UNIVERSITY OF SOUTHAMPTON

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The Reconstruction and Analysis of Archaeological Boats and Ships

by

Pat Tanner

Thesis for the degree of Doctor of Philosophy

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ABSTRACT

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The Reconstruction and Analysis of Archaeological Boats and Ships

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Old ships and shipwrecks have long held an almost mythical fascination in the human mind. Ever since the Renaissance, Greek and Roman ships have been a subject for antiquarian interest, often with speculation rife due to the paucity of evidence, limited mainly to literary sources and representations on monuments, mosaics, and art works. People have always had a fascination with, and a desire to imagine, visualise or reconstruct the ships that have come from the antiquarian and archaeological records. Ship reconstruction from archaeological remains is almost as old as ship archaeology.

This thesis presents the techniques and methodologies developed and used for accurate and efficient data capture, in the form of three-dimensional digital documentation, allowing innovative approaches to organising, analysing, comparing, and disseminating data pertaining to the archaeological find. Subsequent advanced digital three-dimensional modelling, combining all the documented data enables detailed accurate reassembly of the surviving elements, as well as the ability to digitally model missing elements to aid in hypothetical reconstructions. These digital reconstructions can have future uses in terms of physical reassembly replica building, and ongoing conservation/analysis of ongoing changes in reconstructed physical remains in a museum.

The final phase involves the use of naval architecture software to accurately calculate factors such as centre of gravity and total weight, allowing the establishment of actual floatation conditions, as well as examining external factors such as crew, cargo, wind and wave loading in order to examine hydrostatic and stability performance, as well as potential speed and power analysis, thereby resulting in a more definitive hypothetical reconstruction of archaeological ship and boat finds.

"Those who fall in love with practice without science are like a sailor who steers a ship without a helm or compass, and who never can be certain whither he is going" – Leonardo da Vinci

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Academic Thesis: Declaration of Authorship

I, Pat Thomas Tanner declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

The Reconstruction and Analysis of Archaeological Boats and Ships...

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:

Jones, Toby, Nigel Nayling, and Pat Tanner

2013 Digitally Reconstructing the Newport Medieval Ship: 3D Designs and Dynamic Visualisations for Recreating the Original Hull Form, Loading Factors, Displacement and Sailing Characteristics. , editors Colin Breen and Wes Forsythe. *ACUA Underwater Archaeology Proceedings 2013, SHA Leicester*:123–130.

2017 Physical and Digital Modelling of the Newport Medieval Ship Original Hull Form (England). In *Ships And Maritime Landscapes: Proceedings of the Thirteenth International Symposium on Boat and Ship Archaeology, Amsterdam 2012*, p. 79. Barkhuis.

Tanner, Pat

2013a 3D Laser Scanning for the Digital Reconstruction and Analysis of a 16th Century Clinker Built Sailing Vessel. In *ACUA Underwater Archaeology Proceedings 2013, SHA Leicester*, Colin Breen and Wes Forsythe, editors, pp. 137–149.

2013b *Newport Ship Specialist Report : Digital Reconstruction and Analysis of the Newport Ship*. Newport Medieval Ship Archive. Archaeological Data Service, York.

2017a The Testing and Analysis of Hypothetical Ship Reconstructions. In *Baltic and Beyond: Proceedings of the Fourteenth International Symposium on Boat and Ship Archaeology, Gdansk 2015*, J Litwin and W Ossowski, editors, pp. 143–150. National Maritime Museum, Gdansk, Gdansk.

2017b *The Bremen Cog Reconstructed*. Internal Museum Report. German Maritime Museum, Bremmerhaven, Germany.

2018 *The Bremen Cog A Seakeeping, Stability, and Performance Analysis*. Internal Museum Report. German Maritime Museum, Bremmerhaven, Germany.

Tanner, Pat, Julian Whitewright, and Joe Startin
2020 The Digital Reconstruction of the Sutton Hoo Ship. *International Journal of Nautical Archaeology*.

Signed: Pat Tanner

Date: 19/09/2020

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A special thank you to my wife Angela, daughter Clodagh and son Sam for their continued support, and to my mother Noirín, and father Sam, who sadly passed away before I undertook this mid-life crisis.

To the memory of Brian Cumby a friend, sailor and fellow boatbuilder who also dipped his toe into the academic realm, and Donal Lynch another friend, colleague and sailor, who was instrumental in the Traditional Boats of Ireland project, both of whom have hauled anchor for their final voyage. Wishing you both fair winds and following seas and long may your big jib draw.

Definitions and Abbreviations

ISBSA	International Symposium on Boat and Ship Archaeology
IJNA	International Journal of Nautical Archaeology
MDF	Medium Density Fibreboard
DWL	Design (or Datum) Water Line
AP	Aft Perpendicular, the point where the design water line (DWL) intersects with the stern
FP	Forward Perpendicular, the point where the design water line (DWL) intersects with the stem
LCG	Longitudinal centre of gravity
TCG	Transverse Centre of Gravity
VCG	Vertical Centre of Gravity

Overall Dimensions:

LOA	Length Overall, the length of the vessel, from forward end of stem to aft end of sternpost. Length Extreme is the length of the vessel, including fixtures and fittings such as bowsprit and rudder
BOA	Beam Overall, the maximum beam of the vessel
D	Depth Overall, the maximum depth of the vessel, from the deepest point in the water to the highest point above the water excluding rigging.
Loa/Boa	The ratio of the Length Overall to the Beam Overall
Boa/D	The ratio of the Beam Overall to the Depth Overall

Waterline Dimensions:

Lwl	Waterline length of the vessel
Bwl	Waterline beam of the vessel
T	Navigational Draft, the distance, perpendicular to the flotation plane, from the flotation plane down to the deepest point on the vessel
Lwl/Bwl	The ratio of the Waterline Length to the Waterline Beam.
Bwl/T	The ratio of the Waterline Beam to the Navigational Draft.
D/T	The ratio of the Depth Overall to the Navigational Draft

Volumetric Values:

Displacement	The overall weight of the vessel, as defined in the input or calculated from the defined flotation condition.
Volume	The integrated underwater volume of the vessel
LCB	The longitudinal centre of buoyancy of the resultant vessel orientation
TCB	The transverse centre of buoyancy of the resultant vessel orientation
VCB	The vertical centre of buoyancy of the resultant vessel orientation
Wet Area	The area of the underwater surfaces
Moment to Trim	The longitudinal moment required to trim the vessel between the fore and aft ends of the waterline.
D/L Ratio	The displacement length ratio, which is always expressed in imperial units of long tons/ft^3. It is defined as (Displacement in long tons / (Length in feet/100)^3)
FB/Lwl	The ratio of LCB to LWL, measured from the forward end of LWL; a value less than 0.5 means that the LCB is forward of the midpoint of LWL.
TCB/Bwl	The ratio of the transverse centre of buoyancy to the waterline beam.

Waterplane Values:

Awp:	The area of the waterplane of the resultant vessel orientation
LCF	The longitudinal centre of flotation of the resultant vessel orientation
TCF	The transverse centre of flotation of the resultant vessel orientation
Weight to Immerse:	the weight required to sink the vessel one unit in the direction perpendicular to the equilibrium flotation plane.
FF/Lwl	The ratio of LCF to LWL, measured from the forward end of LWL; a value less than 0.5 means that the LCF is forward of the midpoint of LWL.
TCF/Bwl	The ratio of the transverse centre of flotation to the waterline beam.

Sectional Parameters:

Ax	The maximum underwater sectional area calculated using sections. The maximum value is interpolated from the sections, by fitting a parabola to the station of maximum sectional area and the two stations on either side of it.
Ax Location	The longitudinal location of the station of maximum area (see note on interpolation above)
Ax Location / Lwl:	The ratio of Ax Location to LWL, measured from the forward end of LWL; a value less than 0.5 means that the Ax is forward of the midpoint of LWL.

Hull Form Coefficients:

Cb	The block coefficient of the resultant vessel orientation due to the defined flotation condition, defined as (displaced volume / (LWL x BWL x T)), where T is the maximum navigational
Cp	The prismatic coefficient of the resultant vessel orientation, defined as (displaced volume / (LWL x Ax)), where Ax is the maximum sectional area
Cvp	The vertical prismatic coefficient of the resultant vessel orientation, defined as (displaced volume / (AWP x T)), where T is the maximum navigational draft
Cx	The maximum section coefficient of the resultant model orientation, defined as (Ax / (BWL x T)), where T is the maximum navigational draft
Cwp	The waterplane coefficient of the resultant vessel orientation, defined as (AWP / (LWL x BWL)).
Cws	The wetted surface coefficient of the resultant vessel orientation, defined as (wetted surface / SQRT(displaced volume * LWL)).

Static Stability Parameters:

I (transverse)	The transverse moment of inertia of the waterplane
I (longitudinal)	The longitudinal moment of inertia of the waterplane
BMt	The transverse metacentric radius (distance from the vertical centre of buoyancy to the transverse metacenter) of the resultant flotation condition
BMl	The longitudinal metacentric radius (distance from the vertical centre of buoyancy to the longitudinal metacenter) of the resultant flotation condition
GMt	The transverse metacentric height (distance from the vertical centre of gravity to the transverse metacenter) of the resultant flotation condition
GMl	The longitudinal metacentric height (distance from the vertical centre of gravity to the longitudinal metacenter) of the resultant flotation condition
Mt	The height of the transverse metacenter in the resultant flotation condition, measured from the equilibrium flotation plane
Ml	The height of the longitudinal metacenter in the resultant flotation condition, measured from the equilibrium flotation plane.

Conventions used

Dimensions are normally used in metric format such as 5 m – five metres, or 20 mm – twenty millimetres, however when referencing historic documents, the historical units will be used with metric equivalents in parenthesis such as the imperial length 90 ft – 10 in. (27.686 m) or imperial mass 215 tons (218.45 tonnes).

A brief description of the weight units used:

The tun, ton and tonne are probably the most mis-used and misunderstood unit of measurement known to humanity, often indiscriminately substituted, and generally leading to utter confusion. The tun is based on the old cask measurement system and as such is a measure of volume rather than weight.

Ton or imperial ton is equal to 2240 pounds (abbreviated lbs), while in the United States US ton means 2,000 U.S. pounds. Consequently, came the development of the Long Ton or British ton at 2240 pounds, and the short ton at 2,000 pounds. Tonne or metric tonne, often abbreviated to ton, is equal to 1,000kg.

Throughout this document weights will be given as kilograms (abbreviated kg) or metric tonne, unless specifically noted otherwise.

As discussed in Chapter 3.3, after nearly a century of excavating archaeological shipwrecks, from differing levels of preserved remains, various labels were applied to the resulting models or drawings, like; 'as-built'; 'as-found'; 'torso'; 'minimum reconstruction'; and 'capital reconstruction', often with overlapping or inconsistent definitions. As a general principal the following conventions are used:

Reassembly – the putting back together of surviving elements.

Reconstruction – the recreation of the perceived original shape

Replica – the creation of a copy of the original item.

Chapter 1 **Introduction**

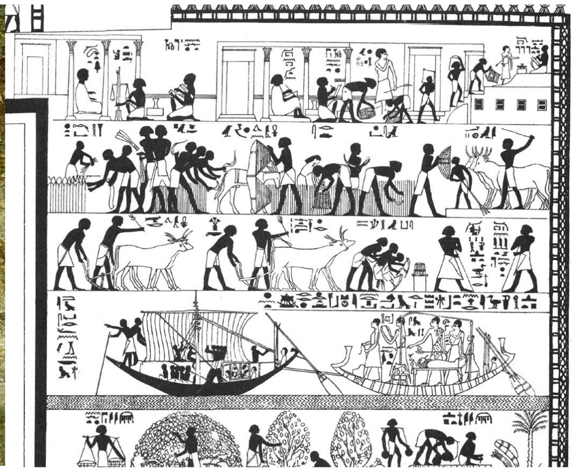
'*Nothing a sunken ship might have been carrying was as complex as the carrier itself. No artefact required as much thought and time to produce, no artefact touched the lives of as many people as did the hull that carried it, nor did any artefact have as profound an effect on society, either technologically, economically, or socially. And for most of us, nothing in that hold could have been nearly as mysterious or as beautiful as this ship whose rotted remains we now investigate*'

J. Richard Steffy (2001:560)

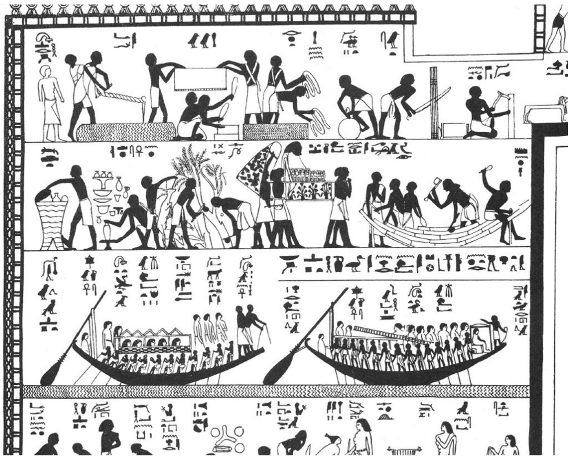
With about 71 percent of the Earth's surface covered by water, and evidence of ships dating back over 4,500 years (c.f. Papathanassopoulos 1977; Kadry 1986; McGrail 2001:10–11) is it any wonder the extent of mankind's fascination with past watercraft? From the ancient Egyptian frescoes depicting ships and shipbuilding scenes (Figure 1-1), to literary descriptions (see Appendix A) of seemingly fantastical ships such as the *Syracusia* (Casson 1971:185; Turfa and Steinmayer 1999:108–118) from circa 240 BCE (Figure 1-2) described in detail by Moschion and later included in an account of sundry remarkable ships by Athenaeus, which describes a vast ship of three decks.

As noted by Muckelroy (1978:3) and Steffy quoted above, ships tended to be very large complex assemblages, rivalling in terms of size, variety of materials used, or construction time any of the individual artefacts recovered from a maritime archaeological site. Even the Roman Empire achieved a gigantism in shipbuilding, reaching its peak with the grain ships running between Egypt and Rome (Casson 1971:184–189). It is easy, as is often the case, to dismiss these iconographic and literary depictions of ancient craft as artistic licence or exaggeration. Perhaps in the light of some archaeological discoveries such as Khufu's boat dating to circa 2600 BCE, discovered in 1954 (Kadry 1986), which measured 43.4m in length when reassembled, the six boats contemporary with the paintings of Beni Hasan discovered at Dashur (de Morgan 1894), or Caligula's Lake Nemi ships which were over 70 m in length (Ucelli and Paribeni 1950), many iconographic and literary depictions of ancient craft should be re-evaluated.

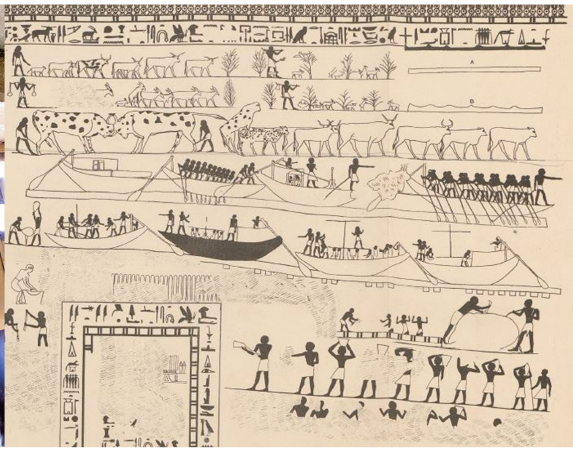
Muckelroy (1978:10) states that ever since ships first voyaged on the seas, there have been shipwrecks, and these in turn have attracted the attention of salvage operations. For thousands of years, the only tools available were nets, grabs or grappling hooks, aided in warmer waters by free diving. In recent centuries these operations been made more efficient by the development of means of getting people onto the sea-floor: first in bells, later with hard-hat diving gear, followed by the development of the aqualung in the mid-20th century, and most recently with the use of R.O.V.'s (remote operated vehicles) for exceptionally deep wrecks (Pacheco-Ruiz *et al*. 2019).

Tomb 3 Beni Hassan Circa 1870 BCE (Photo Ziad Morzy 2016) (Survey after Newberry 1893a Plate XXIX)

Tomb 3 Beni Hassan Circa 1870 BCE (Photo Ziad Morzy 2016) (Survey after Newberry 1893a Plate XXIX)

Tomb 17 Beni Hassan Circa 2000 BCE (Photo Ziad Morzy 2016) (Survey after Newberry 1893b Plate XII)

Figure 1-1 Egyptian ship fresco from Beni-Hassan dated circa 2000 - 1870 BCE (Newberry 1893a:Plate XXIX; Newberry 1893b:Plate XII)

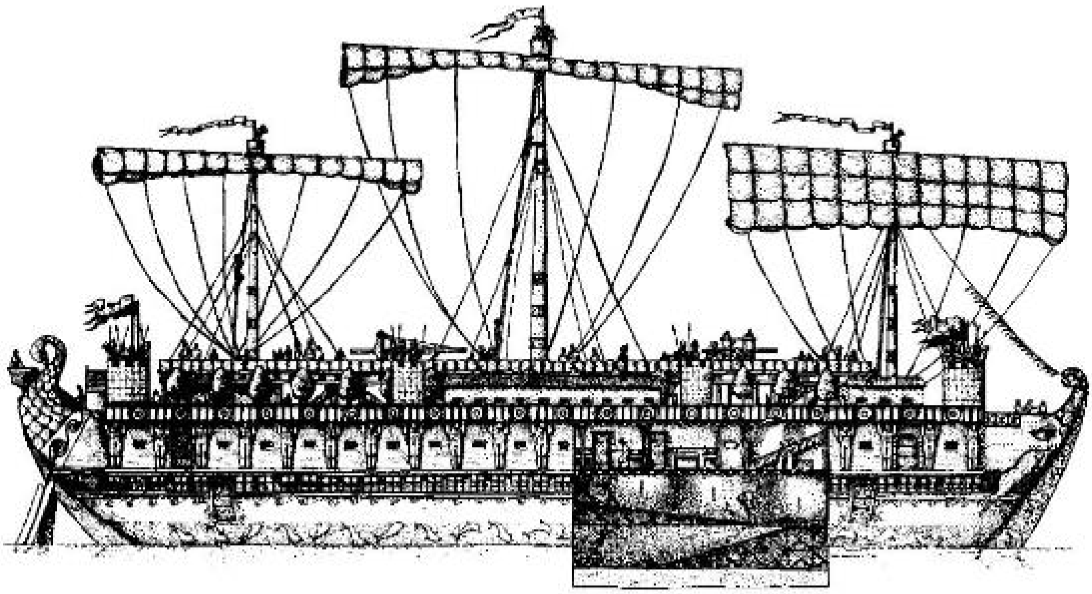


Figure 1-2 Artist's conception of the *Syracusia*, (after Turfa & Steinmayer 1999: Fig. 3)

Ship reconstruction from archaeological remains is almost as old as ship archaeology itself, and people have always had a fascination with, and a desire to imagine, visualise or reconstruct the ships that have come from the antiquarian and archaeological records. As early as Renaissance times there was some interest in the ships of ancient times, often with speculation rife due to the paucity of evidence, limited mainly to literary sources and representations on monuments, mosaics, and art works. Much of these early instances are summarised by Basch (1972).

As noted by Basch (1972:3), one of the first work devoted to classical shipping - *Annotationes in L. (Annotations in Latin)* published in 1536 by Lazarus de Baif – however much of de Baif's iconography derives from Trajan's column, the reliefs on which represent many naval scenes. Basch notes that the sculptor of the reliefs on the column was guilty of many inaccuracies, some due to style, others to his ignorance, but they should receive serious scientific attention (ibid: 3).

1671 saw the publication in Amsterdam of the history of naval architecture, *Aeloude en Hedendaegsche Scheepshouw* by N. Witsen, a compendium of naval information for the period, which was subsequently republished with revisions in 1690 (ibid: 4). Basch (1972:6) also notes the 18th century gave birth to a new idea: the evolution of classical naval construction. In the plates of *La marine des anciens peuples, expliquie*, 1777, Paris, J. Leroy relates primitive contemporary craft (pl. II), Erythraean and Indian rafts made of reeds, Indian skiffs made from split cane, and logs dug out by hand, to the mythical beginnings of navigation : the raft of Chrysor, followed by that of Ulysses. Leroy also proposed that the Greeks were no more than pupils of the Phoenicians and Egyptians, the invention of a ship with 50 rowers being attributed to an Egyptian, Danos, and follows in chronological order their invention of various type of galley which evolves one from the other. Bash (1972:7–8) further criticizes 19th century authors as armchair scholars rather than naval architects and the reconstruction they proposed are hardly less preposterous than those of Witsen. Another amateur archaeologist, Napoleon III had a Roman trireme reconstructed, not on paper but to full size, which was launched in 1861, and manoeuvred with disappointing results despite a crew of hand-picked oarsmen.

Little in the way of maritime archaeology can be detected before the 20th century, but some enquiring minds were fascinated by the possibility of such remains. Elmers (1973:177–8) notes that the earliest known example being a ship find by the 11th century abbot Ealdred of St Albans, whose men found 'oak timbers with nails sticking inside and smeared with naval pitch' while digging for stones in the ruins of the Roman town of Verulamium. Towards the end of the Middle Ages notes are more frequent, but without the antiquarian interest, any still usable wood ended up in the fire. As a result of the interest of Cardinal Colonna in the tradition of large Roman ships said to lie within Lake Nemi in Italy, an attempt to salvage one was made in 1446 CE. Continued interest in this site led, a century later to one of the earliest examples of diving using a crude suit by Franchesco Demarchi in 1535 CE (Muckelroy 1978:11). Subsequent draining of the Lake in the 1930's on Mussolini's orders resulted in the recovery of two very large ships (Ucelli and Paribeni 1950), the first ship was 70m long with a 20m beam, and the second ship was 73m long with a 24m beam.

The first really scientific consideration was published by Lyell (1832) which includes a summary of shipping losses, and in which he concludes 'it is probable that a greater number of monuments of the skill and industry of man will in the course of ages be collected together in the bed of the ocean, than will exist at any one time on the surface of the Continents' (ibid, 258).

A complete ship find was first salvaged in 1785 and made accessible to the public in a museum, it was a dugout from the *Teufelsmoor* near Bremen, which was sent to the Academic Museum of the University of Göttingen. The museum, having recently acquired the South Sea collection from Captain Cook's circumnavigation classified the native German dugout as a boat that resembled the Indian Ocean canoes! (Ellmers 1979:487). There were regular excavations of ships during the Napoleonic period in France, followed shortly by England and the Netherlands, which were recorded with detailed reports and in some cases well-measured drawings but failed to generate any impetus for ship archaeology.

Archaeology began to emerge as an academic discipline in 1818, when Caspar J C Reuvens started to teach at Leiden University, and thus became the first archaeology professor in the world. Both Reuvens and the naval architect Cornelis Jan Glavimans excavated, recorded and published the reconstruction of a ship (Figure 1-3) found close to one of the tidal branches of the River Meuse at the village of Capelle between 1819 – 1822 (Maarleveld 1997:35).

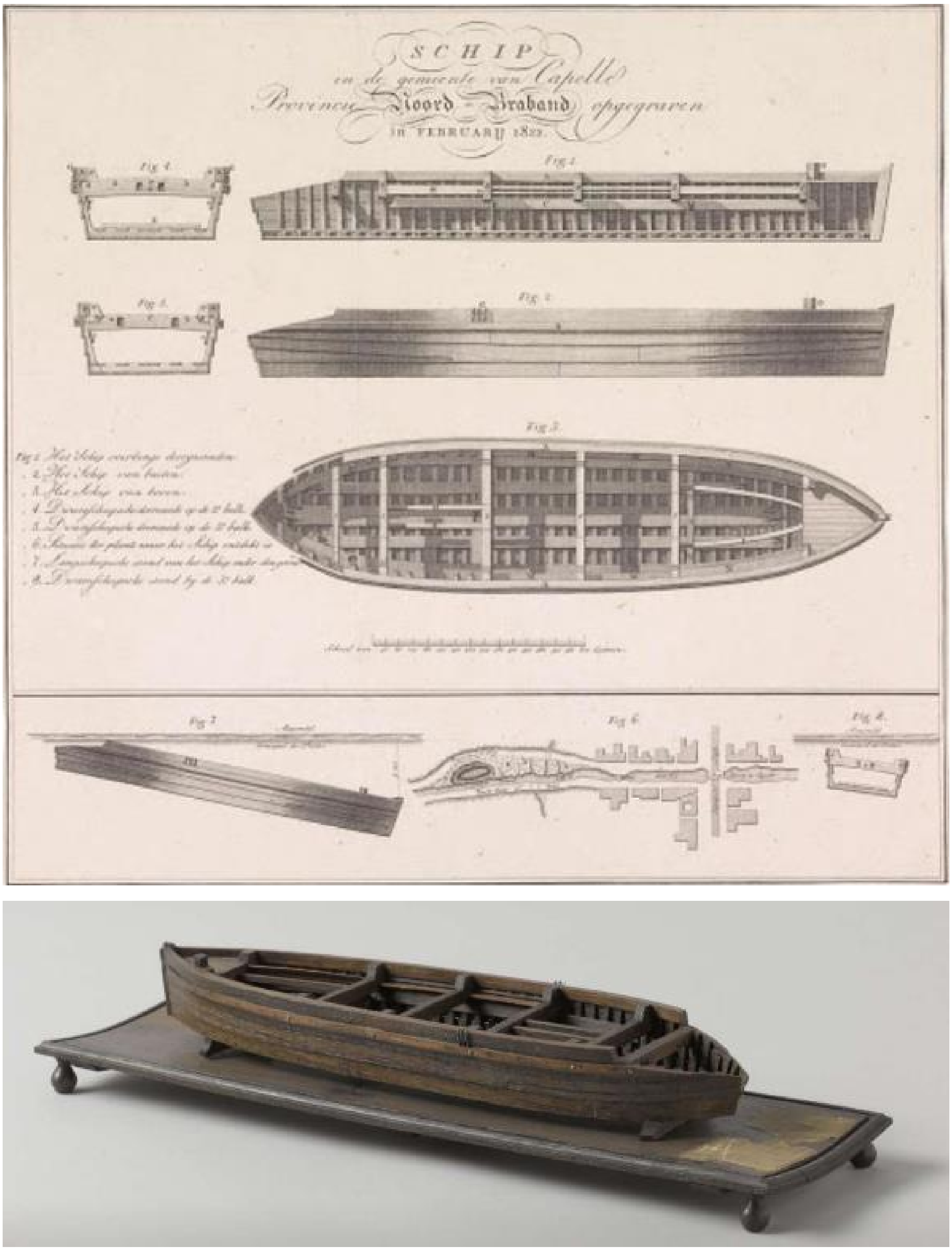


Figure 1-3 The ship excavated by Reuvens and Glavimans in 1822

This could be one of the first example of ‘reconstruction for interpretation’, since it appears, they made a model of what was actually there, rather than reconstructing the whole vessel.

This was closely followed by the excavation of: the **Rother barge** in 1822 (Rice 1824); the **Tune ship** in 1867 (Shetelig 1917; Bonde and Christensen 1993); the first substantial evidence of a ship used by the Vikings; the more well-known excavations by Engelhardt at **Nydam** (Engelhardt 1865) of a 25 m ship, which was excavated, conserved and placed on display in a museum; and the Norwegian grave ship at Gokstad discovered in 1880 (Nicolaysen 1882), which was the subject of one of the earliest known full-scale replicas based on an archaeological shipwreck.

At the beginning of the 20th century antiquarianism evolved into what is now referred to as contextual archaeology. This early archaeology involved the excavation of an artefact which was then catalogued, described and slotted into the appropriate timeline. Prior to the 1950's, archaeology could be classified as 'total archaeology', where the objective was to collect all the evidence of past human activity. The incompleteness of the archaeological record was not thought to be due to the incompleteness of the record, but rather due to the incompleteness of the collection and as long as data continued to be collected it would eventually add up as a whole (Lucas 2012).

A large ship discovered at **Woolwich** in 1912 (see Appendix C.1) – originally reported to be a mid-18th-century merchant vessel, subsequently thought to have been Henry VIII's largest ship the *Henry Grace á Dieu* – received much attention (see Laughton 1914; Anderson 1959; Salisbury 1961; Glasgow 1971; Anderson 1972), the identity of the vessel was narrowed to either the *Henry Grace á Dieu* or the *Sovereign,* with the latter seemingly the most likely, however the vessel was never reassembled or reconstructed as the primary focus was aimed at identifying the wreck in order to finalise the dating.

The second half of the 20th century saw a great increase in the number of vessels excavated, and with it, the focus shifted from reassembly for public display, to detailed research in an effort to understand and reconstruct those vessels for the purpose of archaeological interpretation. This has given rise to a mixture of reconstruction processes, from a variety of perspectives, with a range of success and failure. The level of interest and expense of such projects dictates that the process of reconstruction should be as accurate as possible in representing the archaeological remains in their original form. As such, the following thesis aims to examine **what is being recorded**, **why is it being recorded**, and **how should that record be presented**? And subsequently, if a (hypothetical) reconstruction is created, **how is it evaluated** and **how does the published reconstruction compare and relate to the recorded archive**? Experimental boat and ship archaeology, and digital reconstruction versus actual physical reconstruction will also be examined.

My initial foray into the realms of maritime archaeological reconstruction began during the summer of 2010. I was giving a presentation about the ongoing work of the Traditional Boats of Ireland (TBOI) project (Mac Cárthaigh 2008) at the 2010 Glandore wooden boat summer school organised by Donal Lynch. At the time I had been building, repairing, and sailing both traditional wooden and modern GRP sailing boats for over 25 years, and was teaching wooden boatbuilding at Meitheal Mara in Cork. My presentation was focussed on the digital boat recording work for the TBOI project, which at the time was focussing mainly on museum and builder's scale models.

One such model was the Kinsale Hooker model, from the National Museum of Ireland collection, which represents a long extinct craft, used for longline fishing on the Labadie and Nymph banks off the South Coast of Ireland in the 19th century. In the 1820s a class of racing yachts in Dublin were modelled on the Kinsale Hookers, but 50 years earlier, the yachts of the Water Club of Cork were so similar to these working craft that they could race together, with both yachts and hookers required to sail without topsails. The model is superbly detailed, complete with all internal structure and rigging, and although its provenance is unknown, it is believed that this model may have been commissioned for one of the Great Exhibitions, but the builder is not known.

During the presentation I described the process whereby the museum’s scale model (Figure 1-4 top left) was 3D laser scanned using the Faro Platinum Arm and LLP2 laser scanner to generate a three-dimensional point cloud of over 3 million data points (Figure 1-4 top right). A subsequent surface mesh model (Figure 1-4 middle right) which was then re-scaled from the modelled 1:36 (3/4” = 1’-0”) to full size, thereby removing the issues of model, scale and measurement effects discussed in Chapter 5.6.1. The digital modelling of every constituent element of the vessel (Figure 1-4 bottom), in effect a digital re-building of the vessel just as I would have built a real-world version, in order to perform hydrostatic analysis using Orca 3D as described in Chapter 6. As well as providing basic hull characteristics such as length, beam, draft and displacement, this also generated the vessel’s hydrostatic data such as form coefficients, cargo capacity and stability criteria, as well as generating lines-plans and construction drawings (Figure 1-5) and sail plan drawing (Figure 1-6).

Figure 1-4 Kinsale Hooker scale model, 3D point cloud, surface mesh model and full-size digital reconstruction (Pat Tanner)

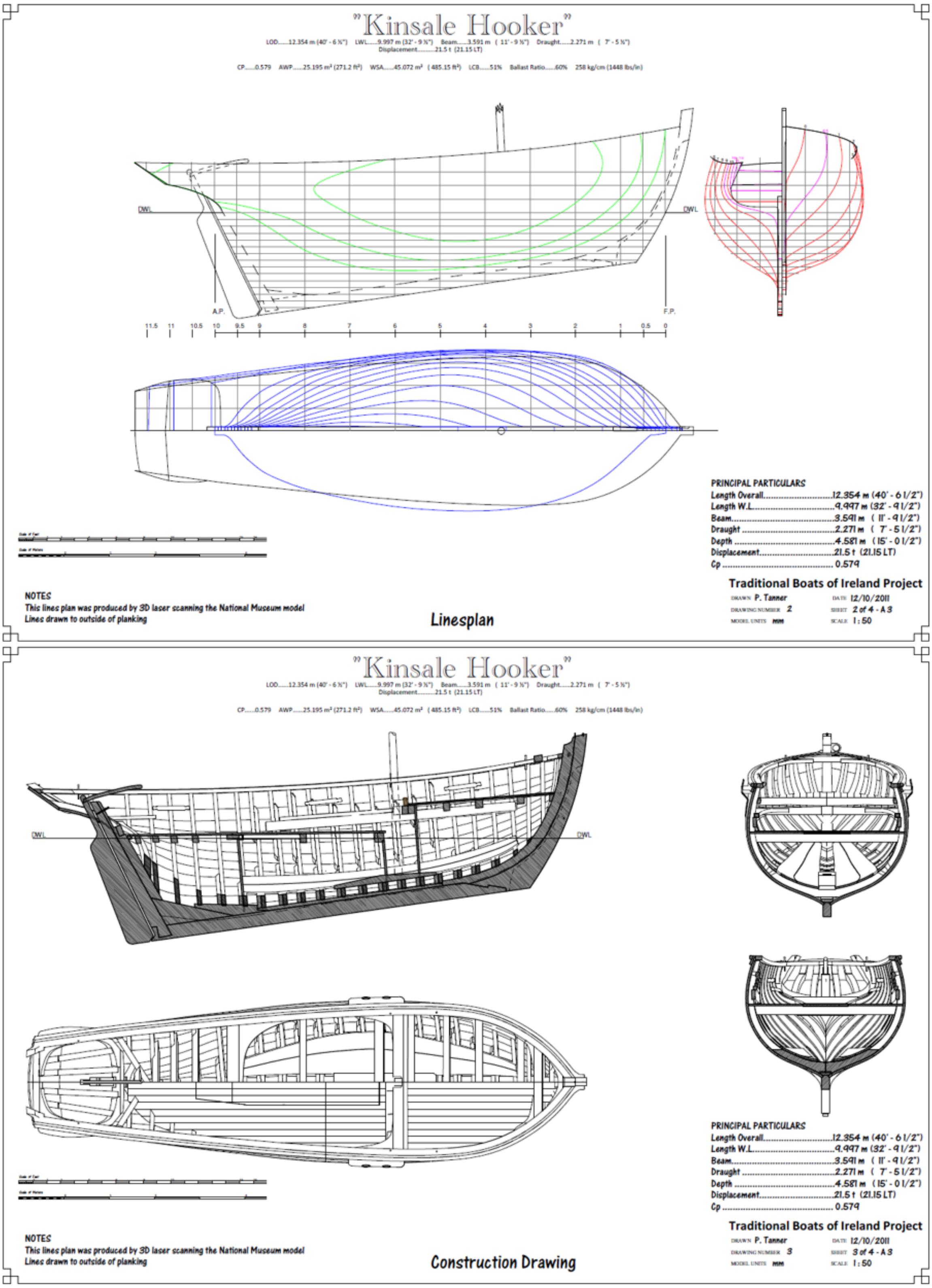


Figure 1-5 Kinsale Hooker lines plan and construction drawing (Pat Tanner)

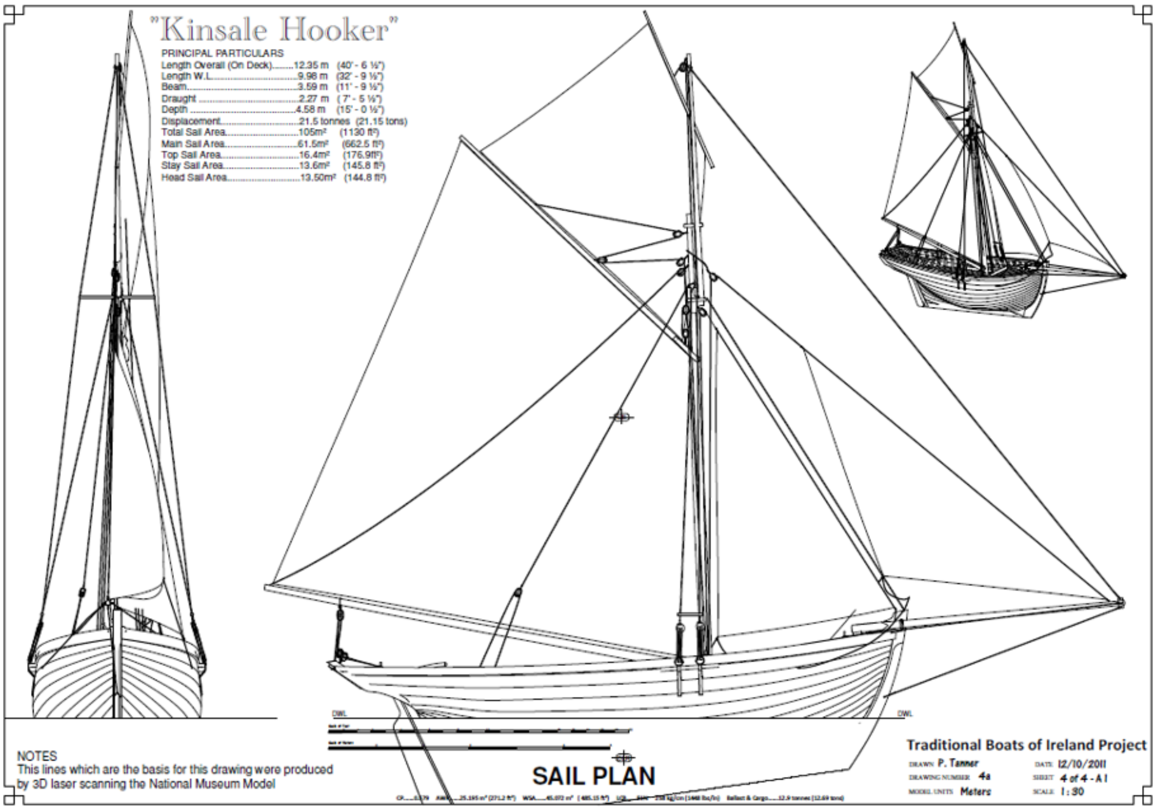


Figure 1-6 Kinsale Hooker sail plan drawing (Pat Tanner)

Unbeknown to me, Holger Schweitzer was in the audience waiting to give a presentation on the Drogheda boat (Schweitzer 2012). Drogheda is located c 40 km north of Dublin, and the Drogheda boat was a 16th century vessel discovered in 2006, c. 1.5 km east of Drogheda town near the southern shore of the River Boyne. The wreck had c 9 m overall preserved length and c 3 m in width, and both stem and stern post partially preserved, representing almost the entire original length of the boat (ibid: 225-27). Following the guidelines devised by the Newport Ship project (Jones and Nayling 2011; Soe *et al*. 2012; Nayling and Jones 2014; Jones 2015), all excavated timbers were documented by contact digitising using a Faro Arm and Rhinoceros 3D, capturing accurate three-dimensional data, which allowed the creation of digital solid models of each timber.

Rapid prototyping was used to 3D print 1:10 scale models of each timber, which were then reassembled using the existing documented fastener holes to generate a physical scale model of the articulated hull remains (Figure 1-7). At this stage, the Drogheda boat being a much smaller vessel had overtaken the Newport Ship project (in terms of progress) and Holger asked if I could do a Kinsale Hooker style analysis on his scale model (see Appendix G for a detailed description). This analysis was completed in 2012 and the reconstruction of the Drogheda boat was published at the ACUA Underwater Archaeology Proceedings 2013 (Tanner 2013a). That work set me on the pathway to undertaking the reconstruction and analysis of a number of different vessels, and the experience gained along the way is distilled into the chapters and pages of this thesis.

Figure 1-7 Drogheda Boat physical scale model of the articulated hull remains (Pat Tanner)

The following section briefly outlines the layout and content of this thesis. In addition to an extensive literature review of scholarly publications, this work is not solely based on academic research. It is heavily influenced by the practical experience gained over 25 years of building and repairing both traditional and modern vessels, as well as over 100,000 nautical miles of sailing and seafaring experience. The approaches and methods described have evolved through a series of practical applications including:

- The Newport Medieval Ship (Jones *et al*. 2013; Tanner 2013b; Jones *et al*. 2017)
- The Auxiliary Ketch AK Ilen (Smith *et al*. 2013)
- Two wrecks from the Grand Hotel site Stockholm (Hansson and Sundberg 2014:38–41)
- The Unbelievable Ship (Hirst and Beard 2017)
- The testing and analysis of hypothetical ship reconstructions (Tanner 2017a)
- A digital reanalysis of the Bremen Cog (Tanner 2017b)
- A Seakeeping, Stability and Performance Analysis of the Bremen Cog (Tanner 2018)
- Digital comparisons of the Poole Iron-Age logboat (Tanner 2019)
- 3D documentation of the Marsala Punic ship (Polakowski and Tanner 2020)
- The Newport Medieval Ship Phase Two – Capital Reconstruction (Tanner 2020 see Appendix G)
- A digital reconstruction of the Sutton Hoo ship (Tanner *et al*. 2020)

Following each publication and subsequent feedback, the methodology and approach proposed in this thesis has been continuously developed and refined.

Chapter 2 examines wherever possible from previously published sources, the details of how those recovered archaeological materials were documented and subsequently utilised in each **[hypothetical]** reconstruction(s). **However, as noted by Jones** (2015:71) **the focus of many published reports has been on the results rather than the process and methodology**. This lack of detail, what the London Charter (Denard 2009) refers to as paradata[1], makes it difficult to understand how, and critically, why certain methods or decisions were chosen while others were rejected.

[1] Paradata is information about the human processes of understanding and interpretation of data objects. Examples of paradata include descriptions stored within a structured dataset, of how evidence was used to interpret an artefact, or a comment on methodological premises within a research publication. It is closely related, but somewhat different in emphasis, to “contextual metadata”, which tends to communicate interpretations of an artefact or collection, rather than the process through which one or more artefacts were processed or interpreted.

Chapter 3 examines the conceptual approaches used in ship reconstruction and experimental archaeology, examines the goals of a reconstruction project and discusses the issues identified in both chapters two and three.

Having identified the main themes and primary goals which developed in boat and ship archaeological reconstruction from a practical and conceptual perspective, **Chapter 4** begins with examining the source data and how that data is recorded and tracks the development of that data capture methodology. **Chapter 5** examines how the recorded data is represented and collated into a ship catalogue as well as examining the traditional approach of scale model making used to represent the three-dimensional format of the archaeological data.

Chapter 6 proposes a digital approach, where the techniques and methodologies developed for accurate and efficient data capture, in the form of three-dimensional digital documentation, allow innovative approaches to organising, analysing, comparing and disseminating data pertaining to the archaeological find. Subsequent advanced digital three-dimensional modelling, combining all the documented data, enables detailed accurate reassembly of the surviving elements, as well as the ability to digitally model missing elements to aid in hypothetical reconstructions. Finally, with the aid of naval architecture software (Orca 3D), the digital reconstruction is tested and analysed to compare the results to a known baseline, in this case, a vessel built and sailed by the author.

Having established a methodology which is shown to be accurate in Chapter 6, attention then turns to applying that methodology to archaeological data sets. **Chapter 7** begins by looking at the archaeological evidence, identifying what it is that the evidence represents, and examining how to interpret that evidence. The concept of minimum and capital reconstructions is examined, and issues such as distortion in the evidence are identified, together with methods to analyse and repair that distortion to allow the reconstruction process to proceed.

Chapter 8 then takes the archaeological evidence, and utilises the approach developed in previous chapters to create a hypothetical minimum reconstruction based on the archaeological evidence. Case studies are used to demonstrate the various stages, in a manner which clearly identifies how the data is interpreted, the decision-making processes involved, and how the hypothesis is tested to demonstrate its validity.

Finally, **Chapter 9** uses the Newport Medieval ship as a case study to demonstrate how that hypothetical minimum reconstruction is further developed and refined, using the same iterative processes to create a hypothetical capital reconstruction providing more insight not just into the vessel itself, but also the people and processes involved.

Chapter 2 **Literature Review of Practical Approaches**

2.1 Introduction

The following two chapters reviews and examines what has been published in relation to the documentation and reconstruction of shipwrecks with a view to understanding, both conceptually and practically, the methodology used in documenting those wrecks and attempting to understand the methods and techniques used in their reconstruction. However, as noted in the previous chapter, the focus of many publications has been on the results rather than the process and methodology, making it difficult to understand how, and critically, why certain methods or decisions were chosen while others were rejected.

Standardisation as a concept to facilitate ease of handling can be seen throughout antiquity, from the Mediterranean amphorae, to the medieval cask followed by modern shipping containers. However, the concept has largely eluded maritime archaeological publications. For any vessel there are several critical details required to better comprehend the object. Location and date provide temporal and cultural background, while dimensions such as length, beam, draft and displacement give an indication of size, scale and general characteristics of the vessel. All other aspects and details provide additional understanding of the form, structural characteristics, appearance and use of watercraft. If included, these principal characteristics of date, location and dimensions, seldom appear on the first page of a report, but rather are scattered deep within, often requiring archaeological excavation to be rediscovered. In many cases it has been necessary to ‘reverse engineer’ the published material in order to comprehend the published results.

Due to the sheer scope of material to be reviewed, Chapter 2 deals with individual reconstructed shipwrecks, which demonstrate various different approaches, or represent changes in the reconstruction methodologies employed. Chapter 3 examines the conceptual approaches to ship reconstruction, with both chapters together discussed in the conclusion of Chapter 3.

2.2 Scholarly Sources

The ***Mariner's Mirror*** is the international journal of the Society for Nautical Research. It has been published since 1911 and is recognized as the world’s leading journal of naval and maritime history. The subject matter ranges from archaeology and ethnography to naval tactics and administration, merchant seafaring, shipbuilding and virtually anything that relates to humankind's relationship with the sea. Of the many articles published, a mere **68 articles** discuss ship reconstruction, and five of these are reviews of other publications (see Appendix B1).

The ***International Journal of Nautical Archaeology*** is a forum for the exchange of ideas and research relevant to all aspects of nautical and maritime archaeology. The journal covers all aspects of the study of nautical archaeology, exploring the use and development of water transport, maritime trade, coastal resource use, and the infrastructures that supported these activities from prehistory to the recent past. Between 1972 and 2019 the journal has more than 2,260 published articles or reviews, in dealing with vessels a mere 24 articles have the word reconstruction in the title (see Appendix B2), nine have the word replica in their title (see Appendix B3), and only 254 discuss or mention reconstruction in the main text. Of that 254 papers, 80 are related to the debate on the trireme replica, on which, it seems everyone has an opinion, leaving a mere **174 articles** or just 8%, which 'discuss' to some extent, the reconstruction of other ship finds (see Appendix B4).

The ***Journal of Maritime Archaeology*** describes itself as the first international journal to address all aspects of maritime archaeology, both terrestrial and under water. It encompasses theory, practice and analysis relating to sites, technology, landscape, structure, and issues of heritage management. From 2006 to 2019 with 242 published articles, the journal has only two articles with the word reconstruction in the title (discussing Experimental Reconstructions of Norwegian Iron Age Slab-Lined Pits, and Recording, Publishing, and Reconstructing Wooden Shipwrecks (Castro *et al*. 2018)), none with replica in the title. There are 64 articles which mention reconstruction, of which only **11 articles** (4.5%) deal specifically with vessels of any type.

In addition to these three mainstream journals, additional publications in Archaeonautica which has two articles with restitution (reconstruction) in the title, the Oxford Journal of Archaeology which has no articles with reconstruction in the title and 48 which mention reconstruction, World Archaeology has one article with reconstruction in the title and 85 which mention reconstruction, individual ship find publications have also been consulted. In the mainstream maritime history/archaeology journals, the topic of reconstruction – the natural end point for our analysis – equates to between less than 8% of content in the best case, and much less more generally.

2.3 Antiquarian or Early ship finds

2.3.1 Rother Barge 1822

Muckelroy (1978:11) states that a more general 19th century attitude to such antiquities is nicely illustrated by the case of an old boat found at Rye (Sussex) in 1822, which was put on display in London for a time, but broken up when public interest flagged. Discovered in 1822, the timbers and fastener dimensions were recorded, construction features described, and unique features such as metal plates and merchant marks were discussed in detail. The overall vessel dimensions were listed as having a length of 63 ft 8 inches (19.4 m), a beam of 15 ft (4.57 m), a height from the internal planking to the beams of 4 ft 2 inches (1.27 m) midships, and an additional 1ft 2 inches (0.36 m) to the top of the bulwark. The vessel (Figure 2-1) described by Rice (1824) as being built entirely of oak, with near vertical stem and stern posts; flat-floored and clinker built. The planks being riveted together with iron and fastened to the frames with oak treenails wedged at either end. The planking inside and out were listed as being 1 ¾ inches thick, some with surprising dimensions such as 18 ft 10 inches (5.75 m) long and up to 29 inches (0.74 m) wide, and Rice states '*from its texture certainly not of British growth*'. Five principal beams are noted, bolted to the sides and 'very ingeniously' scarphed together. A mast step was noted positioned about one third aft from the bow, and evidence of a bowsprit which rested atop the stem.

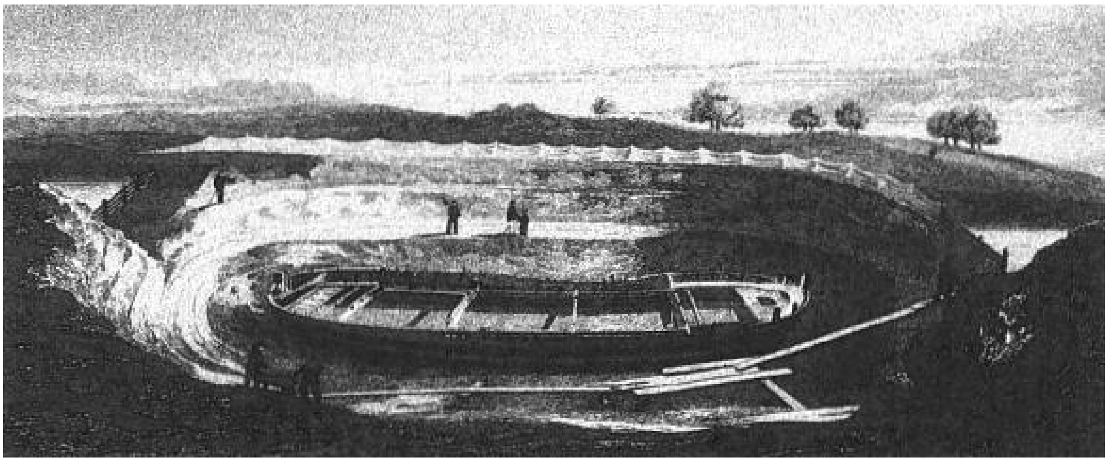


Figure 2-1 Rother barge (after Rice 1824: Plate XXV)

A detailed site sketch and at least one section drawing were recorded. Other details such as application of tar, moss and animal hair was also noted. Finds from around the site, including ceramics, animal and human bones were also recorded. This accumulated information led Rice to conclude a vessel of Dutch origin and having sunk between AD 1287 and 1570. The report by Rice does not have a single mention of reconstruction, replica or reassembly, with the presumed provenance and dating based on the artefacts and observed construction features.

2.3.2 Nydam Bog 1859

First investigated by Conrad Engelhardt between 1859 and 1863, the discovery included three vessels, parts of an oak ship, the 25m Nydam ship was raised, conserved and eventually put on display, and the so-called pine ship which was subsequently lost during the Danish – Prussian war. As well as making the find accessible to the public in a museum, Engelhardt (1865) also published his findings (Figure 2-2 and Figure 2-3) as well as the abundance of artefacts. Although the excavations carried out by Englehardt were halted due to conflict, the original report included illustrations of the overall site and detailed drawings of selected elements. Articles by Arenhold (1914) and van Nouhuys (1936) in The Mariner's Mirror criticized the way that the excavated remains had been reassembled in the Schloss Gottorp Museum in northern Germany.

Salisbury (1965) states that Åkerlund's (1963) publication on the Nydam Ship is notable, not only for its evaluation of the evidence for this boat, but also for its clear identification of the qualities needed by those who undertake the study and publication of excavated boats.

> 'A naval archaeologist must in fact possess unusual qualifications. A professional archaeologist without a wide knowledge of practical shipbuilding and its history, and without some experience of elementary seamanship, will produce some horrible howlers. Conversely, a practical seaman or shipwright lacking an adequate archaeological or historical background cannot avoid introducing anachronisms.' (Salisbury 1965:279)

Such 'naval' archaeologists, according to Salisbury (1965:279), must possess unusual qualifications: a professional archaeologist needs wide knowledge of practical shipbuilding and its history, and some experience of elementary seamanship, while a practical seaman or shipwright needs an adequate archaeological or historical background. This precept still holds good today yet not every person undertaking such research has sought to acquire those essential characteristics. Salisbury notes that no notes or drawings are known to exist which are contemporary with the original excavation, the actual reconstruction of the vessel was carried out by Stephenson, and the surviving accounts and drawings were made *after* reassembly of the vessel had been completed, and it is Åkerlund's publication which clearly illustrates which parts of the vessel were original, and which parts are reconstructed. The site was further excavated from 1989 to 2000 by Rieck, (Crumlin-Pedersen and Rieck 1993; Rieck 1994; Rieck 2014) and this field research coupled with analysis of the archival records and re-measuring of the displayed remains, resulted in an alternative hull form reconstruction being suggested. The initial focus of the original work at Nydam was on reassembly of the remains to facilitate public display, which was subsequently criticised and reappraised.

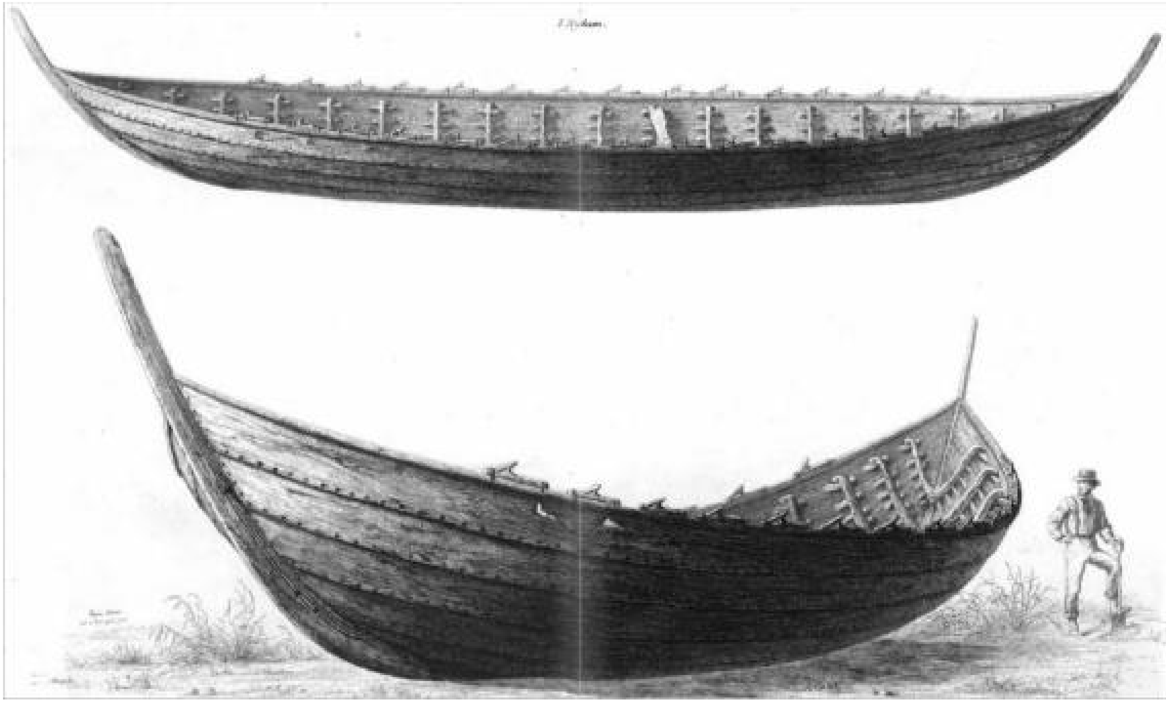


Figure 2-2 Reconstruction of Nydam Mose (after Engelhardt 1865: plate I)

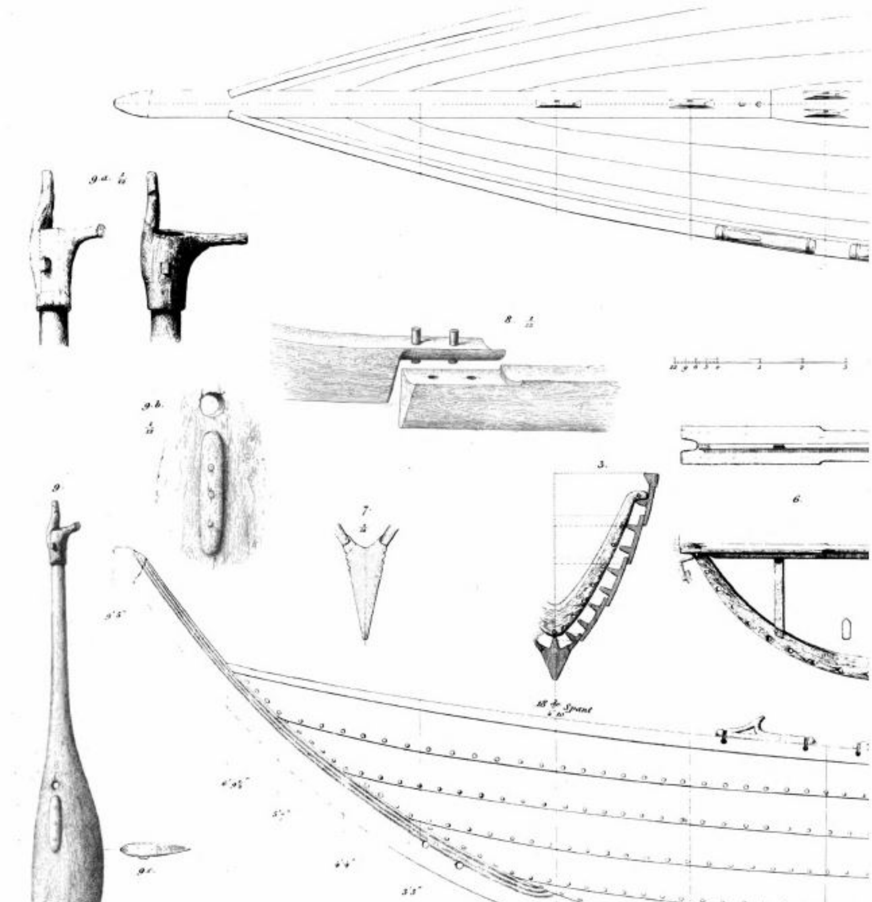


Figure 2-3 Reconstruction details of Nydam Mose (after Engelhardt 1865: plate II)

2.3.3 The Gokstad vessel 1880

One of the earliest known full-scale replicas based on an archaeological shipwreck was of the Norwegian grave ship at Gokstad measuring 23.5m long by 5m wide (Figure 2-4) which sailed across the Atlantic to the United States to demonstrate the seaworthiness of Viking ships. Discovered in 1880, the vessel was uncovered by digging into the side of a burial mound, with the artefacts' position and relationship to the vessel being noted, before the vessel itself was raised in sections and removed. The vessel is described in general detail, including scantlings, and a catalogue of drawings for the artefacts. The construction features were documented, but a detailed recording of the individual timbers was not carried out. The drawings of the hull are clear and detailed, but represent an idealized hull form, with most of the timbers shown as complete and unbroken. Section drawings included show a completed and faired hull form as opposed to the in-situ shape of the surviving remains (Nicolaysen 1882).

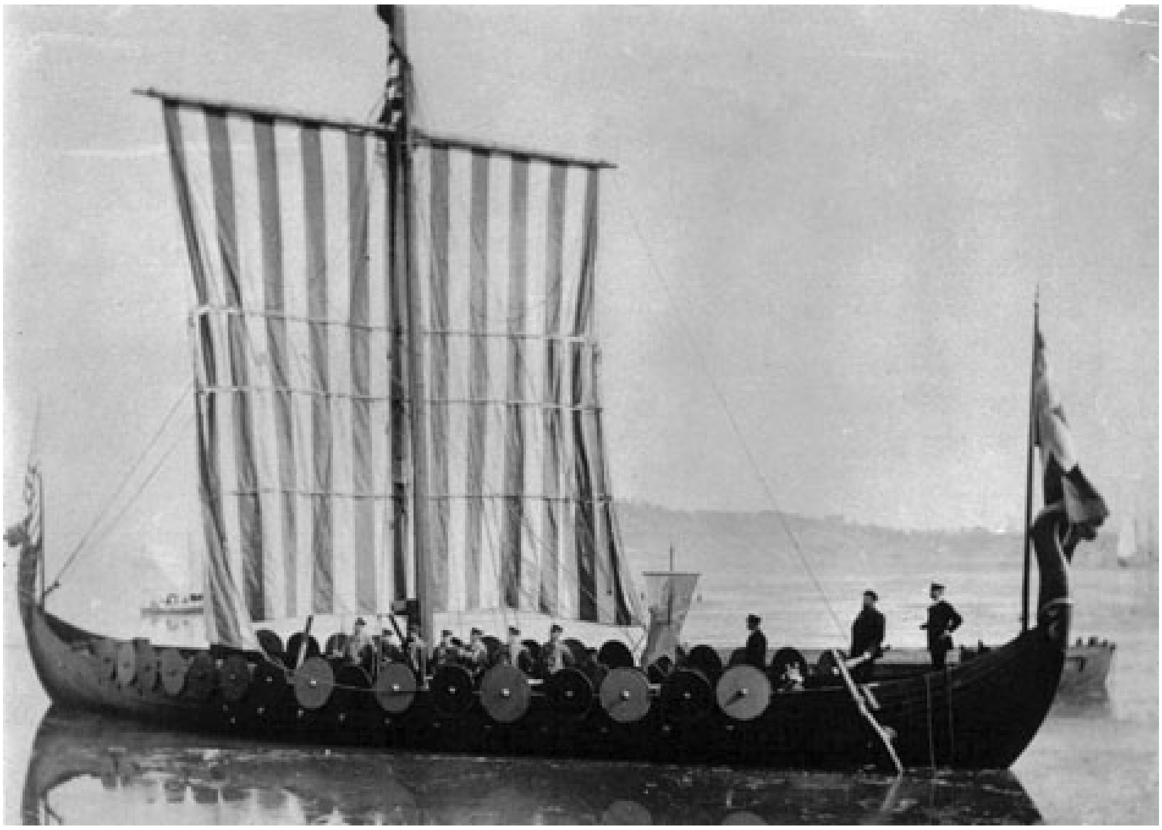


Figure 2-4 The replica ship 'Viking' built in 1892. (Swedish National Maritime Museum Photo Archives)

The Gokstad excavation would have benefitted from a detailed in situ site plan (along with sections), showing accurately plotted fasteners and the extents of the original recovered material. However, the site records are still of a sufficiently high standard to remain archaeologically valuable today. The primary focus was on reassembly of the remains to facilitate public display, as well as the subsequent construction of a full-scale replica.

2.3.4 The Oseberg Ship 1904

Discovered in southern Norway in 1903, and excavated in 1904, the 22m long by 5m wide ship was carefully documented in-situ with sketches and measurements despite much distortion and fragmentation (Brøgger 1917). The ship with almost 95% of the original timber remaining was re-assembled for a museum exhibit in 1907.

Figure 2-5 The well preserved Oseberg Ship (Photo: The Viking Ship Museum, Oslo)

In 1987 a full-scale reconstruction of the Oseberg ship, named *Dronningen* was built in Norway based on drawings of the exhibited ship. *Dronningen* sank in dramatic fashion during its very first sea trial, while sailing on a close reach in a force 5 (17-21 knots, 9-11m/sec) wind, at circa 8 - 10 knots (Bischoff 2010:4). Subsequent analysis in an unpublished report by J. Godal in 1988 of the sailing trials and tank testing of a 1:10 scale model in a hydrodynamics laboratory, indicated that the bow wave generated by the forward momentum shipped over the gunwale when the vessel reached 9 knots and at 10 degrees angle of heel. Following on from the dramatic failure of *Dronningen* during its very first sea trial, and the many hypotheses proposing what 'might' have gone wrong, the only way to find out was through a detailed examination of the exhibited remains. **The Oseberg Project 2006** was established with the belief that new methods and new expertise, through new documentation techniques and a reconsidered interpretation of the preserved parts would bring new answers (Bischoff 2010; 2012; 2016). Bischoff (2016:27–29) clearly illustrates how a reappraisal of the hull form, combined with hydrodynamic testing demonstrates that it was the original reassembly and replication that were flawed, rather than the original vessel.

2.4 Reconstructions based on archaeological evidence

While the four examples discussed in Chapter 2.3 were primarily focused on reassembly for public display first and archaeological interpretation second, the following examples examine in detail, projects where the vessel has been fully reconstructed for the purpose of archaeological interpretation. Examples have been chosen based on key developments in methodology.

2.4.1 Kalmar wrecks 1932

During the 1930s, the draining of the moat around Kalmar castle led to the discovery and excavation of more than 20 wrecks in the harbour of the Medieval town and castle of **Kalmar** and their subsequent publication (Åkerlund 1951). The Kalmar 1 wreck is described by Åkerlund as a smaller ship from the Middle Ages, probably the middle of the 13th century. Surviving remains measured 11m long and unexpectedly wide at 4.55m, circa 2m deep, with the widest section 1 or 2m aft of midship. During the excavation the disarticulated timbers as well as the wreck were recorded using 1:10 scale drawings (Figure 2-6).

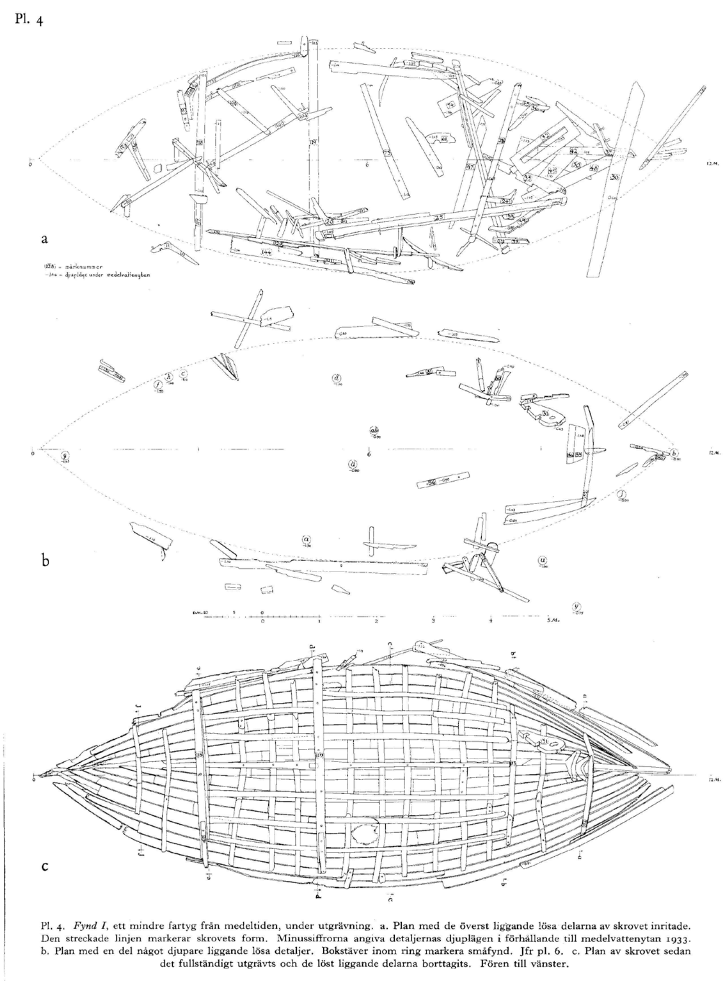
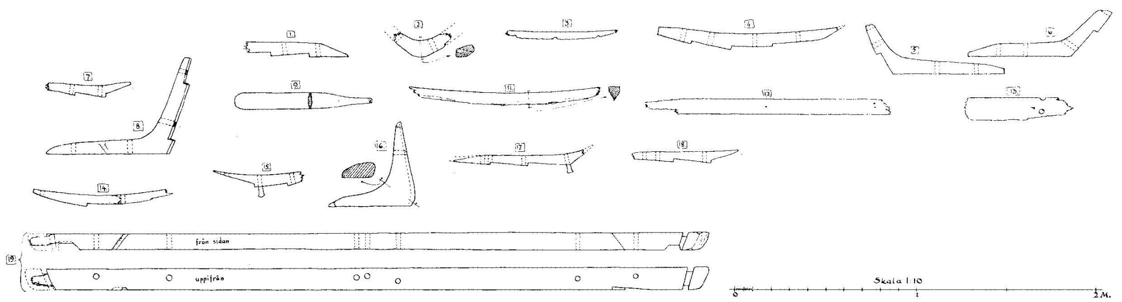
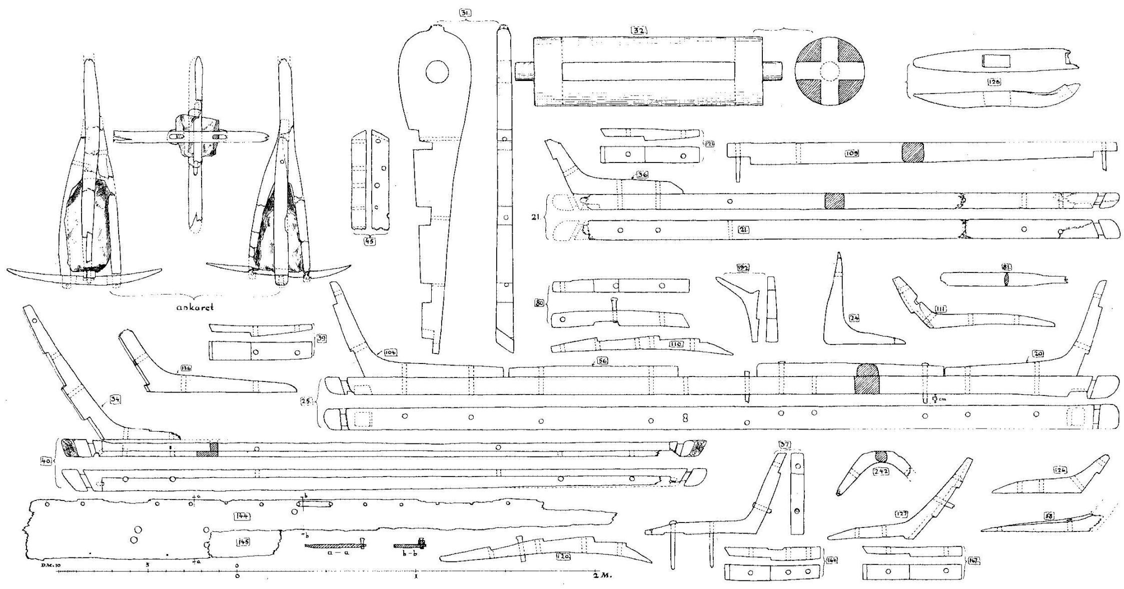


Figure 2-6 Kalmar 1 Site plan drawing and disarticulated timbers (after Åkerlund 1951)

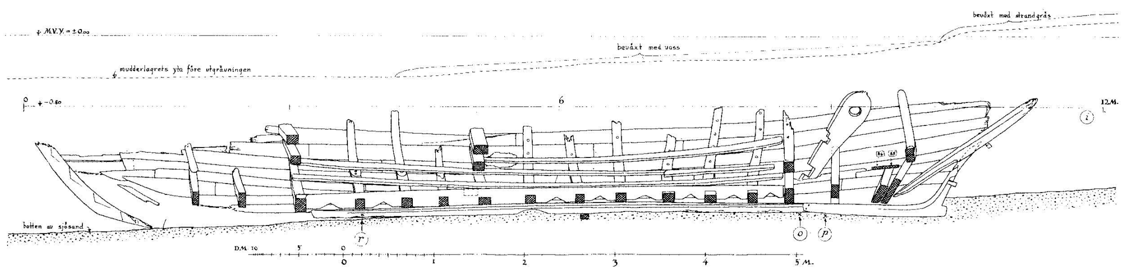
Pl. 5



Pl. 5, a. *Fynd I.* Uppmätning av de lösa delar, nr 1—19, vilkas läge vid påträffandet ej blev närmare angivet.



Pl. 5, b. Uppmätning av en del viktiga lösa detaljer i Fynd I.



Pl. 5, c. *Fynd I.* Längdsektion, med styrbords insida visad.

Figure 2-7 Kalmar 1 Detailed drawings of individual timbers (after Åkerlund 1951)

For the reconstruction, the drawings recorded during the excavation at 1:10 scale (Figure 2-7 and Figure 2-8) were used for a preliminary reconstruction drawing, then following careful recording of each of the disarticulated pieces, observing nails and nail holes, allowing the reintegration of those parts, reconstruction drawings (Figure 2-9, Figure 2-10 and Figure 2-11) at 1:10 scale and a reconstruction model at 1:12 scale were created. Åkerlund describes the vessel as being

> "a little unimportant medieval ship, decked at bow and stern, but otherwise open, and fitted with a single mast. It has a rounded, midship fairly flat bottom, curved stem and straight stern, fitted with rudder. The hull is remarkably wide with a ratio of width to length of 1:2.5" (ibid: 38).

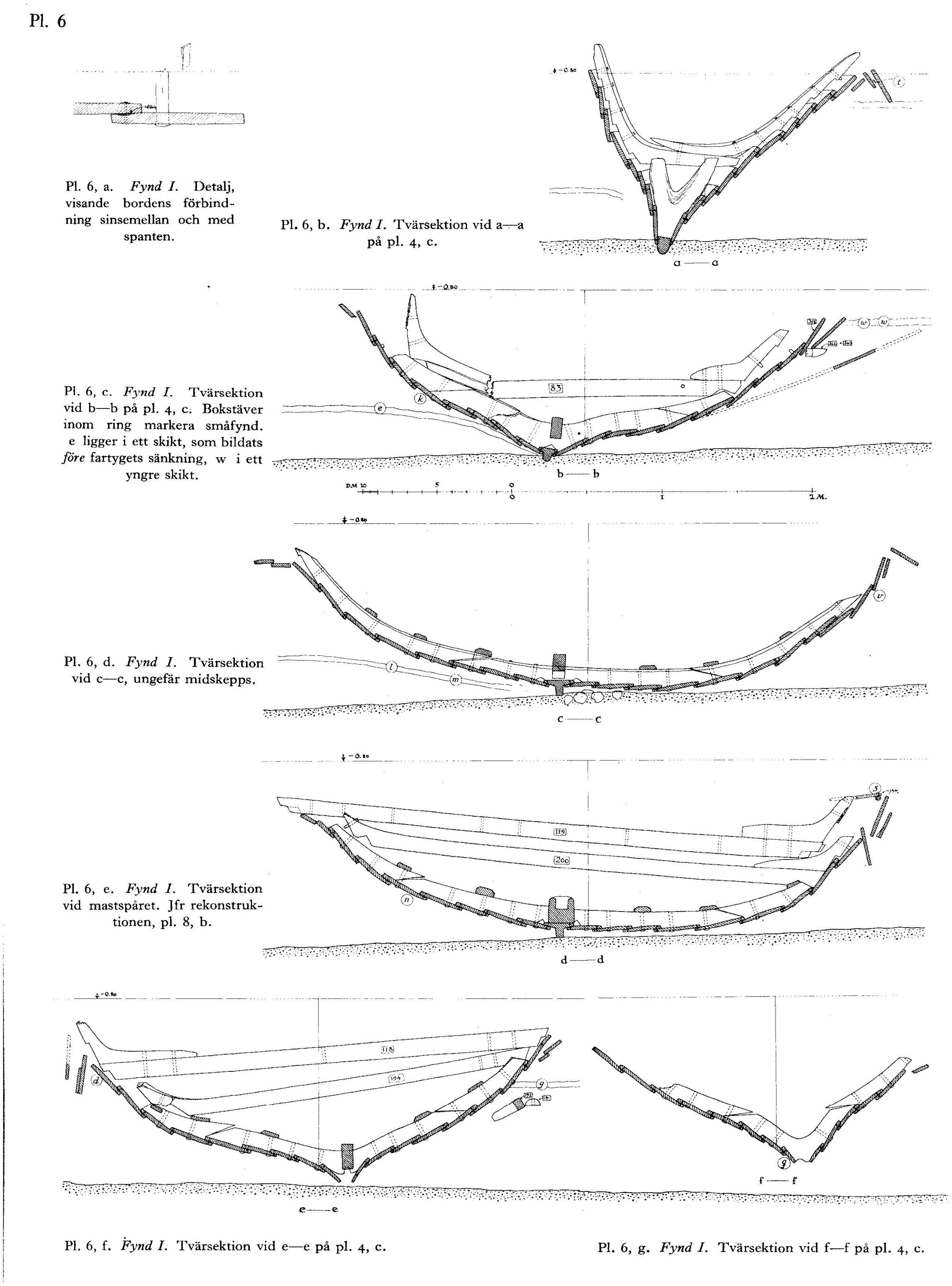
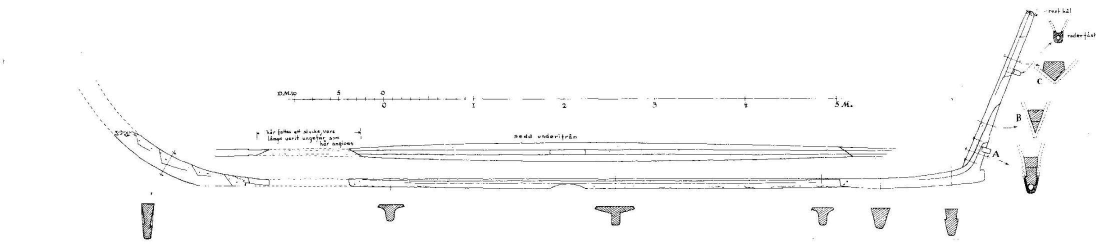
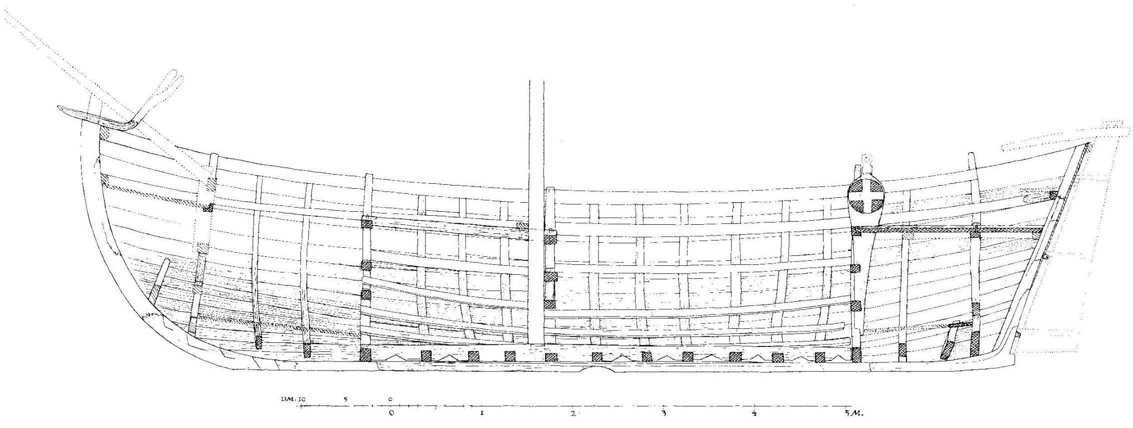


Figure 2-8 Kalmar 1 Site sections drawings (after Åkerlund 1951)

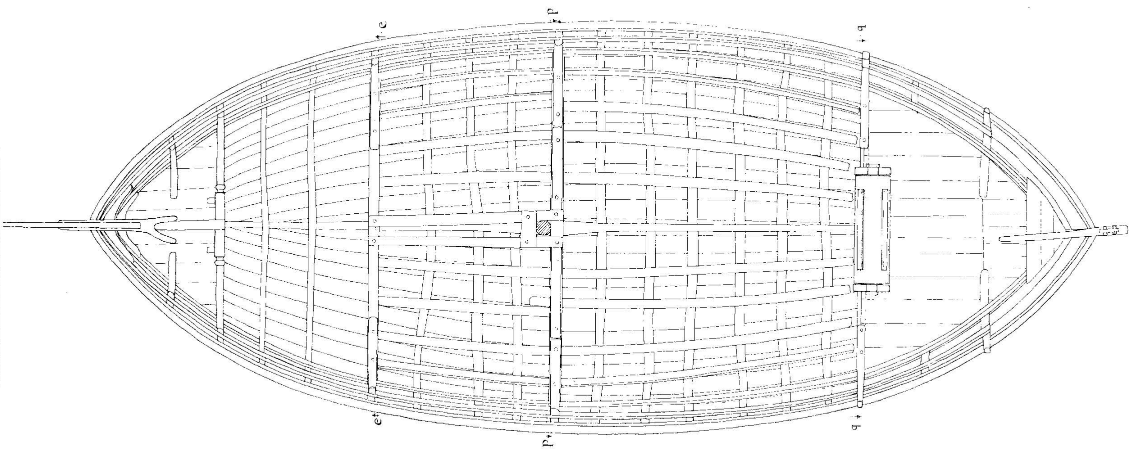
Pl. 7



Pl. 7, a. *Fynd I.* Uppmätning av köl och stävdelar efter delarnas hoppassning i riktigt läge. Vid A och C roderfästen.



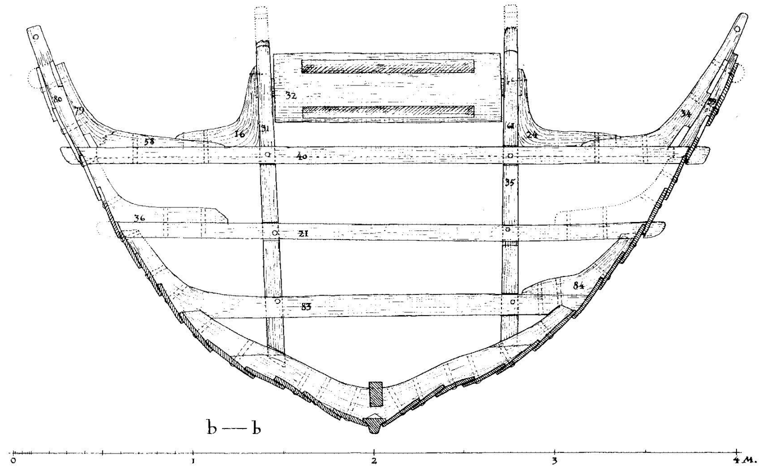
Pl. 7, b. *Fynd I.* Längdsektion med styrbords insida visad. Rekonstruktion. Streckade partier voro bevarade. Jfr pl. 8.



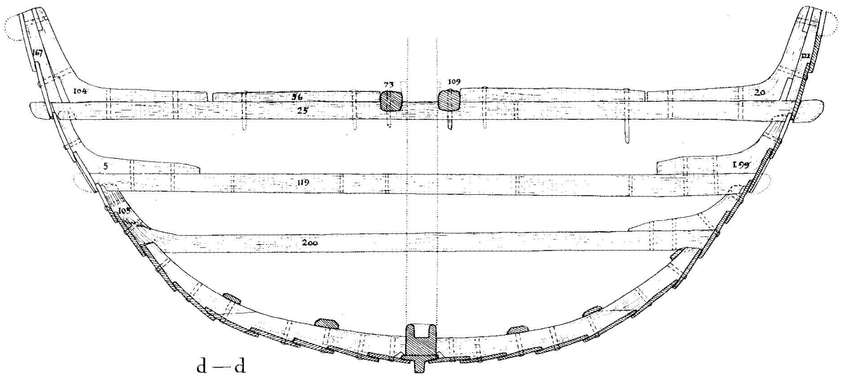
Pl. 7, c. *Fynd I.* Rekonstruerad plan av fartyget.

Figure 2-9 Kalmar 1 Reconstruction drawing (after Åkerlund 1951)

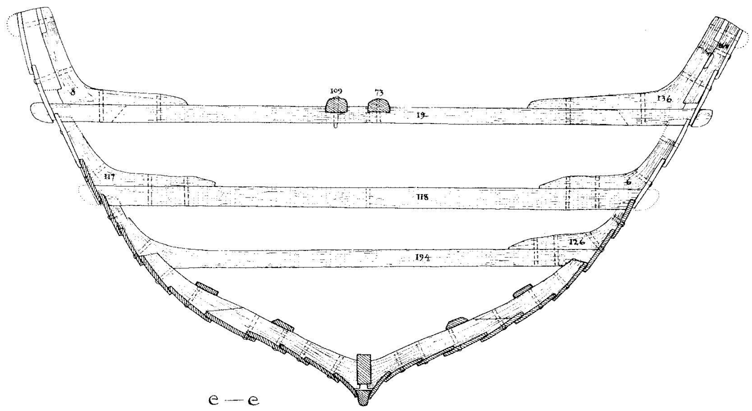
Pl. 8



Pl. 8, a. *Fynd I.* Rekonstruktion av tvärsnittet vid b—b (pl. 4, c) med spelet.

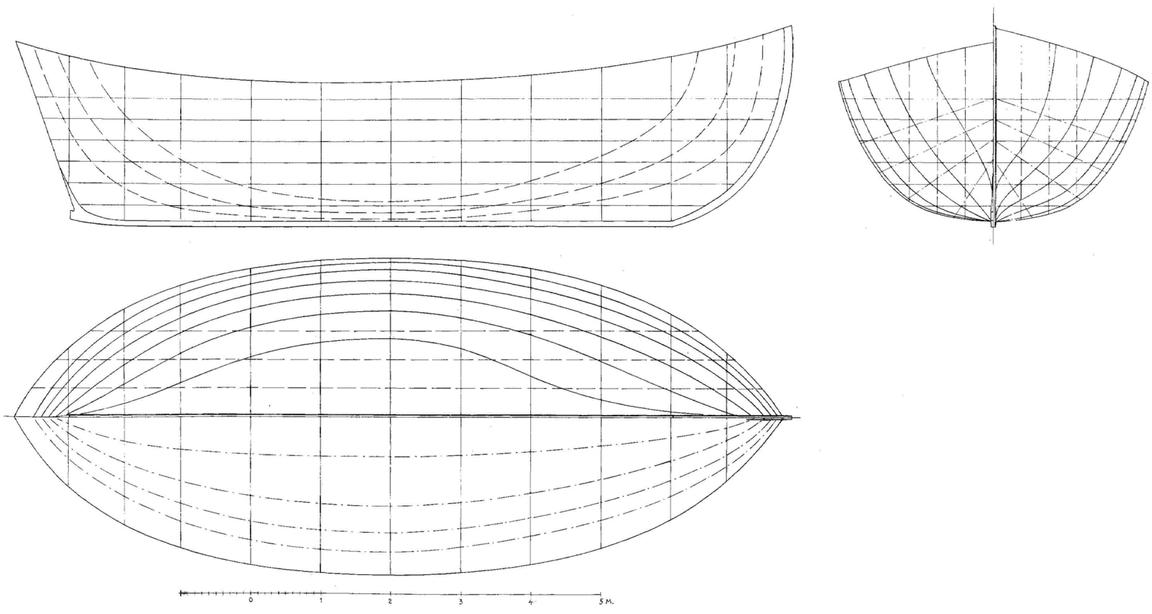


Pl. 8, b. *Fynd I.* Rekonstruktion av tvärsnittet vid mastspåret.



Pl. 8, c. *Fynd I.* Rekonstruktion av tvärsnittet e—e på pl. 4, c.

Figure 2-10 Kalmar 1 Reconstructed sections (after Åkerlund 1951)



Pl. 9. *Fynd I.* Linjeritning. Rekonstruktion.

Figure 2-11 Kalmar 1 Lines plan drawings (after Åkerlund 1951)

Åkerlund (1951:39–40) noted the strangest construction detail in the small ship is the protruding beam heads which had not been found in any previous finds[2], and states

> "this is apparently only because earlier finds from the Middle Ages have been retained to such a small extent as two more medieval vessels among the [Kalmar] finds also contains such through hull beams."

This reconstruction process would appear to be based on the scale drawings used for the creation of a scale model. As well as describing significant or unusual features, a general overall impression of the vessel is given. The site survey drawings clearly depict the material as-discovered, rather than the interpreted 'torso/as-found' versions subsequently recommended by McGrail and Crumlin-Pedersen (2006:57). The reconstructed vessel does not appear to have been subjected to any form of hydrostatic analysis.

[2] In the 1951 publication Åkerlund also stated that he was aware of a similar through hull beam being discovered at Koldingfjord in 1943, as well as a similar beam discovered as part of the Bursledon ship find, and another from the excavation at Skanör 1907-09 which was nearly 6m long, and due to the angle of the plank rebates did not come from the widest part of the ship, therefore suggesting a large ship of at least 7m width.

2.4.2 Ferriby prehistoric, sewn plank boats 1937

For a more detailed discussion see Appendix C.2:31-37.

The Wright brothers began to record the first of the Ferriby prehistoric, sewn plank boats that they had found on the northern foreshore of the Humber estuary in 1937. The initial find consisted of three planks which were photographed and carefully measured, before being reburied. Excavated again in 1939, and examined in more detail, the boat was described as being made of oak planks set edge to edge and the seams caulked with moss, covered with thin battens of oak (Figure 2-12), with yew withes sewing the planks and batten together (Wright and Wright 1939; 1947).

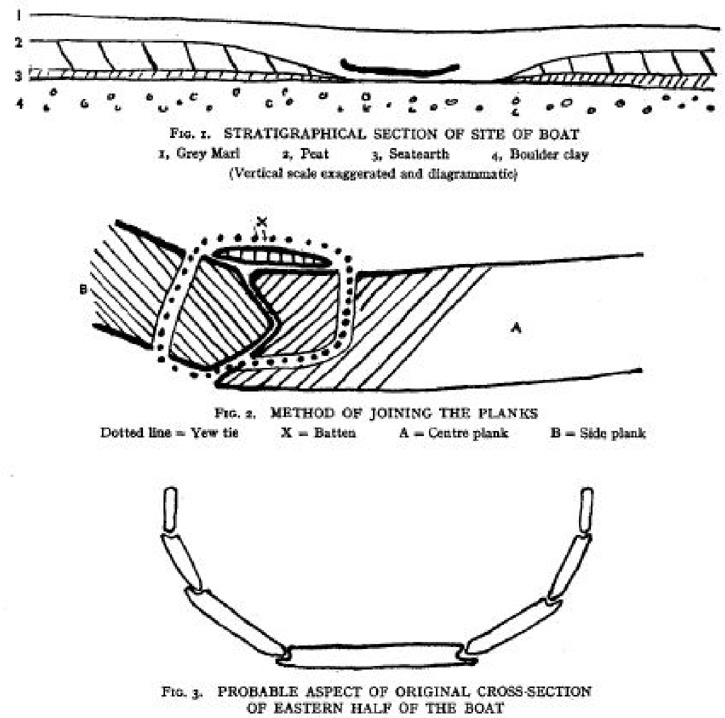


Figure 2-12 Ferriby 1 sewn boat (after Wright 1939)

Further excavations in 1946 revealed more details of the original vessel and uncovered the keel portion of a second boat labelled Ferriby 2. A drawing of (presumably) the surviving excavated material is included in the 1947 report (Figure 2-13)

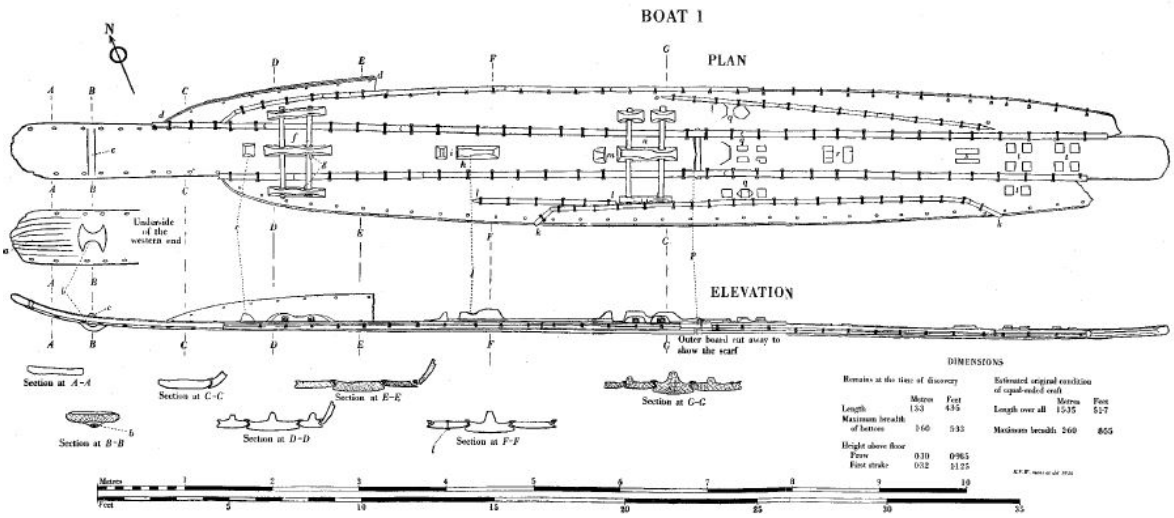


Figure 2-13 Ferriby 1 Excavated remains (after Wright 1947)

For the reconstruction Wright states that Ferriby 2 adds little information and focusses mainly on Ferriby 1. Wright made the first step towards reconstruction by assembling a 1/8 scale model of the excavated remains according to his records and the surviving remains. In this model the bottom planks were flat for most of their length as they lay in pieces on the concrete floor, apart from one end where the keel plank curved upwards over a length of about 2 m. During intermittent studies over many years, certain details of the original records were either forgotten, neglected or set aside. Between 1946 and 1988 at least five attempts were made on paper and by small scale models to reconstruct Ferriby 1, but all had difficulties with closing the ends of the hull, and none had sufficient depth to be useful in anything but calm water.

After consideration of alternatives together with John Coates (Wright 1990:85–116), Wright's preferred hypothesis for a reconstructed boat (Figure 2-14) consisted of: an equal-ended rockered bottom-structure composed of a keel strake and outer bottom-strake on each side; 3 strakes per side; up to 6 frames, secured to the side-strakes by lashing to cleats and to the sheer strakes by slotting rib-ends through vertical holes in rails moulded on their inner top edges (feature derived from Ferriby 4); and up to nine thwarts located at the level of the top edge of the second side-strakes, notched over the plank-edges and protruding to the outside of the hull with the lower edges of the sheer strakes cut away to accommodate ends of thwarts (feature derived from Ferriby 4).

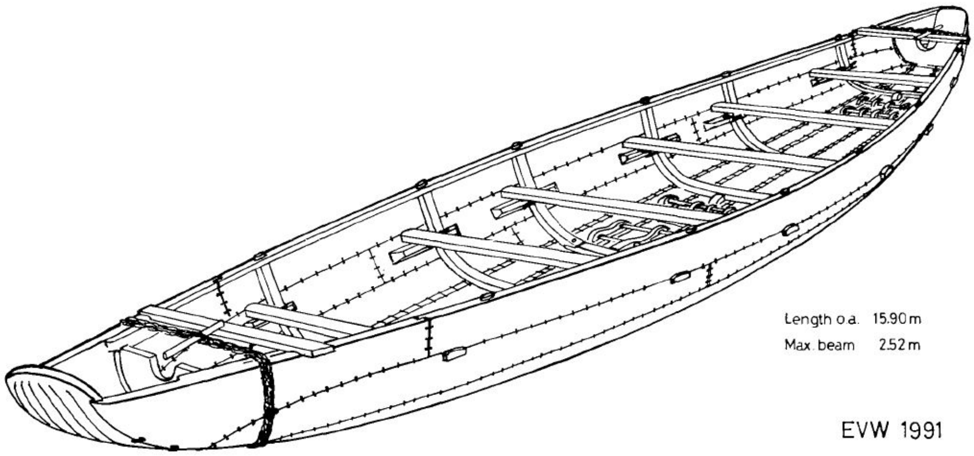


Figure 2-14 Hypothetical reconstruction of Ferriby 1 (after Wright 1994)

For this reconstruction it would appear to be based primarily on scale models constructed from the scale drawings and survey notes, albeit from at least two vessels[3] . The 'excavated remains' drawing is clearly an interpretation, devoid of the rocker which Wright states was present. While traditionally calculated basic hydrostatic coefficients and performance analysis were employed, uncertainty remains regarding the actual reconstructed hull form[4] and the vessels proposed sphere of operations[5].

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[3] Ferriby 4 was dated to circa 535-355 BC, at least 1,500 years later than Ferriby 1

[4] Crumlin- Pedersen noted that in the case of both the Ferriby and Dover boats there is considerable uncertainty about the shaping and height of the sides, the sheer of the hull, and the boat's rocker. He states that while Wright and Coates estimate the vessel to have been quite seaworthy, employed for navigation in the estuary as well as coastal cargo carrying and short open sea crossings, McGrail on the other hand favours Wright's initial flat-bottomed minimum reconstruction, which would make it a vessel suitable for a ferry used for river crossing in the Humber River where it was found (Crumlin-Pedersen and Trakadas 2003:213–14).

[5] Van de Noort states that while the debate has always centred around the assessment of seaworthiness of reconstructed vessels (see Coates in Wright 1990; McGrail 1981a; McGrail 1998a), the distribution of all known sewn plank boats of Bronze Age date such as at Kilnsea, Brigg, Caldicot and, most significantly, Dover are all in tidal rivers near estuaries or the coast (Appendix C.2 Figure 2.18). As such, Van de Noort states the assessment of seaworthiness may well be considered of limited value in terms of the late Neolithic Bronze Age exchange, and concludes that sewn plank boats were sea-going vessels, capable of carrying small cargoes, and reaching Continental Europe (Van De Noort *et al*. 1999:134–35). However, is it just a case that this is where the survival of remains is most likely – in the intertidal mud?

2.4.3 Yassi Ada 7th century AD Shipwreck 1961

For a more detailed discussion see Appendix C.3:38-43 and C.4:43.

The underwater documentation techniques developed during the Yassi Ada excavations were a revolutionary development which were led by George Bass from the University of Pennsylvania. It was decided that photography was probably the best way to document the site in order to make use of the limited bottom time and speed up the recording process. The artefacts and hull structure were then traced over and correctly scaled to repair issues such as parallax and refraction[6]. Steffy (1982:65) states the remains of the Yassi Ada ship were so sparsely preserved (Figure 2-15) that the exact construction sequence remains in doubt.

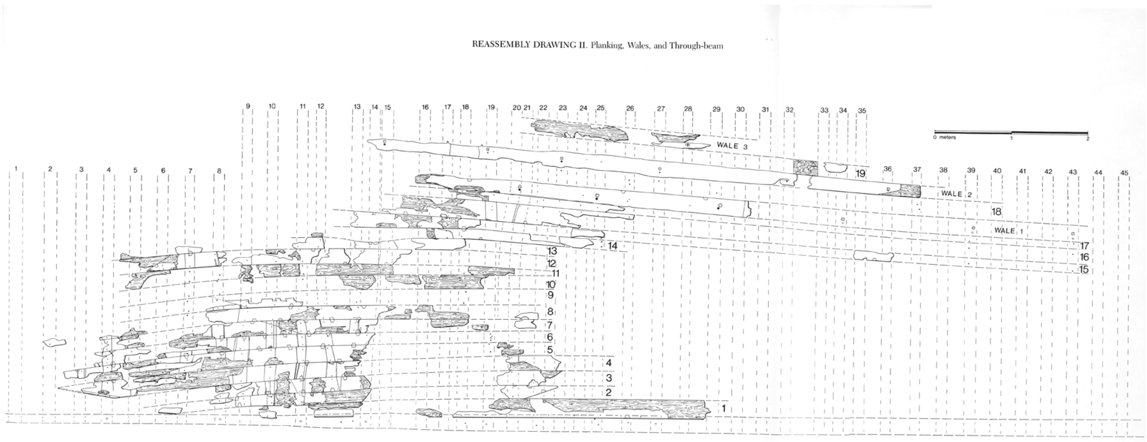

Figure 2-15 Yassi Ada Planking, wales and through hull beams (after Steffy 1982)

Experimentation with several models[7] and years of research allowed the application of the excavated material to a three-dimensional study which generally produced valuable disclosures and allowed the development of a set of lines[8] . Steffy (1982:65) states this was a tedious method, but the most accurate one which could be devised to satisfy such a small amount of excavated evidence.

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[6] The resulting site plans were compared to direct measurements taken from the site and found to be accurate (Bass 1975:96–106).

[7] 1:10 scale replicas of all the wood that had been recorded were made, with nail and bolt holes indicated. The strips were then bent to various shapes until the pieces of model planking were aligned with respect to the fastening holes. External and internal planking assemblies were next aligned to each other using known bolt holes and angles, these were then shimmed apart at the estimated 14 cm frame thickness and adjusted until the maximum amount of evidence was satisfied.

[8] The reconstruction of the 7th century merchantman is described by Steffy as largely hypothetical based on 10% of hull survival (Steffy 1994:80–81).

Hull section drawings were then created from the assembled partial model (Figure 2-16 left), allowing the creation of what Steffy labels a 'mould and batten' model[9] (Figure 2-16 right), and once the battens produced a satisfactory form in agreement with as much of the evidence as possible their positions were fixed, and a series of hull sections were measured in order to produce a set of drawings of the ship's lines[10].

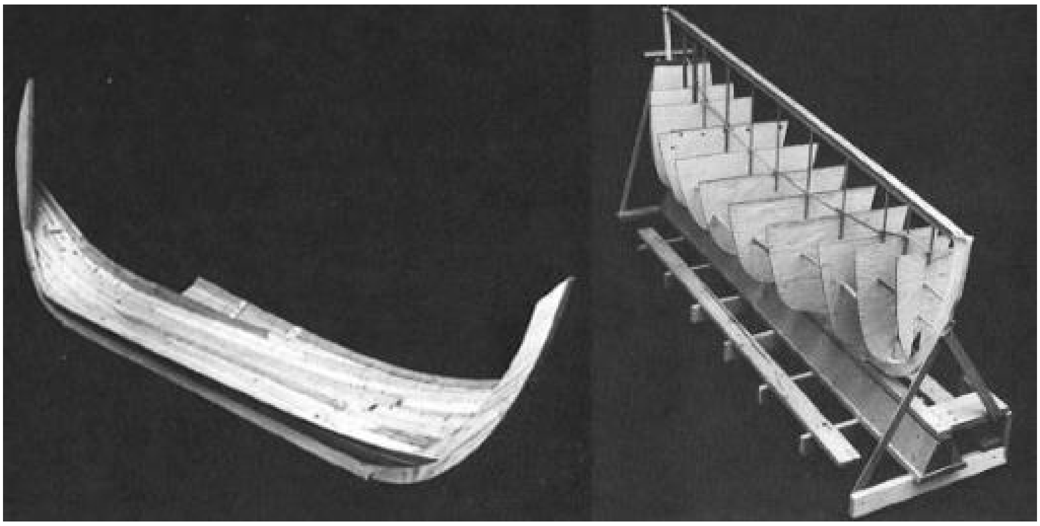

Figure 2-16 Yassi Ada Research model and 'Mould and Batten' model (after Steffy 1982)

Further highly detailed 1:10 scale models (Figure 2-17) were produced using additional information learned during the excavation of the *Pantano Longari* ship remains and the *Kyrenia* ship. Steffy (1982:66) states that new lines (Figure 2-18) and construction plans evolved based on this new information[11] as well as many countless hours of additional research and model building, and while the bow area remains conjectural, there is at least a basis of fact for it.

[9] This involves the creation of moulds of the hull section shape, generated from the hull section drawings, which are placed at their assigned locations along the keel. Battens (thin strips of wood longer than anticipated length of the hull) are then laid along the edges of the moulds. All moulds are then trimmed or shimmed to produce a fair batten curve, extended to meet the stem and stern.

[10] Steffy (1982:66) notes that these published lines drawings were largely correct for the area of the ship below the waterline, but they were not satisfactory in the bow and stern area above the water.

[11] The Pantano Longari is dated to the 7th century AD (Throckmorton and Throckmorton 1973:262), while Kyrenia is dated to the 4th century BC (Steffy 1985), with a span of 1,000 years, how valid is the additional information learned?

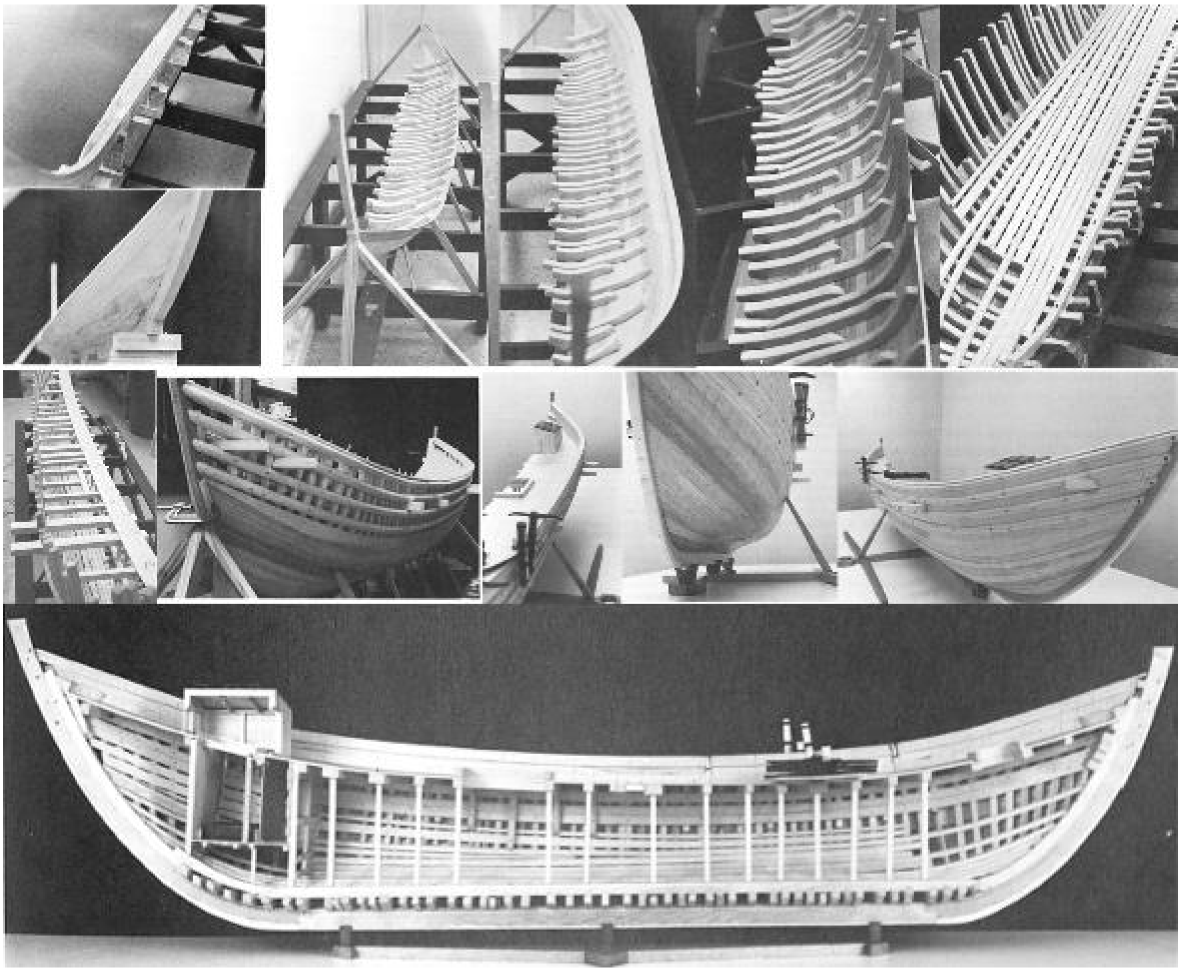

Figure 2-17 Yassi Ada additional research models (after Steffy 1982)

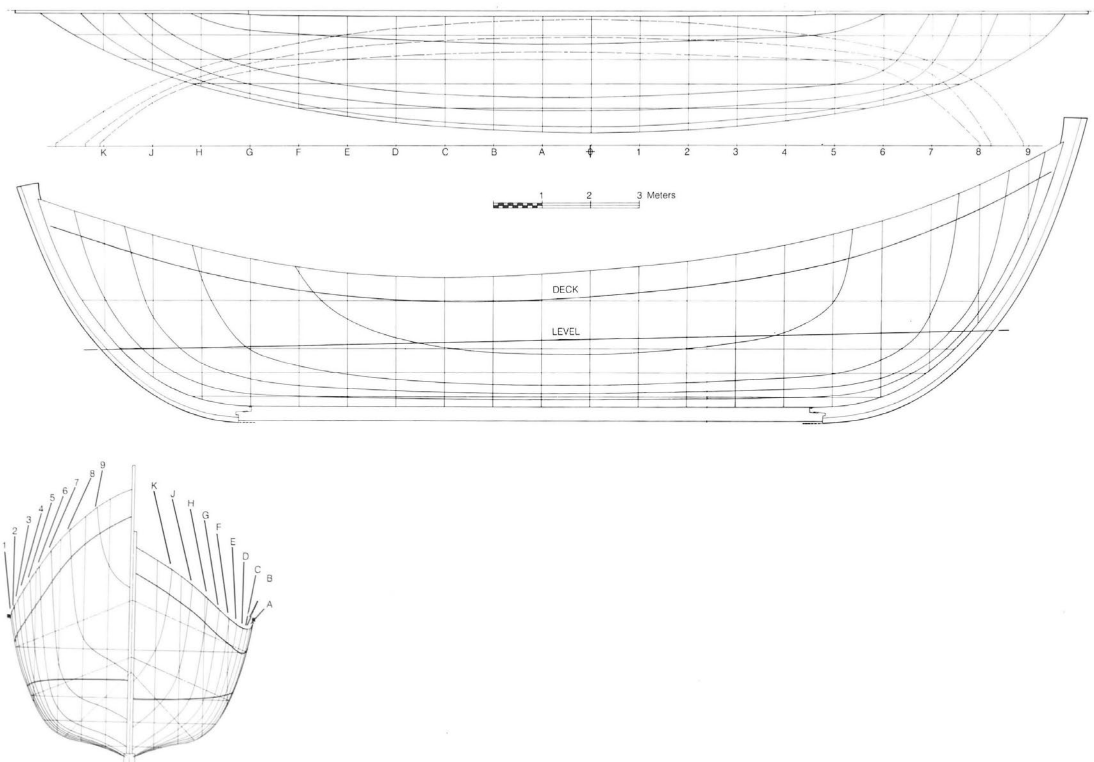

Figure 2-18 Yassi Ada lines plan (after Steffy 1982: Fig. 4.4)

For this reconstruction, the scaled site survey drawings were created from photography. Together with timber drawings (it is unclear whether these were scaled or full-size drawings), these were then used to create an initial scaled research model to determine the shapes of the surviving planks. Subsequent models were created to develop the hull shape. With further detailed models employed to develop additional features. The reconstruction process would appear to be based primarily on scale models which are adjusted or modified until a satisfactory result is achieved, somewhat akin to a trial and error process.

The resulting methodology makes it difficult to document alterations made during the reconstruction process. Tonnage formulas and calculated displacement were used as a means to validate the resulting reconstruction, however as noted by Steffy, Yassi Ada and Kyrenia had a similar heavy afterbody and fine bow. A critical observer might be forgiven for asking if there was really no change in 1,000 years of hull form development, or is this a result of two reconstructions by the same individual?

2.4.4 Skuldelev Vessels 1962

For a more detailed discussion see Appendix C.5:44-53.

Discovered in 1958, the remains of five 11th century Viking ships[12] were located, recorded and excavated from a site in Roskilde fjord, Denmark (see Johnstone 1969; Crumlin-Pedersen and Olsen 2002). Following the construction of a coffer dam and the pumping out of the water, the visible remains were documented and removed. The delicate and fragmentary nature of the wrecks (Figure 2-19), as well as the sheer volume of material meant a detailed survey using traditional methods with grid lines and drawings would have been exceedingly difficult and time consuming. The waterlogged hull timbers were documented in-situ using stereo photogrammetry, which was later used to create 2D in-situ site plans of the excavated vessels[13] (Crumlin-Pedersen 2002a:51).

