{14}C dates of the individual samples and the additional 70 rings present towards the outside; b) Modelled date for the felling of the tree based on sapwood statistics published by [42,43] and compiled and modelled by [44,46].

possibly Denmark), and ii) the range of years they cover, which is wider than the Baltic ones (therefore they would include the felling date range of a tree grown in the Baltic). Considering that the number of sapwood rings for oaks growing in Germany may range from 6 to 34 according to the model elaborated by [44], the Beam1 could still be missing up to 24 sapwood rings until the waney edge. Departing from the probability of the radiocarbon dates obtained for the outmost ring, and modelling this number of missing sapwood rings in R [45] with a script developed by [46], the felling date of the tree was estimated to have occurred between 1791 and 1824 C.E. (Fig. 7b; see Supplementary Material_Extended methods).

5. Discussion

The combined results of our stepwise multi-technique research shed light into the manufacture, chronology and potential production place of the historical wooden stocks from the Rijksmuseum collection targeted by this investigation. From the tool traces, the annotations and (indirectly) the ironwork it has become evident that the stocks were manufactured from fresh wood, hence shortly after the felling of the tree, and using traditional woodworking methods. If an automated saw such as those powered by windmills would have been used in their production, the saw would have left regular and evenly spaced marks on the surface. These are often found in the supports of 17th century panel paintings for example [47]. Manual woodwork could be easily executed in the forest, facilitating the transport of the processed timbers by land (carried by animals or by cart) or by waterways to nearby towns, villages, or harbours [48–50]. However, the fact that the ironwork was also applied into the wood while fresh, implies that long-distance transport by sea can be excluded. Transport over sea would add time to the lapse between the felling of the tree and the production of the final product, time in which the wood would progressively lose moisture. Consequently, the stocks were likely made close to the source, probably in a small town of a rural area.

While the tree-ring analysis failed to provide the date and provenance of the wood, the examination of the growth pattern made evident that the tree had grown slowly (discarding the first 35 years of juvenile growth, the Beam 1 has an average growth of 0.79 mm/year), likely in a dry area or in a close canopy [51–53]. Furthermore, it also revealed that the beams originate from the same tree. This interpretation of the results was a crucial piece of information for follow up analyses because it implied that both, the wood provenance based on DNA and the radiocarbon date obtained for one of the beams, could be inferred to the other beam as well. In the 1990s, [54] proposed a Student's t-value higher than 10 to determine that two oak timbers derived from the same tree. Three decades further, we have learned that this value cannot be taken strictly, as there are other factors that play a role in identifying timbers from the same tree [55]. The growth pattern around the stem of an oak tree can be very variable [8,56], and in the case of these stocks, the beams seem to have originated from different halves of the stems, as deduced from the different (not mirrored) saw marks on their outer sections. Furthermore, the measurement of tree rings in an oblique section adds a distortion that alters the visual and statistical match. However, the initial portions of the tree-ring series, which have been measured on the transverse sections of both beams, show a very high agreement (Fig. 5), supporting the conclusion that they originate from the same tree.

The DNA results have unveiled that the wood has a European origin, with the area covered by the distribution of the Haplotype 1 of oaks as the potential geographical source (Fig. 6b). This is a large area that covers from Sicily and the Pyrenees on the southern limit, to the east of France, west of north Italy and of Austria, Belgium, the Netherlands, Germany, and up to Denmark and the coastal Baltic basin [24]. Though it should be made clear that the

haplotype groups for oak in Europe are based on DNA analyses of living trees, it is very unlikely that the reference haplotypes defined in the 1990s have changed since the tree used for the stocks germinated around the mid-17th century. The possibility that the tree in question may have grown from an acorn planted elsewhere outside the distribution area of the Haplotype 1 also seems improvable, as plantations seek fast turnovers of timber, which would be discordant with the slow growth observed on the tree-ring pattern. Therefore, even when the results obtained with this technique have a much lower spatial resolution than determining the provenance of the wood by dendrochronology [9], they have been crucial i) to demonstrate that the wood originated from Europe, and ii) to decide on the sapwood statistics to be applied to infer the felling date of the tree.

Wiggle matching radiocarbon dating has provided a date range for the last ring present in the stocks in the interval 1789–1814 C.E. Combined with the sapwood statistics, the felling date for the tree has been estimated to have occurred most likely between 1791 and 1824 C.E. This range of dates is well in agreement with the time in which the tools that were used for manufacturing the stock were in use, and especially with the use of a pencil [17,18]. All results considered lead to the conclusion that the stocks were likely produced in the first quarter of the 19th century.