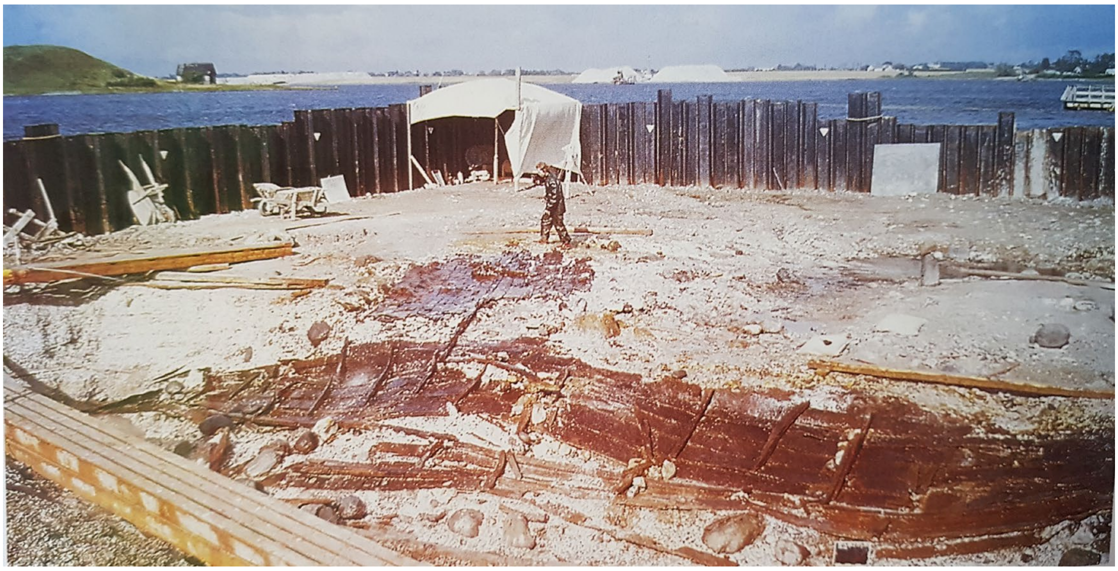

Figure 2-19 Skuldelev 5 wreck uncovered (after Olsen and Crumlin-Pedersen 2002)

In a change to earlier approaches where the vessel was recorded as a complete object, Crumlin-Pedersen, with his naval engineering background believed that it was possible to collect enough data from the individual ship timbers to recreate the original hull form, and was also seen as

[12] Initially thought to be 6 wrecks, wreck 4 turned out to be a few coherent strakes about 20 m away from wreck 3, but actually belonged to wreck 2. For simplicity the numbering system wreck 1 – 6 was retained, with wreck 4 becoming amalgamated into wreck 2.

[13] The work of creating the site plans took place sometime after the excavations, and as no independent control points were taken in the field, the accuracy of the recordings could not be verified. However, controlling the site plans against the actual ship timbers showed the accuracy of the photogrammetrical survey equalled that of traditional methods. The delay in processing the plans also meant it was not possible to check if all parts of the site had been photographed, or whether the photographs matched the strict requirements of the photogrammetrical method (Crumlin-Pedersen 2002a:51–2).

critical to understanding the design and shape of the original hull form as well as probable construction sequence. The individual ship timbers were cleaned and documented using 'elevated plane tracing'[14] (Figure 2-20)

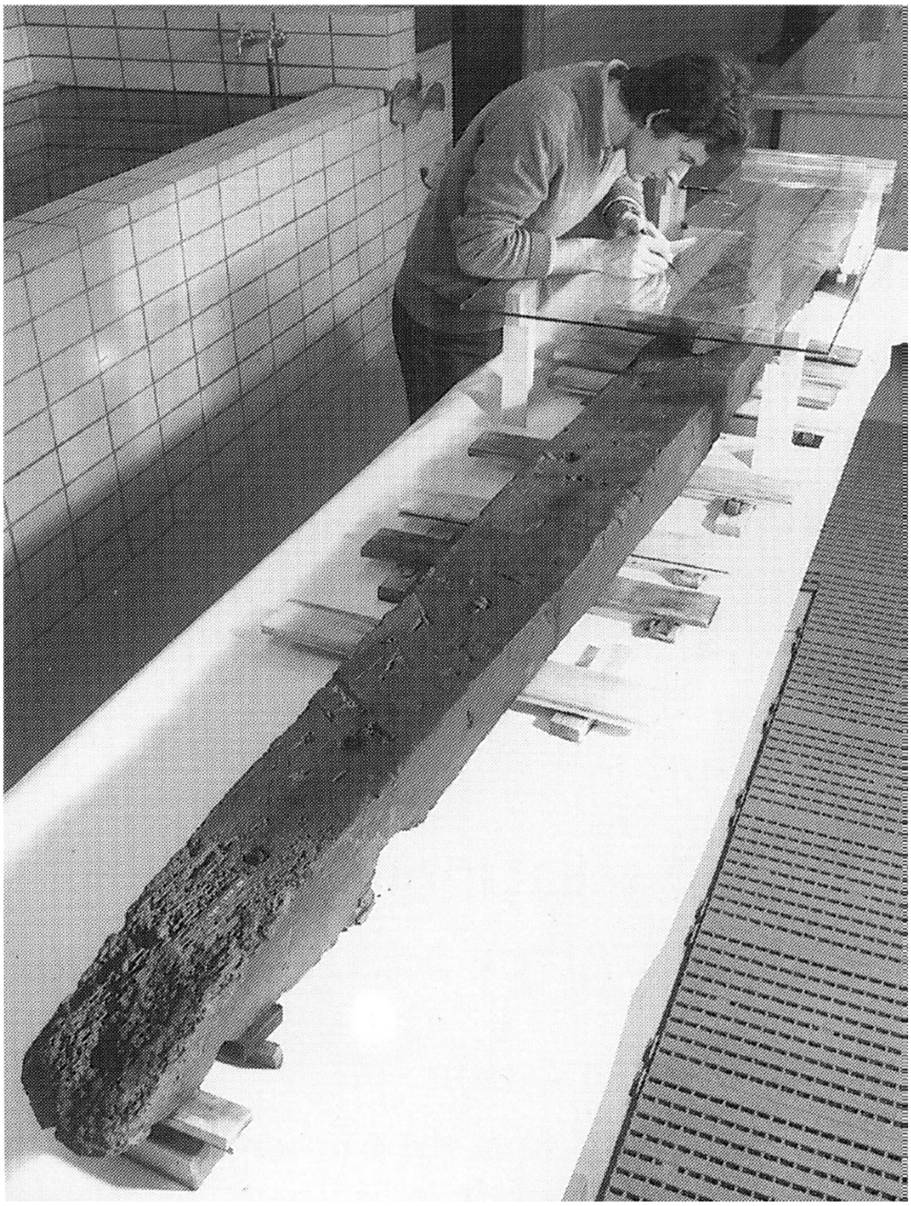

Figure 2-20 Elevated plane tracing (after Crumlin-Pedersen 1997:74)

Since the technique was developed, several kilometres of drawings have been used as patterns for the reassembly of ships as well as controls for conservation (Crumlin-Pedersen 2002a:54). These full-scale drawings (Figure 2-21) are subsequently reduced to 1:10 scale drawings using photography or computer scanning for use in the ship's timbers catalogue.

[14] The process involved a transparent sheet of drafting film supported on a glass plate suspended above the individual ship timber. The features to be recorded were then projected onto the drafting film, and with some training, the reflecting surface of the folio could be used to indicate when the feature being recorded, the tip of the pen and the mirrored reflection of the draftsman's eye were merging, showing that the projection was perpendicular to the glass plate – See Appendix C.5:45-47 for further details.

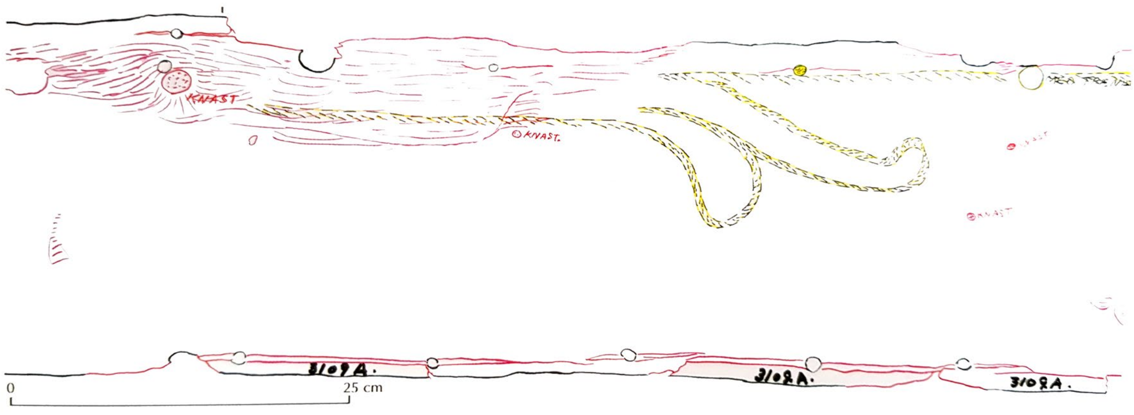

Figure 2-21 Example of full-scale drawing of a section of Skuldelev 5 plank (after Crumlin-Pedersen 2002)

However, Crumlin-Pedersen (1977:168–173) notes that for curved timbers the accuracy was not as high and other methods had to be used, but experience from using this documentation technique, first developed in the 1960’s is very good[15].

The ships were restored as museum exhibits between 1968 and 1993. The exact shape and form of each hull was not known when the restoration commenced as the 1:10 scale drawings and models were still under construction at the model workshop, and moulds based on the full-scale drawings were used in a trial-and-error basis by the restoration team. Skuldelev 1 was the first ship to be restored as a museum exhibit in 1968-9. Decisions had to made at an early stage during the reconstructions, and some of the assumptions made during the early stages turned out to be incorrect and led in some cases to somewhat dubious appearances of the ships in the museum[16].

For the three-dimensional representation of each ship at 1:10 scale, the plank and frame elements were traced onto cardboard or wood and cut out. The holes for rivets and treenails were used as a key in positioning each element in relation to the next leading to the construction of working models in cardboard or wood, as well as scale models at 1:20 and 1:10 for museum exhibits (Figure 2-22).

[15] Crumlin-Pedersen states that recording in full scale is usually considerably more accurate than with scaled drawings. The full-size tracing of edges, holes and other features leaves no room for false readings and imprecise plotting. The traditional method of manual recording and scaled drawing, based on measured coordinates of a limited number of points, and completing the outline between those points by eye, does not eliminate errors to the same degree (Crumlin-Pedersen *et al*. 2002:53–54)

[16] An error with the planking for Skuldelev 1 being left to fall outboard too much meant the internal knees did not fit. By the time the error was realised it was not possible to repair or alter the hull shape, meaning the bow area of this ship is not a genuine reflection of its original appearance (Crumlin-Pedersen 2002b:95).

Figure 2-22 Skuldelev 1 museum exhibit model (after Crumlin-Pedersen 2002)

Once a satisfactory model had been achieved the lines were recorded and drawn as an 'inner-edge lines-plan'[17] (Figure 2-23),

[17] An inner-edge lines-plan is a tracing all of the inboard upper edges of each strake as well as the external outline of the keel. According to Crumlin-Pedersen this 'inner-edge lines-plan' provided a very reliable representation of the original shape of the ship before it was scuttled, as the well-preserved port planking and internal timbers leaves practically no room for variation in its shape or size.

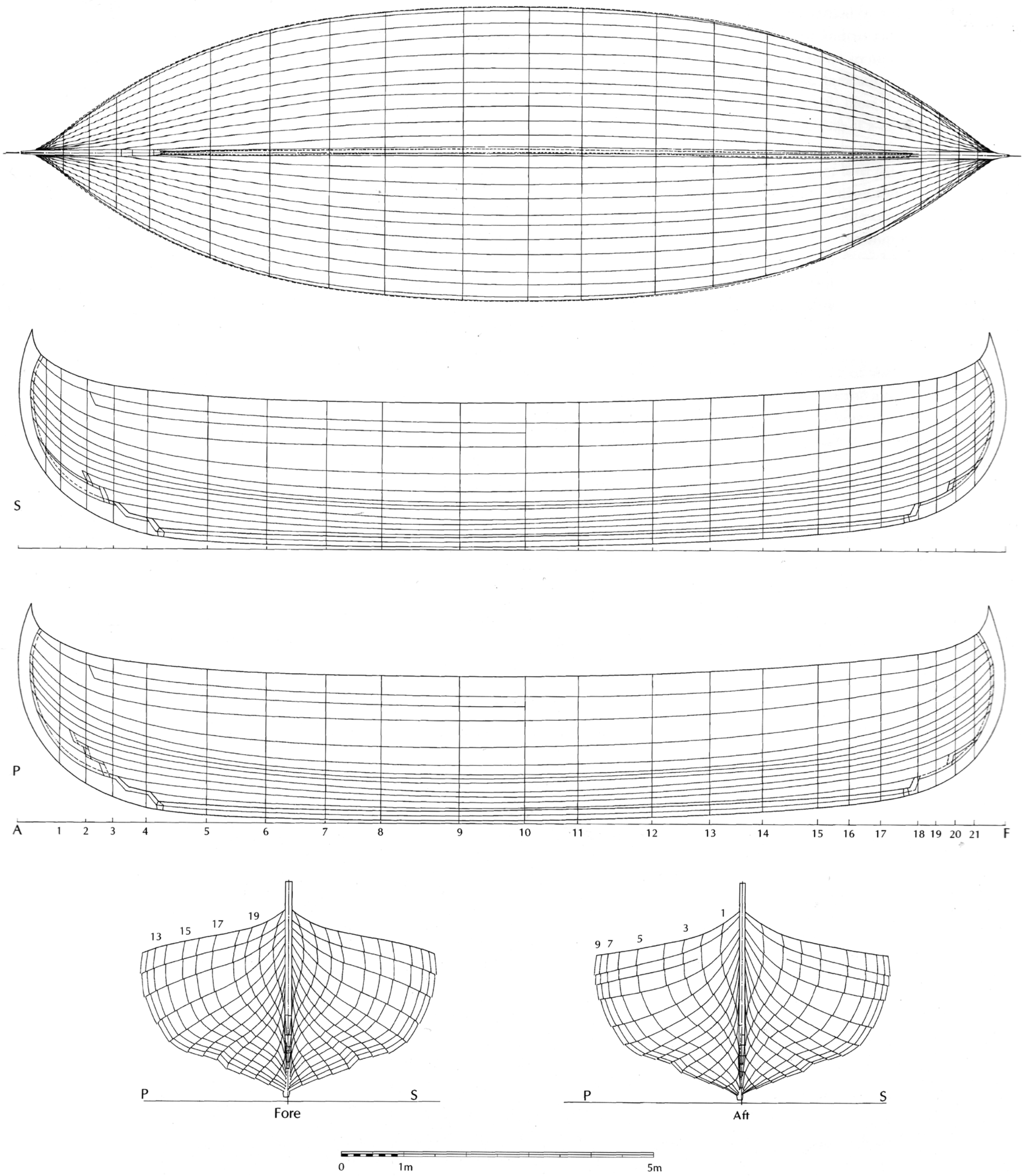

Figure 2-23 'Inner-Edge Lines-Plan' of Skuldelev 1 (after Crumlin-Pedersen 2002)

This 'inner-edge lines-plan' is then used as the basis for the creation of a 'torso drawing'[18] (Figure 2-24). Further analysis work allowed the creation of additional drawings such as the distribution of wood species (Figure 2-25), repairs and or alterations to the original hull.

[18] A torso drawing is described as a drawing of all the recovered parts for which the original position in the ship could be identified (Crumlin-Pedersen 2002c:125).

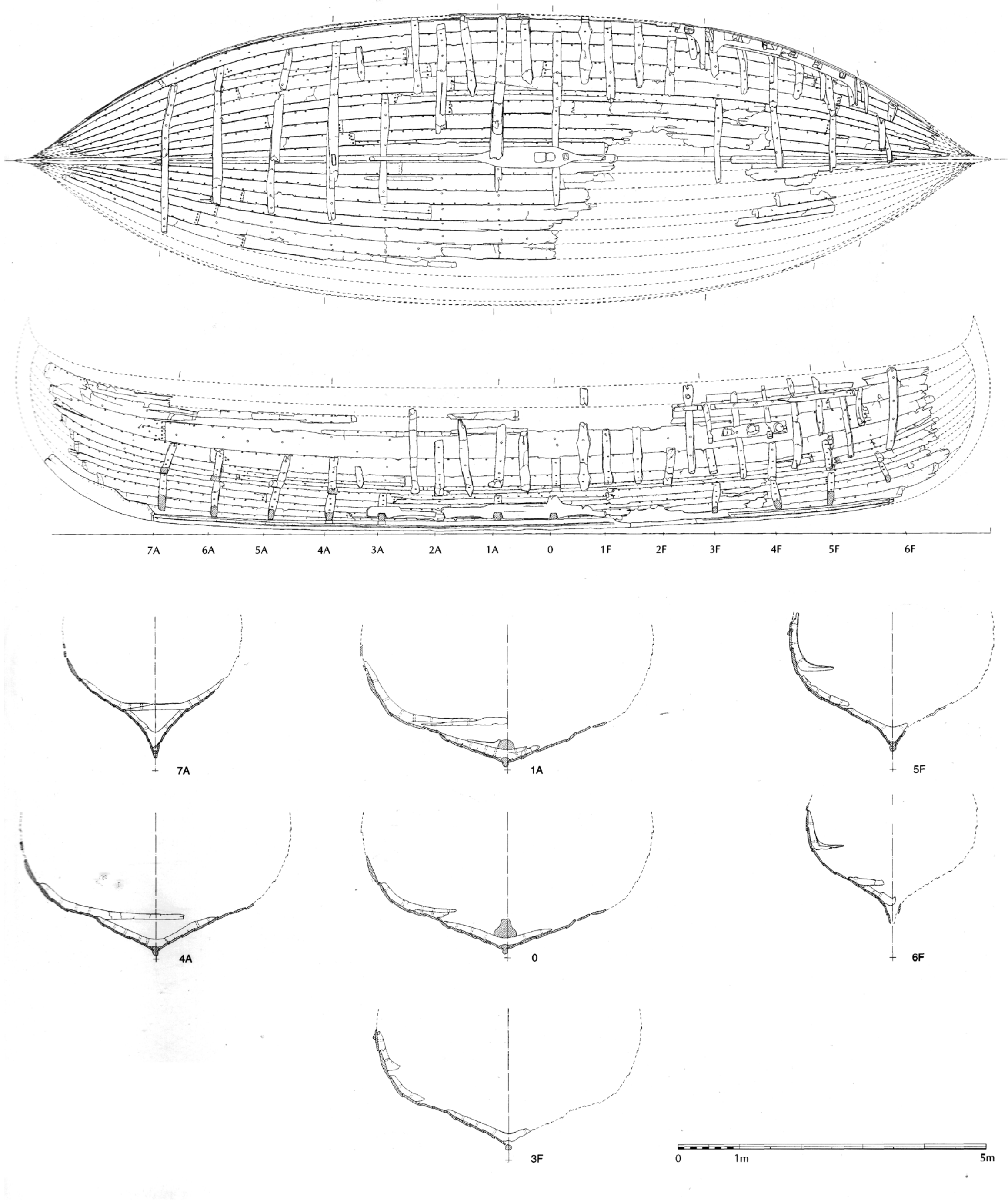

Figure 2-24 Skuldelev 1 'torso' drawing (after Crumlin-Pedersen 2002)

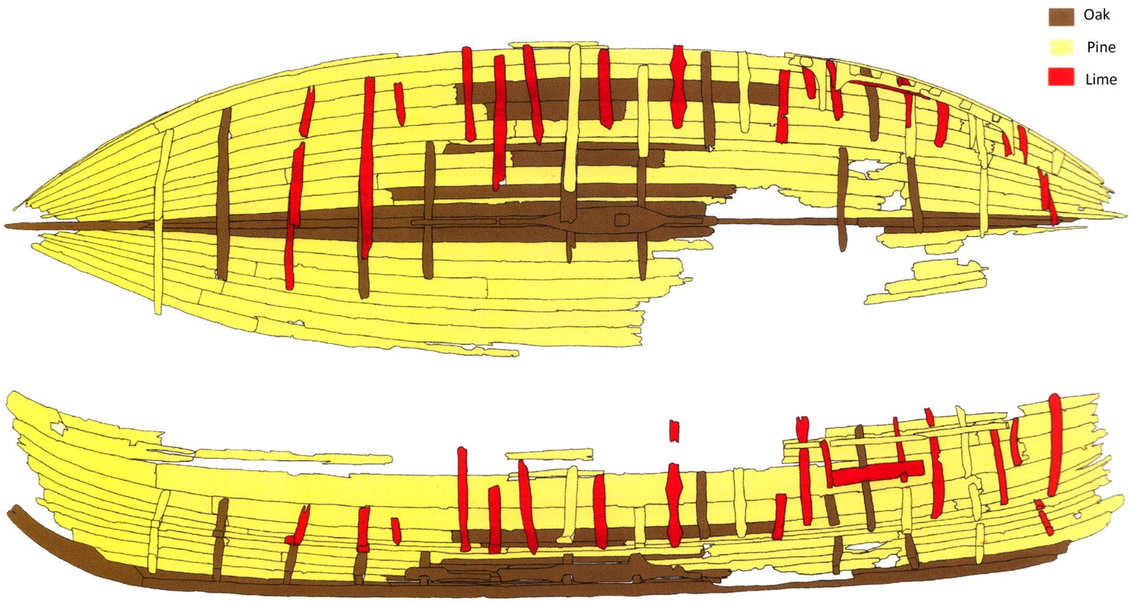

Figure 2-25 Skuldelev 1 wood species distribution (after Crumlin-Pedersen 2002)

Throughout the publication *The Skuldelev ships I: topography, archaeology, history, conservation and display*, the authors mention references to 'The Skuldelev Ships Volume II' which discusses the models and replica constructions in further detail[19], however, this second volume remains unpublished.

The Skuldelev process created scaled site plan drawings from photogrammetry, while the ship timbers were documented using full-scale elevated plane tracing. All the Skuldelev ships were reassembled for public display prior to detailed hull reconstruction or analysis. The full-scale drawings were reduced to 1:10 scale and cut-out from cardboard stock as flat two-dimensional planks, where damaged or distorted planks were repaired prior to being re-shaped to create the perceived three-dimensional hull form. The subsequent 1:10 scale reconstructed model was then documented and drawn as the scaled 'inner-edge lines plan'. From this a 'torso drawing' was created representing the original timbers with displaced elements repaired or repositioned. Static hydrostatic calculations were completed using proprietary software to determine hull form coefficients and displacements. Scaled display models for the museum are then constructed followed by a full-scale replica, at times requiring alterations (full-scale trial and error) due to the differences between model cardboard and real timber[20].

[19] Mc Grail was never certain how Crumlin-Pedersen and his Roskilde associates transformed their Skuldelev reconstruction drawings into full scale vessels, since his boatbuilders used traditional Viking Age boat-building methods such as 'by eye and using rules of thumb'. A year before Crumlin-Pedersen died, he told Mc Grail he would deal with that matter in his Skuldelev II volume, but he never completed it (S. McGrail 2015, pers. comm., 29 Jan.).
[20] Drawings sometimes have to be altered due to the fact that oak planks do not behave in exactly the same way as the material used in the scale model (Ravn *et al*. 2013:239).

2.4.5 Kyrenia Ship 1968-69

For a more detailed discussion see Appendix C.6:54-59.

Excavated in 1968-69 under the direction of Michael Katzev, the 4th century BC *Kyrenia* ship included a cargo of approximately 400 amphorae belonging to more than 8 different types. The well-preserved wooden hull[21], which had been sheathed in lead, consisted of nearly 6,000 wooden fragments in an area of circa 6 x 12 m (Figure 2-26).

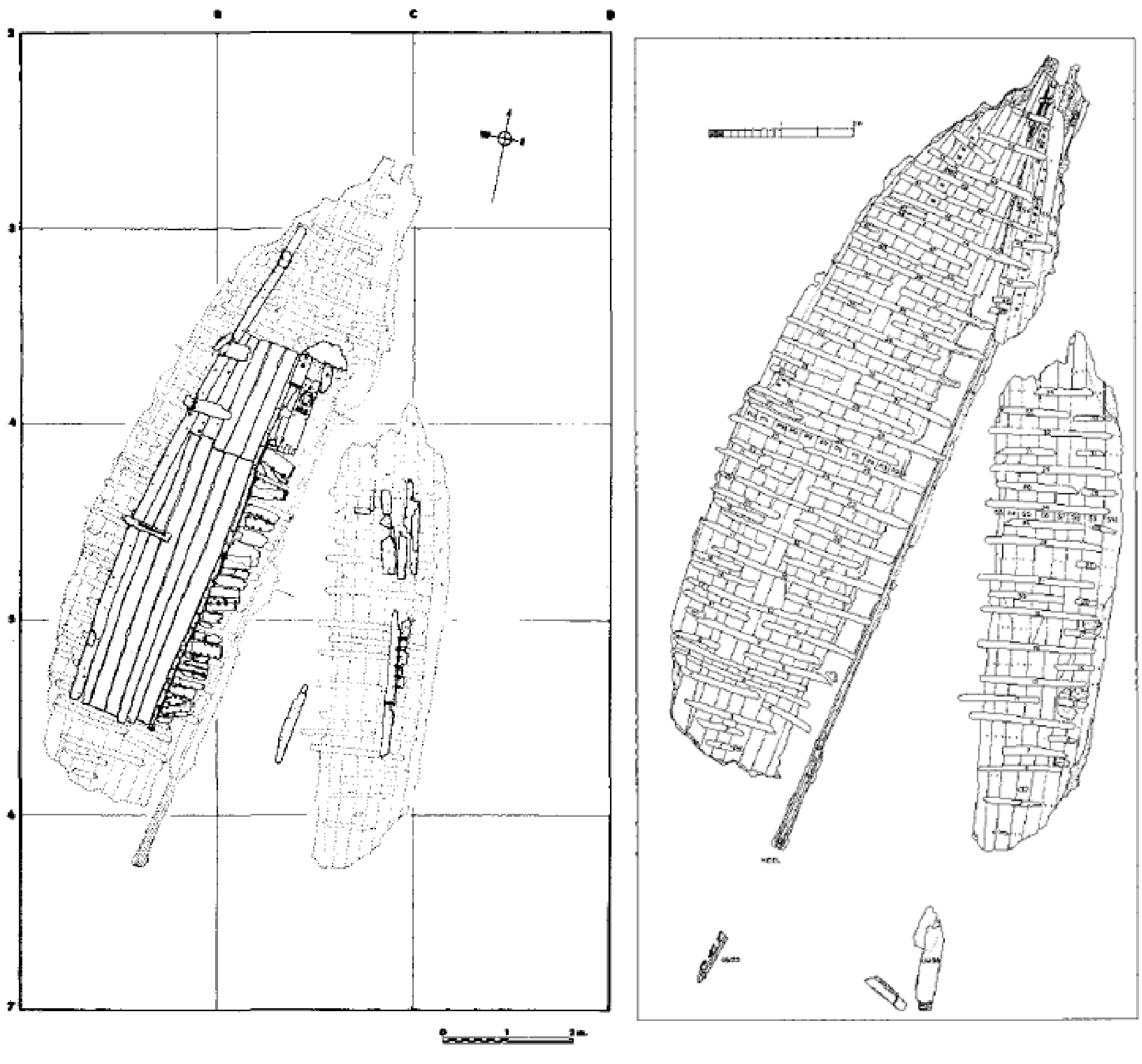

Figure 2-26 Kyrenia site plan (after Steffy 1985)

[21] Steffy estimated that nearly 60% of the hull survived including rigging artefacts, a steering oar blade and scattered fragments of fastenings providing additional information about the portion of the ship which had disappeared (Steffy 1985:72–74).

As noted by Steffy (1989:250) it is not possible to replicate an ancient ship, or even draw its hull lines, by directly reproducing what is seen on a shipwreck. That vessel has been distorted and flattened into the seabed, some of the timbers being bent or cracked to shapes and sizes which contradict their original true characteristics[22]. A dimension which can add to the study of ship construction and handling which overrides some of these shortcomings is what Steffy calls three-dimensional research, a form of experimental archaeology utilising models, mock-ups, replicas of individual components, fragment assemblies, and other physical devices designed to solve problems.

During the reconstruction of the *Kyrenia* ship a total of 18 such research models were employed, ranging from a working model of the mast step to a full scale two-meter long replica of the hull's midship section. Some were as simple as a single plank scarph, while others duplicated every joint, nail and curvature in the original hull. The final remains assembly (Figure 2-27) and full-scale replica (Figure 2-29) being the latest and most elaborate of these three-dimensional research models, all of which have the potential for probing subject areas which graphic and archival research cannot satisfy.

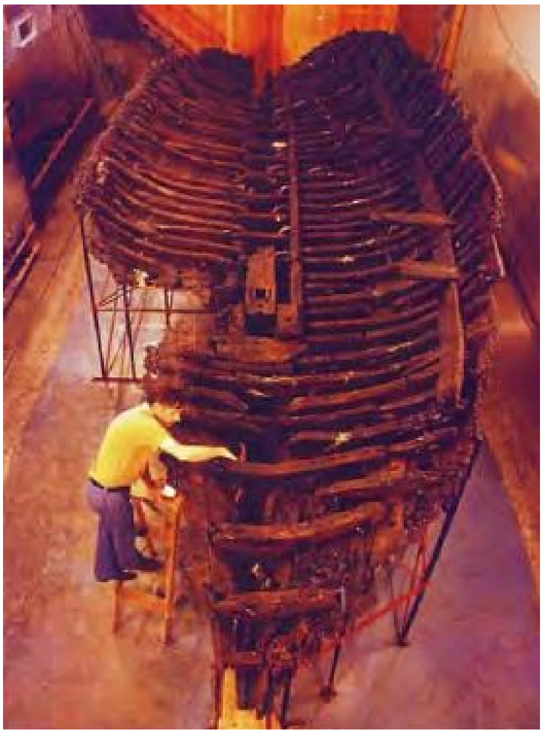

Figure 2-27 J. Richard Steffy reassembling the Kyrenia Ship (after Katzev 2008)

Steffy (1989:252) states:

"it would be unwise to attempt to reassemble the wreck remains without first learning something about the vessel's design and construction."[23]

[22] Steffy (1989:249) states that nautical archaeology through the medium of well-preserved shipwrecks often clarifies what could only be summarised before, but archaeology alone cannot supply all the answers. Some materials are so fragile that they are destroyed even by the most careful removal of overburden, some do not survive recording and conservation, and the greatest obstacle is that no shipwreck is completely preserved, there are gaps where nothing survives, topsides usually disappear, and distortion belies the original hull shape.

[23] In 1969 Skuldelev 1 had already been reassembled as a museum exhibit, prior to any research model or reconstruction work being completed, it is unclear if Steffy' s comments are related to the issues the Danes were having with reassembly, or whether it is his own common sense approach.

In all a total of five ‘mould and batten’ models were used to develop the final *Kyrenia* lines (Figure 2-28), and it took several years to arrive at what Steffy considered to be the most accurate set of lines possible. Steffy states that these ‘mould and batten’ models had been replaced by 1989 with computer generated graphics, and more complex details analysed with what he calls fragmentary models (Steffy 1989:253).

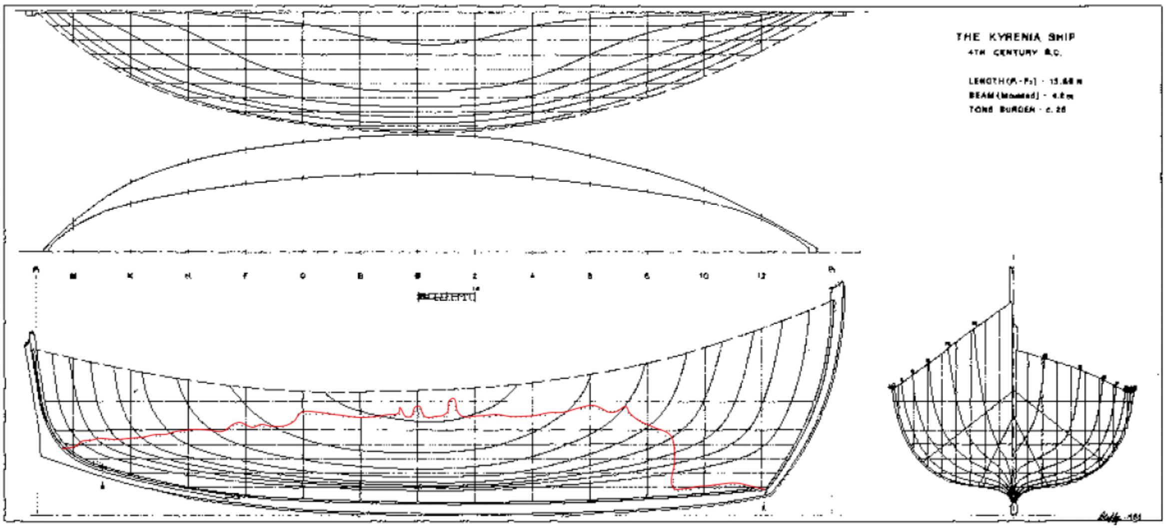

Figure 2-28 Kyrenia lines plan[24] (after Steffy 1985)

The final lines drawings (Figure 2-28) were the result of a combination of information sources, most of which was confirmed by the three-dimensional models[25].

[24] The extant remains were indicated as a dashed line by Steffy and have been highlighted in red for clarity by this author.

[25] On the subject of models Steffy (1989) states that the nature of their construction is such that one is forced to duplicate the original builder’s movements, thereby revealing original techniques and processes. Just like all other forms of investigation, the resultant value of research models is directly related to the faithfulness of reproduction and the extent of applied information. It cannot be expected to obtain reliable information from a replica if it is built from different materials or by different techniques than that of its prototype. Most importantly, these models are subject to the laws of physics and geometry, and thereby their conclusions can be proven (ibid: 249-50). By 1974 the reassembly of the *Kyrenia* wreck in Kyrenia castle provided most of the information for the full-scale replica *Kyrenia II* but some of the details had to be acquired from the models used to determine the hull design and construction. He concludes that three-dimensional models have weaknesses, they are time consuming, require a certain level of manual dexterity, and consequently are expensive to produce. While models should not replace two-dimensional graphic or archival studies, they were seen by Steffy as making significant contributions where results cannot be obtained by other means and as having an important niche in the study of shipwrecks.

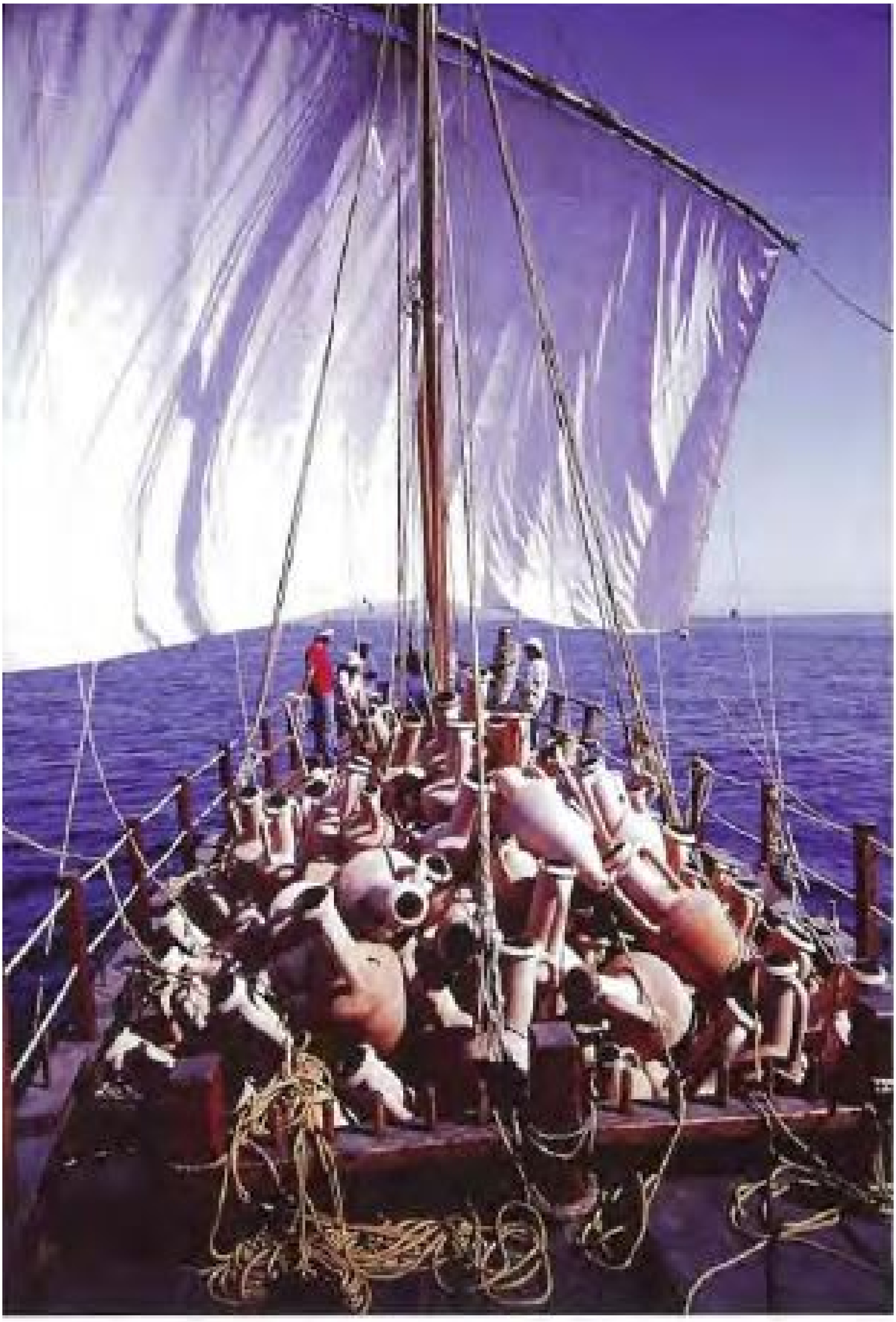

Figure 2-29 The Kyrenia replica loaded with Amphora (after Katzev 2008)

Steffy estimates the Kyrenia ship to have been 13.6 m long, 4.6 m wide and circa 25 tons burden.

As part of the ongoing research into the *Kyrenia* ship Suzan Katzev and Laina Swiny were investigating the cargo[26] within the ship (Figure 2-29). When the replica ship sailed from the old port of Limassol, she carried 12 metric tonnes[27]. Steffy had already added two extra strakes to what had been physically preserved of the hull's height. Both sailing replicas *Kyrenia II* and *Kyrenia Liberty* had proven extremely seaworthy while carrying circa 10 tons, but neither had sailed with the full 17 tons of cargo[28]. Had some evidence been overlooked? Perhaps the ancient hull had been higher still? (Katzev 2008:77–79).

The Kyrenia project initially used cargo distribution and seabed hull dispersal as well as a graphical two-dimensional site plan and the excavated timbers were drawn full-size. Then the project switched to three-dimensional research in the form of models. As timbers were excavated, they were photographed, and full-size drawings made. Simple models were used to study the hull form, crude models to provide answers needed to proceed, a full-size replica of the port bow section consisting of a suspected replacement strake with the so-called 'patch-tenons', 'mould and batten' models used to develop the final hull lines, and even the reassembly of the vessel for display to answer some outstanding issues. A total of 18 different models were employed, in what appear as a trial-and-error approach. The final lines drawings were the result of a combination of information sources, most of which was confirmed by the three-dimensional models. Tonnage formulas and calculated displacement were used as a means to validate the resulting reconstruction.

[26] In 2004 all 384 of the original amphorae in their various shape and size were replicated and used in experiments loading them onto a full-scale replica of the ship Three layers of amphorae were loaded with the smaller ones nestled on top at random angles. All of the upper level of amphorae were empty, and these were piled noticeably high. The sheer volume of jars excavated from the wreck were not fitting comfortably within the conjectured hull.

[27] 29 volcanic millstones found during the excavation weighed on average 57 kg each. The main cargo of 220 Rhodian amphora weigh 49 kg each. This equates to a total of 1,653 kg for the millstones and 10,780 kg for the 220 Rhodian amphorae giving a cargo weight of 12,433 kg (12.5 metric tonnes).

[28] The total cargo was estimated at 17 tons based on material found in the ship during excavation.

2.4.6 Graveney Boat 1970

For a more detailed discussion see Appendix C.7:60-68.

In 1970 this 10th century clinker-built boat, excavated under 'rescue' conditions from a north Kent tidal channel that flowed into the River Thames, was taken to Greenwich for study and conservation (Fenwick 1972). Described as a merchantman of circa 14 m long with a beam of 3.9 m. Much of the methodology used in documentation and reconstruction had its roots in the Skuldelev project, largely due to the influence of Crumlin-Pedersen who came over to help with the excavation. With only ten days to record and excavate the vessel, an enormous effort was made to record the ship in every detail. Closely measured (Figure 2-30) and, photographed, a plaster cast of the surviving hull shape was subsequently constructed before, the timbers were lifted, washed and re-photographed prior to packing and transport to the National Maritime Museum. The underlying principle (as in the Skuldelev project) being that even if the timbers could not be preserved, the recorded detail alone would be sufficient to enable a reconstruction (Fenwick 1978).

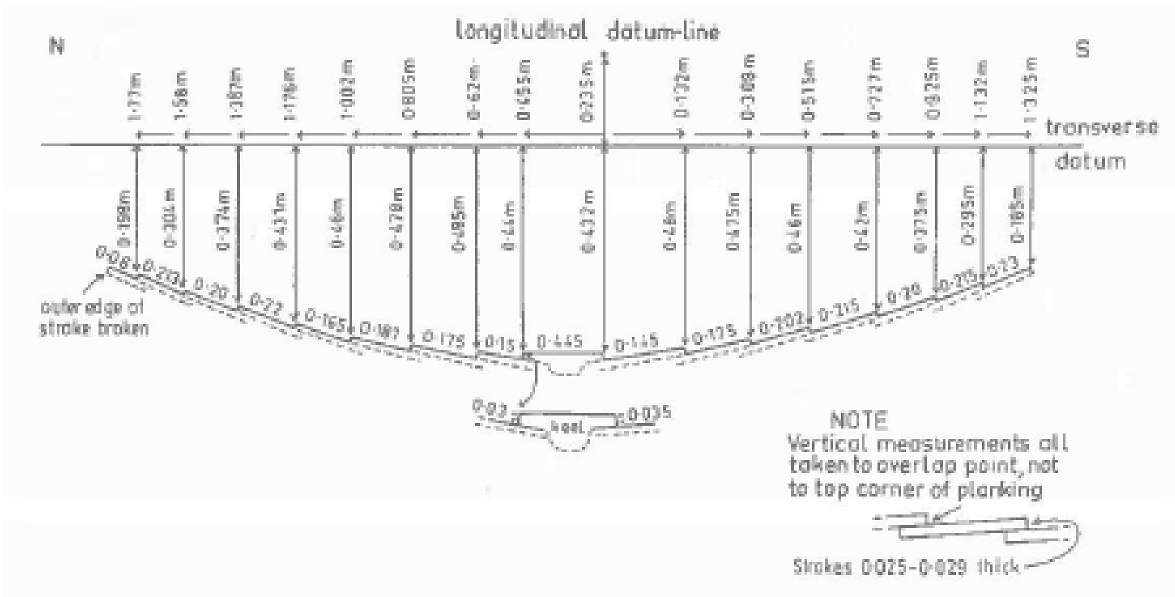

Figure 2-30 Graveney boat site cross-section (after Fenwick 1978)

McKee as an experienced draftsman was well aware of the various issues when recording and subsequently representing a three-dimensional object using two-dimensional drafting techniques, and noted (1978a:35) that

> "A tracing is a development of a part's surface, while direct work on the grid table gives a projection of it."

McKee was aware that the *Skuldelev* 'elevated plane tracing method' also generated projected surface drawings of each timber, and developed a method of contact tracing to record each surface of the timber. Each timber was examined and measured using two approaches, the first measured the timber using a direct measurement system[29] (Figure 2-31 left). The second used the contact tracing method[30] (Figure 2-31 right). See Appendix C.7:61-63 for a detailed description of the issues and process.

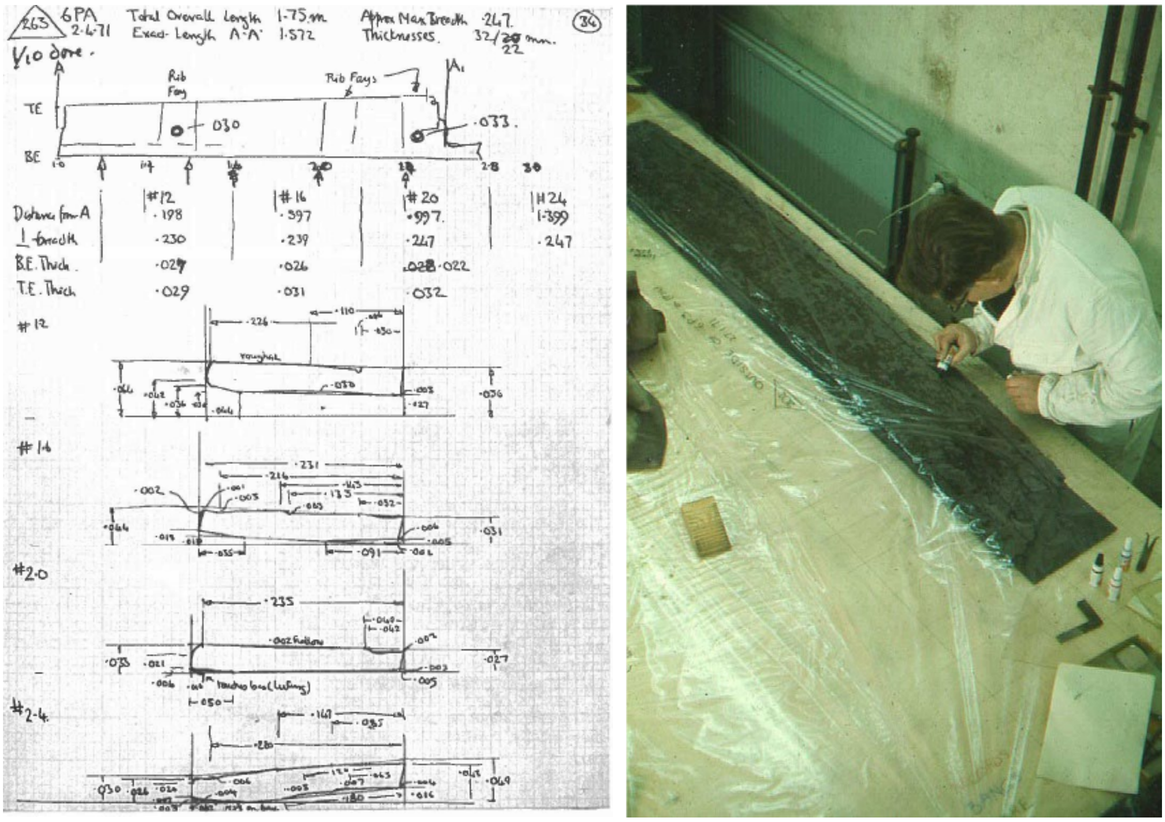

Figure 2-31 Page from McKee's 'Direct measurement book' left, and contact tracing method right.

For the reconstruction, an initial paper based (two-dimensional) attempt used the site plans, photographs and 1:10 scale drawings of the boat timbers. Neither of the two initial attempts could be demonstrated to be correct and these attempts were abandoned. Reconstructing a three-dimensional shape on paper, particularly when considering the shape of a boat, was considered too forbidding and liable to all sorts of errors[31] (McKee 1978b:265–6),

[29] Effectively, the timbers were recorded as a series of offsets from a baseline grid, an incredibly inefficient method even by 1970 standards, however it was more accurate than the available alternatives.

[30] The timber was covered with a film of polythene and felt-pens were then used to record the timber reference number, recording date, and to trace the features such as original edges, fastening holes and builders tool marks, with additional colours used to record damaged edges or wear marks or other material adhering to the timber surface

[31] The task of keeping track of changes on the sheer, body and half breadth plans together meant that all corrections involved simultaneous changes in all three planes.

The shell of a boat may adopt a number of different but related shapes (Figure 2-32) until one or more dimensions are fixed as is the case with partial shipwrecks. The sides will come together if the ends are forced apart, such as altering the rake of the stem or stern post, and if the rocker is increased the midship section will flatten[32].

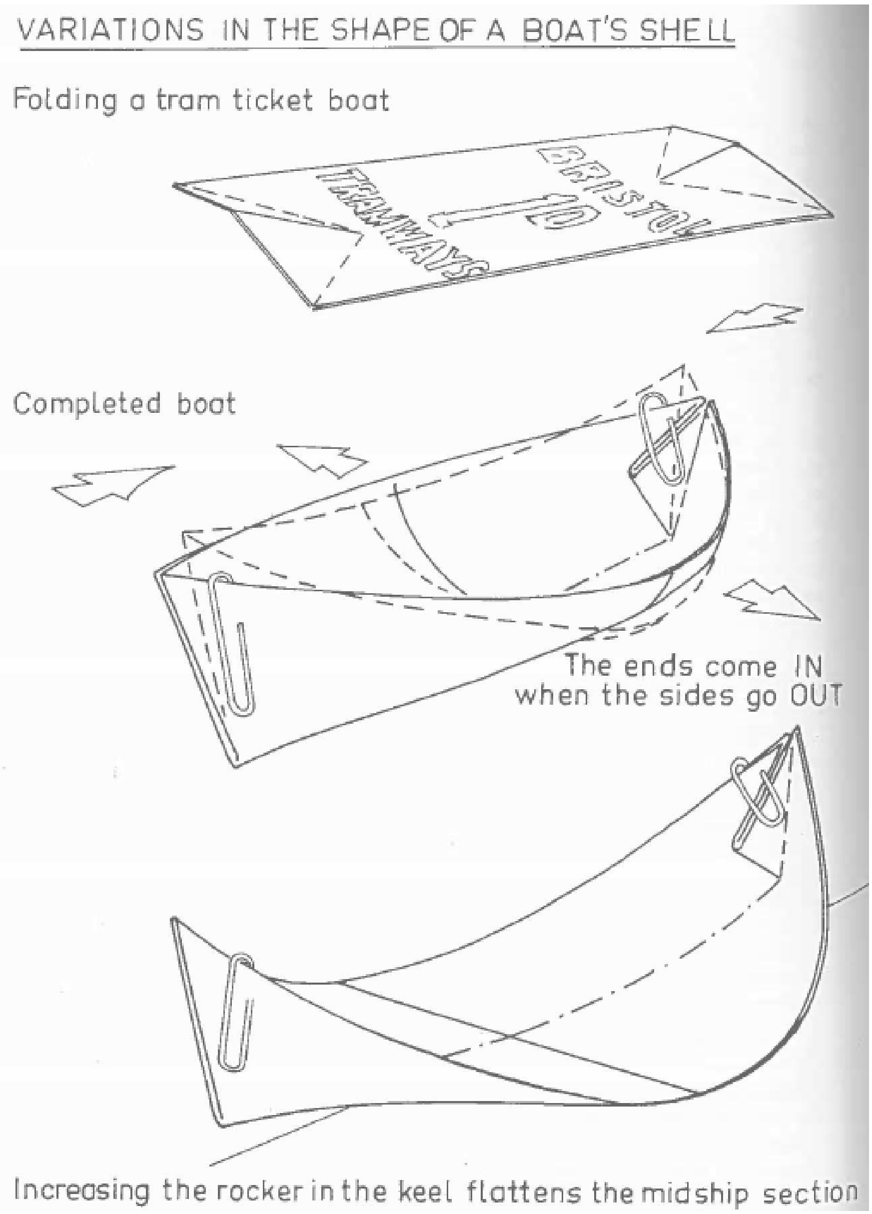

Figure 2-32 Variations in Shape of a boat's shell (after McKee in Fenwick 1978)

Three-dimensional model building was seen by McKee (1978b:267), as the obvious solution:

> "A model certainly met the requirements of flexibility, deferred decisions, and ease of correction. Even when it was well advanced, it worked like a three-dimensional pencil drawing, which could be easily modified when necessary. (Should a set of conventional drawings be required, the lines could be taken off in the usual way)."

[32] These are some of the issues with the original *Dronningen* replica of the Oseberg ship as identified by Oseberg project 2006 (Bischoff 2012:340)

Three separate models were constructed before a satisfactory result was achieved, see Appendix C.7: 65-68 for a detailed discussion of the various issues with each model. On the models, in order to distinguish what was real from what had been assumed, a colour code was used[33].

Evidence from the surviving material indicated a minimum of at least 8 strakes per side, boats with from eight to twelve strakes were drawn and their weight plotted on a displacement curve based on the underwater shape of the find. Eleven strakes were selected as the most likely number, as more than this would have given an excessive overall length in relation to the keel [34], even though McKee commented that the vessel looked like it could take more freeboard (ibid: 275-7). An alternative plum stem arrangement[35] which would not contradict any of the archaeological evidence is also illustrated by McKee (Figure 2-33). Instead a compromise between the minimum and maximum reconstructions was selected as the hypothetical reconstruction with eleven strakes per side (ibid: 285) despite the apparently low freeboard (Figure 2-34).

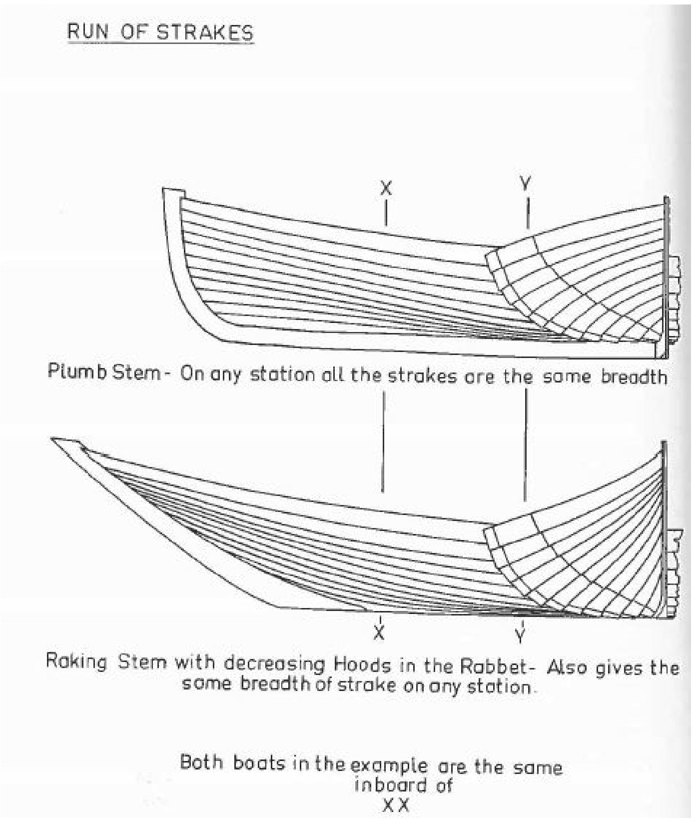

Figure 2-33 Alternative stem arrangements (after McKee in Fenwick 1978)

[33] Unfortunately, on all the published lines plan and construction plan drawings none of these colour coded identifiers were included, nor was the outline of the surviving remains indicated, making it difficult to discern factual from conjectural.
[34] The relationship between the overall length of the vessel and the number of strakes is not a normal consideration and is only caused in this situation with the assumption by McKee, that both posts extended as straight continuations of the angled 2.2 m length of surviving sternpost.
[35] If the plum stem or some version of it were used, additional strakes could be added to increase the seemingly low freeboard without and excessive increase to the overall length.

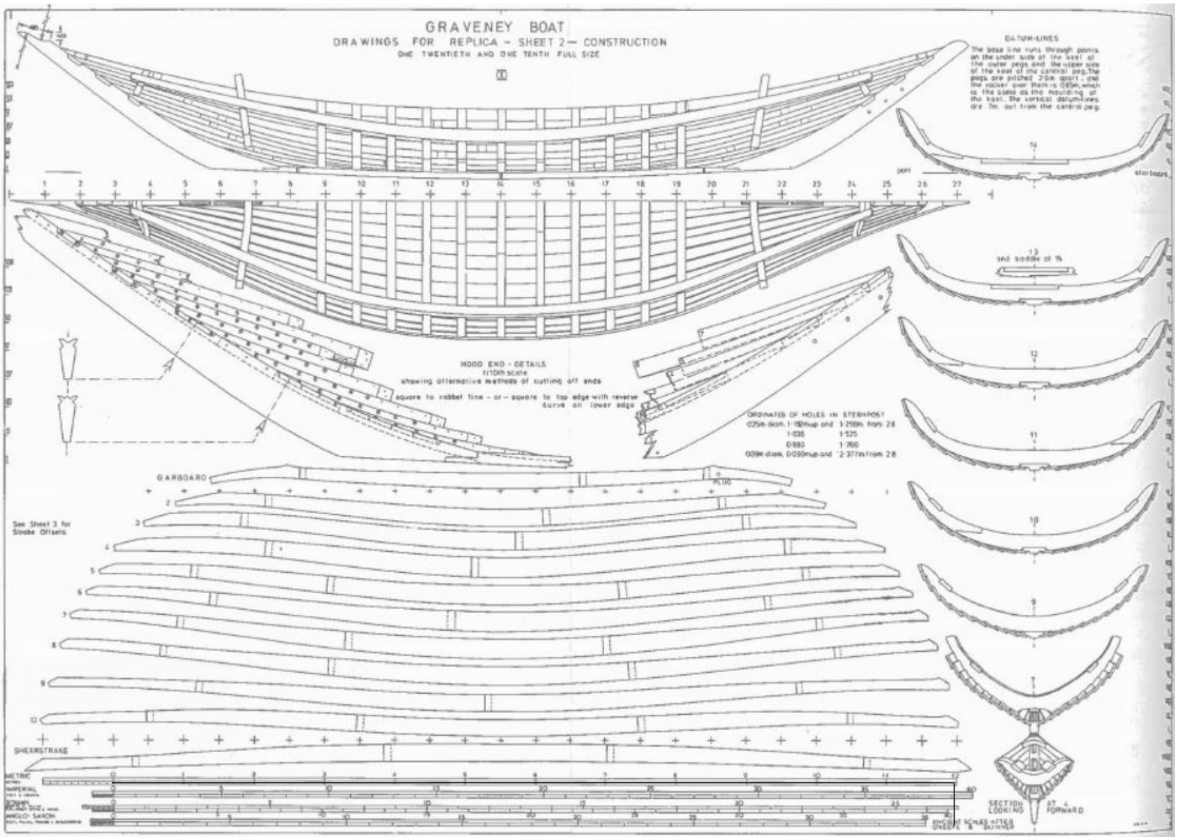

Figure 2-34 Construction drawings for Graveney replica (after McKee in Fenwick 1978)

Graveney site plan was documented using traditional measurements and offsets. Initial recording of individual timbers used offset measurements and scale drawings. This was supplemented with full-scale contact-tracing of the timbers. Full-scale drawings were subsequently redrawn to scale and cut-out to create two-dimensional cardboard models of each plank, which was reassembled into a scale three-dimensional model of the perceived hull form. Basic static stability and hydrostatic coefficients were calculated. Additionally, a half-scale replica was constructed by Gifford (1996) to analyse seakeeping qualities.

2.4.7 Serçe Limani 1977-79

For a more detailed discussion see Appendix C.8:69-70.

First discovered in the early 1970's, the 11th century site was not excavated until 1977 due to the outbreak of hostilities when Turkish forces invaded Cyprus in 1974. The underwater excavation techniques developed for other Mediterranean sites such as at *Yassi Ada* were employed**.** The fragmentary hull remains were documented using 1:1 elevated plane tracing, recording each side of every fragment. The individual timbers were also documented using photography with banks of lighting to illuminate features such as wood grain.

These tracings and photographs were used by Steffy to create a 1:10 scale diorama of the wreck site as it lay flattened on the seabed. Steffy then created physical 1:10 scale models of each timber fragment and used the nail holes to align the pieces to create a 1:10 scale model of the fragmentary hull remains, including additional elements such as anchor concretions and the rock outcropping which had added to the hull distortion. This was a new form of model devised for the *Serçe Limani* project, given the dubious name 'fragment model' and is essentially a three-dimensional expression of the revised wreck plan. The resulting three-dimensional site plan, Steffy claimed was infinitely better to work with than 2D drawings (Steffy 2004a:125).

For *Serçe Limani,* the scaled site survey drawings were created from photography as with *Yassi Ada*, and timbers were documented full-scale using elevated-plane tracing. Steffy again immediately switched to three-dimensional research, creating a site diorama model of the as found wreck. Various models were then used to develop the hull form and create reconstruction drawings (Figure 2-35). Tonnage formulas[36] and calculated displacement were used as a means to validate the resulting reconstruction.

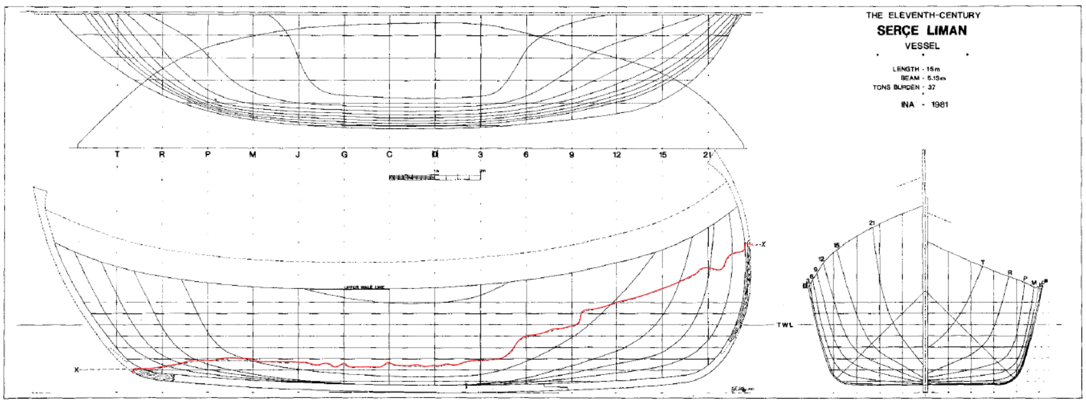

Figure 2-35 Serçe Limani lines plan the red line indicates extent of surviving remains (after Steffy 1982)

[36] There are some discrepancies in Steffy's quoted tonnage figures – See Appendix C.8:70 for details.

2.4.8 Grace Dieu 1980-85 -2005

For a more detailed discussion see Appendix C.9:71-75

An 1874 survey reported in The Graphic, dated 27th November 1875, described a wreck (Figure 2-36) measuring over 130 ft (39.6 m) long and more than 10 ft (3 m) deep, as well as a figurehead which was reportedly removed from the wreck, 'a lion with its paws erect', which stood outside a nearby cottage, and was ultimately cut-up for firewood.

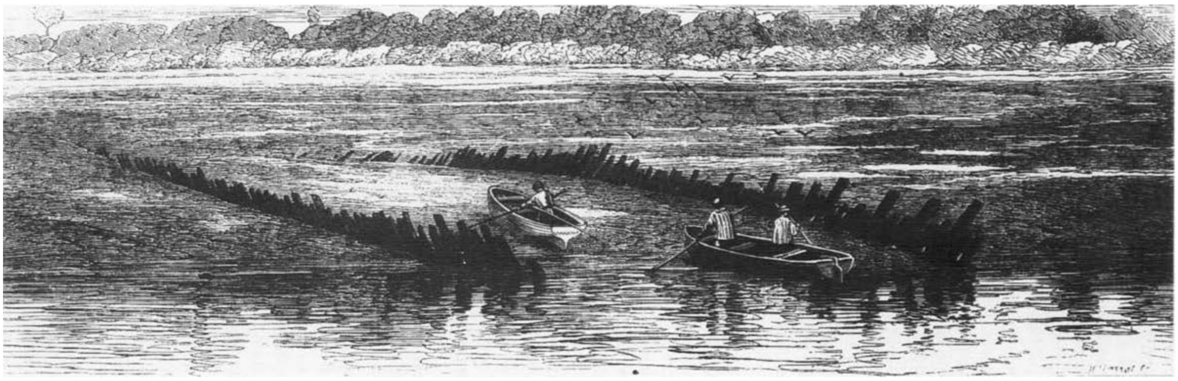

Figure 2-36 A drawing of the R. Hamble wreck published in The Graphic 1875 (after Friel 1993)

Subsequent fieldwork in 1933 confirmed the remains as still being 135 ft (41.1 m) by 37½ ft (11.4 m) and identified the vessel as potentially that of Henry V's flagship the *Grace Dieu* (Anderson 1938:112–3). Prynne estimated the ship based on the shape at the widest portion had a greatest beam in the order of 50 ft (15.24 m) wide[37], suggesting a ship of 1,400 to 1,500 'tons', and an estimated 2,750 'tons at 21 ft (6.4 m) draught (see Prynne 1968:115–28; Prynne 1976).

Further annual fieldwork excavations on *Grace Dieu* were carried out from 1980-1985 by the National Maritime Museum, Greenwich's ARC[38], and three articles on this work and on related documentary studies were subsequently published in the IJNA (Clarke et al. 1993; Friel 1993; McGrail 1993). Sampling of the small number of available timbers[39] from the wreck confirmed oak planking, as well as the existence of the unusual triple thickness clinker planking with a combination iron nails and wedged treenails for fastenings (Figure 2-37). Radiocarbon dating confirmed a felling date of late 13th to late 15th century at 95% probability, dates which bracket the known building date of AD 1418 for *Grace Dieu* (Clarke *et al*. 1993:25).

[37] Prynne states "the Grace Dieu is worth salving, because she is worth seeing in herself due to the massive size, and the inevitable 'bits and pieces' sure to be found, together with a model and pictures would present a view of medieval nautical history unrivalled in the world." (Prynne 1968).
[38] Archaeological Research Centre of the National Maritime Museum.
[39] Of the 14 available timbers, 11 were parts of planking, 3 were framing fragments and 1 piece of internal structure. All pieces are small fragments of circa 1.6 m or less.

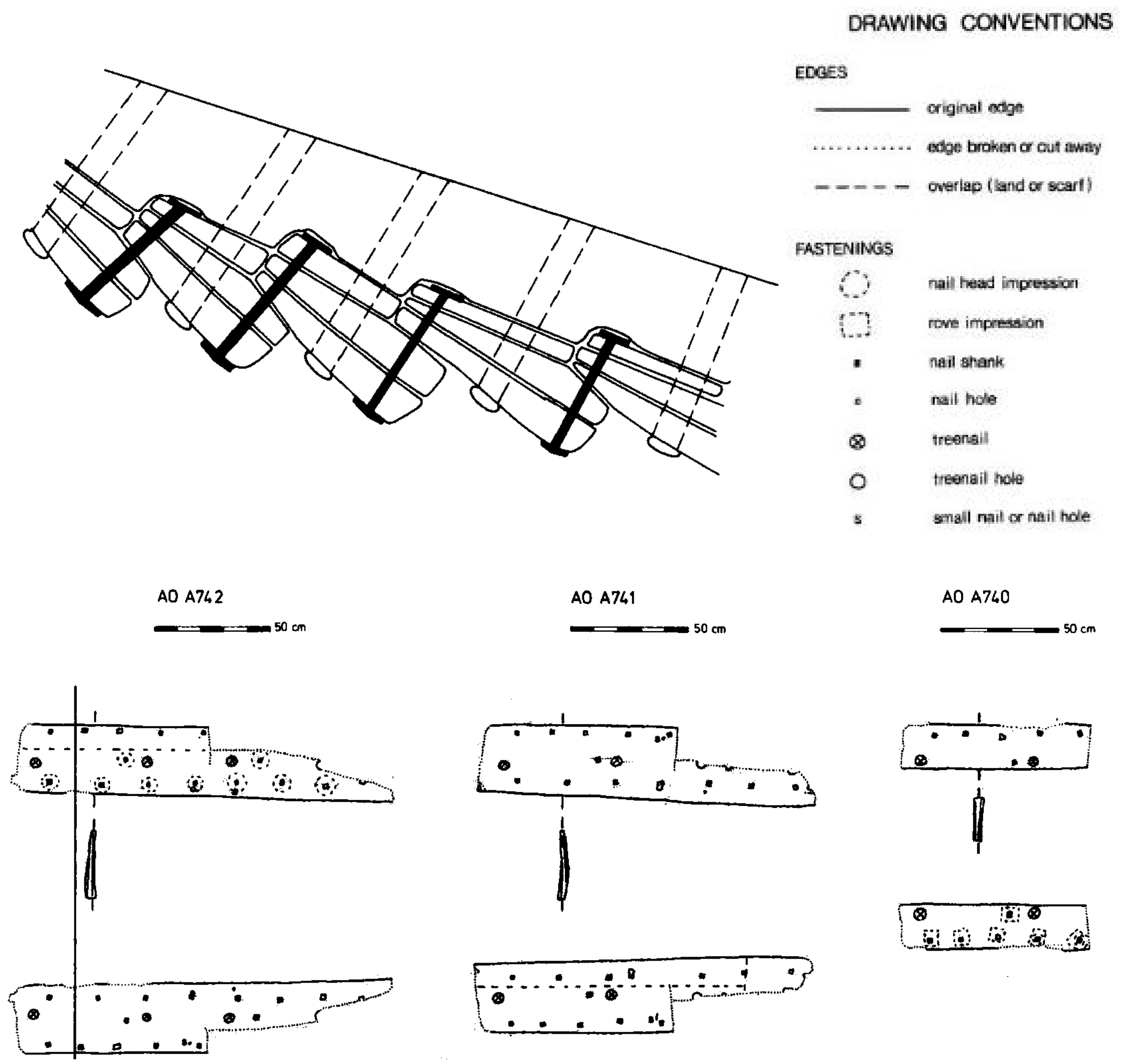

Figure 7. Greenwich triple planking fragment. Left to right, outer plank (AOA742); middle plank (AOA741); inner plank (AOA740). (Drawing: NMM, Greenwich.)

Figure 2-37 Triple clinker planking and plank fragments from Grace Dieu (After Clarke *et al.* 1993)

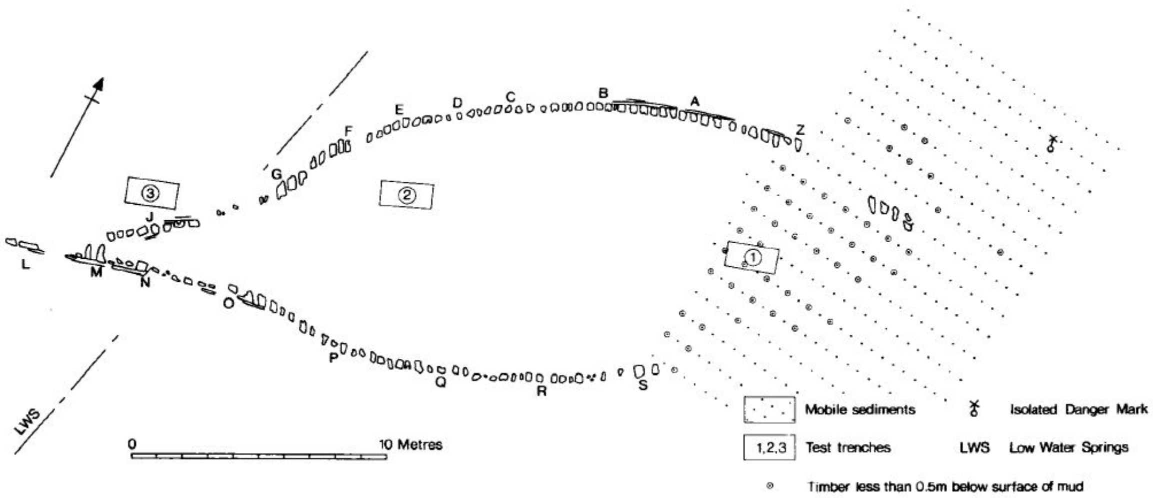

Figure 2-38 Grace Dieu site plan 1983-84 (after Clarke *et al.* 1993)

A site survey of the visible wreck structure was carried out in 1983-84 (Figure 2-38) and also identified a second nearby contemporaneous wreck, which has been tentatively identified as the *Holigost,* the second of the four great ships[40] all built for Henry V between November 1413 and the autumn of 1416 but remains un-investigated to this date (Clarke *et al*. 1993).

Friel (1993) provides a comprehensive account of the literary evidence relating to the *Grace Dieu* (see Appendix C.9:73-74), however as noted by Rose (2011:65), even armed with plentiful literary resources, and supplemented with rigorous scientific archaeological investigations, there is still considerable uncertainty regarding the overall dimensions of the vessel as well as the design and construction of the upper works and castles of this ship. Likewise, there is evidence for three masts, spars and sails as listed in her inventory, but the arrangement of masts and rigging is only conjectural (ibid:68). McGrail (1993) notes the importance of the *Grace Dieu* wreck as being one of the very few, from a period of great change[41], in both shipbuilding and rigging techniques used in Atlantic Europe.

A more recent investigation in 2005 (Plets *et al*. 2009) used a 3D Chirp sub bottom profiler, a form of acoustic underwater system used to detect shallowly buried objects in very shallow waters. The stated resolution of said system was between 7.6 to 11 cm vertically and 40 to 70 cm horizontally with positional accuracy controlled by a terrestrial RTK system to an accuracy of 2 cm. Plets *et al*. note that while the 3D reconstruction with decametric levels of accuracy will never obtain the same accuracy as can be recorded manually from exposed wrecks, the acoustic data can be used to portray a faired 3D version of the original hull of the vessel (Figure 2-39).

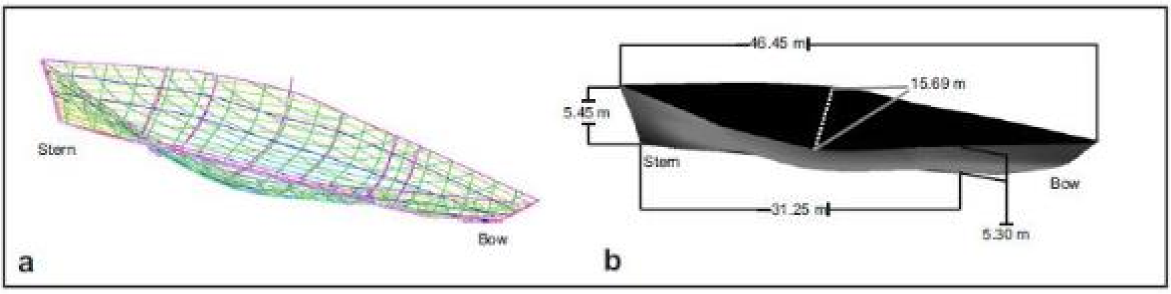

Figure 2-39 Hypothetical faired 3D reconstruction of the Grace Dieu wreck (after Plets *et al*. 2009)

However, there still has not been any attempt at a reconstruction of what both Prynne and McGrail have noted is a very significant shipwreck.

[40] The Four Great Ships were: The *Trinite Royal* (500-540 tuns burden); *Holigost* (740-760 tuns burden); *Jesus* (1,000 tuns burden); and Grace Dieu (1,400 tuns burden).

[41] McGrail notes that during this time period, as well as a change from single-masted square-rigged, to three masted rigs and lateen sails, there was also a change in construction techniques. From the 'shell-first' sequence of construction to the 'frame-first' sequence of construction. As these technological changes are not well documented, any wreck from this period is of great importance

2.4.9 Ma'agan Mikhael Ship 1985

For a more detailed discussion see Appendix C.10:76-80

In 1985 off the shoreline of Kibbutz Ma'agan Mikhael, the remains of a circa 14.4 m small sailing merchantman of approx. 23 tons displacement, dating to the 5th century BC and believed to have been in good to new condition at the time of sinking was discovered. The preserved remains were 11.5 m long by 3.11 m wide and 1.5 m deep and was excavated over three seasons under the direction of Jay Rosloff, a former assistant to Dick Steffy, who had assisted Steffy with the *Serçe Limani* ship reconstruction.

Underwater recording consisted of direct manual measurements from fixed datum points using measuring tapes (DSM method), and depths recorded with plumb lines. The wreck was abundantly photographed using colour and B&W film as well as videography. Hull timbers were cleaned, and all sides recorded for their main features such as contours, main dimensions, nail remains and sewing holes. Post conservation the timbers were again recorded in minute detail to the level of wood grain, knots, tapered pegs and nails. Wood species identification was also carried out post conservation[42].

Kahanov (2011:166–167) states the hull was reassembled using two main guiding principles: archaeological accuracy and research accessibility. The ship was reassembled 'shell first', with the keel and posts placed on temporary adjustable scaffolding, followed by the garboard and subsequent strakes, supported by MDF transverse supports which were cut following the original shape of the frames which provided accurate information regarding the original hull form[43] (Figure 2-40).

Based on the reassembled remains, two reconstructions of the hull lines were suggested (Winters and Kahanov 2004). Later with evidence from contemporary shipwrecks, iconography and the creation of both computer based and physical scale models, a third and more comprehensive reconstruction, including planking patterns was proposed (Ben Zeev *et al*. 2009). Adina Ben Zeev studied under Patrice Pomey at the University of Provence, where she learned that centre's working methods, and applied these techniques to the *Ma'agan Mikhael* evidence.

[42] This approach of drawing the main features prior to conservation and detailed hand drawings after conservation was considered a good compromise by Yaacov Kahanov, due to the condition of the timbers and the documentation tools available at the time (Kahanov 2011:162–164).
[43] It would appear that Kahanov is assuming the frames (as documented), have retained the shape of the original hull form and not altered in any way or form.

Figure 2-40 Reassembly of Ma'agan Mikhael ship (photo: Hect museum)

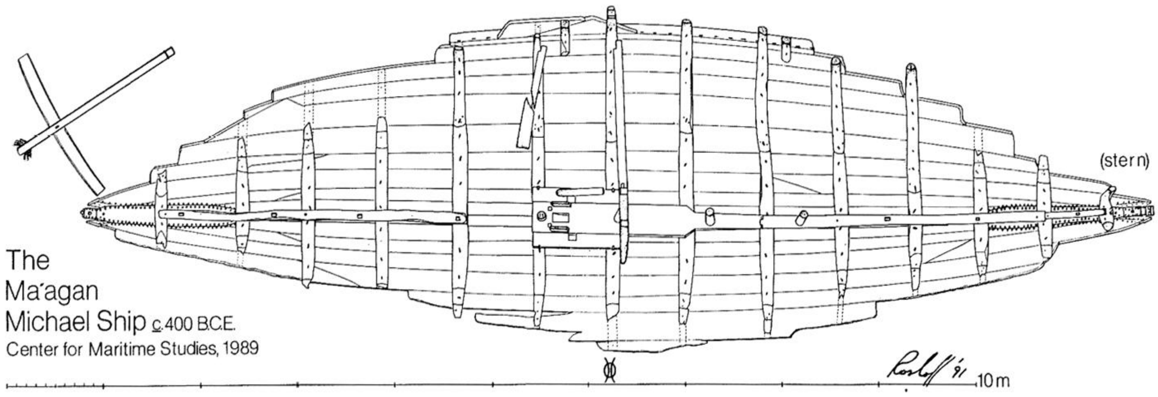

Figure 2-41 Ma'agan Mikhael Ship site plan (after Kahanov 1998)

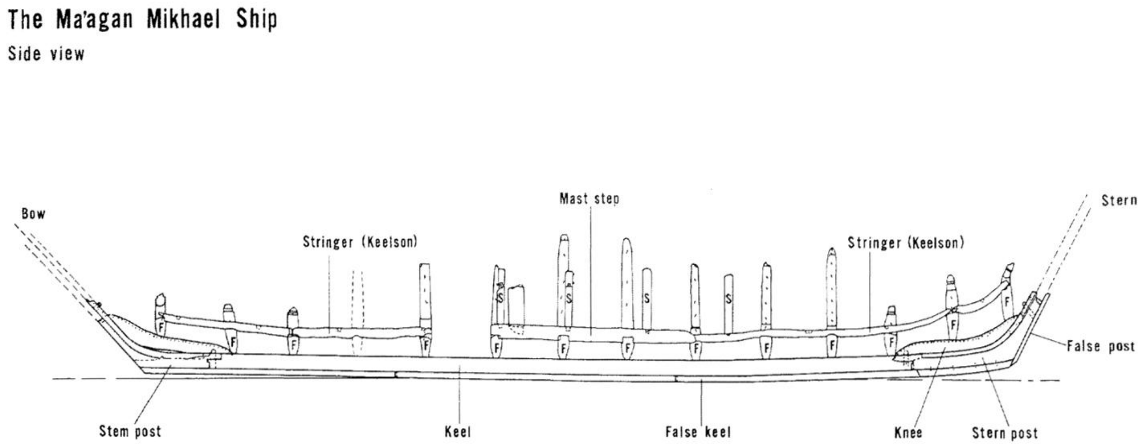

Figure 2-42 Ma'agan Mikhael Ship side view (after Kahanov 1998)

For the reconstruction Kahanov (2004:130) states that the archaeological remains defined the bottom part of the ship (Figure 2-41 and Figure 2-42), including the turn of the bilge, meaning the range of possible reconstruction options was considerably narrow (see Appendix C.10:77-80 for further details).

The Haifa team had to rely heavily on iconographic evidence as well as evidence from two near-contemporary Mediterranean reconstructions, *Jules Verne 7* and *Kyrenia.* It was decided that the *Ma'agan Mikhael* ship had been similar in hull shape to the *Kyrenia* ship and the resulting reconstructed lines (Figure 2-43) were tested for displacement and static stability. These results indicated a displacement of 15 tons and freeboard amidships of 76 cm. Further examination of the archaeological data revealed a cargo of 12.5 tons, and conservative estimates for the weight of ship and crew were 5.5 tons giving a combined weight of 18 tons. Such results led Kahanov to the conclusion that the ship as drawn was not seaworthy as the gunwale would be awash as just 24° angle of heel. As a result, the shape of the vessel was modified (Figure 2-44) above the extant remains to create a revised hull form of 23 tons displacement (a massive 27.7% increase) with a positive stability up to 60° angle of heel. With the upper part of *Ma'agan Mikhael's* reconstruction extrapolated from the reconstruction of *Kyrenia* (Ben Zeev *et al*. 2009:62), then completely modified to produce the desired hydrostatic results, I have to agree with McGrail's review[44], and ask the question – how valid is the reconstruction? The original vessel did sink, why create such an oversized reconstruction?

[44] McGrail (2010:447) suggests that prior to building any replica, the Haifa team should firstly re-examine all published evaluations and subsequently either publish a detailed and well-argued case for the validity of this reconstruction, make further attempts to evolve a valid reconstruction, or decide that insufficient evidence was excavated to justify any reconstruction.

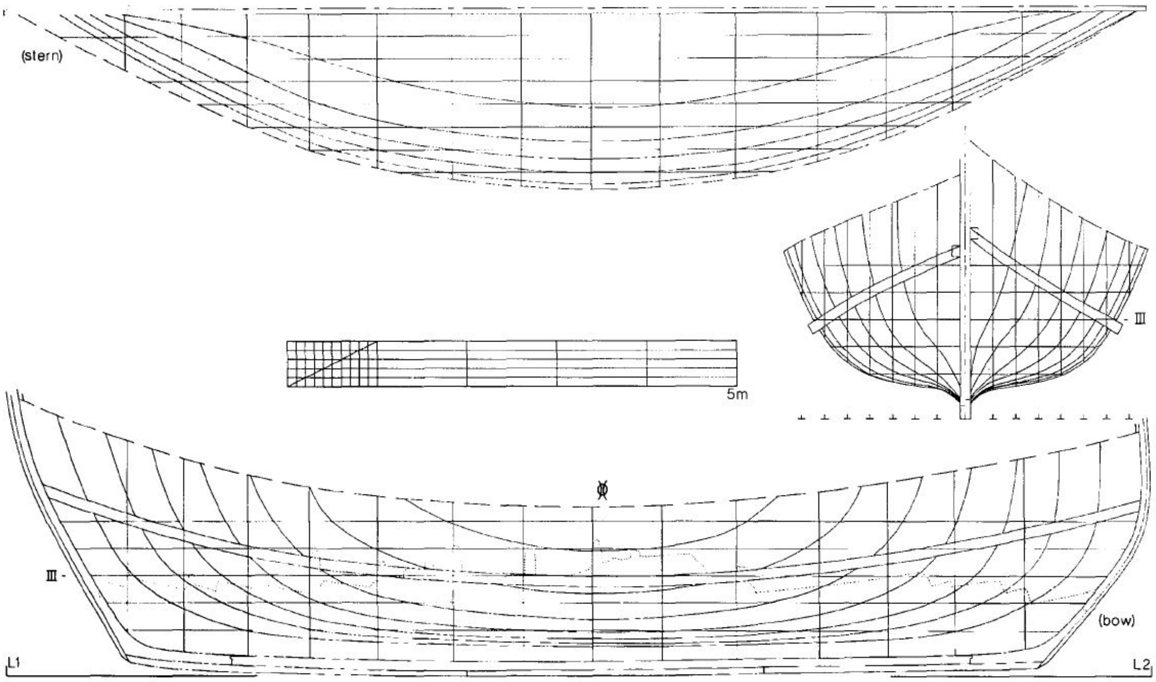

Figure 2-43 Ma'agan Mikhael initial lines plan drawings (after Winters and Kahanov 2004)

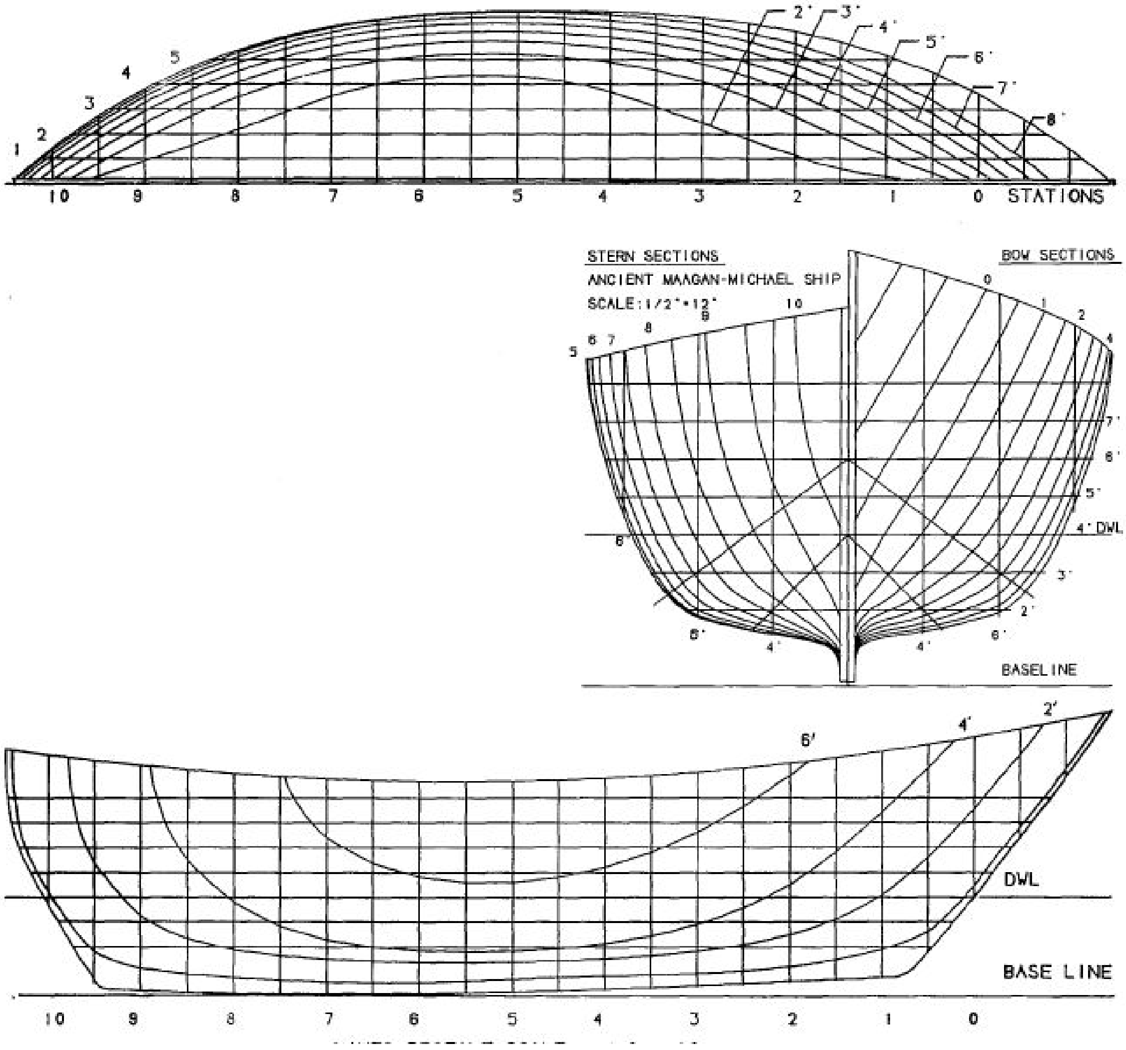

Figure 2-44 Ma'agan Mikhael revised lines plan drawings (after Winters and Kahanov 2004)

2.4.10 Barland's Farm 1993

For a more detailed discussion see Appendix C.11:81-86

In 1993 at Barland's Farm, Magor, Gwent, Wales, the remains measuring circa 9.7 x 2.6 x 0.7 m of a planked boat were discovered. The timbers were dated by dendrochronology to the late 3rd century AD, and many features, identified by McGrail (1995) as characteristic of the Romano-Celtic tradition, led to labelling the vessel as Romano-Celtic (see McGrail 1995; McGrail and Roberts 1999; Nayling and McGrail 2004).

Documentation of the remains included: photography; traditional survey using baselines and offsets to produce two-dimensional site sections all related to Ordnance Datum, and photogrammetric survey (Figure 2-45) once the ship was fully exposed.

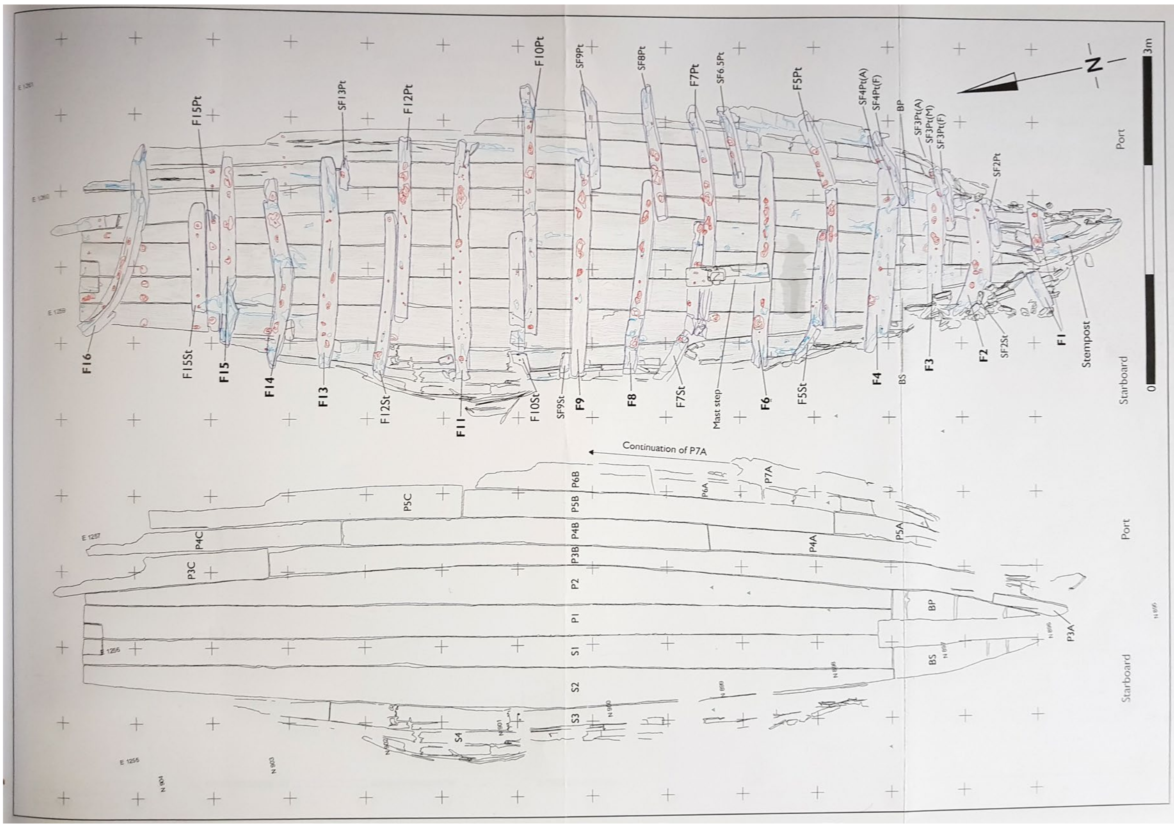

Figure 2-45 Barland's Farm photogrammetric survey plan (after Nayling and McGrail 2004)

Individual timbers were recorded using 1:5 scale drawings[45], which were subsequently reduced to 1:10 scale and used by a model builder (not an archaeologist) to create a 1:10 scale 'as found'

[45] The institute for archaeologists recommends that survey drawings produced at a scale less that 1:1 should be annotated with or accompanied by a table of 1:1 measurements (Institute for Archaeologists 2008:7).

model[46]. The model was then measured to produce 'original measured drawings' of the remains. It should be noted that these 'original measured drawings' were created at half the size of the research model[47], 1:20 scale as the resulting drawing measured 0.65 x 0.5 m and was considered, by the authors, to be a more manageable size (Nayling and McGrail 2004:165).

It should be noted that these 'original measured drawings of the remains' were created

- at half the size,
- with measurements taken from the 1:10 scale 'as-found' model
- a model created by a model maker rather than an archaeologist using
- drawings at 1:10 scale which were half the size of
- original 1:5 scale timber record drawings of
- individual post-excavated timbers

That would seem to imply up to six potential levels of interpretation, not to mention any interpretation used to convert the excavated evidence into McGrail's as-found state. Reconstruction of the boat used these 1:20 scale drawings. Details of that reconstruction process, and a subsequent reanalysis (Ali 2012), which concluded that the reconstruction drawings put forward in the original publication do not fit the archaeological record, and that the proposed reconstructed form requires further investigation, are discussed in more detail in Appendix C11:82-86.

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[46] McGrail's definition of 'as-found' is – 'the boat as found, but with distortions and compressions removed, displaced elements replaced, fragmented timbers made whole, and the hull rotated to its deduced attitude when afloat' (Crumlin-Pedersen and McGrail 2006; McGrail 2007). This involves interpretation and differs from Steffy and Pomey who both construct the initial model 'exactly' as-found devoid of interpretation.

[47] As noted by Arnold (2005:349) if the scale of a drawing is reduced, it becomes necessary to omit details for reasons of clarity and to avoid a cluttered drawing – "…we note that the tool-marks have been omitted, no doubt because recording was done on a 1/5 scale and not with a transparency on a 1/1 scale, a frequently used method."

2.4.11 Reanalysis of the Hjortspring boat and Kolding Cog 2000

The summary of selected projects covered above also demonstrates the range of documentation processes. Documenting ship timbers has traditionally followed four principles:

- sketches with dimensioned annotations to enable the later production of scaled plan-elevation-side-view and orthographic drawings;
- direct scaled drawing from measurements taken as offsets from a baseline;
- full-scale elevated plane (projection-by-eye) tracing to produce orthographic projections;
- full-scale contact tracings on clear plastic film to produce developed-surface drawings.

As noted by Hocker (2003:2) this has the indirect effect of training archaeologists to think in two dimensions instead of three, and what is recorded is not the true shape of the timber, but a series of orthographic projections of that shape onto reference planes, requiring much care and interpretation to visualize the three dimensional shape represented therein.

After a series of trials with various documentation and recording methods at the Viking ship centre in Roskilde, a more efficient method which would also produce three-dimensional drawings of the ship timbers was developed. A Microscribe 3D digitising arm[48] (Figure 2-46) was used in the initial trials (Holm 1998), and in 2000 a Faro Sterling digitising arm was purchased by Fred Hocker. The probe tip of the digitising arm is positioned on the relevant feature to be recorded and a single point is recorded. By connecting subsequent points, a three-dimensional drawing (rather than the traditional two-dimensional projection) is created.

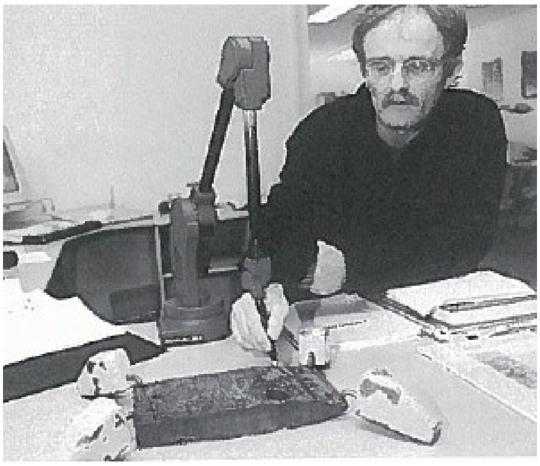

Figure 2-46 Measuring a plank sample with a MicroScribe 3D (after Holm 1998)

[48] A digitising arm can best be imagined as a mechanical version of your arm from shoulder, elbow and wrist, culminating with the fingertip, which is used to touch the object to be measured. The angle, orientation and distance of each joint is measured by the device (to sub-millimetric accuracy) to record a single three-dimensional point into a graphical computer program.

Both digitising arms were employed in the documentation of *Tilia* a replica of the *Als* or *Hjortspring* boat (see Anderson 1936; Hocker 2000; Hocker 2003) and the *Kolding cog* (see Hansen 1944; Hocker and Dokkedal 2001; Hocker 2003). Hocker (2003:84–88) noted that in documenting the hull form of *Tilia* (Figure 2-47), the recording took four forms:

1. Direct measurements using tapes to serve as baseline to check data against digital methods as well as recording scantlings of major timbers.
2. Survey of points on the interior and upper surfaces by TotalStation, recording both control points for use in registering the positions of the recording arm, and surface points to produce a surface or curvature model of the inner hull surfaces.
3. Documentation of the contours, structure and surface details of the complex ends with the digitising arm, by recording surface edges and sections across curved areas.
4. Extensive photographic and video documentation of the boat and the recording process.

Figure 2-47 Digitally recording Tilia (after F. Hocker in Crumlin-Pedersen and Trakadas 2003)

Both digitising arms were capable of interfacing directly with the NURBs[49] based three-dimensional modelling software Rhinoceros 3D[50]. For *Tilia* the raw polylines[51] which were a series of straight-line segments delineating each feature were faired (converted to NURBs curves) and stored on a new computer layer (Figure 2-48).

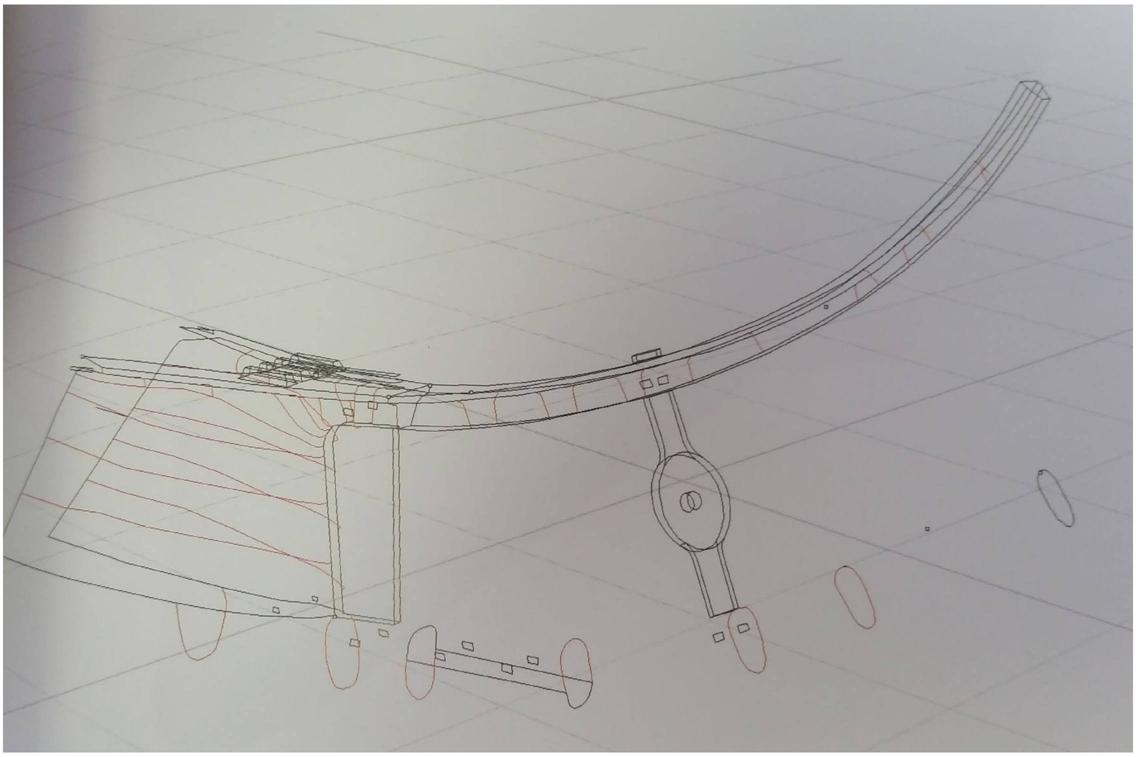

Figure 2-48 Raw point data and faired curves (after F. Hocker in Crumlin-Pedersen and Trakadas 2003)

NURBS surfaces (Figure 2-49) were then created using a variety of Rhinoceros 3D processes, with issues arising in areas of dramatic shape change in small areas, leading to a refinement of the recording process, taking a larger number of points and sections at transitions from flat to highly curved areas, and greater care in the even spacing of recorded sections. Conventional lines drawings were derived by taking a series of sections through the digital 3D surface models at regular intervals (Crumlin-Pedersen and Trakadas 2003:84–94).

[49] Non-uniform rational basis spline (NURBS) is a mathematical model commonly used in computer graphics for generating and representing curves and surfaces. It offers great flexibility and precision for handling both analytic (surfaces defined by common mathematical formulae) and modelled shapes
[50] Rhinoceros 3D can create, edit, analyse, document, render, animate, and translate NURBS* curves, surfaces, and solids, point clouds, and polygon meshes. There are no limits on complexity, degree, or size beyond those of the computer hardware used.
[51] A polyline in computer graphics is a continuous line composed of one or more straight line segments, created by specifying the endpoints of each segment (the probed points in the case of arm digitising).

During the documentation of the Kolding cog timbers, a basic template for particular kinds of timbers was developed, either those that consist of two large faces and thin edges, such as planks, and those that have substantial thickness in all dimensions and will thus need to have all faces drawn separately, such as frames. This involved using layers, with selected features such as original edges, tool marks, wood grain or fastening details being assigned to individual layers (Fred Hocker 2003:10).

Figure 2-49 NURBs surfaces applied to the recorded data (after F. Hocker in Crumlin-Pedersen and Trakadas 2003)

The data recorded can be utilised much more effectively if it organised onto separate layers (Hocker 2003:14), and the toggling of layer visibility allows for exponentially greater quantities of data to be recorded, which would rapidly overwhelm traditional two-dimensional drawings, where multiple versions of the same drawings would be required to illustrate the same level of detail.

In my view, an added benefit is that all the recorded data can be ‘stored’ in the same single digital drawing, negating any concerns such as differing scales or differing reference coordinates and control points. The same drawing can simply be reprinted (either at full-scale, or reduced to a suitably convenient scale) and by toggling layer visibility, showing only features which are pertinent to the current research question.

2.4.12 The Roskilde Method 2002

The digitising arm methodology developed by Holm (1998) and Hocker (2000; 2003) was adopted by the Viking ship museum in Roskilde in what has become known as the 'Roskilde Method' when the approach was used to document the *Roskilde* ships. The nine *Roskilde* ships (Figure 2-50 and Figure 2-51) were discovered in 1996-97 as part of the construction of the museum-island complex designed to house the five *Skuldelev* ships (Gøthche 2006).

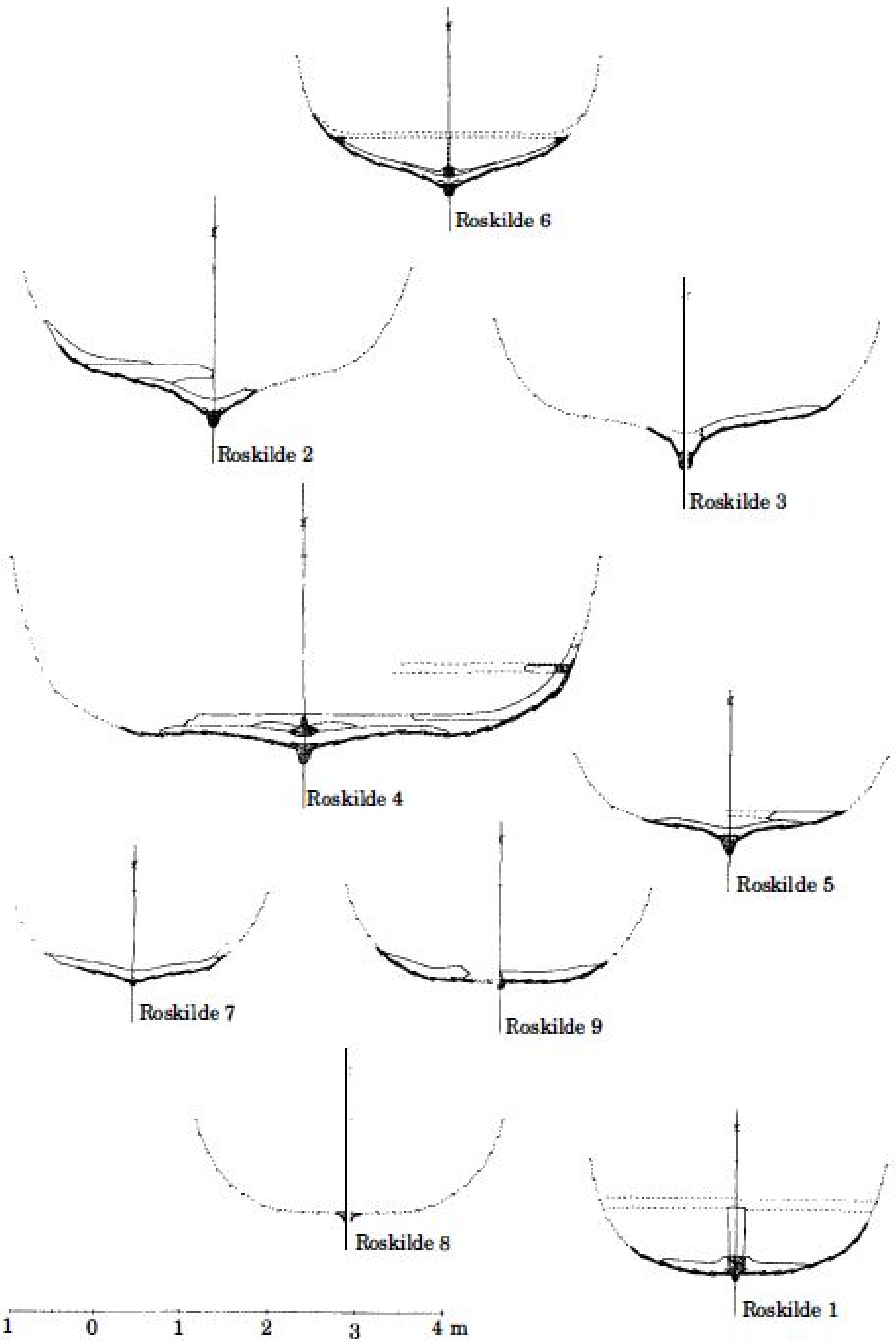

Figure 2-50 Cross-sections of the nine Roskilde ships showing parts actually found (after Gøthche 2006)

ship	type	date	length	beam	draft	cargo capacity	state of preservation
Roskilde 6	warship	aft. 1025	36.0	3.50	1.0	100 crewmemb.	25%
Roskilde 2	cargo ship	ca. 1185	16.5	4.50	1.1	15 t	60%
Roskilde 3	cargo ship	ca. 1060	18.0	4.40	1.0	11 t	20%
Roskilde 4	cargo ship	ca. 1108	20.5	6.60	1.5	50 t	50%
Roskilde 5	cargo ship	ca. 1130	14.0	3.60	0.7	5 t	30%
Roskilde 7	cargo ship	1270	10	3.00	0.8	5 t	35%
Roskilde 8	cargo ship	aft. 1248	0	0	0	0	1%
Roskilde 9	cargo ship	ca. 1175	11.0	3.40	0.8	5 t	30%
Roskilde 1	cargo ship	ca. 1336	10.0	3.25	0.6	7 t	65%

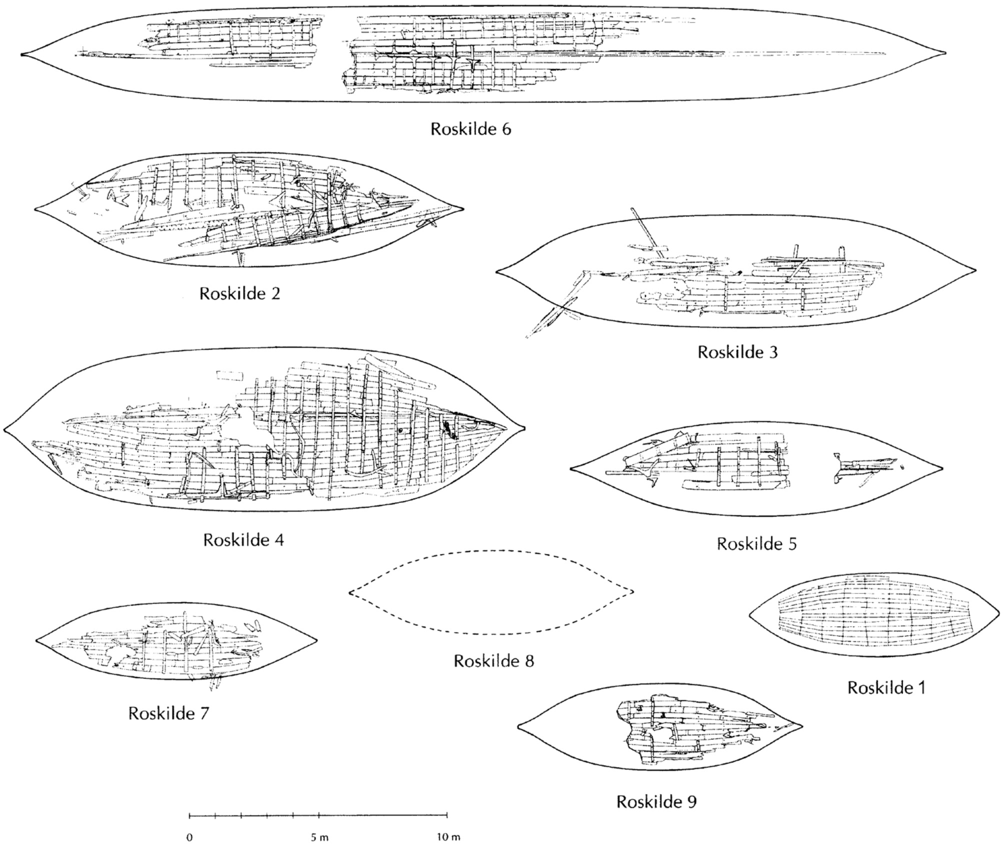

Figure 2-51 Site plans of the nine Roskilde ships (after Gøthche 2006)

While most of the Roskilde ships were documented using the by-now standard elevated plane tracing methodology, developed as part of the *Skuldelev* project (Crumlin-Pedersen 2002a:54) and already well established at Roskilde, the Faro Arm was also introduced to document some of the timbers. This replaced the previously projected or flattened depth measurement with actual recorded three dimensional depth measurements, and features of the timbers are recorded onto a customised layering system allowing the display or hiding of detail as required (see Ravn 2012; Ravn *et al*. 2013; Bischoff 2014; Bischoff *et al*. 2014; Bischoff 2016). In addition, the computer software (Rhinoceros 3D) is capable of generating two-dimensional orthographic projection drawings of each face of the timber, as used in traditional shipwreck timber catalogues.

Describing the Roskilde reconstruction process Bischoff (2016:24) states:

> "When the ship was found, its parts were flattened out on the seabed, so the ships original shape was not apparent. In order to exhibit the ship-find in a coherent shape, as was done with the Skuldelev ships at the Viking Ship Museum in Roskilde, the ship was reconstructed as a 1:10 physical model using scaled-down drawings from the initial documentation of the timbers.
> The 1:1 hand-drawn or digitised 3D drawings of the parts were scaled and traced on cardboard or wood in scale 1:10 and their outlines cut out. The cardboard needs to be the same scaled thickness as the ship elements in order to ensure that the planks are assembled correctly."

In a seemingly backward step, the 'Roskilde method' involves converting or projecting the documented three-dimensional timber record back to two-dimensional drawings on paper which are then cut out and glued to cardboard or timber of appropriate thickness to represent the scaled thickness of the ship element. In effect, returning from the documented three-dimensional shapes, to a flat two-dimensional record, in order to attempt to recreate the original three-dimensional shape of the hull (see Ravn 2012:316; Ravn *et al*. 2013:236; Bischoff 2014:236; Bischoff *et al*. 2014:22; Bischoff 2016:24).

The cardboard research model (Figure 2-52), developed in the 1970's analog world, as part of the *Skuldelev* project (Crumlin-Pedersen and Olsen 2002:96–304), had become such a feature of the Roskilde method, that one of the requirements for a digital approach to documentation, was that it still allowed the use of this partly two-dimensional cardboard modelling methodology (F. Hocker pers. comm May 08, 2016).

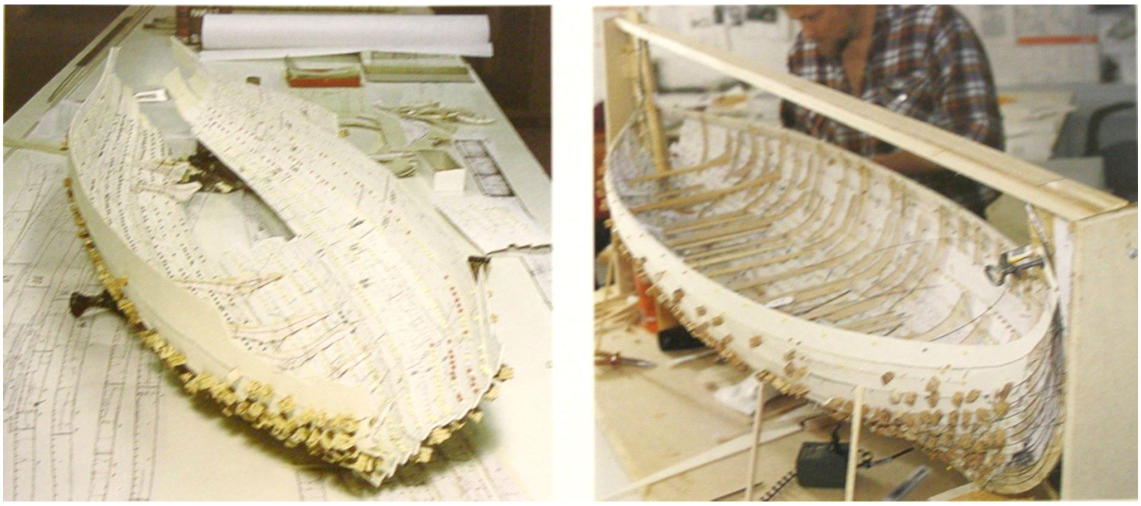

Figure 2-52 Cardboard research models of Skuldelev 1 (after Crumlin-Pedersen 2002)

In analysing the reconstructed ships, the Roskilde team typically record what is labelled an ‘inner edge lines drawing’ (Figure 2-53), by tracing all of the inboard upper edges of each strake as well as the external outline of the keel. These ‘inner edge lines drawings’ have been recorded manually as well as with the digitising arm. Once completed, the information is entered into the 3D ship database program ‘NMF-Ship’[52] (Jensen 1999:12). The data pertaining to the ‘inner edge line drawing’ is then transferred to another program ‘I-Ship’[53] (ibid: 8-15). The software then translates or converts the documented ‘inner edge line drawing’ into a drawing representing the outer surface of the ship’s hull.

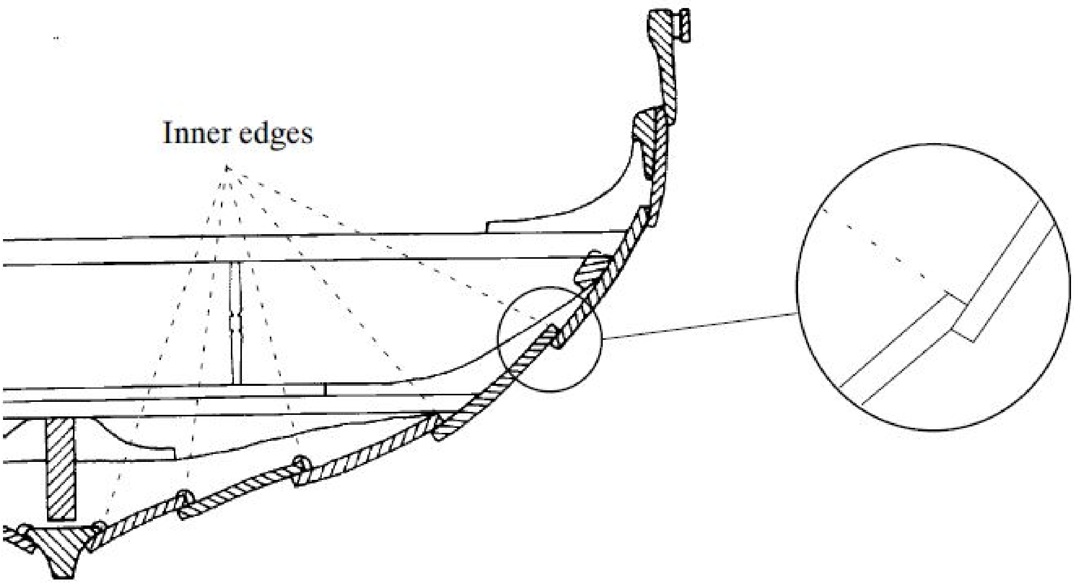

Figure 2-53 Roskilde 'Inner Edge Lines Drawing' (after Jensen 1999)

Since the NMF-Ship software was not based on standardised commercial software, and dependent on one single expert, its longevity was never guaranteed. In future work at the Viking Ship Museum, the NMF-Ship® and I-ship® programs will be replaced by Rhinoceros 3D and ORCA 3D, a plug in to Rhinoceros 3D (Bischoff 2016:31).

It should be noted that ‘I-Ship’ was unable to deal with clinker overlapped hull forms and an averaged carvel hull was created by the software (ibid: 15-22). Depending on where this averaged hull shape is developed from, has a direct bearing on the displacement and hydrostatic analysis of the vessel. Jensen states the averaged hull is based on certain assumptions such as all strakes are assumed to be straight in the YZ-plane (cross sectional plane) rather than curved, and on geometric formulas.

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[52] a program developed at the National Museum’s Centre for Maritime Archaeology in Roskilde (NMF).
[53] a ship calculation program developed at the Department of Naval Architecture and Offshore Engineering (ISH) at the Technical University of Denmark (DTU) in collaboration with the Danish Maritime Institute.

Traditionally naval architecture lines plans are drawn to the lower inboard edge for clinker vessels (Figure 2-54 C red line), not the outer edge as shown in Figure 2-54 C.

If a 10 m long by 3.25 m wide hull (similar overall dimensions to Roskilde 1) were loaded to 0.6 m draft, it would have a displacement of 7.0 tonnes. Decreasing that same hull size by removing 12.5 mm all over (approx. half the planking thickness) would decrease the displacement to 6.67 tonnes, a decrease in the overall displacement of 4.7%.

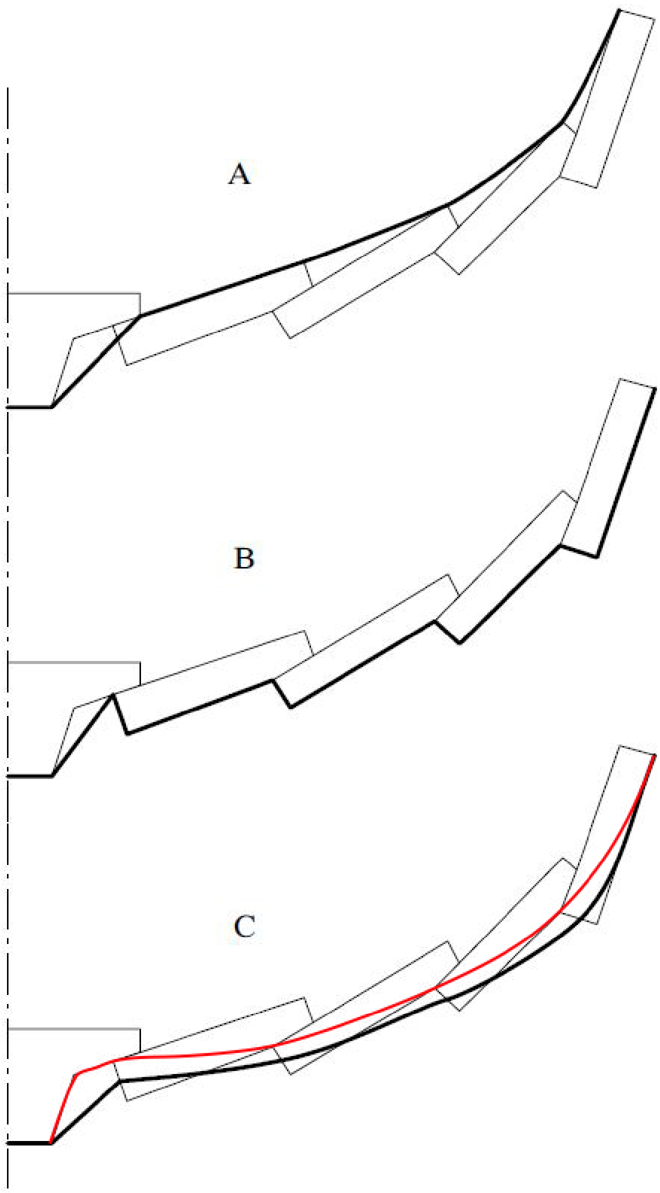

Figure 2-54 Inner Edge drawing to outer hull lines[54] (after Jensen 1999)

[54] Figure 2-54A illustrates the inner edge lines drawing which is manually recorded as part of the process. Figure 2-54B illustrates the clinker nature of the outer hull drawing, and the black curve in Figure 2-54C is the interpolated carvel curve generated by the I-ship software. The red curve added by this author represents the traditional Naval Architectural convention when drafting lines plans for clinker vessels. And results in approximately 5% less hull volume than the I-Ship hull form.

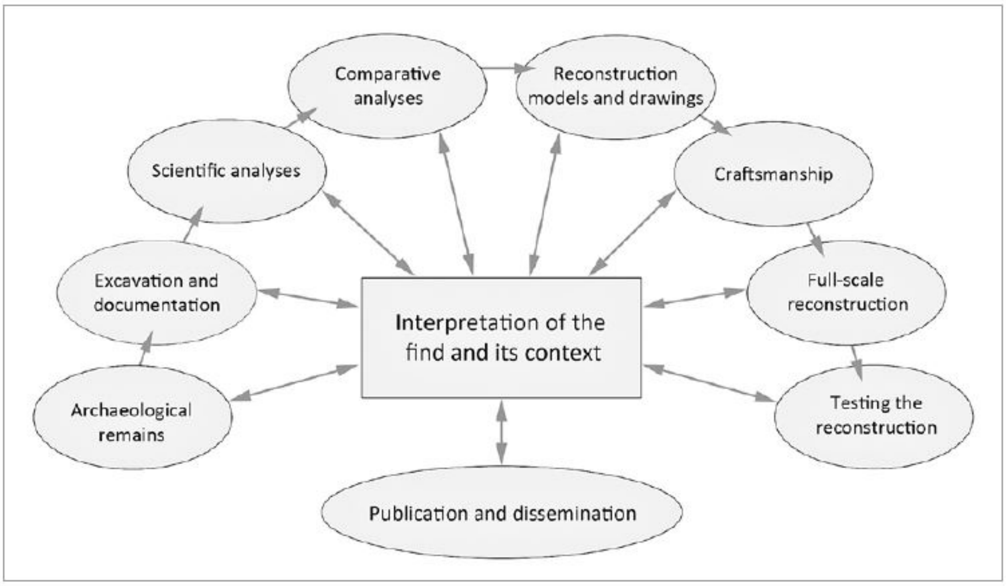

Figure 2-55 'The Roskilde method' - process and methods as applied at the Viking Ship Museum, Roskilde (after Bischoff *et al*. 2014)

If the ‘Roskilde Method’ is numbered from clockwise for each phase illustrated in Figure 2-55 there are 8 phases which all feed into the interpretation of the find and its context, leading to a publication detailing the ship find. In the case of the *Skuldelev* vessels, the publication - The Skuldelev ships I: topography, archaeology, history, conservation and display (Crumlin-Pedersen and Olsen 2002) went as far as phase 4, with a partial phase 5. The publication discusses:

1. the archaeological remains
2. excavation and documentation
3. scientific analysis
4. comparative analysis
5. and partial details of the reconstruction models and drawings.

Most chapters cite volume II, which was to deal in more detail with the research models and reconstruction drawings, the so called ‘wet wood technology’ of building Viking ships, the full-scale reconstructions as well as results from using these reconstructions, phases five to eight of Figure 2-55. To date, almost 60 years after their initial excavation, Volume II remains unpublished.

For the Roskilde method, timbers were initially recorded with elevated plane tracing, and subsequently using a Faro Arm to accurately record the three-dimensional shape of each timber. The timbers are then flattened back to two dimensions, reduced to 1:10 scale and cut-out from cardboard. The cardboard planks are then reassembled, aligned using extant fastening holes, to create a three-dimensional 1:10 scale, reconstructed shape model. This model is measured to produce the ‘inner-edge lines plan’ and the ‘torso’ drawing. The model is then measured to produce construction drawings for a full-scale replica, and hydrostatic analysis carried out to provide coefficients of form and displacement values. Then begins a series of iterations (trial-and-error) at full-scale between what is possible to construct with timber and what has been modelled in cardboard. Once launched, the full-scale replica is used for sea-trials to analyse performance.

Ravn *et al*. (2013:232–249) state that by building a full-scale reconstruction it is possible to examine questions regarding the knowledge of ancient shipbuilders, the relationship between natural resources and boatbuilding, the man-hours required in the building process, and the tools used. To ensure the reconstruction is authentic, it is important to build on the information gained during the documentation phase of the ship find, and the building of the scale model. If that reconstruction is to be scientifically useful, the parts based on archaeological evidence and the parts based on educated supposition need to be documented, and such documentation should consist of reports, drawings, and photographs, making them an integral part of the published project reports.

The main purpose, according to the authors (2013:241), in constructing a full-scale physical reconstruction, is to gain an understanding of the original vessel's design, function, and qualities, and to relate these to the society in which it was built. The building process requires many different specialists besides the boatbuilders. In addition, blacksmiths, rope makers, weavers, sail makers, painters, tar-burners, charcoal-burners, as well as the craftsmen who extract iron ore, fell and transport lumber, and make the flax and wool are all essential to the overall process. A rigorous reconstruction process allows the examination of all these crafts, as well as the tools and equipment involved.

Sea trials have become an important component in the experimental analysis of ship finds. The experimental use of the reconstructed vessel under realistic conditions makes it possible to investigate and interpret the use of the original vessel and its significance to the society that relied on it. Just as vessels were lost in the past, the same can happen today, such as the full-scale reconstruction of the Oseberg ship, *Dronningen*, built in 1987 which sank during its first test trial under sail in 1988 (Carver 1995), and the reconstruction of Skuldelev 1, *Saga Siglar*, built in 1983, which was lost off Catalonia in 1992 after her circumnavigation of the world in 1984-1986 (Thorseth 1988; Thorseth 1993). However other reconstructed vessels endure many seasons afloat, and thus over time needing numerous repairs, can help by adding to the understanding of traces of usage and repair in the original vessels[55] (Trakadas 2011; Ravn *et al*. 2013; Bischoff *et al*. 2014; Bischoff 2014).

[55] To my knowledge the 'Roskilde method' does not include the measuring of the replica vessels during or after construction. It would be valuable to compare the shapes recreated in the Roskilde boatyard, as well as any other full-scale replica building project, to the shape of the research model as well as the original archaeological shape.

2.4.13 Newport Medieval Ship 2002

The Newport Ship, discovered in 2002 on the bank of the River Usk in Newport, Wales, with the archaeological remains indicating strong Iberian connections. The ship was shored up possibly for repairs shortly after the spring of AD 1468. It was abandoned after extensive salvage, and more than 23 m of the clinker-built ship were recovered, together with significant artefact and environmental assemblages (see Roberts 2004; Jones 2005; Jones 2009; Jones and Nayling 2011; Jones *et al*. 2013; Nayling and Jones 2014; Jones and Stone 2018).

Documentation of the remains included: photography; traditional survey using baselines and offsets to produce two-dimensional site plans and sections all related to Ordnance Datum[56], and two phases of photogrammetric survey once the ship was fully exposed, the first with ceiling planks removed to expose framing, and the second when framing was removed to expose the inboard faces of the hull planking, keel and stem. Individual ship timbers were assigned unique codes during the excavation and removed from site for further detailed documentation at a later stage (Nayling and Jones 2014:1–5).

For post-excavation documentation, the extraction of 3D line data from the photogrammetric survey was carried out in collaboration between the archaeologists and photogrammetry specialists ensuring appropriate data capture, layering and labelling. A pilot study examined various recording methods for documenting the individual timbers, comparing: 3D laser scanning, full-scale elevated plane tracing and contact digitising, with contact digitising proving the most efficient in term of time and costs (Barker and Nayling 2004). Initial training in contact digitising as well as templates were provided by the Viking Ship Museum in Roskilde[57] (Nayling and Jones 2014:6).

In a departure from the 'Roskilde Method'[58], an approach while viable, was seen as essentially modelling three-dimensional forms from two-dimensional data. Given that the Newport ship timbers were recorded in a digital three-dimensional format, it was seen as logical to use the three-dimensional data directly in the modelling stage[59]. The reconstruction and analysis are examined in detail in Chapter 8 and Chapter 9.

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[56] Ordnance Datum (OD) – the reference level for land mapping in the United Kingdom

[57] Layering and templates developed at Roskilde were found to be more suited to Viking ship construction and Toby Jones subsequently developed a tailored timber recording manual and templates (Jones 2013).

[58] Printing two-dimensional drawings of timbers which are then cut-out and glued to cardboard which is experimentally assembled, fastened, twisted and bent until a viable hull form is achieved (Crumlin-Pedersen 2002c:121)

[59] Details of the documentation and modelling stages are well published (see Jones 2009; Jones and Nayling 2011; Jones *et al*. 2013; Nayling and Jones 2014) and full detail are available in Toby Jones' doctoral dissertation (Jones 2015).

2.4.14 Additional Projects

The projects so-far discussed, by no means represents a complete nor even comprehensive list, but rather specific examples over the period of the last century, where an alternative approach or new methodology has been applied, to the process of documenting and ultimately attempting to reconstruct the hull form represented within each archaeological excavation. Collaboration and dissemination through publication and International conferences such as ISBSA (see Appendix D) have led to the majority of other projects using either one, a combination, or in some cases even a hybrid mix, of the previously described methodologies.

For example, Patrice Pomey at the Centre Camille Jullian, has slightly refined the approach used by Steffy, while Steffy created his initial research models with dislodged or disarticulated pieces replaced in close proximity to their original neighbours, Pomey prefers his first research model to be an 'exactly as-found' model with the damaged or displaced parts modelled as recorded on site (Figure 2-56). In effect a model free from interpretation, after which a second model with dislodged or disarticulated pieces replaced is created, followed by subsequent modelling as required to arrive at the proposed reconstructed form (Pomey *et al*. 2005:89–154). Pierre Poveda is currently applying the same techniques, but in a digital format, using Rhinoceros 3D and Orca 3D (Poveda 2012).

Figure 2-56 As found model of Jules Verne 7 (after Pomey and Reith 2005)

In 2006 during excavations for a new underground metro station at Yenikapi in Istanbul, Turkey the remains of 37 vessels dating from the AD 5th to 10th Centuries were discovered, and two research groups were tasked with documentation and excavation. The Istanbul University Department of Conservation and Marine Archaeological Objects, and the Institute of Nautical Archaeology at Texas A&M University. Both groups used similar in-situ documentation techniques, scaled drawings, full size 1:1 tracing and photographs to record the in-situ remains as well as photogrammetry and high-resolution photo mosaics to document the cargo and selected construction features. Midway through documentation in-situ recording switched to total-station recording (Pulak *et al*. 2015; Kocabaş 2015).

Interestingly the two teams differed significantly in the post-excavation documentation techniques employed. The Institute of Nautical Archaeology considered using contact digitisers to document the individual timbers, (they had access to a Faro Arm in the Conservation Research Laboratory at Texas A&M), the project directors chose instead to use the methodology developed by Fred Van Doorninck and J. Richard Steffy in their excavations and studies of the *Yassi Ada* and *Serçe Limani* wrecks in the 1960's and 70's, of recording individual hull timbers full size using 1:1 scale drawing on clear plastic film. These traditional drawings were ultimately scanned to create digital copies thereby allowing the archaeologists create digital plan and section drawings using Rhinoceros (Pulak *et al*. 2015). In contrast the Istanbul University team were willing to utilise the advances in post-excavation documentation, recognising the efficiency and accuracy of contact digitising. Following advice and training by Fred Hocker, the team purchased Faro Arm contact digitisers for documenting the ship timbers and recording templates similar to those developed at Newport were used (Kocabaş 2015).

Another project from Marseille in 2011 is the remains of a Roman barge excavated and raised in sections cut through the hull. Detailed documentation of these sections was carried out using a Creaform 3D C-Track, a wireless contact digitiser consisting of a handheld probe device which is tracked in three-dimensional space using two infra-red cameras together with a series of reference targets positioned around the artefact to be recorded. The individual 3D point data recorded was exported to Rhinoceros for subsequent reconstruction and analysis work (Ranchin-Dundas 2012).

The Norwegian Maritime Museum in 2007 sought to improve on its method of documenting timbers in full-scale by tracing onto clear film and for the recording and reconstruction of *Sørenga* 7, a 17th-century boat from Oslo harbour (Falck *et al*. 2016), used a hybrid version of the Roskilde and Newport methods (Figure 2-57). After documenting the timbers using contact digitising, two-dimensional drawings of strakes were printed onto cardboard as done in Roskilde, but the 'four sided timbers' such as keel, stem, stern and frames, were 3D printed as was done in the Newport Ship (Jones 2015) and the Drogheda boat projects (see Schweitzer 2012; Tanner 2013a).

However, the 3D printing of the 'four-sided' timbers such as stem, stern and frames would appear to be an assumption that these elements have not been distorted between the wrecking, deposition, excavation and documentation phases of a project. This has been clearly demonstrated (Figure 2-58) to not be the case in the Newport medieval ship project (Tanner 2013b:33–34). This problem is also discussed further in Chapter 7.9.

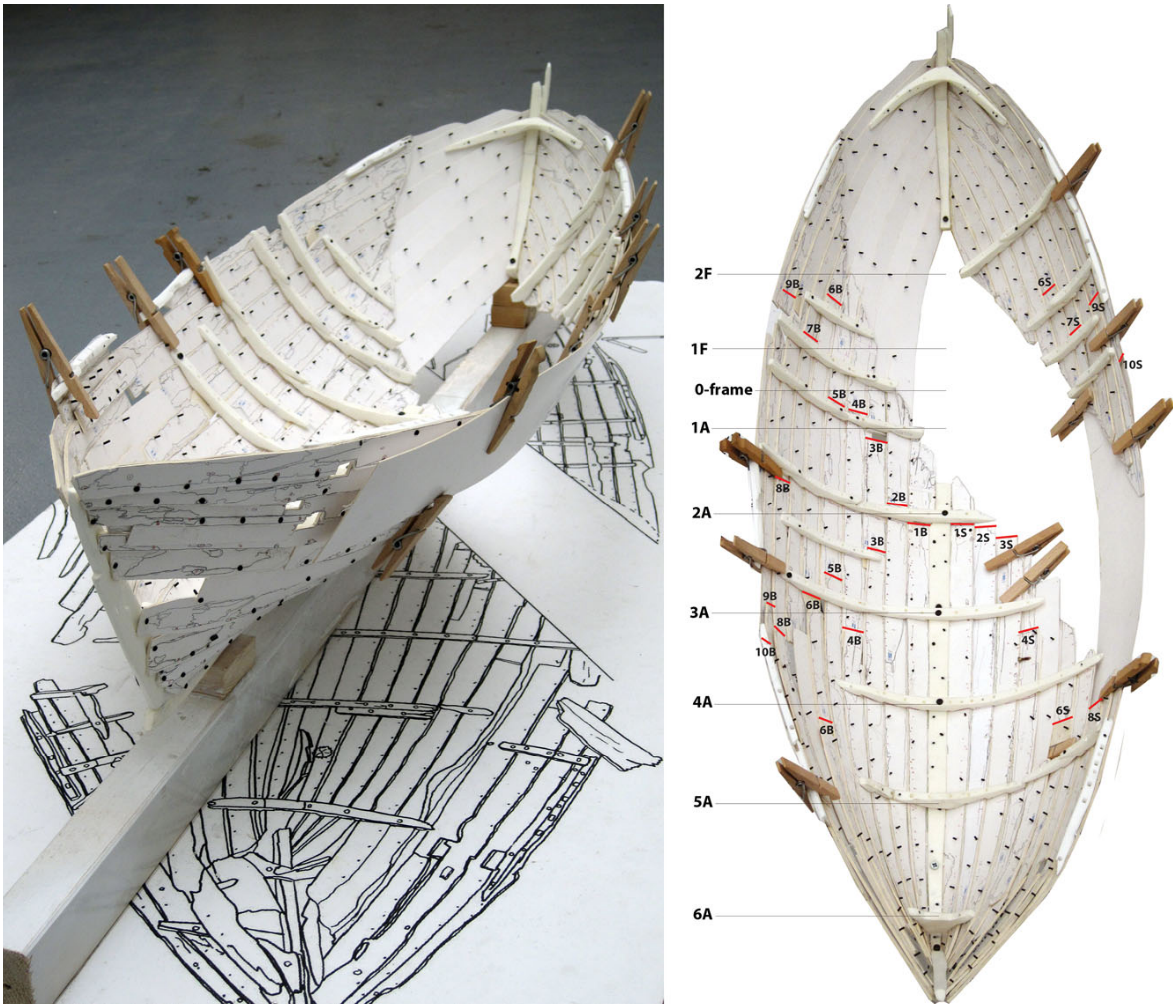


Figure 2-57 *Sørenga* 7 ‘hybrid’ model (after Falck *et al*. 2016)

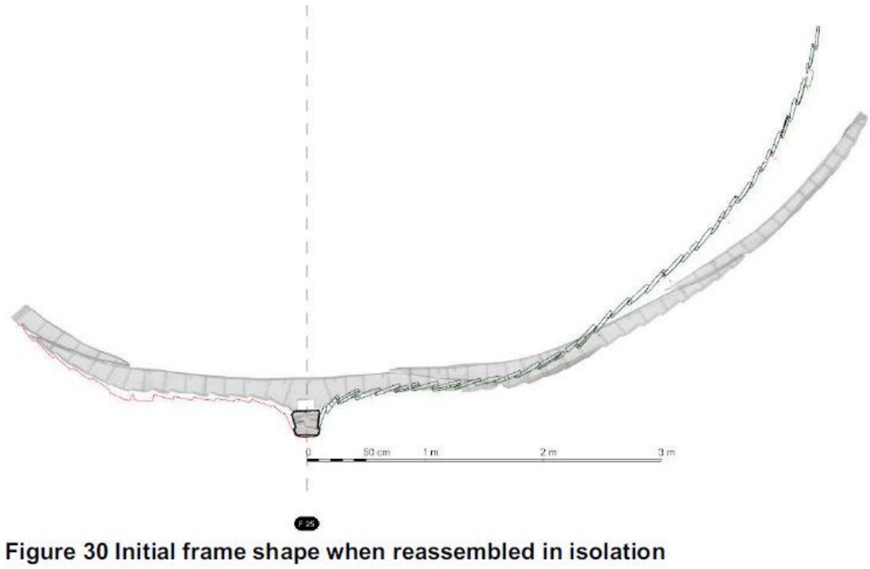


Figure 2-58 (Newport Ship Frame 25) Distorted shape of frames when taken in isolation (Tanner 2013: Fig. 30)

2.5 Partial or Contributory Reconstructions

One of the reconstruction techniques described by Steffy (1994:216–218) is contributory reconstructions. In cases where little or only poorly preserved parts of the hull timbers survive it often is not possible to attempt a complete hull form reconstruction. The surviving elements can, however, be reassembled in the form of a contributory or partial model for further research. That is how Thomas Oertling learned so much from the sparsely preserved Molasses Reef wreck (Oertling 1989) and Jay Rosloff from the bow area of the Ronson ship (Steffy 1994:168–172). The following section considers three examples which represent a drawn, a full-scale construction and a digital modelled version of contributory reconstructions.

2.5.1 1985 Vessels from St Peter Port

The first vessel was discovered at St Peter Port Guernsey during 1982. **St Peter Port 1**, which was dubbed the '*Asterix ship'* by the media, was excavated and recovered in 1985 under the direction of Margret Rule (Rule and Monaghan 1993). Between 1988 and 1997 a further 7 vessels were also discovered (Adams 1998). **St Peter Port 2** which was discovered in 1985 was in the path of dredging operations and needed to be '*removed or otherwise destroyed'* (Adams and Black 2004:233). The timbers were salvaged and comprehensively recorded by Martin Dean, including a plan of the complete structure (Figure 2-59), which was subsequently dismantled and recorded as individual elements, as well as the many other disarticulated elements recovered. Adams describes the remains as the central lower hull portion of a small robustly built clinker ship, including parts of the keel, floors, keelson and other loose timbers, and notes that a more detailed evaluation is to be included in a future Guernsey Museum monograph (ibid: 233).

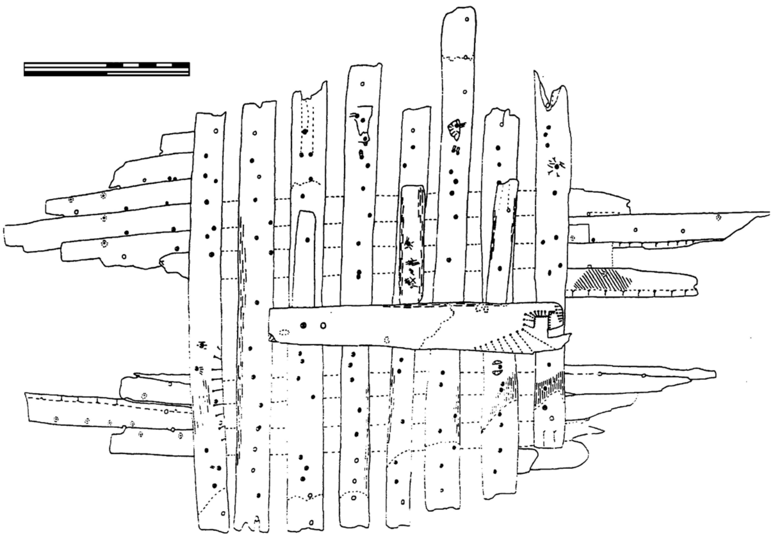


Figure 2-59 Plan of the articulated section of St Peter Port 2 – scale bar is 1m long (after Dean)

St Peter Port 3 is described by Adams as a heavy built ship with close set framing in which the sided dimension (the room taken up by the frame) is more than twice the space between frames. The futtocks (individual elements making up a complete frame) were joined end to end with splayed scarf joints having a treenail through the joint. The internal structure is noted as significant by Adams, rather than the through hull beams such as found in the Kalmar 1 wreck (Åkerlund 1951), instead three adjacent stringers formed a shelf assembly for the beams, the thickest central stringer having large rebates to take main beams, as well as smaller rebates to take the lighter intermediary beams. Surviving treenails indicated the positions of missing lodging knees which had secured the beams to the sides of the ship. The angles of the beam rebates, the curvature of the planking and direction of plank scarfs indicated the remains came from part of the lower hull. Figure 2-60 is a good example of a partial reconstruction to illustrate specific construction details and show the probable origin of the remains from within the original vessel.

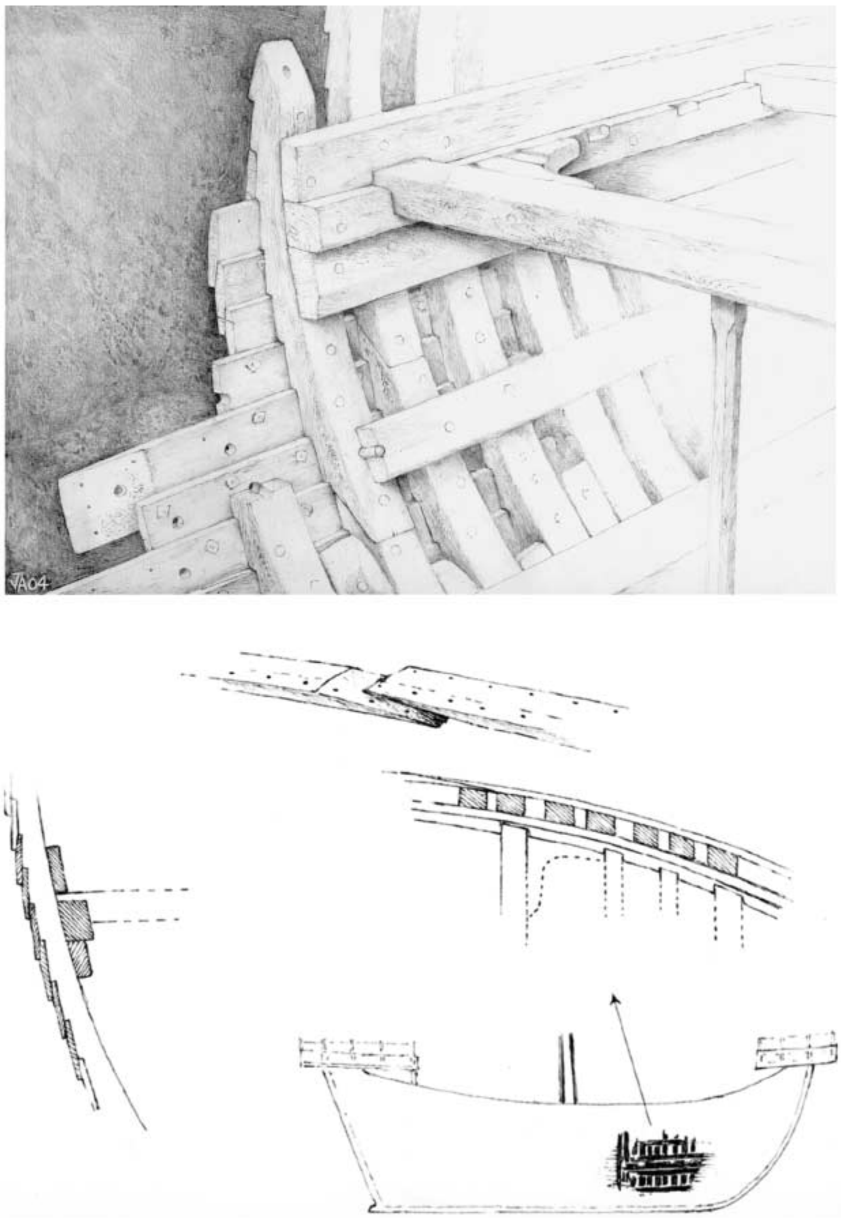


Figure 2-60 Reconstruction of hull structure and location within the vessel (after Adams 2004)

2.5.2 1993 Pepper Wreck

Castro (1998) notes the discovery in 1993-94 at the mouth of the river Tagus in Lisbon of a wreck site designated SJB2 containing the remains of a wooden hull, fragments of Chinese porcelain from the Wan-Li period (1573-1620), lead sheathing and a quantity of peppercorns. The preserved structure appears to represent the floor of the ship, immediately forward of the master frame (or frames) measuring about 12 m long by about 7m wide (Figure 2-62), including a section of the keel, eleven frames, and some of the planking (ibid: 382). Based on the documented loss of the Portuguese Nau, the *Nossa Senhora dos Máirtires,* returning from Cochin in western India with a cargo of pepper at this location, and a recovered astrolabe dated to 1605, the year the armada including *Nossa Senhora dos Máirtires* set sail from Lisbon, the wreck was assumed to be that of the Portuguese Nau (ibid: 282). As stated by Castro (2003:20), we do not know for sure if there was only one standard for the India naus in Portugal, during the 16th and early 17th centuries. We do not know exactly what these ships looked like, or how they evolved over time. We know little about their construction sequence, and are almost wholly ignorant about their structural strength.

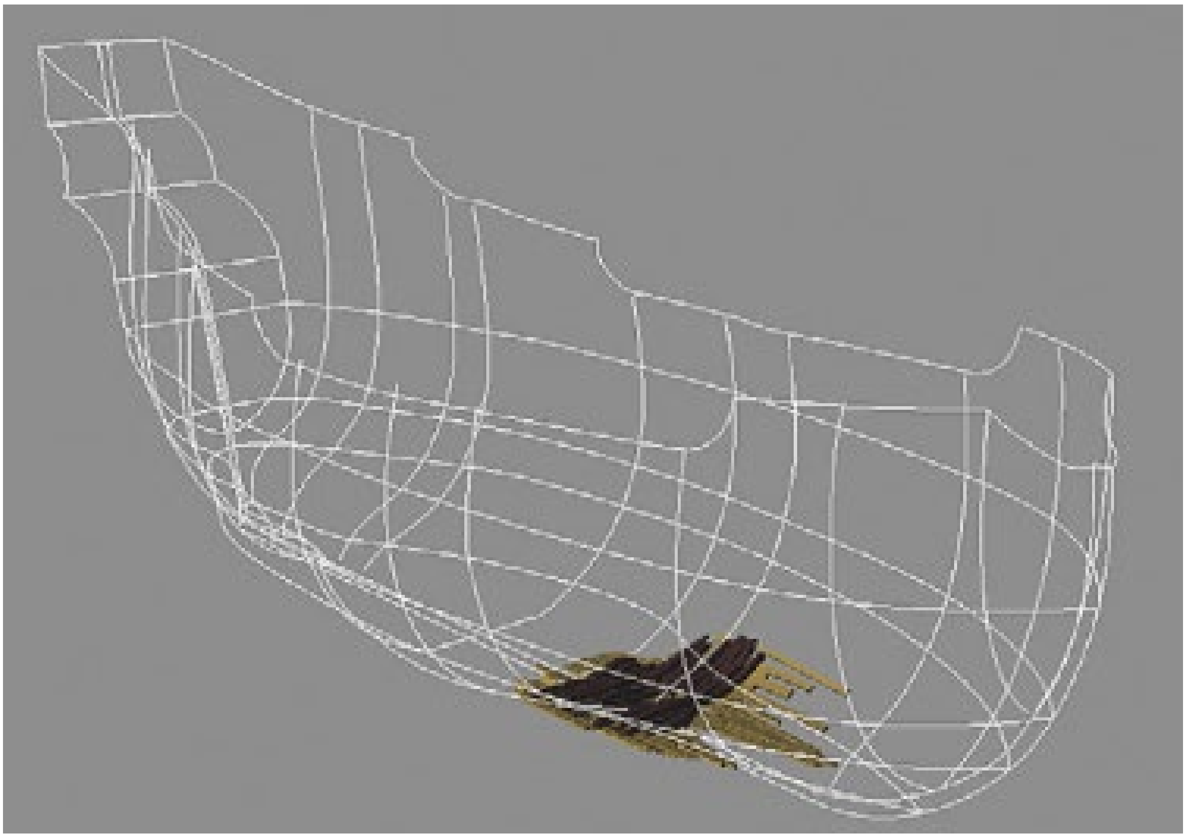
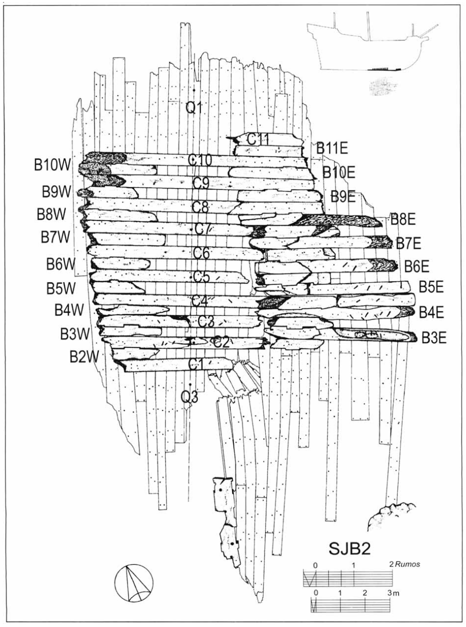


Figure 2-61 Estimated reconstruction with recovered elements (Santos *et al*. 2012)

Perhaps this wreck would have been better suited as a contributory reconstruction such as Adams did with the St Peter port 3 wreck (Figure 2-60) rather than the capital reconstruction suggested in Figure 2-63 and Figure 2-64.



Rather than undertaking a contributory reconstruction, a series of three texts (shipbuilding treatises) were consulted, the first was Fernando Oliveira's *Livro da Fabrica das Naus* of 1580, a translation of a previous work by the same author, Ars Nautica, of c. 1570. The second was the manuscript titled *Livro Primeiro de Arquitectura Naval*, by João Baptista Lavanha, written sometime around 1610, and the third was Manoel Fernandez' *Livro de Traças de Carpintaria*, dated to 1616.

Figure 2-62 Pepper Wreck Hull Plan (after Castro 2003)

Based on these treatises, and checked against measurements found on the surviving timbers, it was decided by Castro that a nau of 18 rumos of keel (27.72 m), as described in Oliveira's *Livro da Fabrica das Naus,* seemed to fit 'fairly' well[60]. Did a ship built in 1605 match a treatise written in 1570? As suggested by Rose (2011:71–72), and based on the finding of McGee (2009:223–24), (see Chapter 2.6.1.3) a re-examination of known wrecks should be undertaken to examine how closely their dimensions follow the principles set out in manuscripts.

Despite this, and Castro's own statement relating to the possibility of a false feedback loop[61] the relatively small portion of surviving remains was reconstructed into a ship of over 39 m in length and some 1,700 tons displacement.

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[60] Despite Castro's (2003:17) own reservations – "…given the reduced portion of the hull preserved, the hull reconstruction of the Pepper Wreck is a purely academic exercise, an educated guess at best." – the hull is reconstructed (Figure 2-63) from the lists of proportions supplied by Oliveira's treatise, resulting in a ship with an overall length of 39.27 m, a maximum beam of 12.32 m, and a displacement calculated from the reconstruction drawings of 1,100 tons at a depth of 4.62 m or 1,700 tons at a depth of 6.16 m. Of further significance is the fact that it is unknown from the records what the displacement was or whether the *Nossa Senhora dos Máirtires* had three or four decks. Castro states that despite being drawn as a three decked ship, the lines fit very well over the four decked ship represented in Fernandez' treatise of 1616 (ibid: 20).

[61] "The obvious example would be a shipwreck found with the keel dimensions and frame align nicely with a particular type of ship, that wreck might be assigned to that ship-type category in the database. If these similarities were merely a coincidence, the remaining dimensions from that wreck will then be a part of the classifying information for that ship type. Working with scant information, this type of stacking error is a real possibility and can lead to foundational faults in the database." (Castro *et al*. 2018:64).

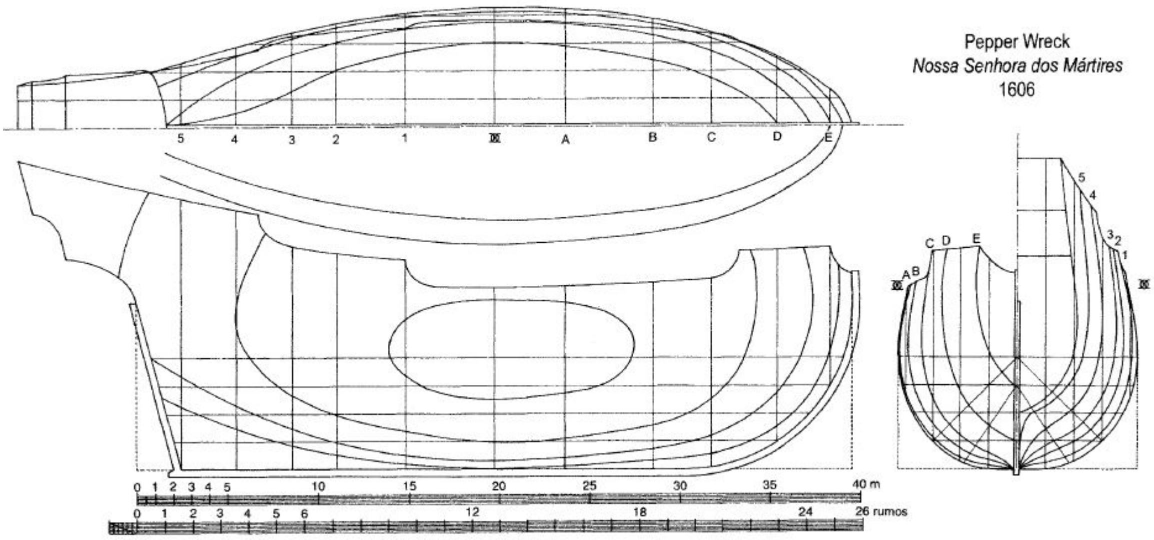

Figure 2-63   Pepper Wreck reconstruction (after Castro 2003)

Figure 2-64   A virtual reconstruction of the Pepper Wreck   (after Castro *et al*. 2010)

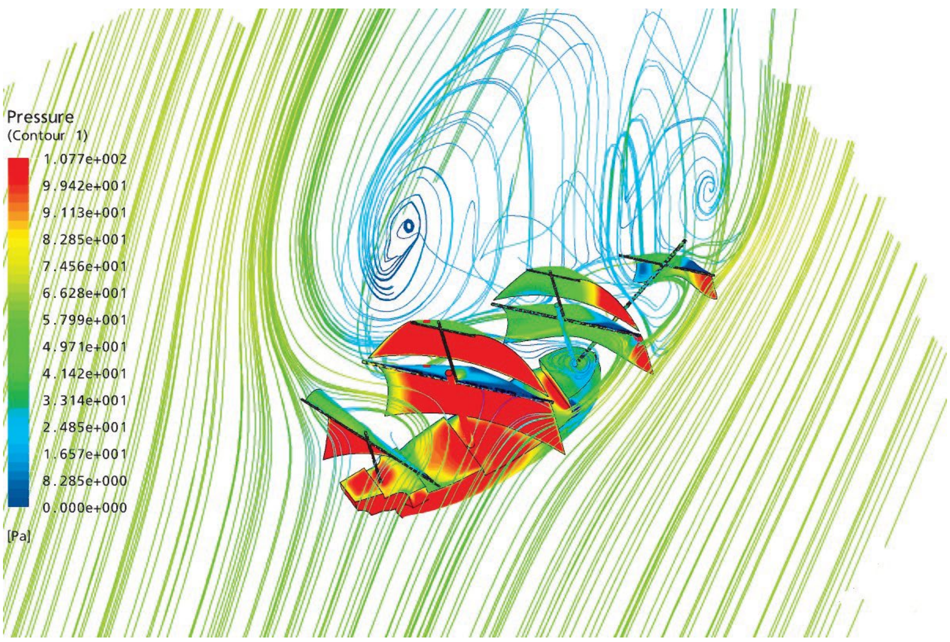

Figure 2-65   A virtual model of the Pepper Wreck under sail (after Castro *et al*. 2010)

The *Pepper wreck,* based on the reconstruction created from the treatise, has an additional 16 publications[62], other than the four cited above.

With a casual glance at Figure 2-65 or Figure 2-64, the reader could be forgiven for thinking some fantastically preserved example of a 17th century Portuguese Indiaman had been recovered, complete with detailed rigging and internal fittings. However, with three Portuguese treatises on shipbuilding and a handful of sets of rules on how to build ships— *regimentos* in Portuguese— combined with a further three *regimentos* with descriptions of rigging (Castro *et al*. 2006:110–11), the resultant reconstruction could at best be described as a hybrid, based on several literary sources, which would have better served as a contributory reconstruction, as depicted in Figure 2-61, or the excellent contributory reconstruction as illustrated in Figure 2-60 (after Adams 2004).

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[62] 2001 The Pepper Wreck: A Portuguese Indiaman: Castro, Filipe. PhD, Texas A&M.

2005a Rigging the Pepper Wreck. Part I—Masts and Yards: Castro, Filipe. *International Journal of Nautical Archaeology* 34(1):110–122.

2005b *The Pepper Wreck: A Portuguese Indiaman at the Mouth of the Tagus River*: Castro, Filipe. Texas A&M University Press.

2005 Study of the Intact Stability of a Portuguese Nau from the Early XVII Century: Fonseca, N., T. A. Santos, and Filipe Castro. *Proceedings of the IMAM 2005 Conference: Maritime Transportation and Exploitation of Ocean and Coastal Resources*.

2006 Os Navios Do Mar Oceano. Teoria e Empiria Na Arquitectura Naval Portuguesa Dos Séculos XVI e XVII by Francisco Contente Domingues: Castro, Filipe. *International Journal of Nautical Archaeology* 35(1):168–169.

2006 Sailing the Pepper Wreck: A Proposed Methodology for Understanding an Early 17th-Century Portuguese Indiaman: Castro, Filipe, and Nuno Fonseca. *International Journal of Nautical Archaeology* 35(1):97–103.

2006 Rigging an Early 17th – Century Portuguese Indiaman: Castro, Filipe, Nuno Fonseca, and Tiago Santos. In *Edge of Empire HELD AT THE 2006 ANNUAL MEETING OF THE SOCIETY FOR HISTORICAL ARCHAEOLOGY*, pp. 177–200. Caleidoscópio, Sacramento, CA.

2006 The Pepper Wreck: A Portuguese Indiaman at the Mouth of the Tagus River by Filipe Vieira de Castro: Loewen, Brad. *International Journal of Nautical Archaeology* 35(1):169–171.

2006 Stability Characteristics of an Early XVII Century Portuguese Nau: Santos, T. A., N. Fonseca, and Filipe Castro. *Proceedings of the 9th International Conference on Stability of Ships and Ocean Vehicles (STAB 2006)*.

2007 The Nau of the'Livro Nautico': Reconstructing a Sixteenth-Century Indiaman from Texts (Portugal): Hazlett, A. D. PhD, TEXAS A&M UNIVERSITY.

2007 Naval Architecture Applied to the Reconstruction of an Early 17th Century Portuguese Nau: Santos, T. A.; Fonesca, N. Fonseca, and F. Castro. *Marine Technology* 44:254–267.

2009 Rigging the Pepper Wreck. Part 2—Sails.: Castro, Filipe. *International Journal of Nautical Archaeology* 38(1):105–115.

2010 Numerical Models and the Dynamic Interpretation and Reconstruction of Medieval and Early Modern Shipwrecks: Castro, Filipe. *CMAC News and Reports, 2.1: 1-3*. (Figure 2-65 and Figure 2-64)

2012 Loading and Stability of a Late 16th Century Portuguese Indiaman: Santos, T. A., N. Fonseca, F. Castro, and T. Vacas. *Journal of Archaeological Science* 39(9):2835–2844. (Figure 2-61)

2013 Tonnages and Displacements in the 16th Century: Castro, Filipe. *Journal of Archaeological Science* 40.

2015 Moulds, Graminhos and Ribbands: A Pilot Study of the Construction of Saveiros in Valença and the Baía de Todos Os Santos Area, Brazil: Castro, Filipe, and Denise Gomes-Dias. *International Journal of Nautical Archaeology* 44(2). September 1:410–422.

2.5.3 2001 Cavalière wreck research models

In a combination of experimental archaeology and contributory research models, a project founded in 2001 at the Centre Camille Jullian (CCJ – Aix-en-Provence) under the supervision of Patrice Pomey, was carried out by Sabrina Marlier. It was based primarily on the construction at full-scale of hull sections of various boats that utilised different methods of sewn construction techniques (Marlier 2006). Inspired by the work of Steffy, who had led the way in the construction of research models of Mediterranean shipwrecks, the staff at the Centre Camille Jullian built a research model, at full-scale, of the lower portion of a Greek sewn boat – *Jules-Verne 9* (Pomey 1998:151–152, Fig 5 and 6).

In order to continue this research, the project set up a program adopting similar research models, which addressed different boats that displayed sewn construction techniques. The Cavalière shipwreck dating to circa 100 BC, found on the French Mediterranean coast in 1972 (Charlin *et al*. 1978) was selected as a good example of a specific family of boats found in the Northwest Mediterranean which date from the 3rd century BC to the 1st century AD. Characterised by a shell fastened with mortice and tenons, and frames fastened to the shell with stitching (Figure 2-66) secured by treenails (Marlier 2006:44).

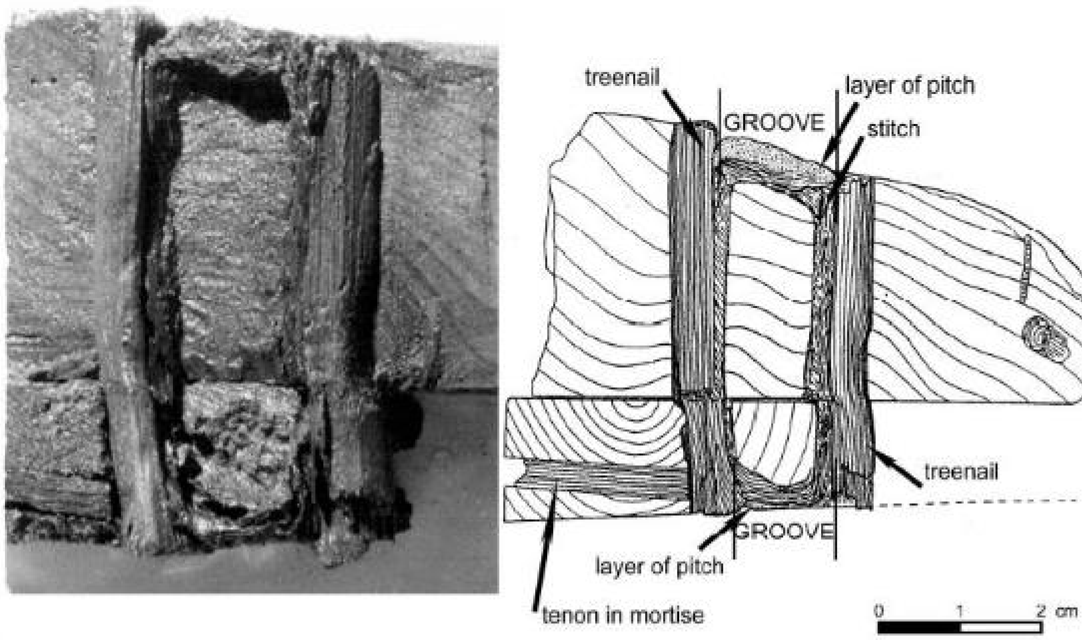
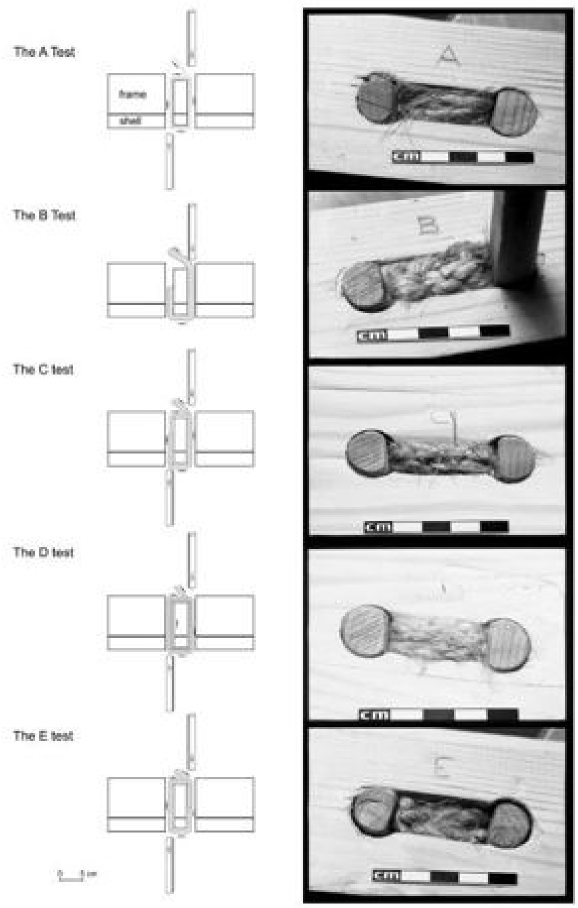


Figure 2-66 Detail of the *Dramont C* and drawing of the *Cavalière* stitching (after Marlier 2016)

The research model focussed on the central part of the lower hull including the keel, six strakes, two frames and two half-frames. A three-dimensional drawing was created from the published sections and plan drawings and was used as a reference for the construction of the research model. The keel, garboard and strakes were cut according to the original dimensions (Charlin *et* *al*. 1978) and assembled with mortice and tenons secured with pegs according to the drawings provided by the archaeological remains. Frames and half-frames were similarly cut out based on the archaeological drawings and with the help of cardboard templates (Marlier 2006:45).

The holes, channels and grooves matching the archaeological evidence (Figure 2-66) were created in the frames and corresponding strakes. Archaeological evidence from all the known shipwrecks indicated the stitching was likely vegetable fibre, but it proved difficult to determine how many strands formed each stitch, and whether the strands were twisted (two strands) or braided (three or more strands), drawings and the majority of photographs appeared to indicate braided stitching. However, the thickness of strands, and number of turns or passes through the material to be fastened, as well as the direction of insertion of treenails was difficult to discern from the archaeological evidence. Evidence of single treenails securing strakes and framing in addition to the sewn fastening was also included in the research model. A series of tests using differing diameters and lengths of strands was conducted (Figure 2-67).



- Test A, comprised a twist composed of two 3 mm diameter strands but not a braid, was rejected because it had no braid;
- Test B comprised a braid of 5 mm diameter strands, was too big and thus rejected;
- Test C, comprised a braid of 3 mm diameter strands, was rejected because the length of the braid was too short (50 cm);
- Test D, comprised a braid of 2.5 mm diameter strands, was rejected because the strands were too fine;
- Test E, comprised a braid of 3 mm each, as in Test C. However, with this length (min. 60 cm), the number of turns through the channels and the grooves, was more than two. Thus, this braid having been threaded still allowed sufficient passage for the insertion of the treenails, without protruding above the grooves and was considered successful.

Figure 2-67 Tests of various stitching methods (after Marlier 2016)

The locking treenails were driven from either side, following the direction of stitching, as being driven only from one side would cause loosening of the stitching where the treenail direction was against the stitching direction. The single treenails were found to resist the frames tendency to slide on the shell (Figure 2-66) thus avoiding the risk of snapping the stitching. The research model (Figure 2-68), approximately 1 m², has 10 single treenails, 6 m of braid and 20 locking treenails to attach the two frames and two half-frames, allowing an estimation of 750 single treenails, 450 m of braid and 1,500 locking treenails required to fasten the framing to the shell of the Cavalière ship which measured 13 m in length (Marlier 2006:48).

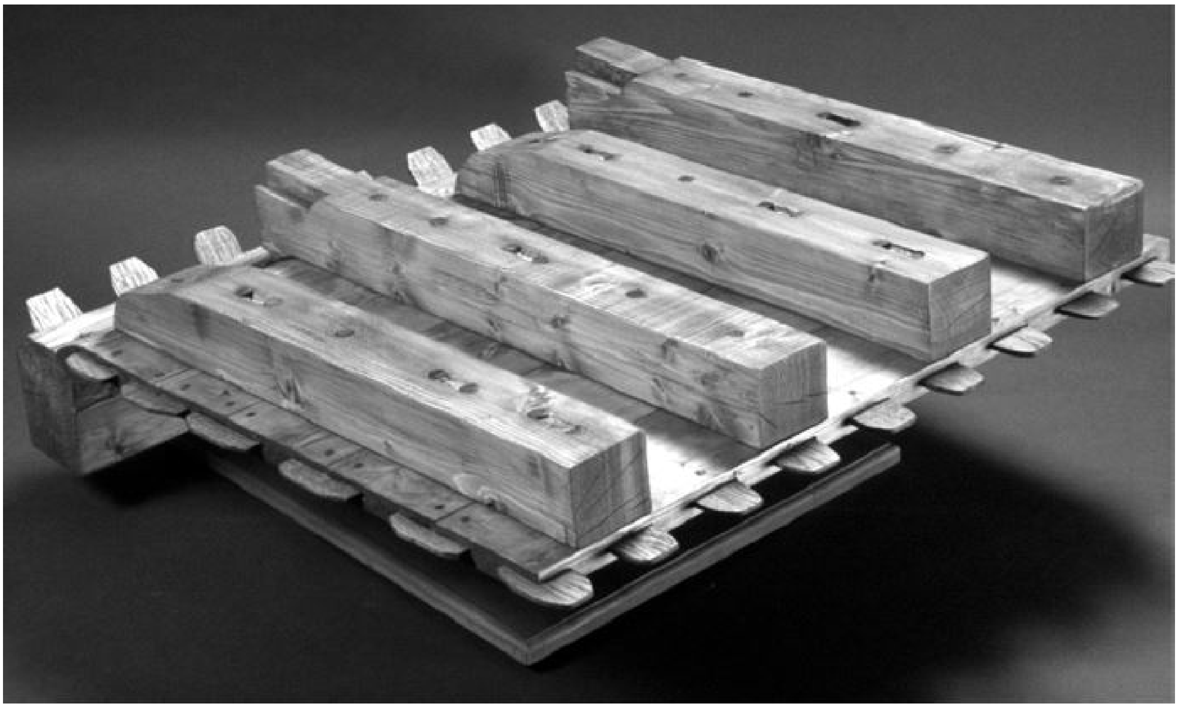


Figure 2-68 Cavalière full-scale research model (after Marlier 2016)

2.6 Source material used in reconstructions

While the majority of reconstructions discussed in Chapter 2.4 are based on the excavated archaeological evidence, in many cases there will be a need for supplementary evidence from other finds, or suitable alternative sources (cf. Crumlin-Pedersen and McGrail 2006:55). Muckelroy (1978) noted that regarding any aspect of researching the past, there are several approaches which may be used, depending on the type of evidence involved. The longest established and most developed of which, in studying seafaring, is the historical one. The ideas and information contributed by these approaches sometimes duplicate, and sometimes contradict each other, but above all should be viewed as complimentary in the overall field of maritime studies[63].

However, just as there is an assumption that iconographic sources (Chapter 2.6.2), such as ships depicted on seals, are accurate representations of the actual vessel, likewise there is an assumption in certain cases that literary sources (Chapter 2.6.1), such as shipbuilding treatises contain written instructions on how to build, or reconstruct a ship. The inclusion of such source material requires careful interpretation, and as noted by Crumlin-Pedersen and McGrail (2006:55) leaves room for a wide variety of proposals which should be narrowed down as much as possible.

2.6.1 Reconstruction based on Literary sources

As noted by Rose (2011:68–69) the correct interpretation of written documents, which were rarely if ever intended to supply technical information, and the use of archaeological material, which can leave important matters such as date and provenance obscure, is not only limited to 15th century ships. Rose states that what we currently know of the *Grace Dieu*, exemplifies how the study of medieval ships has developed:

> "the historian and the archaeologist working together in a *dual approach, both 'documents and digs' is often the most fruitful."* (2011:64).

As the adage states – a picture paints a thousand words – and some of the difficulties attempting to reverse that process, to recreate the image from a literary description can be seen in the attempt by Louis Paul (1915:57–58) to recreate on the drawing board a vessel based on a textual

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[63] As noted by Muckelroy (1978:5–7) the relationship between the two disciplines, the historical and the archaeological, can be complex, with each specialist having their own sets of evidence, and often their own sets of questions to answer, the increasing sophistication and specialised nature of each discipline means no individual can be expert in both. This does not mean that one should ignore the work of the other, but rather carefully consider the conclusions and integrate them within the research, indicating where a dichotomy or similarity occurs.

description. His attempted reconstruction of a sheer plan based on the Felucca described by Michael Scott as being:

> ‘50ft in length with a beam of 17ft, is absolutely flush decked, with her stern tapering to a point and peaked up like a New Zealand war canoe and perforated to receive the head of the rudder. A sharp beak forward like a Roman galley, and the bowsprit was a short thumb of a stick, 10ft high and rising at a sharp angle of thirty degrees. The mast being a strong stump of a spar, 30ft high and stayed well forward. With a large lateen sail affixed to a spliced and respliced yard of immense length which tapered into the sky.’

Paul states that a ‘bow like a Roman galley’ leaves a lot to the imagination, while a ‘stern like a New Zealand war canoe’ is even more vague still. Comparing the sheer plan by Paul with a contemporary photograph of a felucca (Figure 2-69) demonstrates some of the issues of a reconstruction based solely on literary sources.

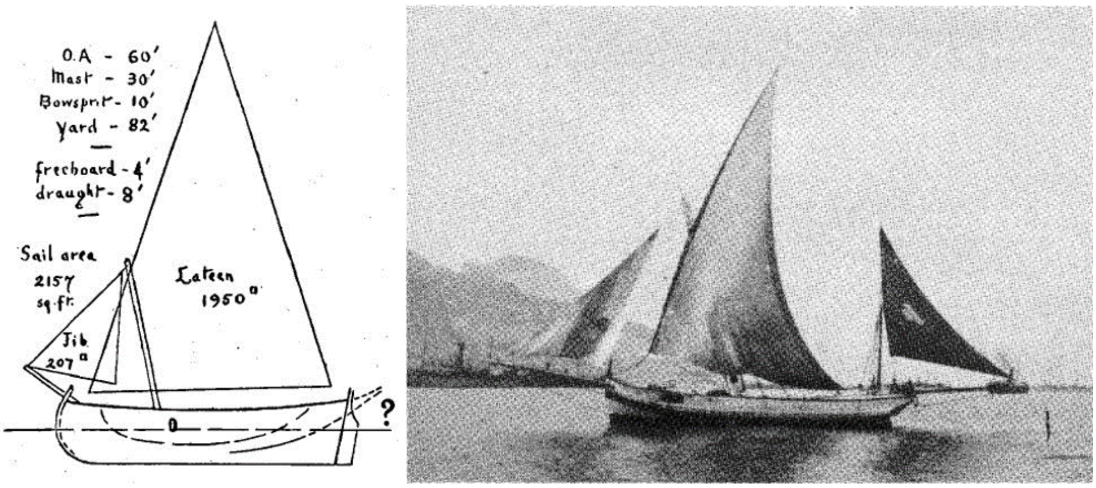

Figure 2-69 A Felucca drawn from litterary sources compared to contemporary photograph

2.6.1.1 The Cog

The term cog appears throughout literary sources, the German historian Paul Heinsius was one of the first to establish a set of criteria for such a vessel, a straight keel, with very high sides compared to the length of the keel, and relatively straight stem and stern posts usually raking (Heinsius 1956). It was suggested by Elmers (Gardiner and Unger 1994:29–46), that the earliest cog like vessels date back to Roman times, and these inland boats seem to have been the regional boat from the Rhine valley to the Wesser valley. In 2000 Crumlin-Pedersen published an article in which he reviewed 18 archaeological ship finds with a view to defining the archaeological use for the term cog. The discovery in 1962 of a wreck, afterwards to be known as the Bremen Cog matched several of the criteria set out by Heinsius, and the exceptionally good preservation of the wreck allowed the identification of a set of features in which this ship differed from contemporary ships built using other traditions. These features were taken to serve as the archaeological criteria for the Bremen vessel. As such the Bremen find for the first time enabled historians and archaeologists to match literary and iconographic sources of the cog with an actual archaeological find (Crumlin-Pedersen 2000:230–233).

Hocker (2004:73–75) notes that while the Bremen ship was not the first excavated vessel to be identified as a cog, it was the first to be widely known, and quickly resulted in the complete rethinking of cog development. Numerous examples built in a similar manner have been excavated or identified from older excavations, and by his count, a minimum of twenty-two share the essential characteristics[64].

[64] Of these, nine from the reclaimed Zuiderzee, five from Denmark, five from Sweden, one from Belgium, and two from Germany. Ranging in dates from ca 1150 to ca 1425, he suggests two noticeable chronological groups, one clustered in the 1150-1250 period and the other 1350-1420. The five earliest finds (Kollerup, Kolding, Skagen Kuggmaren, and Bossholmen) are from Scandinavia and all but Bossholmen show evidence of having been built in southern Jutland (Denmark). While this does not prove ultimate origins of the type, Hocker notes it does strongly suggest the neck of the Danish peninsula played an important role in the development of this type of craft into seagoing merchant craft.
Hocker (2004:75) slightly refines Crumlin Pederson's criteria into a list of characteristics, shared by all or nearly all of the major finds. Other characteristics such as the through beams, false stems or sternposts and the heavy standing knees are excluded as "typical" by Hocker, as they are either not present, or relatively few finds are sufficiently well preserved to reveal details of how the upper works were constructed.

2.6.1.2 The Hulk

The Hulk is another term from literary sources which has been the subject of much discussion and debate. The term first appeared in the laws of Aethelred II, who ruled England around AD 1000 (Robertson 1974). The term hulc or hulk continued to appear throughout literary sources, typically to denote a vessel which differs from the 'keel' (Anglo-Saxon / Scandinavian). The word continued in use throughout the Middle Ages and it has been assumed that the ships termed hulk in the 15th century derived from those termed hulks in the 11th century. The first "archaeological" mention comes from a paper in the Mariner's Mirror by Nance (1911:67) discussing another print of a 15th century ship also created by the Flemish artist known only by his signature "W.A."[65] (Figure 2-70) which is described as '*so strange as to be incredible'* but with sufficient distinctive features as to show some actual vessel such as a flute or hulk [66].

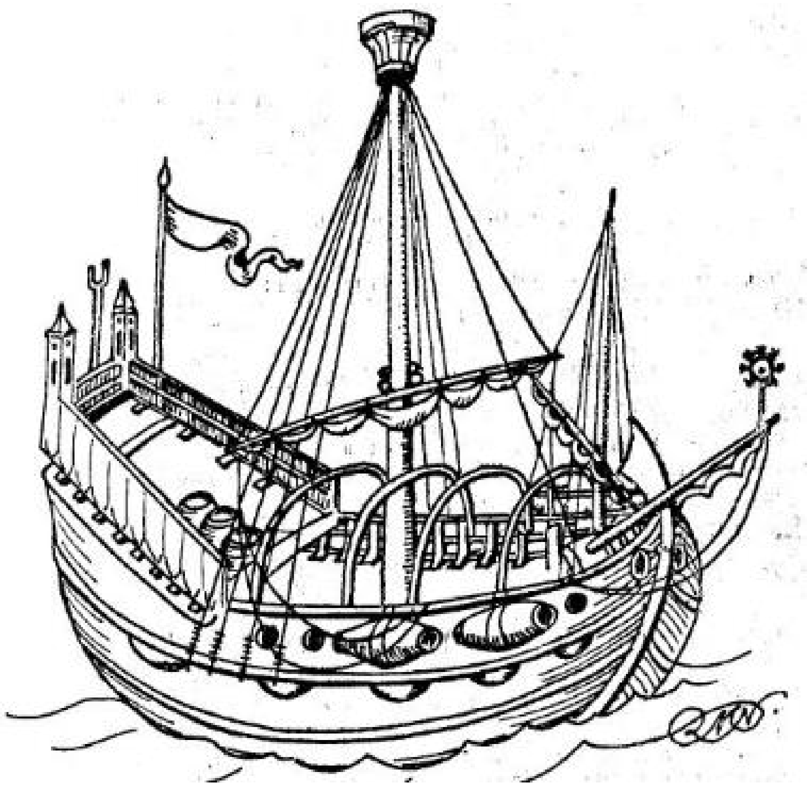

Figure 2-70 W.A.'s 15th century trader redrawn by R. Morton Nance (after Nance)

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[65] W.A. also produced the plate entitled "Kraek" or carrack which Nance (1911:67) describes as '*the most complete and convincing record of the rigging of his time*'.

[66]Nance notes the absence of a forecastle, the poop (stern castle) raised on stanchions, turrets are noted in the two aft corners of the poop, a feature seen in other 15th century ships, which Nance attributes to lanterns. Between these turrets is a crutch, which in other prints by the same artist is shown to support the peak of a lowered lateen mizzen yard. The absence of a mizzen mast would therefore suggest the crutch is to support the main mast when lowered. This together with the many barrels on deck and slung over the sides leads Nance to suggest a deep-sea fishing vessel, but the apparent awning supports need explanation. As do the round timbers beneath the middle wale which serve as fenders, similar to projections shown on medieval seals. Nance concludes that 'On the whole she seems more like a "flute" or "hulk" of the time than a mere "herring buss".

A link between the literary use of hulc and medieval depictions was first made by the German scholar Paul Heinsius (1956) in which he identifies three principal medieval ship types, the keel, the cog, and the hulc[67]. Research continued into the hulk with several publications[68] and Crumlin-Pedersen (1983:6–9) based on the their form and construction features, described hulks as rockered hulls with long parallel strakes without a true keel.

In 1994 Detlev Ellmers summed up the state of knowledge of the ships of the Hanse at that time, and noting the ship depicted on the Danzig seal from AD 1400 is described as a hulk in the written town records, and he confidently stated that the '*by the middle of the 15th century the hulk had completely replaced the cog in the Hanseatic area*' (Ellmers 1994:45).

Figure 2-71 Seal from New Shoreham 1295 and Danzig 1400 (after Ellmers 1994)

Hutchinson (1994:10) stated that archaeologists have applied the term hulk to ships which share specific hull characteristics rather than interpreting it as a general name for ships of a certain size. Those characteristics of the hulk have been deduced entirely from iconographic evidence such as the ship depicted on the New Shoreham seal (Figure 2-71) which features a thin crescent shaped hull with planking running parallel to the upper and lower edge and finishing at the platforms for the castles rather than at stem and stern posts (ibid:10-11).

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[67] The initial link between the verbal and iconographic data for the entire period is the town seal of New Shoreham of 1295, (Figure 2-71) 'by this sign of a hulk I am called mouth' a reference to the towns earlier name of Hulksmouth. Another literary reference written sometime before 1645 by Reinhold Curicke states '*Das Grosse Siegel ist eine grosse alte Holcke'* (The Great Seal is a large old Hulk) (Dunphy 1979).

[68] Cog-Kagge-Kaag (Crumlin-Pedersen 1965), Pictorial representations of the Hulc in 15th and 16th centuries (Waskonig 1969), and a series of papers by Fliedner (Abel et al. 1969) discussing 'The Origins, Development and Meaning of the word Hulc'. Glasgow (1972) agreeing with Heinsius' (1956) deduction that medieval hulks were clinker built with planks that curved upwards towards the ends. Kirby (1972) noted that the 14th century hulk in East Anglia was much smaller than those documented elsewhere, and McKee (1972) pointed out that by the 16th century the term hulk was used to describe large vessels no longer regarded viable. Weber (1973) published a note on a hulk depiction with three masts, and Andersen (1973) noted that hulks were large deep-sea freighters which could be either clinker or carvel built.

Greenhill (2000:4) stated that as far as the keel and cog are concerned, our knowledge has been greatly increased as a result of archaeological excavations, however no wreck of an identifiable hulk has been found and at the beginning of the 21st century we are still dependant on literary and iconographic evidence. He continues by listing more than 100 examples of what he states are depictions of a vessel type quite different from the Scandinavian 'post-Viking' keel type or the cog type. All of this iconography appears to depict a vessel which is curved both longitudinally and transversely, with what appears to be a long narrow flat keel curved up at the ends in place of a stem or stern post. Most depictions illustrate clinker planking, and in some cases the clinker is 'reversed'.

> 'It is by the characteristic run of the strakes, ending on horizontal lines at the bows and stern, or later at the bows only, that the hulc can always be recognised. This feature can be clearly seen. It is, indeed, really all we know beyond all doubt about the hulc, and it is on this feature, pending the discovery of archaeological evidence, that we must concentrate to deduce her hull form and something of her structure and, through these, hypothecate her working characteristics and her raison d'être' (Greenhill 2000:4–6).

While the term Hulk was evidently in use, as pointed out by Hutchinson (1994:10), it is applied to ships with specific hull characteristics rather than interpreting it as a general name for ships, perhaps it demonstrates the ability of archaeologists/historians to construct an entire ship type and set of characteristics with no archaeological remains. Adams (2013:99–109) states that of the five main features – pronounced hull curvature, reversed clinker, collars/stem ropes, planks not ending at the stem, and no visible posts – very few have all or even most of the characteristics believed to define the type. The ones that do are usually the most stylised, generally small, and often made by artists who did not have representational realism in the modern sense as a main priority. Adams concludes that the continuing problem in understanding medieval shipping posed by the hulk has been our continuing search for that which does not exist: 'The tantalising, but as yet unseen shipbuilding tradition is a myth' (2013:109).

Like the patent officer who requested permission from his superiors to close the office because there was nothing left to invent, it is a brave individual that declares there is nothing left to find. However, in the case of the 'mysterious hulk' I tend to agree with both Hutchinson and Adams that hulk as a term probably referred to any generically large cargo vessel.

2.6.1.3 Ship treatises

There are in certain cases an assumption that shipbuilding treatises contain written instructions on how to build, or reconstruct a ship. An example is the lines and body plan, sheer plan and deck layout of a *galea de Fiandra,* reconstructed by Ulrich Alertz (1995:159) using the information contained within the manuscript known as the *Fabrica di Galere*. A manuscript first described and dated to AD 1410 by Auguste Jal (Anderson 1945), but subsequently identified as a copy of the shipbuilding section of the notebook from Michael of Rhodes[69] (Long *et al*. 2009).

As noted by McGee (2009:223–24) the trend with Venetian manuscripts has been to bring all the extant texts together in order to derive from them, a generic technique thought to be applicable to the design of that respective ship type. This often involves the extraction of isolated facts which can be centuries apart, and results in a generic design which ignores the nature of the individual manuscripts. McGee states

> ‘we will discover that the first known Treatise of Shipbuilding has its origins, not in the shipyard, but in the medieval schools of commercial mathematics. We will find that there is very little evidence for the use of proportions, or of any other formal geometry in the text. We will discover that Michael’s drawings are not really “design” drawings – in the sense that they were to be used to determine the shape of ships. Rather, they are best understood as “graphic lists”, whose purpose was to make confusing written lists of measurements understandable to lay persons’

McGee sees treatises as a way of recording basic rules governing hull design or proportions, the finer details of which would be worked out during the construction in the shipyard (cf. Bellabarba 1993; Bellabarba 1996; Hocker and McManamon 2006).

Rose (2011:71–2) suggests that a re-examination of the two galley wrecks, Scandurra (1972:209–10) and D’Agostino *et al*. (2003) in light of McGee’s findings would greatly enhance our understanding of the shipbuilding procedures in relation to the written treatise.

This raises the question – If a shipwreck is reconstructed following the often-incomplete instructions from a shipbuilding treatise (cf. Castro 2005), is it the archaeological evidence which forms the basis for the reconstruction, or the rules and proportions as set-out within the treatise? Does the reconstruction become a circular argument supporting the treatise, resulting in a reconstruction which is based on a set of instructions, not written by shipbuilders for shipbuilders, but rather written by a layperson, for the benefit of lay people?

Rather than reconstructing a wreck in accordance with a written document, we should examine and reconstruct the wreck in its own right to determine how closely does the archaeological evidence follow the principles set out in the literary sources.

[69] Michael of Rhodes was not however a shipwright, and McGee (2009:237–41) has suggested that he included a section on the design of galleys and round ships in his notebook as an aid when teaching the skills needed to be a galley commander, and almost certainly Michael of Rhodes copied much of his text from earlier manuscripts (Hocker and McManamon 2006:10).

2.6.2 Reconstruction based on iconographic sources

Despite little evidence there was an assumption that ships depicted on seals are accurate representations of the actual vessel, the German scholar Herbert Ewe compiled a catalogue of over 250 seals depicting ships from the twelfth to the 16th century, and believed the Mayor or Councillors would have wanted an accurate and modern ship on their town seal (Ewe 1972:7–8). However the Mariner's Mirror has several notes discussing seals and how their circular form could distort the depiction thereby reducing the technical value[70] (see C.F. 1920a; H.B.B. 1920; C.F. 1920b).

It is clear that depictions of ships changed and developed over time, however, as noted by Flatman (2009), the time-lag between an object first appearing and its representation in art can be difficult to determine. As noted by Friel (2011:77) the Mariner's Mirror contains over 180 articles, notes, queries and answers relating to the iconography of medieval and 16th century ships, as well as many more on ancient and post-1600 ship representations.

While images can show details only alluded to in documents or seldom found in the archaeological record, it must be borne in mind, that any image is simply a representation of the creator's idea or concept of what that object or ship looked like, and is not the actual object or ship. These iconographic images need careful consideration if used as reference material, and as demonstrated by (Nance 1919) a French image of the *Grande Louise* appears to be a copy of an image created four hundred years earlier.

Some researcher and scholars have developed a strong case for the changing image of the ship and the development of maritime technology (Unger 1991; Villain-Gandossi 1994; Flatman 2009). Friel (2011:79–82) discusses the variety and richness of the material available in the Mariner's Mirror, as well as mentioning another visual index of early ships which outdoes the Mariner's Mirror, the extraordinary, if sometimes rather eccentric compilation by a German scholar *Das Schiff in der Bildenden Kunst* (Moll 1929) which contains 5,000 images dating from prehistory onwards. Friel cautions that until photographic printing became cheaper, much of the imagery reproduced was in the form of line drawings, and many of the images were probably tracings of

[70] Claridge (1959:77–81) notes that while paintings, sculpture and masonry are all valuable to the student of arts, in relation to maritime archaeology, the same paintings and drawings are so badly out of proportion that no reliability can be drawn from them. He continues that the only source of early shipping that can have any semblance of reliability are the seals of the great sea ports, but as these are also distorted to fit within the confines of the medallion, no hull contour or constructional detail can be ascertained save the assurance that medieval hulls were of clinker construction.

photographs. Some scholars are sceptical of line drawings as iconographic records because of the additional layer of interpretation added, as well as the potential risk of errors (Friel 2011:84).

One of the best exponents of line drawings was the scholar, artist and model maker Robert Morton Nance who always produced clear and concise sketches, and many of his papers ranging over five decades were based on visual representations, and in 1955 published a key two-part article entitled ‘The Ship of the Renaissance’ (Nance 1955a; Nance 1955b) which were based on iconographic evidence and chartered the development of the hulls and rigs from 1400 to 1600 (Figure 2-72).

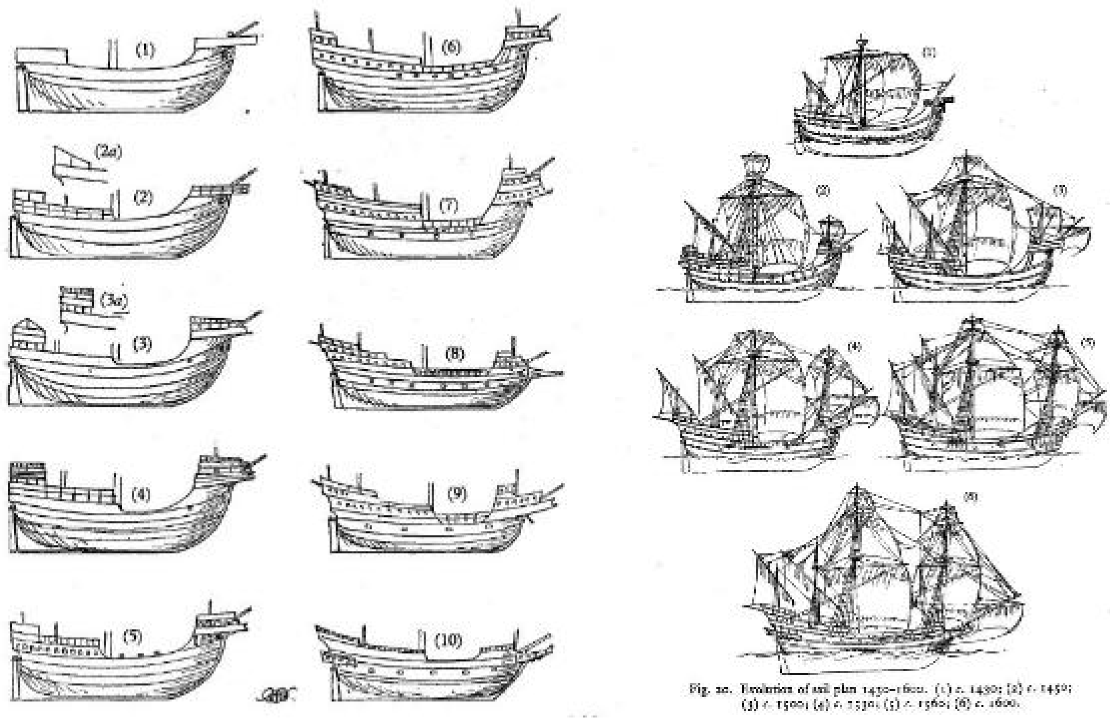
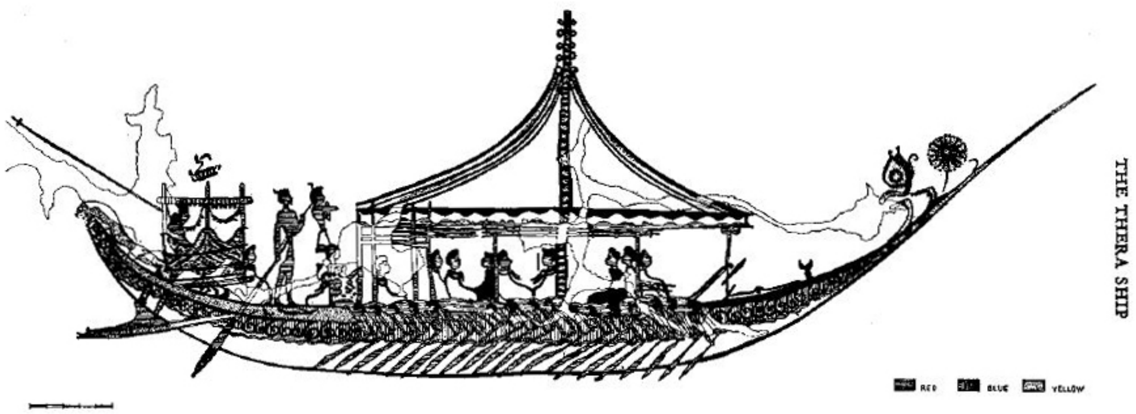


Figure 2-72 Nance's scheme of ship development from 1400 - 1600

Just as most scholarship gets overtaken by later work in some way, discoveries like the *Mary Rose* and Lawrence Mott’s discovery of a three-master as early as 1409 (Mott 1994) challenge some of Nance’s key ideas.

Other examples of ‘reconstructions’ based on iconographic sources include The Ship (Landström 1961), clearly the work of professional illustrator rather than a maritime archaeologist, and as noted by R.C Anderson in the book’s introduction, a welcome fact is the inclusion by Landström of the original images alongside his own interpretations, allowing judgement of whether the interpretations are justified.

Another reconstruction based solely on iconographic sources is the reconstruction proposed by Thomas Gillmer based on the Thera frescoes (Figure 2-73). On the basis that the two species of dolphins depicted within the fresco are technically accurate and lifelike, it is assumed that the other nautical details have these basic truths (Gillmer 1975:322–23). On the assumptions by Gillmer that the fresco is to scale and the artist maintained a reasonable degree of realism, Gillmer calculates the ship to be 28 m long, which based on contemporary (ancient Minoan) length to width ratios, gives a beam of 7.1 m, with a mast height of 13.5 m and sail area of 120 m² (ibid: 326). However, this apparent assumption by the author results in the helmsman figure having a stature of between 2.5 and 3 m.



The restoration of the complete ship in the miniature fresco of the 'West House'. The crew with paddles, the unique stern platform, and the extended bow decorations are all unusual and surprising features.

Figure 2-73 Thera Ship Fresco (After Gillmer 1975: Fig 1)

It seems we would do well to remember Friel's warning (2011:77) that any image is simply a representation of the creator's interpretation of what that object or ship looked like and is not the actual object or ship. Any reconstruction, which by definition is a hypothetical interpretation, when based solely on another individual's graphic interpretation, can only be of limited value.

Take the example of 'reconstruction' based on iconographic sources by Claridge (1959:77–81) as an example of what he calls 'a typical coastal workhorse of that century'. In this peculiar vessel, with pre-standing control frames, which are joggled to take the stepped clinker hull planking, the hull planking itself is triple thickness clinker, and fill-in frames with smooth-faced exteriors are then fitted between the pre-erected framing, where wedges are used between smooth frame and stepped planking to provide good bearing, all secured using both iron clench nails and treenails which are driven outboard from the interior. I can only hope no such 'typical coastal workhorse' is ever discovered, for the soup-like mixture of construction features (Figure 2-74 top), combined with the reversed clinker hull planking (Figure 2-74 bottom) is sure to baffle even the most ardent classification-focussed archaeologist.

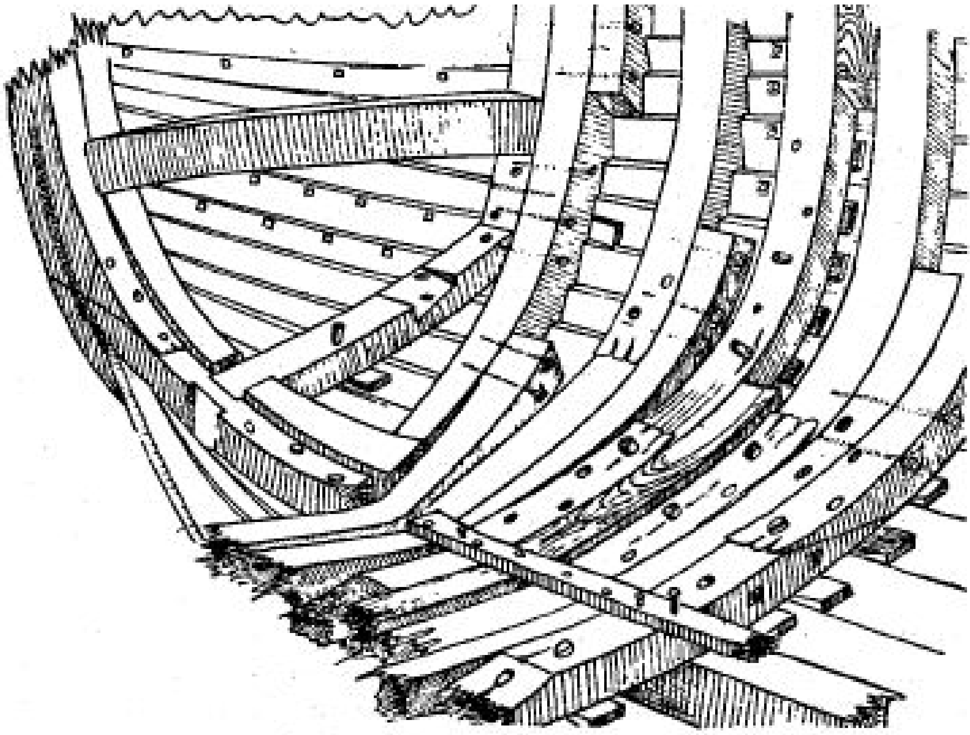


Fig. 2

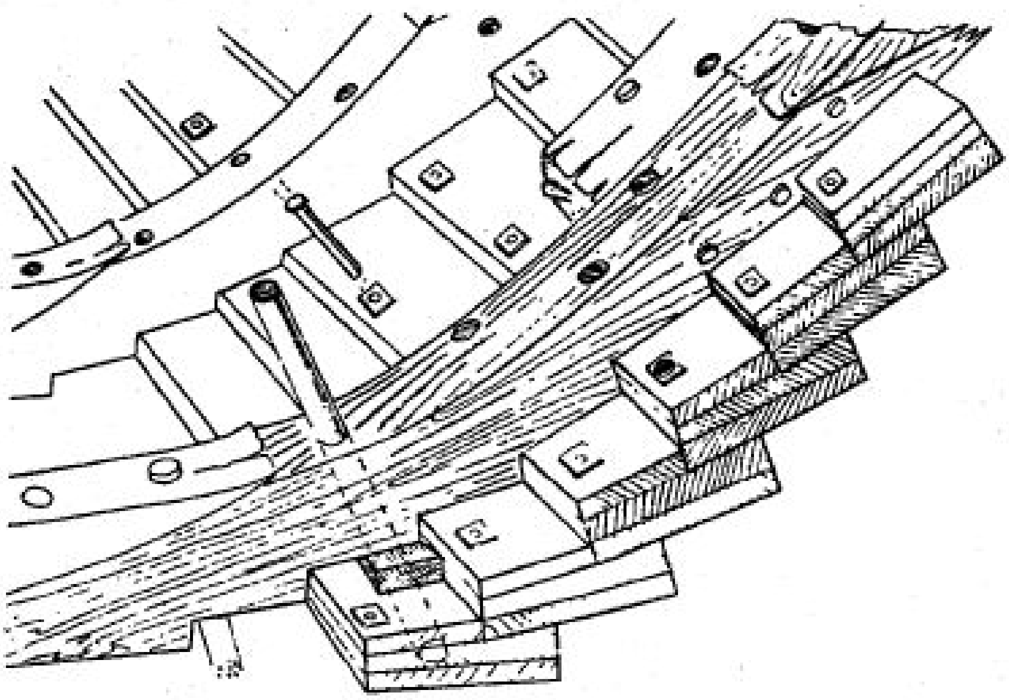


Fig. 3

Figure 2-74 Typical Coastal Workhorse (after Claridge 1959 Fig 2 and 3)

The previous sections have outlined the various, and varied, practical efforts that have been undertaken to reconstruct ships from archaeological, literary, iconography and historical sources. This has taken place since the 19th century, and in earnest since the mid-20th century. But the accompanying conceptual theoretical approaches have lagged behind and have not undergone development within academic literature until the 1990s. It is to that theory that our attention now turns.

Chapter 3 **Literature Review of Conceptual Approaches**

3.1 Introduction

J. Richard Steffy occasionally referred to the philosophy of shipbuilding, by which he meant the fundamental conceptual approach underlying a particular ship's design and construction. This conceptual approach, the product of an individual shipwright's set of assumptions, cultural and personal biases, and technical experience, could be detected in the details of the ship remains. To achieve this required a particular set of skills which Steffy brought to his work, a combination of academic rigor, practical mechanical sense, and the willingness to think in terms outside of one's own practical experience (Hocker 2004:1).

The classification of ships/boats is a theme that runs alongside reconstruction because it is directly related to how we think about and understand the archaeological remains. Literary sources use many terms to describe vessels, the table of ships hired by the Crown in the 15th century includes the types balinger, barge, cog, crayer, dogger, farcost, hulke, navis and spinace, while a similar list of all the ships using Chichester harbour in the years 1464-1514 includes 23 different terms (Burwash 1969). The fact that many literary sources are lists, consisting of classifications or groupings, has by their very nature, unsurprisingly led to a quest for classifying archaeological remains. Many of the conceptual approaches and classification attempts, focussed on archaeological reconstructions, which are discussed in the following sections, have developed within maritime archaeology and history alongside the physical reconstruction work described in Chapter 2. It is worth noting, that the theory/concepts have developed in the wake of the practice, and very rarely has the practice been driven by theoretical ideals.

Some classification attempts have proven more successful, such as the cog (Chapter 2.6.1.1), although a certain unease has led some practitioners to append the suffix 'of the archaeological tradition' (Dhoop 2016:47) to the cog classification (cf. Maarleveld 1995; Weski 1999; Crumlin-Pedersen 2000). Certain *de facto* classifications have arisen from the plethora of excavated examples, while others like the hulk (Chapter 2.6.1.2) have proven less beneficial. It is clear as will be shown, that careful consideration is a prerequisite, as labels by their nature can prove misleading, and perhaps 'of the archaeological tradition' should be appended more frequently.

3.2 Classification of Ships

The classifying of ships has long been a difficult issue, even in the 19th century, the Admiralty struggled with classifying the new types of their own vessel (Brock 1978:21–22). Hornell in 1946 used a grouping system of: Group A, floats, rafts and kindred craft; Group B, skin boats such as coracles, curraghs, kayaks and their kin; and Group C, bark canoes, dugouts and plank-built craft. Plank built craft are discussed in chapters 11 to 19 and are described as having a genetic relationship to the earlier boats of each grouping (Hornell 1946).

Maritime tradesmen and boatbuilders have been aware of the clinker/carvel distinction for centuries, the difference is immediately apparent to the eye, but also represented two types of construction where the assembly techniques are the opposite of each other[71]. During the 16th century this distinction becomes the basis for both a conceptual and practical division of watercraft. Clinker construction was considered a lower, less prestigious form of shipbuilding in the Low Countries, and guild regulations sometimes indicated that clinker building was the only type of work available to non-guild members (Hocker 2004:5).

In 1963 Olof Hasslöf, former director of the Swedish Maritime Museum, introduced the terms ‘shell-built’ and ‘skeleton-built’ instead of ‘clinker’ and ‘carvel’. Hasslöf noted that the shape of a shell-built boat came from planking which was formed, erected and fastened together before the strengthening frames were inserted. While skeleton-built boats on the other hand, it was the framing that determined hull shape, and this was erected first, before planking was fastened to it (see Hasslöf 1963; 1966).

Basch (1972:15–17) further developed the concept of shell and skeleton building as modes of naval construction, noting that the classification using clinker-built or carvel-built only related to the external appearance of the hull and is not particularly illuminating with regard to the underlying construction. Bash describes ‘skeleton built’ as joining the planking (a waterproof skin) to the framework (pre-erected structural skeleton) but notes that nothing prevents the planking from also being edge joined to each other. In ‘shell built’ the planking is assembled first, to produce a watertight shell, which on its own could not stand up to the sea and is subsequently strengthened, by the insertion of an inner framework. In ‘shell built’ the planking can be joined by overlapping (clinker) or by joining edge to edge. In the latter, the outside appearance gives the impression of carvel building, but it is obviously not a sure guide to the underlying construction.

In addition, the actual method of edge joining can be achieved in several ways: by clamps either temporary or permanent; by edge nailing; by tying or sewing; and by mortice and tenon or dowels. In the ‘shell built’ technique the shape of the frames is dictated by the form of the

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[71] In their simplest form clinker vessels are assembled by joining the planking first, to create a watertight shell, with the framing inserted afterwards, to add structural strength, while carvel vessels are assembled by erecting the frames first, followed by bending and fastening the planking around them.

planking and Basch labels these frames as 'passive'. In the 'skeleton built' technique the frames dictate the form of the planking and Basch labels these as 'active'. (ibid: 16).

Basch (1972:18–50) identifies several 'anomalies' which do not appear to sit comfortably in either classification system. Boats with flat bottoms and without keels exist among both clinker- and carvel-built boats, which would appear to derive from neither the 'shell' not 'skeleton' technique (cf. Hocker 1991). Iconographic evidence, as well as archaeological evidence exists in the six boats discovered at Dahshur clearly illustrating Egyptian boats without framework (Reisner 1913:83–86). Hybrid constructions such as edge joined planking, usually the hallmark of 'shell built' combined with one or more pre-erected frames such as used along the Gujarat coast (cf. Hornell 1946:193–4).

The stress on the importance of the shell or skeleton in determining the shape of the hull has remained a primary aspect of the shell/skeleton distinction. Basch (1972:34) states that

> "pure 'shell' technique means that it is the shape of the assembled strakes that dictate the shapes of all the frames. It implies that no moulds have been used..."

The use of moulds generates a fundamental question – What can be the shape of the planking if not the shape of the hull itself? Moulds are subdivided into two roles: a theoretical role, where moulds determine either directly or indirectly (by determining the shape of one or more frames), the shape of the planking and therefore the hull; and a material role, such as a mould used in a shipyard to force the planking into preconceived shapes.

A ship whose planks have not been 'strained' can hardly take anything but 'spoon-like' shapes, consequently 'strained' planking suggests some device such as a mould might have been used to achieve such an artificial shape. Moulds can be temporary, with planking shaped onto the mould, which is then withdrawn, leaving no evidence in the finished hull (type 1) or the midship frame, shaped in accordance with a mould, positioned onto the keel and incorporated into the finished hull (type 2) (Basch 1972:35)[72].

Greenhill (1976:60–75) was one of the first to break from the emphasis on construction sequence. While accepting the difference between edge joined and non-edge joined boats, he noted that if the line of development of each separate boat type was known, it would be possible

[72] Other types of mould not mentioned by Basch are portable moulds used to control the shape, such as: a boat-ell, a stick on which the builder recorded a series of marks that describe important measurements of the ship such as distances from the edge of each strake to a baseline (Christensen 1972:239); boat levels, a board with a small plumb-bob to define angles of strakes (Christensen 1972:240–1 fig 2a and fig. 2b); and bevel boards used to record bevel angles between strakes to control cross-sectional shape, or frame bevels controlling fore-and-aft shape (McKee 1983:110). Likewise, external braces to strain planking into predetermined shapes can also be considered as a form of moulds.

to categorise all boats from their origins into four general groups, because boats began in four principle ways; raft; dugout; skin boat; and planked boat. In the case of planked boats, f**or the edge joined boats the shape was first visualised as a shell of wooden planks, whereas for the non-edge joined boats the shape was visualised as a skeleton which gave shape to the planks**.

According to Greenhill (ibid: 61) edge joined hulls were built in a process akin to sculpture, with little or no measuring devices, save measuring from a centre line for rough symmetry or the use of a building level or boat ell as described by Christensen (1972:240–1 fig 2a and fig. 2b), or they may have been built by eye alone. Greenhill (1976:66) stated edge joined was easily identifiable in the form of clinker planking, and mostly signified a shell first construction, although exceptions were possible, carvel on the other hand as a definition was meaningless and should be dispensed with altogether(ibid: 75). The remainder of the publication focuses on classifying watercraft based on their roots: raft and raft boats; skin boats; bark boats; and dugouts. The remainder of boats having evolved from these principal roots.

McGrail (1977a:126–33) states classification as attempted by Fox in 1926, Graham in 1966 and others, based solely on morphology is inadequate, and Ellmers attempt in 1973, to define five logboats differentiated by their transverse sections and the shape of the ends, is of limited value due to being based on a small sample of finds. Estimates of performance such as ability to carry cargo is suggested as a method to compare and contrast logboats, but only when this data is available for a large sample of logboats can classification schemes be attempted.

McGrail's suggested classification is based on three roles, people carrying, bulky loads, and high density cargoes, resulting in six categories: all-round performance; high density cargo carriers; personnel carriers; bulky cargo carriers; bulky cargo and personnel; and unplaced (relatively poor in all three roles), which are all further sub-divided into first-rate and second-rate (ibid: 127).

Ellmers (1979:491–498) states that scientific research used to process the ship hull, allows for statements about the structure, load capacity, shape and position in the water etc. However, to study the mode of operation of the ship, it is necessary to investigate many elements such as cargo and armament, and naturally the crew. These questions can only be assessed by the person who knows the vessel, just as questions regarding port and loading facilities or shipbuilding sites can only be properly examined by somebody who knows the associated ships. He states that a comprehensive picture of the development of shipping can only be obtained by considering not only the hull, but also the equipment and facilities necessary for the operation and navigation. He suggests ship archaeology be summarised in the following scheme:

1. Watercraft: a) types; b) shipbuilding traditions.
2. Operations on board: a) marine equipment; b) crew equipment; c) cargo.

3. Ports: a) port facilities and loading facilities; b) shipyards and boat sheds; c) harbour settlements (topography and social structure)
4. Waterways: a) Inland waterways; b) artificial waterways (hydraulic works, tow lines etc); c) facilities and organisational forms of traffic on the waterway; d) sea shipping
5. Shipping and Culture: a) sanctuaries of boatmen; b) boat graves; c) votive boats; d) cultic ship representations; e) customs aboard the ship

It is clear he states that there is an overlap between ship archaeology, and what he calls ‘general archaeology and settlement archaeology’ which often occurs (Ibid: 492-3).

With relation to type, Ellmers notes that the historian is directly given a ship or boat type in the form of written designations, whereas the archaeologist is faced with a bewildering array of differing shapes, which are more or less related to each other, and can be grouped into types. However, lacking direct correspondence makes it difficult for the historian to comprehend construction size, carrying capacity or sea-keeping characteristics, and for the archaeologist to comprehend possible uses, destinations or journey times.

> “In a nutshell, the ship find is dumb, and the written record remains blind, as long as it is not possible to relate the two to each other” (ibid :495).

Bringing the historical and archaeological record together while seemingly simple, is more often rarely feasible in practice. Ellmers (1972:11–15) stresses the need for ‘*kontaktquellen’* ‘sources of contact’, and suggests three groups as contact sources:

1. Where the name is either directly inscribed, indirectly by mention of that exact thing in written sources or the identification of the object and name are already given (Vasa cited as an example)
2. A description of a vessel, so detailed and descriptive as to provide sufficient characteristics for a secure identification (ships from the Ijsselmeer polders cited as examples)
3. Ship representations in which the type is known by caption or other text relating to the image (Bremen identified as a Hanse-Kogge through the use of ships on seals of the Hanseatic cities such as *Straslund*, *Elbing* etc cited as an example)

Even where copious written records exist, such as the ‘mysterious’ Holk or Hulk, clearly depicted in side view during the late Hanseatic period, the absence of a ship find merely means the archaeologist must be patient before anything can be said of its exact construction or sea-keeping characteristics.

Ellmers (1979:493–496) notes that other valuable information can be gained from the historical records, such as the Icelandic Sagas which clearly state that warships went from Norway via the Orkney Islands to England, but not to the Faroe Islands or Iceland because of the danger of storms, only merchant ships went there. Ellmers also mentions that each of the five ships sunk in Roskilde Fjord belong to a different type, and warned both archaeologists and historians that the ‘range’ of ship types currently being used is too limited (ibid 1979:495). This comment by Ellmers on the range of ships being interpreted is most certainly valid, and despite the significant sized discoveries such as those at Yenikapi, Barcode, Roskilde, Naples and Dor/Tantura among others, the aggregate assemblage of ship remains is still but a miniscule percentage of the total watercraft constructed.

Crumlin-Pedersen (1983:6–9) identified four classes based on form and construction features, which he believes are the antecedents of most Northern European vessels: Nordic Ships – round bottom clinker vessels; Cogs – flat-bottomed with stem, stern-post and flush bottom planking; Punts or Barges – flat-bottomed vessels with square ends and vertical sides; and Hulks – rockered hulls with long parallel strakes without a true keel. Each of which developed to become ocean-going cargo carriers in Northern Europe.

McKee (1983:80–83) attempted a morphology based classification using British working boats as an example, and set out to describe the shape of vessels. From this McKee states that by no means are the several thousand structurally possible combinations of the available features found in types of British working boats, but about forty would cover the identified types, some fitting into just one classification, while others which are broadly similar types fit into several categories. The situation, he noted, is not static. Starting with a classification based on the keel, its existence, partial existence or absence, and the midship sectional shape resulted in three categories. This was further subdivided using the shape of topsides and ends, producing five categories. Further subdivision based on bottom profile produced seven categories. And further subdivisions resulted in a final 11 categories.

McGrail (1984:26) suggested that if standard rules for describing a boat find, based on internationally agreed attribute lists, can be evolved, then comparisons between finds becomes possible. An objective classification of features, by attribute states, could be achieved by reference to published drawings, thereby minimising language translation problems. Such sets of ordered archival material should be stored in international data banks and are considered essential by McGrail if progress is to be made in maritime archaeology.

McGrail (1985b:289) states that during the past 100 years several attempts have been made to classify the varied material man has used in his exploitation of lake, river and sea. These have not been entirely successful, due in part to the problems of definition and methodology. Early attempts at classification were seldom systematic, with authors often diverted into fields of ‘evolution’ or ‘development’.

McGrail attempts to devise a general classification scheme for boats and ships, to identify primary classes, each composed of individual members relatively similar to other members of their class, but sufficiently dissimilar to members of other classes. If this can be achieved, then each class should convey the same image to all users of the scheme, and newly observed units of water transport may readily be allocated to one of these classes by reference to key, diagnostic attributes (Ibid: 289).

McGrail (1985b:291–98; 1987:4–11; 2001:7–11) suggest an approach in which structural considerations take precedence over choice of raw materials, and in which the attributes identify, whenever possible, choices which have cultural significance. The form or shape will vary with desired function, and emphasis on structural differences may reveal culturally determined principles.

Other structural differences may be seen in the choice of techniques the builder makes when converting his raw material into a boat. For the choice of techniques McGrail (1985b:292–93) lists three approaches: Reduction, where the raw material is reduced in volume as in the hollowing of a log to make a logboat or in the fashioning of a log to make a keel; Construction, the junction of several smaller parts (some of which may have been obtained by reduction techniques); and Transformation, altering the shape of the material without addition or subtraction.

Based on this scheme, McGrail arrives at 14 classes of boat (C1 to C14) distinguished by the states of two attributes: shell or skeleton; and principal techniques (Figure 3-1).

This classification system may work well with simpler vessels such as logboats, but if applied to 'more-complex' vessels, does the classification scheme still convey the same image to all users of the scheme?[73]. The reverse problem can also be seen in the case of the *Hürï*, where the same vessel in the eyes of the builder and user, has, due to changes in material availability or user budget, resulted in differences to building. This makes for two (or more) different classes for a boat which at least socially, culturally, and in general overall form, is the same thing (Blue *et al*. 2017).

[73] take *Skuldelev 1* as an example. Clearly a boat, with its buoyancy derived from the whole vessel. The fundamental concept is 'shell-built' with frames added after planking. For the principal techniques, the builder used: reduction (R) fashioning the keel and posts, as well as radially splitting logs to form planking; construction (C) is used in assembling the constituent parts; and transformation (T) is used bending planks to form curved strakes. This combination of R, T and C puts *Skuldelev 1* in the C7 classification.
Taking another boat, using reduction to form the keel, posts and radially split planking, construction to assemble the elements, and transformation bending planks to form strakes, is also classified as C7, that boat is the *Newport Medieval ship*.

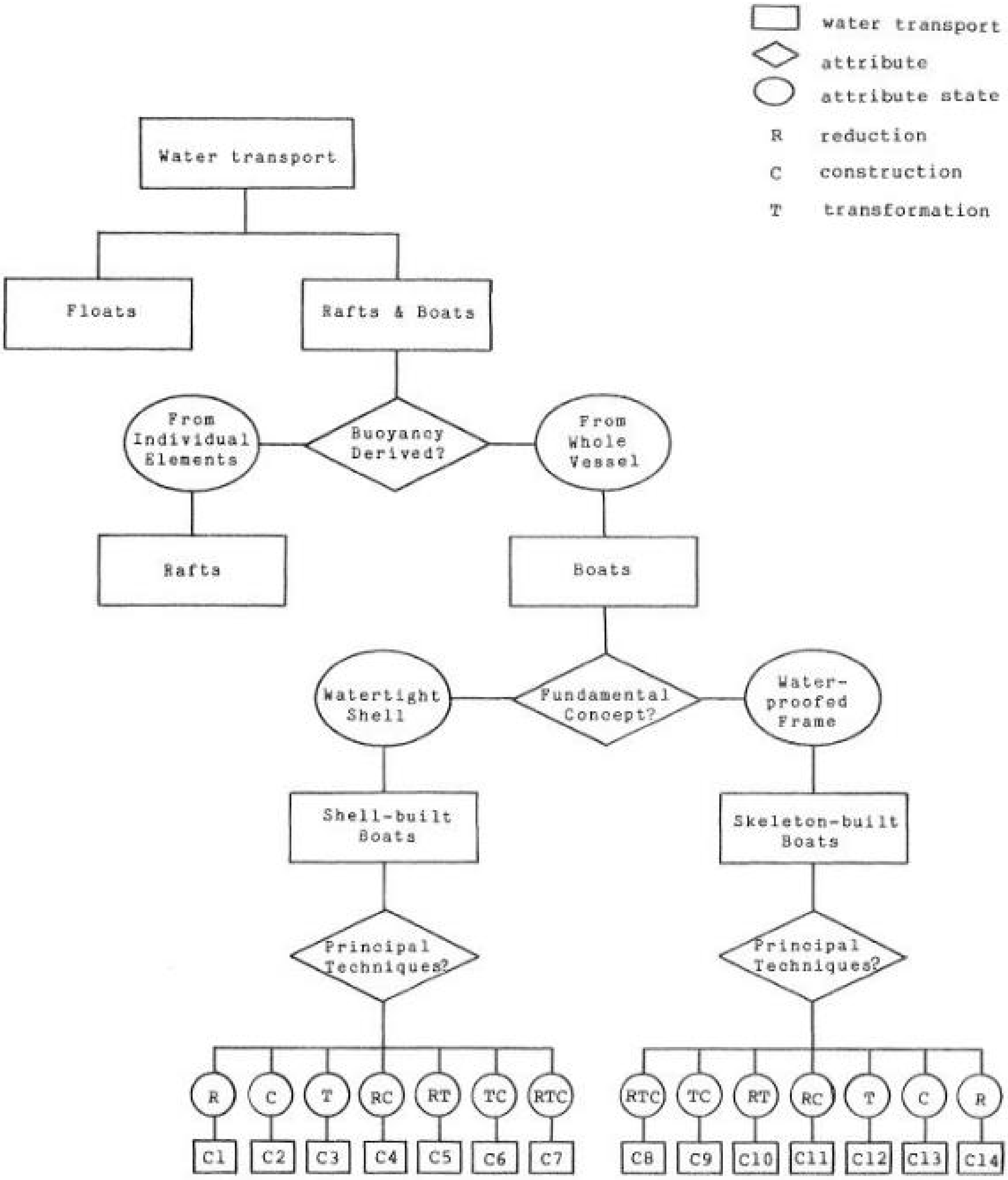

Figure 3-1 Classification of boats (after McGrail 1985: 296)

Perhaps highlighting some of the difficulties with McGrail's classifications, Arnold (1991) suggested at the 1988 International Symposium of Boat and Ship Archaeology (ISBSA) that the flat bottomed craft from Lake Neuchâtel should stand outside the traditional classification and belong to a tradition of their own. These boats with their heavily built, flat bottom, where the bottom was the primary element in determining the shape, were seen as the product of a specialised construction sequence. A conceptual classification of 'bottom-based' was proposed for these and similar watercraft. A separate conceptual stream further developed in a doctoral dissertation by Hocker (1991).

Maarleveld (1991:94) states that 'The classification of ships is known as one of the most dangerous of maritime professions', and that traditionally typology has been an important aspect for archaeologists, as evidenced by the flood of stimulating publications on classification methods and their application to archaeological data since the 1960s. Despite the traditional typological and modern analytical preoccupations with the classification of archaeological data, the literature on ships, ship types and shipbuilding traditions is anything but consistent in terms of classifications and classification criteria.

Regarding archaeological research Maarleveld differentiates between grouping, the organising of data into groups to facilitate ease of handling, and classifying, in order to guide research or use in an analytical sense. The first is a grouping of the data in order to come to terms with the varied and confusing information. This is an arbitrary procedure, where the objects are placed in heaps or groups. Often this grouping can have a very limited validity, with provisional layouts often being reversed or altered, yet they can have a persistent and meaningful life in what we refer to as descriptive typologies. The second is a classification of the data, where the starting point is the ordering principle itself, or the idea, theory, or research question, that underlies it. It tends to be a classification system based on theoretical considerations to gain an insight into a particular problem (ibid: 95 -96).