Could the stocks have been produced in the context of Dutch colonial slavery? The Netherlands abolished Dutch slave trade in 1814 C.E., but this trade persisted in their Caribbean colonies until the 1860s [57,58]. The European origin of the wood excludes the possibility that these stocks were made with north American oak, and its processing in fresh also excludes the wood was exported from Europe to the Americas. The manufacture took place in Europe. Based on the radiocarbon dates, the stocks could have been produced in the context of Dutch colonial slavery, to be used in ships for the slave trade before 1814 C.E., or as one of the products that was made in the Netherlands to be sent to the colonies [15], but which did not find their way there (we doubt that they were employed in the colonized territories because it seems unlikely that they were exported, and then brought back afterwards). Technically, they could have been produced in the Netherlands, with wood from nearby areas (Belgium, NW Germany) transported short distances by the river. However, their manufacture close to a source of dense forests, likely in a rural area and with traditional methods, excludes the possibility that they were produced as part of an industrial (mass-production) process in the more urbanised areas of the western Dutch provinces of Zeeland and Holland. The socioeconomical context of the years 1795–1815, when depopulation of the western Dutch cities resulted in a 10% increase of population in the rural areas [59], makes possible a scenario in which the stocks could have been made with traditional methods in a rural context, with the wood transported short distances from denser forests further south or east. All things considered, a production of the stocks in relation to the Dutch slavery system cannot be ruled out.

Nevertheless, other scenarios should also be considered. The stocks could have been produced (in the Netherlands or elsewhere) to punish enslaved people in other countries or to be used in local prisons (examples of such stocks used in prisons can be found in several European countries, including the Netherlands). By the time they were manufactured, slavery was still practiced by several European countries in their colonies, and some of these countries also allowed it in their mainland. For example, in 1794, France abolished slavery in all their territories and colonies [60], but Napoleon reintroduced it in 1802 in sugar-cane ones [61]. In 1807, the British Trade Act banned slavery from the British Empire, but in practice, its compliance took decades to arrive [62]. In Spain, up until the first quarter of the 19th century, enslaved people were made to work in the rural countryside collecting wood, or growing sugar cane or vines [64]. Slavery was abolished in 1837 in the Spanish territory, but it continued in the colonies of Puerto Rico and Cuba until 1873 and 1886 respectively [63]. These examples illustrate that a production of the stocks in relation to slavery outside the Netherlands is also plausible. Further research will aim to elucidate where they were used before they ended up at a barn in the southwestern province of the Netherlands.

6. Conclusions

Our multidisciplinary study has demonstrated the effective implementation of a stepwise multi-technique approach to unravel the production history of wooden objects, such as in this case, stocks from the Rijksmuseum collections in Amsterdam, the Netherlands. Our findings imply that the stocks could have been produced in the context of the Dutch slavery system. However, their use in the context of slavery in other European country, or of imprisonment practices at a Dutch gaol or elsewhere cannot be discarded. All in all, they remain a historical object that conveys the brutal practices that have been used to punish people around the world throughout history. Therefore, they have historical value, and their preservation at a national museum is duly justified.

Our research illustrates that the observation of woodworking features should not be underestimated. In this study, pencil marks have provided a departure *post quem* date, and tool traces have revealed crucial clues about the manufacturing process of the stocks, and by inference, about the potential production environment. While these observations have been carried out visually, current technology allows for the use of 3D scanning techniques that can aid in the task. This emerging field has ample potential in the research of wooden objects, and we are confident that novel advances in the registration of tool traces will take place in the course of this decade.

The analytical techniques implemented in this study (dendrochronology, DNA analyses and radiocarbon dating) have greatly complemented each other, providing valuable information to unravel the production history of these stocks. Dendrochronology could be carried out by means of digital macro-photography, and cleaning with scalpel blades was only required in some parts of the ends of the beams, representing a minimally invasive procedure. Radiocarbon dating required approximately 10 mg of material per sample, so the collection of samples left a minimal trace on the beam. Therefore, these two methods can be carried out stepwise to date wood from historical (art) objects and should be considered by curators and conservators. DNA analyses, however, required a large amount of material (around 8 ml per sample, with more material being more desirable), resulting in a very invasive procedure. In this case, the nature of the object allowed to collect samples in points where the surface was already altered, thus the sampling remains inconspicuous to the observer; but such a large amount of material can be difficult to collect from smaller artefacts, sculptures or panels for example, deeming this technique unsuitable to find out the provenance of the wood.

Lastly, our study illustrates the knowledge that can be gained by researching the wood of historical (art) objects. We hope that our results encourage museum curators and conservators to consider the implementation of this approach to maximise the understanding and appreciation of cultural heritage objects made of wood.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.culher.2023.06.023.

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