Classification systems from research topics such as living on board, ship shape or sea-keeping characteristics will have a very different character even though they can be applied to the same source material.

> "Classifications are tools to make ideas about data negotiable and classifications are therefore ideally suited for discussion, both in their outcomes and in their design."

Both ordering procedures, grouping and classification are equally justified in archaeology, one to get an overview of the data, the other to guide analytical research.

However, issues arise when as is often the case, the two procedures are not used side by side, but interwoven in an unclear manner. If raw data has been grouped or classified in must be remembered that one is working not with the entire information but rather with a sub-set of the data. In each case the archaeologist focuses on the material and submits it to inductive reasoning to find classification criteria, what Voorips (1982) calls 'constructing variables'.

With regard to the classification of ships, Maarleveld notes that there appears to be a tendency to skip over the first part of the ordering process, and to proceed directly to the identification phase. The identification of a ship type with a historical type designation often appears to attempt to fit the ship find into a pre-existing type that is fixed, thereby skipping the actual classifying, or re-classifying of the ship find (Maarleveld 1991:98).

Maarleveld quotes the *kontaktquellen* or contact sources as described by Ellmers (1979:494) as an accurate method to be followed when identifying a historical type designation, and a valuable method as a basis for type classification for the analysis of a ship find. He notes however, when dealing with historical type designations, it is almost always unclear whether one is dealing with a very specific or fairly generic term. These historical type designations often do not reflect an unambiguous term, and as such cannot be used in the manner described (Maarleveld 1991:99).

Maarleveld states that a descriptive ship typology can never have the rigidity that has been achieved with Roman pottery for example, as a vessel is a much more complicated artefact than a pot. In addition, vessels were produced in exponentially smaller numbers than pots, and being made of mainly perishable materials, the archaeological record provides not only a finite, but a very limited amount of material which is by its nature highly complex and often bespoke rather than mass produced. Maarleveld challenges the identification of ship finds with historical ship types as a primary goal of nautical archaeology, or as an analytical tool in arranging the data (ibid:102).

3.3 The reconstruction debates

After nearly a century of excavating archaeological shipwrecks, many with radically differing approaches, and varying results, the ideas about how to record and reconstruct ancient vessels varied. Between 1992 and 2007 a debate was carried out, mainly in the pages of the International Journal for Nautical Archaeology (IJNA), which sought to clarify and refine, through a series of articles and critical responses, the research process and desired outcomes relating to archaeological ship reconstructions. The debate used a variety of case studies, (the Dover Bronze Age boat, the Ferriby boats (Chapter 2.4.2), and the Brigg 'raft' (Chapter 3.5.3), and methodological frameworks, to classify the possible outcomes of archaeological reconstruction research. Various attempts to recreate the hull forms, from differing levels of preserved remains, were classified as minimum, maximum or capital, scientific and aesthetic reconstructions. And labels were applied to various models or drawings, like; 'as-built'; 'as-found'; 'torso'; 'minimum reconstruction'; and 'capital reconstruction', often with overlapping or inconsistent definitions between authors. The following section examines each of the articles and responses, as these are critical, being the theoretical context to the practical process of reconstruction – albeit the theory is following the practice and not vice versa.

3.3.1 1992: Replicas, reconstructions and floating hypotheses

McGrail (1992:354–5) noted that copies or replicas are built of specific ancient boats, using excavated remains as the primary evidence (Chapter 2.4), while reconstructions or simulations are built of some ancient type, known primarily from written and iconographic sources (Chapter 2.6.1 and 2.6.2). Both are valid research techniques, and the authenticity of the resulting vessel depends on the quality of the recorded data, the rigour of the arguments forming that data into a hypothesis of the form and structure of the original vessel, and the appropriateness of the techniques used to turn such a hypothesis into a ‘floating hypothesis’ or full-scale replica. He also emphasises the importance of full and widespread publication, to allow critical appraisal, and any claim of authenticity to be assessed, ideally prior to building commences.

> "Hypotheses must be investigated and tested by experiment, a process which lies at the foundation of all sciences. And after testing, the research must be published so that it may be criticized." (McGrail 1992:355)

3.3.2 1993: Some further thoughts on reconstructions, replicas and simulations of ancient boats and ships

Goodburn (1993:201–202) added to this by stating that any reconstruction, rigorous or otherwise, has the advantage of exploring early boat and ship building in relation to specific hypothesis testing, as well as more subtle aspects such as labour investment, skills and resources. Exploring the performance, handling and rigging of early craft. Providing three dimensional displays and publications as well as several socio - economic benefits.

3.3.3 1995: Experimental Boat and Ship Archaeology: Principles and Methods

A jointly published paper by ten maritime archaeologists (Coates *et al*. 1995), discussing the need for experimental boat and ship archaeology (EBSA), set out the case for formulating hypotheses, which have to be tested to be tenable as a valuable way to learn more than is immediately obvious, in the study of the maritime past. One form is the building of full-size or scale models, in close collaboration between model makers and archaeologists (ideally being one and the same person) or creating other simulations of ancient boats and ships, and testing them in repeatable sea trials, real or simulated.

Any experimental approach must have clearly stated aims which are addressed by the proposed and tested hypothesis, the evidence must be of sufficient quality and quantity to support the hypothesis, and all relevant kinds of evidence, discipline or expertise should contribute. The key phase being the formulation of the hypotheses; experiments must be accurate enough to test the hypotheses; and the project is virtually valueless unless it is evaluated and published in a manner which allows independent repetition (Coates *et al*. 1995).

3.3.4 1995: Experimental archaeology and ships—bridging the arts and the sciences

Crumlin-Pedersen (1995:303–6) noted the article by Coates *et al.*(1995) is an attempt to provide proper methodology for maritime experimental archaeology, but should be seen as a starting point rather than a definitive answer. He questions the value of a purely scientific approach to replica building, and states that in order to exploit the full potential of a ship find a multidisciplinary approach, as well as a wide range of practical skills is needed.

The archaeologist needs to be supplemented by historians; wood specialists; environmentalists; naval architects; boatbuilders and sailors. In addition, the knowledge and skills required for the utilisation of the materials and tools, the manufacture of sails and rope, navigation and weather forecasting without modern aids, as well as other skills, are all valuable supplements.

Crumlin-Pedersen suggests the approach should be refined based on the above requirements and suggests the main characteristics should be; 1, An archaeological base in substantial remains of an ancient vessel, documented to a rigorous standard; 2, A research strategy for the analysis of the potentials of the ship find; 3, A group of craftsmen and sailors with the relevant skills; 4, Documentation of both the aims and outcomes of the experimental activity; and 5, Publication in relevant context and media.

3.3.5 2006: Some Principles for the Reconstruction of Ancient Boat Structures

In a further paper by Crumlin-Pedersen and McGrail (2006:53–7), the authors sought to further clarify the reconstruction process and suggested the task be undertaken by an independent interdisciplinary group of, experienced maritime archaeologists, naval architects, craftsmen and sailors. They noted that a number of topics should be addressed in order to access the impact of ideas from our modern world which may unwittingly be applied to such a reconstruction, and suggested the problem should be considered under five headings: deformation and its effects on the hull shape; the impact of modern naval standards; the introduction of alien elements to complete the hull; the consideration of propulsion, steering and seaworthiness; and the concept of minimum reconstruction.

3.3.6 2007: The Re-Assessment and Reconstruction of Excavated Boats

The publication of the mentioned articles prompted McGrail to publish an article entitled The Re-Assessment and Reconstruction of Excavated Boats (McGrail 2007), in which he suggested a refinement to the methodology. McGrail notes that excavated wooden objects seldom retain their original shape, between deposition and excavation significant changes are to be expected.

A flat bottom recorded during excavation does not mean that was necessarily the original shape, just as a longitudinal curved shape during excavation does not imply the vessel was originally built with rocker. In both cases the original, pre-deposition shape has to be logically deduced and presented for consultation by an impartial and informed specialist team.

As an approach, McGrail suggests that after the evidence has been excavated and re-appraised, small scale models of every plank and timber should be made and fitted together until a model is formed of the 'as-found' vessel, but with distortions and compressions removed, displaced elements replaced, fragmented timbers made whole, and the hull rotated to its deduced attitude when afloat. This 'as-found' model, or measured drawings developed from it, then becomes the basis for an attempt to fill in the missing pieces, a process which may lead, if the surviving evidence allows, to a rigorously argued reconstruction of the original vessel. Following evaluation and criticism by an impartial and informed group, an agreed reconstruction may subsequently be used to deduce the original vessel's performance, including sea worthiness, and if justified a full-scale model built and tested at sea (McGrail 2007).

In relation to the theoretical approaches, McGrail (1992) suggested that reconstructions from archaeological remains should be labelled as copies or replicas, while reconstructions from literary or iconographic sources are reconstructions or simulations, both equally valid depending on the quality of the recorded data, and the rigour of the arguments employed. Goodburn (1993) argued that rigour was not critical as experience of ship building, as well as labour investment, skills and resources, performance, handling and rigging of early craft was all gained. Coates et al. (1995) developed experimental boat and ship archaeology (EBSA), proposing clear scientific and repeatable concepts, which Crumlin-Pedersen (1995) developed into the multidisciplinary approach combining all the relevant required skillsets, and was further refined by Crumlin-Pedersen and McGrail (2006). McGrail (2007) suggests that after excavation and re-appraisal, a model is formed of the 'as-found' vessel, which is subsequently used to replace missing parts leading to a rigorously argued reconstruction.

While many projects have employed specialists to analyse specific artefacts, how many reconstruction projects have engaged the advice of a boatbuilder, blacksmith, rigger, sailmaker, mariner, or navigator in the reconstruction of the ship itself? Similarly, McGrail's 'as-found' vessel, with distortions and compressions removed, displaced elements replaced, fragmented timbers made whole, and the hull rotated to its deduced attitude when afloat, is a quantum leap away from the originally excavated ship remains. The interpretations and decision processes involved in creating that 'as-found', what Crumlin-Pedersen refers to as 'torso' model seldom surface in any publication. The research for this thesis has discovered this lack of transparency of approach in many of the projects and ships described in Chapter 2.

3.4 Interpreting Shipwrecks

Steffy has noted that in relation to the way in which shipwrights projected and controlled hull shapes, theories have ranged from the use of standing control frames, to the haphazard assembly of planks. Evidence shows at least one of the frames for the 11th century *Serçe Limani* vessel, whose shape was predetermined and erected immediately after the keel and posts were set up, before any planking was fitted. So, by the 11th century in the eastern Mediterranean, and probably long before that, the assembly and resulting shape of the outer shell was controlled by standing frames, at least in the central part of the ship. That control was lateral in orientation[74] (Steffy 1995:418).

By contrast, the 4th century BCE *Kyrenia* ship showed evidence that none of the frames were erected before the planking strakes they spanned. The nine bottom strakes were installed immediately after the keel and posts were erected, fastened to each other by means of closely spaced mortice and tenon joints. Next the floor timbers were fitted, followed by side planking and wales, and finally the remaining frames, futtocks and top timbers. But was the control of the resulting hull shape[75] also lateral in orientation[76]? (ibid: 418-9).

Steffy states that if a faithful model of a mortice and tenon joined vessel were to be constructed, a perspective which becomes practical in the shaping of the hull is that of a longitudinal nature. The initial shaping members being the planks set parallel to the keel, and thus the hull was **possibly** shaped by a series of longitudinal guides (ibid: 418-9).

[74] It is important to note that here, Steffy is discussing control of the shape – the building stage, as opposed to the design stage.
[75] Again, Steffy is discussing the building stage here and not the design stage.
[76] Olaberria (2014:359–60) proposed a transversal 'master-frame' pre-design system for Kyrenia.

Steffy believed that for the ancient shipwright, there was more to the mortice and tenon joint, than simple edge fasteners in these so-called shell-first hulls, they also served in a structural capacity. On relatively small vessels spacing of such joints were spaced a mere 12 cm apart. Similar spacing was used on larger double skinned vessels such as *Madrague de Giens* (Pomey 1978), but also, mortice and tenon joints were also used on the outer skin rather than simply nailing the outer planking to the pre-existing inner shell.

Even when replacing rotten plank edges, where framing existed to facilitate fastening, the structural importance of the mortice and tenon was recognised and maintained by the ancient boat builder. With the little 13.6 m long *Kyrenia* ship having over 4,000 such joints, and large Roman freighters having probably four to five times as many, a lot of expense, not necessarily financial, but also in labour, material and time was expended on this fastening system. Consequently, Steffy was of the belief these ‘fastener’ served a dual purpose as structural elements, what he called ‘little internal stiffeners – miniature inside frames’ (Steffy 1995:420–21).

Steffy concluded that the ancient shipwright considered the planking shell as the primary hull structure, and whether by mental image, traditional proportions or formal documents, he comprehended the hull design, before construction began, and could predict and control that design with a fair degree of accuracy. That shape and form was controlled by careful determination of longitudinal planking shapes, which if formalised and recorded, could have simplified the construction of large numbers of vessels in widespread locations. Cleats, braces, control frames and other devices may have been used to help maintain the hull shape during construction, but the mortice and tenon joint played the most important role (ibid: 424).

Steffy notes that our initial problem in comprehending the form of construction, perhaps lies in our designation as shell-first, this he suggests is misleading and the term shell-first should be retired from use. We seldom refer to Viking ships as shell-built, we say they are clinker-built, a term that simultaneously recognises the primacy of the role of their shell of outer planking, and the method by which those overlapping planks are fastened. Why not then extend the same degree of accuracy to their southern counterparts and call them ‘tenon-built’, a far more descriptive term (Steffy 1995:419).

3.5 Alternative hypothetical reconstructions

As noted by Steffy (1994:216), research and reconstruction procedure is a personal matter that is shaped by one’s preferences, abilities, and experience, so there can be no rigid set of rules defining the proper procedure for reconstructing a wreck. How the available evidence is interpreted and utilised in a reconstruction can vary between reconstructors. Likewise, how the resulting reconstructions are analysed in terms of hydrostatic and seafaring capabilities can produce variable results. The following are three such examples.

3.5.1 The Dover Boat

The Dover boat as reconstructed (Clark 2004) was subsequently re-examined by Crumlin-Pedersen (2006:58–71) in which he noted that the three versions of the boat as presented, Dover 1-3 were all identical except for the length and the way in which the missing stern was closed. Crumlin-Pedersen (ibid: 58) states the three versions presented by Owain Roberts are all laid out with two flat bottom planks, the curved 'ile' or chine log, and one flat plank per side. The work of Richard Darrah is noted as crucial in attempting to determine the original cross-section of the timber, but as noted by Darrah (Clark 2004:104) their exact shape was harder to ascertain with any reliability.

Peter Marsden states the boat was 'originally built with flat transverse and longitudinal profiles. It was a flat-bottomed boat' (Clark 2004:94). Crumlin Pedersen(2006:60) states 'It seems that Marsden and Roberts, working from the two-dimensional documentation evidence, are here affected by the 'straight-lines-and-flat-boards-syndrome' discussed in the previous paper (Crumlin-Pedersen and McGrail 2006:54–5) in relation to the naval architectural approach to reconstruction problems. The uneven wear marks on the underside of the vessel are noted by Crumlin-Pedersen as contra-indicatory to a flat bottomed profile, and concludes that a detailed re-assessment of the Dover Boat is required (Crumlin-Pedersen 2006:62, 69).

Von der Porten (2006:332–3) is equally critical of the proposed reconstruction of the Dover Boat, stating the display and publication show the boat 'as-found' and in three possible lengths, however:

> "the significant questions of number of side strakes, height of side, possible flare of side, possible sheer, possible rocker, and shape of bow (or possibly stern) are dealt with very narrowly. The internal structure is given a starkly minimal interpretation, not even providing thwarts for the paddlers or rowers. It is as if a slab-sided box had been built up on the remains, despite the shipwrights' demonstrated abilities to create complex timber shapes."

A maximalist reconstruction with slight rocker, slight flare of the side strakes above the chine strake, and three side strakes (including the chine strake) could configure the Dover Boat as a strongly built double-ended seagoing successor to the Ferriby-type craft. She would still be low enough to be paddled and could ride waves well. Von der Porten suggests experiments with models of such configurations, clearly marked to show what is known and what is hypothetical could test this hypothesis as well as showing visitors a far wider range of possible reconstructions than exist at present.

3.5.2 Ferriby 1

Owain Roberts (2006:72) noted that Coates recent paper (2005a:38–42) called for an end to the dithering over the definitive interpretation of *Ferriby 1*, as the case has been made for Ted Wright's final published reconstruction. However, Roberts states that aspects of the research need reviewing so that progress can be made towards accepting that *Ferriby 1* was intended for coastal or short sea voyages. Roberts states that there is no evidence for framing in Ferriby 1 and suggests, the slots and clusters of cleats carved into the bottom planks are related to what he calls 'prehistoric proto-framing'.

This he states is from 'before the invention of framing' when lines of pierced cleats were left upstanding to take strong close-fitting timbers to prevent articulation between adjacent planks. Roberts states that

> "In neither Ferriby, Dover, Allteuryn (Goldcliffe) nor Caldecot boats is there any evidence of framing on the plank surfaces. This suggests that no north-European prehistoric boats of their period and earlier had continuous framing."

As a result, Roberts proposes an alternative frameless reconstruction for Ferriby 1 (Roberts 2006:76, Fig. 2)

3.5.3 The Brigg 'raft'

The Brigg 'raft' represents the remains of a stitched prehistoric boat dated to circa 825-760 BC. First encountered in 1888 and subsequently re-excavated in 1974 (McGrail 1975; McGrail 1981a). The boat was published as a flat-bottomed boat, with a shape similar to a lidless box (Figure 3-2, top right). This interpretation was re-evaluated and presented at a sewn-boat conference held at Greenwich (McGrail 1985a:190, fig 11.16) but no reason could be found to revise the hypothesis in any way. This was seen as a minimum solution to the reconstruction problem, and while other solutions were technically feasible, they would require more conjecture (McGrail 1994:283).

Roberts (1992) believed the remains could be reconstructed, based on the curving taper of the left-hand end of the strakes, and the carved strake edge shape (Figure 3-2 bottom right):

> "into a lean, round-bilged, stable, buoyant craft having a versatile operational capacity which would include coastal passage-making and short sea crossings."

Both versions of the vessel were assessed by Crumlin-Pedersen (Crumlin-Pedersen and Trakadas 2003:214–217). For the Brigg vessel (Figure 3-2 left shows the 'raft' during excavation in May 1974 N.M.M. Greenwich) Crumlin-Pedersen notes the 'box like' shape (Figure 3-2 top right) with low almost vertical sides as proposed by McGrail (1985a) as a minimum reconstruction which McGrail supports with recent examples of vessels used on rivers in Poland and elsewhere.

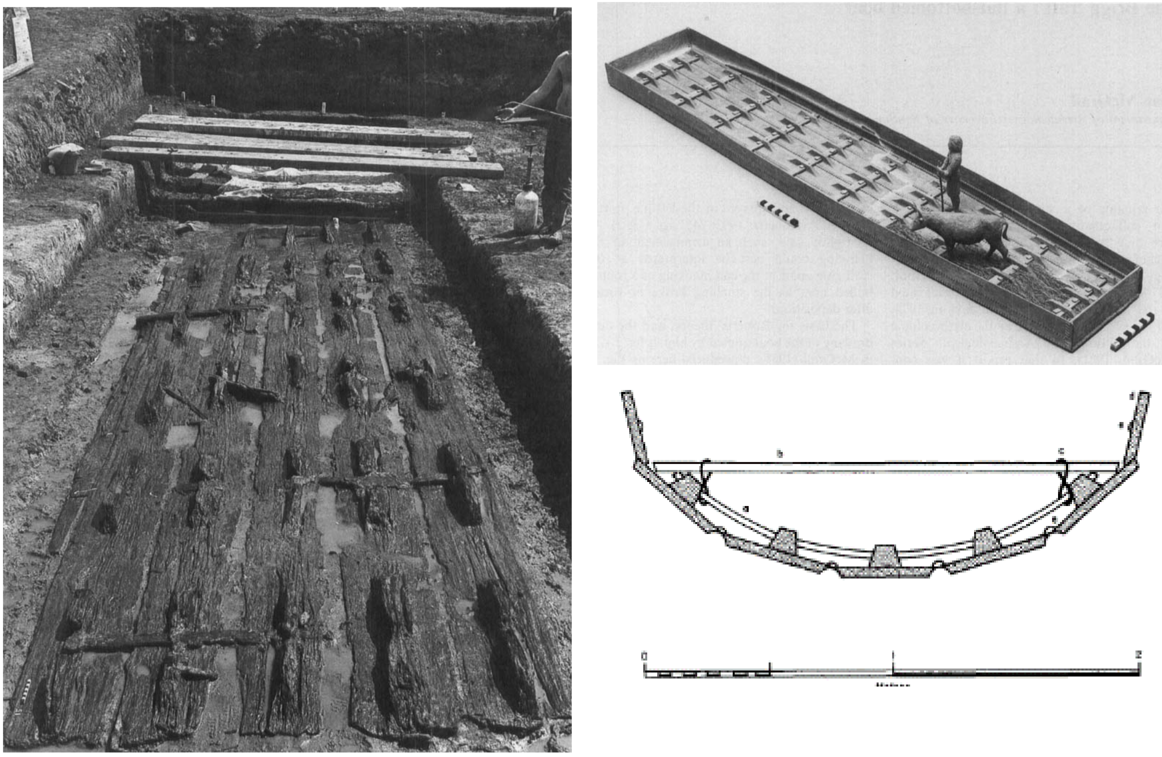

Figure 3-2 The Brigg 'raft', 2 very disparate reconstructions

By contrast the reconstruction proposed by Roberts (1992) puts forward a radically different hull form (Figure 3-2 bottom right after Roberts, 1992) which Roberts argues must have had rocker as well as a transversely rounded bottom with bent ribs similar to the Hjortspring boat (Crumlin-Pedersen and Trakadas 2003). Crumlin-Pedersen notes that while McGrail stands by his flat-bottomed interpretation, as he (McGrail) believes a round hull is not compatible with the evidence, though the possibility of some rocker requires further consideration.

Crumlin-Pedersen (2003:217) noted that as in the case of the *Brigg* 'raft', the presentation of Roberts' hypothetical reconstruction alongside that of McGrail illustrates the inherent uncertainty in quantifying the original capacity of this vessel, as well as other factors of relevance for the assessment of the functionality of the vessel. Crumlin-Pedersen states that McGrail's approach throughout his career in ship archaeology has been to promote methodically stringent standards for documentation and description of ship finds. In an attempt to avoid imaginative but unrealistic interpretations, he consistently chooses to present what he considers to be the 'minimum' reconstruction on the principle that while other reconstructions are possible, they would involve more conjecture (Crumlin-Pedersen and Trakadas 2003:217).

However, As noted by Crumlin-Pedersen (2003:217), the problem arises when a minimum reconstruction is presented as the single, scholarly answer to the question of the original appearance of the vessel, rather than one of two or more alternative hypotheses. As can be seen in Figure 3-2 above, this creates an inherent uncertainty in quantifying the original capacity and functionality of the vessel. With just the minimum reconstruction forming the basis for calculations of performance and area of operation, based on form coefficients, this may produce very misleading results. If the same is applied to hydrostatic and hydrodynamic calculations the results will be exponentially misleading.

It is clear from the three examples cited that quite often, a single definitive solution to the reconstructed vessel, may not prove feasible or entirely satisfactory. Questions have been raised in the above examples about how some of the documented evidence is interpreted and used during reconstructions. Likewise, concerns exist, relating to some of the proposed hydrostatic and seafaring capabilities of certain reconstructions. Similar issues, like the tapered planking interpreted by Roberts (1992) from the Brigg publication, subsequently identified by McGrail (1994) as actually being eroded edges rather than original tapering, highlight some of the issues with the interpretation of published results.

3.6 The Philosophy of Shipbuilding

Hocker (2004:3) notes that watercraft can be classified in a bewildering number of ways, in some cases by the type of buoyancy and building method (cf. McGrail 1985b:291–98; 1987:4–11; 2001:7–11), others grouped vessels by function, Steffy (1994) used four major groups: cargo carriers (which included passenger vessels); warships; fishing craft; with the remainder grouped under utility craft. In *Architectura navalis mercatoria*, Chapman (1768) grouped vessels by function such as vessels for war, merchant vessels, vessels for swift sailing or rowing, privateers, fishing boats, and ships boats.

These were then classified by their shape and rigging. Identifying vessels based on shape and rigging became popular, particularly at sea, during the late 18th century, as the sail could be seen at quite a distance. Warships tended to be classified or rated by the number of guns carried, or the rank required to command them (cf. Lavery 1983; and 1987).

Hocker (2004:6) believes that shipbuilding can be divided into three main aspects: design; assembly sequence; and structural philosophy, and it would be more accurate to speak of ships as being shell-*based* or skeleton-*based* rather than shell- or skeleton-first[77]. The design and assembly aspects he states are more or less self-explanatory, but the structural philosophy requires clarification. This is how the shipwright intends the component timbers to distribute the stress and load, for example thick edge joined planking with light internal reinforcement, or heavily framed hull with light non-edge-joined planking. Hocker also notes that in parallel to developing a general conceptual framework for the interpretation of ship remains, there has been much work in defining characteristic features of shipbuilding traditions. Thus, the methods of shipbuilding best represented in the finds are sometimes referred to by names that reflect the features of those techniques, such as clinker-built, or mortice-and-tenon construction, and sometimes by cultural tags such as Nordic shipbuilding, or Greco-Roman construction (ibid: 6-7). The very idea of attempting to define or name a particular shipbuilding method has been questioned on theoretical grounds in recent years (cf. Maarleveld 1991; Zwick 2013).

Zwick (2013:48) notes that watercraft, despite their complexity, continue to be encased into lignified typologies, which although proven inadequate or outdated continue to be used either for convenience or by force of habit. And stresses the need for a theoretical framework which remains flexible enough to offer interpretive leeway on alternating strands of development, thereby facilitating a fresh and more objective view on the growing body of differential data from shipwrecks (ibid: 46). Zwick also criticises the use of terms such as extended family, archetype, cross-fertilization or hybrid-type when hereditary patterns in the development of shipbuilding traditions were implied, as these stress lineages as though they constitute evolutionary developmental relationships.

3.7 2014: Standards and Guidelines for Nautical Archaeological Recording and Reconstruction

Updated in 2014, the United Kingdom's Chartered Institute for Archaeologists published Standards and Guidelines for Nautical Archaeological Recording and Reconstruction.

It sets out the purpose of nautical recording as having the primary aim of completing an accurate as-found record of the vessel, or parts thereof, so they can be properly interpreted by a nautical

[77] McGrail (1981b:43) noted that the 'shell sequence' or 'skeleton sequence' determined how the vessel's shape was obtained, where the structural strength lay, and how the vessel was made watertight. However, Hocker (2004:10) states that McGrail is not considering a broad shell or skeleton concept, but concentrating on the order of assembly, on the assumption that all else follows from this choice.

specialist. While methodology may vary between sites, there should be a visual record (scale drawings, sketches, photographs or point data) and survey data produced at a scale less than 1:1 (full-size) should be annotated with a table of full-scale measurements.

The stated aim of reconstruction is an understanding of the vessel's hull-form (its 3D shape) and construction, both of which are required to gain a full understanding of any nautical find. Depending on its totality the full original shape, structure, propulsion and steering of the remains being investigated might not always be capable of reconstruction. However, in order to achieve the primary research aim, an understanding of the vessels hull-form and construction, an attempt at reconstruction should be considered.

In reconstructing the hull form, the guidelines state the vessel's 3D shape must be recorded, which is done by recording transverse sections which can be combined into a body plan. The production of a body plan is reliant on the survival of a significant amount of hull timbers, and the less of a vessel that survives the more important the recording of single attributes becomes. The extent of the surviving hull must be considered when reconstructing a vessel, and whether sufficient material survives to allow a meaningful and proper reconstruction.

It concludes with listing 11 coefficients of form (see Appendix E) which are dimensionless descriptions of hull form, allowing comparison between vessels independent of size, in use for more than two decades, and considered important to have for further study (Chartered Institute for Archaeologists 2014).

It should be remembered that hull form ratios and coefficients of form are tools, developed as a guide for naval architects, by naval architects, who spend their days studying hull forms and lines plan drawings. Those tools are useful for the comparison and analysis of variations with those hull forms, and in comparing several alternate versions. As a tool to study an individual reconstructed vessel, or two widely disparate vessels, those tools are significantly less useful.

3.8 The more we learn the less we know

Hocker (2004:2) states that the study of ship remains begins with the recording of seemingly trivial details, the thickness of planks, the number and size of nail, direction of an adze stroke. While some of these details are trivial, it is often difficult to distinguish the trivial from the significant until long after recording is finished. These tool marks and stains, grain patterns and botched repairs are the voices of the people who owned, built and sailed the vessels archaeologists excavate, and ship specialists' study. While minutiae are vital to the reconstruction of ship remains, a purely technical approach places the ship in a vacuum.

These minutiae can add another dimension to the research such as who the people were and why they built the ship the way they did. Hocker (2013:73), takes these minutiae and reveals how Vasa was built with a large and varied workforce, from at least four different countries, speaking at least three different languages, trained in two different shipbuilding traditions, and using at least two different systems of measurement, in what he calls 'the messy reality of ship construction by humans in wood: a species prone to inconsistent behaviour working with a material of inconsistent properties' (2013:73).

Clearly there is much detail and information hidden within these seemingly trivial details and minutiae. But are we asking the correct questions of those details? A great deal has been written on the differentiation between shell and frame. Beginning with Hornell's clinker/carvel distinction, modified to shell-first/skeleton-first by Olof Hasslöf (cf. Hornell 1946; Hasslöf 1963; Basch 1972; Greenhill 1976). This general emphasis on construction sequence, and the knowledge that later Mediterranean hulls were constructed frame-first, led to an interest in the transition from shell-first to frame-first. The fundamental aspects of this transition were identified as early as the 1960's with the systematic study of the 7th century *Yassi Ada* ship (van Doorninck 1982; Steffy 1982). Since then an emphasis often being placed on finding the 'first' skeleton-first hull, but as Steffy' s work on *Serçe Limani* has shown, even that 11th century hull was only partially built frame-first, and his emphasis on understanding the nature and reasons for the transition would be a more fruitful avenue for research (Hocker 2004:6).

> "In the early years of The Mariner's Mirror it seemed clear to its members that, when building 'plank-first', the builder monitored the emerging hull shape 'by eye', but that building 'frame-first' implied the use of formal design methods: that dichotomy is now not so clear. …the evidence at present, is insufficient for us to say how the earliest frame-first builders got the shape of frames that they wanted. It should be noted, however, that it is also not yet possible to say in detail, how early plank-first builders got the shape of planked hull that they required – a question that scholars have been addressing for many years. Clearly there is scope for further research on early methods of designing and building boats and ships." (McGrail 2011:58)

In creating traditions such as shell-first/frame-first, have we created our own causality dilemma?

3.8.1 The Chicken or the Egg

Hornell (1946: 86–7), tells us the planking of the two sub-types ('clinker-built' and 'carvel-built') of European boatbuilding covered 'a framework consisting essentially of a keel, sternpost and internal ribs': a statement that implies that both sub-types were built frame-first[78], whereas elsewhere Hornell (1946: 193–4) differentiates 'clinker' as shell first, from 'carvel' as frame first. Adams (2013:55), using the phrase from medieval to modern, notes the indisputable evidence that change did occur, but its causes and mechanisms have proven elusive. Certain attempts to explain it as a transition from one construction method to another, that of 'shell-first' to 'frame-first' concluded it was both a technological and conceptual revolution with mysterious origins. This Adams notes possibly derived from Hornell's impression that there could have been no smooth transition between the two, and that

> "the pre-erection of transverse frames (was) clearly an act of invention…" (Hornell 1946:194)

Although the idea was dispelled by Olof Hasslöf in 1958, Greenhill (1995:256) still described it as 'a complex technical revolution'.

Adams (2013:56) notes that even on technological grounds, there are various precedents which undermine the idea of revolution in the sense of a sudden overturning of tradition or ideology, and states,

> "...it is the terms 'shell-built' and 'skeleton-built' that embody the conceptual gulf perceived to exist between the two approaches."

In principle 'skeleton-built' requires a pre-conceived design that is difficult to alter or adapt once construction has started, whereas builders of 'shell-built' boats proceed plank by plank, controlling the shape as they go ((Christensen 1972:239; Greenhill 1976:73).

However, Adams (ibid:56) points out that, in view of the relative simplicity of early carvel design criteria, it is debatable how limited the builders ability to adapt really was, and it must also be asked, how 'free-form' the clinker approach really was? Clinker boats were often not entirely 'built-by-eye', their form was regulated by the use of various guides, such as the boat ell or control level, or even with moulds and templates as suggested by McGrail (1987:98–103). Christensen (1972:252) argues that these moulds were a later borrowing from the carvel tradition, McGrail (ibid) suggests that some means of controlling the final form are likely, but finding such evidence in the archaeological record appears unlikely.

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[78] Technically, Hornell is correct at this stage in construction, the keel, stem and sternpost, often referred to as the backbone by shipwrights is a de facto skeleton. The setting up of a backbone also indicates the existence of pre-design (a key feature of frame-built) in 'shell-built' construction. The keel-stem-sternpost requires a pre-determined overall length, and possibly predetermined height. Depending on the completion level of the backbone, other predetermined design decisions may be evident. Winged stem and sternposts indicate a predetermined hull form where the planking meets the ends. The rebate pre-cut in the keel indicates at least an initial predetermined deadrise angle.

Adams (2013:56–7) believes that while guides and other templates might not have been necessary for the skilled builders of smaller craft, some Nordic vessels reached such a size that it is difficult to believe such enormous investments would be entrusted entirely to the shipwright's optical judgement. Any idea of conceptual incompatibility is eroded by the various instances of practical merging of the two methods.

Adams (ibid: 57) notes that it was not uncommon in the Baltic to repair or consolidate a clinker-built hull by adding a layer of carvel planking, and in some cases, they may have even been built in this way. Similar examples in Tudor England included the Great Bark, clinker built in 1515, and rebuilt carvel in 1523. Other variations included by Adams are the Baltic galleases having clinker-built lower hulls, with carvel construction above the bilge.

These examples, Adams states, demonstrates that shipwrights have had no conceptual problem in adapting their procedures, and other examples such as the so-called 'Dutch flush' technique of building carvel hulls, which initially begin in a sense as shell first, with temporary cleats holding the planks in place prior to the insertion of frames. Large carvel hulls were not always simply a matter of applying planks to a previously erected skeleton of frames. In many cases, particularly in early carvel building, framing and planking advanced together, based on the erection of a few control frames, with the intervening timbers controlled by ribbands (ibid: 60).

Another significant factor is the development of the Nordic clinker tradition, with some examples of extremely large clinker-built ships, (*Newport* clinker-built after 1449, the *Sovereign* clinker-built circa 1489, rebuilt and converted to carvel in 1509) at the same time when large carvel-built carracks were beginning to appear in northern Europe.

3.8.2 Disruptions in the timeline

In particular for Mediterranean shipwrecks, a linear development had been established, and an explanation for the transition between shell and frame in the ancient world was widely accepted circa mid. 1990's. Adams (2013:67) states that this series of archaeological finds, (*Uluburun* circa 1305 BC (Pulak 1998) – *Kyrenia* 4th century BC (Steffy 1994:42–58) – *Madrague de Giens* 2nd century BC (Pomey 1978) – *Yassi Ada B* – 4th century AD (van Doorninck 1976) – *Lazaretto* 4th century AD (Riccardi 1991) – *Port Vendres A* circa 400 AD (Parker 1992) – *Yassi Ada A* circa 625 AD (Bass *et al*. 1982; van Doorninck 2015)), suggests a continuing trend with fewer mortice-and-tenon joints, only in the lower strakes, and planks simply nailed to pre-erected framing above the turn of the bilge. Adams describes this as a transitional stage from the earlier shell-built, mortice-and-tenon technique to a non-edge-joined method. The sequence of wreck evidence is completed by the medieval wreck from *Serçe Limani* (Steffy 2004b), dated to the 11th century AD, and the wreck found at *Pelagós* in Greece dated to the mid-12th century (Parker 1992:306) neither of which had edge joined hull construction, and they were effectively a 'skeleton-built' or rather frame-orientated construction.

The progressively reducing mortice-and-tenon joints suggest a logical evolution, from shell-built, via transitional forms to a fully frame orientated approach. The finds were irrefutable, but their apparent linear sequence was an artefact of discovery, and the small sample size at that time. Subsequent finds, *Tantura A* dated to between 5th and 6th centuries AD, and built 'partly frame-first' (McGrail 2001:161) – *Port Bertreau II* dated to the late 6th or early 7th century, and built 'proto-skeleton-first' (Rieth 2000:228) – Dor 2006 dated to the late 6th – early 7th century AD (Navri *et al*. 2013) had unpegged mortice-and-tenon joints and the upper hull was based on frames – Dor 2001 dated to the early 6th century AD (Kahanov and Mor 2014:63) had no plank edge fastening, the frames were nailed to the keel, is described as based on frames and constructed frame-first – Yenikapi 14 dated to the early 9th century AD (Jones 2017) has cylindrical wooden dowels rather than mortice-and-tenon edge joints and is described as being shell-based – Yenikapi 11 dated to the early 7th century AD (Ingram 2018) has unpegged mortice-and-tenon joints below the waterline, with non-edge-joined planking fastened to frames above strake 10 and is described as being of mixed construction – Yenikapi 12 also dated to the early 9th century AD (Özsait-Kocabaş 2018) has similar dowels to Yenikapi 14 but is described as being of mixed construction – have not filled in the gaps, but rather disrupted the perceived linear timeline. While analysis of this process is relatively new, in the light of recent finds, a single cause for the demise of mortice-and-tenon joinery is scarcely credible in a process of change that occurred at different rates in different regions over so long a period (Adams 2013:68).

3.8.3 A fusion of technologies

The first known two-masted ship in England is a Genoese carrack, captured by pirates in 1409 and taken over by the Crown, thereafter, known as *Le Carake,* (Friel 1994:80) and in 1416-7 a further six large two-masted carracks were captured. Between 1416 and 1420 six English ships are fitted with a two-masted rig. At this stage however English ships were still clinker-built, to the extent that foreign shipwrights had to be hired to maintain and repair the frame-built carracks (Adams 2013:70).

By the 1430's mention of caravel was beginning to appear in English sources, and the earliest known reference to a carvel ship being built in England is between 1463 and 1466 in Ipswich (Friel 1995:164). Adams (2013:76) states that for the *Mary Rose,* completed in 1511 and carvel-built, the framing was probably based on the partial erection of control frames which were set up at key stations along the keel, including the midship station. However, of the framing that can be seen between the decks, although many of the timbers meet in various forms of butt, overlap, or simple scarph, very few of them are actually fastened to each other. This implies that the framing and planking advanced in an alternating fashion.

For the *Sea Venture*, the construction date for which is obscure, but Adams estimates 1603. Almost 100 years after the building of *Mary Rose*, and despite a hull form and framing system which changed dramatically, the construction of Sea Venture still did not involve the erection of a complete skeleton of frames prior to the planking being applied. The vast majority of the frame elements were not even fastened to each other, let alone scarphed, and assembly must have been in a timber by timber fashion (Adams 2013:130–31).

It is more appropriate Adams states, to judge these ships as 'frame-led' rather than 'skeleton-built'. The latter term implying just the sort of free-standing framing system that is more typical of later 18th and 19th century practice in the larger dockyards.

3.8.4 Shipwreck as a result of bad design

Hasslöf (1963:163) has argued that the wreck database is biased towards failure, inevitably accounting for poorly maintained, old and rotten vessels and the generally less successful design. As noted by Adams (2013:17–18) all voyages are hazardous to some degree, and while the terminology of risk assessment may be an invention of modern bureaucracies, the measuring of risk has always been a human constant, with individual voyages involving a balance of environmental, human and technological factors. The 'Laws of Oleron' clearly stated the rules under which, the decision to postpone a departure, are to be made. A newer or better ship can still be overwhelmed by environmental conditions. Muckelroy (1978:232) pointed out that vessels in either condition can be lost due to human error, quite independent of their suitability to the task.

Adams (2013:18) states that while there are exceptions, such as ritual deposition or abandonment, deliberate scuttling, bad design, or alterations which culminated in an unseaworthy vessel, the majority of wrecks, where they have been used over many voyages, and sometimes for many decades, are a measure of success of both the individual vessel, and the building tradition within which they were created.

3.9 Summary

Since its early beginnings with antiquarian interest, and some of the earliest excavations such as the published reconstruction by Glavimans of a vessel excavated between 1819-1822 (Maarleveld 1997:35), the study of shipwrecks has developed and evolved at a rapid pace over the last two centuries. Many of the early approaches (Table 3-1) tended to focus more on the reassembling of vessels for museum display such as the 25 m Nydam Mose. The early 20th century saw the in-situ recording of ship finds, some like the Woolwich ship primarily focused on identifying the vessel in order to secure a dating.

Project	Date	Site Survey	Timbers Recorded	As Found	Initial basis for Hull Form	Development of Reconstruction	Validation of Reconstruction
Rother Barge	1822	Detailed site sketch	Some scantlings recorded		Reassembly for Display	Details of artefacts recovered	
Nydam	1859	Traditional 2D offsets survey	Detailed sketches and scale dwgs.		Reassembly for Display	Detailed sketches of artefacts recovered Subsequently re-excavated	
Gokstad	1880	Traditional 2D offsets survey	2D Offsets		Reassembly for Display	2D scale dwgs. Full-scale Replica	Full-scale Replica
Oseberg	1904	Traditional 2D offsets survey	2D Offsets		Reassembly for Display	Full Scale Replica	Sinking of full-scale Replica
Woolwich	1912	Traditional 2D offsets survey		Survey Drawing	Name Identification	Name Identification	

Table 3-1 Summary of reconstruction approach for early ship finds (Pat Tanner)

Åkerlund's (1951), *FARTYGSFYNDEN I DEN FORNA HAMNEN I KALMAR* (Boat finds in the former port in Kalmar) which, although primarily in Swedish, is an excellent publication of the Kalmar 1 wreck discovered in 1932, with its clear evidence of exactly what was found, and clearly detailed reconstruction, it rivals many more modern publications. The mid-20th century (Table 3-2) saw a shift to documenting individual timbers rather than the vessel as a whole, which has brought with it a new understanding of both the tools and techniques used in the building on these vessels.

As can be seen from Table 3-2, the majority of projects used similar approached to initial site documentation, either traditional 2D offset survey techniques or a photogrammetry based approach depending on site conditions. The full scale documentation of individual ship timbers became the standard approach from the 1960's, with the two initial approaches being elevated plane tracing and contact tracing, see Chapter 2.4.6 for an explanation of the difference between both approaches. This developed into the highly accurate 3D digitising from about 2000 onwards.

Project	Date	Site Survey	Timbers Recorded	As Found	Initial basis for Hull Form	Development of Reconstruction	Validation of Reconstruction
Kalmar	1932	Traditional 2D offsets survey	2D Offsets	Survey Drawing	Scale Drawings	Scale Model	Scale Model
Ferriby	1937	Traditional 2D offsets survey	2D Offsets	Interpreted excavation dwg.	Scale Drawings	Scale Drawings and 5 Scale Models	Coefficients + displacement and ½ scale replica
Yassi Ada 7th C	1961	Underwater Photography		Corrected and scaled from photographs	Reassembly of scaled model strakes	Scale Models	Tonnage
Skuldelev	1962	Photogrammetry Then scale dwg.	Full-scale Elevated plane tracing	Interpreted Torso dwg.	Reassembly of 2D scaled model strakes	Scale Model	Coefficients + displacement and full-scale replica
Kyrenia	1968	Underwater Photography	Drawn full-scale Photo-graphed	Corrected and scaled from photographs	Initial hull form model	18 models – some full-scale	Tonnage and 2 full-scale replicas
Graveney	1970	Traditional 2D offsets survey and full-scale plaster cast	Full-scale Contact tracing	Reduced scale dwgs.	Reduced scale drawings	Scale Drawings and 4 Scale Models	Coefficients + displacement and ½ scale replica
Serçe Limani	1977	Underwater Photography	Full-scale Elevated plane tracing	Site Diorama model	Site Diorama model and mould + batten model	Various models	Tonnage
Grace Dieu	1980 -	Traditional 2D survey and Sub-bottom profile	Some with 2D Offsets				
Ma'agan Mikhael	1985	Underwater 2D offsets survey and photographs	2D Offsets	Survey Drawing	Surviving frame shape and reassembly of hull remains	reassembly of hull remains and 3 scale models	Coefficients + displacement causing hull redesign and full-scale replica
Barland's Farm	1993	Traditional 2D offsets survey	2D Offsets	Interpreted 'as-found' dwg.	Reassembly of scaled model strakes	Scale Model	Coefficients + displacement
Roskilde	2002	Photogrammetry Then scale dwg.	3D full-scale digitising	Interpreted Torso dwg.	Flatten data to 2D and assemble scaled model strakes	Scale Model	Coefficients + displacement and full-scale replica
Newport	2002	Traditional 2D offsets survey and Photogrammetry	3D full-scale digitising	As surveyed and post-deposition model	3D Post deposition model	Full-scale 3D digital model	Full Orca3D hydrostatic and hydrodynamic analysis
Sørenga 7	2007	Traditional 2D offsets survey	3D full-scale digitising	Traced from on-site digital scan	Surviving frame shape 3D printed and reassembly of hull remains	Scale Model	Orca3D hydrostatic analysis

Table 3-2 Summary of reconstruction approach for archaeological reconstructions (Pat Tanner)

Model making is not a modern phenomenon in archaeological ship research, there is a model of Glaviman's vessel from 1822 (Chapter 1), similarly Åkerlund created a 1:12 scale model based on his reconstruction drawings (Chapter 2.4.1), though it would appear as a validation tool more than a research tool. Wright (1994) created at least five models to study various potential shapes for the *Ferriby 1* reconstruction(Chapter 2.4.2). The approach of developing the reconstructed hull form by reattaching scaled models of individual planking using the alignment of fastener holes also developed in the 1960's about the same time as full-scale documentation of individual ship timbers.

As discussed in Chapter 2.4.4 and 2.4.12 the entire Skuldelev and Roskilde method are founded on the principle of documenting the three-dimensional timbers, flattening the data onto two-dimensional cardboard prior to reassembling as a 1:10 scale three-dimensional research model. From these models, drawings are created, which are used by the boatbuilders to construct a full-scale replica. However as noted:

> "…drawings sometimes have to be altered due to the fact that oak planks do not behave in exactly the same way as the material used in the scale model."(Ravn *et al*. 2013:239)

I believe all of Steffy's reconstructions were based on three-dimensional research models, to the extent that Steffy builds diorama models of the wreck site. For Kyrenia (Chapter 2.4.5) a total of 18 research models were employed. Yet, as Steffy conceded, it still often required the full-scale reassembly of the vessel remains to reach definitive answers to certain specific issues (Steffy 1989:249–52).

Some published reconstruction drawings have indicated the extent of surviving material, but this has tended to be more the exception than the norm.

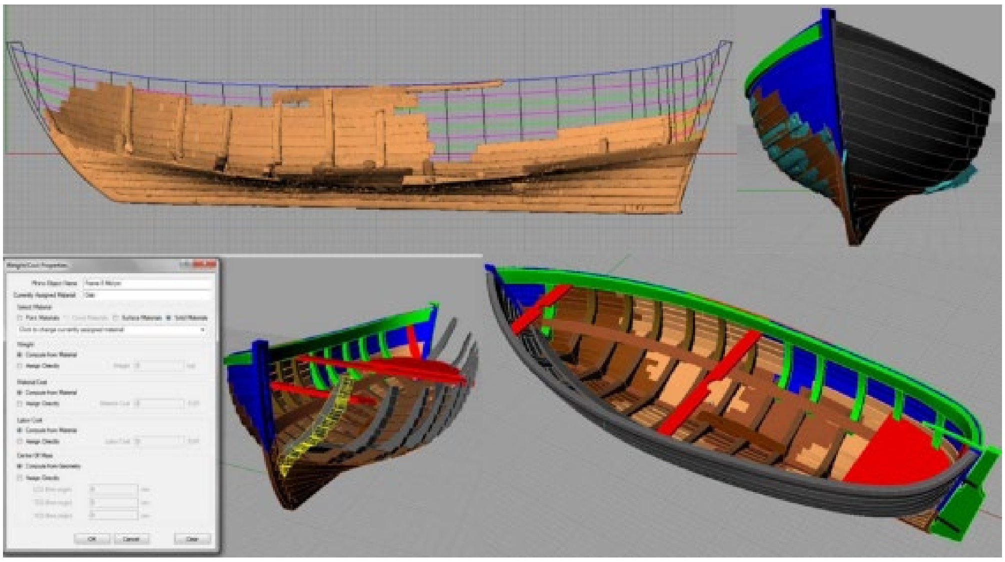

Figure 3-3 Indicating surviving elements in a hypothetical reconstruction (Tanner 2013a:140 Fig. 2)

A simple colour scheme (Figure 3-3), with brown for surviving elements, blue to complete watertight hull, green indicating partial evidence, grey for mirrored sections, and red for conjectural elements provides a clear indication of the various levels of confidence.

The validity of the hypothetical reconstruction is another matter which needs to be addressed. While it is possible to reassemble all the constituent elements into a physical model, which violates none of the archaeological evidence, the result is not a definitive solution to the original form of the vessel. That form needs to be further analysed to determine the validity of the proposed hypothesis. Table 3-2 illustrates that the majority of reconstruction projects have used the estimation of tonnage using formulas, ratios of form and hydrostatic coefficients as the only real method of validating the proposed hypothetical reconstructions.

While all are methods of determining relative assessments of a boat’s capabilities, this is a valid method of checking than nothing abnormal or unbelievable has been created during the reconstruction process. However, does the use of average results, or relative assessments, when interpolating missing sections, or analysing reconstructed forms, result in the hypothetical reconstructions incorrectly becoming 'average' boats?

Conversely, taking the example of the Oseberg ship (Chapter 2.3.4), the 1954 lines drawings were used for analysis by Jensen (1999:216) to determine ratios of form and hydrostatic coefficients. These were included in a database of circa 34 vessels (ibid: 204), all of the form ratios, and each of the hydrostatic coefficients for the original Oseberg hull shape are within average parameters when compared to the other vessels, but still the full-scale replica sank. It was with the benefit of 3D laser scanning the displayed remains, as well as detailed research on the original reassembly process that issues with the original proposed hull form were identified. A subsequent revised hull form resulted in a remarkably different flow of water around the hull, providing lift to the bow, rather than diving as speed increased in the original (see Bischoff 2010; 2012; 2016).

3.10 Conclusion

3.10.1 The goal

Based on the review offered above, of the key developments in ship/boat archaeology from a classification, conceptual and reconstruction perspective, there are a number of themes that come to the fore. These are summarised below and comprise the fundamental goals of these approaches. Some are related simply to the vessel itself, and others to the factors, people and societies that are related to the vessel.

- The object itself (the shipwreck)
- The person or people who ordered the object
- The person or people who constructed the object
- The person or people who used the object
- How the object performed
- The society in which the object was used

The ideal solution should be, a reconstruction which violates none of the archaeological evidence, in order to know what the ship or vessel looked like, how it was used, and to reconstruct both the object (the vessel) and the process (the construction) in a scientific and repeatable manner.

All stages of the archaeological process have traditionally involved interpretation to some extent. Decisions on what exactly to record, or more significantly what not to record, what method to employ during the recording process, and what to actually use the recorded data for, are all forms of interpretation. Even the human eye reading a measurement or documenting the colour of an object is an interpretation.

As demonstrated in Chapter 3.5 any reconstruction can only be the reconstructor's interpretation, another reconstructor can take the same raw data or evidence and create a different but equally viable outcome. In the case of Ferriby 1 the two hypothetical reconstructions (Chapter 3.5.2), one a flat bottom version (E. V. Wright and Wright 1947; McGrail 1987:120; Cunliffe 2001:68; McGrail 2001:184–7; Clark 2004) and the other a rockered bottom version (Wright 1990; Coates 2005a:40–42; Coates 2005b:518–19; Gifford *et al*. 2006; Van de Noort *et al*. 2014) are two very different boats, which are both based on the same archaeological excavation.

Even more stark are the two hypothetical reconstructions (Chapter 3.5.3) of the so-called Brigg 'raft', the 'box like' shape with low almost vertical sides as proposed by McGrail (1985a) as a minimum reconstruction, and the rockered as well as a transversely rounded bottom proposed by Roberts (1992) suggest two radically different hull form hypotheses.

A reconstruction can never achieve the actual original as constructed shape, unless that original shape was somehow recorded at the time of construction. Even if the data survives, the question remains, has it been contaminated, deteriorated or distorted, and how accurate is the original recorded data, if a drawing, it has also probably been idealised or faired to some extent.

This does not mean that a shipwreck reconstruction should not be attempted, McGrail (2010:446) states that, on projects in which the surviving timbers include the keel, an undisturbed, near-complete bow and stern, and at least part of the top edge of the sides, a valid reconstruction may well prove possible, and further noted that:

> "In a few cases, there will be sufficient evidence preserved from a wreck to draw up a complete reconstruction of the hull based on the 'torso/as-found' drawing, with the missing parts determined by mirroring existing parts or by extrapolation from the preserved majority of the hull." (Crumlin-Pedersen and McGrail 2006:55).

In most reconstruction projects there will be a need for supplementary evidence from other finds or other relevant sources. These procedures may not always be possible for lack of comparative evidence, and additions to the hull or rigging will inevitably alter the appearance of the vessel, and more importantly could lead to circular arguments (ibid: 55).

Steffy (1994:189) stated the piles of rotted timber and broken artefacts constitute a wealth of information, yet much of that knowledge will remain unrecognised, unless a proper method to access it is developed, and accessing that information is the mastery of a discipline. For Steffy that discipline consisted of three main stages: recording; research and reconstruction; and interpretation and dissemination. Steffy subdivided wrecks into two primary categories, which he designated as capital and contributory. Capital reconstruction are from the well-preserved remains of a wreck, resulting in hull lines or elaborate construction plans. Contributory reconstructions are typically from less extensively preserved wrecks, thereby supplying new information, but lacking the potential to provide elaborate design or construction contributions (ibid: 215-221).

As pointed out by Adams (2001:293), of the vast numbers of ships constructed, the hazardous nature of water transport has bequeathed to us an enormous database of wrecks, augmented by those craft that were abandoned or ritually disposed of in various ways. And in that incomplete database we observe similarities and differences in physical features, period, and geographic regions.

Adams (2013:7–13) noted that some criticisms of early maritime archaeology included the work being of an almost totally descriptive nature and orientated towards historic particularism. While there is a great deal of validity in this criticism according to Adams, there are also mitigating factors. Firstly, in terms of data collection and analysis, the majority of projects were still at a very early stage. Secondly, as many projects were using methods and techniques for the first time, it was inevitable that the authors would discuss methodologies.

Adams (2013:12) states that while archaeology's theoretical pendulum has oscillated violently over the last few decades, maritime archaeology has quietly profited. Often perceived to be lagging behind, maritime archaeology generated its own approaches as well as selectively adapting elements from the wider discipline. Over time a gradual lessening of the focus on method, and a reduction in the dominance of ship-related research, focusing more on other aspects of the maritime past, encompassing not only ships, but other submerged structures, landscapes and maritime communities ashore and afloat.

Has that pendulum swung too far, as noted by McGrail (1995:139) what we identify as a tradition is our construct, which as a classification system is an abstraction from reality? A significant quantity of both time and paper have been expended on the shell – frame issue, a large portion of which I believe, has stemmed from, and is based on the erroneous statement by Greenhill (1976:60–61) that for the edge joined boats the shape was first visualised as a shell of wooden planks, whereas for the non-edge joined boats the shape was visualised as a skeleton which gave shape to the planks.

Here Greenhill is describing the building process, and not the actual visualisation of the shape. Whether planks are edge-joined or not is the physical act of creating the desired object. Steffy (1995:419) notes that our initial problem in comprehending the form perhaps lies in our designation, and Adams (2013:56) states '...it is the terms 'shell-built' and 'skeleton-built' that embody the conceptual gulf perceived to exist between the two approaches.' My experience as a shipwright leads me to believe that the builder visualised the hull they would build, as a three-dimensional shape, which in its most basic form was perhaps just overall dimensions (length, width and height) possibly inter-related. At a more advanced level possibly they visualised the actual form, position of widest beam, underwater profile shape, and the manner related factors making up a complete vessel.

As Steffy (1995:417–424) noted, in the 20 years since the publications by Casson (1971), and Basch (1972), a lot of frames, planks and nails have been recorded. But the research has added virtually nothing concerning the way in which shipwrights projected and controlled hull shapes.

3.10.2 A boatbuilders perspective

Rather than just considering ships from the perspective of an archaeologist, an alternative, and useful viewpoint can be gained if we consider the ships and boats contained in the archaeological record, from the perspective of a boat builder or shipwright.

In terms of boat or ship building, from the boatbuilders point of view, the most basic issue is the shape of the vessel. Often beginning with the shape that the customer thinks they want, developing as a dialog (or compromise) between the customer and boatbuilder, normally this will be dictated by the planned use, and to some extent the operating environment of that vessel, but it can in addition, be influenced by external factors such as customer demands, availability of materials etc. Concluding with the actual shape of the vessel after completion. So, before the vessel set sail on her maiden voyage there has already been at least three 'shape-states'.

What is that design intent shape, where does it come from, and can we find any evidence in the archaeological record?

Throughout a vessel's life, it will invariably pass through several further 'shape-states'. These can include, but are not limited to general wear and tear, any repairs or alterations carried out during its use, as well as the gradual deterioration over time due to effects such as hogging, sagging and twisting, and eventually to its abandonment or wrecking shape.

A potential list of those varying shape states could be:

1. Customer's desired shape
2. The design intent shape as imagined by the builder
3. The actual as-built shape once completed
4. The use-life shape, which may include repairs and/or alterations
5. The abandonment or wrecking shape
6. The 'as-found', or archaeological discovery shape
7. The post-excavation shape state
8. The target reassembly 'shape state'
9. As displayed or 'achievable shape state'
10. Previously published reconstruction shape
11. The full-scale Replica 'shape'

If we take Muckelroy's observation (1978:3) about the ship being the most complex machine produced, then the shipwreck, if it is to successfully disclose all of its potential information, its study, is an order of magnitude more complex. Most commonly in the archaeological context, it is at number 6 in this list, the 'as-found' shape state where a project begins.

Many of the preceding publications suggest the 'as-found' shape is the basis, from which:

> "small-scale models of individual timbers are brought together to build a coherent structure representing the pre-depositional state of those parts of the boat that were excavated. With this as a basis, and using other forms of evidence where appropriate, it may be possible to build up, by trial and error where necessary, one or more hypothetical reconstructions of the full form and structure of the original vessel" (Coates *et al*. 1995:296)

> "The term 'minimum reconstruction' is now used to describe one or more (partial) reconstructions based on the excavated evidence-as depicted in a 'torso/as-found' scale model or drawing in which allowances have been made for distortion, displacement and shrinkage-using valid comparative evidence to 'fill in' the missing parts, but without

> recourse to naval architectural conjectures, alien elements, or anachronistic intrusions." (Crumlin-Pedersen and McGrail 2006)
>
> "After the evidence has been re-appraised, small-scale models of every excavated plank and timber should be made and fitted together until a model is formed of the boat as found, but with distortions and compressions removed, displaced elements replaced, fragmented timbers made whole, and the hull rotated to its deduced attitude when afloat. This 'as-found' or 'torso' model, or a measured drawing developed from it, then becomes the basis for an attempt to 'fill in' the missing pieces, a process which may lead, if the surviving evidence allows, to a rigorously-argued reconstruction of the original boat." (McGrail 2007:255)
>
> "First reconstruction is considered to be the as-found record but with obviously distorted parts restored to shape, displaced parts reinstated, fragmented timbers made whole, and the vessel rotated to a vertical and horizontal plane (consideration of the correct waterline plane is considered in the second level of reconstruction). All first reconstruction is reliant on full and unequivocally interpretable archaeological evidence.
> Second stage reconstruction is considered to be an interpretation of the original vessel based on an interpretation of the archaeological record.
> Third Stage reconstruction is considered to be further interpretation of the vessel based on documentary or iconographic evidence not directly linked to the site or vessel." (Institute for Archaeologists 2008; Chartered Institute for Archaeologists 2014)
>
> "Excavated wooden objects seldom retain their original shape; between deposition and excavation significant changes are to be expected. A flat bottom recorded on a boat during excavation does not mean that such was necessarily her shape when in use; conversely, a longitudinally curved bottom on excavation does not necessarily imply that the boat was built with rocker. In both cases, the original, pre-depositional shape has to be logically deduced and presented for criticism." (McGrail 2007:256)

This approach would appear to suggest that from stage 6, the 'as-found', or archaeological discovery shape, and possibly with a brief examination of stage 5, it should be possible to jump directly to stage 2 the design intent shape of the original builder. And from this the reconstruction shape for a potential full-scale replica is taken.

Consequently, like a mythical phoenix rising from the ashes, once rediscovered and excavated, the vessel is often transformed to an idealised, faired (design intent) shape, and possibly a replica is built.

That initial or as found shape state can be subjected to many interpretations or preconceptions, resulting in a 'reconstruction' sometimes far removed from the original, and the leap from stage 6 (the 'as-found' shape) to stage 2 (the idealised or design intent shape) and then stage 10 (the replica shape) ignores many of the intervening stages, and the associated information which they can reveal.

During the reconstruction work for the Newport ship, as will be shown in Chapter 7.4, the recorded timbers were 3D printed and reassembled using the alignment of fastening positions as was typical with many other projects, and the result was always referred to simply as 'the model'. As publication approached, a label was required for this research model, Coates *et al*. (1995:296) state this was a coherent structure representing the pre-depositional state, which would possibly relate to stage 5 (the abandonment or wrecking shape) on the list. However, we knew many of the timbers had deformed or changed shape between excavation and documentation. The resulting model was clearly not representing the 'as-found' shape, (that had been documented using traditional site survey and photogrammetric survey techniques), equally the model did not represent Coates 'pre-depositional state', It was decided that what we had created was a post-excavational shape state (number 7 on the list).

From number 7, the post-excavation shape state, it is then possible to move in two directions.

Moving forwards:

For a museum exhibition, the recovered timbers, following conservation, are typically reassembled to represent the ship in some form. The post-excavational shape state (number 7 on the list), is an achievable shape of the timbers prior to conservation, and a record of their shape and dimensions, as such it is a valuable asset to any conservation and monitoring programme. This shape will also form the basis for number 8 on the list, the target reassembly shape, which may alleviate some of the issues described by Crumlin-Pedersen (Jensen *et al.* 2002) where the reassembled *Skuldelev* ships are not identical to the originals.

Likewise, the as-displayed shape (number 9), which should also be documented, will provide valuable data relating to the conservation and reassembly processes, as well as monitoring the exhibited remains.

Moving backwards:

Starting again with the 'as found' shape, firstly considering what is presented in publications, more often than not, the 'as-found or torso drawing', by their very definition – *'in which allowances have been made for distortion, displacement and shrinkage'* (Crumlin-Pedersen and McGrail 2006) – are an interpretation. Some notable exceptions include the Kalmar 1 drawings (Åkerlund 1951) shown in Figure 2-8, the site diorama models used by Steffy (2004a:125), and Pomey's (2005:89–154) 'exactly as-found' model with the damaged or displaced parts modelled as recorded on site (shown in Figure 2-56), which are in effect, free from interpretation.

Many of these 'as-found or torso drawings' lack what Denard (2009) called paradata, describing the process of understanding and interpreting the data, and as such, make it difficult to understand how and why decisions were chosen, and exactly how the damaged or displaced elements were reinstated.

Stage 5, the abandonment or wrecking shape, will take into account what Adams (2013:21), called the wrecking event. As pointed out, an event which can vary from short-term and dramatic, to longer durations involving material alterations to both the vessel and the elements onboard. Evidence may be found in the archaeological remains indicating some of those emergency alterations or repairs, involved in that wrecking process.

Stage 4, the use-life shape, is an important consideration in any reconstruction, apart from the obvious (or not-so obvious) repairs to any vessel, quite often, as a result of the vessel changing ownership, and as noted by Murphy (1983:74) sometimes between ethnic groups or nationalities, alterations are an almost inevitable part of any vessels life. As pointed out by Adams (2013:20), the ship often arrives at its place of wrecking, with an onboard stratigraphy, which if undetected, can become 'built-in' to the perceived original form of the vessel.

Stage 3, the actual as-built shape, will represent what our shipbuilder managed to achieve in comparison to what they intended to build. It would be unusual for a boatbuilder to set out to build a suboptimal boat, so we can reasonably assume that the design intent is for a fair, and probably symmetrical design, although Hocker's (2013:73–79) article on the myth of symmetry should be noted. However what Hocker calls the messy reality of boatbuilding, can have a significant effect on the actual outcome, and if the as-built shape can be determined, potentially an insight into the process, and the obstacles preventing that goal can be better understood.

Stage 2, the design intent, this will be the three-dimensional expression of the vessel the boatbuilder intends to construct. Steffy (1995:424) concluded that the ancient shipwright whether by mental image, traditional proportions or formal documents, comprehended the hull design before construction began, and could predict and control that design with a fair degree of accuracy. In archaeological terms this shape has often been considered the most important, as the design of the vessel, and the basis for analysis to examine a vessel's capabilities, capacity and seafaring characteristics.

Stage 1 The customer's desired shape, this is ultimately the starting point of the entire process, the reason to undertake the building of a new boat or ship. This can vary depending on circumstances, from the sovereign who desires the biggest or most elaborate, as a status symbol, a vessel destined for a specific task, to the fisherman who simply wants a better boat than his rival. The example I often like to use is the fisherman in need of a new vessel to replace his tired old craft. He will firstly observe what is in use by his competitors and selecting the most appealing will approach the boatbuilder to build a similar, but better version. The same size, for the same cost, but it must be faster and have additional cargo capacity. An incompatible set of criteria, which begins the process of debate between builder and customer, resulting in some compromise represented by the design intent shape.

Of note here is Prynne (1968:122) who stated that there are two principles in nautical archaeology, which he believes to be of primary importance; firstly, that nearly every development occurred earlier than one believes, and secondly, shipbuilders were (and still are) almost obsessively conservative. It would seem unlikely that the shipbuilder, if left to his conservative ways, would have created vessels such as *Syracusia*, *Vasa*, or *Grace Dieu*. While the shipbuilder may evolve and develop his design, it is the external influences such as the customer, among others, which will push and accelerate that development to new heights.

Many of the projects reviewed have used tonnages, form coefficients or full-scale replica building as measure of a ship's characteristics. Most have drawbacks to varying extents. While tonnage is the measure of a ship's capacity, it is one of the single most confused and misused measurement relating to ships, due in part to its often indiscriminate usage (cf. Nantet 2017)(please use only with extreme caution and disregard all correction factors). In the strictest sense tonnage is a measure of volume, where gross tonnage is a function of all the internal enclosed volume of a vessel. Gross register tonnage represents the internal volume where one register ton equals 100 cubic feet (2.83 m^3). Net register tonnage is the volume of cargo the ship can carry, that is the gross register tonnage, less the volume of spaces which do not hold cargo. Equally measurement tonnage, and its many derivatives such as Builders Old Measurement and Thames Tonnage, are volumetric measurements and typically expressed as tons burden (burthen).

Steffy(1982:86) states these formulas, which calculate the volume tonnage were fairly accurate when applied to the full-proportioned hulls of the seventeenth and eighteenth centuries for which they were intended, but do not necessarily determine the payload that could be carried by the spoon or crescent-shape ancient hulls or those ships where the keel had no relationship to the length of their holds. Steffy (1994:202) noted that eventually rugged field type computers with sophisticated transfer devices and limitless memory will become practical enough to draw the hundreds of hull fragments directly onto a graphic system at the excavation site or the conservation lab. When such systems become economical and easy to manage, most hull recorders will abandon the above methods. But the basics will remain the same. This reflected Steffy's thinking, he was not fixated on the details of methodology, he was focused on the results and foresaw a future in which the methods he used would become obsolete.

Another approach has typically been to use various coefficients that can describe the form and the hydrostatic qualities of a vessel. McGrail (1987) gives a brief introduction to using weight calculations and hydrostatic curves to determine the stability, displacement and draft calculations of ancient boats in chapter 3 (1987:12–22), and discusses methods of assessing performance of a vessel in chapter 11 (ibid: 192-203). The use of simple form coefficients is suggested by McGrail as a method of determining relative assessments of a boats capabilities such as length to beam ratio, or beam to depth ratio. The use of hydrostatic curves defining the underwater form of a vessel being used to generate coefficients of form which give forecasts of performance. However, coefficients[79] are a multiplier or factor that measures a particular property and are based on the underwater form of the vessel. The range of various coefficients are described in Appendix E.

3.10.3 A mariner's perspective

The initially reconstructed Ma'agan Mikhael ship resulted in a draft of 1.2 m, leaving just 65 cm of freeboard amidships. Such results led Kahanov to the conclusion that the ship as drawn was not seaworthy as the gunwale would be awash as just 24° angle of heel. As a result, the shape of the vessel was modified above the extant remains to create a revised hull form of 23 tons displacement (a massive 27.7% increase) with a positive stability up to 60° angle of heel (Winters and Kahanov 2004:131–32).

As noted by Vibeke Bischoff (forthcoming) at ISBSA 15 in Marseille, just because a reconstructed ship does not function or perform as we expected or predicted it to do, does not mean that the reconstruction is flawed or incorrect. It can equally be a case that our preconceptions are at fault. As an example, during the 21 hour leg of its journey from Dublin to Land's End, the Sea Stallion from Glendalough, a replica of Skuldelev 2, took on board over 18,000 litres of seawater, the pumps onboard constantly in use and the crew permanently drenched by waves (Nielsen 2011).

This does not necessarily imply that the *Skuldelev* 2 replica is somehow flawed, it could mean that vessel type is unsuited to the sea conditions typically found in the Irish sea. Others might argue that it was suited to those sea conditions due to the probable build location. Maybe it was simply a fact that Vikings got wet, and expended considerable energy removing water on those ship types, when used in those locations.

While the 'limitless memory' envisaged by Steffy may not have come about yet, computers are easily capable of handling the complex three-dimensional data sets typical of an archaeological

[79] The use of coefficients such as block, prismatic, midship, volumetric and slenderness coefficient are all values on a scale from 0 to 1. The values give no numerical values for what is good or below average.

shipwreck and can be used to provide accurate results such as shape deviation analysis. The use of computer simulations and naval architecture software can quickly analyse aspects such as displacement tonnage, which in contrast to measured tonnage, relates to the weight of a ship based on the weight of water it displaces at varying loads, Typically calculated for lightship displacement, the weight of the vessel without stores, fuel or cargo, and loaded displacement, the weight of the ship, stores and cargo. It is measured indirectly using Archimedes principle by calculating the volume of water displaced by the vessel and converting that volume into weight displaced.

Additional analysis can determine detailed hydrostatic and hydrodynamic results, which rather than the relative assessments of a boat's capabilities, will provide detailed and more important, specifically comparable outputs. These can greatly enhance our understanding of a hypothetical reconstruction and allow testing of various alternative hypotheses in the search for a more definitive solution.

But as I have already stated, any reconstruction can only be that reconstructor's interpretation, and as Steffy (1994:216) noted the research and reconstruction procedure is a personal matter that is shaped by one's preferences, abilities, and experience, so there will be no rigid set of rules defining the proper procedure for reconstructing a wreck. Dick Steffy had a saying which he often repeated, both in the classroom and on projects, you need to listen to the timber, it will tell you what it wants to do (F. Hocker 2020, pers. comm., 28th January). Do we use a design by committee approach to reconstruction, and create a hypothetical reconstruction based on conceptual approaches to the philosophy of shipbuilding (by people who in many cases have never built a ship/boat, or been trained to build a ship/boat)? Very few people set out to make any task more difficult, and a 'time-served' shipwright or master mariner spends more time 'learning', than a doctoral dissertation takes to complete. The builder is unlikely to fabricate superfluously complex features. We need to closely examine the details, the construction joints, the methods, and understand their reasons as clues to the missing components,

The following chapters aims to apply the technology that we now have, potentially in the manner that Steffy might have envisaged, to solve some of the conundrums thrown up. That technology allows us to record in 3D, research and reconstruct in 3D, all done digitally and at full-scale. It also allows us to test in terms related to the actual hull-form, rather than proxy coefficients or faired block models. Chapter 6 will demonstrate the application of this solution methodology to a real-world vessel as a proof of concept to show that this is possible to achieve.

Chapter 4 **Source Data**

4.1 Introduction

From the reviews in Chapter 2 and Chapter 3 the main theme is that all archaeology is contingent on the source data and everything stems from that. That source data, by its nature can be difficult to understand, and as noted by Hocker (2004:2)

> "the study of ship remains begins with the recording of seemingly trivial details, the thickness of planks, the number and size of nail, the direction of an adze stroke."

The examining of the minutiae of trivial details to understand the workforce involved in building the *Vasa* (Hocker 2013) is a good example of the great level of detail it is possible to achieve. Achieving this level of detailed understanding of both the object and the processes involved is predicated on the quality and detail of the underlying source data.

This chapter examines the development of methods employed in the surveying of an archaeological excavation site, in essence the capture and recording of the raw primary data from the site or artefact. Reconstruction is not an end of its own, but a logical continuation based on appropriate source data in which we have confidence. Past reconstruction projects may have used the source data, but it is not always possible to understand or interrogate how that source data has been used or interpreted, due to the lack of published paradata (Denard 2009:13), and the fact that the raw source data is rarely published in a form devoid of interpretation.

As George Bass points out in his introduction to the Oxford Handbook of maritime archaeology (2011:10–11), archaeologists publish only a fraction of the sites they investigate, and noted that it can take years or decades to produce excavation reports that are more than simple catalogues. This practise inhibits the continuous flow of information and slows down the collective research efforts to reconstruct the past. Primary data is often kept away from peer review even after final publication of an excavation. Roger Hill (1994:141) proposed a development plan for the application of computer technology to archaeology and argued that the purpose of archaeological recording is to transfer the ground based record into a form accessible not just to the site archaeologist but to all potential users. As such, the technology used to record site data is not a secondary concern but is central to the activity of site archaeology. We have an obligation to bridge the gap between the exclusive knowledge of the excavator and the published record, a mode of data capture and record that is devoid of interpretation, or where interpretation is inevitable, paradata is used to explain the human processes of understanding and interpretation of the data objects.

4.2 Traditional Surveying

The quality and detail of the source data is directly proportional to the accuracy of the measurements recorded, as well as the level of interpretation employed in that recording, and the completeness of the elements recorded. As can be seen from Table 3-1 and Table 3-2 the recording of source data has developed from the 19^{th} century two-dimensional site sketches, which were interpretive by their nature, to the 20^{th} century traditional 'baseline and offset' survey technique, which involved a degree of interpretation in the reading of measurements, and more significantly, interpretation in the selection of which elements were recorded, often due to either time or economic constraints. The manual surveying of complex sites or objects can be a very time-consuming process and presents challenges in terms of subjectivity and accuracy (Holt 2003), and as noted by Baltsavias (1999:84), measurement without interpretation is sometimes very difficult or impossible.

4.3 Tacheometric surveying

Tacheometric surveying such as with a theodolite or total station, involves the measurement of individual three-dimensional points relative to one another, using a combination of angular and distance measurements. Both the theodolite and total station have a long history in surveying. One of the first uses of a total station to record large ship structures in Denmark was pioneered by Christian Lemée in 1996 during the excavation of the renaissance ships at the B&W site in Christianshavn (Lemée 2006). The concept developed was based on identifying the different structural parts of the ship and carrying out a complete survey of the ship as a whole, through the selective field recording of individual elements, combined with small sections removed for later detailed documentation (Figure 4-1). Differences occurred when 'others' documented portions of the wreck, not in the shape of the lines created, but in the omissions of features recorded by not knowing exactly what was important to document (Lemée 2006:87). This clearly highlights some of the issues with interpretive or subjective recording techniques, as pointed out by Lemée when he acknowledged that the process requires the operator to possess specific knowledge and understanding of ship structures when determining which elements to document. In addition, a decision was taken during recording at Christianshavn not to document the 'Z' or height measurement as the equipment used was capable of logging the 'X' and 'Y' coordinates of a point in two to three seconds, while the addition of logging the 'Z' coordinate added another seven to eight seconds. With typical logging of up to 1,200 points per day, and a total of circa 32,000 points logged, the additional 'Z' coordinate logging would have added days to the process (Lemée 2006:82).

Figure 4-1 Total-Station recording Photo: after B. Gyldenkaerne, (in Lemée 2006:83)

Initially Lemée examined existing historical naval architecture texts to establish a design and construction 'pattern' for these carvel-built ships. When this proved unsatisfactory, it was decided to attempt reconstruction using the existing established methods called reverse naval architecture by Crumlin-Pedersen (Lemée 2006:97). However, a major problem arose in that, with few exceptions, the shape of all planks and compass timbers were only known in the horizontal projection or plan view, due to the absence of height measurements from the total station data. The extent of data recorded from the excavations was the accurate drawings of the plan view of the ships as excavated but including distortion, and the 1:10 scale drawings of the four different hull sections which were cut from the excavation for detailed documentation. Lemée (2006:87) concludes that the total station is an important tool for recording large coherent structures, however, in most cases it needs to be complemented by traditional methods. Clearly, fewer points which included the Z coordinate, or height measurement, would have provided a more valuable three-dimensional data set, rather than the two-dimensional data which was recorded.

The recording of multiple wrecks in Yenikapi, Turkey, also employed a total station with a recorded point density of between 4000 and 10,000 points per wreck depending on its size (Kocabaş 2008:51). The Yenikapi excavation also insists on the necessity of including photos, sketches and visual remarks (Figure 4-2) to reach the best possible result (ibid: 53). As noted by Hyttel (2011:24), based on the quantity of points recorded on both the Christianshavn and Yenikapi sites, an estimated duration of four to nine days is required to produce a detailed model of a relatively simple vessel. In terms of accuracy, Hocker (2003:85) reported a repeatability of single-point measurements within 10 mm over a 20 metre length while recording the reconstructed Iron Age vessel *Tilia Alsie*, and a similar offset error was estimated for the Christianshavn excavations (Jensen and Lemée 1999:86).

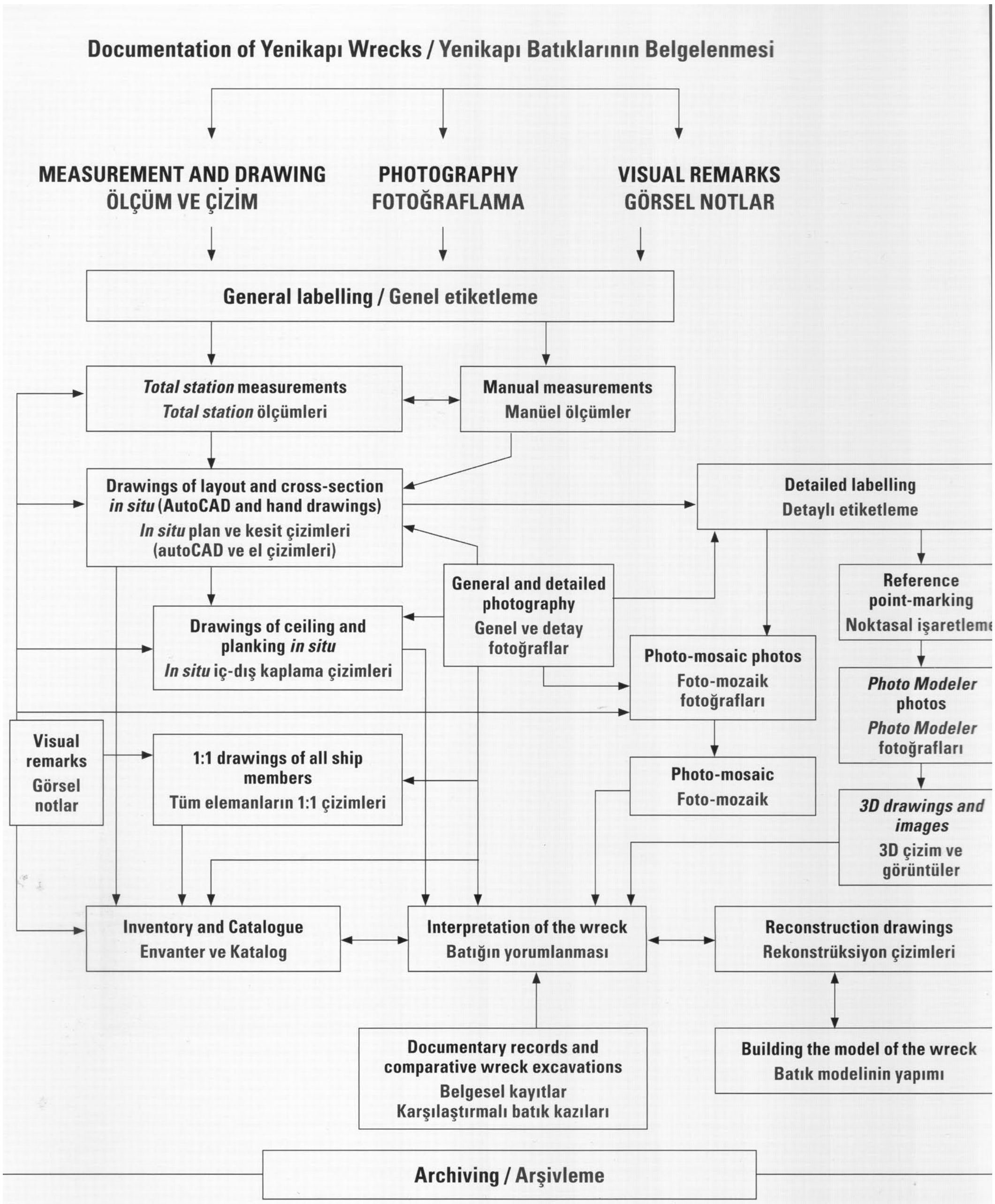

Figure 4-2 Flowchart of the documentation of Yenikapi wrecks (after Kocabaş 2008:40)

4.4 Photogrammetric Surveying

Stereoscopy is the science of using overlapping imagery acquired from different locations to produce a 3D model that emulates true binocular vision. The technique was developed in the 19th century and more fully developed during World Wars I and II to identify and accurately measure topographic and ground features visible in aerial photographs. The main applications of stereo-paired photogrammetric techniques are the identification, measurement, and manual digitisation of three-dimensional features. For underwater surveying of archaeological sites, the potential of photogrammetry was recognised as early as the 1960s when George Bass used paired cameras mounted on a mini submarine to document a late Roman wreck (Bass 1966:112–118). The resulting measurements were manually processed and used to create a plan of the wreck site. This approach minimised the time required by divers underwater for surveying but required extensive manual post-processing.

Advances over the last two decades have included a move away from stereo paired photogrammetry with the advent of multi-image photogrammetric software such as Agisoft Photoscan, capable of automatically resolving issues such as parallax and lens characteristics in order to calculate the relative position of the camera. In multi-image photogrammetry, also commonly known as structure from motion, the software is used to compare large sets of images in order to identify matching features, making it possible to calculate both the optical characteristics of the camera used and the relative position of the matched features. Photogrammetric survey as a low-cost and rapid tool for maritime archaeological surveying is highlighted by Canciani *et al.* (2002), Skarlatos *et al.* (2012), Henderson *et al.* (2013), McCarthy and Benjamin (2014), Costa *et al.* (2016) Yamafune *et al.* (2017) and McCarthy *et al.* (2019).

As noted by Skarlatos (2012:1), photogrammetry is not a real time or automated process and most photogrammetric tasks are laborious and tedious. In most cases the surveyor can only be sure of the data collection consistency only after they had successfully resolved image bundle adjustment during the post-processing phase. It is the software which produces a 3D model by extracting a dense point cloud from the bundle adjusted and stereo matched images. The resultant point clouds created have arbitrary scale, orientation and position in 3D space. Yamafune (2017:710) states that while modern photogrammetry software does not require camera calibration as the software uses exchangeable image file format (EXIF) metadata from the camera and lens, distortions are however inevitable, and this factor alone argues for the necessity of establishing a network of precisely positioned control points. As a result, all 3D photogrammetric models will require the application of a scale factor correction, as well as a rotation and translation matrix to known correspondence points, obtained from other surveying techniques in order to obtain the correct scaling and georeferencing.

Photogrammetry and LiDAR are often juxtaposed and presented as being at odds with each other. LiDAR, which stands for Light Detection and Ranging, is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances). The significant difference between the two is that photogrammetry uses two-dimensional photographs to generate measurements between objects and create a three-dimensional geometric representation of the objects themselves, while LiDAR uses lasers to detect the position and geometric shape of an object by generating three-dimensional point clouds based on laser shots, and each individual point within the point cloud has its own measured X, Y and Z coordinates .

With photogrammetry, it is the computer processing which generates "accurate and measurable" three-dimensional models from the captured two-dimensional photographs using image matching. However, image matching of tie points (Skarlatos *et al*. 2012:2; McCarthy and Benjamin 2014:98) used to calculate the position and orientation of each camera relative to adjacent images is just one part of modern digital photogrammetry. Another part of the photogrammetry process is what is known as the "stereo correspondence problem" which concerns the way software determines the X, Y and Z coordinates from measurements of just two dimensions in the form of X and Y coordinates. It is necessary for an object point to be present in at least two images, and the more images used, the more advantageous and accurate the multiple stereo view calculated.

If the computer software can correctly identify a sufficient number of tie points, then the relative position and orientation of the cameras can be correctly calculated (Figure 4-3 top). However, an insufficient number, or incorrectly matched tie points, may produce inaccurate camera positions, resulting in a distorted representation of the source data (Figure 4-3 bottom). The resulting ortho-photo mosaic produces a timber of 131.85 units length (Figure 4-4 top) for the accurately calculated camera positions, while the misaligned camera positions from Figure 4-3 bottom, produces an inaccurate timber dimension of 126.43 units length (Figure 4-4 bottom). Figure 4-5 illustrates the potential errors in the resulting 3D models. The ratio of the number of photos to the level of accuracy is a relationship that also directly affects the length of time it takes to match more images because more and more computing power is needed to do this effectively and efficiently. One thing purveyors of photogrammetric software often neglect to mention is how long it takes to process high-resolution photos and how much computing power is needed.

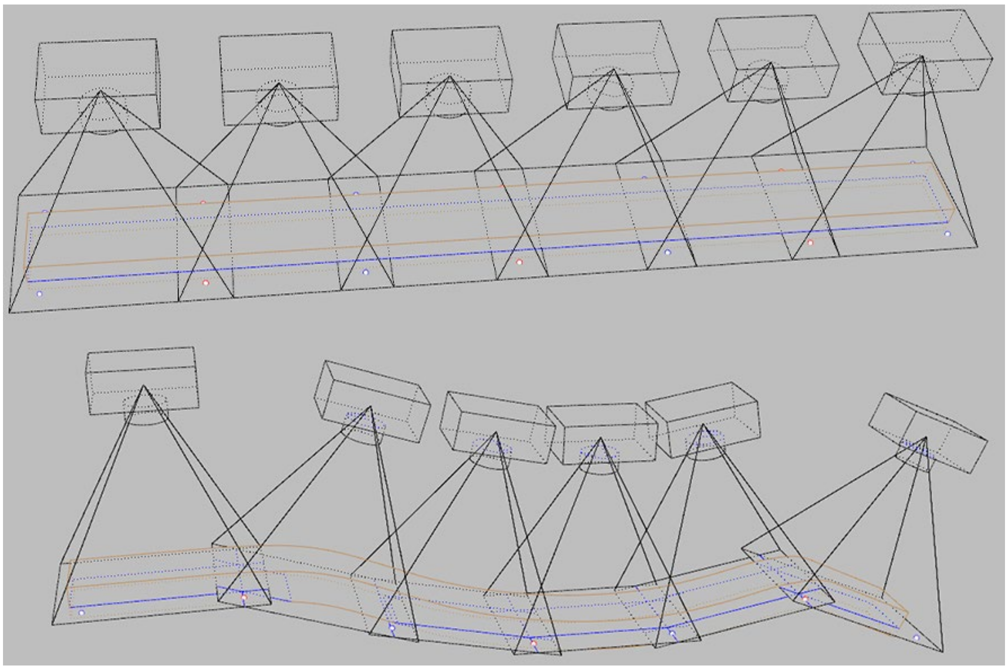

Figure 4-3 Calculating camera positions using correctly aligned tie-points (top) and misaligned tie-points (bottom) (Pat Tanner)

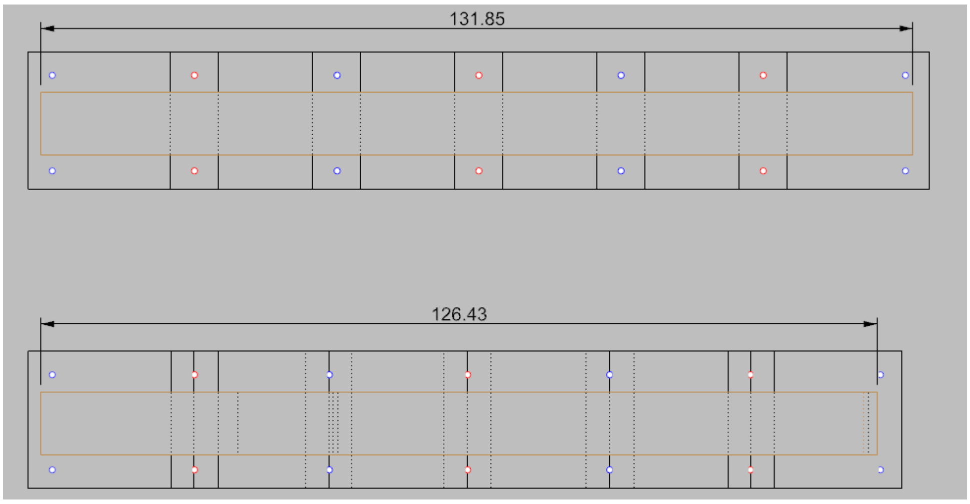

Figure 4-4 Ortho photo-mosaic of the images correctly aligned (top) and misaligned (bottom) (Pat Tanner)

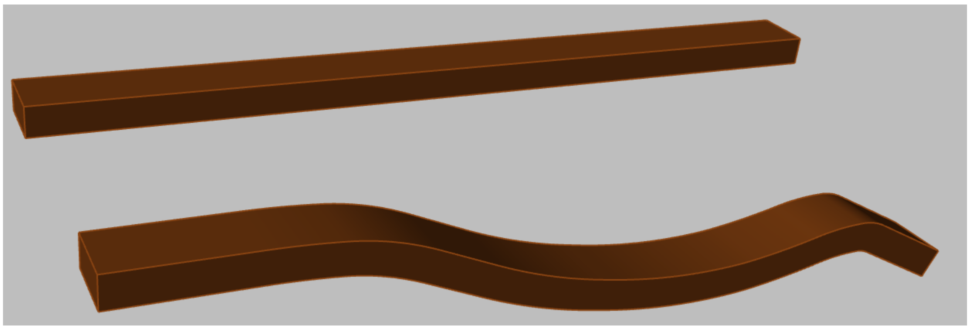

Figure 4-5 Photogrammetry 3D models from the images correctly aligned (top) and misaligned (bottom) (Pat Tanner)

Representation versus geometry, or digital “smoke-and-mirrors”.

To better comprehend the value of a photogrammetry derived 3D model, it is necessary to understand how a computer generates a three-dimensional representation of an object. 3D computer graphic models are typically represented by a mesh containing a series of triangular polygons, with each polygon being a flat triangular surface between three adjacent points from the three-dimensional point cloud. The more complex the object’s form, the more polygons required to represent that three-dimensional shape, and the more polygons used, the greater the model’s file size and the heavier the workload on the computer graphics system. The video games industry has long sought methods and techniques to reduce this file size and graphics workload, in order to speed up and improve the human interactivity. To reduce the graphics workload, a low-resolution proxy or simplified mesh model is often used, and a series of colour, normal and bump maps generate an illusion of the high-resolution detail.

Figure 4-6 illustrates an example of a complex three-dimensional mesh model where each individual rivet is made up of over 100 triangular polygons representing the real geometry (Figure 4-6 right), and the visible portion of the model (Figure 4-6 left) contains a total of almost 89,000 polygons, requiring 33 individual calculations by the computer’s graphics sub-system.

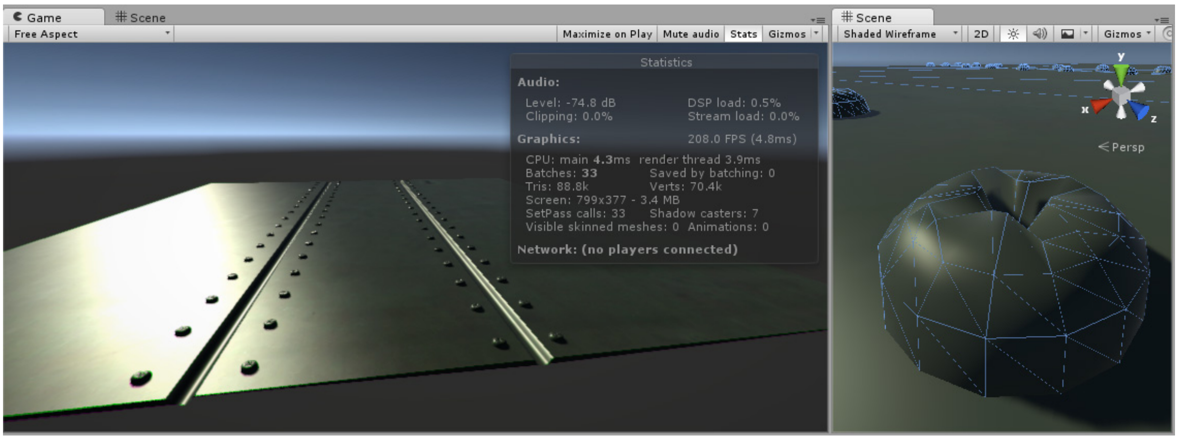

Figure 4-6 Example of geometry heavy 3D model (image courtesy Unity Manual 2019.3)

In contrast, Figure 4-7 illustrates a low geometry 3D model, in this case, just two triangular polygons, with surface features such as the metallic colouring and weathering supplied by a colour or albedo map, and all the panel’s seams, scratches and rivets simply an illusion generated by the normal map. If the low geometry model shown in Figure 4-7 were to be 3D printed, the result would be a simple flat featureless surface. Whereas, the high-resolution model shown in Figure 4-6, if 3D printed, would contain all the surface bumps, scratches and rivet shapes.

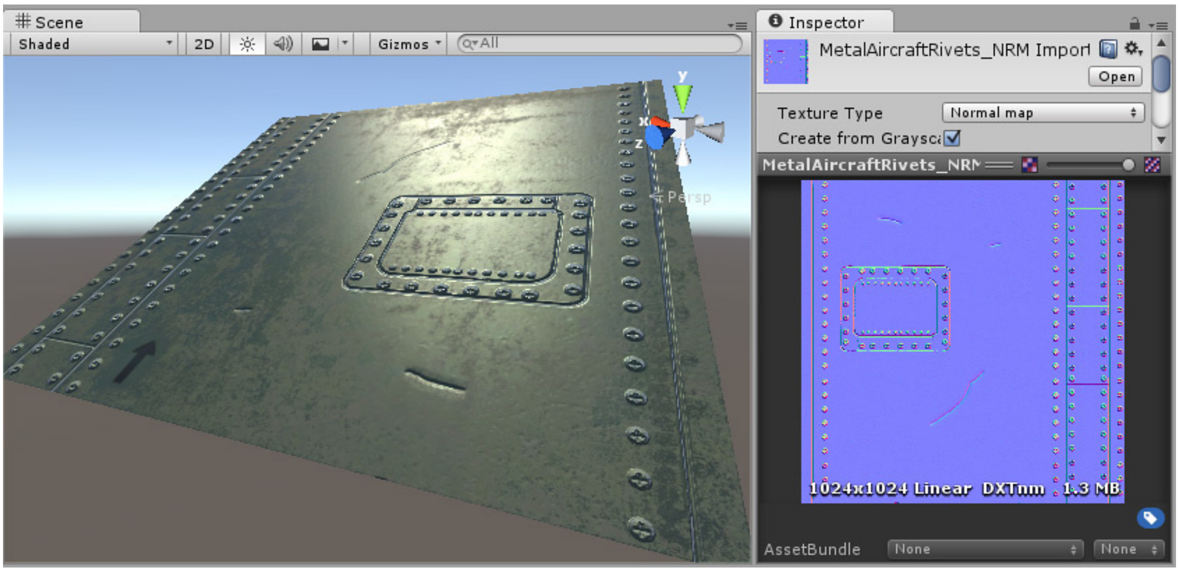

Figure 4-7 Low geometry 3D model with normal mapping (image courtesy Unity Manual 2019.3)

In the case of photogrammetry, it is not sufficient to simply generate a 3D model with a very high polygon count if there is an insufficient quantity of photographs for the software to calculate the underlying geometry. Figure 4-8 shows a photogrammetry model which was generated from some 200 photographs using Aqisoft Photoscan and would appear to have captured the internal structural details of the *Bremen Cog*. Whilst the model appears to be high resolution, with a total of over 22 million polygons, a closeup view of the same model (Figure 4-9) with the texture colour removed, shows the lack of geometric detail. Clearly, the number of images used will determine the quality and detail of surface features within the model.

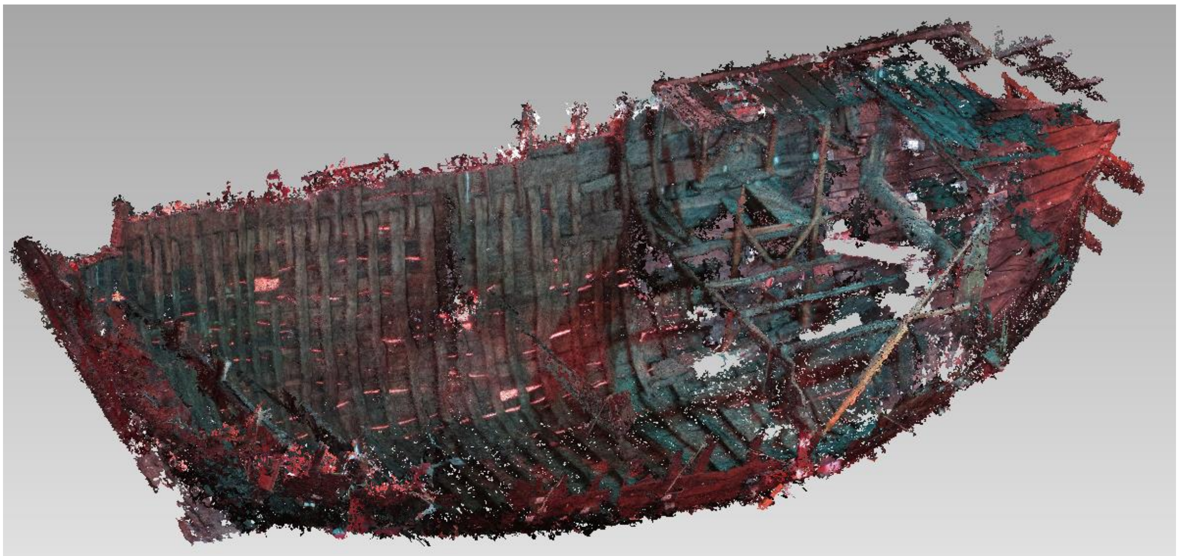

Figure 4-8 Textured photogrammetry model of the Bremen Cog (Pat Tanner)

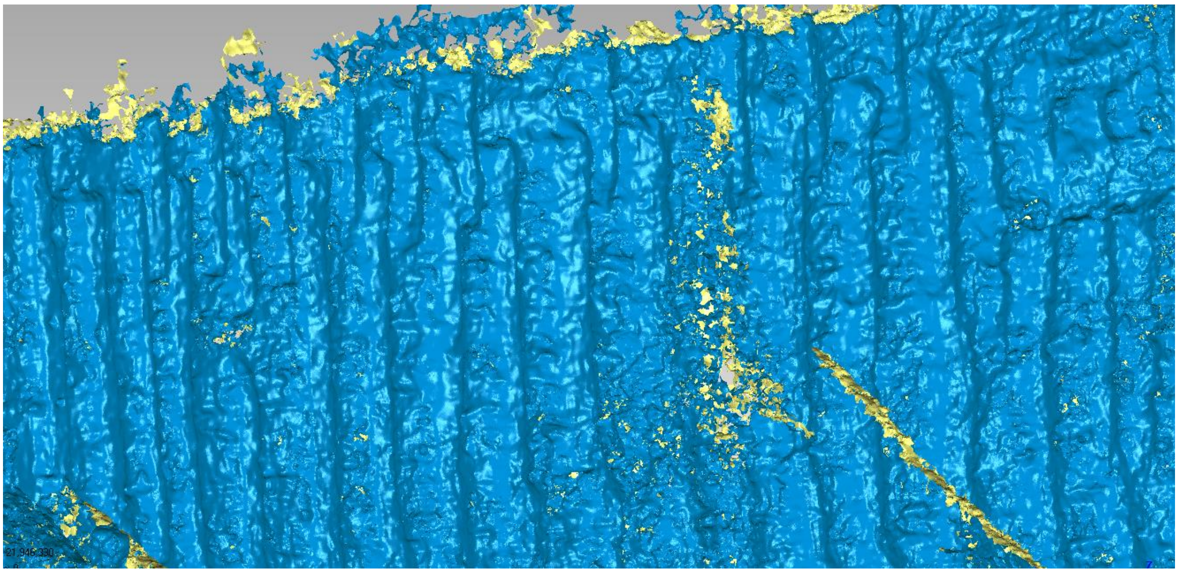

Figure 4-9 Photogrammetry model from Figure 4-8 with the texture removed (Pat Tanner)

4.5 LiDAR or terrestrial laser scanning (TLS)

Laser scanning has often been discounted as a viable surveying option with the hardware expense cited as one of the main reasons, and the sheer volume and size of the captured data files as another significant disadvantage. The issue of file size is a moot point as the “dense cloud” generated from the photogrammetry process will typically be of the same size as the point cloud physically recorded by the terrestrial laser scanning, resulting in similar data file sizes. Additionally, in the case of laser scanning it is the measured point cloud, which is the raw data, and the file size for archival storage will be quite small by comparison to photogrammetry, where the often several thousand RAW image files are the raw data, and these also require additional archival storage.

With photogrammetry requiring more archival storage than terrestrial laser scanning, the only other issue is cost. While the initial cost of the laser scanning hardware can be high, a less expensive alternative is equipment rental, which also includes the necessary software applications. If the equipment is rented for a short period, a lot of scanning can be completed and processed later once the hardware is off hire. Additionally, as discussed in Chapter 4.4 photogrammetry requires more powerful and hence more expensive computer hardware than terrestrial laser scanning for the post processing phases.

The principal difference between photogrammetry and terrestrial laser scanning is that photogrammetry interpolates the three-dimensional points based on two or more images, whereas laser scanning uses actual physical measurements to define every three-dimensional point as a series of X, Y and Z coordinates, with the option to also record colour in the form of RGB (red, green, blue) data for each individual data point.

Current terrestrial laser scanners such as the Faro® Focus S series have a range of 0.6 – 350 m, with an accuracy of ±1 mm, integrated camera allowing the colour capture of data points, as well as multiple internal sensors including GPS, compass, altimeter and inclinometer which facilitate the registration of multiple on-site scan locations, as well as geo-location based on internal GPS data. Multiple scan locations (Figure 4-10) are required in order to prevent occlusion for the line-of-sight based laser recording system. The on-site registration feature allows for real-time checking of the recorded data, which enables the surveyor to maintain a consistent level of data collection. The instrument is lightweight (4.2 kg), making it easy to transport to site, and being tripod mounted, simple to reposition for multiple scans. The unit has various resolution settings and at full resolution a point spacing of 1.5 mm at 10 metre distance from the scanner is achieved. As the laser is emitted in a conical beam, the nearer the scanner is to the target object, the closer the point spacing. At 5 m distance from the scanner the point spacing reduces to 0.75 mm. A setting of 3 mm spacing at 5 metre distance will it result in a scan time of circa 6 minutes.

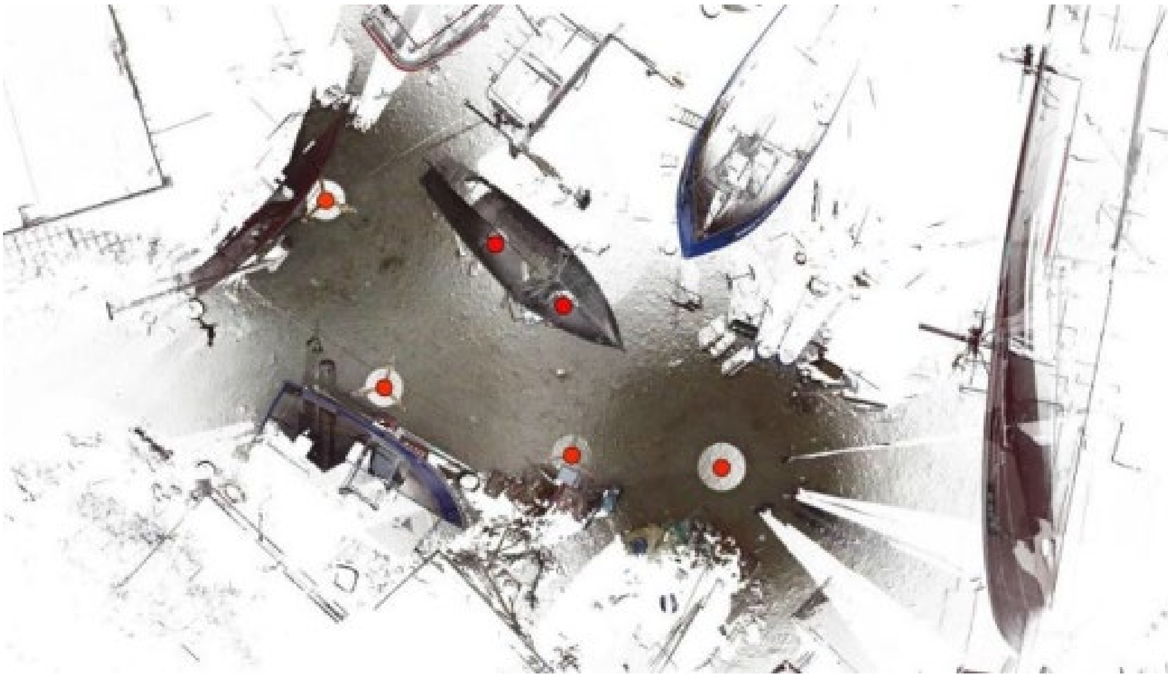

Figure 4-10 Four external and two internal laser scan positions to record a 10 m vessel (Pat Tanner)

One of the key differences between terrestrial laser scanning and photogrammetry is that every data point from a laser scan is an actual three-dimensional measurement, and the only interpretation involved is during the registration of individual scans when creating a combined project point cloud. While the initial on-site registration between individual scans is based on the internal GPS sensors and may be accurate to within a few centimetres, the post processing software allows for further refinement in the detailed registration using a target-based, or cloud to cloud registration (Figure 4-11), typically resulting in 2-3 mm accuracy. The individual scans are not modified, but rather, a translation and rotational matrix, based on the optimised registration, is stored as metadata with each individual scan file. The result is a geometrically accurate (± 3 mm) digital three-dimensional point cloud record of the source data (Figure 4-12), which is free of interpretation or more significantly, misinterpretation.

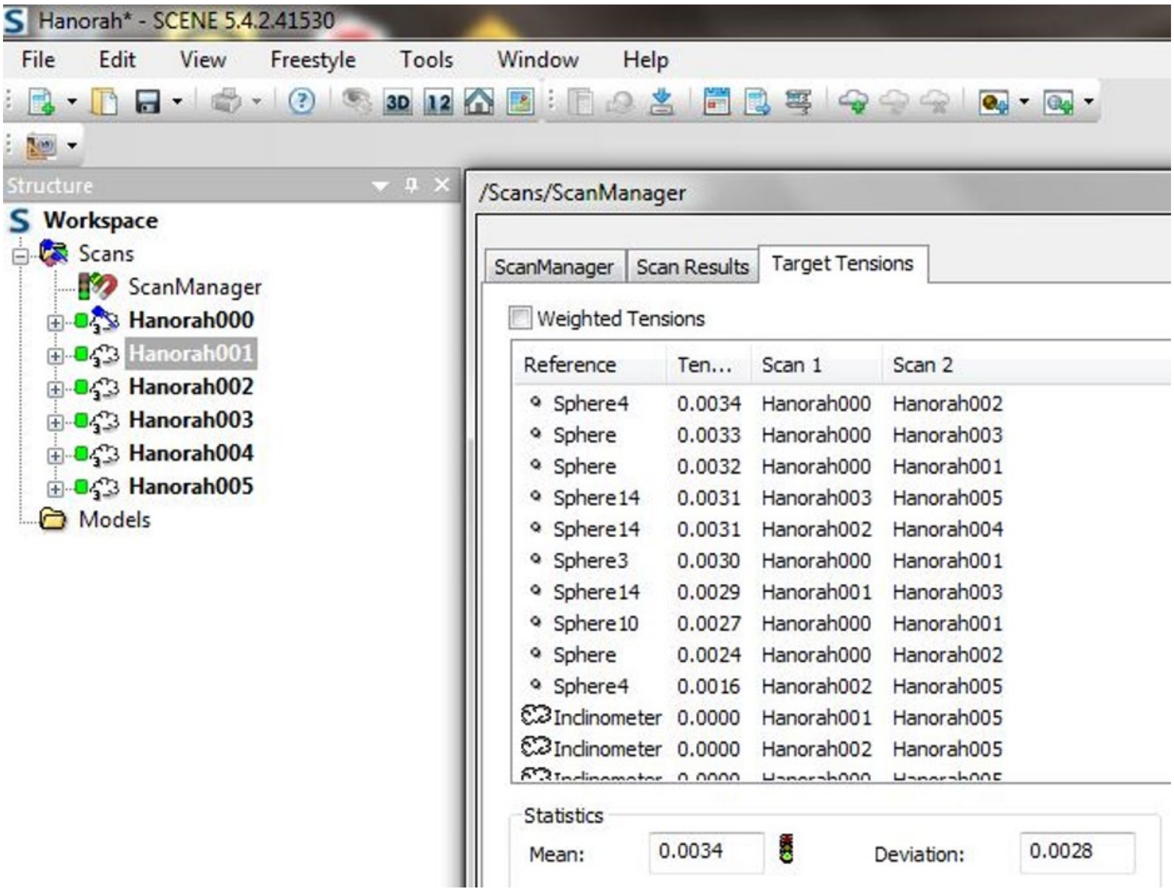

Figure 4-11 Registering the six individual scans from Figure 4-10 together (Pat Tanner)

The example in Figure 4-10 used 6 scan positions, and with each scan taking 10 minutes the total scanning time was 1.5 hours, allowing for repositioning and equipment set-up. This generated six individual point cloud scans, with a combined total of 128.6 million individual three-dimensional points. The ½ day of post-processing registered the individual scans, to generate a single project point cloud (Figure 4-12) with a maximum deviation of 2.8 mm. A video flythrough of the project point cloud can be viewed online at https://www.youtube.com/watch?v=3BiFlYdAxFE and a 3D point cloud model of the target vessel is available for viewing at https://sketchfab.com/3d-models/hanorah-3d-laser-scan-ea58f096f2904cc69f7bbf35495a2c61 .

Figure 4-12 Three-dimensional registered point cloud from the six scans in Figure 4-10 (Pat Tanner)

Laser scanning captures geometrically accurate, high-resolution three-dimensional data points (Figure 4-13), however, the colourised textured models tend to be of a lower resolution when compared to photogrammetry models. This is due mainly to the fact that the scanner's onboard camera tends to be of lower resolution, and the surface colour of the model is calculated from the colours of the adjacent individual point, creating an interpolated or blended colour (Figure 4-14).

Figure 4-13 Laser scan data from the six scans in Figure 4-10 showing intensity rather than colour (Pat Tanner)

Figure 4-14 Coloured laser scan data (Pat Tanner)

4.6 Hybrid or combined techniques

While multi-image photogrammetry software creates point clouds using pixel information from digital images to produces data files similar to those obtained from three-dimensional laser scanners, it would appear that for terrestrial recording, photogrammetry is not best suited to capture digital representations which require extreme geometric detail, which the point cloud data created by LiDAR scans is much better suited to capture. Lidar or terrestrial laser scanning on the other hand, produces geometrically accurate point clouds, which tend to have a lower surface colour resolution. Given the current technical difficulties with utilising LiDAR in an underwater environment, photogrammetry still remains the best option for sub-marine surveying (Canciani *et al*. 2002; Telem and Filin 2010; Skarlatos *et al*. 2012; Henderson *et al*. 2013; McCarthy and Benjamin 2014; Van Damme 2015; Yamafune *et al*. 2017; Pacheco-Ruiz *et al*. 2019). However, it must be remembered that all photogrammetric surveying requires some form of external control points, and any resultant 3D model is a computer-generated interpretation based on the source images and will require some form of independent verification.

Recent software developments such as RealityCapture® now mean there is no reason why the two techniques cannot be used together. This software can use the geometrically accurate laser scanning as a control network for scale and relative positioning, while using the high-resolution photography for colour and surface texture. In addition, any occluded areas which are not recorded from one source can be augmented by the other and vice versa. In a proof of concept type case study, thanks to Eleanor Schofield and the team at the Mary Rose museum, Henry VIII's Tudor ship the *Mary Rose* was recorded using a combination of 22 individual laser scans, and a total of 374 photographs by Rodrigo Ortiz. As it was not an organised or pre-planned survey, the conditions were less than ideal, with limited access and constant changes in lighting conditions.

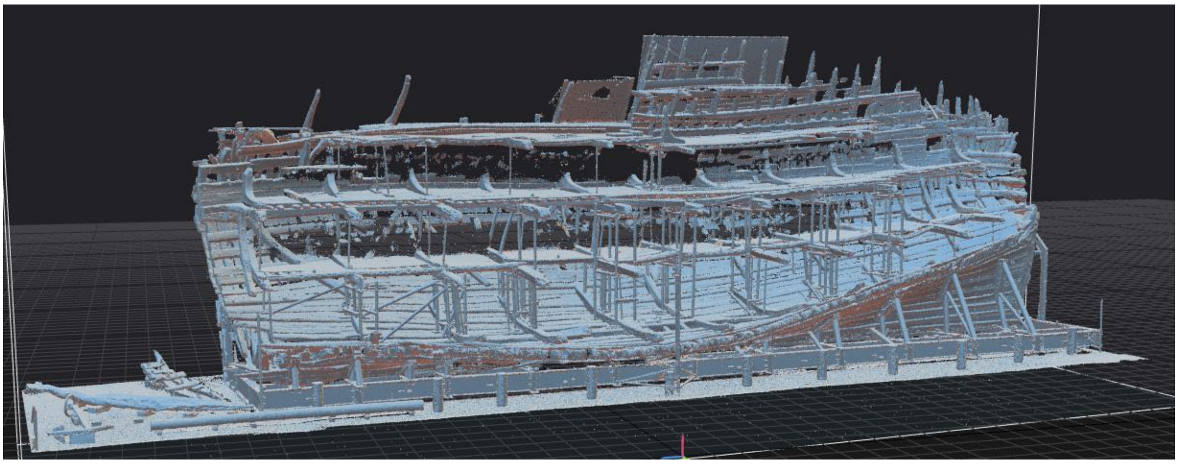

Figure 4-15 22 Laser scans of the *Mary Rose* combined into a single point cloud (Pat Tanner)

Scanning consisted of 11 locations at ground floor level inside the ship hall, and a further 11 locations on the third-floor gallery in order to avoid the glass partitions on the intermediate levels. The 22 scans were recorded without colour, taking a total of two hours to complete and were registered with the Faro Scene software to an accuracy of two millimetres. The limitations on scanner positioning caused occluded areas, resulting in missing data from the intermediate decks and is clearly visible in Figure 4-15. With this dimensionally accurate 3D model being used as the control network, RealityCapture then aligned the photographs, which enabled the creation of the missing geometry in the occluded areas (Figure 4-16), and the application of high resolution photographic quality colour texturing (Figure 4-17).

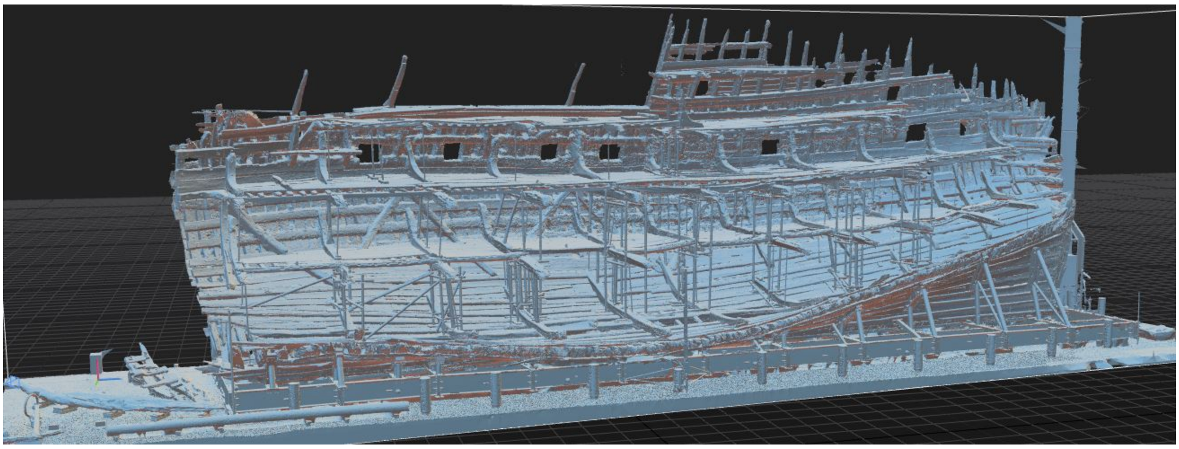

Figure 4-16 22 Laser scans and 374 image photogrammetry model combined (Pat Tanner)

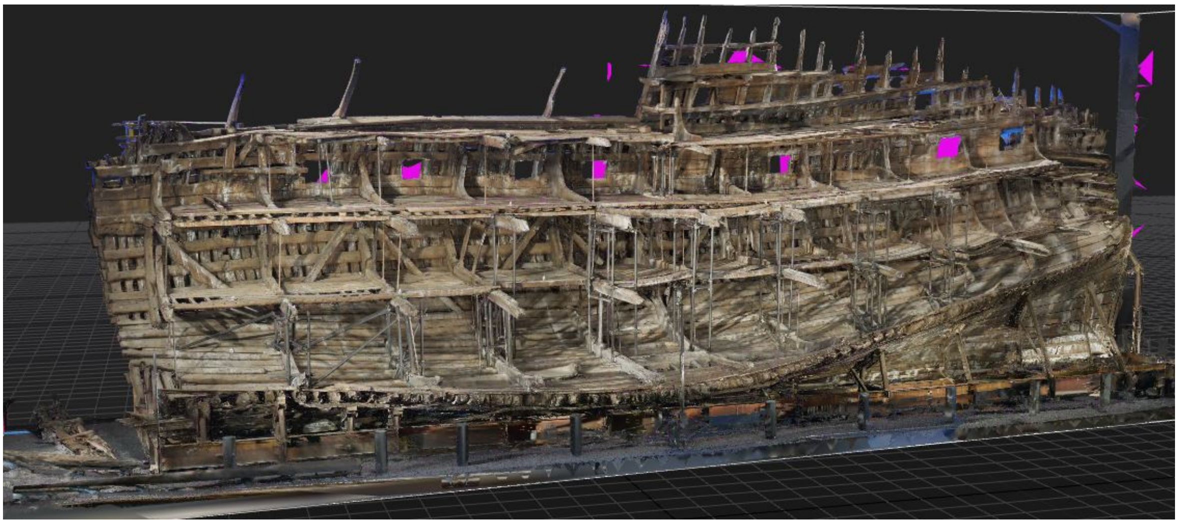

Figure 4-17 Colour texture applied to the combined 3D model (Pat Tanner)

For this case study the entire surveying time was less than one day, and post processing took approximately three days. Outputs include a high resolution video fly-through, which can be viewed online at https://www.youtube.com/watch?v=gHvRR03O1p0, as well as a very high resolution digital research model (Figure 4-18), as well as a lower resolution three-dimensional sketchfab model - https://sketchfab.com/3d-models/mary-rose-316db8d7099b42b28f889aedddc86e9d which has had almost 10,500 views.

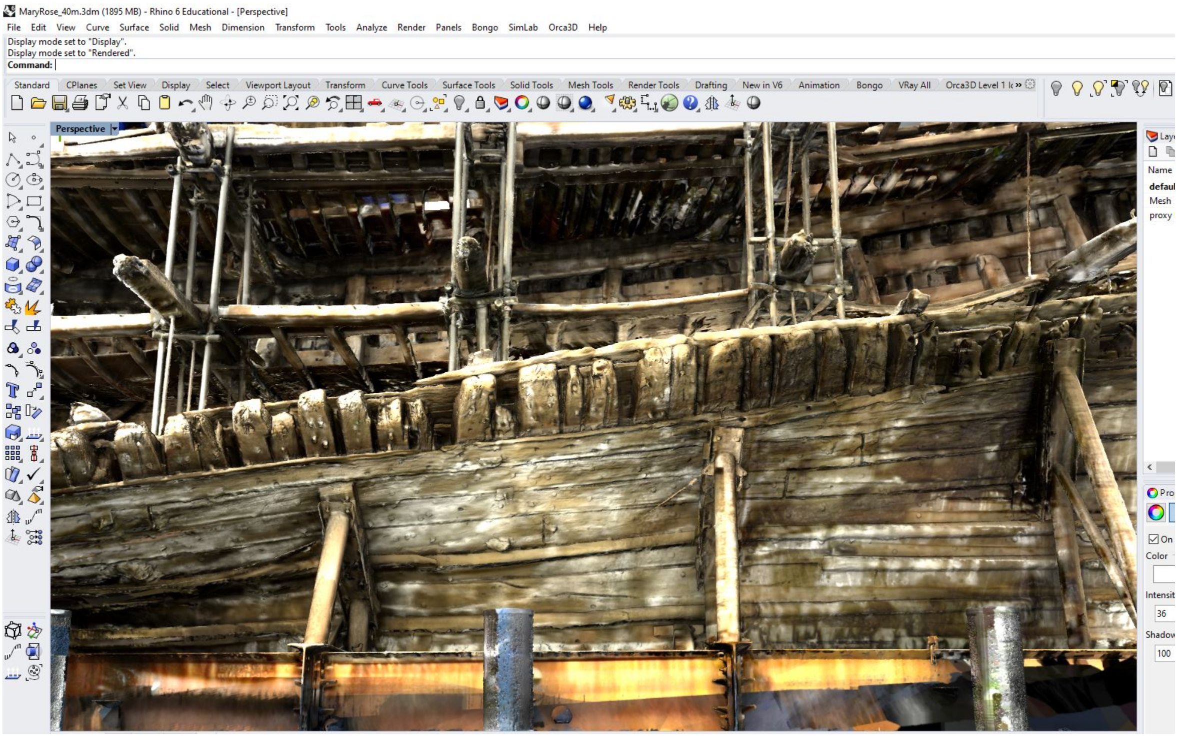

Figure 4-18 Close-up detail of high-resolution textured 3D model (Pat Tanner)

4.7 Detailed recording of individual artefacts

Traditionally, individual ship timbers and other artefacts have been recorded in 2D using scale drawings or full-sized using elevated plane tracing (Chapter 2.4.4) or contact tracing (Chapter 2.4.6). The Faro Arm, a coordinate measuring machine (CMM) was first used at Mystic Seaport in the United States during the mid-1990s to document ship's models (Starr 1996:69–72), and its use, combined with Rhino 3D software was pioneered by the National Museum of Denmark in 2001 to record 56 timbers from the *Kolding Cog* (Hocker 2000; Hocker 2003). As noted in Chapter 2.4.12, at that time, the digitally captured three-dimensional data was being flattened to produce two-dimensional timber catalogue drawings.

3D Contact digitising

The use of contact digitising continued to develop, being used on projects such as the *Gotta* wreck (Nestorson 2004), recording of the steam engine from the *U.S.S. Monitor* by Fred Hocker (Broadwater 2012:162–165), the reconstructed longboat from the *Vasa* (Cederlund 2006:472) as well as several gun carriages which were digitised and digitally reassembled using specialised templates to organise the data. In 2004, following the discovery and excavation of the *Newport Medieval ship*, a series of initial recording trials were carried out (Barker and Nayling 2004), in order to determine the most accurate and efficient method for post-excavation documentation of the individual ship timbers and associated artefacts (Jones 2015:160–164). Contact digitising was selected, and after a week-long training workshop at the Viking ship museum in Roskilde, a modified version of the Roskilde template system, which was more suited to documenting Viking type vessels, was developed into a timber recording manual by Toby Jones (2013). A digital version of the timber recording manual can be downloaded from:
https://archaeologydataservice.ac.uk/archiveDS/archiveDownload?t=arch-1563-1/dissemination/pdf/Newport_Medieval_Ship_Project_Timber_Recording_Manual.pdf

Figure 4-19 Four identical contact digitiser work stations were created to efficiently record the large assemblage. (Photo: Newport Museums and Heritage Service)

The process involves tracing features along the timber surface with the Faro Arm's probe tip (Figure 4-20), while the digitising arm constantly detects the degrees of rotation and angle at each joint, in order to constantly calculate the X,Y, and Z coordinates of the probe tip at sub-millimetre (typically ±0.025 mm) accuracy. The net result is that the user "draws" a three-dimensional wire frame representation of the timber being recorded (Figure 4-21), in full scale, with the relevant features, such as original edges, damaged edges, nails, fastenings, wood grain, tool marks and builders inscribed marks all recorded onto their appropriate separate layering system. The entire process is fully documented in Three-Dimensional Digital Recording and Modelling Methodologies for Documentation and Reconstruction of the Newport Medieval Ship (Jones 2015:165–227).

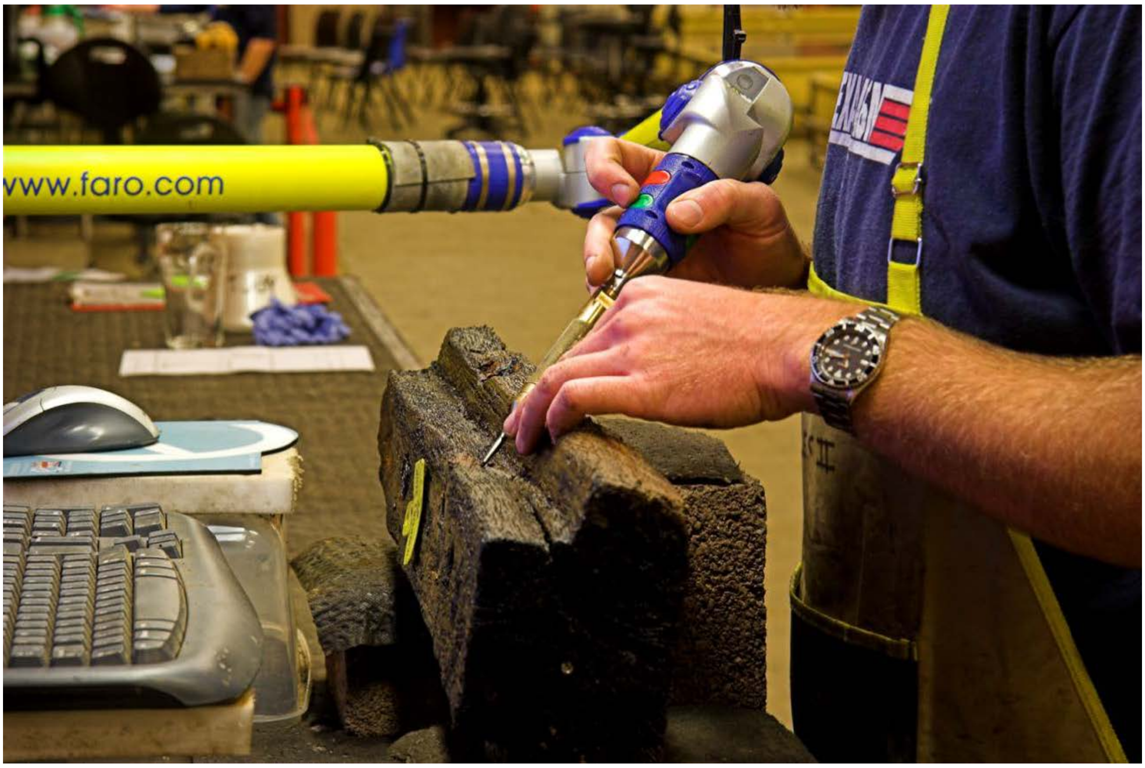

Figure 4-20 Tracing timber features using a Faro Arm (Photo: Rex Moreton)

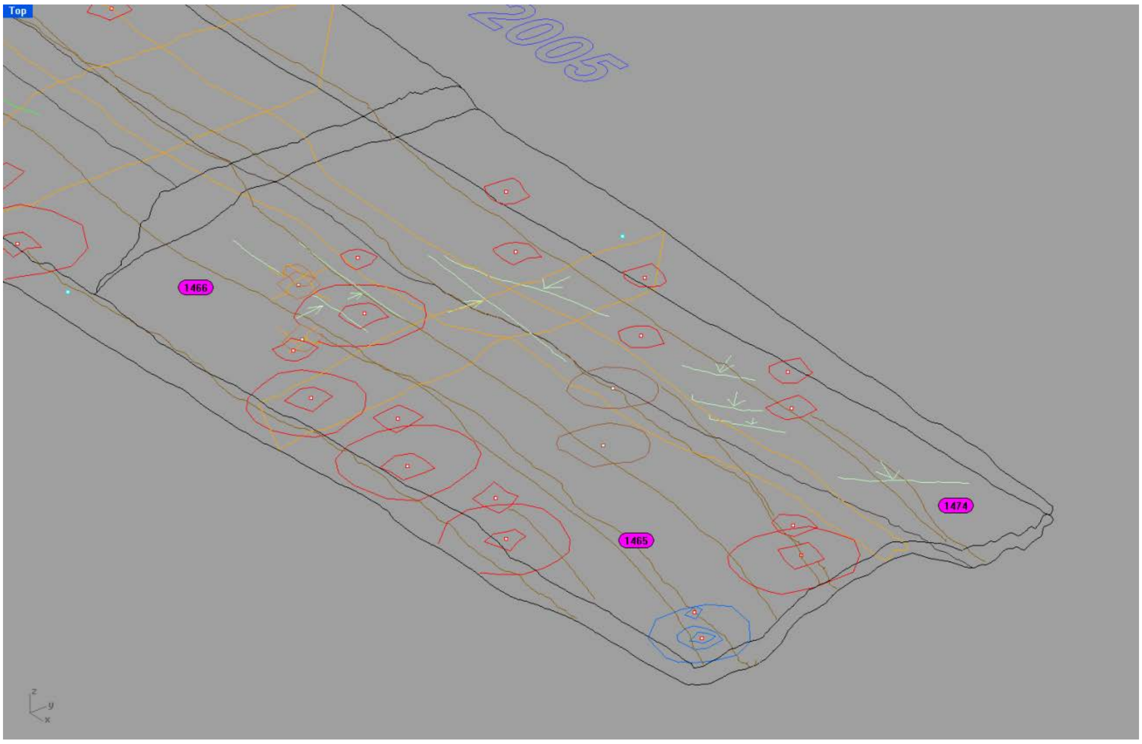

Figure 4-21 Three-dimensional wire frame timber drawing (Jones 2015:289)

Once the digital wire frame drawing of the timber is recorded, the next stage is to generate a digital solid model from the source data. A series of polysurfaces are created for each face of the timber in order to generate a closed watertight surface model (Figure 4-22) suitable for 3D printing (Jones 2015:285–299). In a notable revision to the “Roskilde method”, no attempt was made to flatten timbers during either the documentation or the digital modelling process. While the three-dimensional shape of the timbers was acknowledged as probably not being their correct original shape, their residual shape was deemed to be of some value. A conscious decision was taken to document and model the timbers in their recorded post-excavational shape state, and not in any idealised or flattened way.

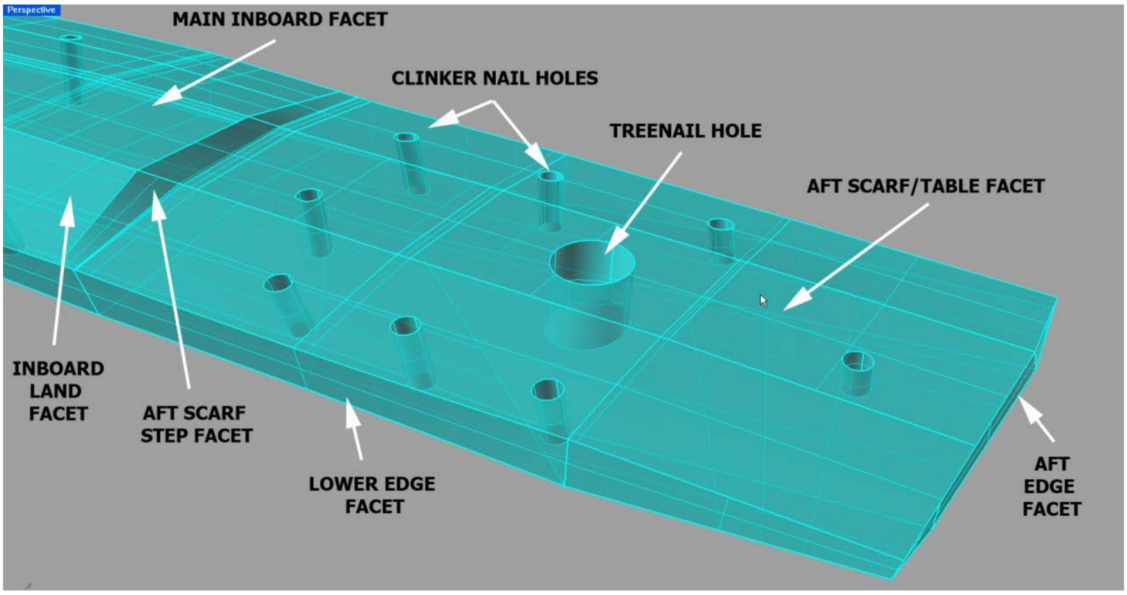

Figure 4-22 Digital solid modelling of timbers (Jones 2015:293)

The process developed during the Newport Medieval ship project led to its adoption by several other projects including the Drogheda boat, the Doel Kogge, several of the Yenikapi shipwrecks, the Norwegian Maritime Museum in Oslo, the German National Maritime Museum in Bremerhaven, the Maritime Archaeology Programme at the University of Southern Denmark in Esbjerg and led to the formation of the Faro Rhino Archaeology User Group (FRAUG) which continues to develop and share techniques and resources.

Typically, this process involved cleaning the timber, several hours to contact digitise the relevant features, and a further one or two hours to create the digital solid model, resulting in an average of one timber recorded per day. While this process still involves a certain degree of interpretation in which features are digitised, interpretation can be limited by skilled operators. An alternative or slightly modified approach would be using the optional laser line probe (LLP) attachment to laser scan the timber surface (Figure 4-23). This laser scanning would replace the manual digital solid modelling phase, while taking similar or less time, and capturing a high resolution (±0.07 mm) 3D surface model, suitable for immediate 3D printing. With both the laser scanned surface model and the contact digitised wire frame data positioned and aligned to each other, both data sets can be viewed simultaneously or separately, with the wire frame data adding a layer of interpretation to the scanned surface model.

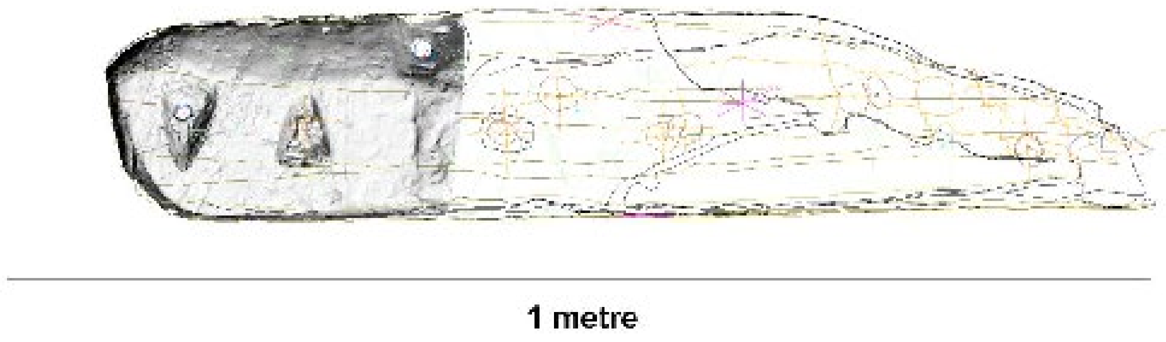

Figure 4-23 Combination of laser scan and contact digitised data (Jones 2015:251)

Annotated laser scanning

Another approach to documenting individual timbers has been developed at the University of Southern Denmark by Thomas Van Damme, Massimiliano Ditta and Jens Auer. The process involves the use of a hand-held laser scanner, in this case an Artec Eva 3D scanner, which has a stated accuracy of up to 0.1 mm and a resolution of up to 0.5 mm, and generates a 3D mesh model (Figure 4-24), on the fly in real time, Meaning the digital solid model is immediately available for further computer based modelling or 3D printing (Figure 4-25).

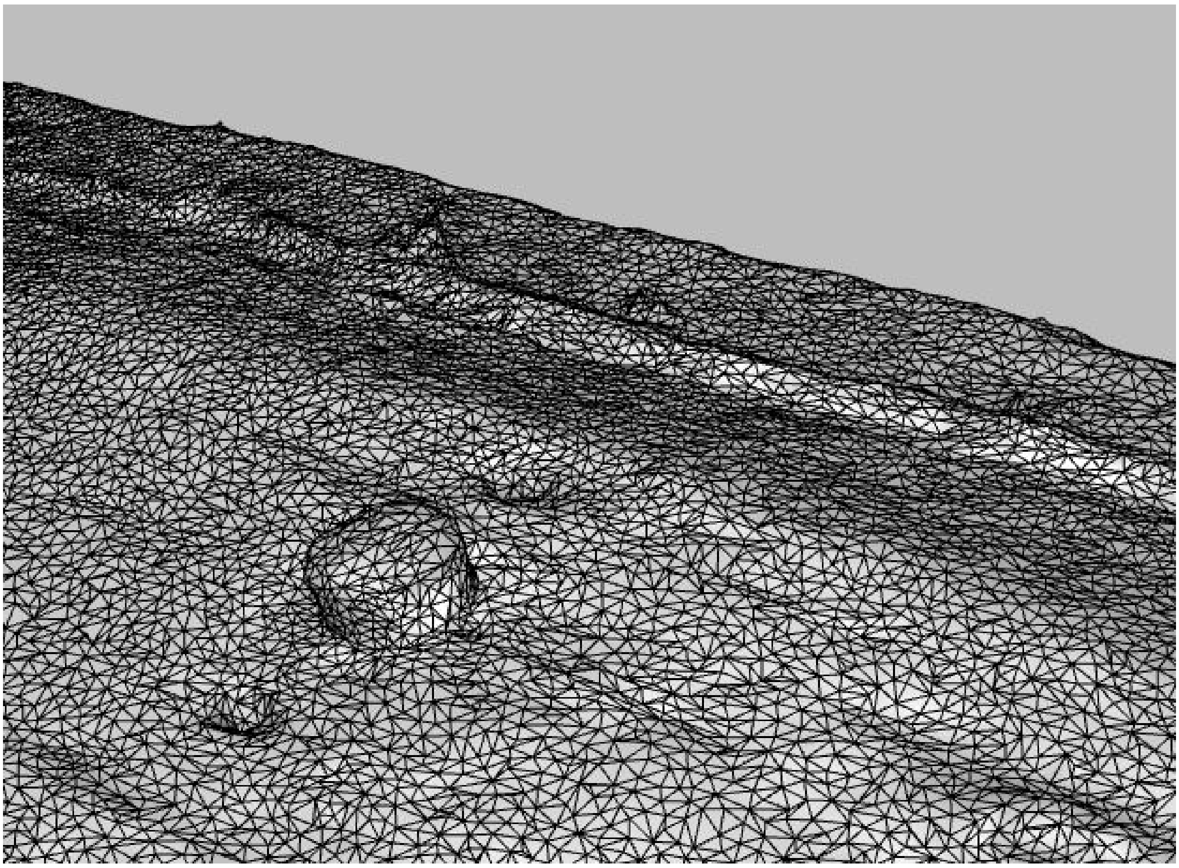

Figure 4-24 3D polygon mesh to create surface model of ship timber (image Jens Auer)

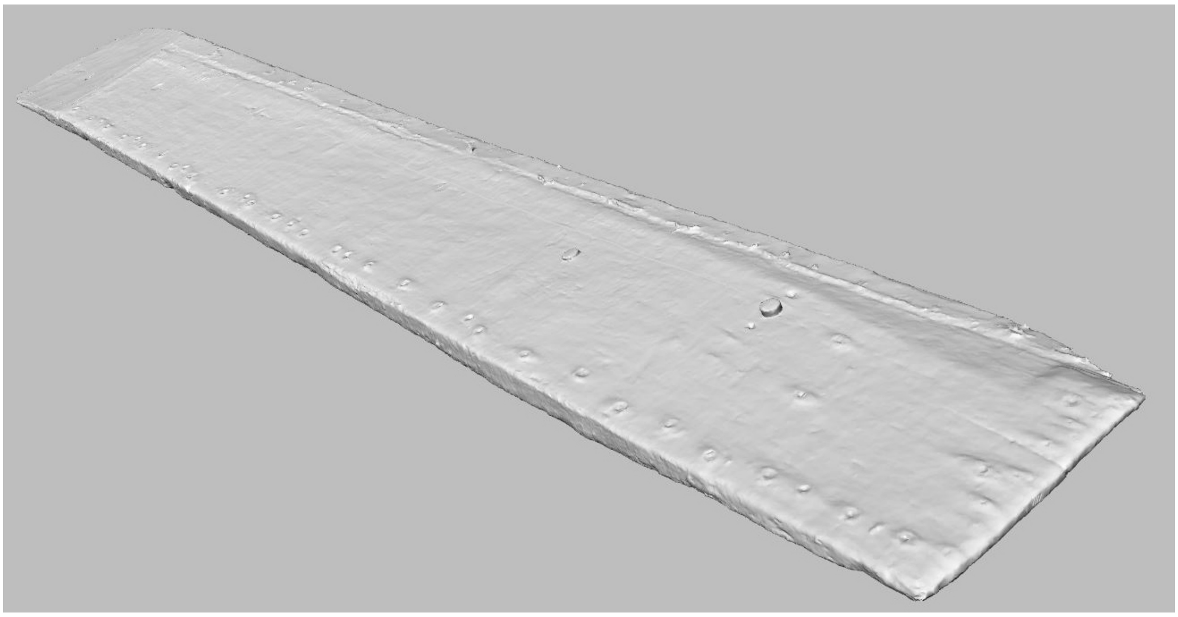

Figure 4-25 Artec Eva surface model of 3D scanned ship timber (image Jens Auer)

While the Artec scanner captures a colour textured surface of the object, it can still prove difficult to distinguish pertinent details on the 3D model. As a result, the 3D model is imported into Rhino 3D, and a layering convention similar to that used for contact digitising with different layers representing features such as woodgrain, treenails, other fastenings, repairs, tool marks and intentional inscribed marks is used (Figure 4-26). Rhino's 'PolylineOnMesh' command is used to allow the user to draw 3D polylines directly onto the textured mesh surface. As well as the 3D digital model suitable for 3D printing, it is also possible to automatically generate a traditional 2D timber catalogue and an optional colour textured version (Figure 4-27). Van Damme *et al*. (2020) state an average of six timbers per day can be documented using this process, In comparison to the one timber per day with contact digitising, using hardware which costs 1/3 of the price.

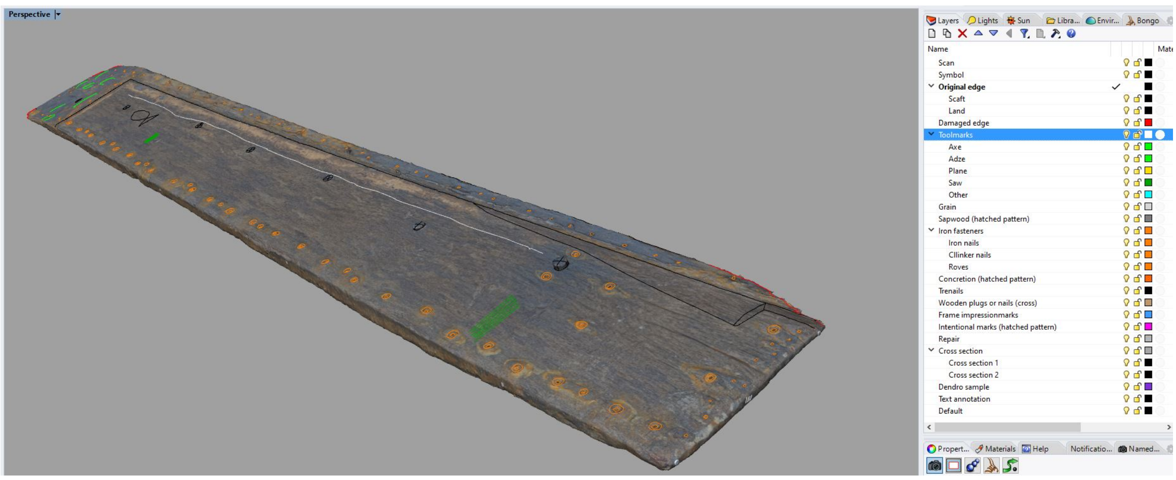

Figure 4-26 3D scanned ship timber with annotated lines (image Jens Auer)

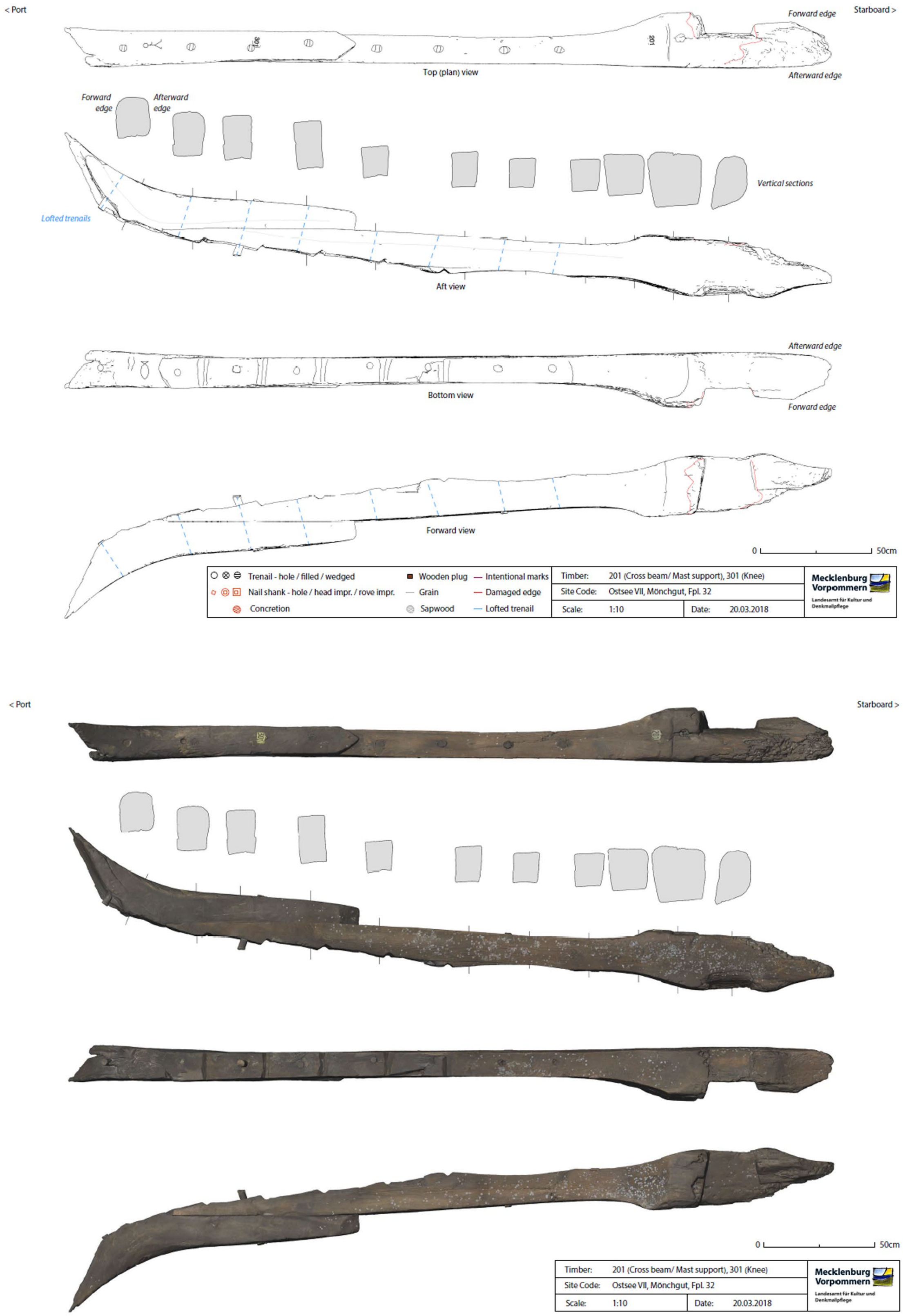

Figure 4-27 Example of 2D timber catalogue and colour textured version (image Jens Auer)

Photogrammetry

The use of photogrammetric modelling for the detailed recording of individual timbers or artefacts is also possible, however, the same issues which affect large scale or site-based photogrammetry still apply. The photogrammetric models will require the application of a scale correction factor which will require the use of reference targets and dimensional controls obtained from other surveying techniques. Similarly, a large number of high-resolution photos and adequate lighting to prevent shadows will be required, and the number of photographs will result in a requirement for significant computing power and long processing times.

The Norwegian Maritime Museum, who were already documenting individual ship timbers using the contact digitising method, trialled photogrammetric recording for full-scale individual timbers. The photogrammetric approach was found to be both difficult and time-consuming by comparison. Issues such as having to process the images through Agisoft in order to check the successfulness of data capture prior to moving or changing timbers, issues with arranging sufficient and adequate lighting to maintain consistent colour and avoid shadowing, and problems with aligning both sides of a single timber when the timber was turned over to document the underside. The Faro Arm contact digitising, and subsequently, the Artec Eva annotated scanning were both found to be significantly easier to monitor real-time recording progress, and simpler to align opposite sides of the recorded timber. The Museum has now changed to using the annotated laser scanning process as the primary documentation process (Tori Falck 2020, pers. comm., 6th May).

4.8 Conclusion

In the case of cultural heritage sites and historical artefacts, the physical context of the objects contained within a site are just as important as the artefacts themselves. Just as a site has stratigraphy, ships also have a stratigraphy in themselves, which must be carefully recorded. The rapid advances in both hardware and post-processing software means it is now possible to easily capture high volume and high-quality 3D data, and this raises the question: as archaeologists should we all be doing this? As each stratigraphic layer is excavated, and the subsequent layer exposed, it is now possible, using photogrammetry, laser scanning or a combination of both, to accurately (and objectively) capture the site information as each subsequent stratigraphic layer is excavated and exposed (Pacheco-Ruiz *et al*. 2018). This would capture an accurate, three-dimensional, point-in-time snapshot, at various significant stages throughout an excavation, and as archaeological excavation is destructive by its very nature, each 3D survey would capture information otherwise impossible to re-examine at later stages.

For example, the Eyemouth International Sailing Craft Association Limited's (EISCA) collection of some 288 boats from all over the world were formerly stored within two farm buildings (the Potato Shed and the Ostrich shed) in Eyemouth, Scotland. After the company was liquidated, the collection was to be sold off and disbanded. With only five days available to “audit and survey” the collection, laser scanning was the obvious solution, and a total of 157 laser scans were carried out between the two buildings. The individual scans were registered together to within 3mm tolerance and Figure 4-28 shows a portion of the 2D overview map, which is in effect an automatically generated, full-scale site survey plan. Figure 4-29 shows a screen capture of the full-scale three-dimensional point cloud data of the vessels within the “Ostrich shed”.

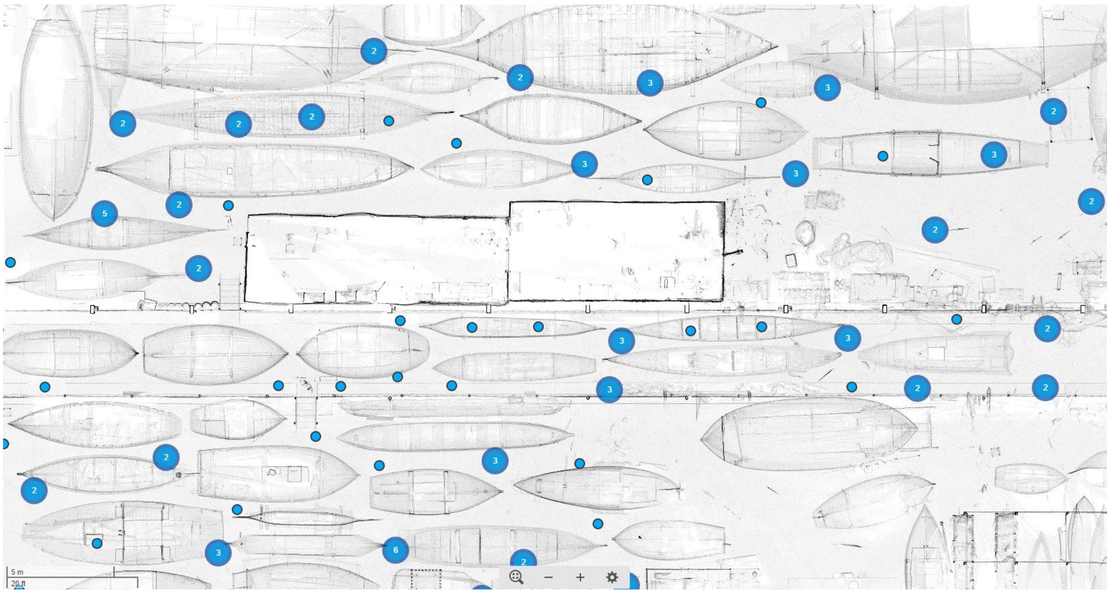

Figure 4-28 Partial overview map of the "Ostrich Shed" at Eyemouth (Pat Tanner)

Figure 4-29 3D point cloud view of the "Ostrich Shed" (Pat Tanner)

As noted by Crumlin-Pedersen (1977:165), the traditional method of manual scale drawing is considered discontinuous as it is based on measuring a number of points on the object and completing the remaining drawing by interpolating between the measured points. In addition, the selection of what is actually represented, or omitted on a drawing is a further interpretation by the draftsperson. As noted by Hocker (2000; 2003) representing complex three dimensional shapes on two dimensional paper led to the development of a set of drawing conventions, in which the object is represented as a series of intersecting views, traditional 'top down' or plan, side and front orthographic views typically perpendicular to each other. When the instability of paper (Uesaka *et al*. 1989) is also taken into account, two-dimensional paper drawings are a less than ideal medium for the archival storage of complex three-dimensional data sets.

The capturing of three-dimensional high volume, high quality raw data, using either photogrammetry, 3D laser scanning, or a combination of both, generates a superior archival record, which is stored as a full-sized three-dimensional object, rather than a reduced scale, two-dimensional paper-based interpretation. Advances in viewing technology allow for three-dimensional interactive models to be viewed on a computer monitor, allowing the user to view the object from any angle or viewpoint.

From this detailed source data, it is then possible to generate 3D models suitable for 3D printing or full-scale reconstruction, as well as providing a more detailed basis for theoretical classifications. This form of digital data should go a long way towards bridging the gap between the exclusive knowledge of the excavator and the published record, allowing lots of people to use the data in new and novel ways.

Without high quality raw (digital) data all these opportunities are lost.

Chapter 5 **Modelling**

5.1 Introduction

Model making as an archaeological research tool is as old as maritime archaeology itself. In 1822 Glavimans created a scale model of the vessel excavated near the Dutch village of Capelle (Chapter 1) and, as a validation of his reconstruction, Åkerlund (1951:37–40) created a 1:12 scale model of *Kalmar 1* based on his reconstruction drawings (Chapter 2.4.1). This chapter examines the use of model building as a tool in archaeological reconstructions and how it has evolved and developed over the past one and a half centuries. Scale models have long been synonymous with boat and ship design. In 1716 the Navy Board issued a warrant to the master shipwrights at the Royal Dockyards, requiring models and plans to be produced for all ships proposed to be built or rebuilt (Ball 2017), and even in the 20th century the making of a 'block' or 'half model' was still a requirement of the shipwright's apprenticeship. As noted in Chapter 4, reconstruction is a logical continuation in the study of the archaeological remains, based on appropriate source data in which we have confidence. From the examples in Chapter 2, the majority of reconstruction projects have involved, or been based to some extent, on some form of three-dimensional scale modelling, fully understanding that process is therefore critical to understanding the reconstruction process itself. This chapter aims to establish such an understanding of the modelling process.

5.2 Types of Model

It should be noted at this point that there are two main types of model. The block model or half model (with the generally symmetric nature of hulls, often only half of the shape is created) which is a basic representation of the overall dimensions and general form of the hull shape. This model is typically a solid block of timber, or sometimes made up of layers sandwiched together giving the model its other name - the bread and butter model, which is carved to represent the shape and dimensions of the proposed hull form. This is a simplified representation of the vessel which will provide the principle dimensions and characteristics of the overall hull, such as overall length, beam and draft, which may then be used to calculate overall displacement and provide some hull form coefficients. If the floatation condition, and hence the draft, is not known for the vessel, then these calculations will need to be performed at varying drafts in order to provide a range of results. As noted in Chapter 3.7, these ratios and coefficients of form provide an impression of the overall vessel, but are of limited value when comparing disparate vessels.

One very obvious benefit of this type of model was demonstrated to me by George Bush, another boatbuilder friend of mine. George had become tired of the repeated requests to build a boat of the same dimensions (and hence the same cost) but with a greater cargo capacity or greater speed and manoeuvrability. George built a scale model of his boat, but with a significantly different form on either side. While both sides of the model had identical dimensions for length, width and depth, the port side had a very fine entry near the bow and the widest beam well aft toward the midship point, while the starboard side had the widest point far forward towards the bow. Now whenever George was asked that same impossible question, he simply showed that model and replied:

> "you can have this port side shape, which will be fast and manoeuvrable, but only carry a limited cargo, and with the fine bow cutting through the waves she will be very wet on board – alternatively, you can have this starboard side shape, she will carry half as much again in cargo, you will probably be late for Mass, but you can wear your Sunday clothes, because she won't take a drop of water on board – you cannot however have both."

The second form of model, commonly referred to as a built-up model, is usually constructed in the same manner as the original vessel, using scaled replicas of each individual component. The result is in effect, a scaled miniature of the complete vessel, which has been assembled presumably in a similar manner and sequence as the original vessel, potentially generating insight into some of the original construction techniques. By using the same shape and dimensions for each constituent component, the resulting model will have the same form, proportions, and more importantly centre of gravity as the original, allowing the establishment of the vessels flotation condition, albeit at a reduced scale. The theory of similitude and scale states that for length, the difference is simply the scale factor, while for area the difference is the scale factor squared, and for volume it is the scale factor cubed. For example, a scale of 1:10 will have a difference factor of 10 for any length measurement, but a difference factor of 100 for any area measurement and a difference factor of 1,000 for any volumetric measurement. In the case of a vessel, volume, specifically underwater volume is the single most important factor as it directly effects how the vessel will float. Any minor errors or differences in a scale model result in exponential differences in the real-world counterpart.

5.3 Research Models

Between 1946 and 1988 at least five attempts were made on paper and by small-scale models to reconstruct Ferriby 1 (Wright 1990). The approach of developing the reconstructed hull form, by re-attaching scaled models of each individual timber, using the alignment of fastener holes as a guide also developed in the 1960's about the same time as the full-scale documentation of individual ship timbers. One of the most prolific archaeological model builders was Dick Steffy, which is not surprising, as model shipbuilding had been his lifelong hobby, and his introduction into maritime archaeology. Steffy (1994:214–215) believed that three-dimensional research using models, and even replicas of individual components, surpassed the shortcomings of two-dimensional paper-based research, and led to a better understanding of how the disarticulated components fit together, and how the ship as a whole should be reassembled.

During the 1960's, the reconstruction of the 7th century merchantman from Yasi Ada, which Steffy described as largely hypothetical, as it was based on a mere 10% of hull survival (Steffy 1994:80–81), created 1:10 scale replicas of all the timbers that had been recorded. The scaled timber strips were then bent to various shapes until the pieces of model planking were aligned to each other with respect to the fastening holes. External and internal planking assemblies were next aligned to each other using known bolt holes and angles. Other highly detailed 1:10 scale models were produced using additional information learned during the excavation of the *Pantano Longari* and the *Kyrenia* ships. Steffy states that new lines and construction plans evolved based on this new information, as well as many countless hours of additional research and model building (Steffy 1982:66). For the *Kyrenia* ship, excavated in 1968, a total of 18 separate research models were created during the reconstruction process.

The reconstruction approach developed by Crumlin-Pedersen in the late 1960's, for use on the *Skuldelev* ships (Chapter 2.4.4), involved creating site plan drawings from photogrammetry, with the individual ship timbers documented using full-scale elevated plane tracing. The full-scale timber drawings were subsequently reduced to 1:10 scale and cut-out from cardboard stock as flat two-dimensional planks. In a similar approach to that used by Steffy in the *Yassi Ada* reconstruction, once the damaged or distorted planks were repaired, they were re-shaped to create the perceived hull form model using the documented fastener holes for alignment (Crumlin-Pedersen 2002a:97–301). The 1:10 scale reconstructed model was then documented and drawn as a scaled 'inner-edge lines plan'. From this a 'torso drawing' was created representing the original timbers with displaced elements repaired or repositioned.

During the 1970's several paper-based (two-dimensional) attempts to reconstruct the *Graveney* boat (Chapter 2.4.6) proved unsuccessful. Eric McKee (1978b:265–6) noted that reconstructing a three-dimensional shape on paper meant that all corrections involved simultaneous changes in all three planes, and keeping track of these together was considered too difficult and liable to all sorts of errors. Three-dimensional model building was seen by McKee as the obvious solution, allowing flexibility, deferred decisions, and ease of correction, and if a two-dimensional set of lines drawings were required, these could be taken from the model in the same way as taking the lines from a full-sized boat (ibid: 267) or just as traditional boatbuilders lifted the lines and offset dimensions from a block model.

The 21st century saw the development of the Roskilde method (Chapter 2.4.12), where the timbers, initially recorded with elevated plane tracing (Chapter 2.4.4) and Figure 2-20, were subsequently documented using a Faro Arm to accurately record the three-dimensional shape of each timber. However, the modelling process never evolved, and the accurately recorded three-dimensional data was flattened back to two dimensions, reduced to 1:10 scale and cut-out from flat cardboard stock, using the same modelling process developed for the *Skuldelev* ships by Crumlin-Pedersen in the 1960's (see Ravn 2012:316; Ravn *et al*. 2013:236; Bischoff 2014:236; Bischoff *et al*. 2014:22; Bischoff 2016:24).

5.4 The 'as-found' model

These drawings and models which were based on the excavated evidence came to be labelled as 'torso or as-found' drawings/models despite the excavated material having gone through several layers of interpretation. That interpretation included the initial full-scale documentation, which often included disassembly, flattening of three-dimensional shape to two-dimensional drawings, scaled reduction, repair of damaged or distorted timbers, and final reassembly into a three dimensional scale model (Crumlin-Pedersen 1977; Sanders 2007; Crumlin-Pedersen and McGrail 2006; McGrail 2007). With up to five separate occasions where interpretation may have been employed, I submit that these drawings and models should no longer be referred to by the name 'as-found', for this title implies that the material was discovered or excavated as represented in this state. Instead these models should be renamed to 'First Reconstruction' as suggested by the Chartered Institute for Archaeologists (2014):

> "First reconstruction is considered to be the as-found record but with obviously distorted parts restored to shape, displaced parts reinstated, fragmented timbers made whole, and the vessel rotated to a vertical and horizontal plane (consideration of the correct waterline plane is considered in the second level of reconstruction). All first reconstruction is reliant on full and unequivocally interpretable archaeological evidence."

Two new forms of models, the site diorama model, and the fragmentary model, were developed by Steffy during reconstruction work on the *Serçe Limani* ship excavated in 1977. Using the photographs and 1:1 elevated plane tracings of the timbers, Steffy created a 1:10 scale diorama of the wreck site as it lay flattened on the seabed. Steffy then created physical 1:10 scale models of each timber fragment as well as anchor concretions and the rock outcropping which had added to the hull distortion. This was a new form of model and is essentially a three-dimensional expression of the wreck plan. The resulting three-dimensional site plan, Steffy claimed was infinitely better to work with than 2D drawings (Steffy 2004a:125). These site diorama models used by Steffy, and Pomey's (2005:89–154) models with the damaged or displaced parts modelled exactly as recorded on site (see Chapter 2.4.14 - Figure 2-56), which appear to be free from interpretation, are probably closer to actual "as-found" models.

5.5 The pros and cons of model building

On the benefits of model building, Steffy (1989:249–50) noted that the nature of their construction is such that one is forced to duplicate the original builder's movements, thereby revealing techniques and processes. Their shape permits volume interpretations where only areas could be interpreted when using two-dimensional graphical methods. Their comparative strength sets limits for error, and their resistance to unnatural curves refutes blatantly false assumptions. Most importantly, these models are subject to the laws of physics and geometry, and thereby their conclusions can be proven.

Yet, as Steffy conceded, it still often required the full-scale reassembly of the vessel remains in order to reach definitive answers to certain specific issues, or the creation of a full-scale replica, being the latest and most elaborate of these three-dimensional research models, all of which have the potential for probing subject areas which graphic and archival research cannot satisfy (Steffy 1989:249–52). For the construction of full-scale replicas, drawings are typically created based on measurements taken from the scale models, which are subsequently used by the boatbuilders to construct the full-scale replica. However as noted by Ravn *et al*. (2013:239):

> "…drawings sometimes have to be altered due to the fact that oak planks do not behave in exactly the same way as the material used in the scale model."

Steffy (1989:254–5) also noted that three-dimensional physical models have weaknesses, they are time consuming and consequently expensive to produce, and a certain level of manual dexterity is required to design and produce such models, and for those reasons Steffy was experimenting with graphical computer alternatives.

Three-dimensional modelling is without doubt, a valuable and necessary approach in the reconstruction process. However, as illustrated by Ali (2012), the reconstruction drawings, the research model and archaeological record do not always agree (Chapter 2.4.10). In many cases the initial assembly of recovered parts is clearly explained, and has often been labelled the 'as-found' model, despite having "distortions and compressions removed, displaced elements replaced, and fragmented timbers made whole" (McGrail 2007:255). By this very definition, the resultant model is not an 'as-found' model, but an interpretation based on the actual 'as-found' record, and how that initial model has been extrapolated into an 'as-found' model is frequently vague in the published results, which may call into question the level of confidence in both the data and the reconstruction.

In essence, every model, either scaled or full-size, whether it is labelled as a replica or a reconstruction, is a modelled representation of our perceived understanding of the original object, and as such, it is an individual's interpretation of the original source data. As stated by George Box (Box and Draper 1987:424):

> "... all models are approximations. Essentially, all models are wrong, but some are useful. However, the approximate nature of the model must always be borne in mind..."

Coutinho *et al*. (2016) state that the testing of sub-scale models is a valuable design tool, helping engineers to accurately predict the behaviour of real-world prototypes, through scaling laws applied to the obtained experimental results. However, the correct use of dimensional analysis or differential equations, while mathematically simple, requires great effort and skill. When selecting the complete and independent set of quantities affecting the structural behaviour, even the smallest of details cannot be forgotten.

5.6 Conclusion: Removing the scale from the model

Clearly, as noted by McKee (1978b:265–6) and Steffy (2004a:125), model building provides many advantages when compared to two-dimensional paper based reconstruction attempts. However, as Steffy (1989:254–5) noted, model making requires a certain level of manual dexterity, and, it could be argued that an element of craftsmanship is also involved. Bearing in mind Box's comment that all models are approximations, and issues such as model effect, scale effect and measurement effect as noted by Heller (2011), this raises the question - how do we assess the value and reliability of a model?

A scale model, in isolation, is somewhat of an enigmatic entity. It can be difficult to comprehend how the model was created, or how accurately the model reflects the source data. The craftsmanship or artisanal element of model building introduces a certain unknown factor into the process which can be difficult to quantify (cf. Campana *et al*. 2016). In the case of individual timbers, crafted as scaled model elements, we can only assume that these are accurately scaled reproductions, and *model effects,* such as incorrect reproduction of geometry features, should be borne in mind. Fine detail, such as rivet or nail heads, one or two centimetres in diameter, resulting in a one or two millimetre scaled size at 1:10 scale, may be difficult to reproduce at scale, and may be either omitted or implied using averaged sizes on the scale model.

Likewise, the use of average dimensions when recording or documenting any features can be a misleading representation of the original artefact. Take for example, framing elements such as floor timbers or futtocks, which often appear in the published record with average sizes quoted. The majority of such framing elements tend normally to be constructed parallel sided for the sided (fore-and-aft) dimensions but are often tapered in the moulded (athwartship) dimension. That is to say, a floor timber, which may be 300 mm or more moulded depth at the centre-line where it crosses the keel, will often be tapered to say 200 mm at the turn of the bilge, with the futtock continuing to taper, possibly to as little as 75 mm as it nears the upper sheer of the vessel. Such a framing assemblage will often be published in the form of “floor timbers 100mm sided by 250 mm average moulded depth” and “futtock timbers 100 mm sided by 137 mm average moulded depth”. While this format is a technically accurate description, it does not clearly represent the actual timbers, and makes it impossible to accurately recreate the framing as it existed. This tapering of framing timbers, together with a reduction in scantling size higher up in a vessel, is common shipbuilding practise in order to keep weight, and consequently the centre of gravity as low as possible in the vessel. A model recreated using averaged dimensions may result in an identical external form, and possibly identical overall weight, but its internal volumes will be different and its centre of gravity will be substantially higher, which will result in a less stable vessel. Additionally, averaged data recording, or the averaging of results in reconstruction models can obscure some of the minutiae of details critical to a more comprehensive study of the remains (cf. Hocker 2013).

As noted by Heller (2011:293) a physical scale model represents a real-world prototype, and in the case of vessels, is often used as a tool for finding technically and economically optimal solutions to hydraulic engineering problems. Considerable differences between a scale model and the real-world prototype parameters may result due to model, scale, and/or measurement effects.

5.6.1 Model, Scale and Measurement effects

Model effects may originate from the incorrect reproduction of prototype features such as geometry, flow rate or wave generation techniques, or fluid properties. *Scale effects* arise due to the inability to keep each relevant force ratio constant between the scale model and its real-world prototype. *Measurement effects* include non-identical measurement techniques used for data sampling in the scale model and real-world prototype. These are some of the reasons why there are clear difficulties with half scale replicas (cf. Gifford and Gifford 1995; Gifford and Gifford 1996; Gifford *et al*. 2006) – which are in effect very big models.

Taking *Sae Wylfing,* which Gifford (1995:124–25) described as a half-scale replica of the Anglo Saxon *Sutton Hoo* ship (Figure 5-1), many of the model and scale effects are obvious. While the archaeological evidence exists for 26 frames, the half-scale replica only has 13 frames. Evidence also exists for 14 pairs of rowing tholes, with a potential additional six pairs of tholes in the central burial chamber area (Bruce-Mitford 1975:403–406; Tanner *et al*. 2020:21), despite this, Gifford's half-scale replica used only four pairs of full-scale thole positions (Figure 5-2). Other less obvious differences are the materials used in building the half-scale replica. Gifford (1995:125) notes that planking, with the exception of the top two strakes, which were of radially sawn oak, was of pine rather than the original oak. Additionally, laminated pine was used for the frames, stem and stern post. The difference in weight was made up with extra crew weight and water-bag ballast. However, this does not take into account the centre of gravity shift caused by the differences in construction. Gifford (ibid) estimates the corrected weight of the full size vessel and crew to be 12.8 tonnes, while Tanner *et al*. (2020:24) states a digital model of the vessel with oak material gives 8.13 tonnes for the vessel and 3.36 tonnes for 42 crew, giving a combined total weight of 11.5 tonnes, a 10 % decrease compared to Gifford's estimation. The lack of half-scale people and testing the vessel in full-scale wind and waves can only cast doubt on the value of any results.

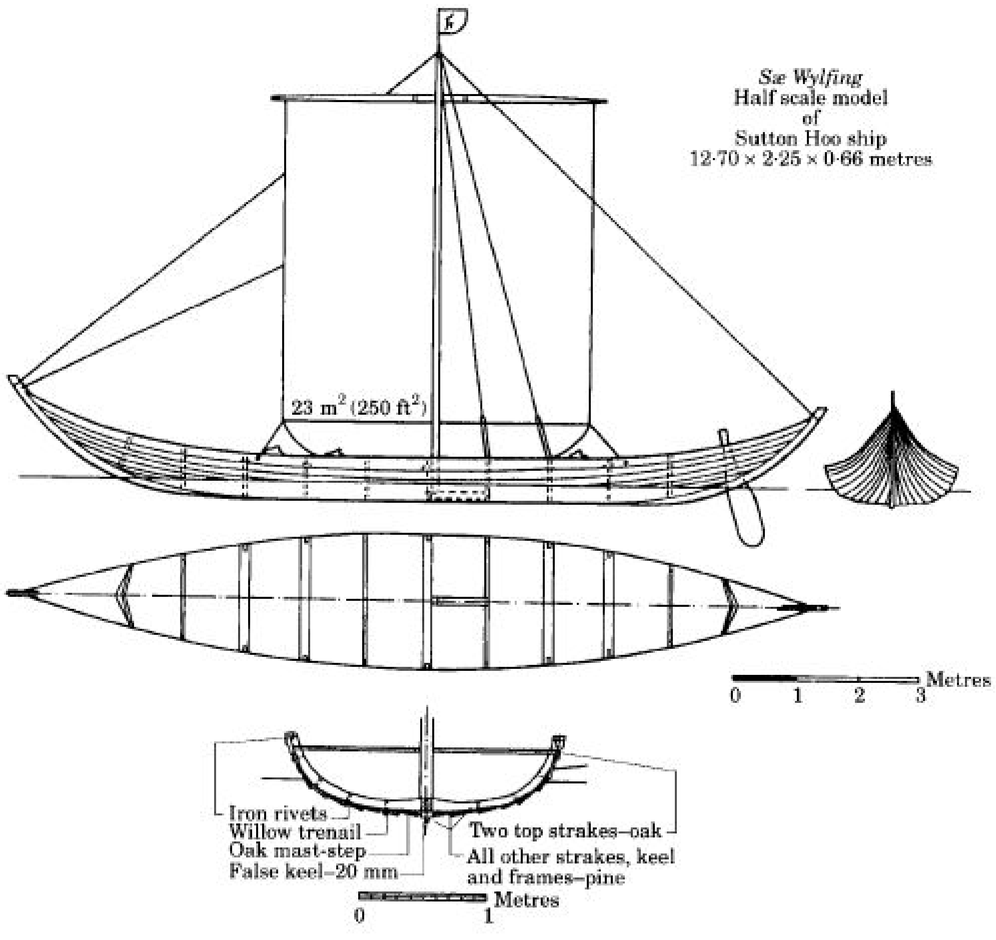

Figure 3. *Sæ Wylfing*, half-scale model of the 7th-century Sutton Hoo ship.

Figure 5-1 Half scale model of the Anglo Saxon Sutton Hoo ship (after Gifford 1995: 125 Figure 3)

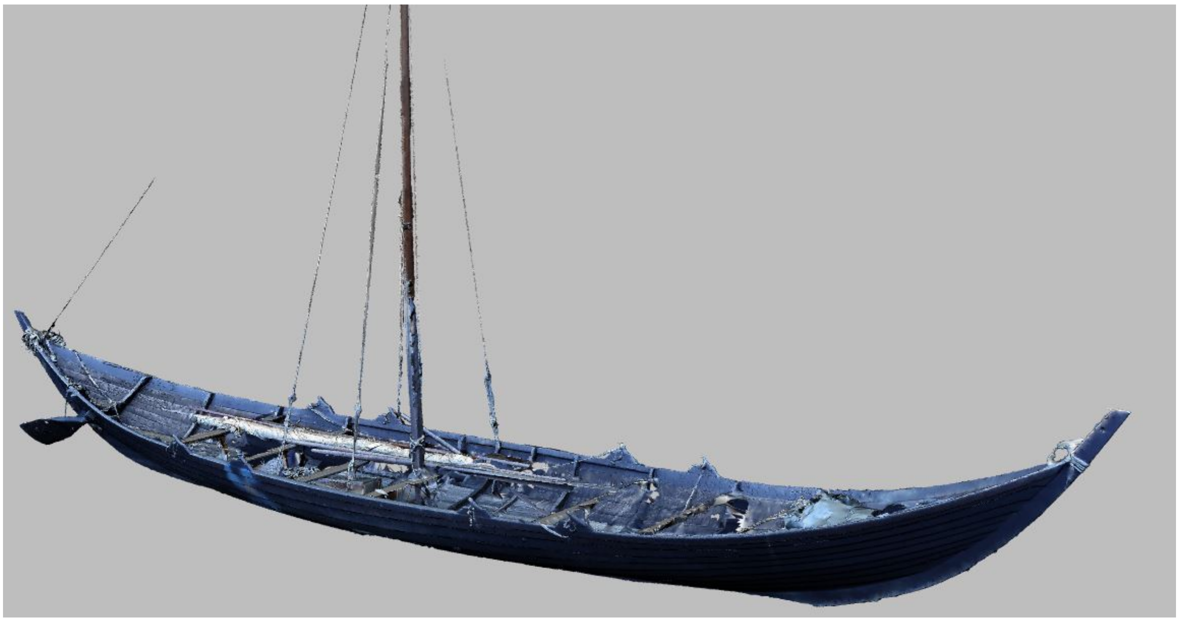

Figure 5-2 3D laser scan completed in 2018 of Sae Wylfing the half-scale Sutton Hoo replica (Pat Tanner)

With the advances in digital modelling, it is now feasible to digitally model any object at full-scale. The ability to capture high volume, high quality three-dimensional data (Chapter 4.8) and basing the digital modelling on that high quality raw data, removes the issue of model effect such as the incorrect reproduction of geometry, as the geometry is digitally created directly from the accurate three-dimensional raw data. If the research model is created at real-world full-scale, then there is no requirement to approximate scaled flow rates, scaled wave generation models, or scaled fluid properties. Likewise, with a life-sized research model, the issue of unscalable force ratios is completely avoided. The result is that running a wind loading and wave rolling test on a life-size digital research model, using real-world wind, wave and weather models, should provide more accurate and repeatable results than scaled models in wind tunnel tests. If the research model is life-size, then there is no requirement for data sampling on a scale model, and the same measurement techniques can be employed for the research model and the original raw data.

Digitally modelling the exact geometry at full-scale would appear to be the obvious solution. If a scaled model is required for research, discussion, display or museum exhibit, the life-size digital model can be scaled three-dimensionally to any required scale size and rapid prototyping technologies (Jones and Nayling 2011; Soe *et al*. 2012) such as 3D printing (Figure 5-3) can be used to generate an exact miniature.

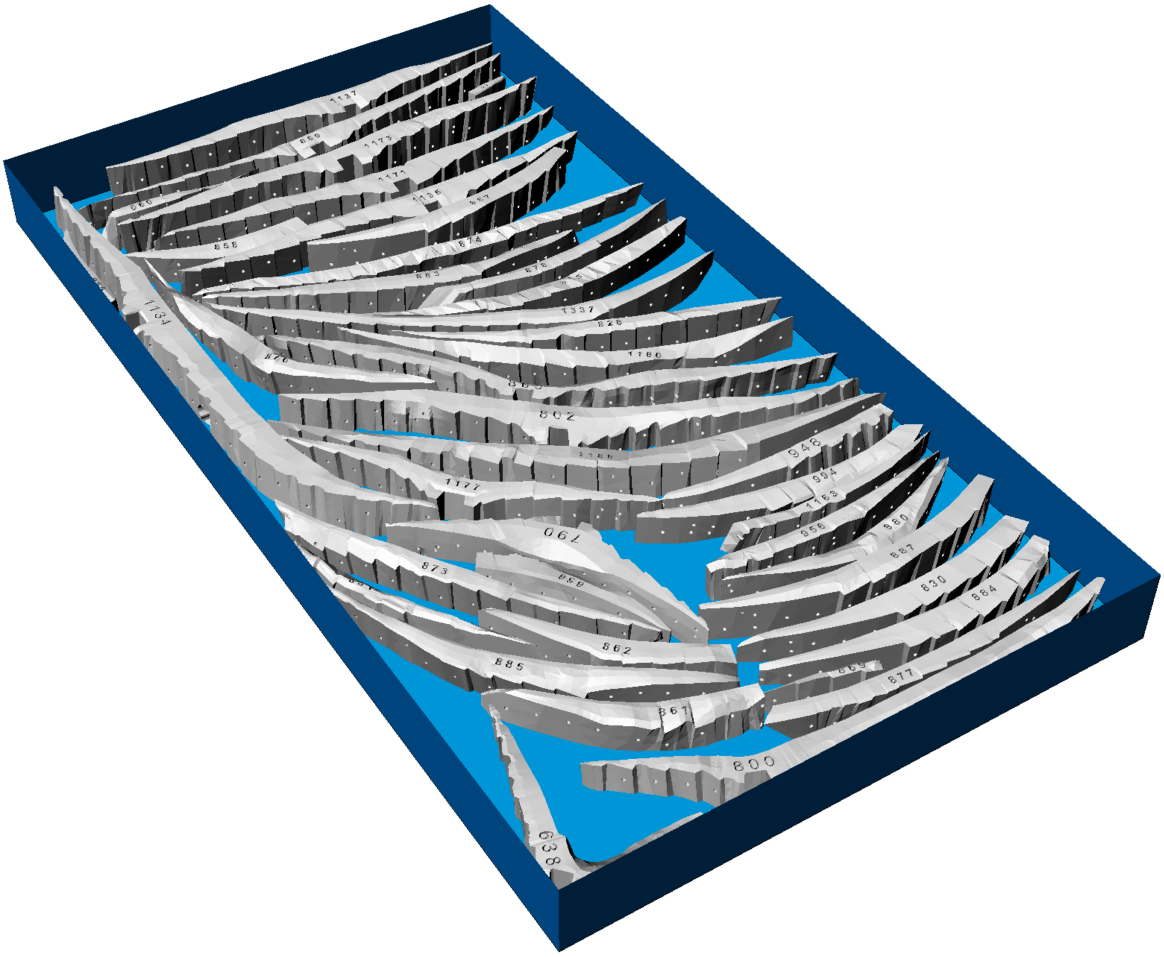

Figure 5-3 3D printed 1:10 scale replicas created from the accurate full scale raw data (Toby Jones)

The use of digital scaling and 3D printing would remove the model effect issue of incorrect model geometry, and using similar techniques such as fastener hole alignment, used in past methodologies (McKee 1978b; Steffy 1982; Crumlin-Pedersen and Olsen 2002), allows for the reassembly of the individual components into a coherent structure (Figure 5-4). Such an approach has been used on projects including the Newport Medieval ship (Jones and Nayling 2011; Nayling and Jones 2014; Jones 2015), the Drogheda boat (Schweitzer 2012) and the Doel Cog (Vermeersch *et al*. 2015).

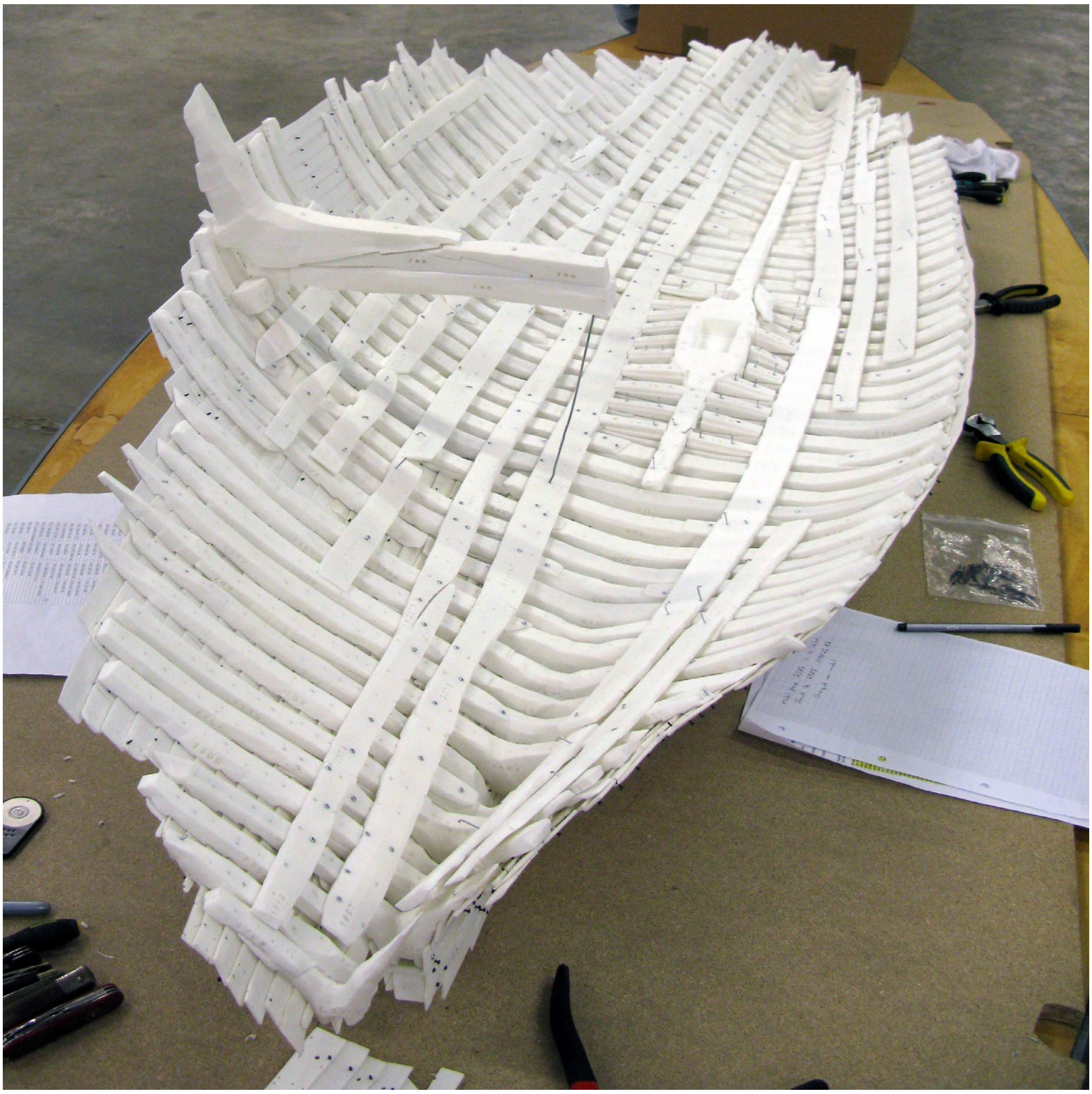

Figure 5-4 Reassembled final 1:10 scale model of the articulated structural ship timbers (Jones 2015: 343)

Remembering Box's statement that all models are approximations (Box and Draper 1987:424), the process of digital modelling at full-scale, based on high quality digitally captured raw data, generates geometrically accurate results, with all the interpretations of past methodologies removed. With the proviso – what you do with the data will always outstrip a model, you redo your models depending on the available data, and your understanding of that data – then a digital modelling approach would appear to be the most accurate, scientific and repeatable process currently available. It is to the methodology that can underpin such a process that the next chapter of this thesis now turns its attention.

Chapter 6 **A Proposed Digital Methodology**

6.1 Introduction

This chapter examines the techniques and methodologies developed and used for accurate and efficient data capture, at full-scale, in the form of three-dimensional digital documentation (Chapter 4), which allows innovative approaches to organising, analysing, comparing and disseminating data pertaining to the archaeological find. Subsequent advanced digital three-dimensional modelling as suggested in Chapter 5.6, combining all the documented data, enables detailed accurate reassembly of the surviving elements, as well as the ability to digitally model missing elements to aid in hypothetical reconstructions. The final phase involves the use of naval architecture software to analyse and test hypothetical reconstructions by accurately calculating factors such as the vessel's centre of gravity and total weight, allowing the establishment of actual floatation conditions, as well as examining external factors such as crew or cargo loading in order to determine the vessels hydrostatic characteristics and intact stability. Carrying out this process will allow us a greater chance of achieving that understanding of the ship or boat, that I believe we are seeking – as outlined in Chapter 3.10.

Coates *et al*. (1995:291) discuss the need to produce one or more hypothetical reconstruction which needs to be tested to be tenable. In Maritime Archaeology, experimental archaeology takes the form of building full or reduced-scale models, or other simulations, and testing them in repeatable sea trials, either real or simulated. In the testing of hypotheses, full-size replicas can prove expensive, while desk-based methods are usually based on small-scale drawings and lines plans. The article notes the ability of computers to speed up calculations thereby allowing a level of testing previously considered too cumbersome. Likewise, the use of small-scale models in tank tests and wind tunnels are noted as producing reasonably accurate estimates, but as noted by Crumlin-Pedersen (2003:218), the correlation factors which permit reasonably reliable predictions of performance for new vessels of known types, have not been fully undertaken in order to corroborate the results for ancient ships.

Larger scale models are mentioned as providing promising results for sailing performance predictions, but again the effects of scale as discussed in Chapter 5.6.1 are noted. The advantages of a full size replica are detailed, but the complexity of rigorous trials as well as the obvious monetary and material expense are cited as areas of concern (Palmer 2009a; Palmer 2009b:27), and a belief by some that full size replicas are at worst a waste of money and at best a poor use of archaeological resources. As noted by Crumlin-Pedersen and McGrail (2006:55), in a few cases, there will be sufficient evidence preserved from a wreck to draw up a complete reconstruction of the hull based on the surviving evidence, with the missing parts determined by mirroring existing parts or by extrapolation from the preserved majority of the hull. This leaves room for a variety of proposals which may need to be tested.

McGrail (2007:255) suggests that in order to establish a boats original form, structure, propulsion and steering and, hence, her most likely operational role, a model is formed of the boat and the hull is rotated to its deduced attitude when afloat, creating what McGrail (1992:354) calls a floating hypothesis. This becomes the basis for an attempt to fill-in missing pieces, a process which may lead, if the surviving evidence allows, to a more rigorously argued reconstruction of the original boat. McGrail (1992:354) states that the authenticity of reconstructed ancient boat remains depends on:

> “the quality of the data excavated; the rigour of the arguments for transforming that data into a hypothesis or hypotheses of the full form and structure; the appropriateness of the techniques used to turn such a hypothesis into a ‘floating hypothesis’; the rigour, relevance and effectiveness of the testing programme to measure and otherwise evaluate performance and operational limitations; and the full and widespread publication of the experiment so that it can be critically appraised.”

That simple statement by McGrail that ‘*the hull is rotated to its deduced attitude when afloat*’ is one of the more complex aspects of ship science, and how this is dealt with is rarely included in published archaeological reports. The process of achieving this is outlined in the following sections, concerning flotation (6.2), volumetric shape (6.3) and weight (6.4) , before an example is presented that serves as a proof of concept of the validity of this approach (6.5).

6.2 Floating the hypothesis

One of the principal aims in reconstructing the hull shape of a vessel is to generate a floating hypothesis for the vessel in order to arrive at lines plans and hydrostatic data such as displacement, sailing characteristics and cargo carrying capabilities. In order to generate a floating hypothesis – literally a hypothesis that will float, a floatation condition must firstly be established for the vessel. Any individual body floating in water is directly influenced by two distinct elements; the volumetric shape of the body (length x width x height); and the weight (volume of body x density of material). Using Archimedes' principle, any object, wholly or partially immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object. Proposition 5 of Archimedes' Treatise on Floating Bodies states that: Any floating object displaces its own weight of fluid.

Consequently, if the shape and weight of an object are known, then the volume of water displaced will be equal in weight to the weight of the object, and the object will ‘sink’ into the water until that volume of water is displaced, achieving a flotation condition, or continuing to sink if insufficient volume can be displaced. As the density of water is known, 1,000 kg/m³ for fresh water and 1,025.9 kg/m³ for saltwater, a perfect cube measuring 1 m on all sides and weighing 500 kg, will sink to a depth of 0.5 m in fresh water (Figure 6-1). The same cube of a denser material, weighing 1,000 kg will sink to a depth of 1 m in fresh water.

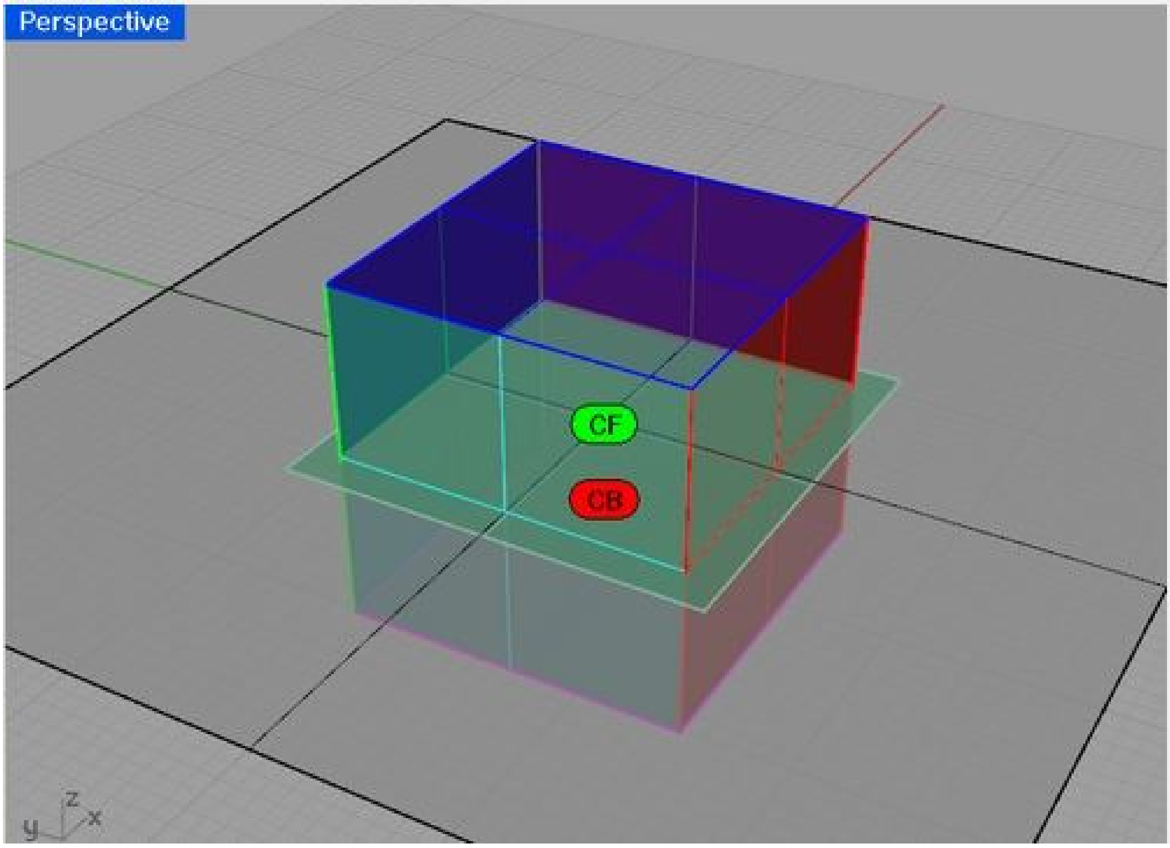

Figure 6-1 A 1m square cube weighing 500kg will sink 0.5 m in fresh water (image: Orca 3D)

Equally if the weight of the cube is unknown, but it sinks to a depth of 250 mm in fresh water, then the cube can only weigh a total of 250 kg. However, the cube shown in Figure 6-1, while it is in an equilibrium condition – the weight of water displaced is equal to the weight of the cube – it is not a stable equilibrium, as the cube is equally happy to float with any of the six sides up. None of these flotation conditions are actually stable. The centre of buoyancy and centre of gravity are aligned, but if the cube is disturbed, it would rotate until arriving at a condition which maximises the waterplane's inertia as shown in Figure 6-2.

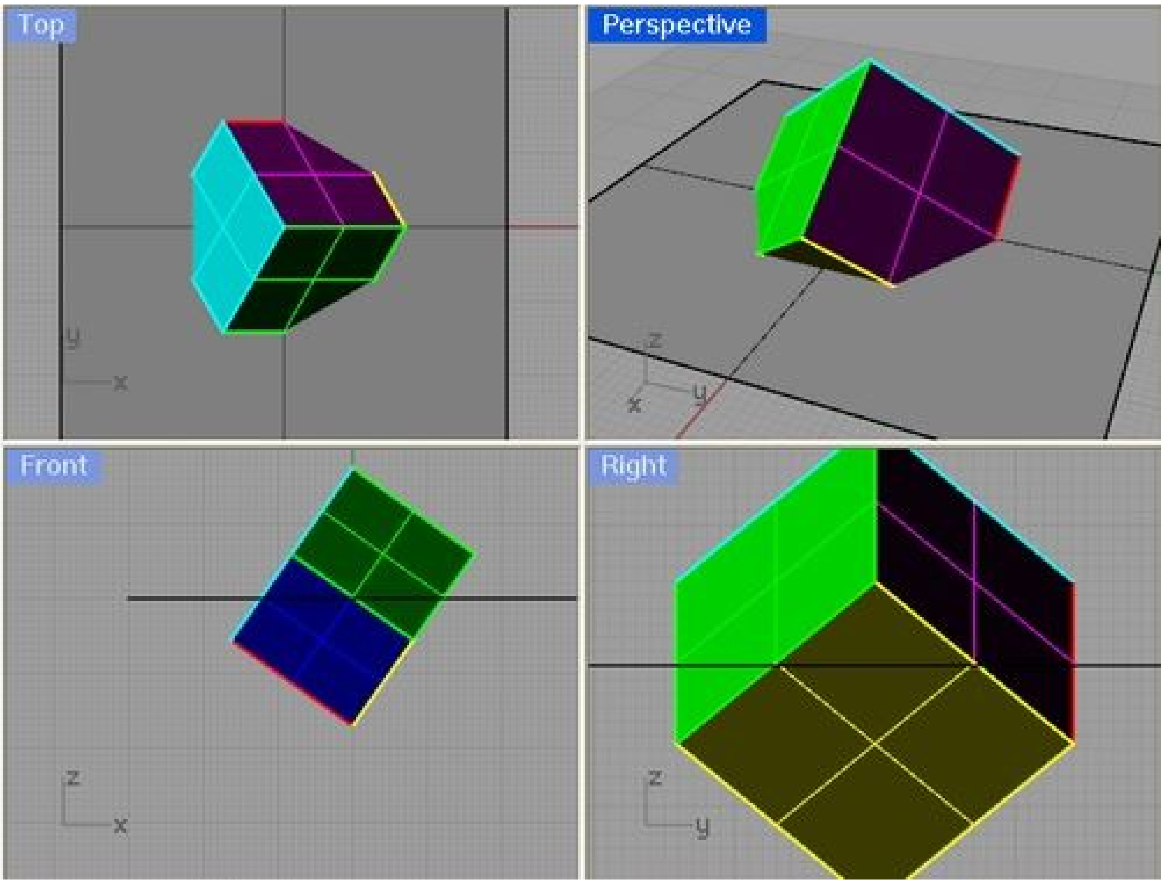

Figure 6-2 The same cube from Figure 6-1 rotated to a stable equilibrium condition (image: Orca 3D)

These principals are fundamental to studying and analysing our ship reconstructions, at the most basic level, purely to check if our reconstruction can float, while more advanced study will determine factors such as cargo capacity and seafaring ability. If the objects centre of gravity can be calculated, it is possible to determine how that object will 'float' (or sink) in water resulting in the calculation of the flotation equilibrium (Figure 6-5). Likewise, if the shape of the object, and how far it 'sits' into the water (draft) is known, the volume of water displaced can be calculated, and simply multiplying that volume by the weight of water will result in the weight of the object.

In the case of a floating vessel, flotation is the result of the hydrostatic pressure on the immersed part of the hull. This pressure acts perpendicular to the wetted surface and increases with its depth (Figure 6-3). The resultant upward pressure, or buoyancy Δ, is typically treated as the sum of all the partial pressures P, and is equal to the static displacement of the vessel. The line of action of this force (buoyant lift) passes through the "centre of buoyancy" CB, which is at the centre of gravity of the "boat-shaped" mass of water displaced by the vessel (Marchaj 1964:430–31). The vessel rests in a static flotation equilibrium while the vessel's own centre of gravity CG, is directly above the vessel's centre of buoyancy CB, as long as no external forces such as wind, wave or cargo loading are brought to bear on the vessel.

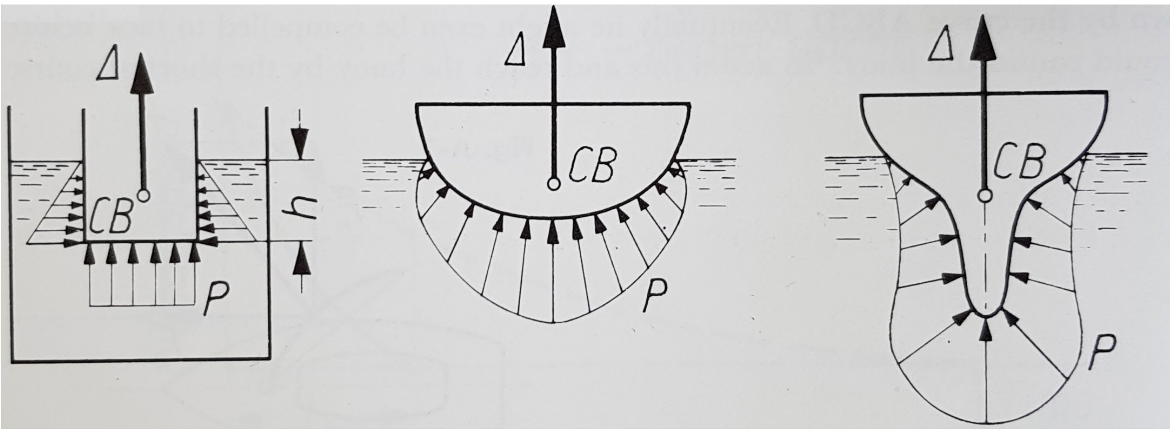

Figure 6-3 Hydrostatic pressure on submerged portions of a hull (after Marchaj 1964: 430)

The three main factors which affect the flotation condition are heel (number 1 in Figure 6-4), trim (number 2 in Figure 6-4) and sinkage (number 3 in Figure 6-4). All three are inter-related and in a state of constant flux, changing any one of these will affect the other two. If a heeling moment is generated by adding weight to one side of the vessel, or by external forces such as wind loading on the rigging and sails, the vessel will rotate about its longitudinal axis. This will have the effect of modifying the submerged portion of the hull, resulting in a revised “boat-shaped” mass of water. If that revised volume of displaced water is less than the displacement weight of the vessel, the hull will sink deeper (model sinkage) until the buoyant force equals the displacement. Likewise, the revised underwater volume will probably have a different centre of buoyancy CB, resulting in either a bow-down or bow-up trim to reposition the centre of gravity (Figure 6-5). This very issue was identified in the digital re-analysis of the Poole Iron-Age logboat (Tanner 2019:48–51).

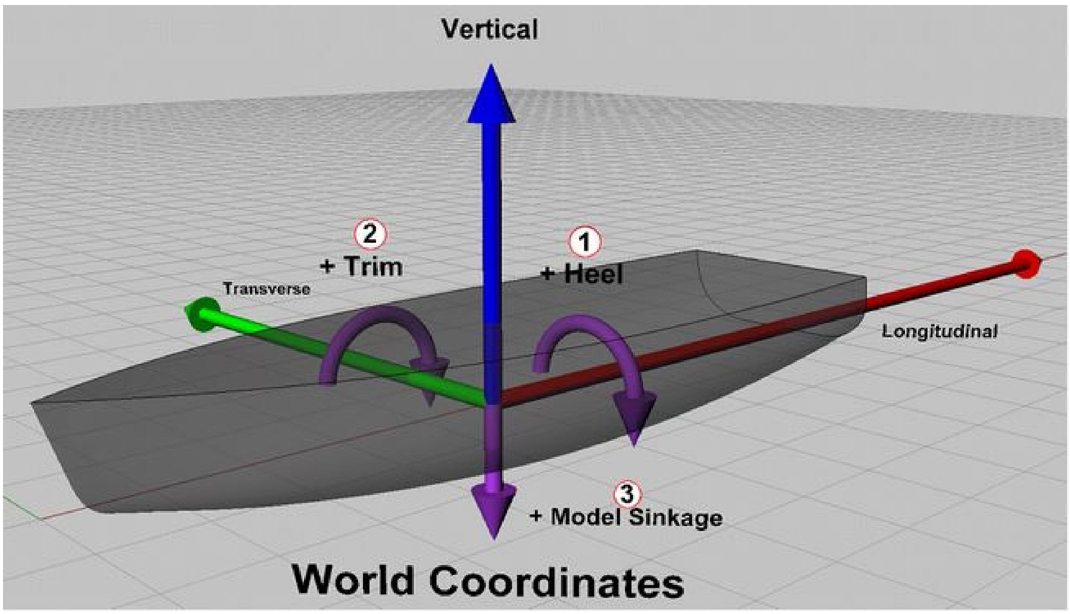

Figure 6-4 Variations in a vessel’s flotation condition (image Orca3D)

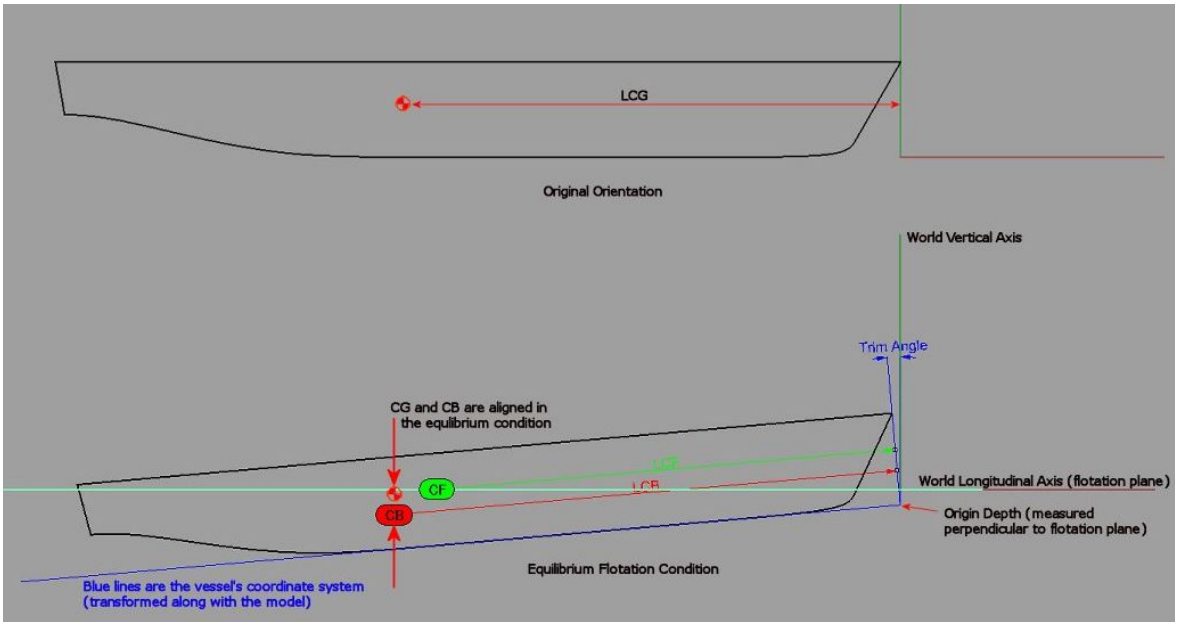

Figure 6-5 Moving the vessel's centre of gravity aft changes the equilibrium condition (image Orca3D)

In order to establish a floatation condition for a vessel:

- the volumetric shape of the underwater hull surface
- the weight of the vessel with and without loads
- the positions for centre of gravity and centre of floatation

all need to be established using detailed calculations before any static stability calculations can be examined.

The volumetric shape of the underwater hull will typically be determined from the archaeological remains. The weight of the ship is determined by the summation of all the constituent elements used in its construction, including any elements of rigging, as well as any additional equipment required for the normal operation of the vessel, what is termed lightship displacement.

This lightship displacement (weight) combined with volumetric shape results in a lightship flotation condition. The next consideration is known as the departure condition, which is the lightship weight of the vessel, to which is added the crew, personnel effects and provisioning supplies necessary for the planned voyage, and the final flotation condition is often termed loaded displacement, which is normally based on hull factors such as maximum draft or minimum freeboard, determined by how the vessel 'sits' in the water. The difference between departure condition displacement and loaded condition displacement is the actual (calculated) cargo capacity of the vessel.

6.3 Determining the volumetric shape of a vessel

A ship's hull is a very complicated three-dimensional shape. With few exceptions, the shape of a ship's hull cannot usually be described by mathematical equations. Therefore, naval architects have placed great emphasis on the graphical description of hull forms. Traditionally, the ship's hull form is represented graphically by a lines plan drawing. The lines plan drawing consists of the intersection of the hull with a series of planes (Figure 6-6). The planes are equally spaced in each of the three dimensions.

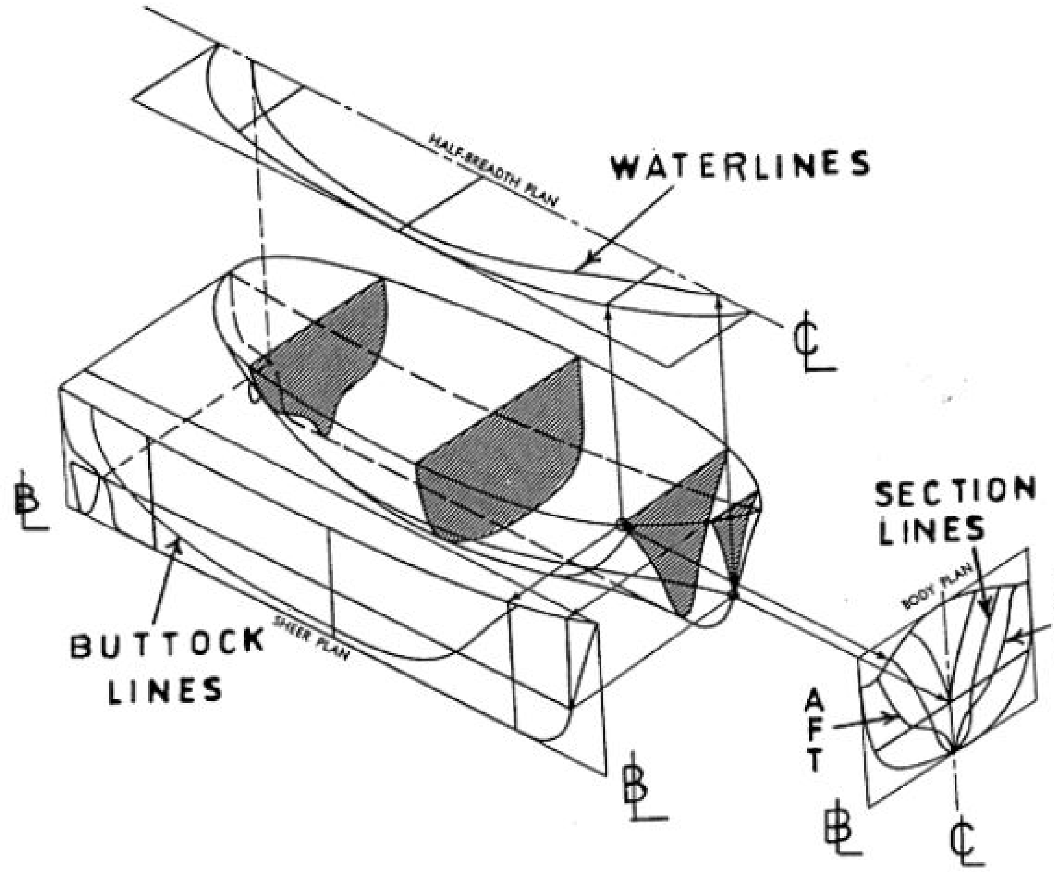

Figure 6-6 Generating a Lines Plan drawing (image: USNA Principles of Ship Performance: Fig 2.2)

Simpson's rules (after the English mathematician Thomas Simpson 1710-1761) may be used to find the areas and volumes of irregular figures (Derrett and Barrass 2006:68). The rules assume that the boundaries of such figures are curves, which follow a definite mathematical law. When applied to ships they give a good approximation of areas and volumes. The accuracy of the results obtained will depend on the spacing of the ordinates, and upon how closely the curves follow the mathematical law. The underwater volume of the vessel is traditionally calculated using Simpson's 1st Rule: $V=h/3(A0+4A1+2A2+4A3+2A4+4A5+2A6+4A7+2A8+4A9+A10)$. Where: V is underwater volume, h is the section interval, and A is the section area at each of the 11 stations. For

Simpson's rules to function an uneven number of ordinates (stations) equally spaced along the waterline length is required. These stations have traditional used 10 divisions creating a total of 11 stations (Figure 6-7), numbered 0 – 10, with station 0 positioned at the forward perpendicular (the junction of the waterplane and the forward extremity of the vessel), and station 10 position at the aft perpendicular (the junction of the waterplane and the aft extremity of the vessel).

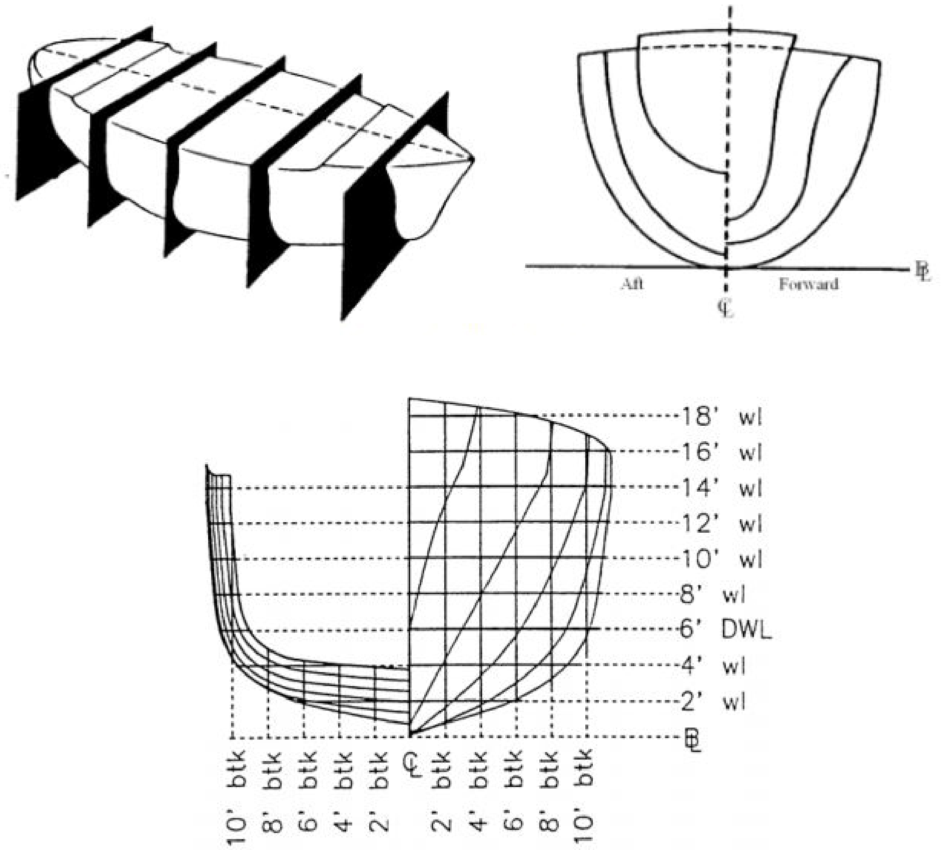

Figure 6-7 Body Plan stations (image: USNA Principles of Ship Performance: Fig 2.7a)

The area of each section is typically calculated from the cross-sectional curves taken from the line drawing of the vessel, and again Simpson's Rules are used to calculate the cross-sectional area at each station. Additional hydrostatic data such as Longitudinal Centre of Buoyancy LCB and Longitudinal Centre of Gravity LCG are also required in order to determine the fore and aft trim of the vessel. Until very recently, most of this work was done by hand (see for example McGrail 1978). In order to calculate the fundamental geometric properties of the hull, naval architects use numerical methods, often calculated again using Simpson's Rules, which, when applied to ships give a good approximation of areas and volumes (Derrett and Barrass 2006).

6.4 Determining the weight of a vessel

According to McKee (1974:11–13), the most accurate method of determining the weight of a vessel is to weigh it in air and then carry out an inclining test to establish the position of centre of gravity. In order to weigh the vessel and perform an inclining test, a complete, rebuilt vessel would be required. A second, more feasible, approach is to perform a weight engineering study, often used in naval architecture applications. This involves a detailed study of all the component parts of the vessel to calculate their volume, and hence their weight in order to give a cumulative weight for the entire vessel. However, the most accurate method still remains the use of Archimedes principle which states the weight of an object is equal to the weight of the volume of fluid (water) it displaces.

6.4.1 Centre of Gravity

The centre of gravity (CG) is the location of the centroid of mass of a vessel. Centres of gravity longitudinally, transversely, and vertically are critical to a vessel's stability and its equilibrium flotation condition (Figure 6-4). The vertical centre of gravity (VCG or KG) is the height above the baseline of the centre of gravity. The longitudinal centre of gravity (LCG) is the position along the length of the vessel of the centre of gravity. It is generally calculated by considering moments about the aftermost portion of the vessel; however, it is often stated as a distance from midship. The placement of the centre of gravity relative to the centre of buoyancy is a factor in vessel trim (Figure 6-5). The transverse centre of gravity (TCG) is the lateral location of the centre of gravity. It is beneficial to maintain the TCG on the centreline of the vessel to maintain a neutral heel (Figure 6-4).

6.4.2 Calculation of Centre of Gravity

Summation of Moments is a traditional method of determining the centre of gravity for complex assemblages. This requires knowing the centre of gravity of each individual component and their location within the ship. The weight of the component is multiplied by the distance from this components CG to a given reference point (generally the intersection of the vessels centreline, after perpendicular, and baseline). This gives the components moment. Summing these moments, and dividing by the total weight of the components, gives the distance from the reference point to the centre of those components. This can be used to aggregate related components or used for the entire vessel if sufficient information is available.

It should be noted however, that all of these calculations create a "snapshot" of the vessel in a single particular floatation condition. If this flotation condition is altered by any means, the addition or repositioning of crew, cargo or ballast, the centre of gravity will shift, resulting in a new flotation condition and consequently a revised underwater hull form. At this stage it is then necessary to repeat all the individual calculations based on the new altered underwater form. As can be seen this involves an onerous amount of calculations, whether done using pen and paper, a calculator, or even with the aid of a spreadsheet. The use of specialised CAD and Naval Architectural software, such as Rhinoceros 3D combined with Orca 3D, using an accurate graphical representation of the vessel, will rapidly and simply complete all these required calculations to provide real-time hydrostatic data, which is updated for each floatation condition.

6.5 A digital approach

With the start of the 21st century, maritime archaeological projects were beginning to use full-scale digitising to document individual ship's timbers (Hocker 2000) and the Rhinoceros 3D NURBs modelling software was being used to convert the results back to two-dimensional scaled drawings. Orca 3D a plug-in for Rhinoceros 3D, is one such naval architectural software.

In February 2000 as part of a demonstration at the National Museum and Gallery of Merseyside a west African dugout was 3D laser scanned (Moreton *et al*. 2000). The resulting scan data was converted to a polygon mesh model, which defined the shape and form of the craft as a full-scale three-dimensional computer model. Once the basics of lines plan drawings were explained to the CAD operator, a series of two-dimensional sections were generated from the three-dimensional model positioned to coincide with the stations of a traditional lines plan drawing.

At the same time the Traditional Boats of Ireland project had been documenting vernacular Irish vessels (Mac Cárthaigh 2008), using the traditional methods of offset measurements and publication via standard two-dimensional lines plan drawings. During the 10th ISBSA conference at Roskilde in Denmark, the Traditional Boats of Ireland project team were invited by Deni Vorst and Nigel Nayling to see how they used the Faro arm to record the Newport Medieval Ship timbers. The benefits were immediately recognised, and a 12ft Faro platinum arm together with 3D laser scanner attachment was purchased, primarily with the intention of documenting both museum and shipwrights scale boat models. The project struggled with the technology and methods and initial results were less than satisfactory. I joined the project in 2009 and realised one of the main issues was that of scaling, the models were all at scale, while any hydrostatic analysis requires the full-size dimensions of the vessel being analysed. By using the computer software, I was able to digitally re-scale the models back to life-size, and Orca 3D was used to examine the digital model.

Orca 3D enables detailed analysis of the digital model by establishing a datum waterline, either from known data such as waterline length and draft, or from actual markings such as painted or scribed lines on the original boat model. If this data is unavailable, Orca 3D can compute flotation planes by digitally recreating each part of the vessel using Rhinoceros 3D, and by assigning a material, Orca 3D uses its dimensions and form to obtain its centre of gravity and weight. All of this data is then combined to generate a floatation condition for the vessel. From this hydrostatic calculations and flotation conditions may be calculated, as well as outputting standard naval architecture lines plan drawings, all taken directly from the digital three-dimensional model.

Could this methodology, so far only used on scaled models, be employed on a full-size vessel, and if so, how accurate was the resulting data, and the proposed methodology? To test the process a benchmark was required. This was found in *Hanorah,* a Heir Island lobster yawl from West Cork, Ireland (Figure 6-8). The original vessel is 7.8 m in length overall, 2.13m beam and 0.83m draft, and was originally built by Richard Pyburn of Heir Island in 1892, and subsequently rebuilt in 1993 by myself and others. This vessel was selected for the case study as the author is completely familiar with the vessels construction and sailing characteristics. Additionally, the vessel sits on a floating mooring for extended periods providing a clear indication of its flotation line in a ballasted lightship condition[80]. In this case study the vessel was to be recorded using 3D laser scanning, and a digital model created to examine the computer-generated hydrostatic results and compare the results obtained to the real-world physical vessel.

Figure 6-8 Hanorah, a Heir Island lobster yawl (Pat Tanner)

[80] Ballasted lightship condition is the weight of the vessel and all its equipment, including any internal ballast, but excludes any crew, cargo or other elements.

6.5.1 Recording the hull shape

The boat was 3D laser scanned using a Faro Focus 3D laser scanner from 6 scan positions (Figure 6-9). With each scan taking 10 minutes the total scanning time was 1.5 hours. This generated six individual point cloud scans, with a combined total of 128.6 million individual three-dimensional points, which were registered using the Faro Scene software. The scans were registered (Figure 6-10) to generate a single project point cloud having a maximum deviation of 2.8 mm.

Figure 6-9 Faro Focus laser scan positions (Pat Tanner)

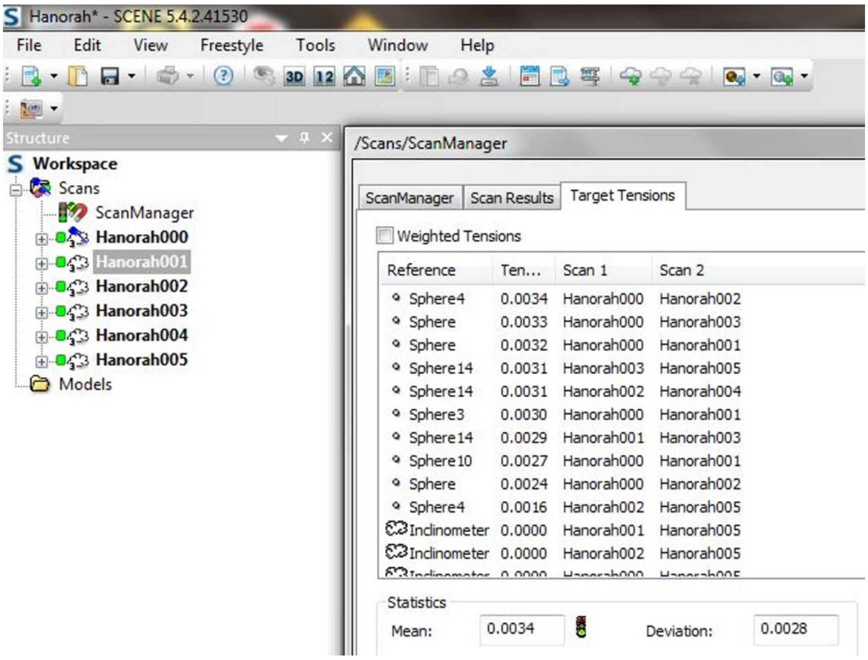

Figure 6-10 Registering the individual scans together to an accuracy of 2.8 mm (Pat Tanner)

Figure 6-11 Registered point cloud (top) and target vessel (bottom) (Pat Tanner)

The target boat was then cropped from the complete project point cloud (Figure 6-11). The resulting point cloud, 7.3 million points of the target vessel was imported into Geomagic Studio software and a 3D polygonal mesh model generated from the point cloud.

6.5.2 Establishing the Flotation Condition

The normal flotation waterline is clearly visible on the actual vessel, located as is normal practice, several centimetres below the painted anti-fouling line (Figure 6-12). The same waterline is not as readily visible in the coloured 3D laser scan, as the scanner uses a medium to low resolution camera for colour capture.

Figure 6-12 Digital photographs clearly showing the flotation waterline

Using the Faro Scene scanner software, it is possible to switch between full colour and intensity value views and take accurate three-dimensional measurements (Figure 6-13). The Floatation waterline is 72.5 mm at the Bow and 102 mm at the stern, below the painted anti-fouling line. As the painted anti-fouling line is clearly visible on the scanned polygon mesh model, this allows for accurate orientation of the digital model in 3D space in relation to its known flotation condition. The polygon mesh model is imported into Rhinoceros 3D and orientated to match the measured flotation condition as identified from the scan data. This establishes the Datum Water Line, DWL, for the vessel as it sits at its mooring, ballasted, but without crew or cargo. If the vessel can be modelled such that the flotation of digital model and real vessel are the same, then it clearly demonstrates that effectiveness of the methodology from an accuracy perspective.

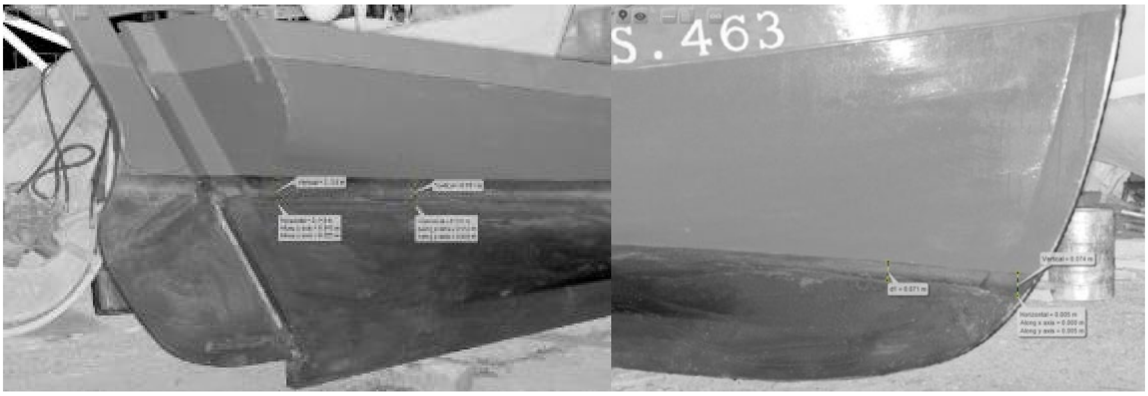

Figure 6-13 Intensity value view of 3D scan data (Pat Tanner)

While Orca 3D is capable of performing analyses on a polygonal mesh model, the nature of these mesh models, which comprise a triangle for every three points within the point cloud, often results in a 'heavy model' consisting of millions of minute triangular surfaces. This can cause a drain on computer resources as the software attempts to resolve calculations based on every miniscule surface fragment. By contrast a Non-Uniform Rational Basis Spline (NURBS) model is a mathematical model commonly used in computer graphics for generating and representing curves and surfaces. It offers great flexibility and precision for handling both analytic (surfaces defined by common mathematical formulae) and modelled shapes. NURBs surfaces can be automatically generated using Geomagic Studio software, or alternatively, manually created using the Rhinoceros 3D modelling environment.

A single skin NURBS surface was manually created using the Rhinoceros 3D modelling software, as this allowed for more detailed control of the number of surface control points than the Geomagic Studio auto-surface feature. The polygon mesh and the NURBs surface were then compared using the 3D deviation feature in Geomagic Studio (Figure 6-14) to confirm that the modelled surface was within the 3 mm tolerance as recorded with the laser scanning process. The rudder and rigging show deviation due to movement during the scanning process, caused by the wind.

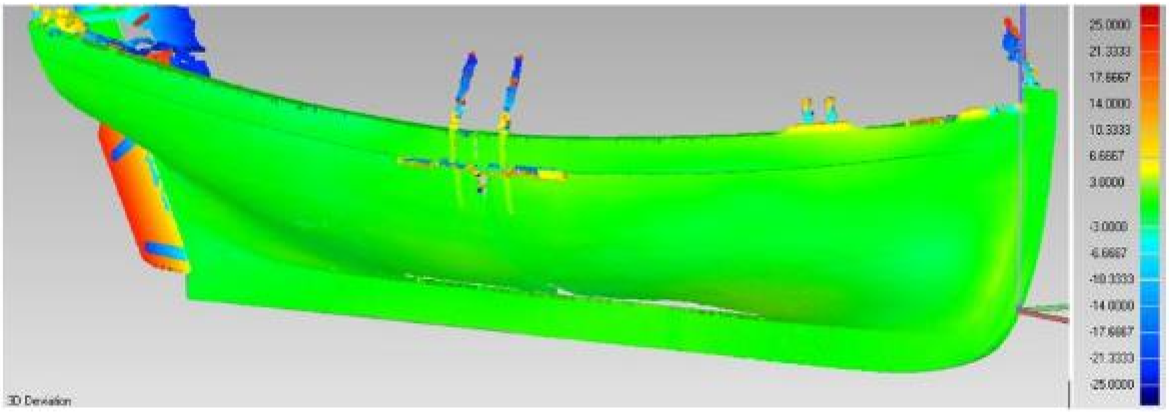

Figure 6-14 3D surface deviation analysis where green is within the 3 mm tolerance (Pat Tanner)

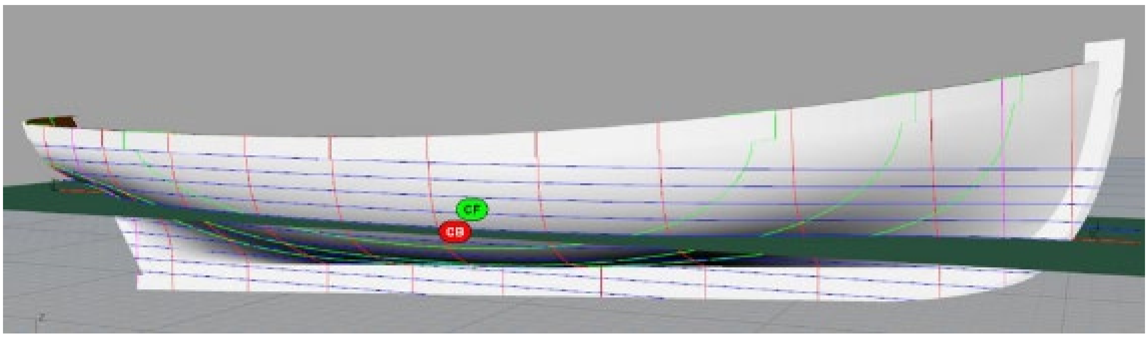

Figure 6-15 NURBs surface model orientated to match the laser scanned waterline orientation (Pat Tanner)

The NURBs surface model was manually orientated to match the documented flotation waterline (Figure 6-15) and was then analysed by the Orca 3D software. This generated a set of baseline hydrostatic data (Figure 6-16) for the digital vessel in its known flotation condition (Figure 6-17 and Figure 6-18), which could be compared to an actual physical vessel.

Condition Summary

Load Condition Parameters

Condition	Weight / Sinkage	LCG / Trim	TCG / Heel	VCG (mm)
Design	0.000 mm	0.000 deg	0.000 deg	None available

Resulting Model Attitude and Hydrostatic Properties

Condition	Sinkage (mm)	Trim(deg)	Heel(deg)	Ax(m^2)
Design	0.000	0.000	0.000	0.49

Condition	Displacement Weight (kgf)	LCB(mm)	TCB(mm)	VCB(mm)	Wet Area (m^2)
Design	1957.855	-3937.462	0.000	-153.063	12.905

Condition	Awp(m^2)	LCF(mm)	TCF(mm)	VCF(mm)
Design	8.377	-3797.153	0.000	0.000

Condition	BMt(mm)	BMl(mm)	GMt(mm)	GMl(mm)
Design	865.320	10164.398	None Available	None Available

Condition	Cb	Cp	Cwp	Cx	Cws	Cvp
Design	0.202	0.550	0.641	0.367	3.503	0.315

Figure 6-16 Baseline hydrostatic data (Pat Tanner)

Load Condition Parameters

Model Sinkage	0.000 mm
Model Trim	0.000 deg
Model Heel	0.000 deg
VCG	None available mm
Fluid Type	Seawater
Fluid Density	1025.900 kg/m^3
Mirror Geometry	True

Resultant Model Attitude

Heel Angle	0.000 deg	Sinkage	0.000 mm
Trim Angle	0.000 deg		

Overall Dimensions

Length Overall, LOA	7799.786 mm	Loa / Boa	3.667
Beam Overall, Boa	2126.885 mm	Boa / D	1.149
Depth Overall, D	1851.833 mm		

Figure 6-17 Load condition parameters (Pat Tanner)

Waterline Dimensions

Waterline Length, Lwl	7113.640 mm	Lwl / Bwl	3.869
Waterline Beam, Bwl	1838.400 mm	Bwl / T	2.546
Navigational Draft, T	722.134 mm	D / T	2.564

Volumetric Values

Displacement Weight	1957.855 kgf	Displ-Length Ratio			151.578
Volume	1.908 m^3				
LCB	-3937.462 mm	FB/Lwl	0.446	AB/Lwl	0.554
TCB	0.000 mm	TCB / Bwl			0.000
VCB	-153.063 mm				
Wetted Surface Area	12.905 m^2				
Moment To Trim	27.975 kgf-m/cm				

Waterplane Values

Waterplane Area, Awp	8.377 m^2				
LCF	-3797.153 mm	FF/Lwl	0.466	AF/Lwl	0.534
TCF	0.000 mm	TCF / Lwl			0.000
Weight To Immerse	85.943 kgf/cm				

Sectional Parameters

Ax	0.487 m^2		
Ax Location	-3973.887 mm	Ax Location / Lwl	0.441

Hull Form Coefficients

Cb	0.202	Cx	0.367
Cp	0.550	Cwp	0.641
Cvp	0.315	Cws	3.503

Figure 6-18 Underwater hydrostatic parameters (Pat Tanner)

6.5.3 Examining dimensional variations

With a 3mm tolerance, the Orca surface model could potentially be ± 1.5 mm in any dimension. A series of four surfaces were created, the first two being altered, using a linear scaling of 1.5 mm in the largest dimension (LOA), and the second two being altered by volumetric scaling of 1.5 mm in all dimensions representing a worst-case scenario. The changes in displacement values were then calculated for each model version. Dimensional change for the first two models results in a maximum displacement range of +1.07 kg to -1.03 kg (Table 6-1). This results in a displacement range of between 1,956.83 kg and 1,958.92 kg. A difference of 2.1 kg or 0.11%.

Volumetric change for the second two models results in a maximum displacement range of +3.43 kg to -3.22 kg (Table 2). This results in a displacement range of between 1,954.54 kg and 1,960.90 kg. A difference of 6.4 kg or 0.33%.

	Original	+ mm	Scaled up	% Increase	- mm	Scaled down	% Decrease
LOA	7799.8	1.560	7801.346	100.02	-1.497	7798.289	99.98
BOA	2126.9	0.426	2127.311	100.02	-0.408	2126.477	99.98
DOA	1851.8	0.371	1852.204	100.02	-0.355	1851.478	99.98
Displacement	1957.8		1958.922	100.054		1956.825	99.947
Kgs diff.	0		1.067	Kgs difference		-1.03	Kgs difference
% diff.	0		0.054	% difference		-0.053	% difference

Table 6-1 Dimensional changes for linear scaling (Pat Tanner)

	Original	+ mm	Scaled up	% Increase	- mm	Scaled down	% Decrease
LOA	7799.8	1.500	7801.397	100.02	-1.500	7798.286	99.98
BOA	2126.9	1.500	2128.248	100.06	-1.500	2125.385	99.93
DOA	1851.8	1.500	1853.562	100.09	-1.500	1850.333	99.92
Displacement	1957.8		1960.902	100.156		1954.538	99.831
Kgs diff.	0		3.047	Kgs difference		-3.317	Kgs difference
% diff.	0		0.156	% difference		-0.169	% difference

Table 6-2 Dimensional changes for volumetric scaling (Pat Tanner)

This would indicate a dimensional accuracy of between 99.67 and 99.89% for the 3D laser scanned digital model when compared to the real-world, full-scale original vessel.

6.6 Vessel Weight and Centre of Gravity

Similar to the approach developed for the Drogheda Boat (Tanner 2013a:140–142), each of the individual components of the vessel were digitally modelled (Figure 6-19 top), based on the 3D laser scanned data (Figure 6-19 bottom), in effect building the vessel again in a digital format, just as it had been physically built. The next stage is to assign a material to each of the solid modelled elements (Figure 6-20) which enables Orca 3D to generate a weight report using each elements geometry and material density, resulting in a combined weight and centre of gravity or the vessel. This is in effect a digital version of the Summation of Moments methodology discussed in Chapter 6.4.2.

The weight analysis resulted in 859.26 Kg for the timber elements, with the Longitudinal Centre of Gravity, L.C.G. located at -3.66 m and the Vertical Centre of Gravity, V.C.G. at 0.1178 m relative to the computer origin point. These weights were then applied to the Orca Surface model to determine its flotation condition, and by changing the analysis study from design condition to free-float condition, the Orca 3D software will reposition and orientate the hull surface model into its resultant flotation equilibrium state, based on underwater hull form, weight and position of the centre of gravity (Figure 6-21). Based on the total weight for the timber hull, and the hull form, this results in a draft of 457.75 mm.

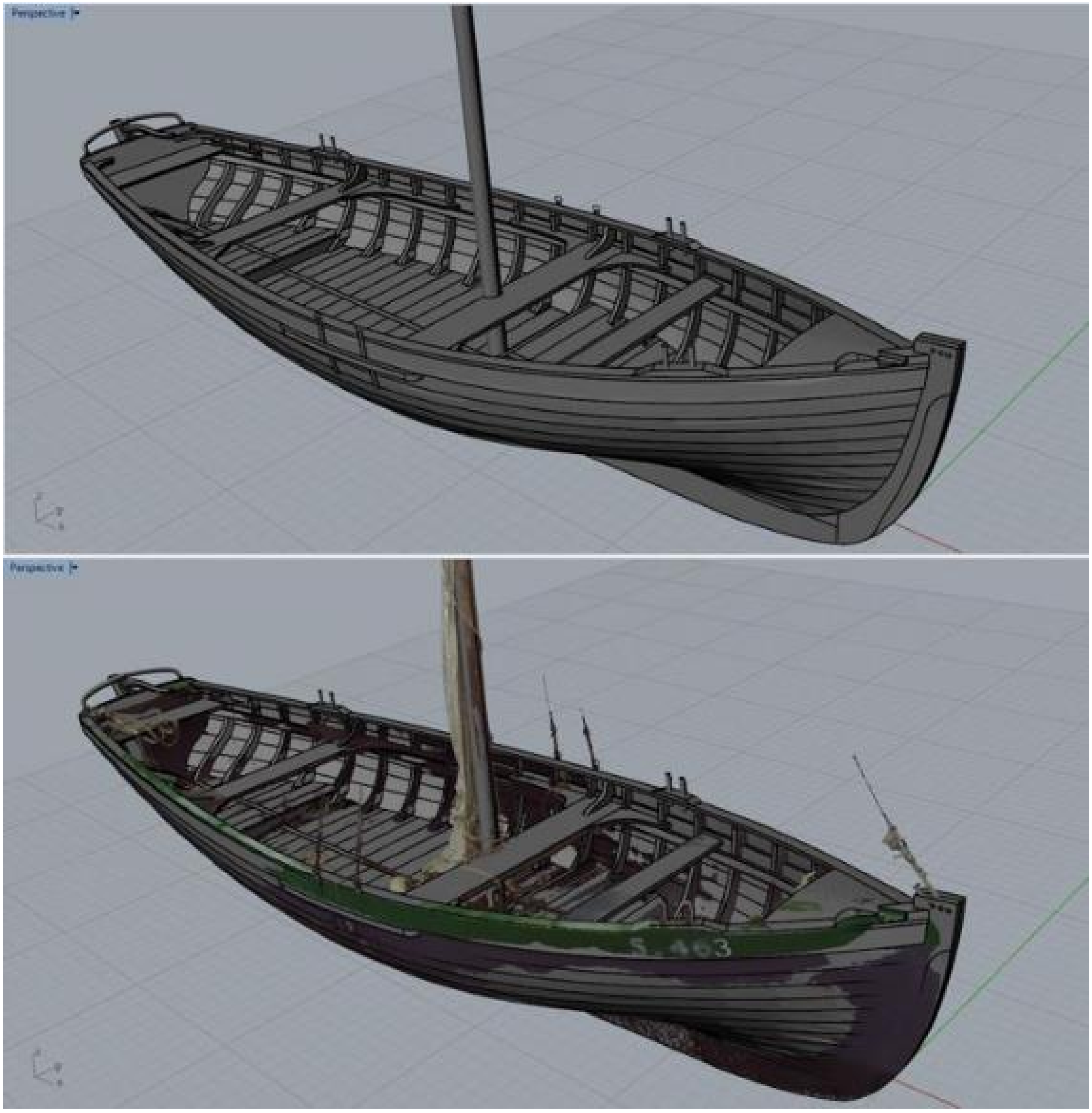

Figure 6-19 Modelling component elements (Pat Tanner)

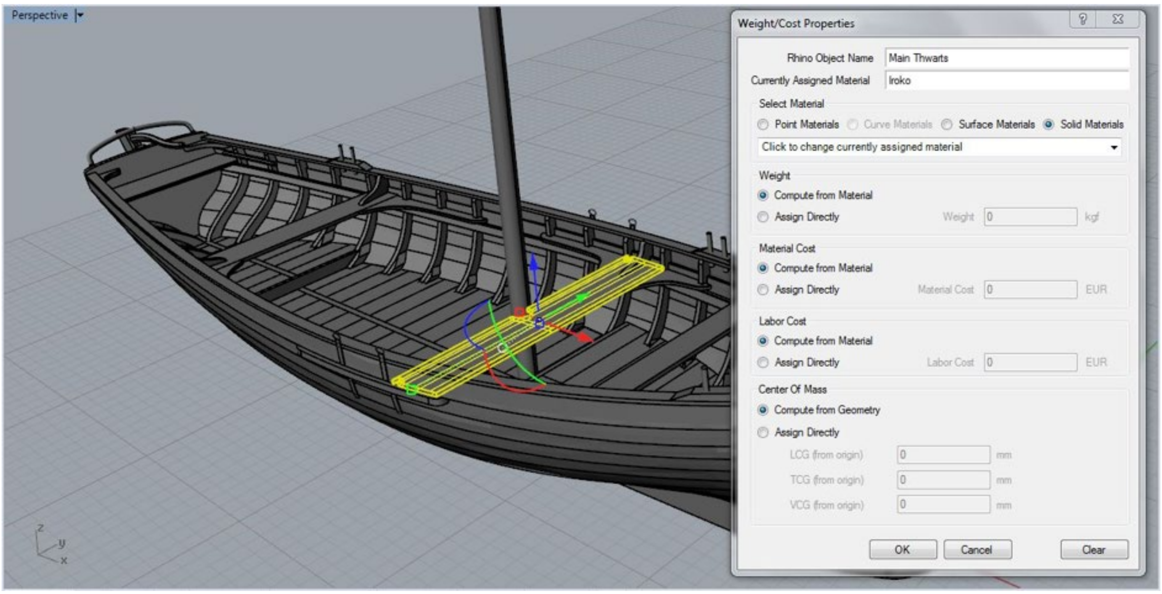

Figure 6-20 Assigning materials to individual components (Pat Tanner)

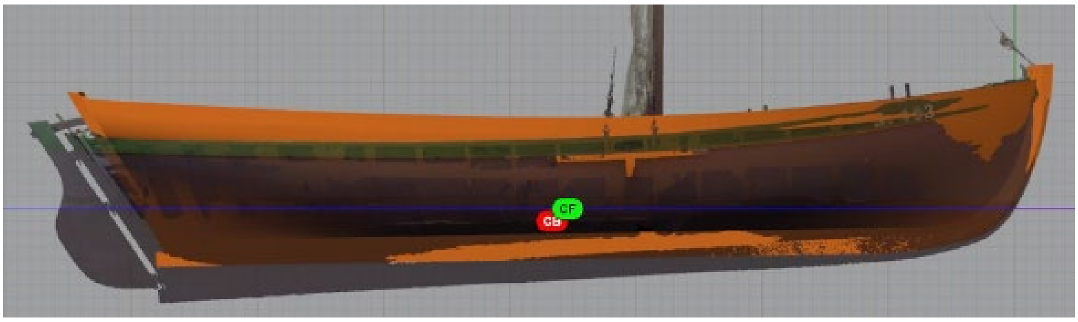

Figure 6-21 "Hull material only" flotation condition coloured brown overlaid on original vessel (Pat Tanner)

It is clear from Figure 6-21 that the brown (timber only) modelled hull form is floating high when compared to the actual physical vessel's flotation condition. Next, the additional elements such as: iron fastenings; flooring; rigging; oars; life raft; additional warps; anchors; and equipment were modelled (Figure 6-22), and the resultant weight calculations applied to the Orca surface model.

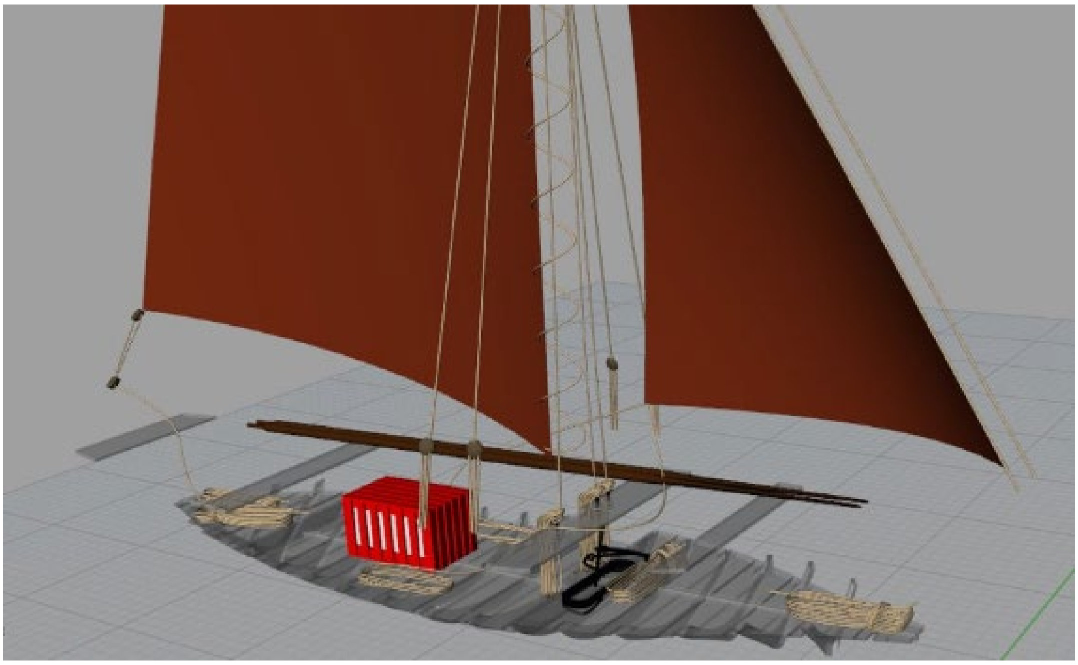

Figure 6-22 Additional elements modelled and added to the analysis (Pat Tanner)

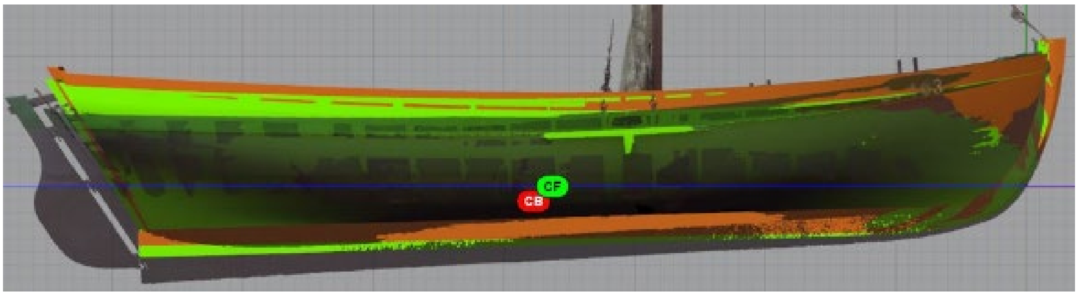

Figure 6-23 Resultant flotation condition in green with all additional elements modelled (Pat Tanner)

The resulting combined weight of 1,154.9 kg, with the centre of gravity located 3.78 m aft of the forward perpendicular (FP), resulted in the vessel floating as shown in Figure 6-23, which, although a little closer to its actual flotation condition, was still floating too high, a clear indication that the internal ballast was still missing from the model. The typical ballast blocks used in the boatyard are cast lead billets measuring 300 x 150 x 50 mm and weigh 25.52 kg each. These were positioned in the inter frame spaces for 7 bays from under the mast step, aft as far as the aft thwart. The quantities modelled were 33 billets, having combined weights of 842 kg. The ballast is then included in the Orca 3D weight analysis, and the Orca 3D free flotation analysis repeated. The results are shown in Figure 6-24 (top) in tabular format, illustrating how the software calculates the revised longitudinal (LCG), transverse (TCG) and vertical (VCG) centres of gravity, resulting in a revised flotation trim. The resultant sinkage of 6.8 mm and trim down by the stern of 0.06 degrees means a revised flotation condition is generated and the new longitudinal (LCB), transverse (TCB) and vertical (VCB) centres of buoyancy are also calculated by the Orca software. A graphical representation, Figure 6-24 (bottom) is also generated to illustrate the new flotation condition.

Condition Summary

Load Condition Parameters

Condition	Weight / Sinkage	LCG / Trim	TCG / Heel	VCG (mm)
Condition 1	1935.430 kgf	-3950.000 mm	0.000 mm	70.9

Resulting Model Attitude and Hydrostatic Properties

Condition	Sinkage (mm)	Trim(deg)	Heel(deg)	Ax(m^2)
Condition 1	-6.784	-0.063	0.000	0.48

Condition	Displacement Weight (kgf)	LCB(mm)	TCB(mm)	VCB(mm)	Wet Area (m^2)
Condition 1	1935.430	-3950.247	0.000	-154.815	12.848

Condition	Awp(m^2)	LCF(mm)	TCF(mm)	VCF(mm)
Condition 1	8.341	-3805.142	0.000	-2.612

Condition	BMt(mm)	BMl(mm)	GMt(mm)	GMl(mm)
Condition 1	867.578	10198.842	641.889	9973.154

Condition	Cb	Cp	Cwp	Cx	Cws	Cvp
Condition 1	0.200	0.549	0.640	0.364	3.508	0.313

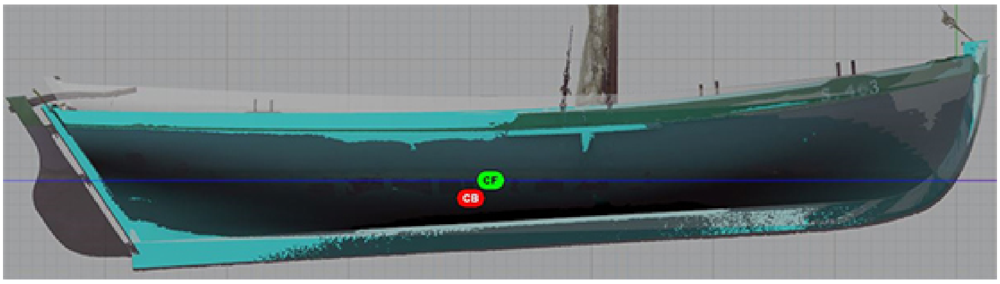

Figure 6-24 Ballasted condition summary (Pat Tanner)

6.7 Conclusion

When the results from the digital modelling process (Figure 6-24) are compared to the baseline flotation condition (Figure 6-16), which is based on the 3D laser scanning of the physical vessel, and has already been shown as dimensionally accurate, the results are almost identical. The baseline vessel has a displacement of 1957.85 kg, while the purely digital modelled version has a displacement of 1935.43 kg, a difference which indicates the digital version is underweight by 22.42 kg or 1.16%.

One potential reason for the minor difference in weights between the two versions is that average densities were used for all the wooden elements. Oak, being a natural material is quoted as having densities varying between 600 and 900 kg/m³, and in this case an average density of 800 kg/m³ was used being typical for oak at 27% moisture content. Some of the constantly submerged timber probably has a slightly higher moisture content and therefore may be slightly heavier.

In addition, the laser scanned physical vessel has a flotation draft of 722.1 mm while the digitally modelled version has a marginally deeper draft of 722.8 mm, indicating a minute difference in the fore and aft positioning of the centre of gravity.

Based on these results, the digital modelling approach provides an accurate methodology, in which there are no issues with scaling, as the object is recorded life-size, working to millimetric precision, to examine both the weight characteristic and the resulting flotation condition (Figure 6-25).

Figure 6-25 Physical and digital version of the same vessel (Pat Tanner)

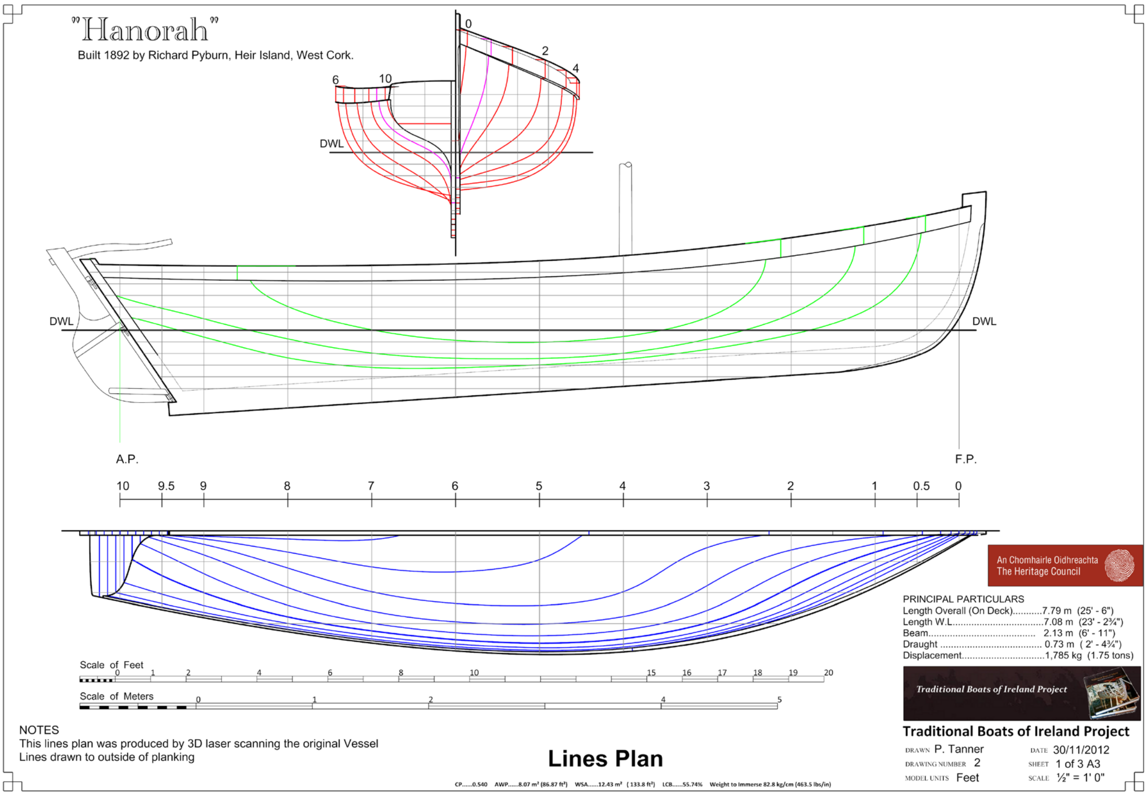

Figure 6-26 Automatic generation of lines plan (Pat Tanner)

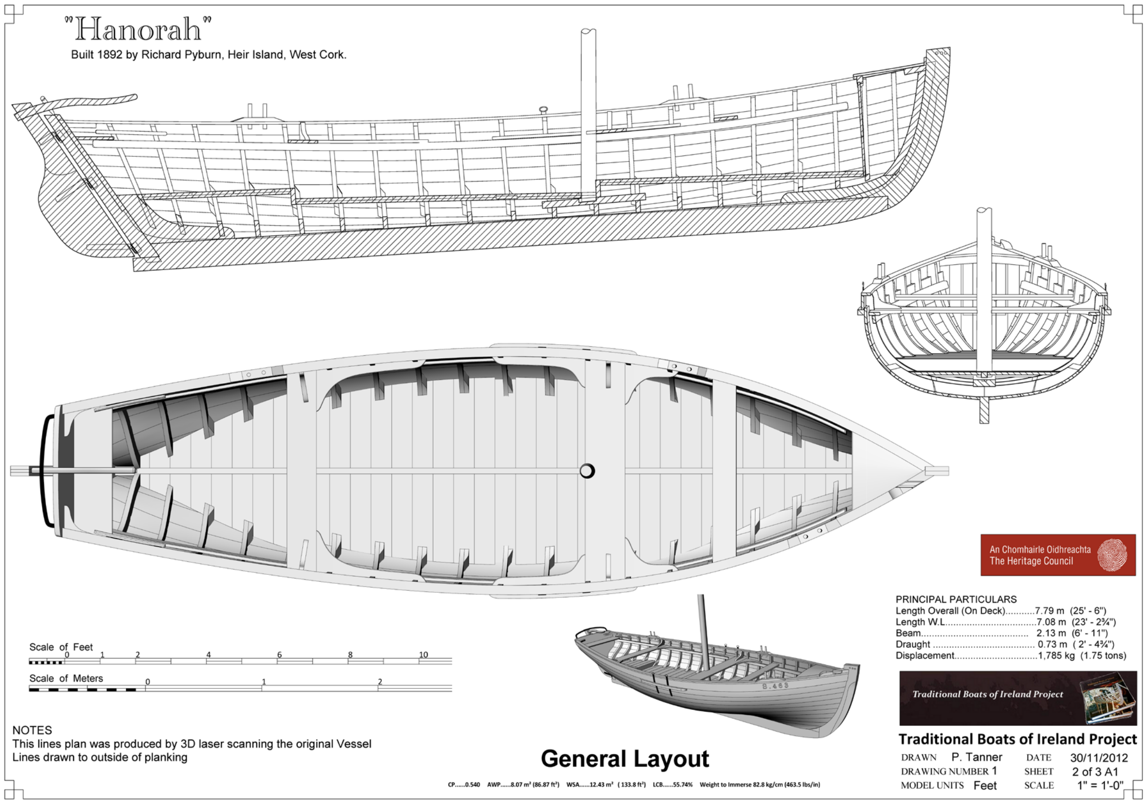

Figure 6-27 General layout drawing created from digital 3D model (Pat Tanner)

The methodology outlined allows for the archaeological remains to be recorded in the most detail currently achievable with the technology currently available. To use that raw data to recreate the 3D shape of the vessel to an accuracy of between 99.67% and 99.89%. Then to digitally rebuild the vessel to a level of accuracy that allows hydrostatic and related testing to be undertaken as if it were a full-size, real world vessel. Factors such as materials, crew, ballast, cargo, equipment, etc can all be experimented with as a means to better understand the vessel. Finally, the nature of the 3D modelling process allows for the restitution of missing elements, in the case of incomplete archaeological remains, and for different options within such reconstruction to be fully explored in a way that is relatively efficient in terms of cost and time.

The process of ‘digitally building’ the vessel adds an additional level of comprehension to the object being documented. And the completed three-dimensional model is an additional asset which has many further and varied uses from the automatic generation of lines plans (Figure 6-26) to simply created general layout drawing (Figure 6-27), as well as a base model for advanced visualisation outputs. All of these factors are investigated and presented in the subsequent chapters 7 to 9.

Chapter 7 **The archaeological evidence**

7.1 Introduction

Based on the reviews in Chapter 2 and Chapter 3 of the key developments in ship and boat archaeology, the main themes that come to the fore are: the object itself (the shipwreck); the person or people who ordered the vessel; the person or people who constructed the vessel; the person or people who used the vessel; how the vessel performed; and the society in which the vessel was used. As noted in Chapter 4, reconstruction of the vessel is a logical continuation in the study of the archaeological remains. The ideal solution should be, a reconstruction which violates none of the archaeological evidence, in order to know what the vessel looked like, how it was used, and to reconstruct both the vessel and the process (the construction and use) in a scientific and repeatable manner, and to make these results available for critical external review, as well as making the results and ideally the source data publicly available.

The central aspect to all the above-mentioned themes is the vessel itself. It is the shape, form and size of the vessel, and possibly it's cargo and find location, which may give an indication of the potential use and sphere of operation of that vessel. If a vessel's use and area of operation are known, it may be possible to determine to some extent, who it was that owned, or commissioned the building of, that vessel. A scientific analysis of the materials used in the vessel's construction will give some insight into the society where the vessel was constructed, issues such as material supply and possible trade routes. For example, the 7th century Saxon burial ship at *Sutton Hoo*, in Suffolk consisted of almost 3,600 iron nails and roves (Tanner *et al*. 2020:14), all of which had to be hand-made and supplied to the vessel's builders, not to mention the supply chain, mining of the ore, transport, smelting, and the coopers making casks to contain the nails. A considerable task, and one that demonstrates the penetration into wider society of the building process of such vessels. Likewise, for the 15th century *Newport Medieval ship,* the minimum reconstruction – just up to the 38th strake – required over 16,790 iron nails and over 10,700 iron roves, which had a combined weight of over 2.68 tonnes of iron (Tanner 2013b:45). Clearly the construction of both vessel's involved significant communities of iron workers.

Techniques like dendrochronological analysis of the timber (Daly 2007; Guibal and Pomey 2009; Nayling and Susperregi 2014; Domínguez-Delmás *et al*. 2019) can provide insights into the provenance, dating and selection of timber used in the vessel's construction. Examination of how the timber is converted (McKee 1976; McGrail 1977b; Guibal and Pomey 2003), the tool marks (Christensen 1972; Christensen 1972; Hewett 1982; Finderup 2006) and any intentional scribed marks may provide an insight into how the vessel was constructed, maintained or repaired. It has been suggested that boats and ships should be appraised by a multi-phase process using an inter-disciplinary group (Crumlin-Pedersen and McGrail 2006), and as an example of this the Newport Medieval ship project included 28 specialist reports, all of which are available on the ADS website: https://archaeologydataservice.ac.uk/archives/view/newportship_2013/downloads.cfm

However, basing a vessel's use, final voyage or its sphere of operations on artefacts such as cargo (cf. van Doorninck 2015:212–3) can be misleading. The terms 'time capsule', 'closed-find', and 'closed-context' have often been applied to underwater sites and shipwrecks. Muckelroy (1978:216) used the term 'closed-community' as one of the categories for analysis, but as noted by Adams (2013:20–23) this depends greatly on the circumstances of the loss and the wrecking process, and the contemporaneity of a wreck site refers to the wrecking event, and not necessarily to the assemblage of materials. While the wrecking locates in time and space, all the constituent materials of the vessel and its contents in the context of that event, it does not follow that the materials present were in use at that same time. Of the materials present at wrecking, some may have only been aboard a matter of hours, and some for several decades.

As pointed out by Gibbins and Adams (2001:279–91) the operation of ships generally militates against the accumulation of redundant materials, so the majority of materials will be related in some way, other items and residual material, what Steffy (1994:216) referred to as 'bilge grunge', may have no direct relationship to the voyage, bar simply being onboard. In effect as stated by Adams (2013:20), the ship arrives at its place of wrecking, with an onboard stratigraphy.

While possibly constructed for a specific purpose or function many ships reached a considerable age before they sank or were abandoned, and, they were often substantially rebuilt, or may have had their roles changed. Ownership changed, through sale, by gift or by force, and repairs (Figure 7-1) or alterations were commonplace. As pointed out by Murphy (1983:74) there may also be a transfer between ethnic groups or nationalities. Adams (2013:20) states that depending on where the vessel sinks, it may be exploited by societies other than the ones that actually sailed it, and the simplistic notion that a wreck is a 'single-event phenomenon' is a dangerous one.

In terms of the wrecking event, Muckelroy (1978:182–95) designated well preserved, coherent wreck assemblages as 'continuous', and described a shipwreck (ibid: 157) as 'the event by which a highly organised and dynamic assemblage of artefacts are transformed into a static and disorganised state'. However, as pointed out by Adams (2013:21), this implies a short-term and dramatic event such as was the case with the *Vasa* (Hocker 2011:121–41) or the *Mary Rose* (Marsden 2009a), when in reality the process whereby the organisation of a vessel breaks down, culminating in a wreck may begin hours or even days before the vessel sinks, as was the case with *Sea Venture*, caught in a great storm, the ship survived four days and nights of continual bailing, before being driven aground between two reefs (Wingood 1982:333; Adams 2013:118). Efforts to avert disaster can radically alter the ship, as well as what it carries onboard, and the way in which it is organised. In violent weather the rigging may be cut-away. Cargo, equipment, fixtures and even fittings may all be jettisoned, in an attempt to remain afloat. In addition to items, and even crew involuntarily lost overboard, the stowage of materials may be re-organised and various emergency alterations or repairs made to the vessel. In these cases, the assemblage deposited on the seabed is not the same as it would be, in a rapid-onset event, such as the vessel foundering, or sinking due to naval action or piracy.

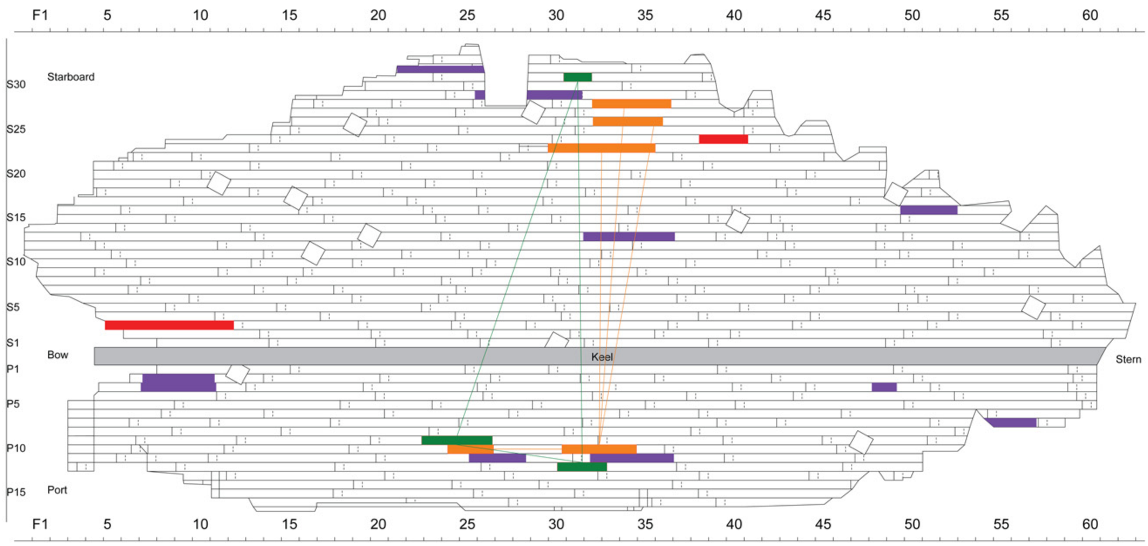

Figure 7-1 Schematic diagram of the hull planks of the Newport Ship indicating the location of repair patches (tingles) found fastened to the outboard face (Nayling and Susperregi 2014:3)

Likewise, vessels are not always used for the purpose they were initially constructed, or in a manner which we would deem as 'normal' or safe practice by our modern day standards (Figure 7-2). In addition, the vessel may not have been specifically designed or constructed for the cargo it was carrying at the time of sinking. The term 'tramp steamer' or 'tramp freighter' refers to a vessel engaged in the tramp trade, in which there are no fixed schedules or ports of call. The 'tramper' will carry any available cargo to whichever destination it is required, and while the tramp trade gained popularity in Britain in the mid-19th century (Buckley 2008), there is no evidence to say the practice did not occur in antiquity

Figure 7-2 Some 'abnormally' loaded vessels

All of these issues mentioned above: the shape, form and size of the vessel; it’s cargo and find location; the materials used; how the materials are converted; the tool marks; the methods of construction; dendrochronological analysis of the timbers; whether a vessel had been repaired, rebuilt or had its roles changed; the circumstances of the loss and the wrecking process; and the site formation process serve to highlight the issues surrounding and underpinning the interpretation of the archaeological evidence. All can be investigated through the reconstruction process, and each can add to, or aid in that reconstruction process, but none should be used in isolation, nor should any be omitted from any final hypothesis.

The subsequent sections aim to examine the process of reconstruction, taking the issues highlighted above, separating them into their constituent parts, and examining each part in turn. The goal being a more holistic approach, where the whole is more than just the sum of its parts, while still employing a scientific and repeatable methodology. A step-by-step process from initial site evaluation to final testing and analysis of the proposed hypothetical reconstruction, where each stage is clearly defined and described, with the high-volume high-quality 3D digital raw data supported with metadata, and the human processes of understanding and interpreting the data objects explained using paradata. The goal being a stepwise process, which maximises research potential by allowing future researchers to navigate both the data and the processes employed, in order to reinterpret or further develop our understanding, or re-evaluate the site at a later date. Should any error or additional supporting data be subsequently discovered, the stepwise process can simply be rewound to the preceding stage, and the research continued in a new direction from that point, rather than starting anew.

7.2 Beginning the Reconstruction

It is extremely rare in an archaeological context, to find a complete and intact vessel, and as a result, the overall dimensions of the vessel, as well as its original shape and form will need to be established. Even where a substantial portion of the vessel's hull survives, the shape and form of that hull will, without doubt, be distorted to some extent. That distortion may be a result of sagging or hogging during the vessel's use life. There may have been repairs, modifications or extensive alterations made to the vessel such as the not uncommon practice in the Baltic of repairing or consolidating a clinker built hull by adding a layer of carvel planking (Mäss 1994; Auer *et al*. 2010:8; Grundvad 2011:24). Impact damage may occur during the wrecking process. Distortion as a result of the site formation process due to the nature of the ground the vessel comes to rest on, tidal currents acting on an exposed wreck, or overburden as the wreck becomes buried. Additional distortion may be unintentionally introduced during the excavation process. Reversing or removing these distortion processes is one of the key things that needs to be done to try to understand the shape/form of the original vessel.

As highlighted above (7.1), any cargo evidence recovered may give an indication of the use of the vessel – at the point in time of wrecking – but should not be taken as incontrovertible evidence of the only use of the vessel, or as an indication of the vessel's port of origin. Factors such as tramp trade or transshipping (the transfer of cargo from one vessel to another) as does the fact that cargoes change over the life of a vessel all need to be considered. Similarly, the find location can suggest at the sphere of operations, but we also need to consider that the vessel may have been blown off-course by foul weather, or even running before a storm for several days may result in a find location hundreds of nautical miles removed from its normal route.

Dendrochronological analysis can suggest accurate dating and provenance of timber, and certain building techniques or styles have been attributed to regional traditions, potentially suggesting a build location for the vessel. Timber trade and whether the vessel is constructed from native or imported timber (cf. Daly 2007; Daly 2009; Hocker and Daly 2016; Daly 2017) is a factor to be considered in attempting to determine build location, just as timber can be carried on board for repair or trade, from a variety of sources or dates, and applied to a ship many miles or years from its origin. Similarly, journeyman shipwrights, travelling from job to job, can lead to a blurring of "regional" construction techniques. This can be seen in the varied workforce from at least four countries involved in building the *Vasa* (Hocker 2013:73), and in England between 1416 and 1420, through the foreign shipwrights hired to maintain and repair the frame-built carracks (Adams 2013:70).

It should now be apparent that simply boiling down all the available evidence into a single "reconstruction" has the potential of resulting in somewhat of a Frankenstein's monster. Likewise using or ignoring elements in isolation can have potential issues. Take Steffy's reconstruction of *Kyrenia* which initially used cargo distribution and seabed hull dispersal, a total of 18 different models were employed in the reconstruction, with tonnage formulas and calculated displacement used as a means to validate the resulting reconstruction. Both sailing replicas *Kyrenia II* and *Kyrenia Liberty* had proven extremely seaworthy while carrying circa 10 tons, but neither were capable of sailing safely with the full 17 tons of cargo that was originally excavated (Katzev 2008:77–79).

Likewise, attempting a reconstruction with insufficient evidence can produce equally unreliable results. A case in point is the theoretical project undertaken by Dr Julian Whitewright, Grant Cox and this author on behalf of Damian Hirst for the "Treasures from the Wreck of the Unbelievable" project (Hirst and Beard 2017). The initial project brief was to "design" a ship dating to either the 1st or 6th century AD and capable of carrying a specified cargo manifest, which was initially estimated to be c. 320-400 tonnes, across the Mediterranean. The Initial manifest consisted of some 200 items, each with a crated volume dimension. From the spreadsheet supplied by the client, the cargo was estimated to have a volume of 680 cubic metres and a total weight of 373 metric tonnes. Using Rhinoceros 3D a rectilinear crate was digitally modelled for each cargo item as per the manifest dimensions, and positioned in an approximate boat-like shape, suggesting a cargo hold of 21.1 x 10.7 x 3.7 m, and a cargo volume of 835 cubic metres (Figure 7-3). At this point we thought perhaps a 40 m version of the 20m long Yassi Ada ship (Steffy 1982) would be a suitably unbelievable ship for the 6th century iteration. However, as 3D scans of the individual cargo elements became available, allowing Orca 3D to assign the correct material density to each, while the volume remained the same, the combined cargo weight jumped from the estimated 373 metric tonnes to a calculated 671 metric tonnes. The initial 40 m long hull was simply incapable of displacing a sufficient volume of water, and as a well-known actor once said – we are going to need a bigger boat. The result was a 61 m long ship (Figure 7-4) for the 1st century vessel, and two ships for the 6th century.

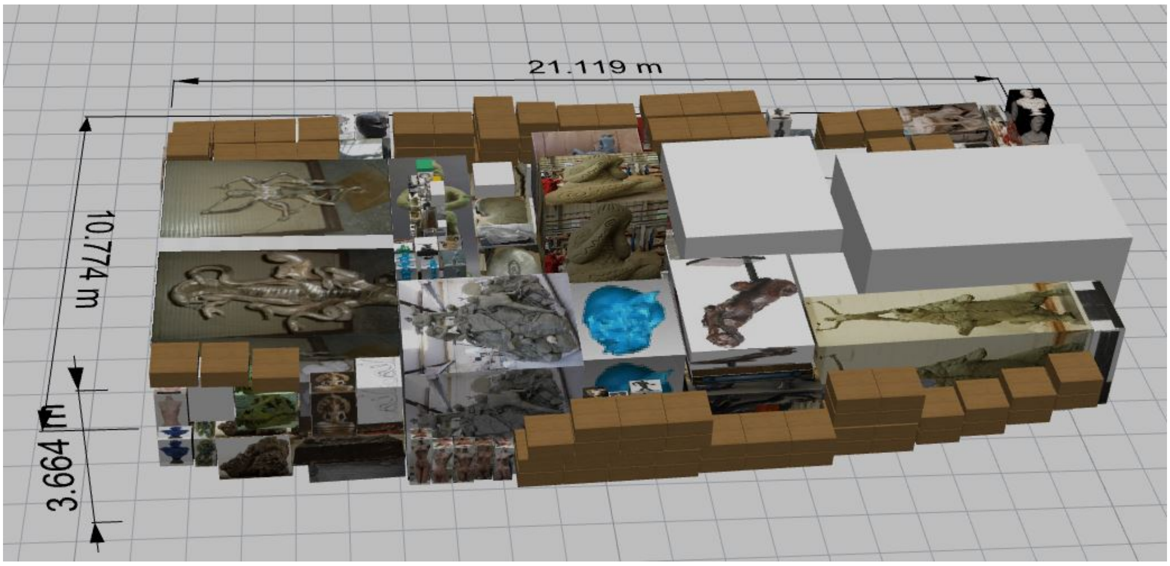

Figure 7-3 Crated cargo volumes for Unbelievable Wreck (Pat Tanner)

Figure 7-4 Scale exhibition model of the Unbelievable Ship (Pat Tanner)

Clearly, the volumetric properties of a specific cargo can produce a clear set of requirements, however, the displacement properties of that same cargo, particularly if the density of the cargo is significantly different to that of seawater, can require a substantially different solution. While the evidence available from a shipwreck site may be sufficient to generate a valid hypothetical reconstruction, how that evidence is employed and interpreted can produce significantly different results. This raises the question of how that archaeological evidence is interpreted.

7.3 Interpreting the archaeological evidence

Just as there are many ways of skinning the proverbial cat, there are so many varying vessel forms, and so many variations in the extent of archaeological remains, that there can be no single approach to a hypothetical reconstruction. It is worth repeating again (Chapter 3.10.2) the various potential shape states which may be observed throughout a vessel's life, these are set out in Table 7-1.

1	The customer's desired shape	This is the shape the customer thinks they want which may not be possible or be the ideal solution to their needs
2	The design intent shape	The shape the builder plans to build after negotiating with the customer
3	The as-built shape	The actual shape achieved during building, which may have varied from the design intent shape
4	The use-life shape	Which may include repairs and/or alterations, as well as the inevitable sagging or hogging of the vessel due to age
5	The abandonment or wrecking shape	The shape at the time of wrecking or abandonment, possibly altered during attempts to stay afloat
6	The 'as-found' shape	The shape at the point of archaeological discovery, the de-facto primary record
7	The post-excavation shape state	The shape which may have become distorted during the excavation or disassembly process
8	The target reassembly 'shape state'	This is the proposed shape for the planned reassembly of the remains for exhibition purposes
9	The 'achievable shape state'	The shape achieved for the display, which may have been limited by constraints in the conserved material
10	Previously published reconstruction	Typically, two-dimensional paper drawings
11	The full-size Replica shape	The shape of any replica should be documented to check how closely it matches the planned goals

Table 7-1 The various potential shape states of a vessel (Pat Tanner)

Specific objectives will require different 'shape-state' results, the conservation team for example will be most interested in states 7 to 9 – the post-excavation shape (7), and how the archaeological material will require to be modified in order to achieve the target reassembly shape (8). A record of the achieved, 'as-displayed' shape (9), will give valuable information regarding the differences between the target reassembly shape (8) and the as-displayed shape (9), which may allow a refining and development of the conservation process, or highlight certain limitation on achieving a target reassembly shape states (8).

The reconstruction process, which most frequently begins at the 'as-found' shape state (6) or the post-excavation shape state (7), will be most interested in the preceding states from five to one. However, as noted in Chapter 3.10, many publications have illustrated some version of the vessel from state six or seven, and a "reconstructed" version of the vessel, presumably intended to represent state two, often with very limited explanation of how that transition was achieved.

The EBSA – experimental boat and ship archaeology (Coates *et al*. 1995) – process, will be most interested in the actual as-built shape once completed (3) and the full-size replica shape (11) in order to better comprehend the construction process and the potential capabilities of the reconstructed vessel. As highlighted in Chapter 2.4.12 to my knowledge, none of the reconstructed full-scale replica vessels have been recorded or documented. This would serve to quantify the replica shape or to compare differences between the actual as-built shape once completed (3) and the full-size replica shape (11), or between the completed replica shape and the reference plans used during the replica building process.

Clearly a more holistic approach, considering all of the potential shape states listed in Table 7-1, would generate a more definitive understanding of the archaeological remains. The vessel, including any changes or alterations, the person who ordered the vessel, the people that constructed the vessel, the crew that used the vessel, how the vessel performed and the society in which the vessel was used.

The first stage in the reconstruction process will be the archaeological evidence, ideally beginning with shape state 6 from Table 7-1, which will include the archaeological remains of the vessel as well as details of the site, allowing for a better understanding of how the remains came to be in its current shape. However, the reconstruction process can equally begin from any one of the shape states listed in Table 7-1, such as the *Drogheda* boat reconstruction (Tanner 2013a) which began at shape state 7 by laser scanning the physical scale model representing the post deposition shape state. The *Newport Medieval ship* reconstruction (Jones et al. 2013; Tanner 2013b; Jones et al. 2017; Tanner 2020 see Appendix G) also initially began at shape state 7, as with Drogheda by laser scanning the physical scale model, but subsequently also employed the raw data captured during excavation representing shape state 6, the 'as-found', or archaeological discovery shape. The *Bremen Cog* (Tanner 2017b see Appendix H; Tanner 2018 see Appendix I), the digital comparisons of the *Poole iron-Age logboat* (Tanner 2019) and the 3D Documentation of the Marsala Punic ship (see Appendix J) all began at shape state 9 – the 'as-displayed' shape state from the museum. While the digital reconstruction of the *Sutton Hoo* ship (Tanner *et al*. 2020) began with the published interpretations from several sources – shape state 10, and the *West Cork Lobster boat* (Tanner 2017a) discussed in Chapter 6 started as shape state 3 – the actual as-built shape once completed.

As already noted in Chapter 3.3, between 1992 and 2007 a debate was carried out, mainly in the pages of the International Journal for Nautical Archaeology (IJNA), seeking to clarify and refine the research process and desired outcomes relating to archaeological ship reconstructions. From a variety of case studies and methodological frameworks, McGrail (2007:256) suggested a refinement to the methodology. McGrail states that

> "Excavated wooden objects seldom retain their original shape, between deposition and excavation significant changes are to be expected."

McGrail suggests that after the evidence has been excavated and re-appraised, small scale models of every plank and timber should be made and fitted together until a model is formed of the 'as-found' vessel, but with distortions and compressions removed, displaced elements replaced, fragmented timbers made whole, and the hull rotated to its deduced attitude when afloat. This 'as-found' model, or measured drawings developed from it, then becomes the basis for an attempt to fill in the missing pieces, McGrail's (1992:354) floating hypothesis, a process which may lead, if the surviving evidence allows, to a rigorously argued reconstruction of the original vessel.

The jump from 'as-found evidence' to McGrail's 'floating hypothesis' is a massive leap. How exactly are distortions and compressions removed, how are the displaced elements replaced and most importantly, how is the hull rotated to its deduced attitude when afloat? All of these either require or assume a knowledge of the vessel's original shape, and underwater hull profile, in order to calculate the flotation condition. Or is it a case of – it looks right, so it must be right?

The approach I prefer to use is similar to the approach I would use while boatbuilding if I were asked to repair or rebuild an existing vessel. The first stage is to observe the overall picture in order to get a sense of the size and scope of the project and begin to appreciate how the vessel came to be in its current state. Looking at the overall forest rather than getting lost amongst the individual trees. The next phase would be to strip away all of the noise and clutter which is distracting from the underlying structure. Just as you would strip away the flaking paint and loose elements to get a better understanding of the solid structure underneath. Once the structure is clearly visible, its condition can be determined, and checked for twist or distortion. Once satisfied that the remaining structure is sound, straight and in alignment, it is possible to begin determining what is damaged, distorted or missing. It is then possible to begin repairing or replacing damaged sections of the articulate structure, replacing or refabricating the disarticulated elements, and fabricating anew the missing portions in order to return to a complete hull.

In order to generate a hypothetical reconstruction process, which will have a scientific and methodological approach, clearly illustrating or describing how each stage is developed and evolved to the subsequent stages, a series of stages are set out in Table 7-2. Where interpretation is unavoidable, that interpretation (and the paradata) is clearly defined, allowing subsequent researchers to clearly follow the entire process, and revert to an intermediate stage if desired.

The site	An initial overview, categorising the remains – articulate hull, disarticulated elements, cargo, ballast, external site formation factors
Initial Orientation of the remains	An improvised orientation purely to facilitate further initial shape analysis
Size and shape of remains	May suggest intended use and operational sphere
Concept of minimum or capital reconstruction	Is there sufficient evidence to attempt a capital reconstruction or only a minimum reconstruction
Global distortion	Establishing symmetry planes and datum points to check for distortion such as twist, hogging or sag
Localised distortion	Fairing the shape to repair localised cracks or damaged areas
The centre-line profile	The shape of the keel, stem, and stern post
The hull planking	Is there sufficient hull planking to suggest a sheerline, and hull cross section form
Closing the ends	Typically, a wreck will be missing one or both extremities, how to determine the ends to create a watertight envelope for the hull
Watertight envelope	This enables new real-world orientation, calculated from submerged hull volume and estimated weight
Floating hypothesis a preliminary analysis	Can the hypothesis function as a vessel, will it float, carry sufficient cargo, and operate in its environment
The hull structure	Framing and other critical structural elements,
Deck and superstructure	Does the archaeological evidence, or the normal operation of the vessel suggest requirements for deck and superstructure
Propulsion and steering	Spars and rigging, and/or rowing as well as means of steerage control
Creating the minimum reconstruction	The completed hypothetical form with all the required elements for that to function as a vessel
Testing and analysis	Validating and refining the hypothesis
Initial publication for peer review	Getting a second opinion
Comparative analysis	Frankenstein's monster or comparable with other contemporaneous vessels
Add elements for Capital Reconstruction	External sources such as iconography or other evidence
Testing and analysis	Validating and refining the hypothesis
Cargo capacity and tonnage	Further refining of the hypothesis
Seakeeping and final testing	Final validation of the hypothesis and definitive publication.

Table 7-2 Stages[81] in reconstructing and testing a hypothetical vessel reconstruction (Pat Tanner)

[81] Red is looking at the overall picture, Pink is repairing the archaeology, Blue is the waterproof skin required to generate a floating hypothesis, Green is the physical structure required to create a minimum reconstruction, and Gold is the capital reconstruction.

	Drogheda boat	Newport Ship	Grand Hotel wrecks	The Unbelievable	Lobster Boat	Bremen Cog	Poole Logboat	Marsala Punic ship	Sutton Hoo
The site	½	✓	½						✓
Initial Orientation of the remains	✓	✓	✓			✓	✓	✓	✓
Size and shape of remains	✓	✓	✓			✓	✓	✓	✓
Concept of minimum or capital reconstruction		✓	✓			✓	✓	✓	✓
Global distortion	✓	✓	✓			✓	✓	✓	✓
Local distortion	✓	✓	✓			✓	✓	✓	✓
The centre-line profile	✓	✓	✓				✓	✓	✓
The hull planking	✓	✓	✓			✓			✓
Closing the ends	✓	✓	✓				✓		✓
Watertight envelope	✓	✓	✓	✓		✓	✓		✓
Floating hypothesis a preliminary analysis	✓	✓	✓	✓	✓	✓	✓		✓
The hull structure	✓	✓	✓	✓	✓	✓		✓	½
Deck and superstructure		✓		✓	✓	✓			
Propulsion and steering	✓	✓	✓	✓	✓	✓	✓		½
Creating the minimum reconstruction	✓	✓	✓	✓	✓		✓		
Testing and analysis	✓	✓	✓	✓	✓		✓		½
Initial publication for peer review		✓			✓		✓		✓
Comparative analysis	✓	✓				✓			
Add elements for Capital Reconstruction	✓	✓		✓	✓	✓			
Testing and analysis	✓	✓		✓	✓	✓	✓		
Cargo capacity and tonnage	✓	✓		✓	✓	✓	✓		
Seakeeping and final testing	✓	✓		✓	✓	✓	✓		

Table 7-3 Applying the stages[82] to various hypothetical reconstruction projects. (Pat Tanner)

[82] Red is looking at the overall picture, Pink is repairing the archaeology, Blue is the waterproof skin required to generate a floating hypothesis, Green is the physical structure required to create a minimum reconstruction, and Gold is the capital reconstruction.

How the stages from Table 7-2 have been applied to the hypothetical reconstructions of various projects undertaken by the author is set out in Table 7-3. Each stage will now be examined and described in further detail with examples of how they were applied to the various hypothetical reconstructions.

7.4 The site

Information from the site will be used primarily to give an overall indication of the archaeological remains. From matters as simple as overall dimensions of the surviving remains and find location, suggesting a possible sphere of operation, to more detailed analysis in an attempt to comprehend the overall site formation process and the processes occurring both during and after the wrecking event. Ideally the site will be recorded using high-volume high accuracy three-dimensional recording as discussed in Chapter 4, and it is now possible to add the fourth dimension (time) employing 4D recording to accurately capture the site information as each subsequent stratigraphic layer is excavated and exposed (Pacheco-Ruiz *et al*. 2018).

A typical maritime archaeological site can range from individual fragmentary remains to massive assemblages of both articulated and disarticulated artefacts. These can often be dispersed over large areas of a constantly evolving seabed surface, or by contrast be confined to a well-defined and sealed deposit, potentially within a terrestrial as well as underwater context. The primary goal at this initial stage is to categorise the archaeological material into articulated vessel remains, as these can be definitively associated to the vessel. Disarticulated elements of the vessel which may have become detached and displaced during the wrecking event, or during subsequent site formation. Other disarticulated elements associated with the operation of the vessel, but also being from distinct fixed locations within the vessel, fragments of standing rigging, such as mast(s) and their associated shrouds (the rope elements used to support the mast).

Non-stationary or mobile elements such as the running rigging (sails, spars and associated rope control lines – sheets and braces) will form additional categories. Other categories will be used for cargo items, crew and personnel, and possible artefacts associated with shipboard operations. Once the recovered material has been categorised, levels of confidence, in terms of their positioning within the hypothetical reconstruction can then be applied to each category or component artefact, and whether or not interpretation is employed on these elements.

An important factor in the interpretation of the site information is the initial site formation phase or the wrecking event. As noted in the introduction to this chapter, the wrecking event, whether a rapid-onset event or a longer-term process, will have a dramatic effect on how the material is presented in the archaeological record. While ‘deep-sea’ wrecks would support Muckelroy’s

(1978:216) category of 'closed-community', it is a very specific 'closed-community' which relates solely to that particular voyage at that point in time. One factor specific to deep wrecks is the depth of water, the distance from the surface to the seabed will have a dramatic effect on the final resting position of each disarticulated piece. An example is the *RMS Titanic* which was 269 m long by 28 m wide and displaced 52,310 tons (imperial), the 1.16 square metre gash allowed circa 400 tons of water per minute to enter, causing the ship to sink in 160 minutes. At a depth of 3795 m, the debris field for the wreck covers an area that is circa 1700 m long in a north-south direction, and 875 m wide in an east-west direction (Uchupi *et al*. 1988:1104). That is over six times longer and thirty-one times wider than the vessel's overall dimensions. By contrast other 'rapid-onset' events such as the *Mary Rose* or *Vasa* occurring in much shallower waters may better fit Muckelroy's (1978:182–95) designation of continuous wreck assemblages.

One such apparent example of a rapid onset event is the **Drogheda boat** (Schweitzer 2012; Tanner 2013a; Tanner Forthcoming see Appendix F). The (partial) survival of cargo within the wreck site (Figure 7-6 top), and the extent of preserved intact hull remains (Figure 7-5) would seem to indicate a sudden sinking of the vessel. A simple explanation could be attributed to either a 'sprung-plank' where the iron nail fastenings corrode to an extent that they lose holding power and the plank springs out from its fastened position (still a surprisingly common occurrence today), or a caulked seam working loose, allowing a rapid ingress of water.

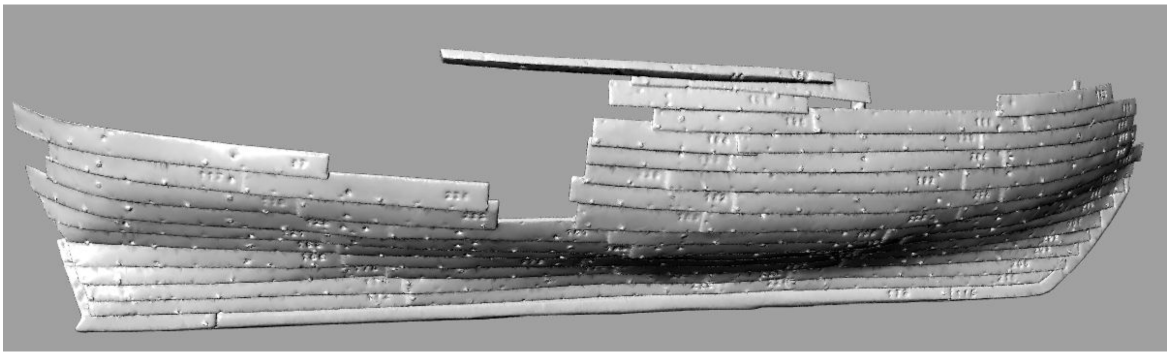

Figure 7-5 Drogheda Boat – starboard side showing the extent of the preserved hull (Pat Tanner)

It should be remembered that a relatively small opening will allow a substantial quantity of water to flood any vessel. The rate of flow of any liquid through a pipe or opening is directly proportional to the area of the opening and the velocity of the liquid. As the depth of the opening is increased, so the water pressure increases, thereby increasing the flow rate. A 5 cm diameter hole located just 30 cm below the waterline will let in over 17,000 litres of water in one hour. If that same hole is located 1 m below the waterline, the flow rate jumps to 31,000 litres of water per hour. At those flow rates, the shallower hole will allow 0.28 tonnes of water per minute, and the deeper (1 m) hole will allow more than 0.5 tonnes per minute. A vessel with a total displacement of 5.7 tonnes will not need much time (between 10 and 20 minutes) to be totally swamped and sink.

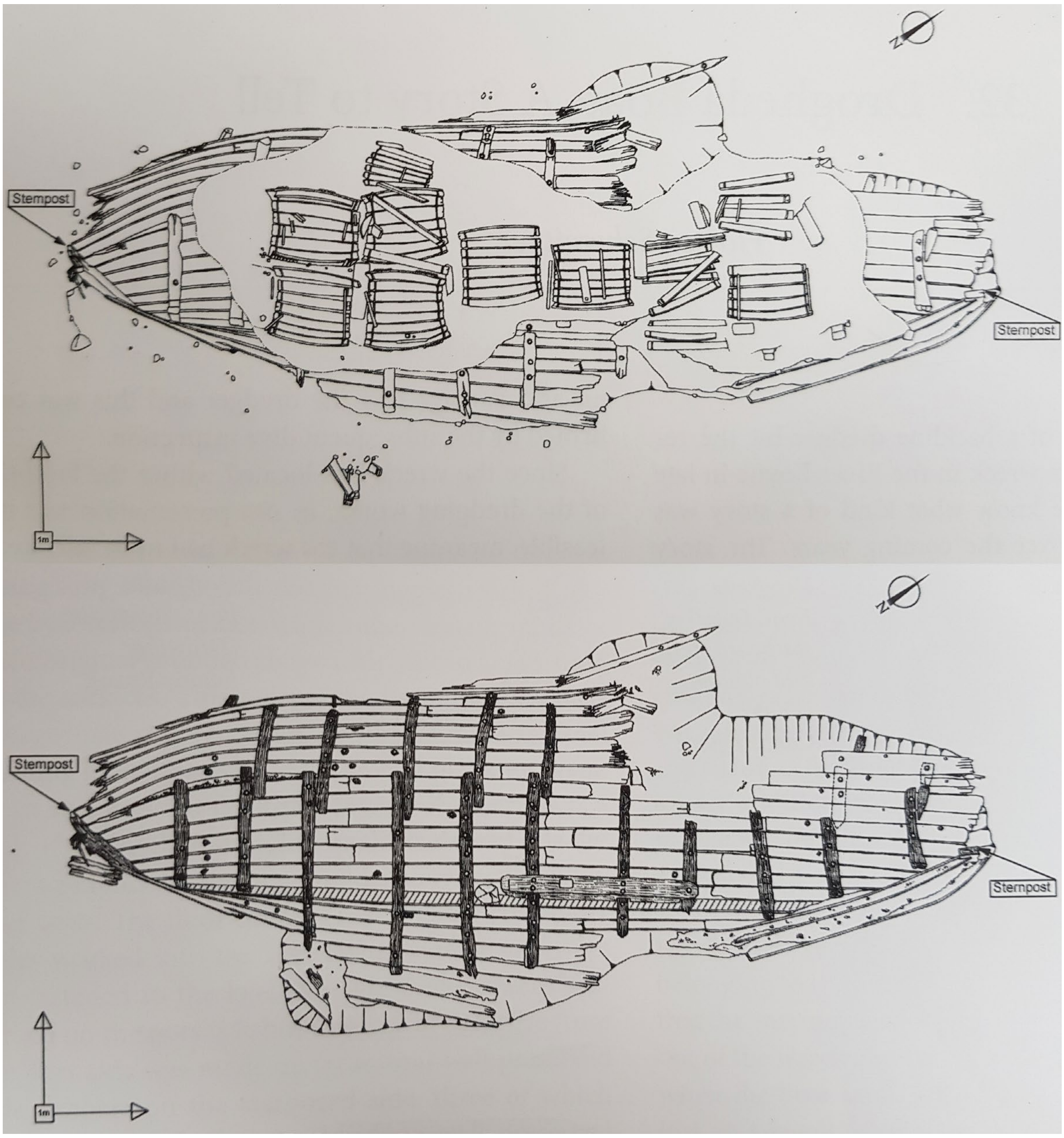

Figure 7-6 Drogheda Boat location of casks within the wreck (top) and Excavation plan of the preserved hull (bottom) (Drawings: Rex Bangerter)

Being an underwater excavation, the site plan was documented by divers, and the result is a top-down or plan view of the site (Figure 7-6). When taken in isolation the site plans indicate the cargo position (Figure 7-6 top), and approximate overall dimensions and positions of internal framing elements in the longitudinal and transverse planes (Figure 7-6 bottom), but is of limited value due to the lack of depth measurements in the two-dimensional drawings. The two-dimensional site plans were imported into Rhinoceros 3D during the reconstruction process and after re-scaling back to full-size, used as a visual reference guide during the reconstruction and for positioning the reconstructed cargo of casks (Figure 7-7).

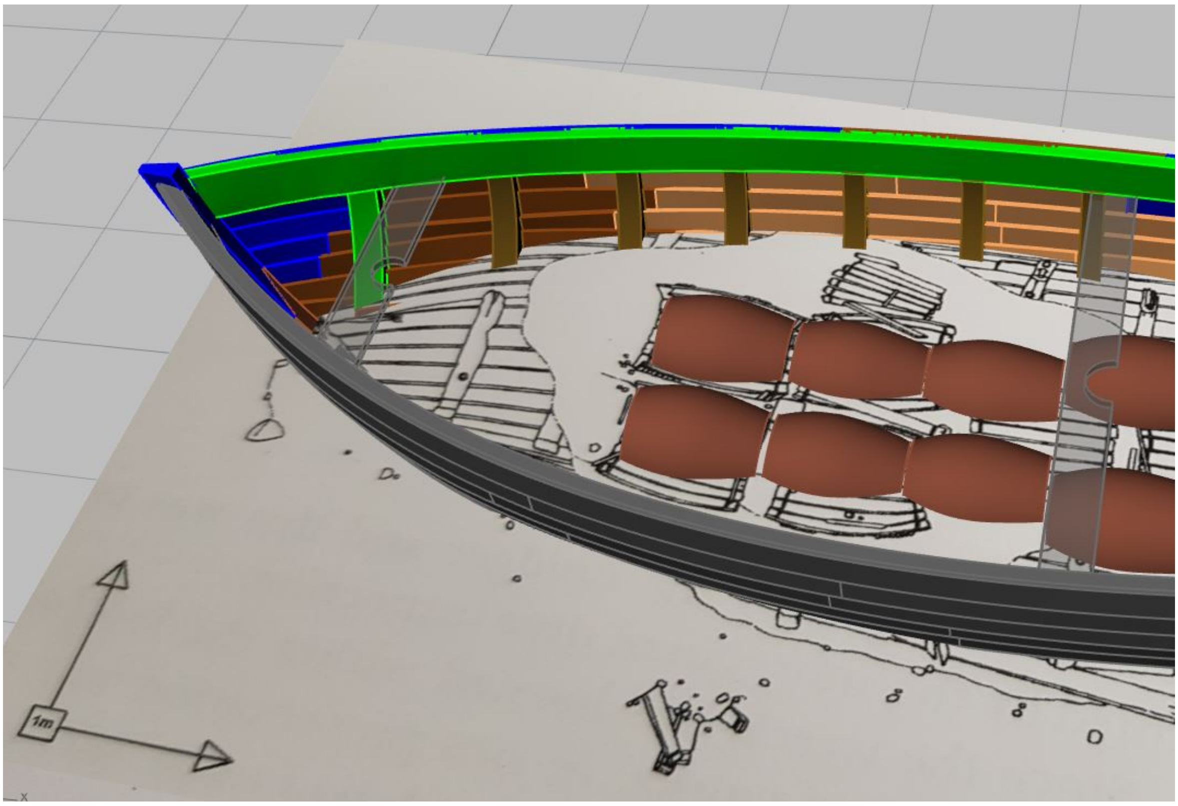

Figure 7-7 Drogheda Boat site plans used to position the casks within the digital reconstruction (Pat Tanner)

Two other forms of deposition also need to be considered in more detail when interpreting site information. These are situations where the vessel is not in 'normal service' or located in its natural environment.

The first is ritual deposition as was the case with the 7th century Saxon burial ship at ***Sutton Hoo***, in Suffolk (see Phillips 1940a; Anderson 1942; Bruce-Mitford 1975; Fenwick 2010; Martin 2018; Tanner *et al*. 2020). In such cases the vessel can be displaced several kilometres from its natural environment, and many of the associated artefacts will have a greater relationship to the individual buried with the vessel, or their wider society, than to the vessel itself.

In the case of *Sutton Hoo*, the general arrangement of the ship, its burial, and place within the wider context of the site has been understood through the initial excavation in 1939, and further re-excavation in mid and late 20th century (see Phillips 1940a; Bruce-Mitford 1975; Carver 1998; Carver 2005; Carver 2017). More specific to Experimental Boat and Ship Archaeology (EBSA) research, a half-scale reconstruction of the ship was built in the 1990s and subjected to trial voyages (Gifford and Gifford 1995; 1996). However, the detail of the vessel has not been reconstructed or investigated from an experimental archaeological perspective using the digital techniques now available (Tanner et al. 2020:6).

The site was initially excavated in May 1939 by Basil Brown, and Charles Phillips took over the project while the ship was being unearthed, and a team of three from the Science Museum, led by Commander J.K.D. Hutchison, surveyed the ship in August 1939. Phillips and Hutchinson pursued several investigations, in particular looking for evidence concerning the keel, stem, and stern. Two capable amateur photographers, Mercie Lack and Barbara Wagstaff, made an invaluable record of the proceedings, the archive of which is held in the British Museum. The process of surveying and recording the impression of the ship in the ground is described by Crosley (1942). However due to a series of unfortunate events all that survives is two drawings (Tanner *et al*. 2020:8 fig 2) and the archive of photos from Lack and Wagstaff as the primary record of the excavation (ibid 2020:7–9).

The site was revisited by the British Museum from 1965 to 1970 (see Carver 1998:25–51). The much-degraded remains, together with the 1939 photographs, were investigated exhaustively as part of the wider publication of the site (Bruce-Mitford 1975). A lines plan (submitted by the naval architect Colin Mudie in 1973) and a reconstruction drawing were published (ibid: figs 324 and 325). However, Bruce-Mitford does not comment on them or even reference them in the text of the 1975 volume.

Of the 1939 data, the photographic archive provides an impressive view of the 'ghost' ship (Tanner *et al*. 2020:10–11 figs 3 and 4) and illustrates the coherence of the surviving remains, both in terms of the overall shape, and rivet alignment. However, the documentation regarding the shape of the hull is sparse. Bruce-Mitford (1975:234–235) identifies limitations (in his view) of the 'provisional' 1939 reconstruction drawing. Bruce-Mitford noted the positions of the scarfs of the stem and sternpost to the keel looked implausible, and so the 1975 volume and accompanying 1975 reconstruction drawings propose (ibid: 392–398) different positions for them to those claimed by Phillips (1940a:348).

The 1939 lines plan and reconstruction drawing show a plausible representation of the hull shape 'as found', although work must have been done on the original measurements to rectify the tilt and twist of the hull which Crosley reports (1942:110) as having been observed during the survey. Additionally, no attempt was made to rectify the spreading of the planks away from the posts at the stem and particularly the stern of the vessel. Examination of the data from the 1975 volume (Bruce-Mitford 1975) highlights variations in both data sets, and reflects the state of the ship as found by the 1965–70 excavation, including the large areas where no archaeological material survived, presumably due to additional site formation processes as a result of the damage to the site between 1939 and the 1960s. As noted in Tanner *et al.* (2020:12–13):

> "An overview of the excavation and recording of the *Sutton Hoo ship* in the two British Museum campaigns indicate that the archaeological record of the ship is a variable one. The 1939 work recorded the remains in their most complete state, but the records of

> this work are limited. By contrast, the 1965–70 project produced a highly detailed, orderly, and coherently published account, but of a much-reduced set of archaeological remains."

In order to analyse the variations, all of the available two-dimensional drawings were re-scaled to full-size, and correctly aligned relative to each other in the digital realm using Rhinoceros 3D software (Figure 7-8).

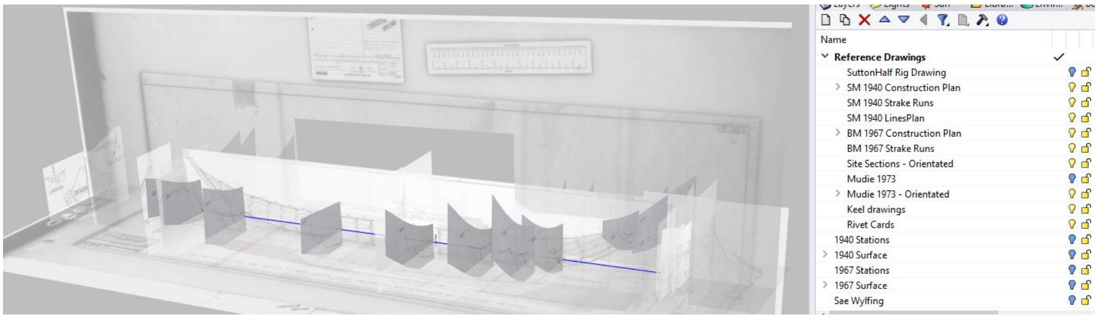

Figure 7-8 2D scaled drawings resized and positioned relative to each other in three dimensions (Pat Tanner)

While working with the two-dimensional paper drawings, an opportunity arose to examine *Sae Wylfing*, the half-scale replica (Gifford and Gifford 1995) of the *Sutton Hoo ship.* The half-scale replica, complete with all its attendant issues as identified in Chapter 5.6.1, was 3D laser scanned, and the resultant model imported into the digital research file, re-scaled to full-size and orientated to align with the original paper drawings (Figure 7-9).

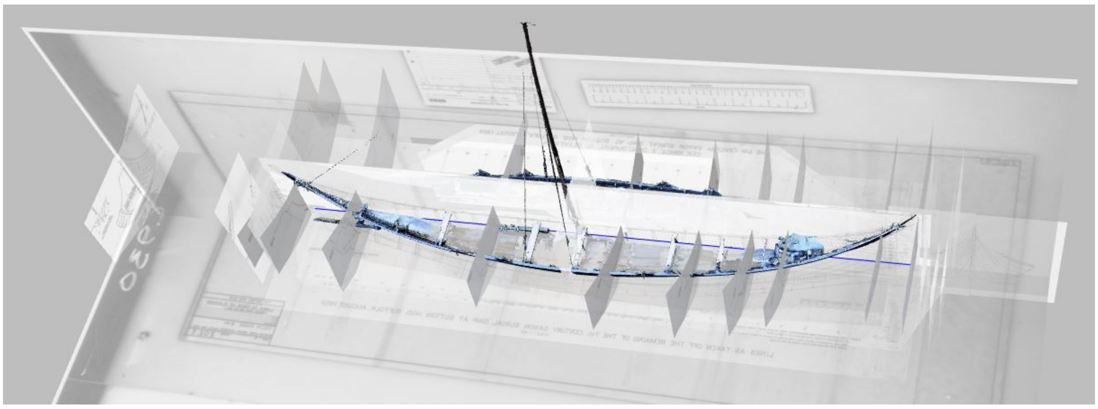

Figure 7-9 3D laser scan of the half-scale replica, resized and positioned relative to the drawings (Pat Tanner)

With two (or three if you include the half-scale replica) sets of seemingly contradictory data, it was important to interpret the available archaeological record of the site. As discussed in Tanner *et al.* (2020:13–21) this was done on the basis that the 1939 excavation represented the most complete access to the archaeological remains of the ship within its burial trench, and therefore, the 1939 data should be considered of primary importance as a record of the vessel. Phillips' team, standing in the excavated trench in 1939, had the best view of the archaeological remains that anyone has ever had, and will ever have. Therefore, Phillips' published papers (1940a; 1940b) represent a key way to resolve discrepancies, by returning to his published observations of what he had observed in 1939. The archaeological site excavated 1965–70 had been subject to additional site formation process, but still have the potential to confirm the existence of features originally recorded in 1939, or to provide observations on the 1939 excavation through discussion with those present at the earlier date. The extreme ends of the ship, as reconstructed in 1939 and 1975 are largely conjectural. Phillips observed (1940a: 348) that the layout was difficult to determine, and that understanding the planking at the ends should be left for experts to address. By 1967 the ends of the vessel were absent with 2.2 m lost from the bow and 1.76 m lost from the stern (Bruce-Mitford, 1975: 256).

Each of the 3,598 plank rivets were plotted using Rhinoceros 3D in three-dimensional space, based on their internal rove (for the rivets) or head (for bolts and spikes), as per their original recording based on the available two-dimensional drawings. The rivets were then given an initial orientation to suit their location in the hull; perpendicular to the assumed run of planks, and with orientation varying depending on their general position in the hull. Once all the rivets had been positioned, they were then compared against two sets of available drawings and colour coded to indicate levels of confidence (Figure 7-10). Black = Correspondence between 1939 and 1975 published location. Pink = Recorded in 1939, not recorded in 1975. Cyan = Position moved between 1939 and 1975. Red = Data absent from 1975 rivet plan, or 1939 and 1975 (central burial area). Green = Thole spikes in the central area. Whilst the result can never be described as a site survey, it does however take two variable sets of archaeological data, and interprets that data in a clearly defined manner (paradata) in order to generate a viable basis on which the further hypothetical reconstruction work can be based.

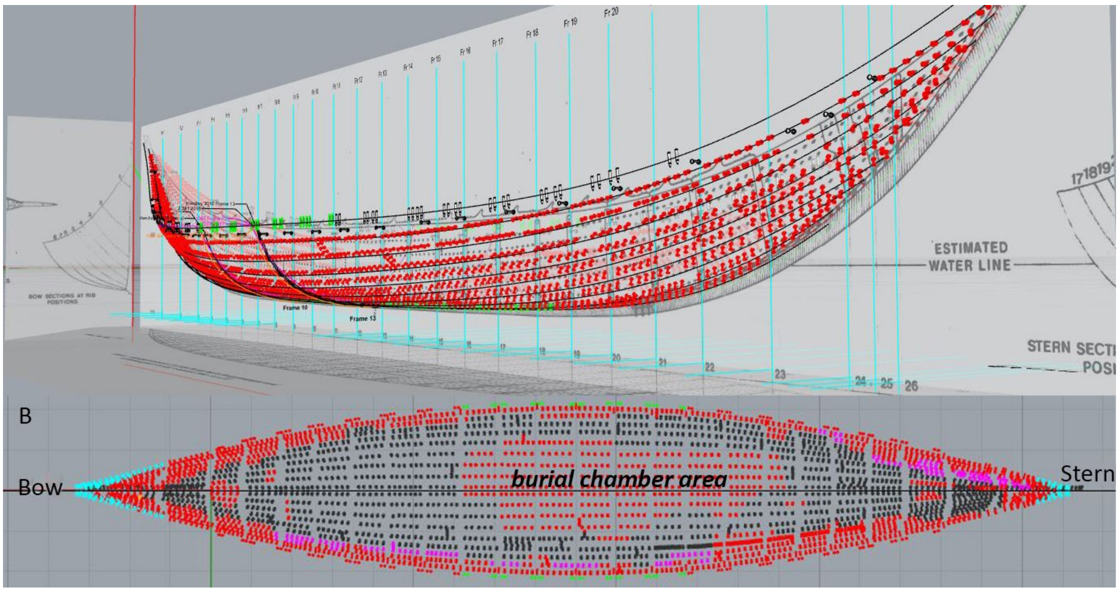

Figure 7-10 A) Top: Initial plotting of rivets in Rhino3D, in this case against the British Museum reconstruction. B) Bottom: Plan of final overall plotted rivet positions. (Pat Tanner)

The second form of deposition is where the vessel is not in its normal operating condition, it may be in the process of undergoing repair or modification, as was the case with the ***Newport Medieval ship*** (Nayling and Jones 2014; Tanner 2013b; Tanner 2020 see Appendix G), discovered on the western seaboard of Britain, but with diverse evidence of Iberian connections. The vessel was found close to the current riverbank of the Usk within the Bristol Channel, downstream from the medieval castle and Town Pill – a formerly large inlet, thought to have been the main focus for medieval shipping (Figure 7-11).

The vessel appears to have been brought into a small inlet, which was active in the prehistoric period based on excavations below the starboard side of the ship, which revealed part of an articulated human skeleton at the base of the palaeochannel, radiocarbon-dated to the late Iron Age. Prior to the arrival of the vessel, the inlet was prepared by the building of a support structure primarily of oak and elm trimmed trunks laid athwartships on the sloping bed on the inlet. Subsequent dendrochronological analysis of one of these logs gave a felling date for the parent tree of the spring of AD 1468, providing a precise *terminus post quem* for the vessel's deposition (Nayling and Jones 2014:7–8).

Figure 7-11 Medieval Newport, c.AD 1469. The Newport Ship is shown undergoing repairs in the centre of the image, with the River Usk, Town Bridge and Newport Castle also visible. (Anne Leaver)

The ship came to rest with a perceptible list to starboard of approximately 14° amidships, and the starboard side had flattened out. The post-depositional distortion became most apparent during the photogrammetric recording phase. The keel which had settled, presumably on the contemporary river bed, showed marked hogging, and an unevenness in the lines of the hull strakes was most marked between frames 20 to 28 on the starboard side, where compression over the underlying support shores had distorted the hull form.

During the site excavation, the surviving remains which measured 22.8 x 7 x 3.6 m, and consisting of some 1,700 articulated ship timbers, and a further 600 associated timbers and small finds all needed to be documented and recorded. Archaeologists documented the position and context of artefacts, disarticulated timbers and hull remains with traditional scaled drawings, photogrammetry, photography, and videography, with an eye towards documenting individual timbers in a high degree of detail at a later date. Plans were hand drawn, usually, but not always, at a scale of 1:10, using an arbitrary site grid set around a baseline aligned with the centreline of the ship. These were annotated with spot heights relating levels to temporary benchmarks with known heights relative to Ordnance Datum (OD—the reference level for land mapping in the United Kingdom). Sections were hand drawn at the same scale, included running sections across the ship (Nayling and Jones 2014:5).

Over 320 individual two-dimensional drawings were generated, including plans, site sections and sketches. In addition, two phases of three-dimensional photogrammetrical recording of the articulate hull remains when the ship was fully exposed with the ceiling planks and inter-frame sediment removed, and later, after the removal of the majority of the framing timbers, to record the inboard face of the hull planks, keel and stem. Some 3,500 photographs were also recorded during the excavation.

GGAT Site Drawing Index					
Drawing Number	**Scale**	**Description**	**Drawn By**	**Date**	**Drawing Type**
13	20	Profile of paved area 112 – slipway	JB	02/07/2002	S
14	10	Section SE corner of site 125	JMB	03/07/2002	S
15	20	Plan timbers (Slipway?) (PC104/2 P1011) 113	JMB	03/07/2002	P
16	10	Section through deposits S. of slipway	JMB	07/07/2002	S
17	5	Plan of windlass 1059	JB	04/07/2002	P
18	5	Elevation of left end windlass 1059	JB	04/07/2002	E
19	20	Articulate timbers 134	JB	09/07/2002	P
20	5	Front elevation of windlass 1059	JB	10/07/2002	E
21	20	Plan of st knee + composite cross-beam 135	JB	10/07/2002	P
22	10	Sketch plan of timber (Adjacent to 135) 136	JB	11/07/2002	P

Table 7-4 Sample listing of various site drawings (Pat Tanner)

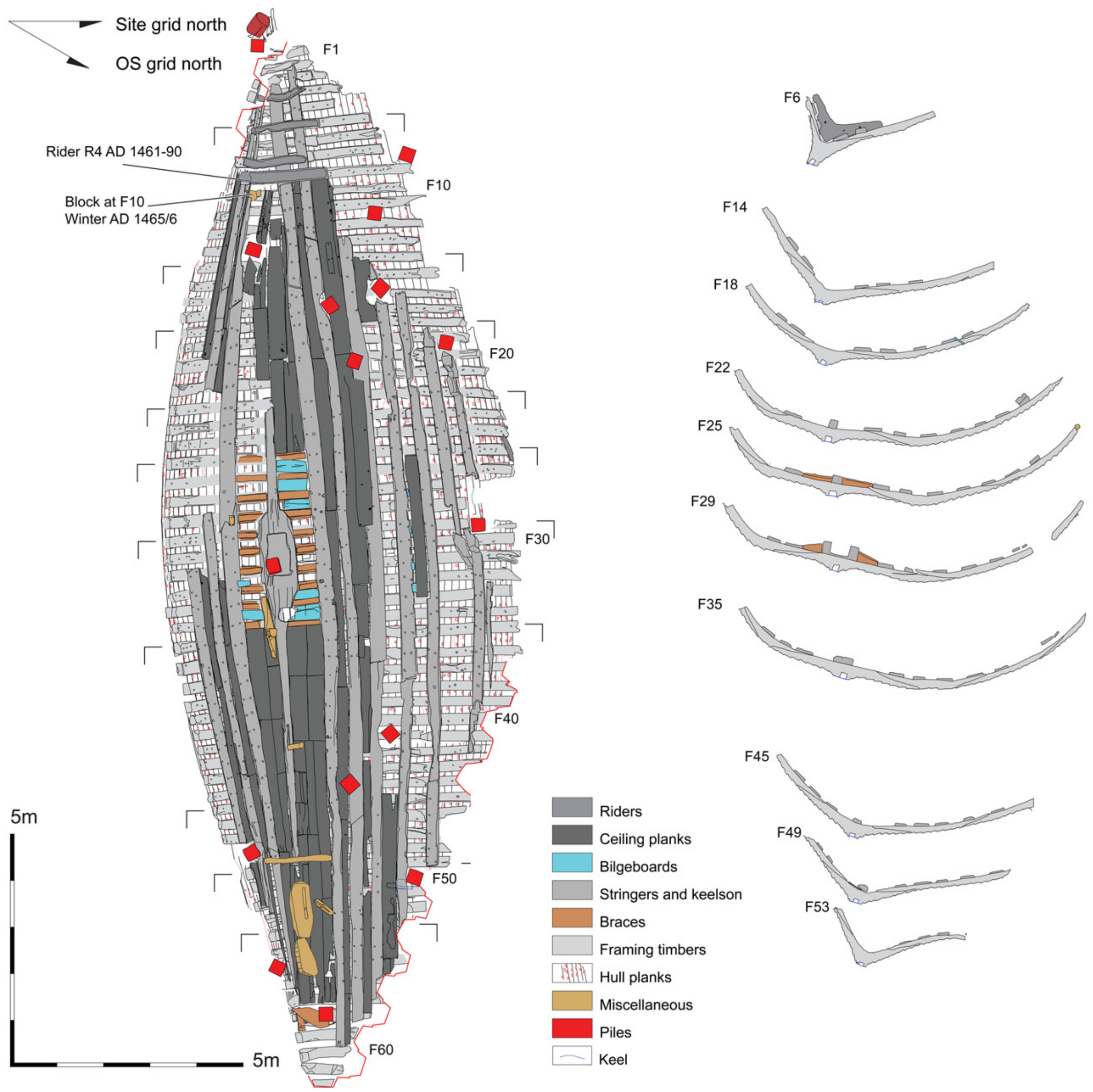

Figure 7-12 Plan of the ship based on photogrammetric recording supplemented by hand drawings (Drawing: Nigel Nayling) (Nayling and Jones 2014:9)

Individual groups of drawings may be combined to create schematic views of certain features of interest, such as the schematic view of the structures below the vessel (Nayling and Jones 2014:7 fig 7), or the plan of the ship based on photogrammetric recording and supplemented by hand drawings (Figure 7-12). Whilst such schematic illustrations have a certain value, with timber functions colour coded and position of cross-section drawings indicated, they are an interpretation, based on several original drawings, and as such of limited value in a detailed reconstruction attempt. These schematic views will often generate as many or more new questions, than the answer they were intended to provide, necessitating the return to the numerous original drawings to correlate or cross reference. Differing scales (Table 7-4), arbitrary baselines and the switching between numerous source drawings, can all add to the correlation and referencing issues. The result being that the schematic illustration can be of questionable provenance, and lacking paradata, difficult to interpret.

Site conditions meant that the ship could not be recovered as an articulated structure, and as a result the excavation process involved the dismantling of the vessel. The intended approach being to follow the well-established procedure of documenting the individual timbers and using scale modelling to reassemble the surviving elements into a scaled research model. This represented a methodology which, as already discussed in Chapters two and three, had, for over forty years, remained relatively unchanged since the early 1960's.

In a development on this methodology, which was essentially modelling a three-dimensional form from two-dimensional source data, and given that the *Newport Ship* timbers were recorded in a digital three-dimensional format, it was logical to use the three-dimensional data directly in the modelling stages, rather than flattening the source data onto two-dimensional paper or cardboard, prior to reshaping into a three-dimensional hull form.

With all of the individual ship's timbers documented using contact digitising (Jones 2015:165–227), resulting in highly accurate, three-dimensional digital models, recorded at full-scale, of each individual timber, it is logical to use these records as the primary source data as the basis for a research model as part of the hypothetical reconstruction process.

However, while post-excavation documentation, facilitated the 'laboratory-like' ideal conditions for the documentation of each individual timber, when compared to traditional on-site documentation with all its attendant difficulties, the net result was that each timber was documented, firstly as an isolated element, but more significantly, what shape was being documented?

Certainly the shape of each timber was not the original as-built shape (state 3 from Table 7-1), this would have changed during the use-life of the vessel as fastenings worked loose, or the hull form either sagged or hogged (state 4 from Table 7-1). Neither was it the abandonment or wrecking shape as the support structure collapsed and the vessel came to rest on its starboard side (state 5 from Table 7-1), as some 530 years of sediment and up to five metres of overburden built up. With the subsequent site development in 2002, and the contractors driving circa 92 concrete piles throughout the site, at least 17 of which, at 0.5 m^2 square-section, smashed through the buried hull remains, causing substantial localised damage and distortion. Additionally, the installation of a 22.5 m long by 7.65 m wide sheet-pile cofferdam effectively decapitated the stem and stern from the articulated hull remains.

Neither was the shape being documented the 'as-found', or archaeological discovery shape (state 6 from Table 7-1). As the individual timbers were dissembled and removed from the hull, fastenings were cut as timbers were pried apart, and the individual timbers were stored in water tanks while awaiting cleaning and detailed documentation. Certain timbers were seen to visible flatten as they were placed on the flat recording surface (Jones 2015:303–304). The result is the shape being recorded is a post-excavation shape state (state 7 from Table 7-1) of the individual components.

Three-dimensional scaled physical modelling was seen as necessary and desirable, as it provided an evidenced-based foundation for further hull form research. The digital and physical modelling of the individual timbers (see Jones 2015:285–350 for a detailed description of the process), required some simplification of the original three-dimensional wireframe data recorded during the contact digitising phase, due to the reduced (1:10 scale) size of the modelled parts required for the physical scale modelling stage. This resulted in some minor loss of detail and fidelity (Figure 7-13) between the recorded data and the digital solid models.

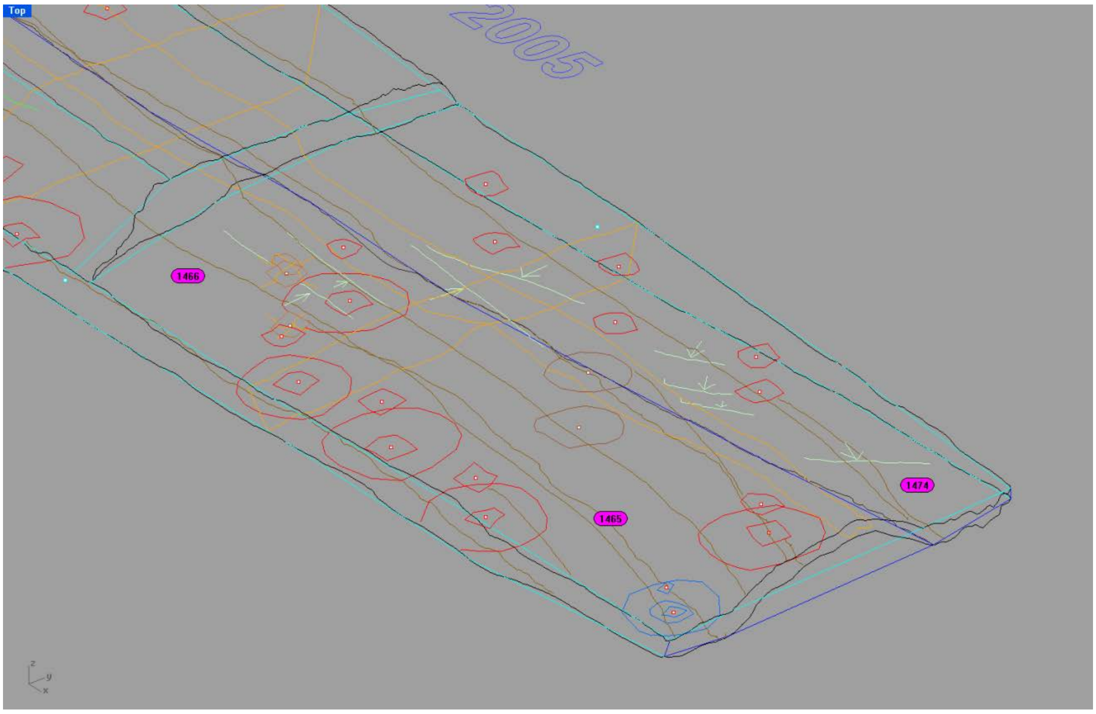

Figure 7-13 Typical hull plank scarf with simplified or rebuilt edges visible in blue. (Toby Jones)

To overcome any loss of detail or fidelity, digital 'master composite' files were generated for each digital solid model and its associated wireframe (recorded) data. This combined the high-quality, high-resolution, three-dimensional recorded data with the lower resolution digital solid model suitable for rapid prototyping (3D printing). This master composite file allowed each individual timber to be positioned relative to one another using the site photogrammetry file as a reference. However, illustrations or drawings created from this master composite file (Figure 7-14), while having the individual timbers positioned relative to one another, are still schematic in their nature as the timbers are positioned two-dimensionally for clarity. Figure 7-15 is a perspective view highlighting the flattened two-dimensional nature of the schematic view represented in Figure 7-14.

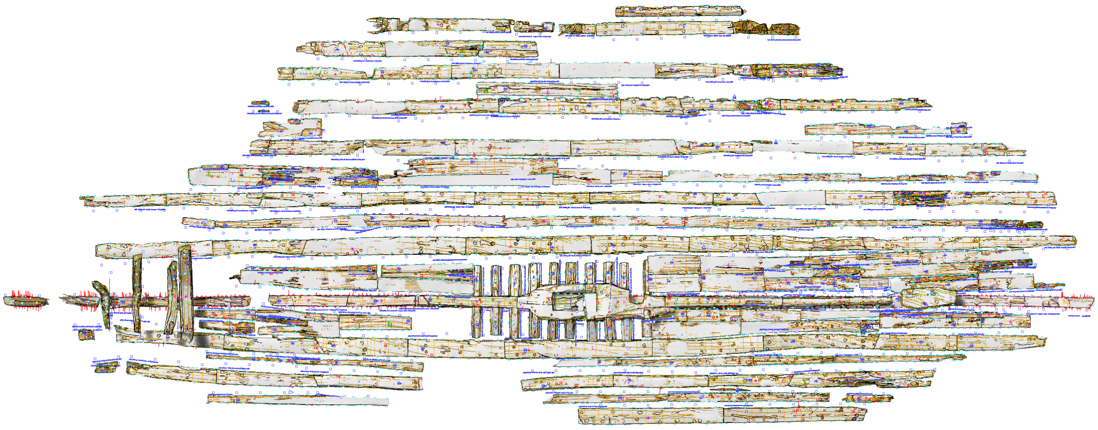

Figure 7-14 Inner Hull timbers master composite, the mast step/keelson, braces, stringers, ceiling and riders. The bow is to the left. (Toby Jones)

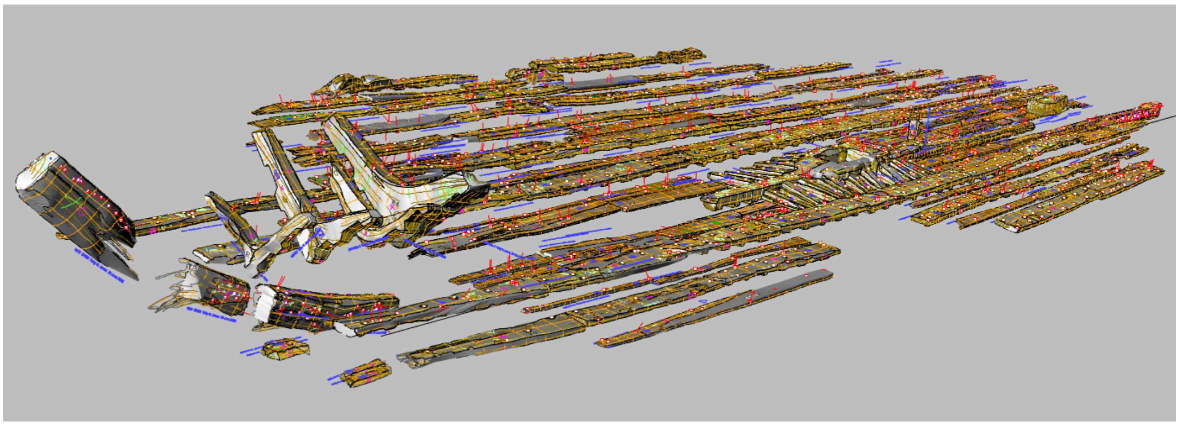

Figure 7-15 Perspective view highlighting the flattened two-dimensional nature of the schematic view (Pat Tanner)

This digital modelling phase included all of the recovered articulate ship's timbers, as well as many of the several hundred disarticulated elements, but no attempt was made to model missing elements. Each of these timbers was then physically manufactured at 1:10 scale using rapid prototyping technology (3D printing). While the internal ceiling planks and bilge boards were digitally modelled, these were not physically manufactured (principally due to cost).

Over 800 individual timbers from the articulated hull remains were reassembled following the perceived sequence of construction (Figure 7-16), using only the recovered material, with the emphasis on letting the hull planking determine the emerging hull shape and form (Figure 7-17 and Figure 7-18). No attempt was made to flatten or repair distorted timbers. The individual timbers were fastened to one another using micro fasteners (small threaded screws), smaller 1.7 mm screws to fasten planking using the documented original clench nail holes, and larger 2.6 mm screws used in the original treenail holes to fasten planking to the framing (see Jones 2015:322–350 for a detailed description of the process).

Figure 7-16 Toby Jones assembling model strakes. The sequence was visually documented using time-lapse photography (Newport Museums and Heritage Service)

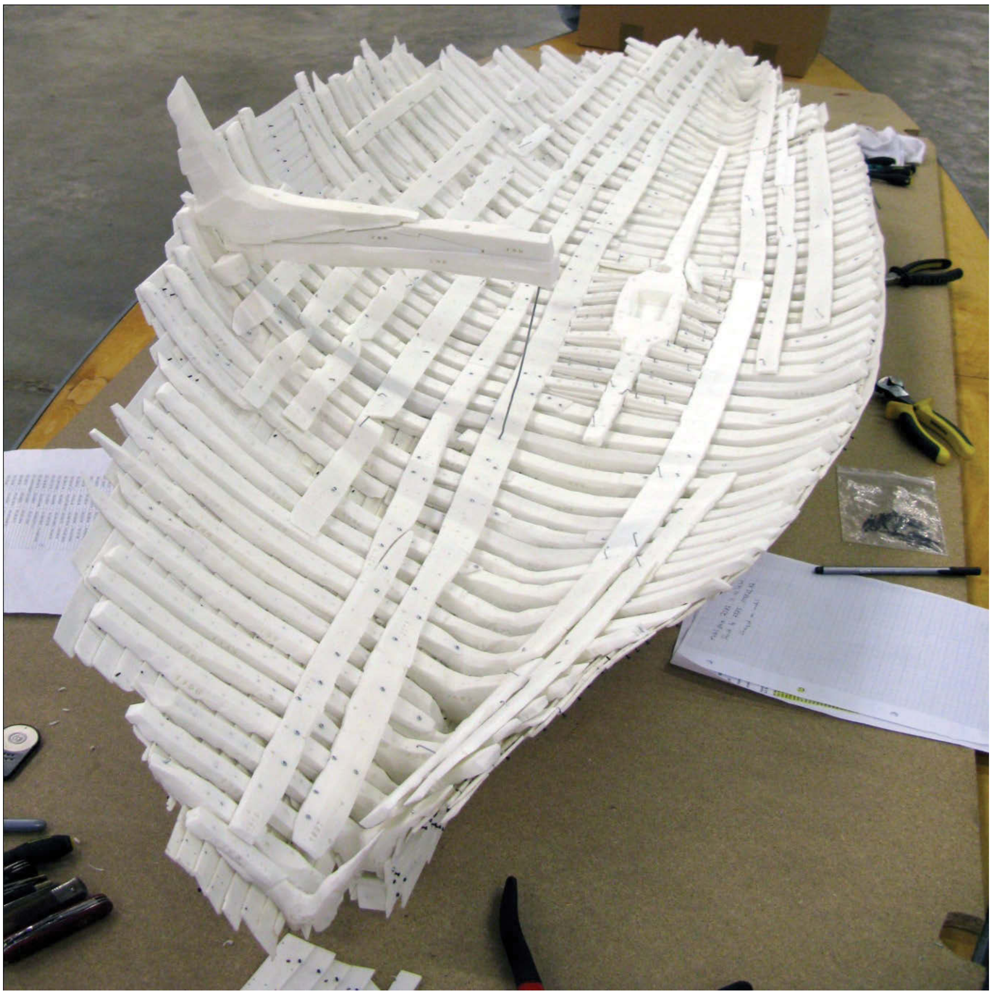

Figure 7-17 Newport ship 1:10 scale physical model of articulate hull remains – ceiling planks omitted for clarity – with the disarticulated composite beam tentatively positioned (Toby Jones)

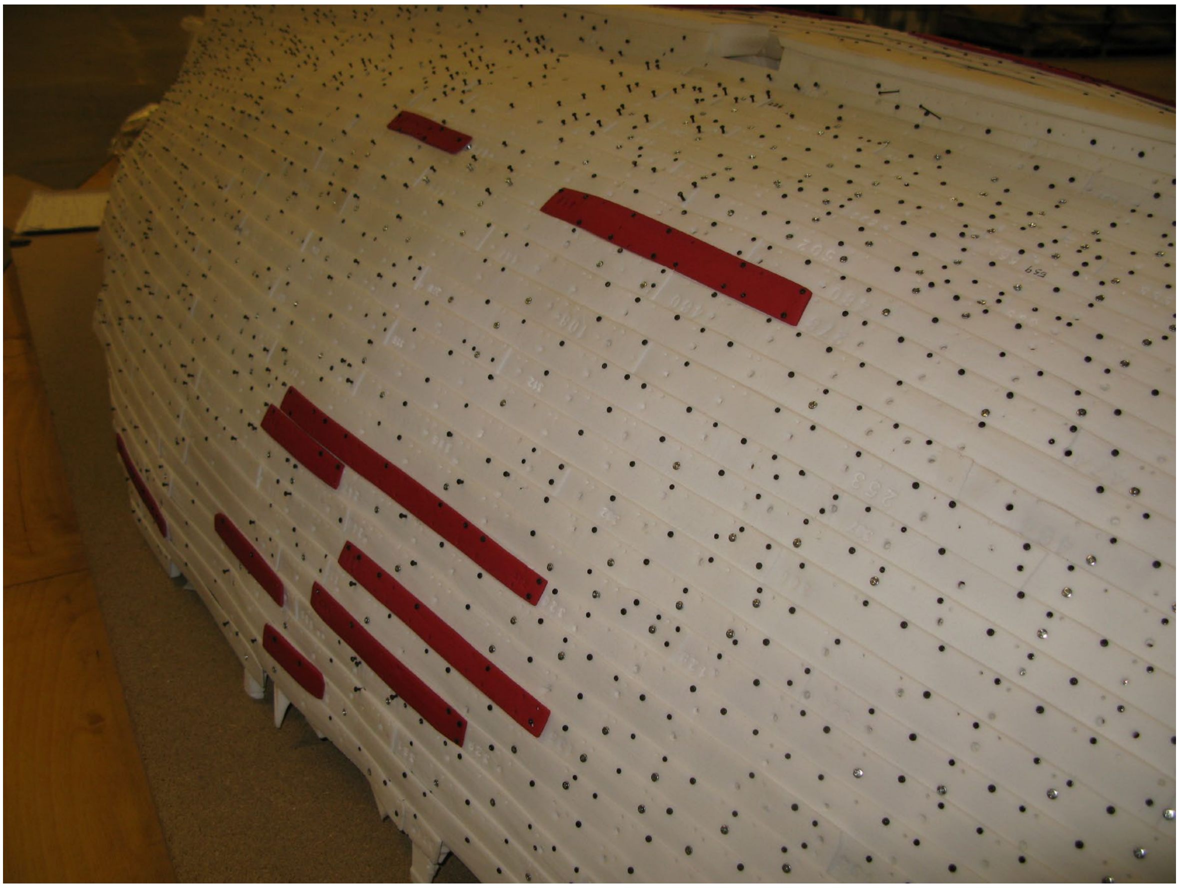

Figure 7-18 Outboard starboard surface of the inverted model. Note the tingles or repair patches modelled in red (Toby Jones).

The sheer quantity of material, and the various stages of cleaning, contact digitising, digital modelling, physical solid modelling (3D printing) and actual assembly of the physical scale model meant that the 1:10 scale research model took several years to build. During this period, the changing and evolving hull form was documented at various stages during the assembly process. This was done in an effort to quantify the evolving shape and to attempt to correlate changes due to the addition of specific timbers.

Documentation took the form of contact digitising, laser scanning (Figure 7-19), and digital photography and videography. In addition to being one of the primary research tools, the model served several other purposes, including providing an interactive display for helping with public understanding and engagement. This was especially important as the ship timbers had entered the conservation phase and were no longer available for public viewing and were difficult to access during the subsequent research and reconstruction phases.

Laser scanning of the completed physical scale model meant that the physical model could also be returned to the digital realm for further detailed shape analysis and comparison with the other available site data (see Tanner 2013b:19–22, for a detailed description of the process).

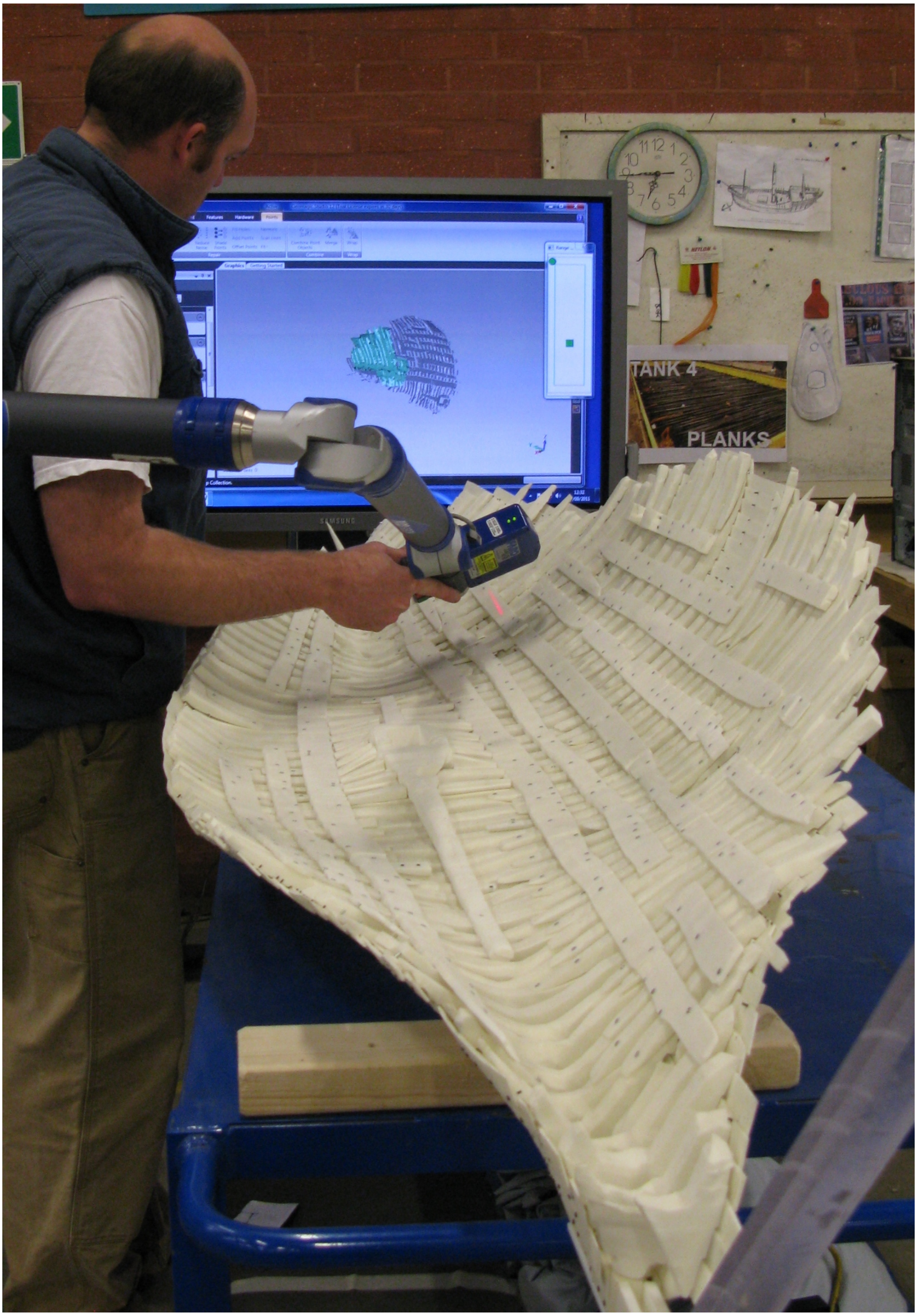

Figure 7-19 Laser scanning the inner surface of the completed 1:10 scale physical model (Newport Museums and Heritage Service).

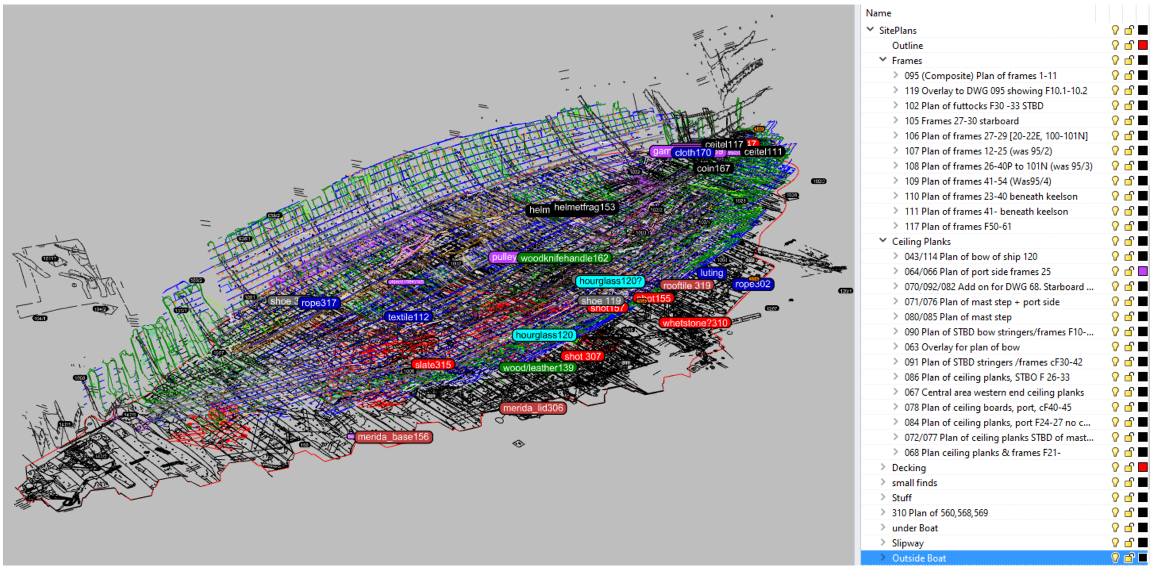

Figure 7-20 All hand drawn 2D drawings and 3D photogrammetry imported and aligned (Pat Tanner)

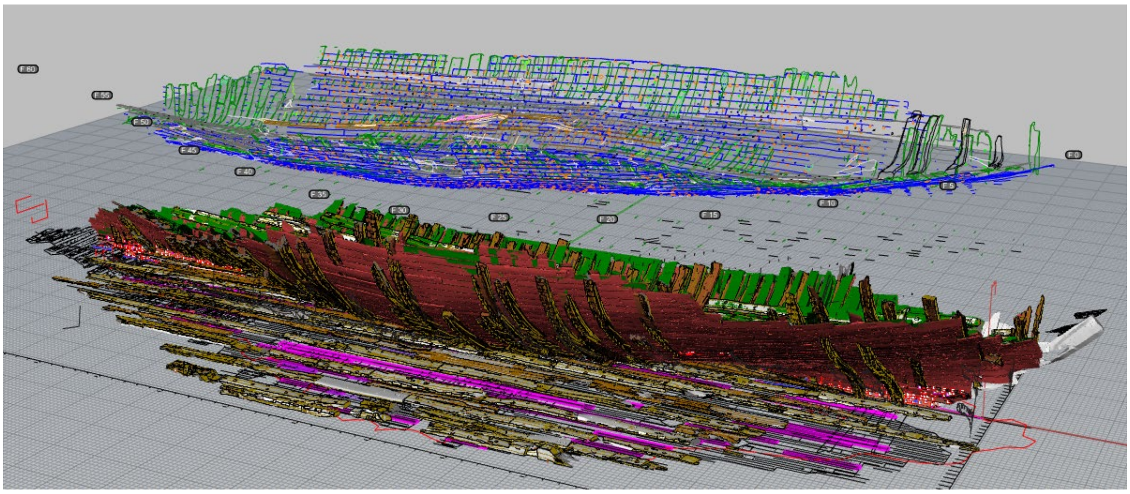

Figure 7-21 Combining both 2D drawings and 3D digital models (Pat Tanner)

All of the available two-dimensional drawings, including plans, site sections and sketches, as well as the three-dimensional data from the contact digitising phase, the digital modelling phase, as well as the 3D laser scan of the physical scale model were all imported into a single Rhinoceros 3D file (Figure 7-21). The Rhino 3D scale 2D function for drawings, and scale 3D function for digital models was used to change the scale of everything back to full size, before being aligned to a common datum. This created a single digital version at full scale of what Steffy (1994:198) referred to as the hull catalogue, the raw materials amounting to an inventory of what has been excavated. The combination of both the articulated remains and disarticulated timbers, as well as merging all extant recorded survey data into a single digital file, has facilitated a more comprehensive overview of the entire vessel and associated site data. In addition, the fact that all data is maintained at full-scale, results in higher levels of detail and accuracy during comparative analysis.

In certain situations recorded site data may not be readily available, as was the case with the Poole Iron Age logboat (see McGrail 1978; Tanner 2019), and the Bremen Cog (see Kiedel and Schnall 1989; Lahn 1992; Tanner 2017b Appendix H). Both vessels were on display as museum exhibits, but site plans were unavailable.

In the case of the **Poole Iron Age logboat**, the available data included some dimensional details, a survey drawing and a hypothetical reconstruction drawing (McGrail 1978), some photographs taken shortly after discovery, as well as the vessel remains, which were on display within a close fitted, glass fronted display cabinet in Poole Museum. The remains required a total of 29 individual three-dimensional laser scans as a result of the limited field of vision from each scan location within the enclosed display cabinet. The laser scanning was carried out in 2013 by 1st Horizon Surveying & Engineering Ltd, who sent the raw unprocessed data to this author.

Figure 7-22 The Poole logboat as displayed Stern view on the left and Bow view on the right (Berry *et al*. 2019:108 fig. 6.3)

Once the 3D laser scan data was registered and processed to create a single three-dimensional model (Tanner 2019:35–39), using the same procedure as described in Chapter 6.5.1, the digital model and available drawings were imported into a single Rhinoceros 3D file. The drawings were re-scaled to full-size using the scale 2D function in Rhino and everything aligned to a common datum point (Figure 7-23).

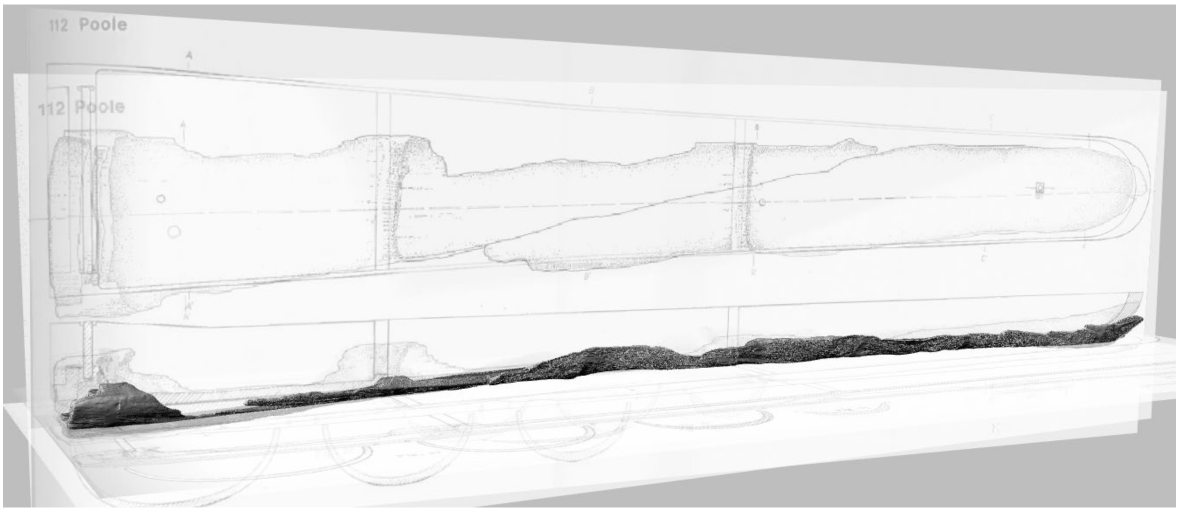

Figure 7-23 Poole Logboat drawings re-scaled to full-size and aligned with 3D laser scan data (Pat Tanner)

In the case of the **Bremen Cog**, the available data sets included two sets of two-dimensional drawings, drawings by either C. Nord or Rita Schultze from W. Lahn’s reconstruction, and drawings prepared by Hanover University based on a photogrammetry survey carried out in 1980 of the reconstructed vessel (Figure 7-24).

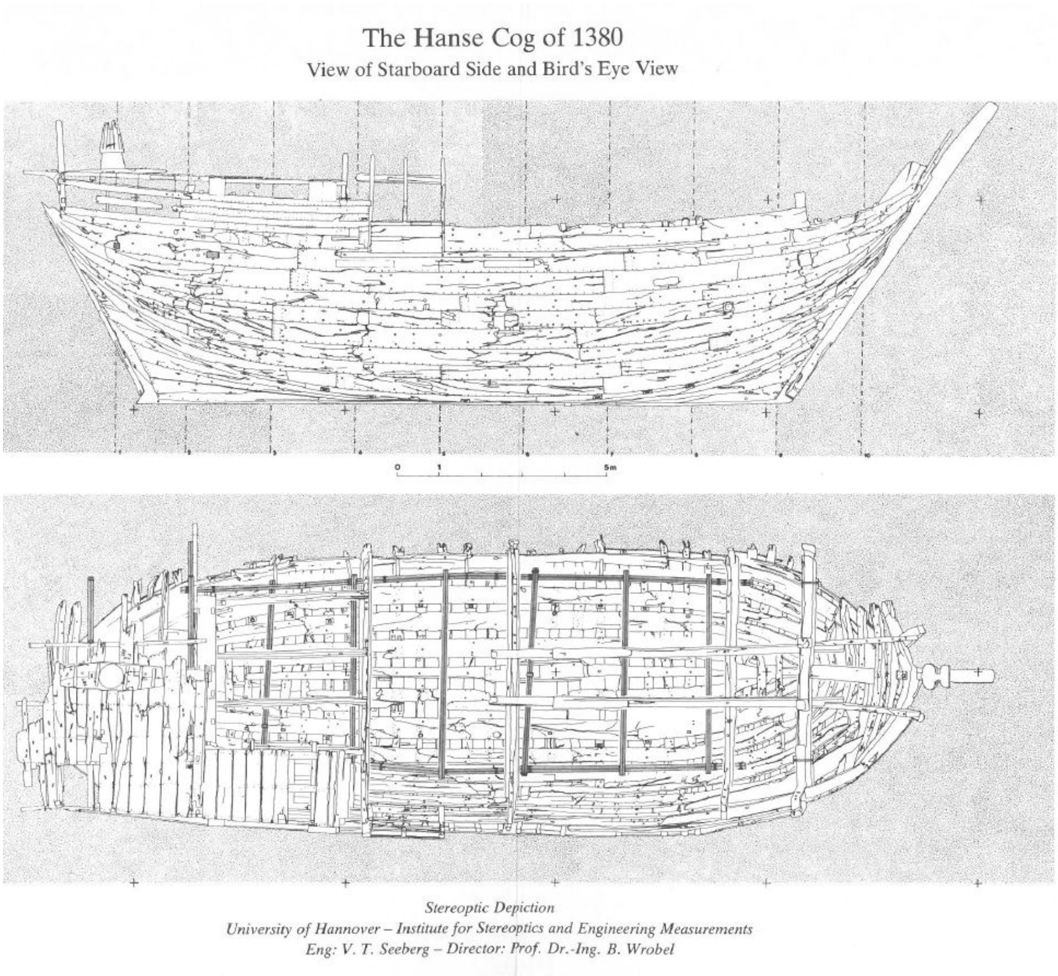

Figure 7-24 Stereoptic view of the Bremen Cog (Kiedel and Schnall 1989)

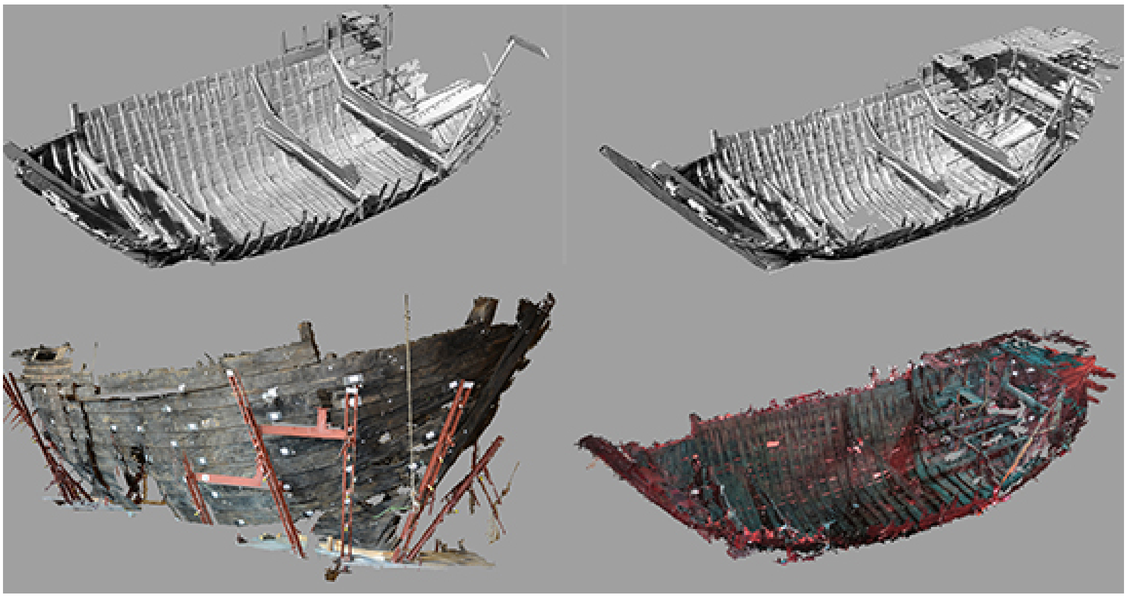

Figure 7-25 The Bremen Cog – four separate phases of three-dimensional data capture (Pat Tanner)

Four separate sets of three-dimensional data were also available. A 3D laser scan carried out in 2011 which was only of the interior of the vessel (Figure 7-25 top left), a photogrammetry survey of the complete vessel carried out in January 2014 (Figure 7-25 top right), a photogrammetry survey of the exterior carried out in April 2014 (Figure 7-25 bottom left), and a photogrammetry survey of the interior carried out in October 2014 based on 200 photographs (Figure 7-25 bottom right). All four sets of three-dimensional data were imported into Rhinoceros 3D, and the 3D scale function used to correct the scale on some of the photogrammetry models. Once the four individual models were correctly orientated and aligned to each other in three-dimensional space, all of the available two-dimensional drawings were imported and corrected to full-size using the 2D scale function (Figure 7-26) (see Tanner 2017b:5–23 Appendix H, for a detailed description of the process). Whilst not a site plan *per se*, these represent a single digital compilation at full-scale of the available hull catalogue data.

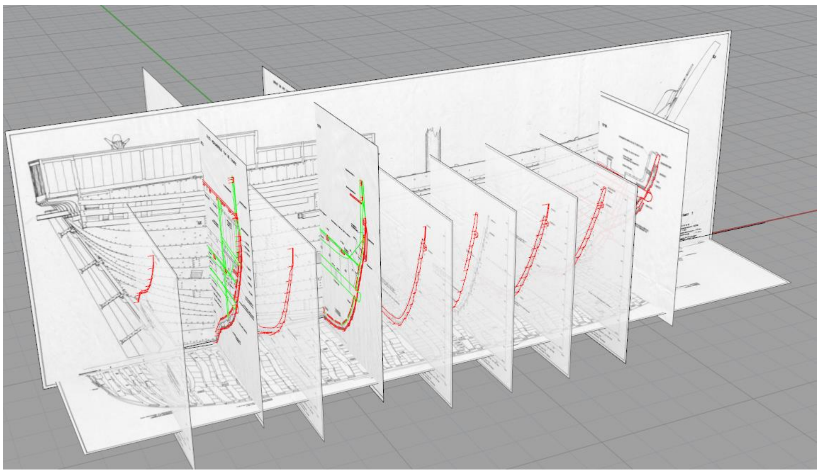

Figure 7-26 The Bremen Cog 2D drawings – re-scaled and orientated in 3D space (Pat Tanner)

7.5 Initial orientation of the remains

McGrail (2007:255) suggested a model of the boat as-found should be formed, but with distortions and compressions removed, displaced elements replaced, fragmented timbers made whole, and the hull rotated to its deduced attitude when afloat. However, how can we determine a vessel's attitude when afloat? As can be seen from Figure 1-5, some vessels have a very different attitude when afloat to their attitude if sitting flat on their keel.

As discussed in Chapter 6.2, there are three critical elements to a vessel's attitude when afloat. Its weight, its hull form and hence the underwater volumetric shape, and its centre of gravity. In order to generate even an initial floating hypothesis, we will first require a watertight envelope representing the hypothetical hull form. Hocker (2013) states that in reconstructing ships, which are usually better preserved on one side, we typically base our reconstruction of the missing or damaged side on the surviving remains of the opposite side. Hocker cautions against taking this process too far, as was the case in Peter Marsden's attempt to reconstruct the missing port side of *Mary Rose*, based on the principle of perfect symmetry of form, construction, and internal fitout arrangements. Marsden (2009b:20–31) expended a great deal of effort to identify the plane of symmetry, basing this approach on the assumption that ships are fundamentally and perfectly symmetrical, citing amongst others, *Vasa* as an example.

As noted in Chapter 3.10.2 it would be unusual for a boatbuilder to set out to build a suboptimal boat, so we can reasonably assume that the design intent is for a fair, and probably symmetrical design, with a few notable exceptions such as the Venetian gondola, although Hocker's (2013:73–79) article on the myth of symmetry and regularity should be noted. As noted by Hocker, while the design intent for the hull is generally a symmetrical form, there is also a degree of deliberate or intentional asymmetry in the building of a vessel. The positioning of certain rigging elements may be offset from the vessel's centreline, necessitated by avoiding interference with other elements, just as the internal fitout may be markedly asymmetrical as a result of functional or symbolic requirements. Unintentional asymmetry may also be introduced during the construction or use-life of a vessel as a result of human factors, the design and construction methodology or material properties. As Hocker (ibid: 76) noted the most jarring lack of symmetry in Vasa is the beakhead (Figure 7-27). While it would be expected to be centred and point along the central axis of the hull, it skews substantially to port. At its forward end, 9.9 m forward of the stem, the centreline of the figurehead is offset 0.78 m to port. Whilst some of the skew is a feature of settling in the museum, most is a feature of the original construction.

For these very reasons, it will be the design intent shape (state 2 from Table 7-1) that we aim to reconstruct digitally, as this is a more quantifiable result. Any discrepancies between that 'idealised' reconstructed shape and the archaeological record may indicate the actual as-built shape, or the use-life shape (states 3 or 4 from Table 7-1). These can then be further investigated for evidence pertaining to the human factors, the design and construction methodology or the material properties involved in the vessel's construction.

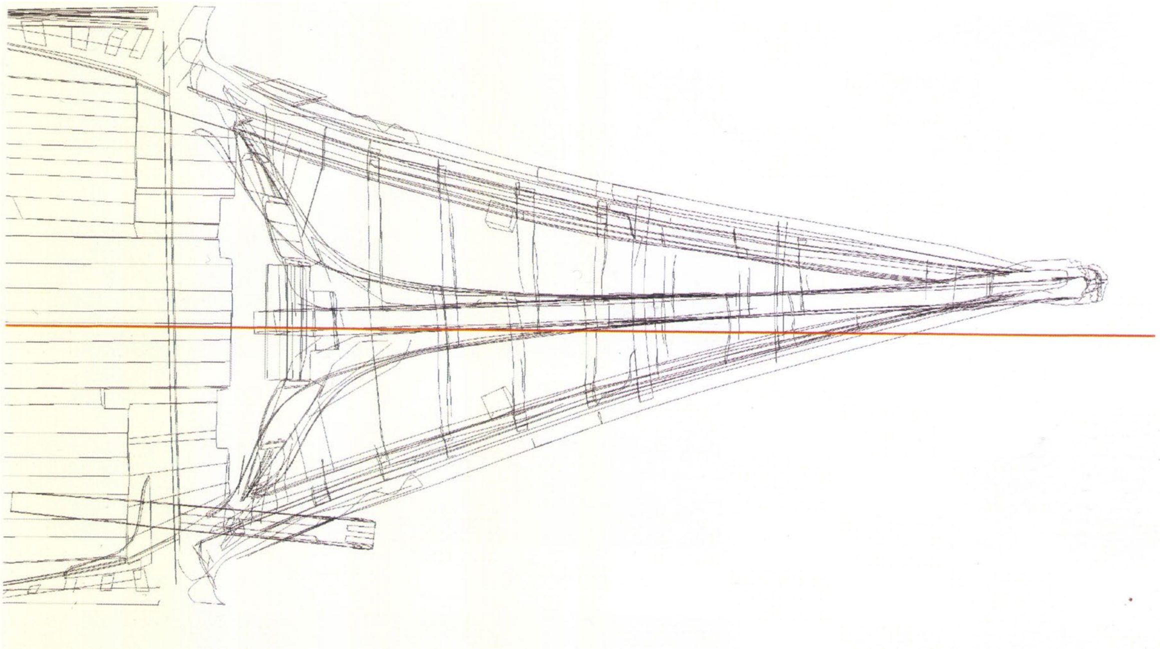

Figure 7-27 Raw total station plot of the beakhead of Vasa, with the hull centreline in red (Hocker 2013:77 fig 6.4)

In order to facilitate the mirroring of hull parts as an aid to 'developing' an enclosed watertight envelope, and to simplify the ability to check corresponding measurements between either side of the vessel, the surviving vessel's remains will need to be correctly orientated. From this stage onwards all processes are either modifying or interpreting the archaeological record, and as a result I use the copy feature in Rhino 3D in order to maintain an original archive record and modify a digital copy. This will facilitate comparisons between the hypothetical process and the original archive.

For the initial orientation, as the flotation attitude is usually unknown, I tend to use what might be labelled the build orientation, with the keel positioned horizontally, and the vessel's backbone, the keel stem and sternpost, orientated to match the CAD system's X,Y axis. I position the remains with the bottom centre point of the keel located at the digital world origin, position 0,0,0 (Figure 7-30). From this starting point I use the rotate function, with the world origin (bottom centre of the keel) as the centre of rotation. Using a side-on view the digital model is rotated in the Y axis to adjust the vessel's fore and aft trim until the keel sits 'as level as possible', bearing in mind any potential hogging or sagging distortion. A similar process is then repeated from an end view, rotating the digital model in the X axis to adjust the vessel's side-to-side heel angle again bearing in mind and distortion of the archaeological form.

This is the single most critical stage in any hypothetical reconstruction – this is setting the foundation for the entire hypothetical reconstruction, and any errors in the initial orientation will be magnified if mirroring is employed in subsequent processes. If the Vasa had survived as only partial port side remains, and the reconstruction centreline were set from the sternpost to the figurehead, it would be 0.8° offset to port, resulting in a distance error of 645 mm at the stem. Any mirroring would result in a decidedly asymmetrical hypothetical reconstruction.

Likewise, any twist or distortion apparent in the archaeological record is unlikely to be a uniform degree of distortion (Figure 7-28) and may cause issues when attempting to identify the exact hull centreline. In order to check the positioning of the assumed centreline and the associated orientation of the vessel's remains, I normally take a series of cross-section curves projected onto the surviving data and mirror these across the assumed centreline plane to check for correspondence between both sides. Or a series of measurement checks from a baseline to features identified on both side (Figure 7-29) in order to check if the surviving remains are correctly levelled and positioned.

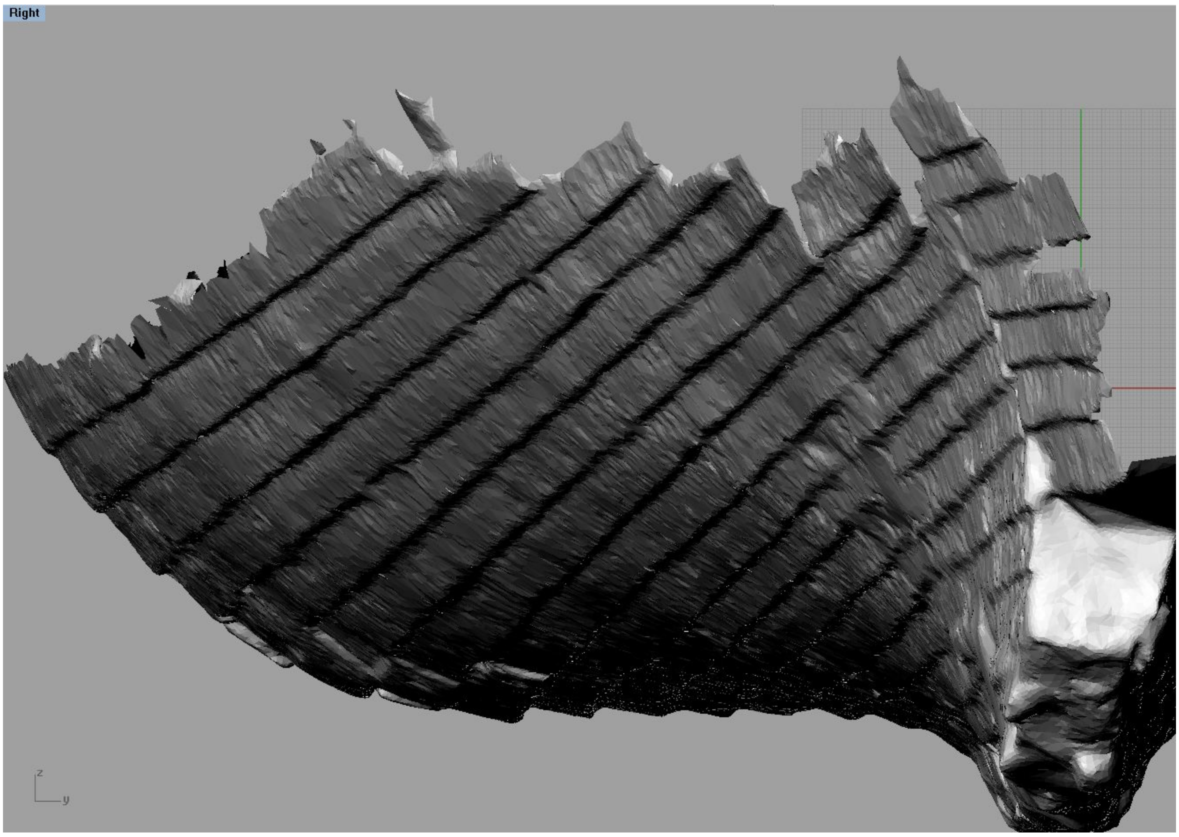

Figure 7-28 Portion of the digital mesh model produced by laser scanning the physical scale model. Note the twist in the keel. (Jones 2015:356 fig 134)

This process will often highlight areas of the archaeological data which are distorted or displaced and require further investigation. These issues are dealt with in the following sections.

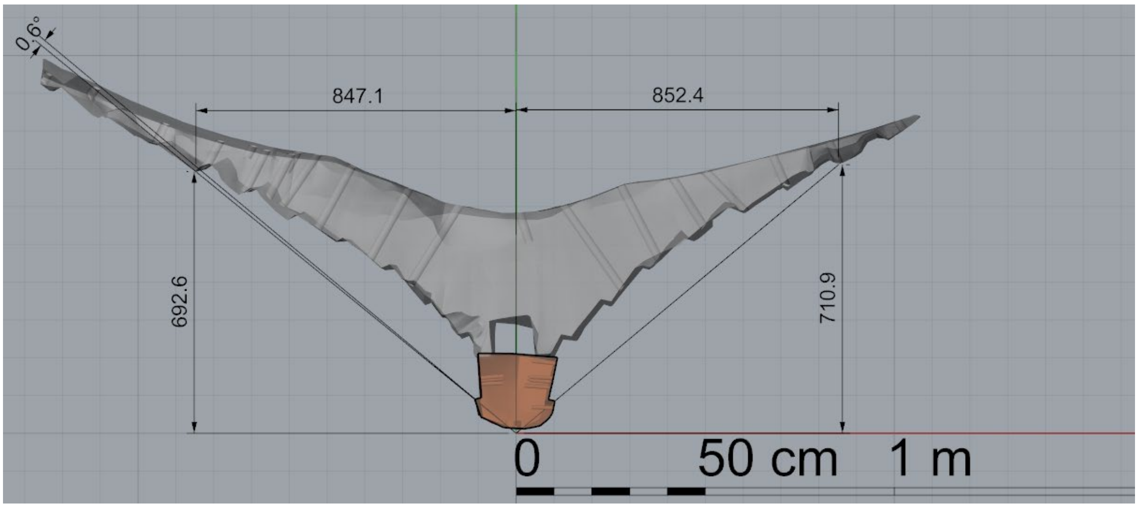

Figure 7-29 Checking for position and level during initial orientation of the archaeological data (Pat Tanner)

7.6 Size and shape of remains

This single digital version at full scale of the hull catalogue is now used to develop an overview of the surviving archaeological remains. This will allow a better understanding of the myriad array of source data sets and begin to formulate a three-dimensional image of the vessel (Figure 7-30). From this the researcher can begin to plan the hypothetical reconstruction approach. Issues such as having one side better preserved than the other, obvious distortions and the potential extent of the missing portions will all have an influence on any hypothetical reconstruction attempt.

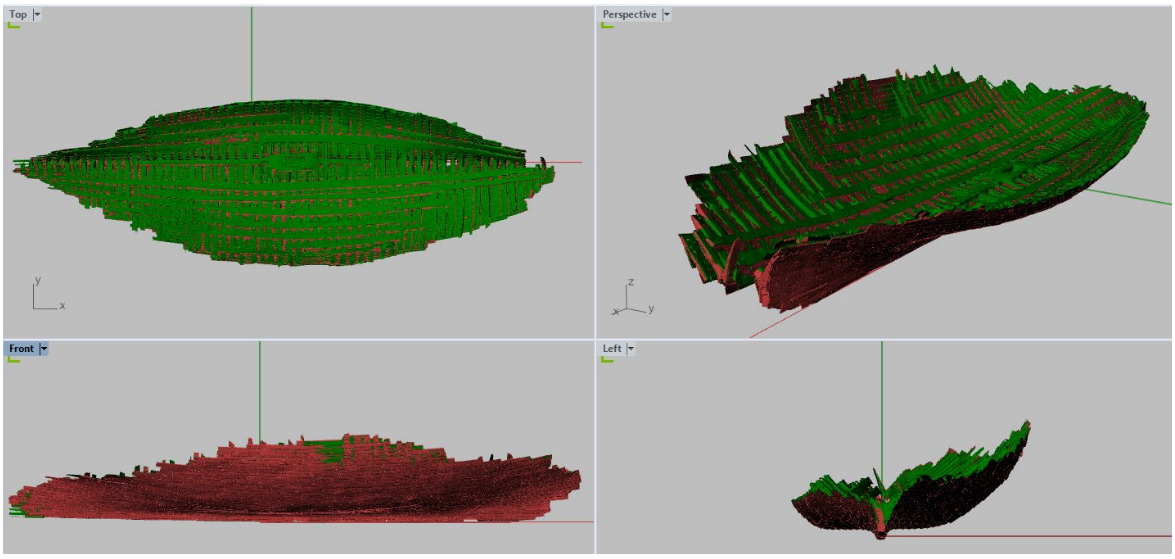

Figure 7-30 Four two-dimensional views representing the 3D form of the articulated remains (Pat Tanner)

The size and extent of the surviving remains may hint at the vessel's overall dimensions, which may in turn suggest potential use and sphere of operations. It is at this early stage that a preliminary list of potential issues will be identified, for example, if the better-preserved side is simply mirrored, does this provide sufficient information to attempt a complete hull form reconstruction. Can the missing extremities of the vessel be extrapolated based on the surviving data? In other words – is it possible to generate a watertight envelope representing the hull form based on the available archaeological record?

7.7 The concept of minimum or capital reconstruction

The concept has long been a contentious issue, with varying attempts at classification (see McGrail 1992; Crumlin-Pedersen 1995; Crumlin-Pedersen and McGrail 2006; McGrail 2007; Institute for Archaeologists 2008; Chartered Institute for Archaeologists 2014). These have ranged from – the excavated evidence in which allowances have been made for distortion, displacement and shrinkage (Crumlin-Pedersen and McGrail 2006:57) – to – a model formed of the boat as found, but with distortions and compressions removed, displaced elements replaced, fragmented timbers made whole, and the hull rotated to its deduced attitude when afloat (McGrail 2007:255) – and – full reconstructions using one or more minimalistic ways to complete the hull and point to the most likely means of propulsion and steering for the vessel (Crumlin-Pedersen and McGrail 2006:57).

In my view a hypothetical minimum reconstruction should:

- represent the vessel in a form whereby it is capable of its intended function. That is a watertight envelope capable of floating.
- This reconstruction should violate none of the archaeological evidence
- Missing elements should be replaced or repaired using valid comparative evidence. Every step used in the 'repairing' of source data, or replacing of elements must be clearly described and included in the publication
- This will allow for some basic hydrostatic calculation to be carried out in order to generate an impression of the vessel's potential capabilities.

A detailed description of how the hull form was repaired and developed, primarily from the articulated hull remains of the Newport Medieval ship can be seen in Newport Ship Specialist Report : Digital Reconstruction and Analysis of the Newport Ship (Tanner 2013b). How that reconstructed hull shape was developed from a floating hypothesis into a hypothetical minimum reconstruction is discussed in detail in Newport Ship Specialist Report : Phase Two Capital Reconstruction of the Newport Ship (Tanner 2020:42–60 Appendix G).

A capital reconstruction will build on the hull form developed during a minimum reconstruction, in the case of Newport Medieval ship, this involved utilising the several hundred disarticulated elements recovered during excavation, as well as iconography, comparable archaeological evidence and ship building knowledge. Capital reconstructions, by their very nature, will involve a greater level of interpretation, and as such the associated paradata describing how the data has been interpreted and utilised is of the utmost importance. Figure 7-31 clearly illustrates the hypothetical reconstruction and how that was developed from the floating hypothesis. The representation is colour coded to illustrate the provenance of each element. Brown is archaeological evidence, blue is elements required to form the watertight hull, green is elements for which some evidence was recovered (dark green for more definitive evidence, light green for less so) and red for elements where no evidence was recovered and is based on comparable evidence or iconography.

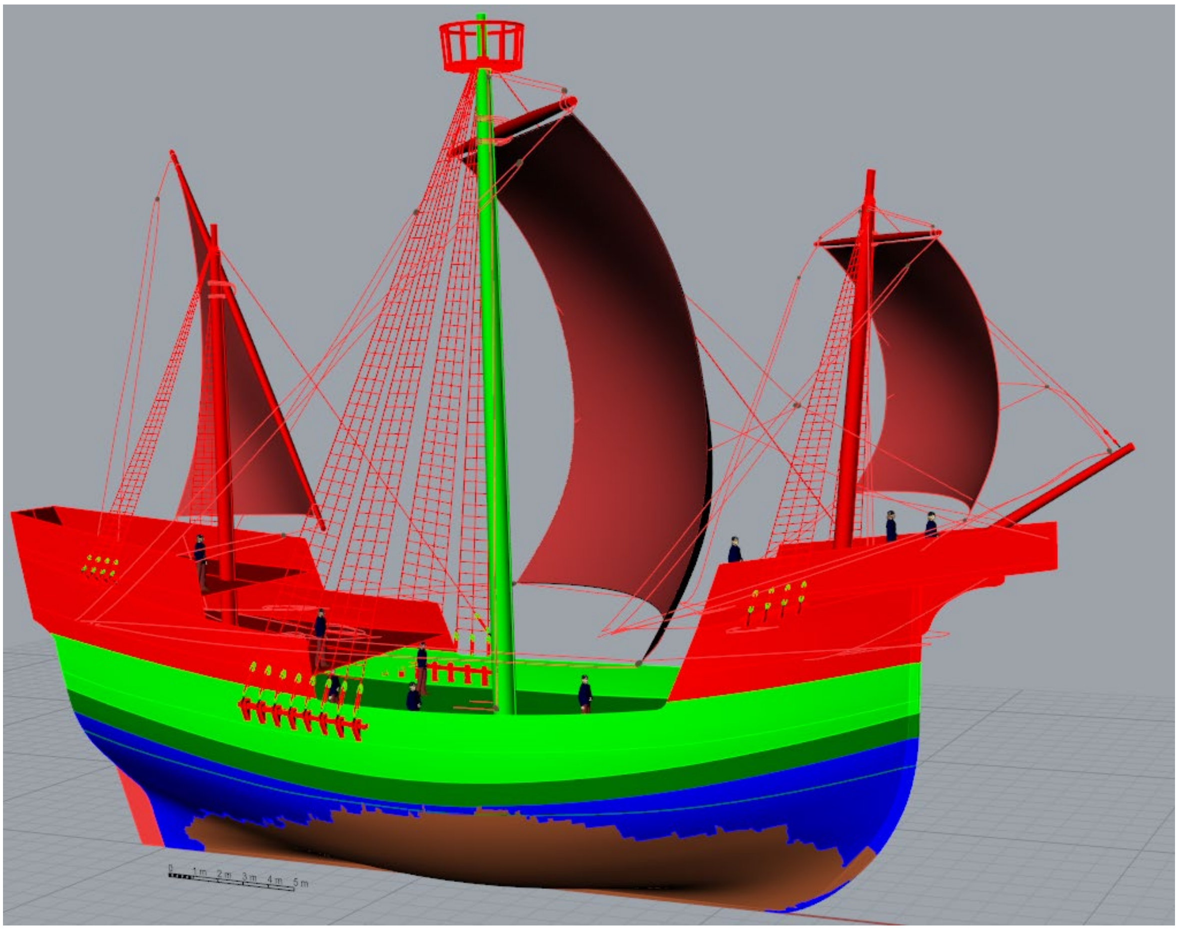

Figure 7-31 Hypothetical capital reconstruction colour coded to illustrate provenance (Pat Tanner)

7.8 Global distortion

Global distortion can develop in a vessel's hull form over time during the use life, or as a result of external factors following deposition. The main issue with global distortion is that it is rarely a uniform amount of distortion and can often be reversed between both extremities of the hull. The three main forms of global distortion are hogging, sagging and twist. Dynamic stress can result in hogging when the centre of the vessel is supported on a wave and both extremities are in a trough causing the centre of the vessel to bend upwards, and sagging occurs when the waves are a similar length to the vessel causing the extremities to be supported and the centre to sag into the trough. Time-induced hogging refers to the semi-permanent bend in the keel, especially in wooden-hulled vessels, caused over time by the vessel's centre being more buoyant than the bow or stern. Cargo loading, and the distribution of that weight throughout the vessel can also contribute to hogging or sagging. Torsional forces will be generated as a vessel travels obliquely over waves which may result in twist developing in the hull form.

Often in the case of a vessel which has come to rest on one side, the hull remains are initially supported by the wider middle section of the hull, which leaves both extremities unsupported until the sediment backfills to support these areas. Over time the unsupported extremities will sag towards the more preserved side causing a longitudinal twist as was the case in the Newport Medieval ship. With the scanned mesh positioned and orientated so that the central midship areas was upright, the twist was measured (Figure 7-32) as 8.4° and 6.8° in the bow and stern areas respectively (Tanner 2013b:23–24).

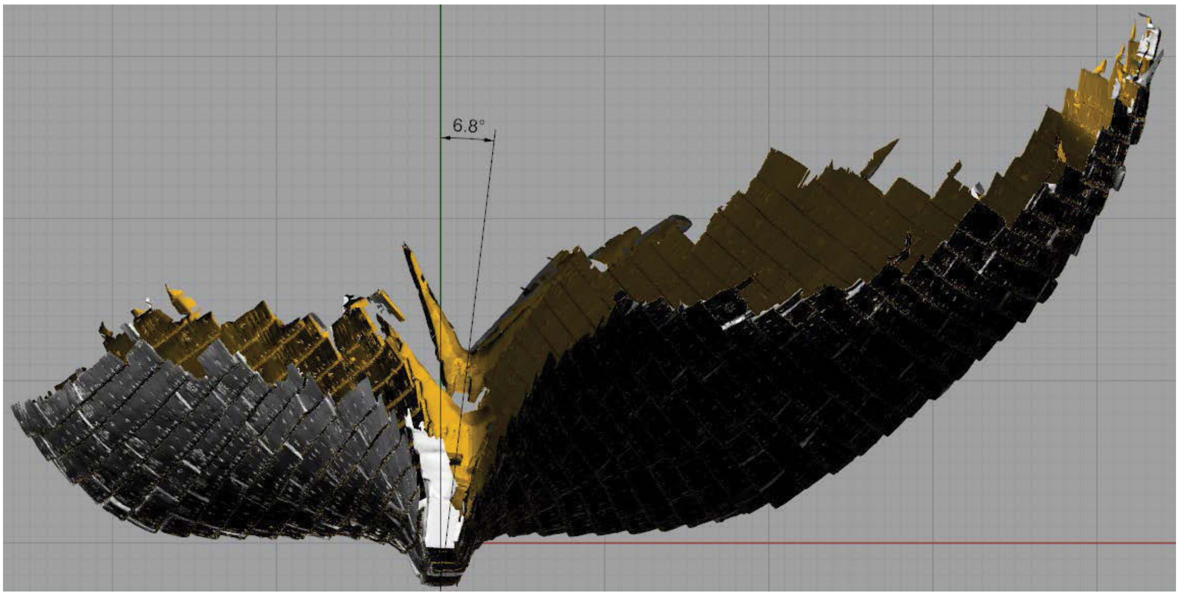

Figure 7-32 Measuring the global twist in the stern area (Pat Tanner)

Using the twist command in Rhino allows the user to reverse the twist which has developed in the recorded hull remains. This is a very powerful command with many optional operators which can be enabled or disabled by the user. Firstly, an axis is set to determine both the position and the length about which the model will be twisted. For example, if the twist is set to infinite, the deformation is constant throughout the object, even if the axis is shorter than the object. If the infinite option is disabled, the twisting is not constant throughout the object. The deformation takes place only along the length of the axis. The length of the axis is important. If the axis is shorter than the object, the twist applies only to that part of the object. In addition, the twist blends in and out at the ends of the axis. By setting the axis to begin at the correct central portion of the hull and extend beyond the extremity in one direction, the twist will be applied progressively, starting at zero in the central portion and increasing to the measured degree of twist at the extremity. Note how the two meshes are coincident in the central portion (far left Figure 7-33) and progressively separate towards the stern as the mesh is repaired and twisted to an upright orientation. The process is carried out separately for both ends of the vessel, in order to maintain the correct orientation midships, while twisting differing amounts at each extremity.

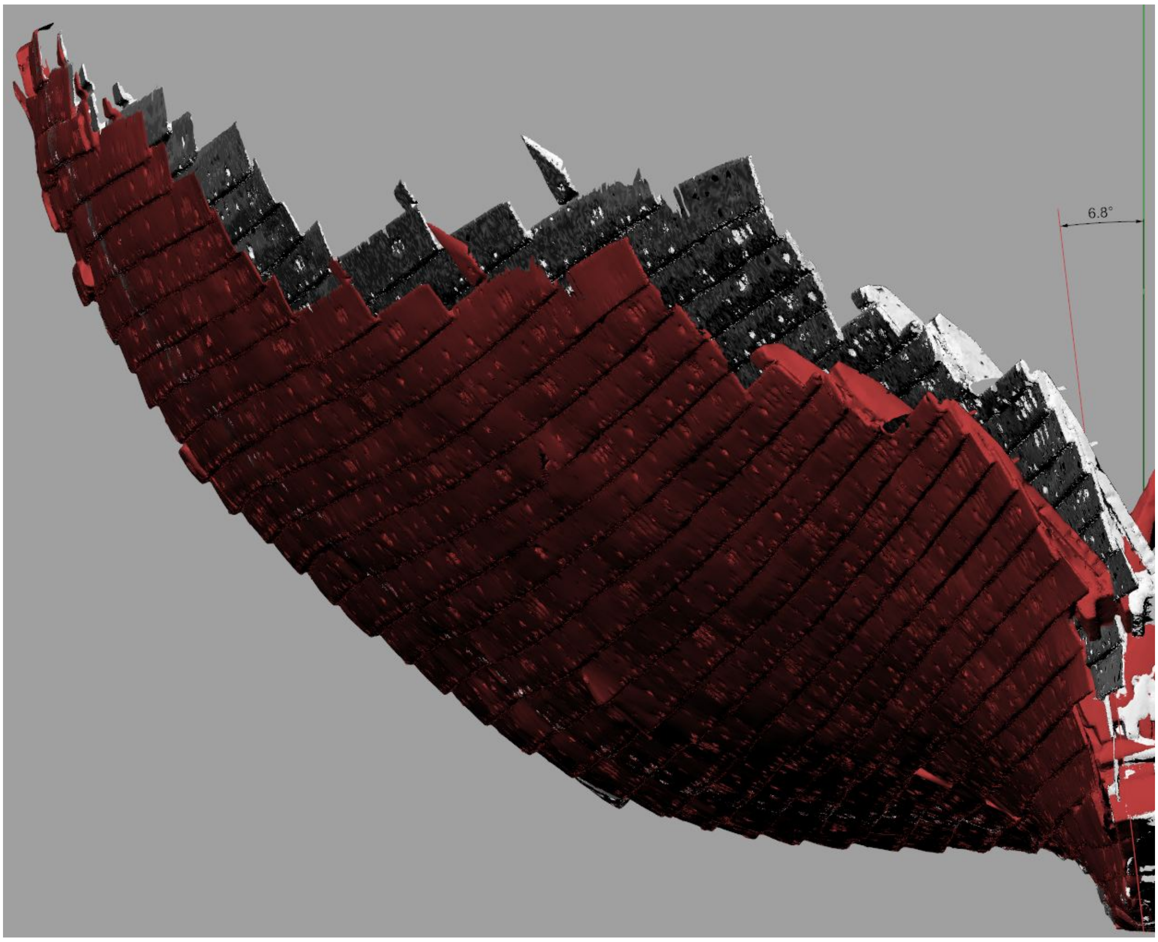

Figure 7-33 Using the 'twist' function in Rhino 3D to digitally repair the twisted mesh model. Original shown red, repaired mesh shown grey (Pat Tanner)

Once the mesh has been digitally repaired, cross-section curves can be generated at intervals along the repaired mesh and mirrored across the central symmetry plane to check if the correct position and orientation has been achieved.

A good example of this technique in practice can be seen in the case of the **3D Documentation of the Marsala Punic Ship: Digital Conservation and Archiving** (Polakowski and Tanner 2020 included as Appendix J). The *Marsala Punic ship* is currently on display at the Regional Archaeological Museum Baglio Anselmi in Marsala, Sicily. The vessel as displayed, clearly shows signs of deformation and distortion, and in 2019 a total of 98 individual 3D laser scans were carried out by this author with the aid of Mateusz Polakowski (University of Southampton), while another team from the Center Camille Julian (Aix Marseille University), at the same time, carried out a photogrammetric survey consisting of over 3,500 photographs. Using the hybrid technique discussed in Chapter 4.6, this author used the Faro Scene software to register the individual laser scans, resulting in a unified project point cloud with an accuracy of 2.4 mm, and this data was combined with the photogrammetry data using Reality Capture software to generate a super-high resolution 3D polygon mesh model of the vessel, consisting of 261 million polygons, which was textured with more than 2,500 high resolution photographs (Figure 7-34).

Figure 7-34 High-resolution 3D mesh model of the aft portion of the Marsala ship as displayed in the museum (Pat Tanner)

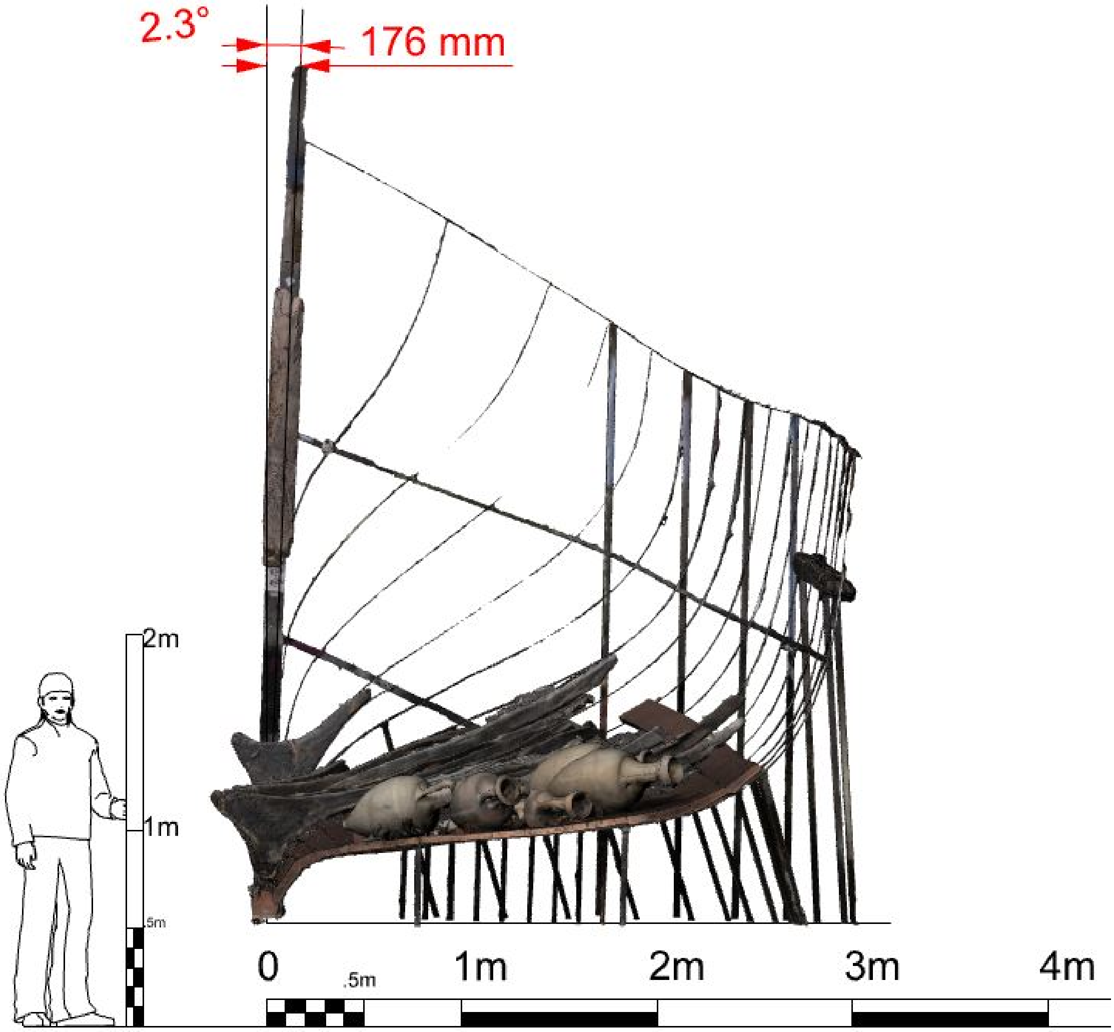

Figure 7-35 Measuring distortion of the stern post in the Marsala Punic ship (Pat Tanner)

Once the 3D model was correctly orientated in 3D world space, it was immediately apparent that there was significant movement and sagging of the support cradle for the vessel. From a central vertical reference plane, the sternpost had leant to port by 2.3°, resulting in a horizontal movement of 176 mm towards the port side at the upper extremity.

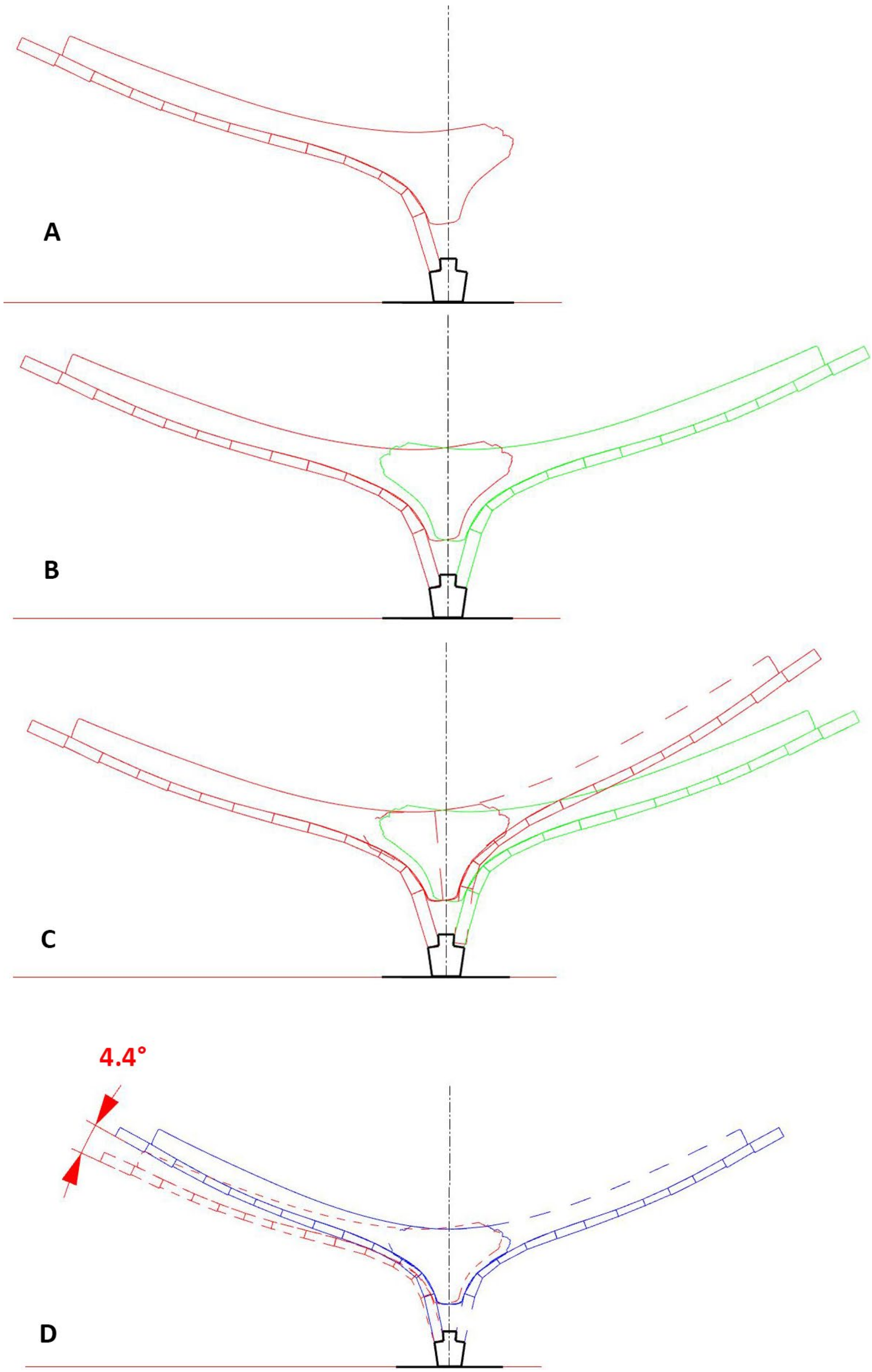

Figure 7-36 Section created 4 m from the stern illustrating the process of determining the degree of twist (Pat Tanner)

As is nearly always the case, the degree of twist along the length of the surviving material is rarely uniform. A section taken through the ‘as-displayed’ vessel, 4m forward of the aft end of the keel shows that the frame and planking appears to be canted towards the port side (Figure 7-36 A). If this is simply mirrored through the vessel’s centre line, the hypothetical frame shape creates an open V form which would contradict the partially surviving starboard side fragment at the base of that frame (Figure 7-36 B). If the surviving port side is mirrored through the extant frame’s centre line, shown as red hatched lines in Figure 7-36 C, while it generates a more realistic hull form, it clearly illustrates the twist towards the port side in the ‘as-displayed’ vessel shape. Rotating this frame shape to align the frame’s centreline with the vessel’s centreline, illustrates the degree of twist (4.4°) at that cross section (Figure 7-36 D). A section taken at the surviving extremity (presumed to be midship) of the remains clearly shows further significant twist to port of 13.4° illustrating directly, the differing twist that can happen within a single component (Figure 7-37).

Figure 7-37 Cross section at the extant extremity of the remains showing the significant degree of twist (Pat Tanner)

7.9 Local distortion

Localised distortion can take several forms and have many causes, from the remains settling onto uneven terrain, to localised damage or cracking of individual timbers which can occur during the wrecking event, post deposition as the weight of overburden increases due to site formation, or post-excavation. In the case of the Newport Medieval ship, many of the distal ends of framing timber scarph joints showed significant distortion (Figure 7-38), and there was a marked unevenness in the lines of the hull strakes between frames 20 to 28 on the starboard side, where compression over the underlying support shores had distorted the hull form.

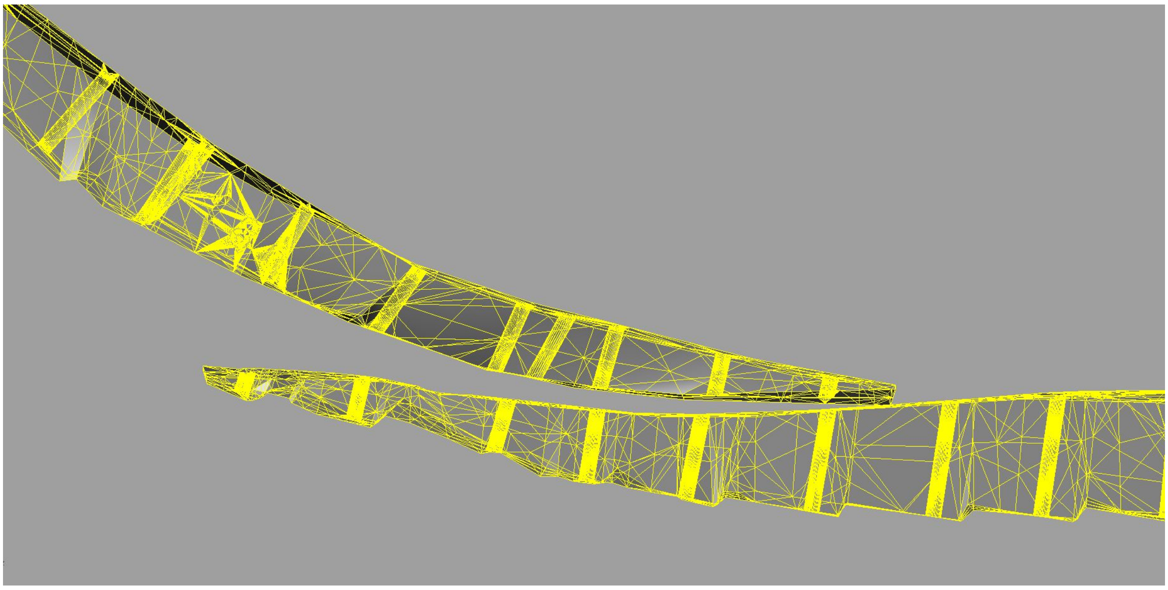

Figure 7-38 Significant localised distortion in certain framing timbers at the scarf joints, with some of the distal ends deflecting downward by more than 100mm (Toby Jones)

As an example, the three constituent components of frame 25, floor, first and second futtock, from the Newport Medieval ship was digitally re-orientated using the documented shape and by aligning the scarphed ends. This created a significantly different cross section profile to that represented by the assembly of the planking elements during the physical scale modelling process (Figure 7-39) . Repositioning the documented frames within the hull form represented by the physical scale model (Figure 7-40) clearly highlights the distorted nature of the distal ends of each scarph joint. This is a clear example, and a cautionary tale for anyone who attempts using certain individual elements in isolation, or believes that the relatively massive nature of heavy structural elements will resist distortion and as such represent the original shape and form of the hull. Figure 7-39 clearly highlight the significantly different profile shape resulting from what may seem minor or insignificant localised distortions. Particularly if the distortion involves angular measurements such as the distal end of the floor timber, resulting in an exponential increase as the distance increases

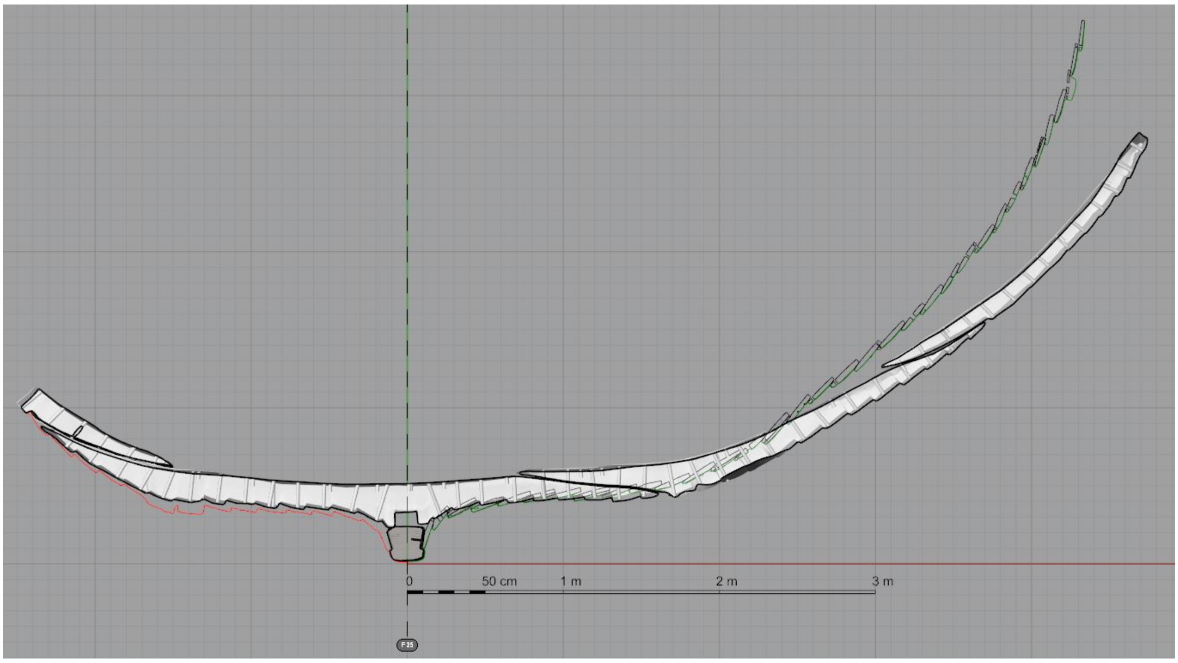

Figure 7-39 Frame 25 assembled relative to the documented shape of the scarph joints ends (Pat Tanner)

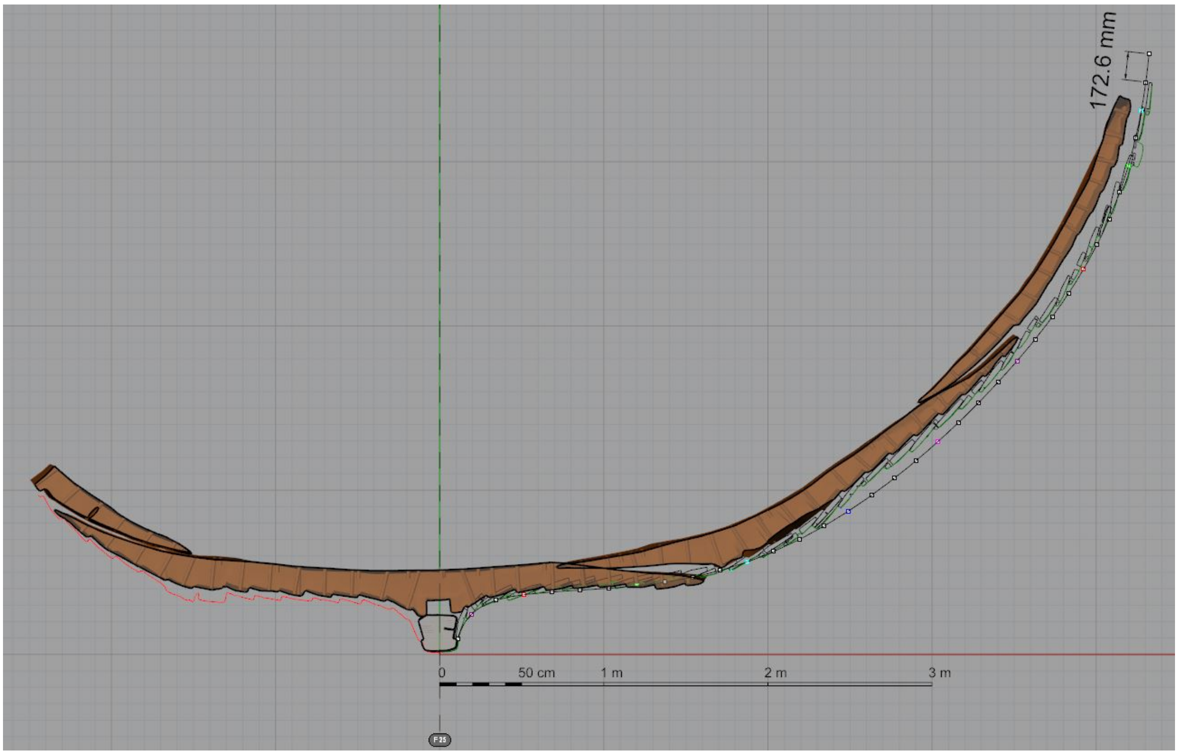

Figure 7-40 Frame 25 temporarily repositioned relative to the documented shape of hull based on the physical scale modelling. Note the misalignment of the scarph ends. (Pat Tanner)

7.10 Fairing the archaeology

Localised distortion will typically manifest itself in the form of unfair regions in what would otherwise be a smooth or fair curvature of the hull. Fair is a term that is used whenever a boat is built. When wood is bent or curved a boat builder must be concerned about fairness. A "fair curve" is one that is as smooth as it can be as it follows the path it must take around the hull of a boat. A fair curve is free of extraneous bumps or hollows and is pleasing to the eye. In addition to the simple aesthetic reasons, a fair surface will also aid the flow of water around and past a vessel's hull, and any bumps or hollows will cause turbulence in the water flow adding to hull drag.

If a clean straight plank of timber, free from imperfections such as knots or unusual grain pattern, is bent, using equal pressure about a fixed central point, that timber will naturally form a smooth arc or segment of a circle which has a fixed measurable radius. Rhinoceros 3D has two features critical to this form of analysis, the dimension curve length command, and the curvature graph feature.

The straight plank represented by the line A – B (Figure 7-41 top) is 12 m long and does not show the curvature graph as it is a straight line devoid of any curvature, bumps or hollows. If the midpoint of the plank is fixed at point C, as the ends A and B are moved 1.77 m, the length of the plank remains fixed at 12 m, forcing both ends to move toward each other, thereby shortening the direct distance between points A and B to 11.3 m. Without further external influence the resulting curvature is constant, forming a partial segment of a circle, which is represented by the equal length and equal spacing of the curvature graph in red (Figure 7-41 bottom)

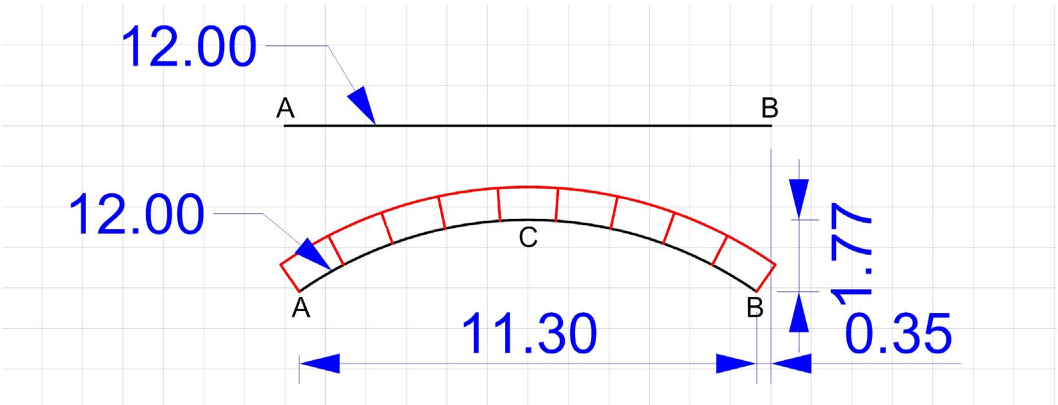

Figure 7-41 Measuring the curvature or fairness as a plank bends (Pat Tanner)

As we rarely build circular vessels, more control points, in the form of internal framing, will be required to force the curvature, which is trying to maintain smooth arcs, into the shape required for a vessel. The insertion of two frames, as at points D and E in Figure 7-42, will result in a localised flattening of the arc form to create an ellipsoidal form. The plank still maintains the overall 12 m total length, and if the end points A and B are maintained, the offset distance between points A – B and points D – E will automatically reduce from 1.77 m to 1.46 m. The curve represented in Figure 7-42 top illustrates the ellipsoidal profile with the shorter red curvature graph lines in the central area between points D and E, indicating less curvature, and the progressively longer red curvature graph lines representing the increase in curvature approaching points A and B. The V shaped anomaly in the centre of the red curvature graph in Figure 7-42 bottom indicates a localised distortion or hollow in the region between points D and E.

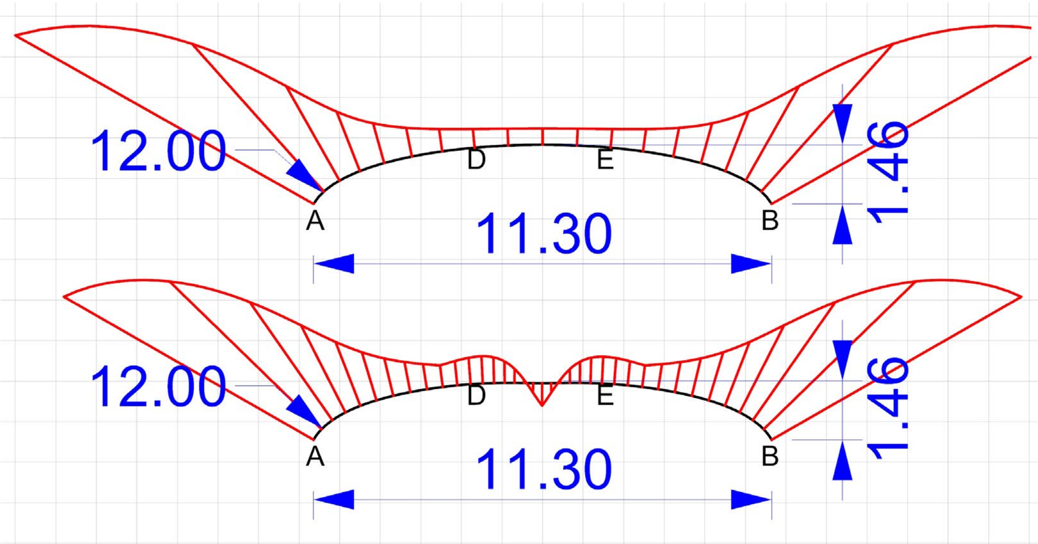

Figure 7-42 Measuring the curvature or fairness on complex profiles (Pat Tanner)

It is this process of generating curves and analysing their fairness or curvature which is at the very heart of firstly repairing, and subsequently developing the shape of the archaeological remains, and the subsequent projection of those remains to extrapolate missing portions of the overall hull shape. In Rhino 3D, all lines and curves are made up of control points which control and influence the degree of curvature between those control points. The 'curve' between points A and B in Figure 7-43 (top) consists of two control points and will remain a straight line no matter where the control points A or B are moved. The 'curve' between points A and B in Figure 7-43 (bottom) consists of three control points and will always remain a fair curve no matter where any of the control points A, B or C is moved.

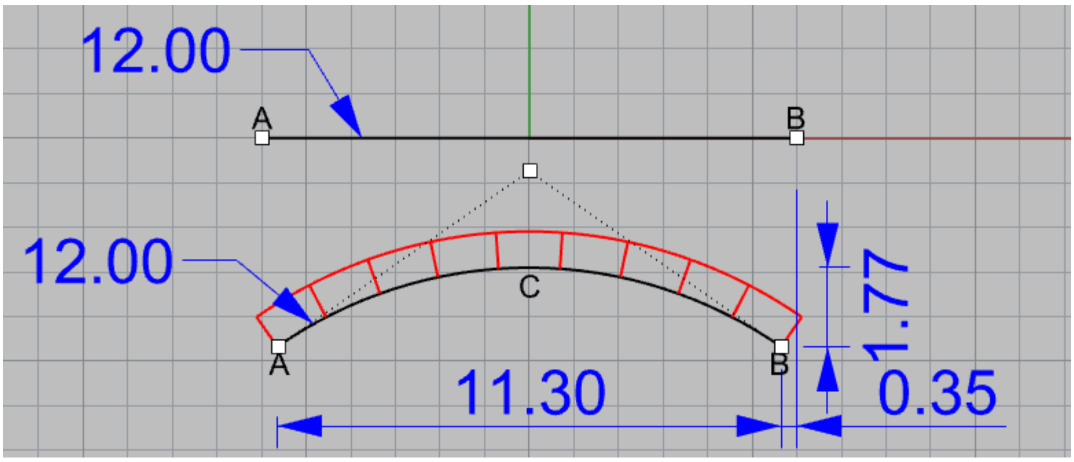

Figure 7-43 The same two curves from Figure 7-41 with their control points visible (Pat Tanner)

If we take the same curve from Figure 7-42 (top), the archaeological evidence represents a top down view for a plank of 12 m in length (chord length), which, as excavated, is curved into a faired elliptical form, represented by four control points, one at each end, A and B, representing the fixed distance of 11.3 m between extremities, and two further control points representing frames at D and E, which the plank was curved around (the control points between A – D and E – B). Subsequent further investigation of the evidence highlights an issue with frame E, it needs to move inwards by half its thickness. If both control points are moved further aft (Figure 7-44 bottom) the corrected curve form does not violate any of the archaeological evidence – frame E has moved inwards, the total plank length is still 12 m, the overall length between points A – B remains at 11.3 m, and the total width remains at 1.46 m – but the shape of the curve now represents the repaired hull shape, and is properly fair.

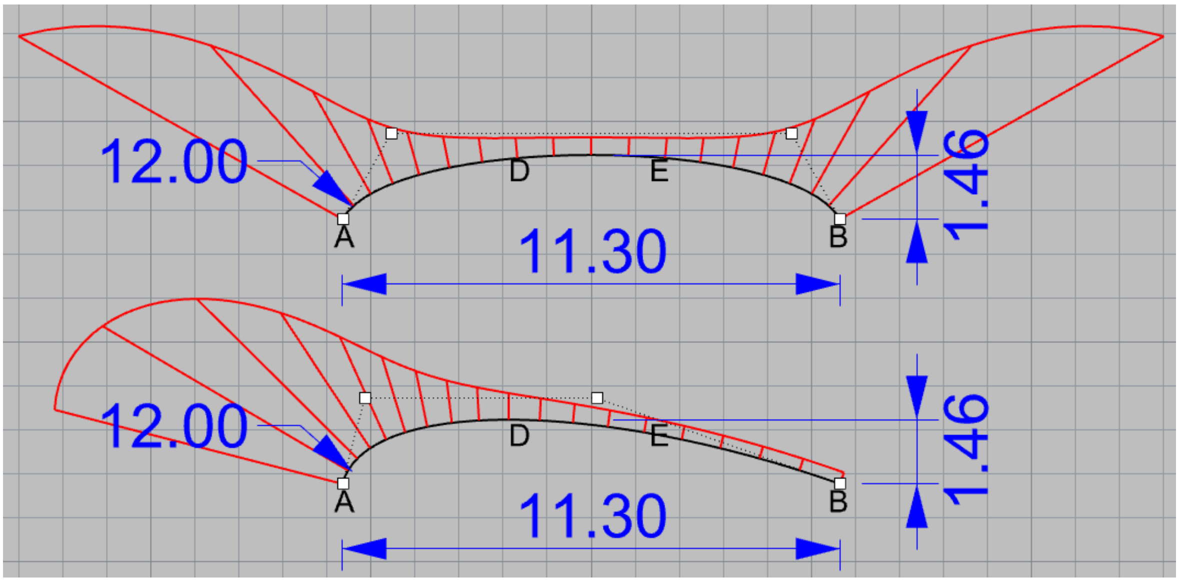

Figure 7-44 The same curve from Figure 7-42 top with the control points visible and repositioned to repair the overall shape (Pat Tanner)

7.11 Conclusion

With fairing curves projected onto the archaeological remains in both longitudinal and transverse directions, these curves are then faired in Rhino 3D to highlight areas of localised distortion. It is important to remember that each individual curve represents the three-dimensional shape of the hull surface and as such any point on a transverse curve must also coincide with the same relative point on the associated longitudinal curve. This has the effect of interpreting the idealised or faired hull form, shape state 2 from Table 7-1, based on the archaeological evidence.

Once shape state 2, the design intent shape imagined by the builder has been established in this manner, this can be compared with the archaeological evidence. Any differences between this idealised hull form and the archaeological record may indicate the actual as-built shape, or the use-life shape (states 3 or 4 from Table 7-1). These can then be further investigated for evidence pertaining to the human factors, the design and construction methodology or the material properties involved in the vessel's construction or caused as a result of the site formation phase.

Such an area can be seen in the middle-right portion of Figure 7-45. This shows the 3D laser scan of the external hull surface of the Newport Medieval ship, recorded from the post-excavation physical scale model. Where the scanned hull surface (grey) protrudes through the faired curves (red) highlights a localised distorted area. This area coincides with the portion of the hull which first came into contact with the underlying collapsed support structure as the vessel 'fell' over onto its starboard side, causing some localised distortion on that portion of the hull surface.

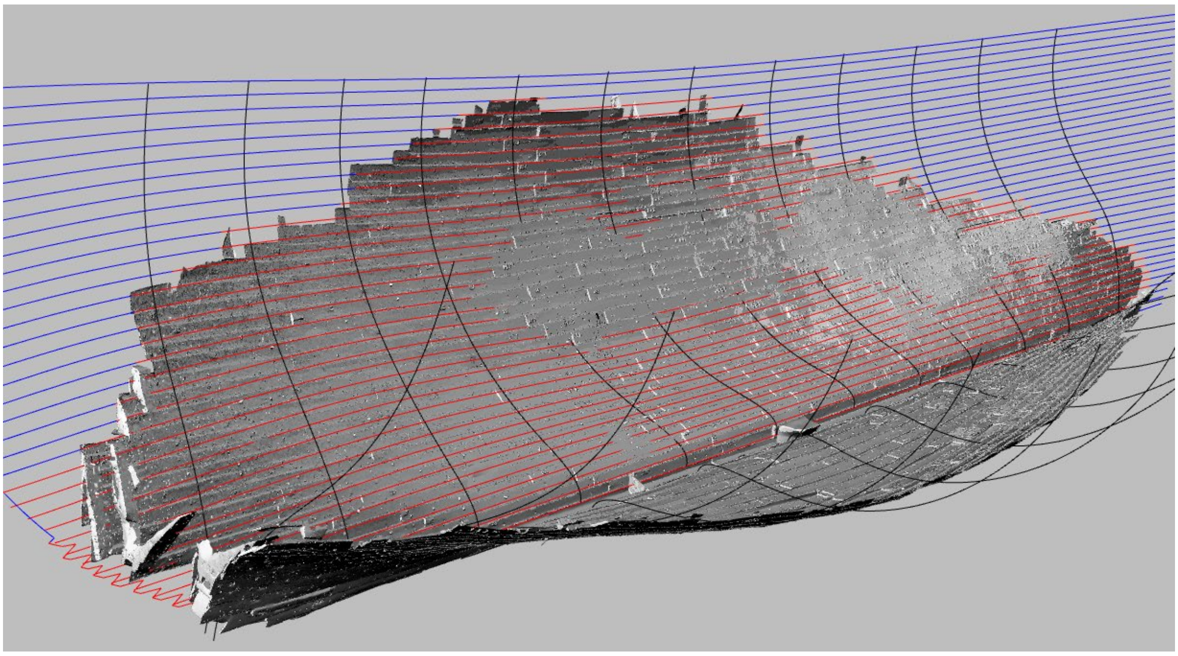

Figure 7-45 Fairing curves projected onto the archaeological shape to check for localised distortion (Pat Tanner)

With the archaeological evidence initially orientated to a reference baseline, and valid explanations developed for any global or localised distortion evident in the surviving material, that material can then be digitally repaired in order to reverse engineer the idealised hull form to recreate the design intent shape as represented in the archaeological evidence. As duplicate copies of the material are used to digitally modify and repair the evidence-based data, the result is a clear record of all the interpretation (paradata), allowing future researchers a better understanding of the processes employed. Once this process has been completed, the archaeological record has been correctly orientated and 'repaired', and attention can turn to the creation of a minimum reconstruction.

Chapter 8 **Creating the minimum reconstruction**

8.1 Introduction

The archaeological evidence, which has been recorded as three-dimensional high volume, high quality raw data, as discussed in Chapter 4, is stored as a full-sized three-dimensional data set, generating a superior archival record, which Steffy (1994:198) referred to as the hull catalogue. That data has been interpreted and categorised in Chapter 7, as well as being orientated and digitally repaired to remove both global and localised distortion.

In returning to the boatbuilding analogy of the processes I use when repairing or rebuilding an existing vessel, the archaeological data represents the original boat ‘as-found’, with all its damage and distortion. Once all the extraneous detail such as disarticulated elements or cargo remnants is stripped away, this leaves the articulated hull structure as the surviving evidence for the hull form (Figure 8-1). The data stripped away to leave the articulated hull form will be used at a later phase as an aid to further detailed reconstruction work.

Figure 8-1 The original damaged and distorted vessel lying at an arbitrary angle (Pat Tanner)

The articulated remains will then be repositioned onto the building strongback, a wooden framework used to both support and anchor the vessel during construction and rotated to a level orientation (Chapter 7.5). Next the stern and stem will be set-up plumb and vertical to remove any distortion, such as twist which may have developed in the original hull form (Chapter 7.8) and allow measurements to be taken from the surviving hull form (Figure 8-2), just as the archaeological remains were initially orientated and the global distortion digitally repaired in Chapter 7.

Figure 8-2 The original vessel positioned on the strongback (framework) and re-orientated level (Pat Tanner)

Next temporary moulds and lightweight timber fairing battens are fitted to the vessel (Figure 8-3) to position planking runs and ensure a faired hull form and even planking runs, just as digital fairing curves were used to highlight and repair areas of localised distortion in the archaeological remains (Chapter 7.10). Just as with the boat building or repairing process, once satisfied that the remaining structure is sound, straight and in alignment, the process of repairing or replacing damaged sections, and fabricating anew the missing portions can continue with confidence.

Figure 8-3 Temporary moulds and lightweight fairing battens to ensure a fair hull form, note the lofting floor in the background with planking being developed (Pat Tanner)

With the archaeological data now correctly orientated and any distortion quantified and repaired the process of developing the remaining hull form can continue. This may involve replacing or repairing some of the disarticulated elements, but at this stage the principle focus is more on the overall hull form. The goal being to recreate the watertight hull envelope, capable of floating, in order to establish the flotation condition. That watertight hull envelope is primarily defined by the centre-line profile – represented by the keel stem and stern post, the upper sheer curve – represented by the top edge of the uppermost hull planking strake, and the cross-sectional shape represented by the hull planking as it builds from the garboard strake at keel level up to the sheer (topmost) strake. All of the stages required to arrive at a 'minimum reconstruction' are set out and examined below.

8.2 The centre-line profile

The centre-line profile will rarely survive in its entirety in the archaeological record, with stem or stern post often displaced, damaged, or completely missing. This will need to be extrapolated from the evidence as it represents the fore and aft extremities of the idealised hull form.

8.2.1 Drogheda boat

In some cases, as with the Drogheda boat (Figure 8-4), sufficient evidence survives to easily extrapolate the missing portions. With the lower portion of the stem surviving up to the level of the eight strake, from a total of 15 strakes, the 50% surviving meant a simple extension as a fair curve should provide a reasonable starting basis. Similarly, the recovered sternhook indicated the sternpost was most likely a straight extension of the surviving material (Tanner 2013a; see Tanner Forthcoming:13–19 Appendix F for a detailed description).

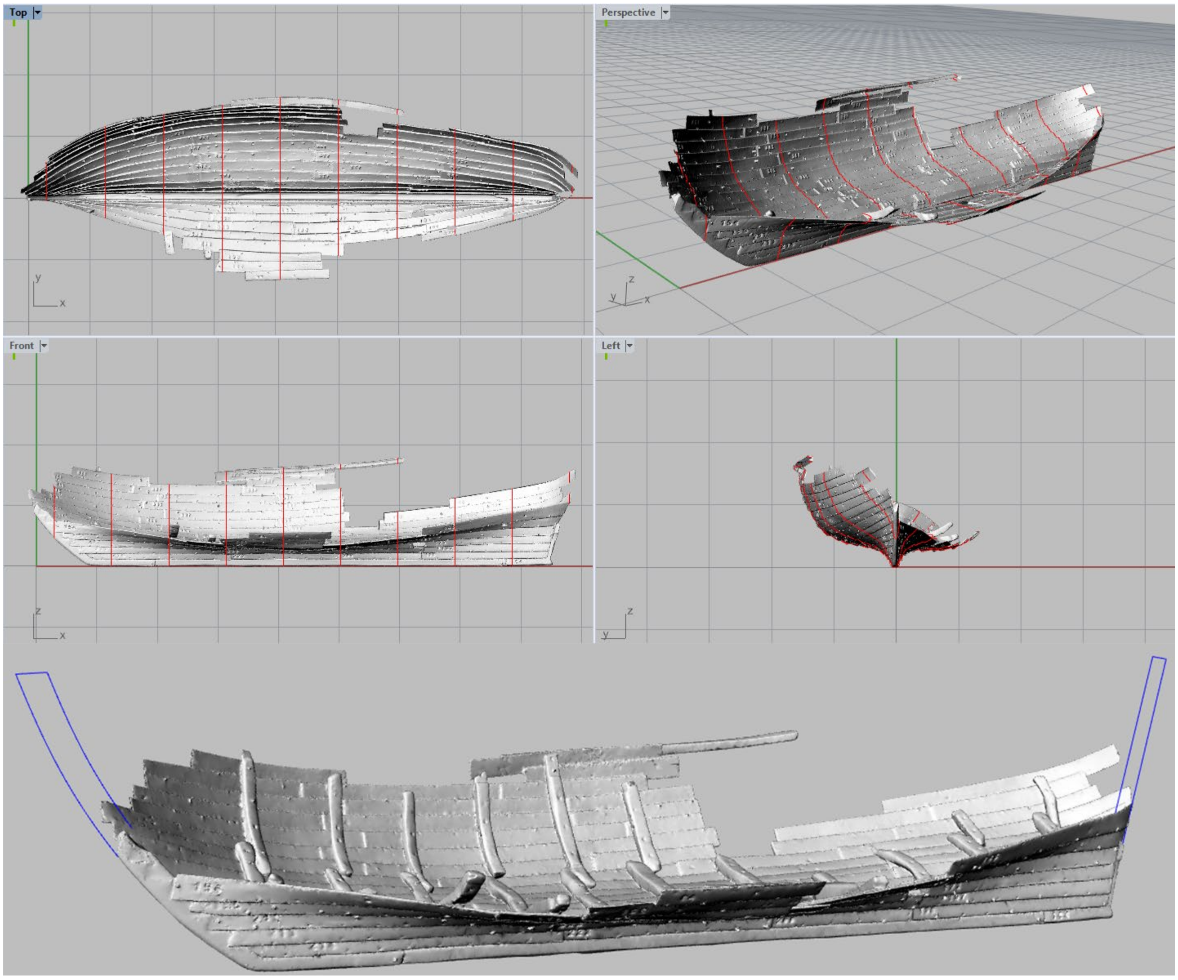

Figure 8-4 Drogheda boat showing outside hull surface (top), and posts extrapolated to recreate the centre-line profile (bottom) (Pat Tanner)

8.2.2 Newport Medieval Ship

However, in many cases, there is insufficient evidence surviving in the archaeological evidence to recreate the centre-line profile based solely on the keel, stem and stern. As occurred with the Newport Medieval ship, the coffer dam installed on-site decapitated both the stem and stern of the vessel. Subsequent excavations recovered some additional partial fragments of the stem and an associated section of hull planking, which allowed these elements to be digitally aligned with the main articulate hull structure (Figure 8-5). However, no evidence for the stern area was recovered apart from the swelling or increase in moulded depth of the keel starting at the aft face of frame 59 (Figure 8-6).

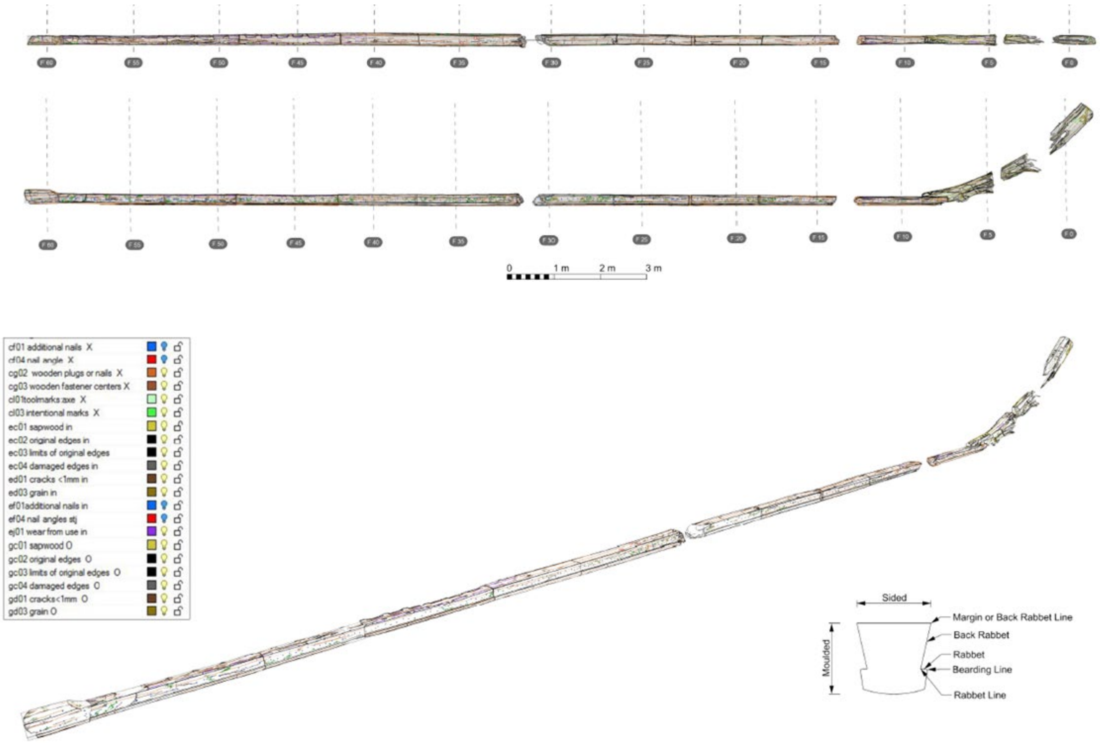

Figure 8-5 Surviving keel and stem fragments of the Newport Medieval ship (bow to the right) (Pat Tanner)

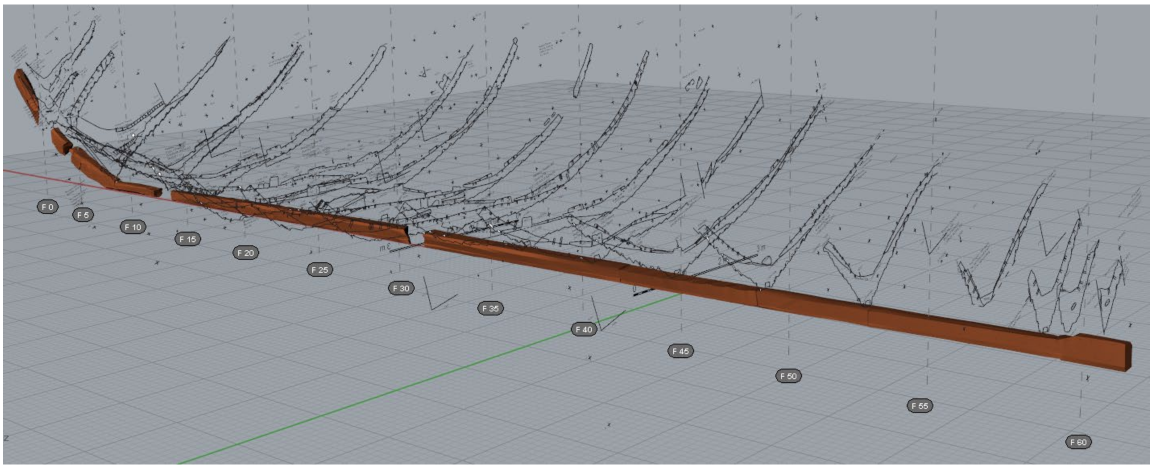

Figure 8-6 Newport Keel and stem timbers with 2D hand drawn site sections (bow to the left) (Pat Tanner)

While the fragmented stem provides some evidence for the shape of the lower forefoot it only represents the lower 10 strakes from a surviving minimum of 34 strakes. In these situations, it becomes necessary to turn to available evidence from the hull planking to supplement the missing areas.

8.3 The hull planking

In relation to the watertight hull envelope, the hull planking represents three key elements. The upper edge of the topmost strake represents the sheerline curve, the fore and aft extremities of the hull are delineated by the location of the hood ends – the extremity of each strake where they terminate at the stem or the stern post, and the changing cross sectional form of the hull as it transitions from a near vertical line at either end towards its widest and fullest shape somewhere along the length of the vessel at the point of maximum beam.

8.3.1 Drogheda boat

With a large portion of the hull planking surviving on the starboard side, up-to and including a portion of the sheer strake and its associated rubbing strake, meant that the archaeological evidence provided a clear limit for the sheer height, at least in the central portion of the vessel. A fairing curve was created to represent the lower edge of each strake, as well as a cross-sectional curve at 0.5 m intervals along the hull (Figure 8-7).

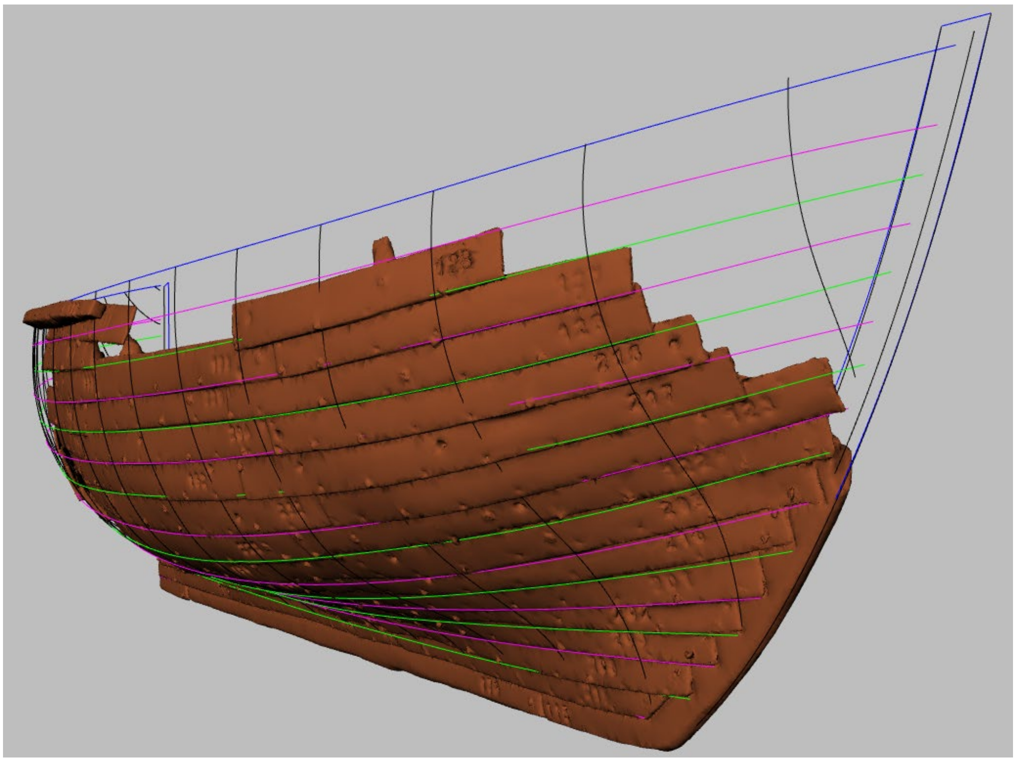

Figure 8-7 Drogheda Boat with fairing curves modelled for each hull strake (Pat Tanner)

This was done using features available in Rhino 3D, such as the project curve onto mesh function for the section curves, and the PolylineOnMesh command for the strakes lower edge. While these curves initially conform to the exact archaeological evidence, representing any unevenness or distortion as documented from the archaeological record, a duplicate set are created and digitally faired using the curvature graph feature as described in Chapter 7.9. It is important to note that these curves are three-dimensional in their nature, and this fairing needs to be checked in all three views, top-down, side-on and end-on, as well as coinciding with one another where the intersect. This provides a record between the as documented, post-excavation shape (state 7 from Table 7-1) and the idealised or faired design intent shape (state 2 from Table 7-1).

8.3.2 Newport Medieval Ship

In cases where more incomplete archaeological remains survive, simply extending the faired strake curves may not provide satisfactory evidence to establish the stem or stern post position with an acceptable level of confidence. Such was the case with the Newport Medieval ship, where the available evidence for the bow area included the forward extremity of the keel with its keel to stem scarph joint intact (Figure 8-8), as well as a small portion of the lower extremity of the stem which were recovered as part of the articulated hull remains. A second excavation outside the site cofferdam area resulted in the recovery of further fragmented remains of the stem and some associated hull planking.

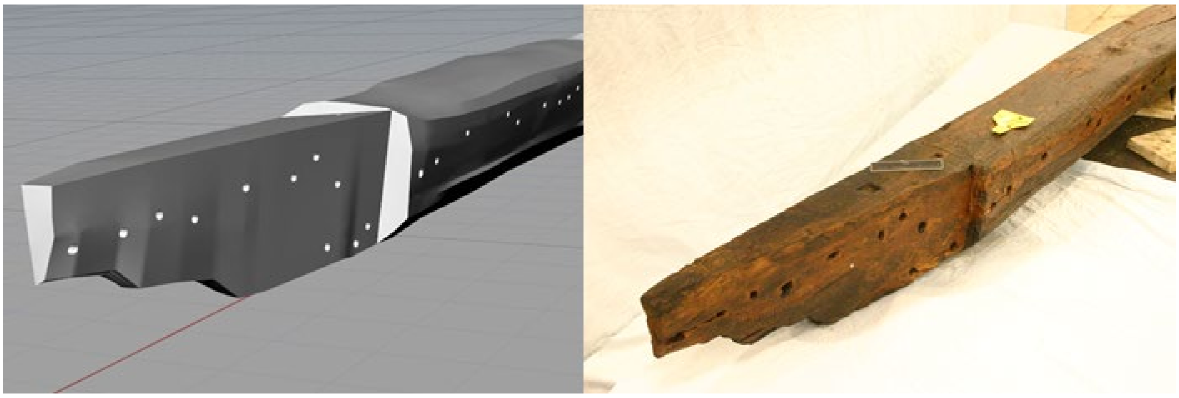

Figure 8-8 Forward end of keel showing keel / stem scarf joint (image courtesy of Newport Museum and Heritage Service)

The recovered hull planking section allowed the recovered fragments to be digitally reassembled and aligned with the rectified mesh scan, which indicated the vessel had a curved stem at least to the level of the 14th strake. In addition, there was clear evidence that the first 11 strakes had individual stepped rebates cut into the stem for the forward hood ends, before transitioning into a continuous single rebate for the remaining strake hood ends (Figure 8-9).

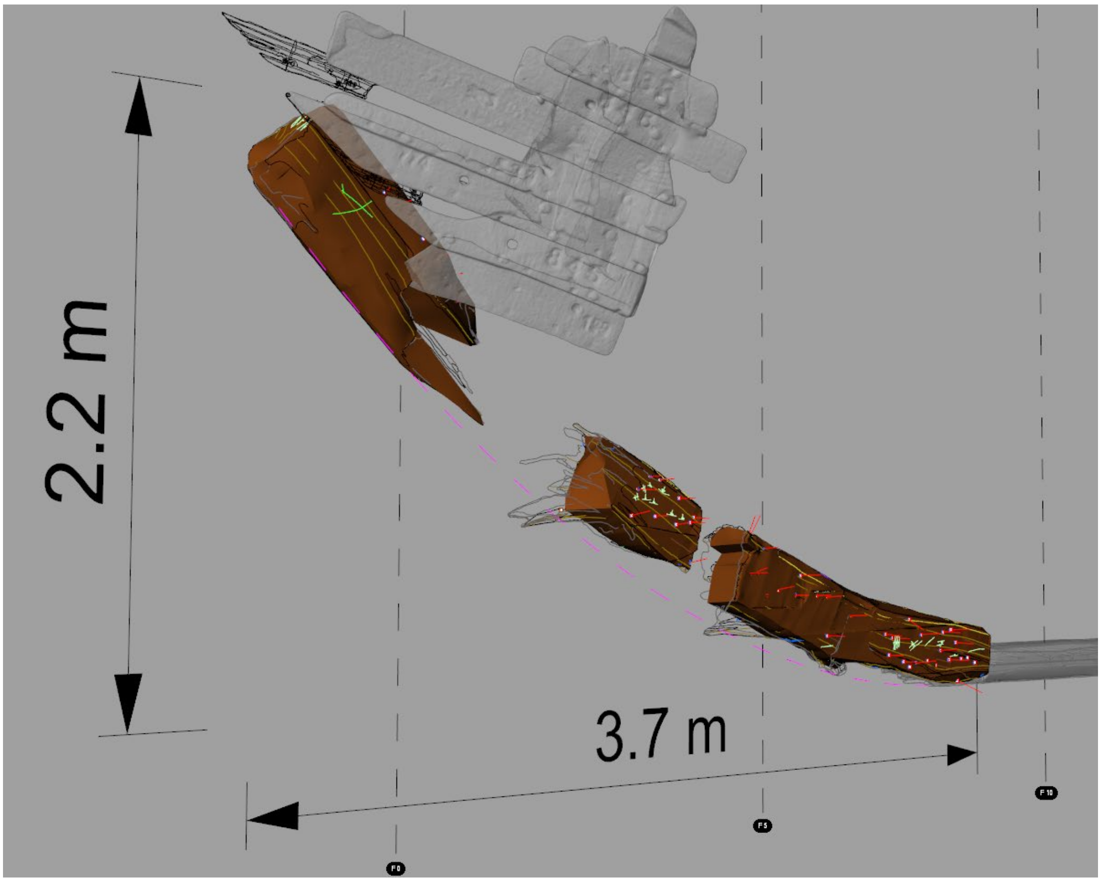

Figure 8-9 Reassembled stem fragments correctly aligned, also showing the transition to a single continuous planking rebate (Pat Tanner)

There was no evidence surviving for the position or angle of the stern post, save for the beginnings of a swelling in the keel commencing at the aft face of frame 59, which was interpreted as representing the beginnings of the stern assembly structure.

Figure 8-10 The recovered aft end of keel with "swelling" (image courtesy of Newport Museum and Heritage Service)

No definitive evidence of the sheer line height was recovered, so a temporary sheer line was established at the height of the top of the highest recovered strake. At frame station 25 there were 34 complete strakes and a partial 35th strake recovered on the starboard side.

In order to extrapolate the height of the sheer line a section curve through the scanned physical scale model was created at every fifth frame station and the strake sections as recovered were best fitted to each section curve. This provided an accurate shape and height for each strake run, based on the physical scale model, which represented the post-excavation shape state (Figure 8-11).

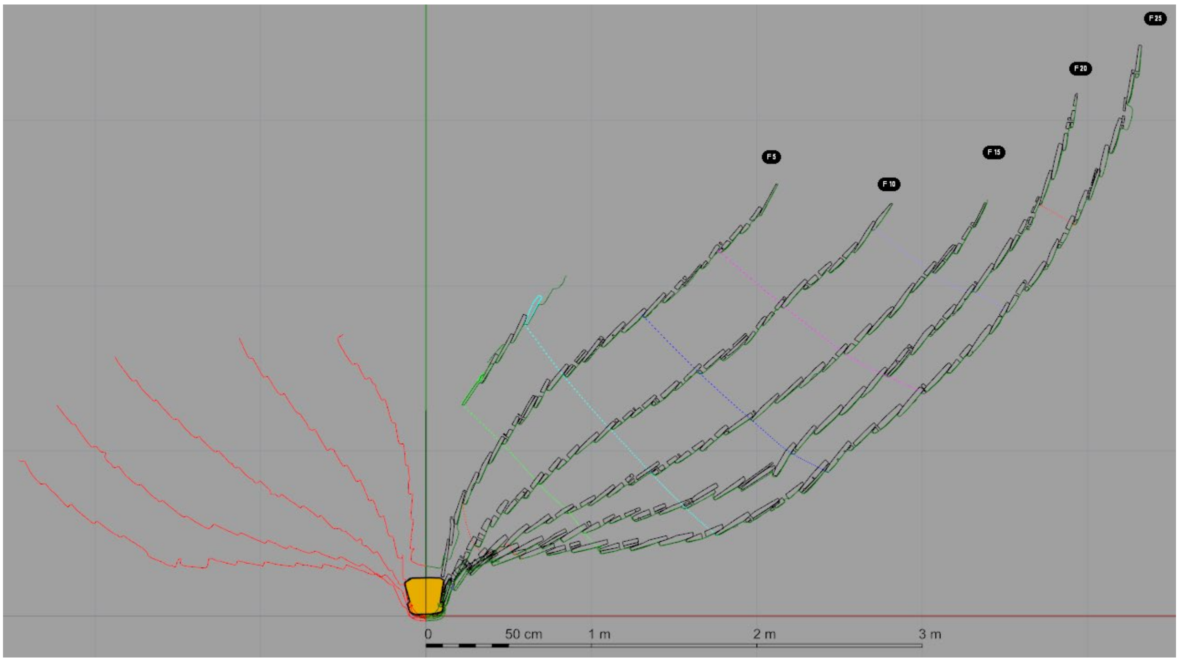

Figure 8-11 Recorded strake widths fitted to sections taken from the physical scale model (Pat Tanner)

Next, each strake was individually examined to determine whether parallel sided non-tapering plank widths were used, or if the strake widths tapered towards both extremities of the vessel. By determining the number of strakes and their widths, a chord length (the distance around the curve) can be estimated for the bow and stern of the vessel, giving an approximate height for the sheer curve at either extremity. In the case of the Newport Medieval ship this is process is detailed in the report: Reconstructing the Hull Shape (Tanner 2013b:33–50).

This provided an average width for each strake at the bow, midship and estimated stern locations, which allowed an approximation of the original sheer height. This allowed a digital fairing curve for the strakes to be extended and faired to generate an approximate hull form for the watertight envelope. However, while the surviving lower portion of the stem allowed the positioning of the estimated stem curve with a degree of confidence, the exact location of the stern post was not immediately apparent (Figure 8-12).

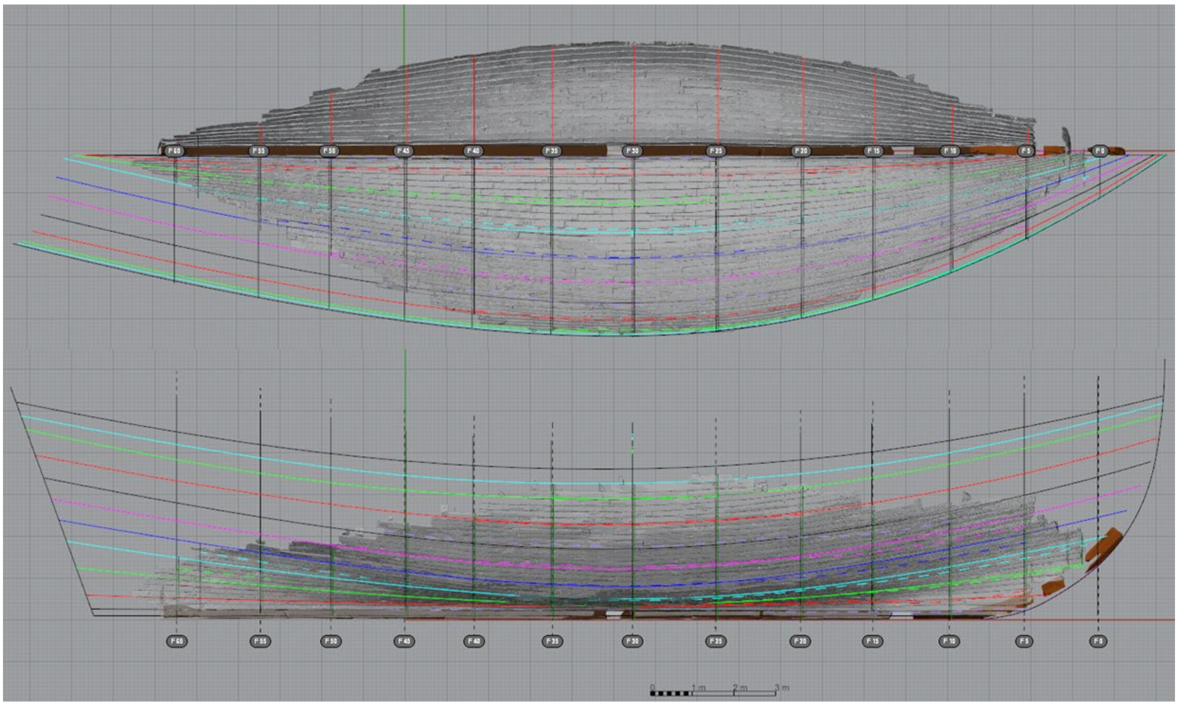

Figure 8-12 Approximate hull form based on extrapolated strake widths (Pat Tanner)

8.4 Closing the ends

In many cases, as previously discussed in Chapter 8.3.2, and clearly illustrated in Figure 8-12, one or both extremities of the vessel may not survive, and it becomes necessary to determine how the ends of the vessel were ‘closed’ to form the watertight envelope required for flotation. Typically, with the bow this is easier to establish, as the termination of planking will (almost always) be into the stem, representing a fixed position in one of the three possible planes of movement. This leaves just the fore and aft length of each strake and the vertical width of each strake to be established to reconstruct the stem area with a relatively high degree of confidence.

The stern can often prove a more difficult area to reconstruct with the same levels of confidence. The possibility of two distinct hull forms – double-ended or transom stern – results in two equally viable solutions, resulting in significantly different hull forms. Evidence suggesting that the hull planking terminated in a stern post (double-ended) allows for a simpler solution as employed in reconstructing the stem area. However, evidence suggesting a transom stern exponentially increases the difficulty, with the added freedom of movement in the transverse plane. Additionally, this movement in the transverse plane is rarely uniform for each hull strake as the shape of the transom often changes as it rises from the keel level to the sheer line.

8.4.1 Drogheda boat

As noted in Chapter 8.2.1, the extent of surviving evidence for the stem and the sternhook provided reliable evidence for the centre-line profile, and the surviving hull planking gave a strong indication for a double-ended vessel. With the width or transverse positioning of each strake thus fixed, it was simply a matter of extending the faired strake runs, while monitoring their length and vertical spacing, to close the ends and generate the watertight hull envelope (see Appendix F: 13-16 for a detailed description).

8.4.2 Newport Medieval Ship

As no evidence was recovered for the stern post, and only a limited quantity of hull planking surviving in the area, contemporary evidence and iconography were consulted to find potential stern post configurations. On the 14th century Sandwich wreck, the sternpost rose at an angle of between 110 and 117° and the vessel had a transom hung rudder supported on three or more pintle and gudgeons (Milne 2004:239). For the Skaftö wreck, von Arbin (2009:70) calculated a sternpost angle of circa 122°. An average sternpost angle of 110° was used for the Newport Ship reconstruction (Tanner 2013b:31–32). While a stern post angle could be estimated based on contemporary evidence, and with both ends of the vessel truncated by the site cofferdam the actual position and hence overall length of the hypothetical reconstruction was still an uncertainty (Figure 8-13).

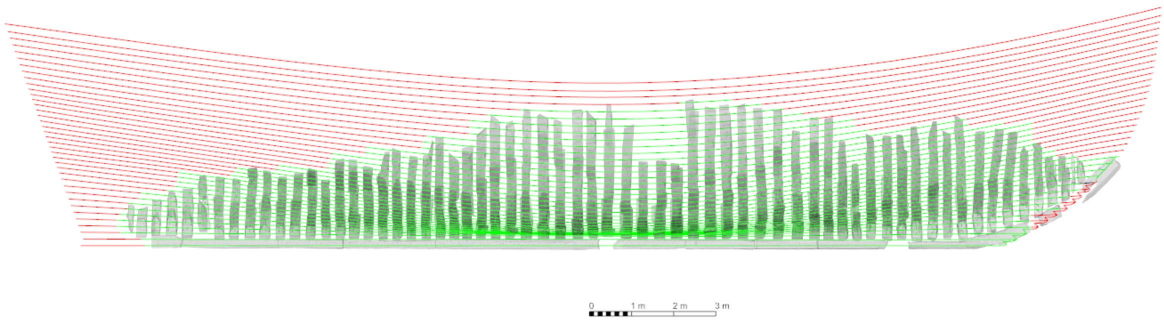

Figure 8-13 Recovered hull shape in green and developing hypothetical hull shape in red (Pat Tanner)

With a potential angle for the stern post, the next question was how the hull planking was terminated, either attached directly to the post, or to a stern transom. Loewen (in Grenier *et al.* 2007:III–132) states that the first-known depiction of a vessel with a flat transom in the Atlantic is a votive painting found in the church of San Pedro in Zumaia in Gipuzkoa, which depicts events of 1475. I have argued (Tanner 2013b:60) that an earlier depiction of a three masted ship, from *Liibre de les Ordinaciones de l'Administrador de les Places***,** folio 67R (Mott 1994:39–40) could also depict a vessel with a flat transom. The vertical line extending from below the aft corner of the stern-castle down to the waterline together with the abrupt change of angle in the strake runs coinciding with this vertical line could, I believe, indicate a transom stern, which would predate the Newport Medieval ship by over 50 years.

Further detailed examination of the recovered portion of the hull and structure were examined for any possible indication of the hull shape as it approached the stern area (see Tanner 2013b:54–60 for a detailed description)). Attempts at both digital and physical modelling to recreate a double-ended hull form resulted in some very distorted frames and 'tortured' strake runs Figure 8-14. Following much discussion and consultation, a transom end was seen as the most likely of the hypothetical solutions.

Figure 8-14 Physical scale model with fairing battens 'forced' into a double-ended hull form (Newport Museums and Heritage Service).

To determine the fore and aft extremities at bow and stern, the plank lengths making up each strake were examined to determine both the shortest and longest lengths used in the building of the vessel (Table 8-1).

Visible Length †	Port Side	Starboard Side	Total Number
< 1m	0	1	1
1 – 1.5 m	3	8	11
1.5 – 2 m	12	19	31
2 - 2.5 m	28	37	65
2.5 - 3 m	28	50	78
3 - 3.5 m	23	42	65
3.5 - 4 m	1	15	16
> 4 m	0	3	3

Table 8-1 Newport Medieval ship recorded plank lengths (Pat Tanner)

† Visible length is from the aft end of the forward scarf to the aft end of the plank on the outboard face. Incomplete, damaged or fragmented planks have not been included.

These lengths were then overlain on the existing strakes beginning at the preceding complete scarf end. Taking a minimum and maximum plank length, and adding that to the preceding complete scarph joint, created a probability box shown hatched in Figure 8-13. The overlapping region within these probability boxes indicated a probable location for the aft hood ends. A stern post at the 110° angle (taken from archaeological and historical parallels) was then created to fit within this probability box. The process is detailed in the report: Reconstructing the Hull Shape (Tanner 2013b:51–60).

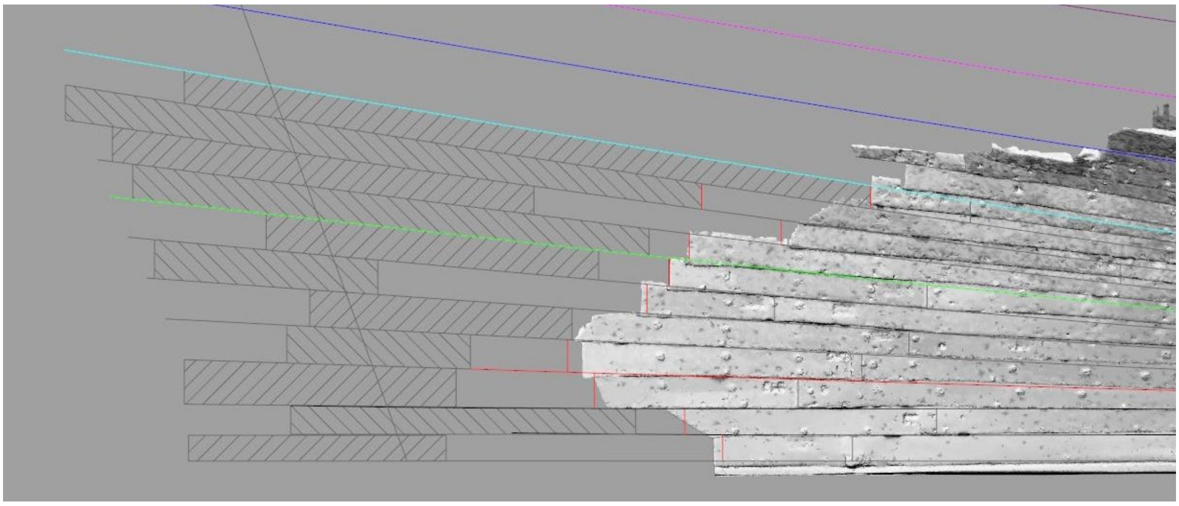

Figure 8-15 Newport ship probability box for aft hood ends (Pat Tanner)

8.5 Watertight envelope

The archaeological remains of the vessel have now been 'repaired' to remove both global and localised distortion (Chapter 7.8 to 7.10). The recovered partial remains have been extended to determine the hypothetical extents of the hull using faired curves, essentially a digital version of Steffy's (1982:65–66) 'mould and batten' model (Figure 2-16 right). This has the same effects as McGrail's definition of 'as-found' [83] but without the assumption of rotating the vessel to its deduced flotation attitude when afloat, as this is still an unknown. In effect it establishes the limits for the watertight envelope which represents the hull form, in an idealised or fair form, representing shape state 2 from Table 7-1 – the design intent shape as imagined by the builder,

8.5.1 Drogheda boat

Once the fair curves representing strake runs and cross section profiles are created, they can simply be extruded to generate a simple surface using the Rhino 3D loft curve command. These surfaces are then colour coded to indicate surviving material in brown, areas required for a watertight envelope in blue (Figure 8-16).

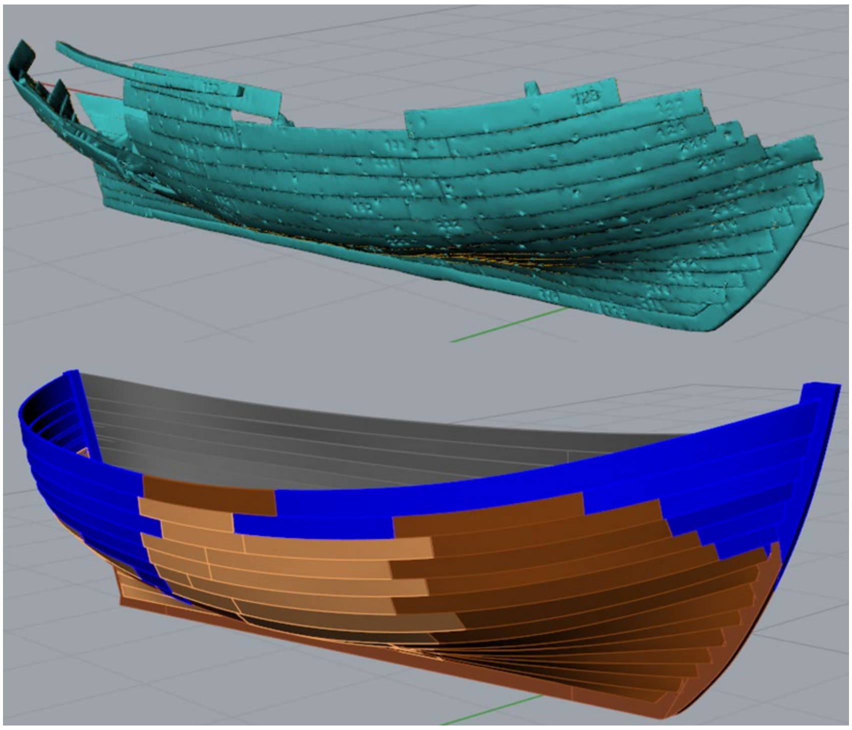

Figure 8-16 Drogheda boat remodelled hull to create watertight envelope (Pat Tanner)

[83] a model formed of the boat as found, but with distortions and compressions removed, displaced elements replaced, fragmented timbers made whole, and the hull rotated to its deduced attitude when afloat (McGrail 2007:255)

8.5.2 Newport Medieval ship

Unlike the Drogheda boat where some archaeological evidence survived as an indication of the sheer height, providing an upper limit to the watertight envelope, no such evidence was recovered for the Newport Medieval ship. In this case the upper limit of the surviving evidence was a partial fragment of the 35th strake, and clear evidence for a deck which coincided with the level of the 33rd strake. Clearly a sheer height based on the surviving evidence would not be commensurate with the evident deck position. As such, the sheer height of the watertight envelope was raised to a suitable (1.2 m or elbow level) height above the deck level.

Again, these fair curves representing strake runs and cross section profiles are extruded to generate a simple surface using the Rhino 3D loft curve command and colour coded to indicate the surviving material in brown, areas required for a watertight envelope in blue, and elements for which partial evidence survived in green (Figure 8-17).

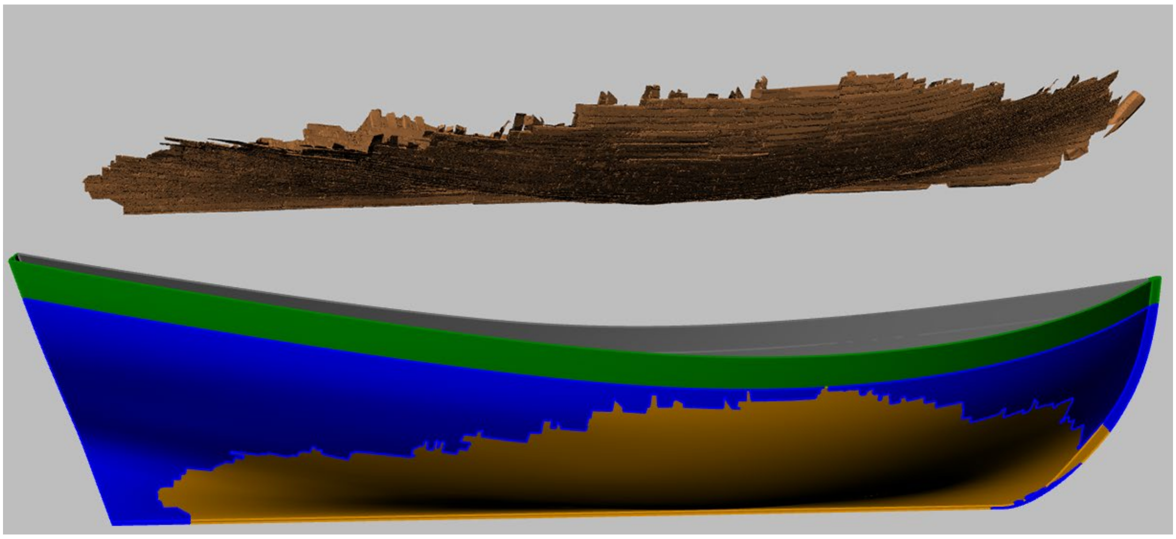

Figure 8-17 Newport Medieval ship remodelled hull to create watertight envelope (Pat Tanner)

While this surface model represents the watertight envelope of the vessel, which can be analysed and measured at various flotation depths to determine the submerged hull volume and hence the weight of water that volume displaces, as already noted in Chapter 7.5, many vessels do not float on an even or level keel as can be seen from Figure 1-5.

This flotation attitude, or fore-and-aft trim, is primarily affected by the underwater hull form and the longitudinal position of the centre of gravity. The underwater hull form has been established from the watertight envelope, and in order to determine the position of the centre of gravity, a weight analysis study of the vessel will need to be completed.

8.6 Floating hypothesis: a preliminary analysis

As already discussed in Chapter 6, Orca 3D a plug-in for Rhinoceros 3D, can be used to determine the exact flotation characteristics of the vessel based on the hull form and its weight. This allows a simplified single surface model of the hull to be analysed and tweaked rapidly and relatively simply. Once the design is approaching the desired results, the individual components are then accurately modelled to produce more accurate and realistic floatation characteristics based on the exact weight and position of each element.

A common practice used in naval architecture when designing, or modifying a hull during the initial phases, is to use average weights to analyse how the hull designs will float and react. One method of doing this is to take an average of the hull construction weight, such as the hull planking and framing and "smear" this average weight onto a simplified single surface hull, rather than modelling each separate component.

8.6.1 Drogheda boat

This was a relatively small vessel, with few internal components (13 frames in total). The extent of the surviving structure, and the overall hull form required little fairing to achieve the watertight envelope stage. Based on my own boatbuilding and sailing experience of similar size and shape vessels, it was possible to estimate the flotation attitude with a high degree of confidence. In any event, if subsequent analysis indicated any changes were required the digital modelling process was such that these could be easily achieved. For these reasons, the process moved directly to the digital modelling of the minimum reconstruction. However, this bypassing of the intermediary steps can be a costly error in terms of time if the subsequent reconstruction is significantly different or incorrect. In this case, the fully modelled minimum reconstruction floated within a few millimetres of the estimated flotation condition.

8.6.2 Newport Medieval ship

For the Newport Medieval Ship, the average strake thickness is 31 mm. Allowing for the double thickness in the overlapping area of clinker construction, results in a notional strake thickness of 46.5 mm. The framing has an average moulded dimension of 195 mm. Average sided dimensions are 230 mm with an average inter-frame spacing of 118 mm. Taking half the frame moulded dimension of 97.5 mm plus the notional strake thickness of 46.5 mm gives a notional solid hull thickness of 145 mm.

The single skin surface model representing the watertight envelope was initially orientated with the keel sitting level, and the bottom centre (relative to the surviving extent) of the keel positioned at the digital world origin (0,0,0,in the X,Y and Z axis) As the keel length had been modified in creating the watertight envelope, the digital world origin was now reset to coincide with the bottom aft extremity of the keel. This provides a more readily identified point of reference for the subsequent flotation calculations.

A standard notional moisture content of 27% was used throughout testing which would result in oak having a typical average density of 800 kg/m³. This allowed Orca 3D to determine the overall weight and centre of gravity for the watertight envelope hull form, based on the single skin surface having a notional solid thickness of 145 mm. A reduced notional solid thickness of 120 mm was used for the deck surface. While this does not generate an accurate analysis of the total combined hull weight, it generates an average result suitable for preliminary testing, and provides an impression of the potential capabilities of the floating hypothesis.

For this configuration, which is the hull structure required to create a watertight envelope, Orca 3D determined the combined weight of the vessel to be 60,959 kg, with the centre of gravity located 11.77 m forward of the aft face of the keel and positioned 2.66 m above the keel lower surface. Based on the hull form, this resulted in the vessel sinking to a depth of 1.42 m, with 0.451° of negative or 'stern-down' trim. This results in the vessel sitting with a draft of 1.42 m at the stern, and a draft of 1.22 m at the bow, which would indicate that the vessel is capable of floating in this configuration, and has more than sufficient freeboard (2.83 m midship) remaining.

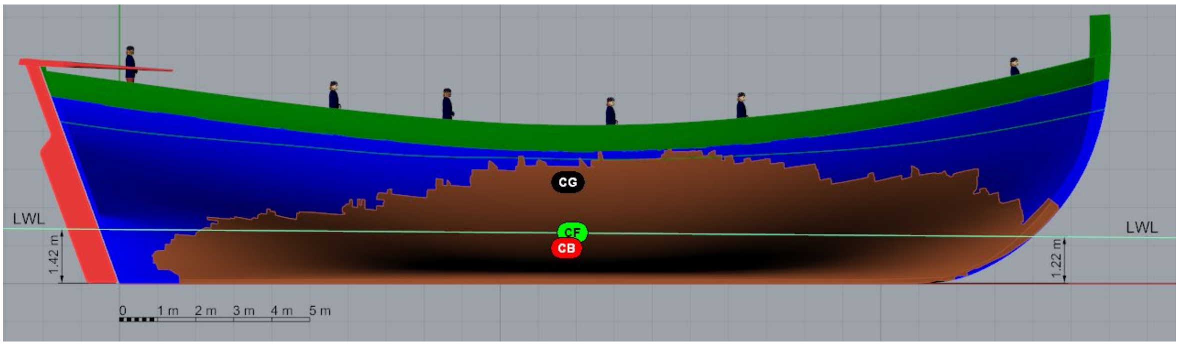

Figure 8-18 Flotation condition based on a notional hull thickness (Pat Tanner)

While ethnographic evidence suggests that for inland waters, small boats were loaded to very little freeboard (McGrail 1978,91). Seagoing data is not readily available, however a medieval Icelandic Law in the *Grågås Codex* states the minimum freeboard (F) of a cargo ship should be F=2D/5 where D=depth of hull amidships (Morken 1980,178). In the case of the Newport Medieval ship, based on the watertight envelope, this minimum freeboard would be 1.67 m. If the vessel were adjusted to this minimum freeboard while maintaining the same flotation attitude, the total displacement would be 206,690 kg.

With the notional hull weighing 60,959 kg, this allows a total of 145,731 kg for cargo and the elements such as rigging and castles which were not included in the watertight envelope calculations. In this flotation condition the draft aft would be 2.62 m, and the forward draft would be 2.33 m, while maintaining the minimum 1.67 m freeboard as set out in the *Grågås Codex* (Figure 8-19).

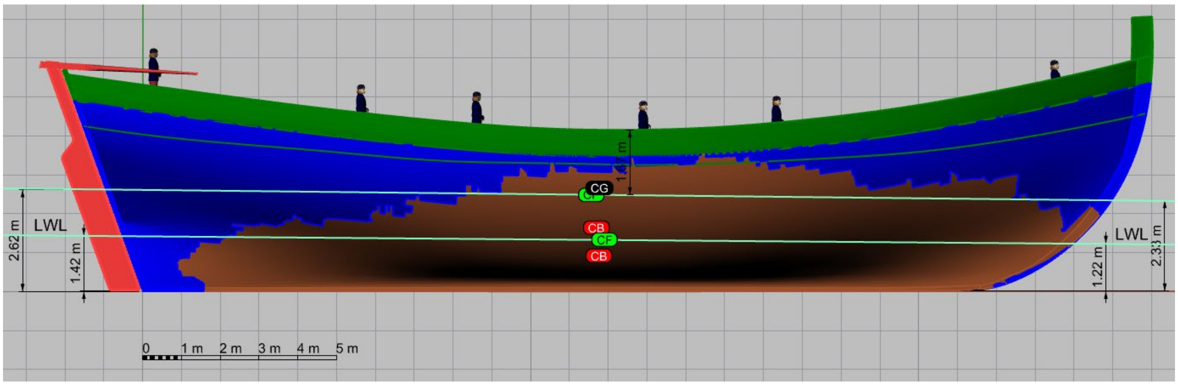

Figure 8-19 Newport Medieval ship remodelled hull to create watertight envelope adjusted to minimum freeboard flotation condition (Pat Tanner)

8.7 The hull structure

Once the floating hypothesis has been created, and analysed to ensure it functions as a vessel, the process of creating the hypothetical minimum reconstruction can proceed. Typically, this will involve digitally modelling each hull strake as a solid object rather than the single skin surface used to represent the watertight envelope. This is followed by creating each component of the internal structure. Either by importing each of the individually recorded timbers and repairing their shape as necessary to match the watertight envelope hull form already created if these are available. Or by creating new digital models to represent damaged or missing components. This process will enable Orca 3D to accurately calculate the hydrostatic characteristics based on the exact dimensions, geometric shape, weight, and position of every component part.

8.7.1 Drogheda boat

Every component part was created as a new digital solid model (see Appendix F: 15-22 for a detailed description). The individual strakes from the watertight envelope surface were thickened using the Rhino offset surface command to generate solid strakes. These were then split along their scarph joints to recreate the individual planks making up each strake. Next, attention turned to the internal structure, and the surviving components were recreated as digital solids before recreating the missing components such as the futtocks shown green in Figure 8-20. Additional elements, where no evidence survived, but deemed necessary based on boatbuilding experience, such as the cant frames to support the hull between the last surviving frame and the stern post were then added (coloured red in Figure 8-20)

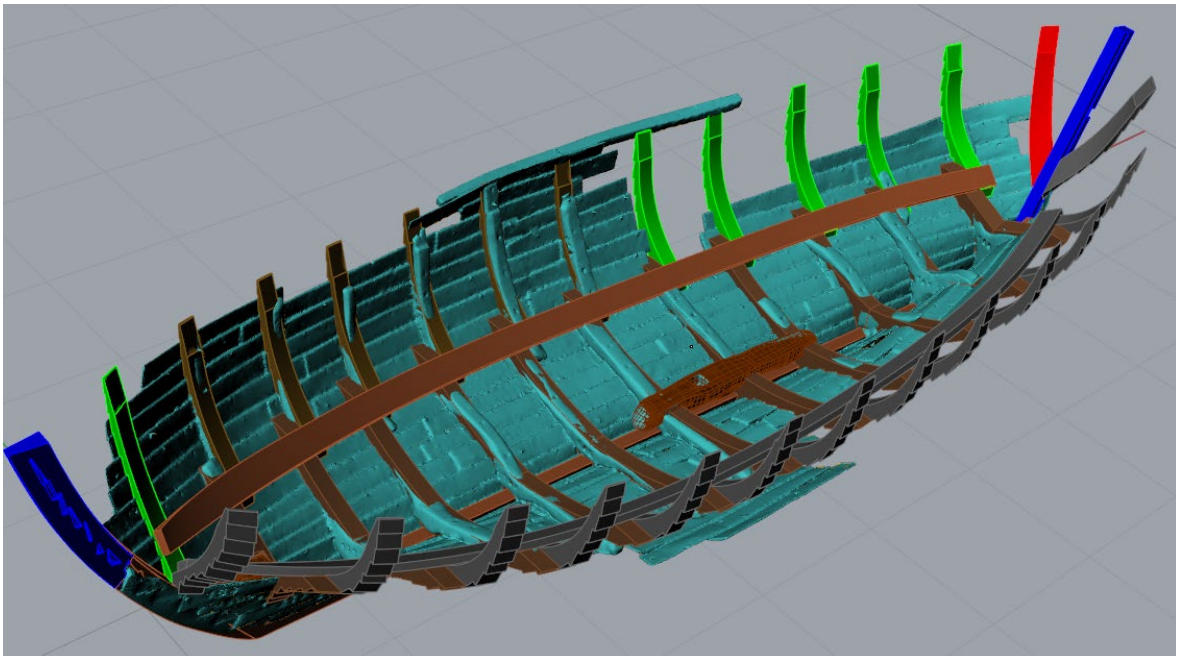

Figure 8-20 Drogheda boat - recreating the internal structure components (Pat Tanner)

8.7.2 Newport Medieval ship

As the 3D laser scan of the physical scale model represented the post-excavation shape state and this had required digital twisting into a rectified shape state, it was decided to align and fit the individual recorded elements to the digital model in order to test the validity of the repaired shape state. This was in effect, a repetition of the physical scale modelling process, but in a digital realm and at full-scale, with the added advantage of including elements which were either not included, or impossible to position in the physical scale model.

Some of these timbers also had localised distortion and these had to be repaired or twisted to conform to the emerging hull shape. Each individual plank and frame element were then aligned to the reconstructed model using a combination of the fixing holes of each adjoining element, the original scanned physical scale model, and the hypothetical watertight envelope hull form.

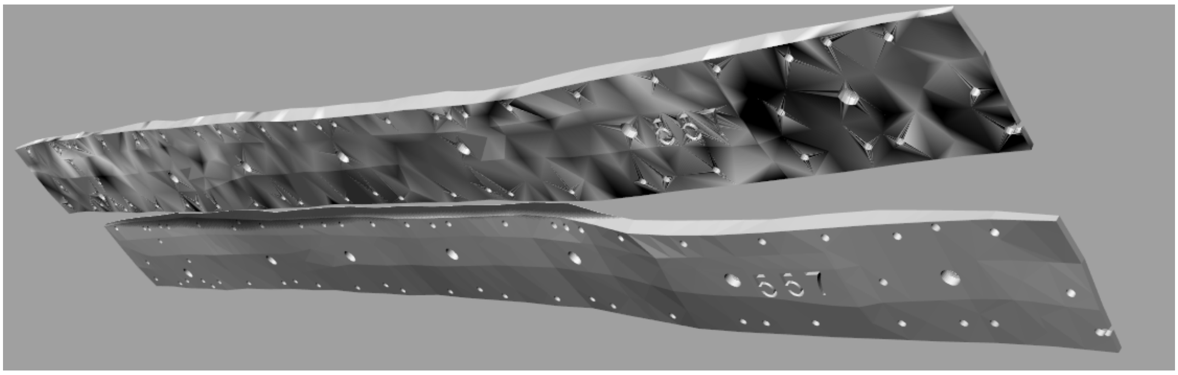

Figure 8-21 Newport Medieval ship - digitally repairing the distortion in an individual hull plank (Pat Tanner)

As the individual timbers had been documented at full-scale using contact digitising, the original wireframe data represented a more detailed record than the lower resolution digital solid model which was used for 3D printing. The wireframe data included information such as wood grain, tool marks and intentional scribed marks which simply were to minute to show in the 1:10 scale 3D printed pieces. If the digital mesh models of each timber were digitally reshaped in isolation, the associated high-resolution wireframe data would become disassociated from the digitally repaired shape, and difficult to interpret in future research (Figure 8-22).

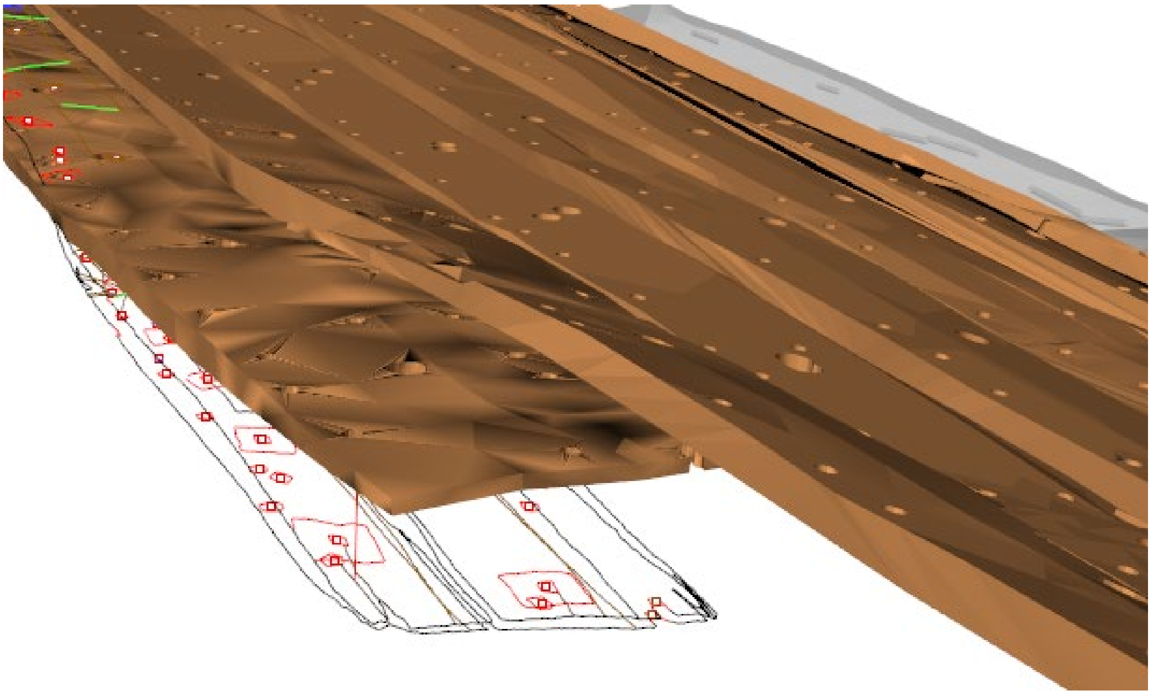

Figure 8-22 Newport Medieval ship - digitally fitting the repaired plank to the hull (Pat Tanner)

Consequently, and in a development of the process first employed on the Drogheda boat, a duplicate of the wireframe data and the digital mesh model of each timber were combined using the Rhino 3D group command, meaning that any movement, bending, or reshaping of the digital mesh shape automatically updated in the high-resolution wireframe data accordingly. This has the advantage of repositioning any relevant recorded information such as fastening locations, tool marks or intentional scribed lines such as builder's marks into the repaired orientation and will be of benefit in any future research and analysis of the reconstructed model.

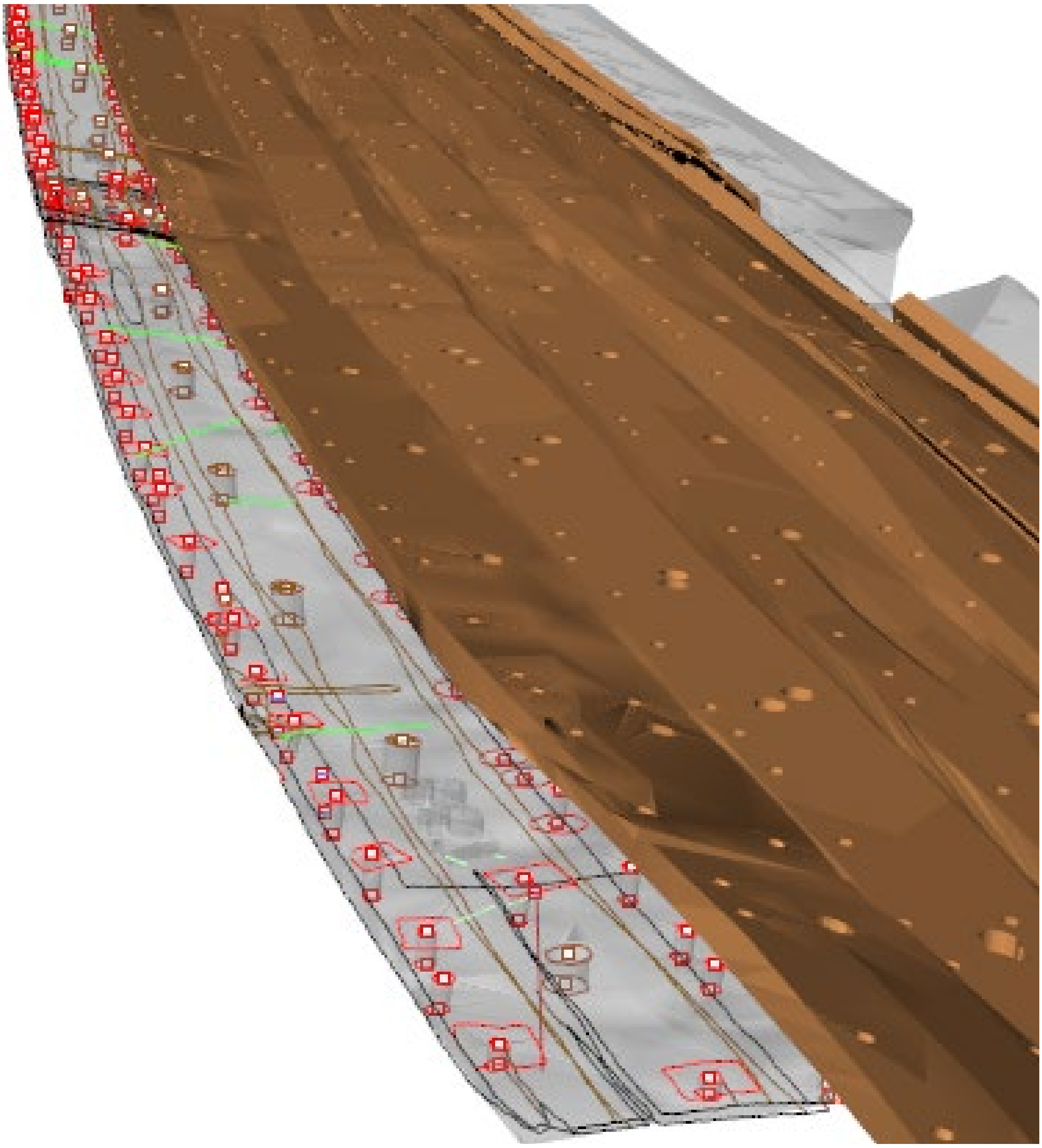

Figure 8-23 A digitally repaired hull plank with its associated full-scale high-resolution wireframe data (Pat Tanner)

Figure 8-24 (top) shows the individual timbers for the keelson, and associated braces being digitally repaired and fitted to the evolving hull shape. Figure 8-24 (middle) shows the articulated hull remains, with each individual timber repositioned and the relevant fasteners digitally modelled, and Figure 8-24 (bottom) shows the extrapolated timbers matching the watertight envelope hull form.

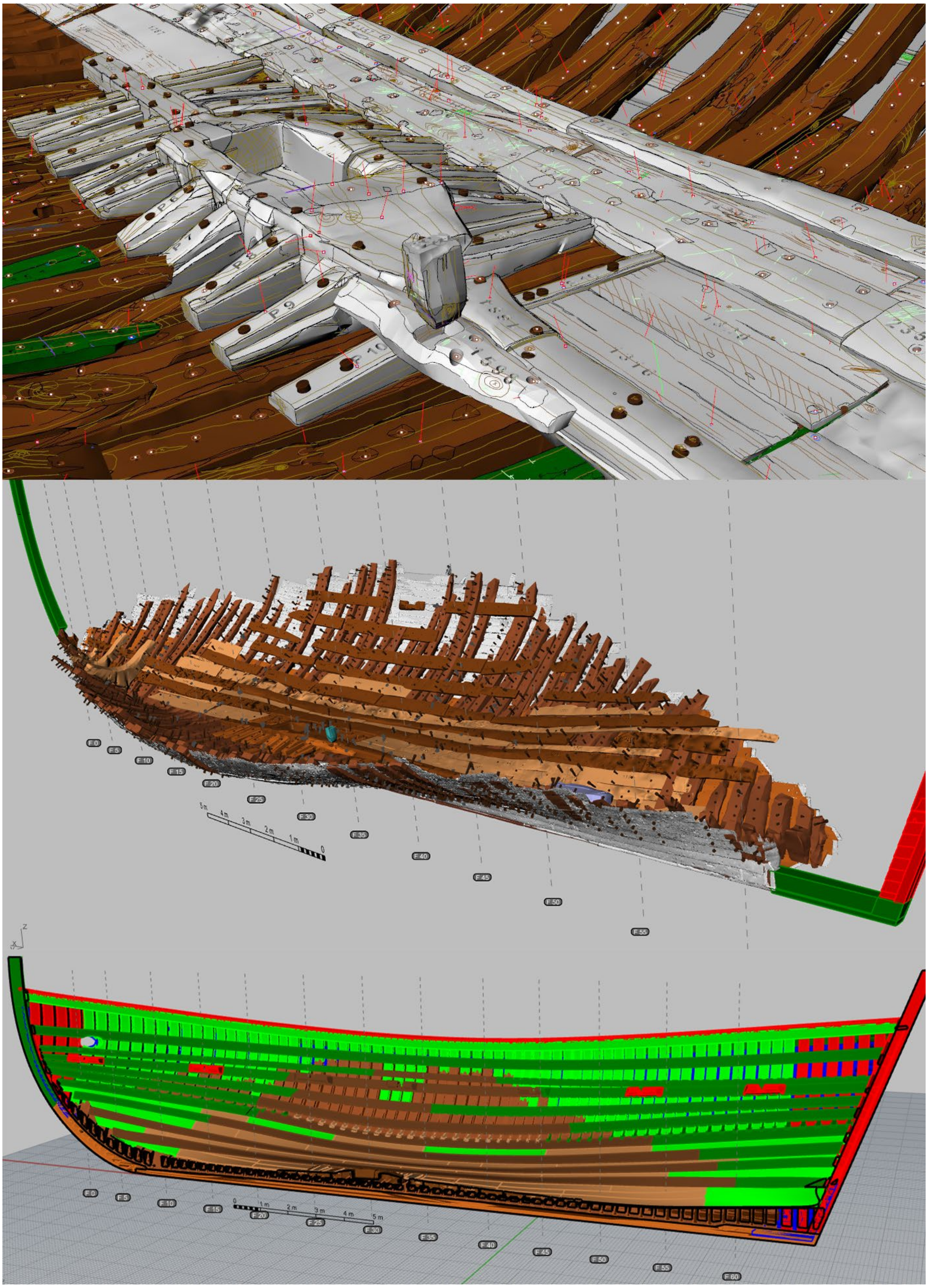

Figure 8-24 Adding additional recorded timbers together with their associated wireframe data to the digital working model (Pat Tanner)

8.8 Deck and superstructure

With the hull construction completed to a minimum reconstruction stage, focus now turns to any evidence which might indicate a deck or superstructure. Typically, such evidence may be extremely limited, as was the case with the Newport Medieval ship, or completely non-existent as was the case with the Drogheda boat, and the only evidence may be components which were necessary for the practical day-to-day usage or based on structural requirements.

8.8.1 Drogheda boat

No evidence for any deck elements were recovered, and with the overall form of the vessel suggesting a small (9.8 m) open boat (based on the cargo of casks), no deck structure was added to the minimum reconstruction, with the exception of a small internal deck or cockpit sole. This was deemed necessary to facilitate the position of a helmsman for steering the vessel, In addition a sheer clamp was added based on the rebated upper inboard ends of the surviving frames, and a single thwart to support each of the two masts (Figure 8-25). The internal deck and mast thwarts are coloured red in the hypothetical reconstruction as no evidence for these was recovered, and the sheer clamp is coloured green, as it is based on the internal rebated face of the surviving frames (see Appendix F: 15-22 for a detailed description).

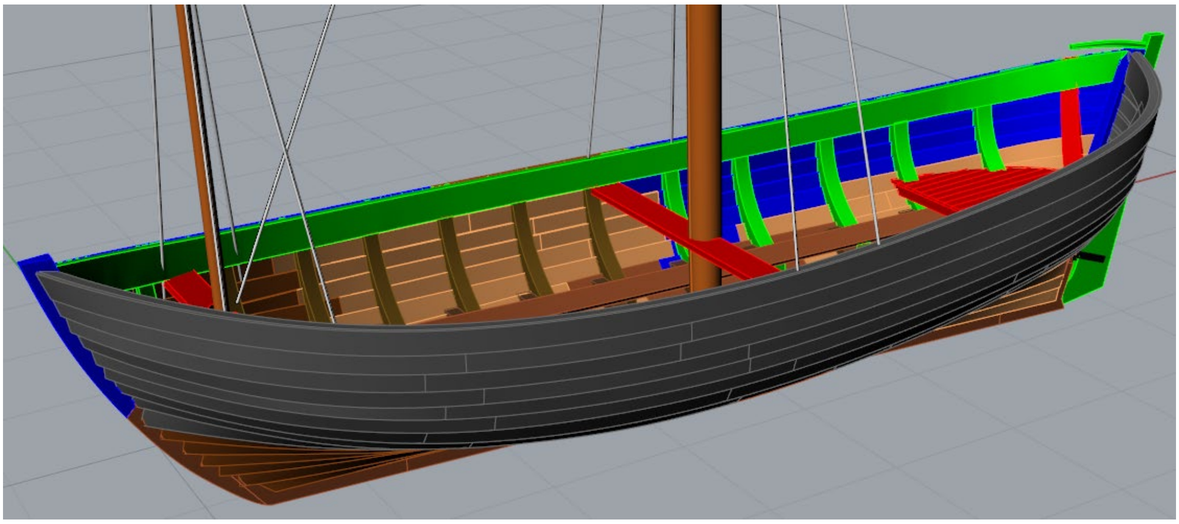

Figure 8-25 Drogheda boat deck elements added to the minimum reconstruction (Pat Tanner)

8.8.2 Newport Medieval ship

In the case of the Newport Medieval ship, while no significant deck structure survived as part of the articulate hull remains due to the ship’s timbers being salvaged in antiquity, a partial beam shelf fragment CT1526 (Figure 8-26 and Figure 8-27) was recovered which was disturbed by the sheet piling but still partially attached to the recovered framing timbers above the 7th stringer, thereby giving an accurate indication of a deck height. The rebates for ledges or deck beams gave an indication of deck beam size and spacing.

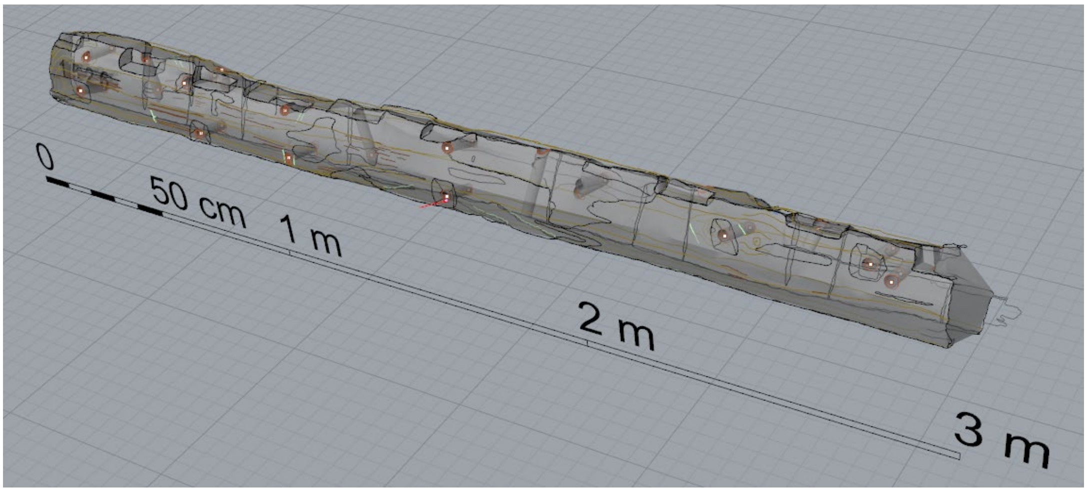

Figure 8-26 Newport Medieval ship partial beam shelf fragment (Pat Tanner)

Figure 8-27 Newport Medieval ship detail of partial beam shelf fragment show deck beam rebate (Newport Museum and Heritage Service)

With evidence for the deck beam spacing and dimensions available from the fragmented beam shelf, a simple flush deck structure was created, complete with two carling beams to allow fitting of the mast. The articulated hull remains survived to a height of the 34th strake on the starboard side, and an articulated portion of the deck's beam shelf survived still attached to the framing at the height of the 33rd strake, providing a known height for the deck. The top edge of the 34th strake would be a mere 33 cm above deck level, and as a result an additional four strakes were added during modelling of the hypothetical minimum reconstruction, in order to set the cap rail at elbow height for crew standing on the deck (Figure 8-28).

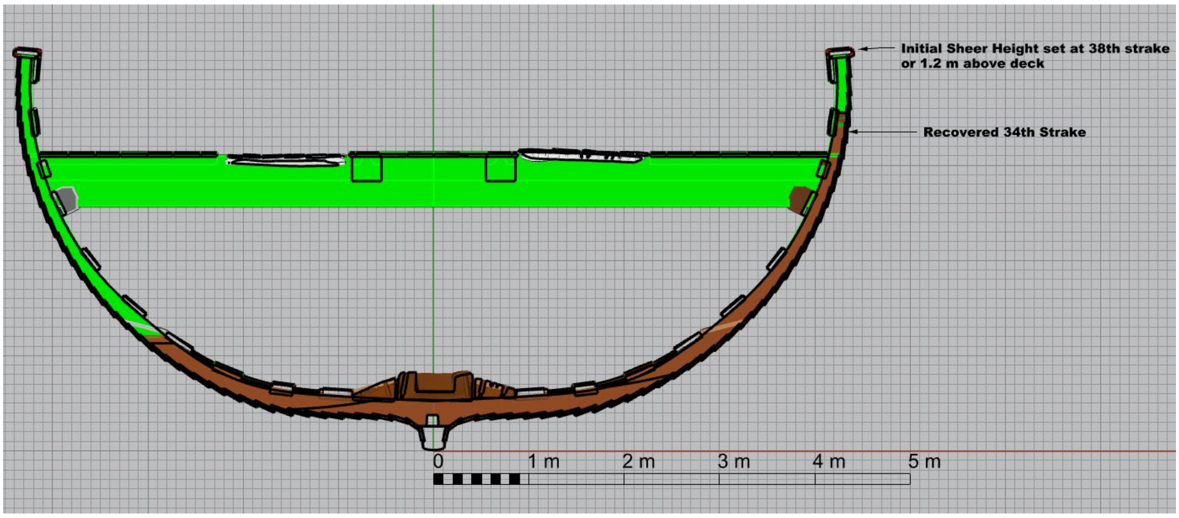

Figure 8-28 Initial Deck based on surviving beam shelf fragment and beam swellings on 7th stringer(Pat Tanner)

Internal consultation, combined with feedback from a number of external archaeologists, concluded the floating hypothesis was a valid hypothetical solution, and the inclusion of castles, in-line with contemporary iconography, would represent a minimum reconstruction. With no evidence surviving for any superstructure, iconography which pre-dated the Newport Medieval ship was consulted as a potential resource for the hypothetical bow and stern castles, and as both castles were conjectural, a simplified reconstruction of both was added to the floating hypothesis model to create a hypothetical minimum reconstruction ready for testing (Figure 8-30). Two anchors, their associated hawse timbers and a windlass for anchor handling were also added based on archaeological and historical parallels

8.9 Propulsion and steering

As well as being capable of floating, the other principal function of a vessel is transportation, and to fulfil that function the vessel will require to be propelled, typically by oar or sail, and once in motion, the direction will need to be controlled by some means of steering.

8.9.1 Drogheda boat

Evidence recovered included a mainmast heel block and a foremast heel block, as well as a clew garnet block and a parrel bead, indicating that the vessel carried a minimum of two masts, no evidence for rowing was recovered. Based on this evidence the minimum reconstruction included two masts (see Appendix F: 36-43 for a detailed description). For steering, the evidence recovered consisted of a rectangular rebate on either side of the sternhook as well as a groove on the aft face, which confirms the existence of an iron gudgeon fitted to receive the mating pintle of a transom hung rudder. No evidence of the rudder was found so a basic representation has been used for the minimum reconstruction (see Appendix F: 35 for a detailed description).

8.9.2 Newport Medieval ship

In the case of the Newport Medieval ship, the only element of rigging which was recovered as an articulate part of the overall vessel was the keelson with its integral mast step, which confirms the existence of at least a single or main mast. The existence of large single masted sailing vessels in this period is well documented, so the Newport Medieval ship could potentially have been constructed with a single main mast carrying a square sail. In keeping with the incremental approach, and complying with the self-imposed rule, to only use articulated material from the recovered wreck, the initial minimum reconstruction would be modelled with a single mast.

A scarcity of shipbuilding or rigging treatises for 15th century vessels means the rigging of the Newport Medieval ship is based on evidence recovered and iconography which was accessed as to accuracy, practicality and functionality based on current understanding of sailing principles. Tanner (2013b:75–85) sets out in detail how the available archaeological evidence, combined with contemporary iconography has been interpreted to recreate a single mast, yard and sail area, along with the minimum of associated elements deemed necessary for that proposed rigging system to function. This resulted in a mast of 23.5 m, a yard length of 18 m, and a potential sail area of 264 m² illustrated in Figure 8-30.

However, rigging artefact by their nature rarely survive as articulated remains. The disarticulated rigging elements recovered, and their find locations are illustrated in Figure 8-29.

No evidence of steering equipment was recovered, however the centreline rudder hung on pintle and gudgeons and attached to a sternpost are relatively common by the mid-15th century, and as a result a basic representation has been used for modelling purposes. A typical modern-day formula for calculating the rudder area of a traditional shape, long keel sailing vessel would be 0.068 x waterline length x draft. Using this formula would give 0.068 x 25.9 x 2.6 = 4.58 m². The modelled rudder as shown has an area of 4.6 m².

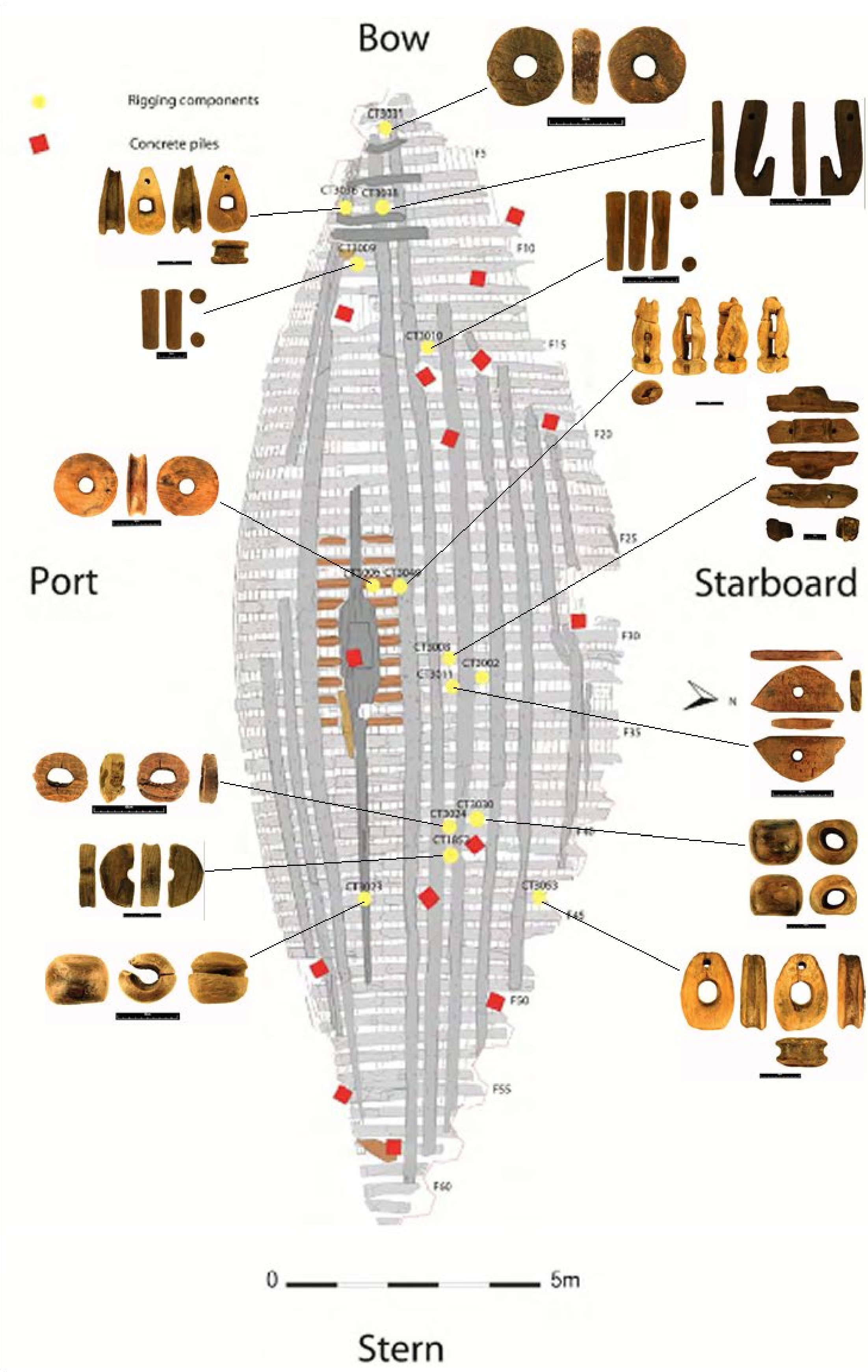

Figure 8-29 Distribution Map of Newport Medieval Ship Rigging Assemblage (Newport Museum and Heritage Service)

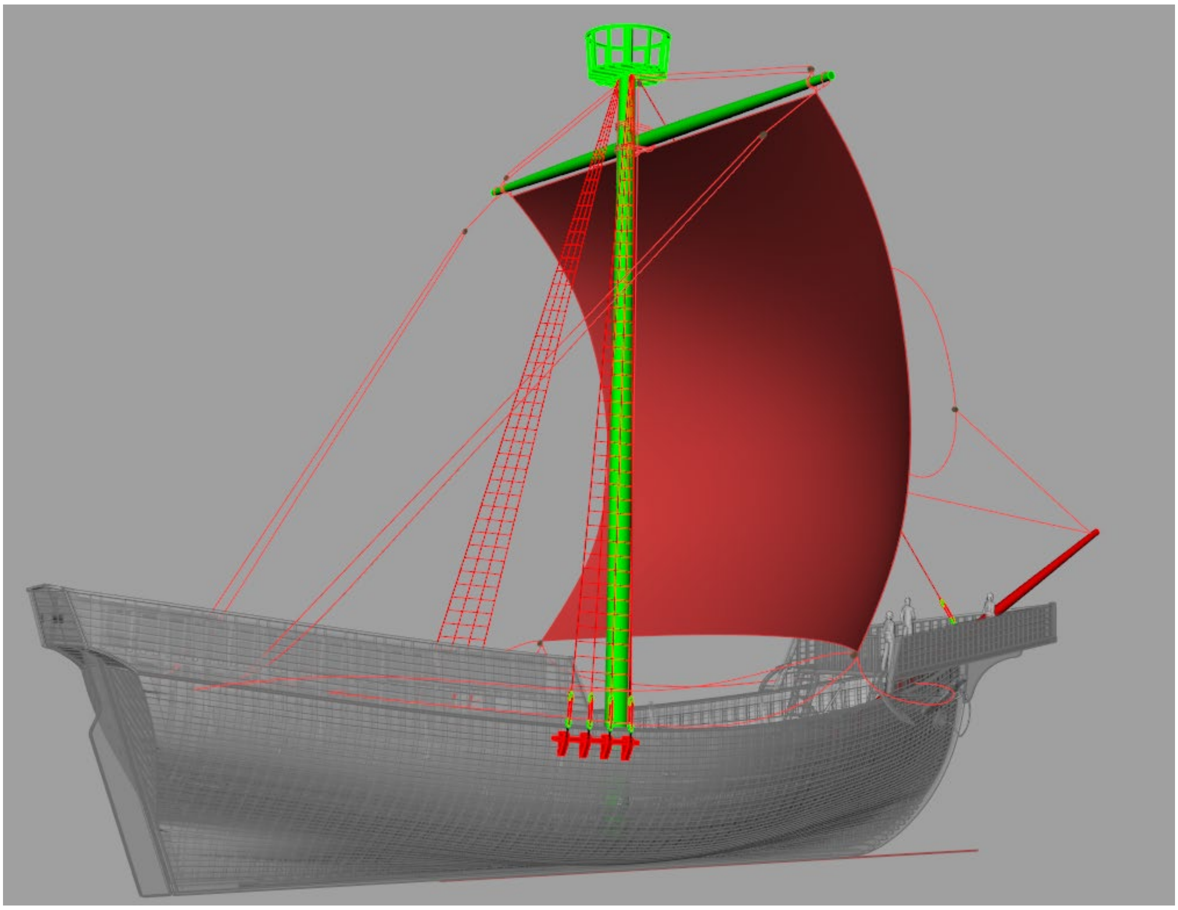

Figure 8-30 Newport Medieval ship modelled with a single mast (Pat Tanner)

8.10 Testing and analysis

With all of the component elements of the vessel digitally modelled, Orca 3D was used to assign physical material properties to each element in order to accurately calculate the total combined weight of the hypothetical minimum reconstruction. This has allowed the establishment of the flotation condition (Chapter 8.6) – whether or not the vessel actually floats based on its hull form and total weight. This however, gives only a partial aspect of the overall analysis. A boat or ship is by definition a non-static object. It is constantly in motion, in a constantly changing medium (waves and sea conditions), at the mercy of constantly changing loadings such as cargo and crew internally, as well as wind and wave loading externally.

As noted by McGrail (2001:5–7), two or more reconstructions may be compatible with the evidence. From these reconstructions, predictions of performance, stability, and cargo capacity can be calculated. But only if the reconstruction is authentic, the data accurate, and the arguments rigorous will the predicted results be credible. All of these characteristics contribute to the safety of both the vessel and crew, and this raises the question of how do we determine the approach to risk assessment in earlier times? Which testing criteria do we apply? As McGrail suggests, it is best to assume that the ancient mariner was also a 'prudent mariner'.

Assessment using modern-day health and safety standards are likely to be an order of magnitude more rigorous than in days gone by, but offer a reasonable proxy to determine a vessel's safety and seaworthiness. However caution is required as this may cause a hypothetical reconstruction to 'fail' when analysed using modern-day requirements. An alternative approach to this issue is discussed in greater detail in Appendix G16:57-61, and Appendix I:16-34.

Modern rules for the stability of ships are formulated by the International Maritime Organisation (IMO), and it is at the discretion of inspectorates or classification societies to adopt these rules or make them even more stringent. Bureau Veritas is one such classification society, founded in Antwerp in 1828, originally Belgian but now a French society (Bureau Veritas 2012:81–97). If the Bureau Veritas criteria were applied to a large vessel (load waterline length greater than 24 m) it would be assessed for certification under four categories. Sheltered areas, Coastal areas, Navigation limited to within 60 nautical miles of a coastline, and Unrestricted navigation. For certification in the first three categories, the vessel would be required to comply with the intact stability rules, which are:

> **2.1.2 GZ curve –** The area under the GZ curve to be not less than 0.055 m-rad or 3.151 m-deg up to 30° angle of heel,
> The area under the GZ curve to be not less than 0. 009 m-rad or 5.157 m-deg up to 40° angle of heel or the downflooding angle if this is less than 40°,
> The area under the GZ curve between 30° and 40° heel angle to be not less than 003 m-rad or 1.719 m-deg,
> **2.1.3 Minimum Righting Lever –** The righting lever GZ to be not less than 0.2 m at a heel angle equal or greater than 30°,
> **2.1.4 Angle of Maximum Righting Lever –** The maximum righting arm is to occur at angle greater than 25° and preferably greater than 30°,
> **2.1.5 Initial Metacentric Height –** The initial metacentric height GM_0 is to be not less than 0.15 m,
> **3.1.3 Wind and Wave rolling –** The heel angle resulting from steady wind to be less than 16° or 80% of the angle of deck immersion, whichever is less.

To better comprehend these stability criteria, it is best to examine a stability or Gz curve for a vessel (Figure 8-31).

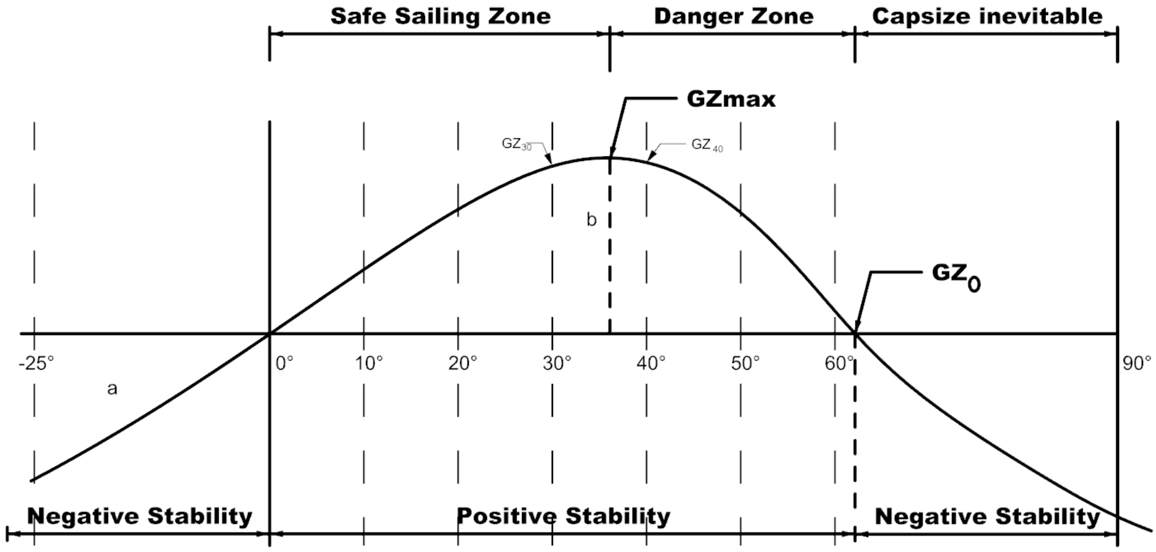

Figure 8-31 Sample stability or Gz curve (Pat Tanner)

For unrestricted navigation, a vessel would also be required to comply with the rules for Damage Stability, which examines flooding control by the inclusion of watertight bulkheads or subdividing the hull using compartmentation. All of the inspectorates and classification societies also give the option for "alternative" compliances and will accept lower values by agreement on a case by case basis.

Taking the fictitious stability curve (Figure 8-31) for a generic sailing vessel, once the sails are set the vessel will begin to heel, due to the wind heeling moment, until a state of equilibrium is reached, whereby the righting arm moment balances the wind heeling moment. As long as this state of equilibrium occurs between 0° and the angle of GZ_{max}, which differs for every vessel, the vessel is sailing in the "safe sailing zone" and the heeling moment will be opposed by an increasing righting moment.

The problems begin when the vessel heels beyond the angle of GZ_{max} where the amount of righting moment is decreasing. In this "danger zone" a small increase in heeling moment caused by a slight wind speed increase, or even, a seemingly insignificant crew movement causing a centre of gravity shift, will result in a large heel angle increase, which could overwhelm the decreasing righting moment, and in this zone between GZ_{max} and GZ_0 the sails should be eased or reduced to decrease the Wind heeling arm. Failure to reduce the heeling moment within this "danger zone" will quickly result in the vessel heeling beyond the angle of GZ_0 which will result in an inevitable capsize.

For the Bureau Veritas criteria, section 2.1.2 is measuring the area underneath the stability curve at various angles of heel, and as such is setting limits for the measure of positive stability as heel angle increases. Section 2.1.3 is setting a minimum for the righting force at 30° angle of heel.

Section 2.1.4 sets the minimum angle for the angle of maximum righting force GZmax, in this case 25° which Bureau Veritas uses as a generic wave roll angle. Section 2.1.5 sets the minimum metacentric height which ensures the vessel is initially stable when resting upright, rather than relying on heeling (angle of loll) to find stability.

All of these testing criteria can be set in the Orca 3D software, and used to examine the vessel in various flotation conditions such as empty vessel with or without ballast, or in a fully loaded state, as well as testing external factors such as wind or wave loading (Figure 8-32).

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 5kts

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Angle At SteadyEquil <= 16 deg	1.1347		16	1.1347	Pass
ResRatio Between SteadyEquil-14.6 deg and DeckImm > 1	-13.4653	23.4986	1	2.2623	Pass
ResRatio Between SteadyEquil-14.6 deg and Flood > 1	-13.4653	45.6671	1	8.4361	Pass
ResRatio Between SteadyEquil-14.6 deg and 50 > 1	-13.4653	50	1	10.1629	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	1.1347		18.7988	1.1347	Pass

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 10 kts

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Angle At SteadyEquil <= 16 deg	4.5154		16	4.5154	Pass
ResRatio Between SteadyEquil-14.6 deg and DeckImm > 1	-10.0846	23.4986	1	1.6134	Pass
ResRatio Between SteadyEquil-14.6 deg and Flood > 1	-10.0846	45.6671	1	7.2378	Pass
ResRatio Between SteadyEquil-14.6 deg and 50 > 1	-10.0846	50	1	8.8822	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	4.5154		18.7988	4.5154	Pass

Figure 8-32 Bureau Veritas wind and rolling wave stability analysis (Pat Tanner)

8.10.1 Drogheda boat

The completed minimum reconstruction was firstly analysed in an empty state with just two crew aboard in order to validate the floating hypothesis results carried out in Chapter 8.6. In this configuration the boat is 9.8 m overall length, with a beam of 3.1 m, and with a total weight of 3.1 tonnes has a draft of 0.68 m and a freeboard of 1.09 m. The boat has a theoretical maximum hull speed of 7.11 knots, and with a sail area of 60 m², could achieve speeds in the region of 4.1 knots in a 10-knot wind speed. However, a moderate breeze of just 15 knots would cause the boat to heel over to 38.8°, and with a downflooding angle of just 46.2° this leaves just 159 mm of freeboard. The relatively low righting moment of 823 kgf-m at this angle means only a slight increase in wind strength would cause the vessel to heel further and sink.

With the vessel configured in its as-found condition, to include the 12 recovered casks, the total weight/displacement increases to 5.7 tonnes, resulting in a deeper draft of 0.84 m and a lower centre of gravity. In the same 15 knot wind conditions the vessel heels to just 16° maintaining 0.5 m of freeboard, While gusty conditions would still not heel the boat beyond 36° with a righting moment at this angle of 1,850 kgf-m. The vessel would be deemed to be safe in these conditions and if fully loaded could carry 32 of the recovered casks, a total cargo capacity of 7.2 tonnes (see Appendix F: 26-49 for a detailed description).

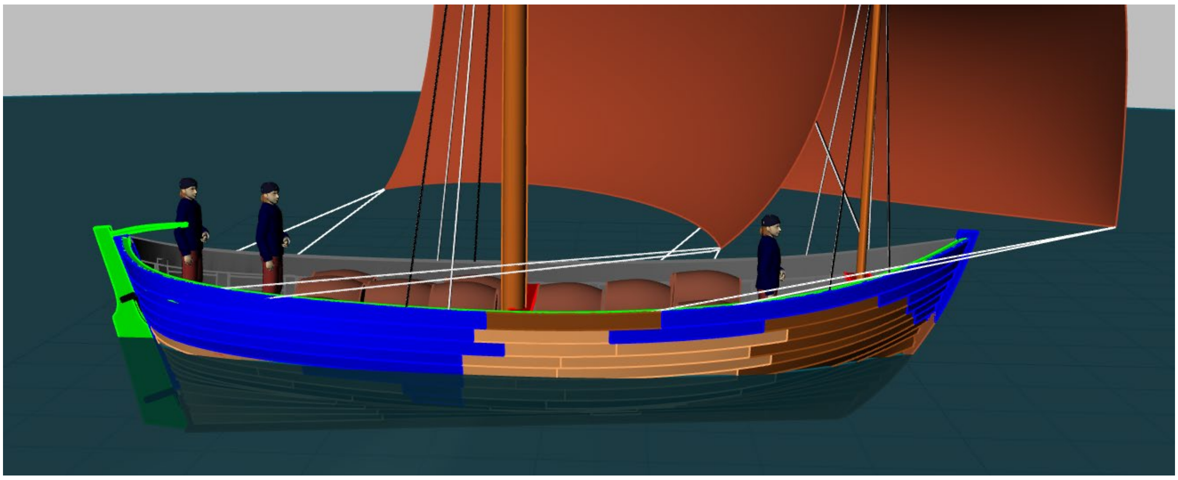

Figure 8-33 Drogheda boat minimum reconstruction fully-loaded (Pat Tanner)

8.10.2 Newport Medieval ship

This resulted in the Newport Medieval ship, in a reconstructed lightship configuration (Figure 8-34), which includes all the constituent components of the hull and rigging, and 31 crew, but excludes any cargo or ballast, weighs 79,603 kg. This represents an increase from the estimated weight of 60,959 kg for the watertight envelope.

The longitudinal centre of gravity (LCG) is located 13.25 m aft of the Forward Perpendicular (FP), the point where the design water line (DWL) intersects with the stem, and the vertical centre of gravity (VCG) located 1.27 m above the DWL, transverse centre of gravity (TCG) is 0 mm located on the centre line as it is assumed the vessel is symmetrical. The DWL was positioned based on the minimum freeboard of 1.68 m, from the *Grågås Codex*. In this configuration the vessel would have a draft aft of 1.65 m, a draft forward of 1.41 m and a remaining freeboard of 2.88 m, with a downflooding angle of 39.25°. However, the vessel would in fact be considered unsafe by modern stability criteria, with the area under the righting arm curve being insufficient, which indicates that the vessel required internal ballasting to improve stability (Figure 8-35).

Figure 8-34 Newport Medieval ship unballasted lightship flotation condition (Pat Tanner)

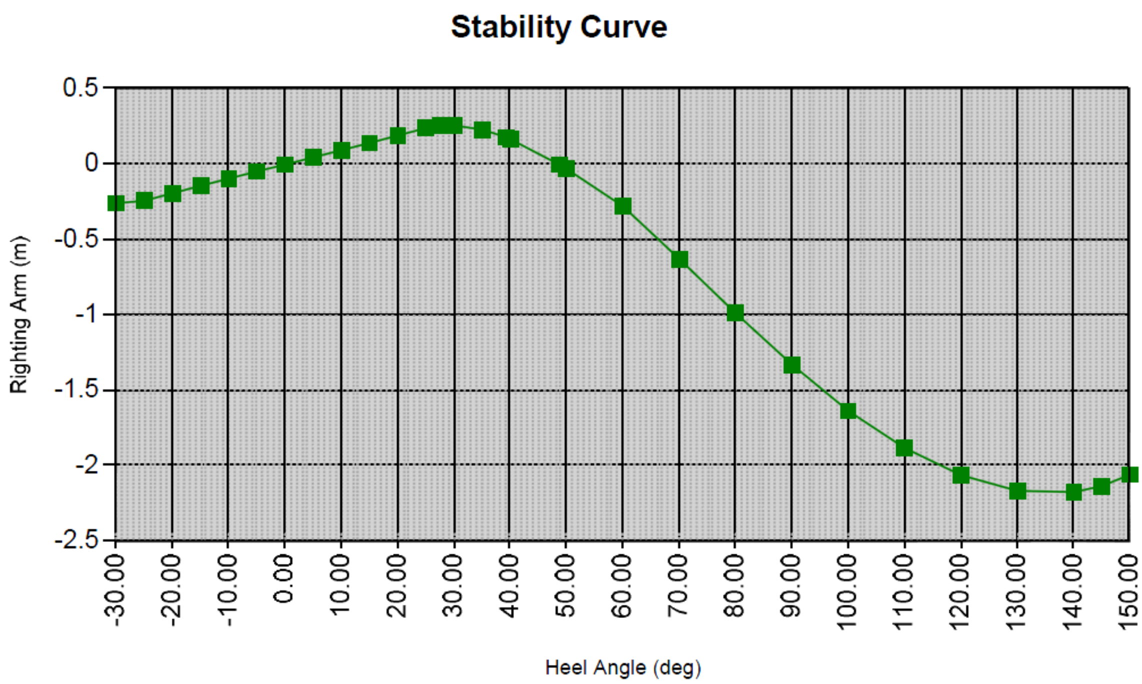

Figure 8-35 Newport Medieval ship – Stability Curve for lightship unballasted condition (Pat Tanner)

While no archaeological evidence was recovered that could positively confirm the existence of ballast stones within the vessel, the vessel was positioned in a pill and undergoing some form of maintenance or repair at the time. It is possible that the ballast was removed in order to reduce the ship's draft prior to "grounding" inside the pill.

The stone artefacts recovered from within the excavation were grouped into eight categories, a single sample (#1055), from group five was calcite, which is abundant in South Wales, and was considered to be associated with rock ballast. Samples within groups seven and eight show no evidence of being worked and were also assumed to be associated with stone ballast. Some of the ballast associated with context 130 were confirmed as not originating from the South Wales area (Horak 2013).

Generally, when loading ballast within a vessel it is desirable to position the majority of the weight as low as possible within the hull shape and ideally centrally located to reduce the effects of pitch and roll. The digital model was "loaded" with ballast stone beginning along the centre line and extended fore and aft. Natural stone was chosen for the digital ballasting, and this was layered atop the internal ceiling planks, from frame 15 aft as far as frame 58. The depth of stones was adjusted until sufficient ballast was loaded to achieve a stable floatation condition, which would allow the vessel to carry the reconstructed sail area in a force four wind (13 – 15 knots) without excessive angles of heel necessitating a reduction of sail area, a total depth 380 mm of stone ballast, resulting in a ballast weight of 17,170 kg.

Further detailed analysis of the floating hypothesis was carried out using Orca 3D (see Tanner 2013b:90–130 for a detailed description). This included analysis of the stability curve, righting moments, wind, and wave loading, as well as heavy lifting, which calculates how much the vessel will heel while lifting a tun wine cask using the yard, and how the vessel would compare if tested using modern stability criteria with a variety of cargo loading scenarios.

With the quantity of ballast calculated at 17.2 tonnes, and the fully rigged ship plus 31 crew weighing 79.6 tonnes, giving a combined weight of 96.8 tonnes. The vessel, based on the submerged hull form has a total displacement of 206.7 tonnes, when floating at the DWL (positioned based on the minimum freeboard of 1.68 m, from the *Grågås Codex*), this leaves sufficient capacity for cargo and provisions of 110 tonnes.

In this configuration the vessel would have a draft aft of 2.7 m, a draft forward of 2.38 m and a freeboard of 1.86 m (Figure 8-37) and a downflooding angle of 23.4°. The loading of cargo will have a direct effect on the positioning of the centre of gravity, but assuming the cargo is loaded in a manner to maintain the flotation attitude (trim) of the vessel, with the heavy items low in the cargo hold (Figure 8-38), the vertical centre of gravity is significantly lowered from the 1.27 m above DWL for the empty vessel, to circa 0.1m above DWL for the fully loaded vessel. This has the effect of increasing the metacentric height (GM) a measurement of the initial static stability of a floating body, from 0.53 m for the empty vessel, to 1.72 m for the loaded vessel. The result is a stiffer vessel, more resistant to heeling forces such as wind loading (Figure 8-36). The angle of maximum righting moment (GZmax) is 25.4°

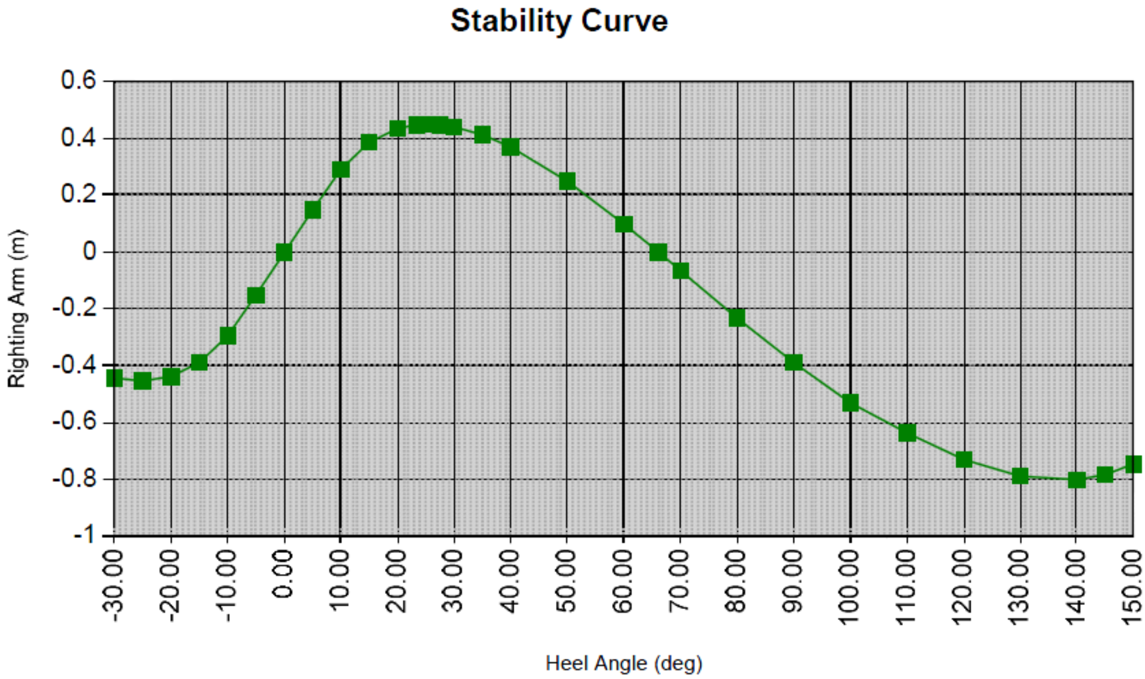

Figure 8-36 Newport Medieval ship Stability Curve for fully-loaded flotation condition (Pat Tanner)

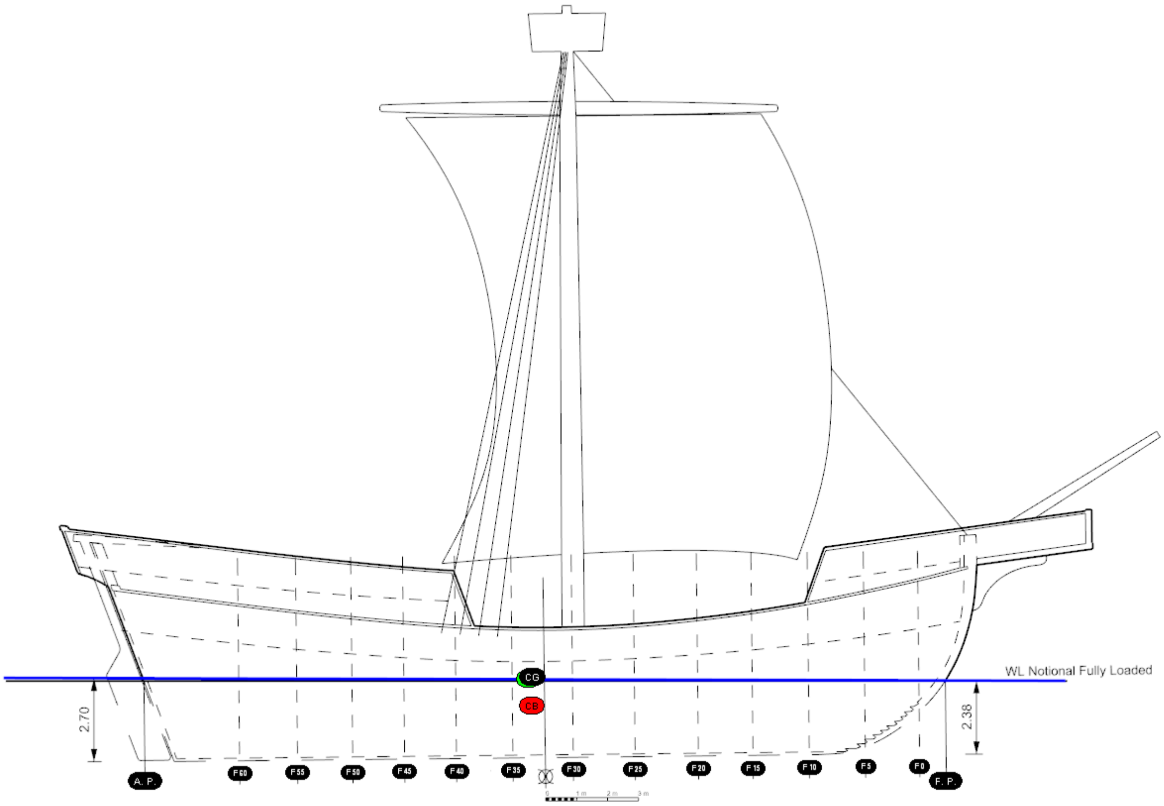

Figure 8-37 Newport Medieval ship Fully-Loaded flotation condition (Pat Tanner)

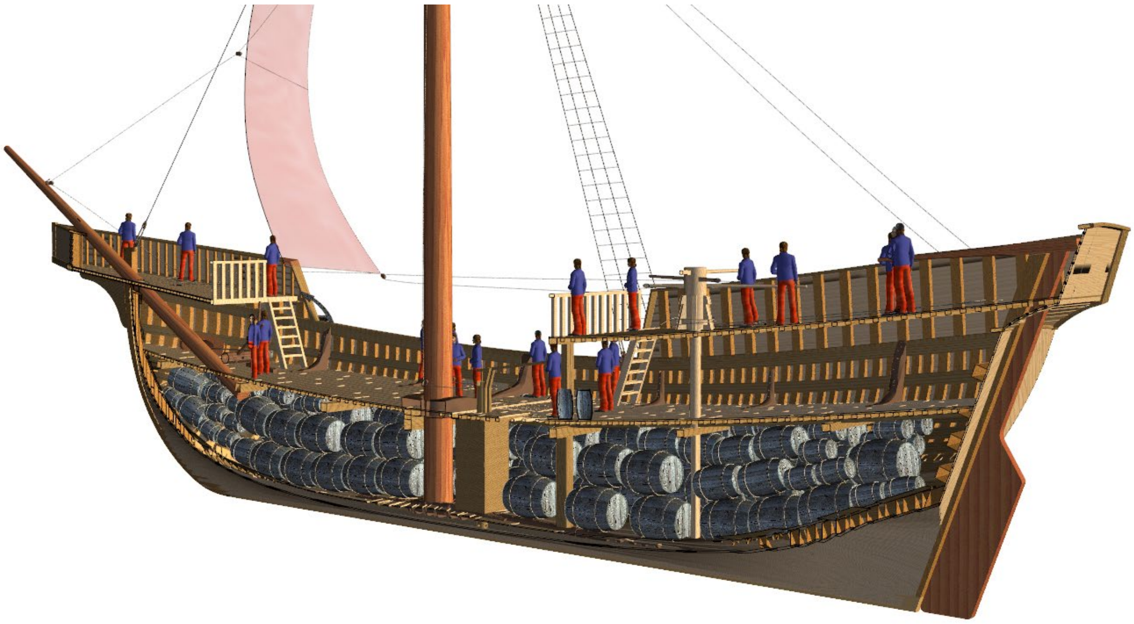

Figure 8-38 Newport Medieval ship rendered model with cargo stowed below deck (Pat Tanner)

8.11 Initial publication for peer review

8.11.1 Drogheda boat

Unfortunately (due to circumstances beyond this authors control), with the exception of (Schweitzer 2012; Tanner 2013a), the Drogheda boat remains in publicatory limbo. Consequently, no further work has progressed on this project.

8.11.2 Newport Medieval ship

Following initial publication for peer review (see Jones *et al*. 2013; Tanner 2013b; Nayling and Jones 2014; Jones 2015; Jones *et al*. 2017), it was suggested that the hypothetical minimum reconstruction would likely have had additional masts.

Friel (1995:160) notes that the mizzen mast were known to be in use in Northern Europe by circa 1416, and foremast by circa 1435. Additional evidence from the disarticulated rigging assemblage included four separate components from one or more parrel truck assemblies. The collar fastening the yard to the mast, which also facilitates raising and lowering of the yards. As noted by Erica McCarthy (2012:22) two parrel ribs, each quite different in form were recovered, and two parrel beads of very similar dimension, but their diameters suggested they were not associated with either parrel rib. This could suggest three separate parrel truck assemblages, associated with three masts.

The minimum reconstruction was revised to include a foremast and a lateen mizzen mast (Figure 8-39). With the revised masts and rigging, the vessel was again examined using Orca 3D. The vessel was configured in the worst-case scenario condition with regard to wind loading, which would represent a "beam on" wind, with the sails sheeted in tight. This is not a normal sailing configuration but represents the worst possible case scenario. To establish this lateral projected area, the yards and sails were rotated as close as possible to the centre line plane, allowing for normal restrictions such as shroud placement.

The projected sail area combined with the hull surface area was then calculated, resulting in a lateral projected surface area of 345.47 m^2. These figures are used for a heeling arm calculation in Orca 3D (Figure 8-40). Results show that a full sail area in 20 knots of wind speed would heel the vessel to 16.5°. With a downflooding angle of 23.4°, and the maximum righting moment at 25.4° this condition is marginal, suggesting that sail area should be reduced in these wind conditions.

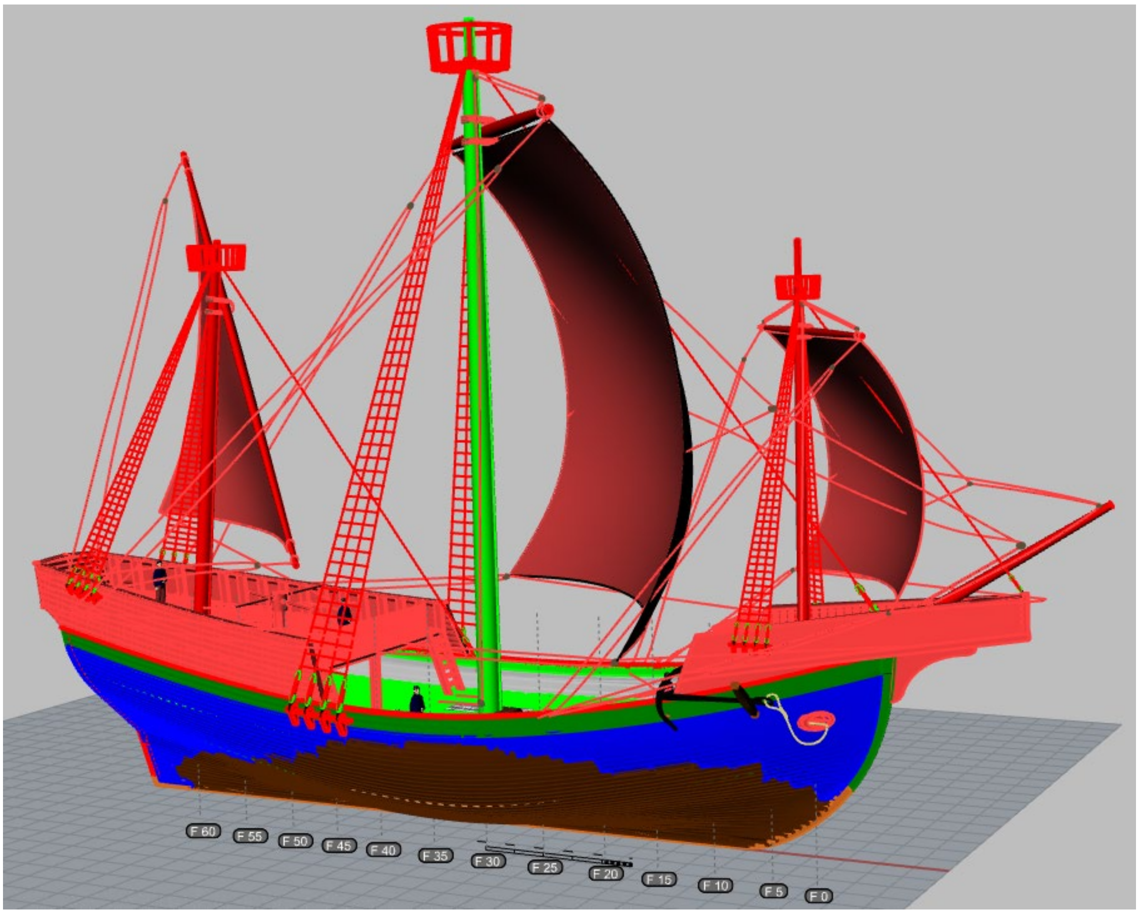

Figure 8-39 Newport Medieval ship Revised minimum reconstruction (Pat Tanner)

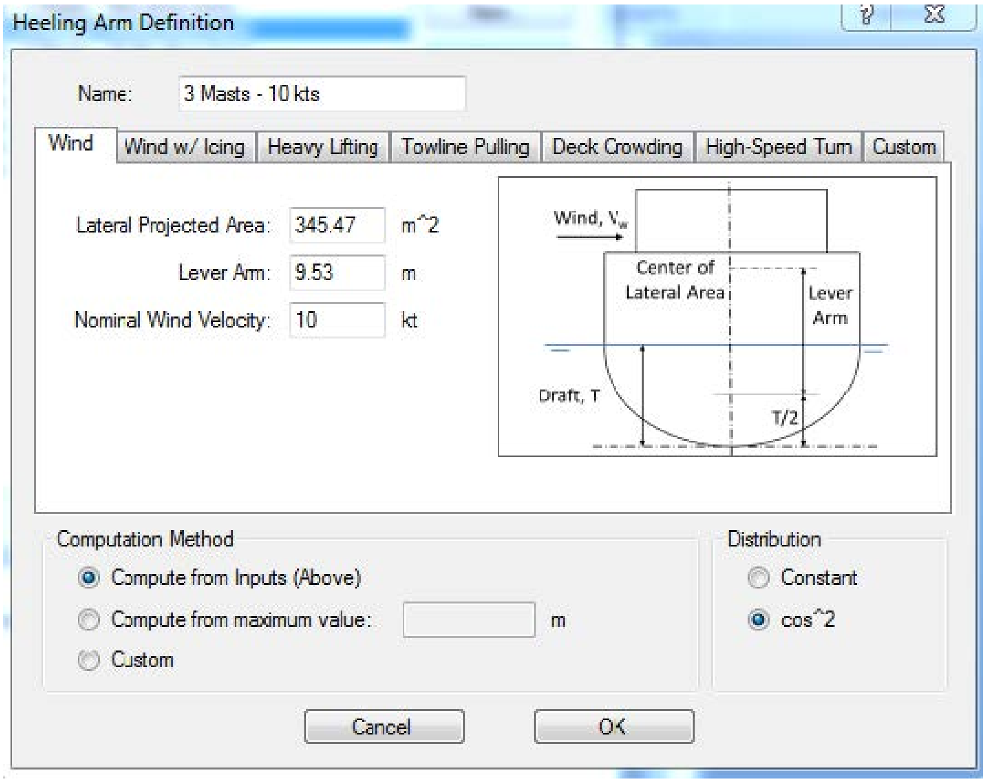

Figure 8-40 Heeling arm test for wind loading criteria (Pat Tanner)

The result of digital testing indicated the hypothetical minimum reconstruction, reconstructed to a height of the 38th strake, based on the archaeological evidence, results in a vessel 28.62 m bow to stern, 35.6 m overall length, with a beam of 8.72 m, which functions properly as a vessel capable of carrying circa 110 tonnes of cargo at a draft of 2.68 m.

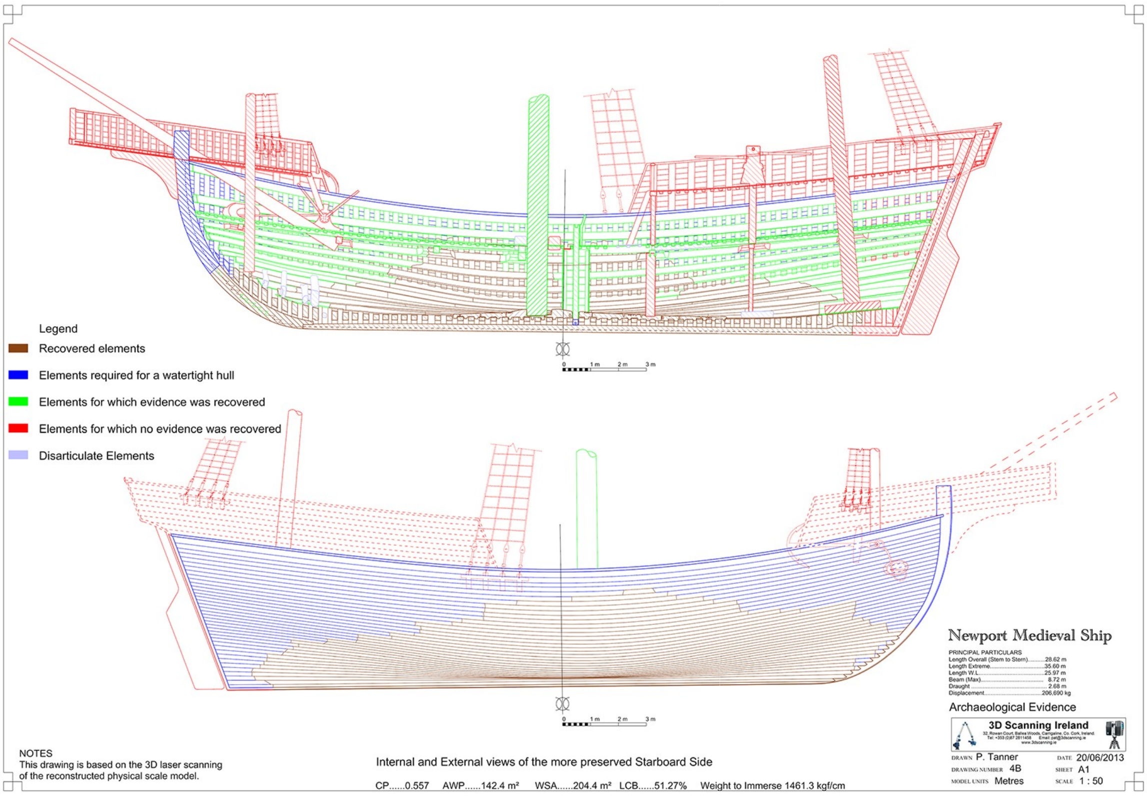

Figure 8-41 Drawing showing what parts of the reconstruction were based on direct archaeological evidence and what parts are conjectural (Pat Tanner)

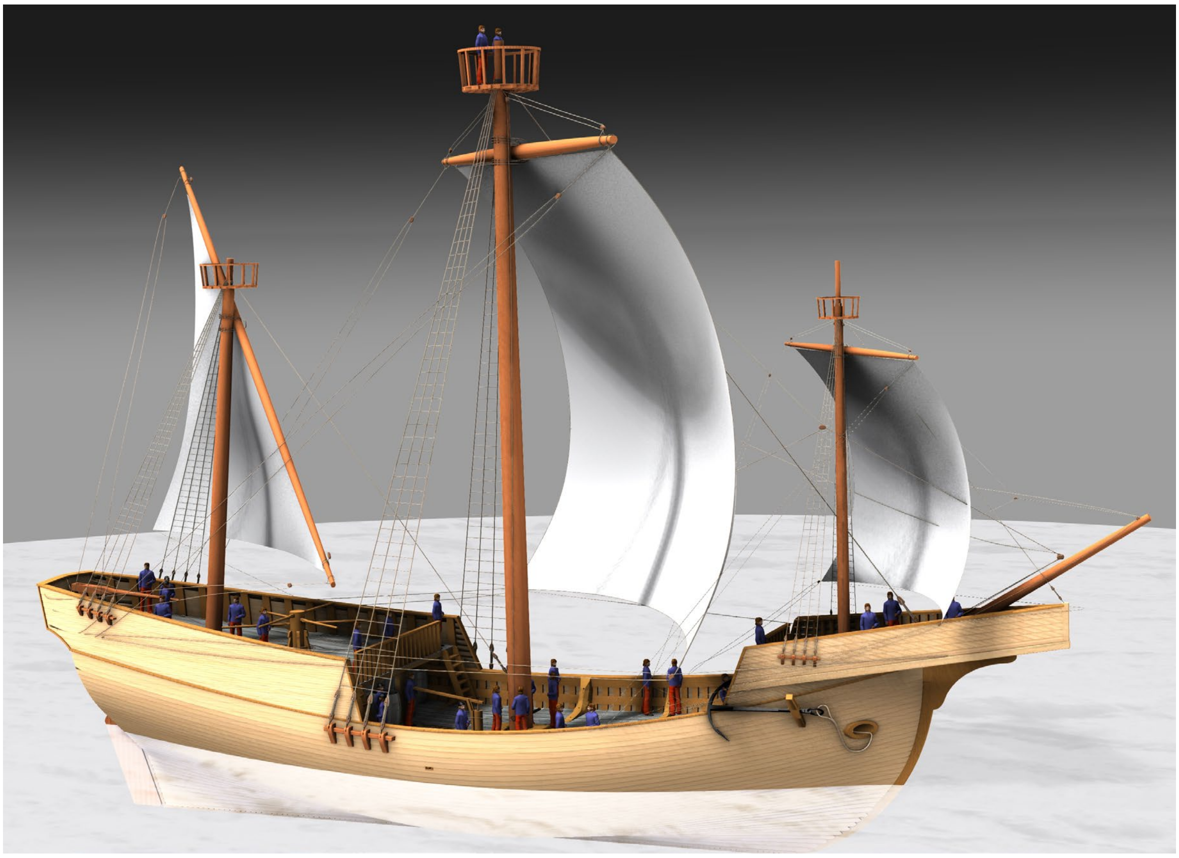

Figure 8-42 Newport Medieval Ship, rendered view of the hypothetical minimum reconstruction (Pat Tanner)

8.12 Conclusion

Crumlin-Pedersen and McGrail's definition of a minimum reconstruction [84] describes a vessel based on the 'torso/as-found' model which represents the archaeological evidence and uses contemporary evidence to fill in the missing parts. It does not however, describe how the 'torso/as-found' model is created based on the excavated evidence, nor does it describe how comparative data is used to 'fill in' the missing parts. McGrail's definition of the 'as-found' model [83] describes a vessel which has had displaced timbers replaced and fragmented timbers made whole. By its very definition, this is not the as-found condition of the archaeological remains.

How are these damaged, displaced, or fragmented timbers replaced? How is the comparative data used to fill in the missing parts? Where does the shape and hull form for these missing parts come from? Is it based on an assumption that their correct shape or position is already known? This lack of information on how the raw data was interpreted to create these 'torso/as-found' models, or how the comparative data was used to fill in the missing parts, what Denard (2009) refers to as paradata, only serves to extend the gap between the exclusive knowledge of the excavator and the published record.

The process described in this chapter takes the archaeological evidence, which has been analysed and digitally repaired using the processes described in Chapter 7 . Then using the full-scale recorded data, digitally rebuilds the vessel based on the surviving archaeological remains, just as a boatbuilder would rebuild an actual vessel, in a clearly defined step-by-step methodology as set out in Table 7-2. The process follows a logical progression following the perceived construction sequence of the original vessel.

With the surviving archaeological remains correctly orientated, just as the shipyard sets the vessel on a building strongback, the twist and distortion has already been repaired in Chapter 7.8 – in effect removing the distortions and compression as per McGrail's definition of the 'as-found' model (McGrail 2007:255). Next, the keel, stem and stern post are examined and digitally repaired or replaced, reconstructing the centreline profile of the vessel. The hull planking is then examined, and digital curves, representing the edge of each strake are created, these are digitally

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84 The term 'minimum reconstruction' is now used to describe one or more (partial) reconstructions based on the excavated evidence-as depicted in a 'torso/as-found' scale model or drawing in which allowances have been made for distortion, displacement, and shrinkage-using valid comparative evidence to 'fill in' the missing parts, but without recourse to naval architectural conjectures, alien elements, or anachronistic intrusions (Crumlin-Pedersen and McGrail 2006:57).

faired, and extended where necessary to reattach to the stem and stern. In effect a digital version of the fairing battens from the shipyard (Figure 8-3), in order to recreate the watertight envelope representing the complete hull form. This watertight envelope hull form is then analysed and tested using Orca 3D for its basic hydrostatic capabilities as a means to check the overall hull characteristics and pre-empt any surprise outcomes (cf. Bischoff 2010; 2012; 2016).

Once a satisfactory shape and form has been recreated, as represented by the watertight envelope, the process of a detailed minimum reconstruction begins. This can be done by digitally modelling each of the component parts of the vessel as a new, solid object 3D part, suitable for the detailed testing and analysis, but an ideal solution would be to utilise the highly detailed raw data if this is available. Duplicate copies of the raw data can be realigned or repaired to match the developed watertight envelope hull form which allows for accurate comparisons between the raw data and their hypothetically reconstructed form.

The damaged portions are digitally 'repaired', just as the displaced elements are replaced, and fragmented timbers made whole in McGrail's definition of 'as-found' model. At each stage, the component parts are examined based on their surviving evidence, and either repaired or replaced, just as is done in the shipyard when repairing a vessel. With the hull structure completed, attention then turns to the deck and superstructure. Missing elements are digitally 'refabricated' using comparative evidence, based on either evidence of their absence in the archaeological raw data, or on structural requirements deemed necessary to create the minimum reconstruction.

McGrail (1992:355) states that a hypotheses must be investigated and tested by experiment, a process which lies at the foundation of all sciences, and after testing, the research must be published so that it may be criticized. In this case the hypothetical minimum reconstruction is tested using the methods discussed in Chapter 6, which have been demonstrated as a highly accurate way to analyse and test the hydrodynamic properties of the vessel.

The manner in which the hypothetical reconstruction is presented, clearly illustrates the various data sets, with recovered material coloured brown, elements forming the watertight envelope in blue, elements not surviving but based on recovered evidence coloured green, and elements with no surviving evidence based on iconography or archaeological parallels coloured red (Figure 8-41).

The results of the minimum reconstruction and digital testing is subsequently published for peer review to allow feedback and/or criticism, which can be further investigated using the same techniques, and will allow if the evidence permits, to continue to a hypothetical Capital reconstruction.

Chapter 9 **The Capital Reconstruction and testing the hypothesis**

9.1 Introduction

As noted in Chapter 7.7, the concept of minimum and capital reconstruction has long been a contentious issue. In reviewing Frank Welsh's Building the Trireme, Christer Westerdahl (1992) questioned whether a 'scientifically based reconstruction' can be made of a ship type for which there is documentary, iconographic and comparative evidence, but no physical remains. McGrail (1992) states that there are comparable, although not identical, problems in building a 'replica' of an excavated vessel, such as that of the $4^{th}/3^{rd}$ century BC Kyrenia ship. McGrail further states that:

> "The Kyrenia ship replica is certainly based on a 'well executed and well published excavation of the highest scientific standards' as Westerdahl (1992: 85) has argued, but the way that this excavated evidence (incomplete, fragmented, distorted and leaving much to be deduced) was transformed into a complete ship Kyrenia 2 and how her sea trials were undertaken have not yet been published in the necessary detail. The reason why Kyrenia 2 has received 'far less attention', to quote Westerdahl again, is that no one outside the experimental team is able to judge the authenticity of this replica or the value of the trials and their relevance to the study of 4th/3rd century BC boat-building and seafaring. Some of the well-known replicas from northern Europe may be similarly 'in limbo' owing to less-than comprehensive publication."

Crumlin-Pedersen (1995) argues that in order to exploit the full potential of a ship find, a multidisciplinary approach is needed, drawing on the expertise of historians, wood specialists, environmentalists, naval architects, boatbuilders and sailors. Crumlin-Pedersen states that Experimental Boat and Ship Archaeology (EBSA) is a welcome contribution, and a key phase is building the hypothesis, which is then subjected to tests yielding observations or physical measurements. He further states that:

> "… the Roar Ege and similar ships, such as the Bremen cog built in Kiel, the replicas of Skuldelev 1 and 5, and the Gislinge and Gedesby replicas, are based on such substantial remains of the original hull that it has been possible to build the hull of the new ship so identical to the original ship that the uncertainty remaining from the missing parts amounts to well below 5% of the original dimensions and features of the vessel."

To my knowledge, none of these replicas have been documented to any extent which could substantiate this assertion, and certainly, the *Hansekogge*, the Kiel replica of the Bremen cog, if built according to the published drawings, falls short of the 95% certainty implied by Crumlin-Pedersen's statement (see Tanner 2017b Appendix H and; Tanner 2018 Appendix I). In fact the three replicas constructed of the Bremen cog have some considerable differences between one another (see Tanner 2018:11 Appendix I, Table 1).

Crumlin-Pedersen and McGrail (2006:57) state:

> "Where considerable portions of the original vessel are excavated, and full reconstruction appears to be a realistic aim, the problem is to determine one or more minimalistic ways to complete the hull and point to the most likely means of propulsion and steering for the vessel. There needs to be a non-biased discussion aiming to produce one or more hypothetical, fully functional reconstructions, judged not by today's standard but by the standards prevailing at the time when the original vessel was built."

The Chartered Institute for Archaeologists notes that depending on its totality, the full original shape, structure, propulsion and steering of the vessel being investigated might not always be capable of reconstruction. However, in order to achieve the primary research aim – an understanding of the vessel's hull-form and construction – an attempt at reconstruction should be considered. That reconstruction's validity and reliability will depend on the reconstruction philosophy. A statement of philosophy should accompany the reconstruction. This will clearly state the use of comparative data, the most reliable being of the same building tradition and of contemporary or earlier date.

This chapter focuses on the capital reconstruction phase. A capital reconstruction will build on the hull form developed during a hypothetical minimum reconstruction (Chapter 8). As will have been noted from Table 7-3, the Newport Medieval ship was the only project to have used every one of the 22 individual stages for reconstruction as set out in Table 7-2. This was primarily due to the available resources. As such the Newport Medieval ship project therefore represents the exemplar for digital reconstruction, and for this reason will be used as the primary example of these processes, unless otherwise stated.

In the case of Newport Medieval ship, the hypothetical minimum reconstruction was based on the articulated archaeological evidence which was definitively part of the original vessel. The following approach combines that hypothetical minimum reconstruction with the several hundred disarticulated elements recovered during excavation, historical research in the form of contemporary iconographic and literary evidence, comparable archaeological evidence, and ship building knowledge.

Capital reconstructions, by their very nature, will involve a greater level of interpretation, and as such, the associated paradata describing how the original data has been interpreted and utilised is of the utmost importance.

9.2 Comparative analysis

In the case of the Newport Medieval ship, using feedback and criticism received following the publication for peer review, the original hypothetical minimum reconstruction (Figure 9-1) is further developed. Figure 8-41 clearly illustrates the hypothetical minimum reconstruction, and how that was developed from the floating hypothesis. The representation is colour coded to illustrate the provenance of each element. Brown is archaeological evidence, blue is elements required to form the watertight hull, green is elements not recovered but for which some evidence was recovered, and red for elements where no evidence was recovered and is based on comparable evidence or iconography.

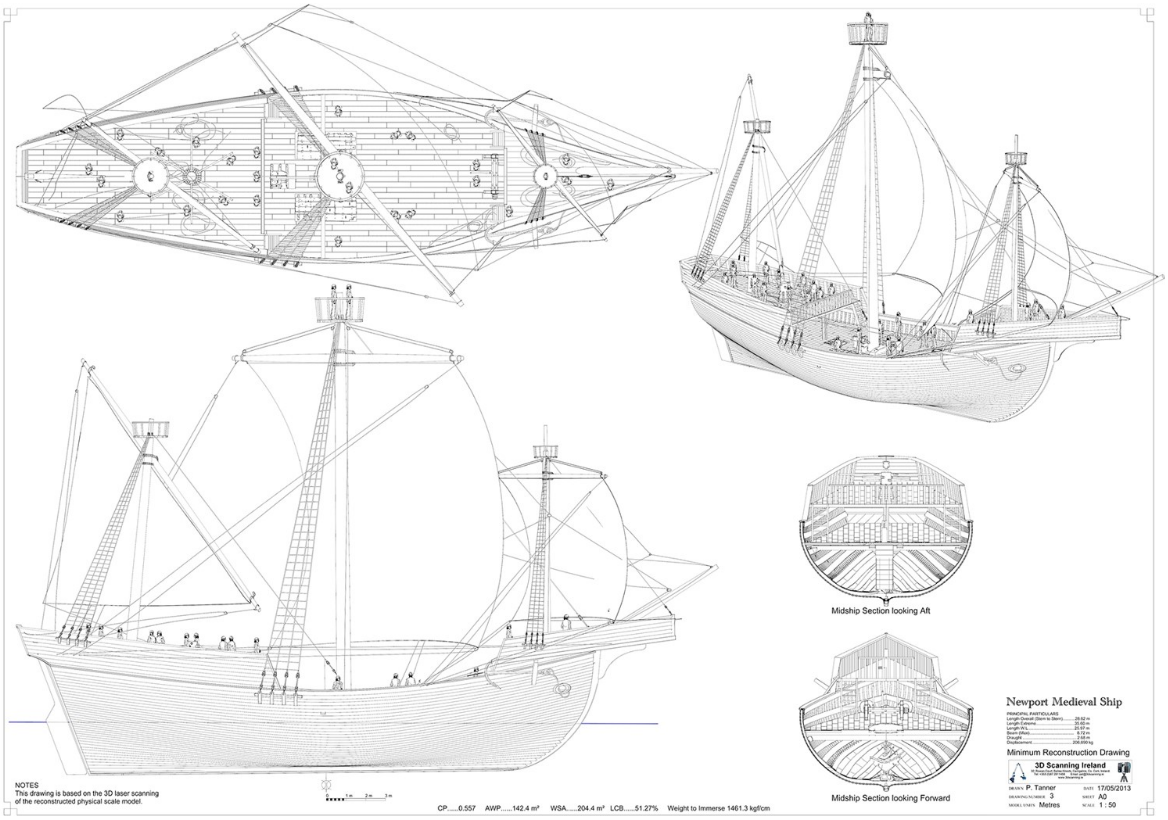

Figure 9-1 Newport Medieval ship hypothetical minimum reconstruction (Pat Tanner)

Some of the feedback received following publication for peer review suggested that the sheer line appeared too low and that the reconstruction looked like a big boat rather than a ship. The upperworks do not resemble the Zumaia tapestries (Figure 9-4 top-middle), and the upperworks look modern when compared to the Beauchamp pageant (Figure 9-4 bottom). Note that the majority of these comments relate to the red conjectural areas of the hypothetical minimum reconstruction and as both castles were conjectural, a simplified reconstruction of both were added to the floating hypothesis.

Were the comments regarding the low sheer line as a result of the reconstructed vessel being depicted at its maximum draft in a fully loaded flotation condition? Compare Figure 9-2 which shows the vessel in a fully loaded flotation condition (top), which might suggest an apparently low sheerline, and without cargo floating over 1 m higher (bottom).

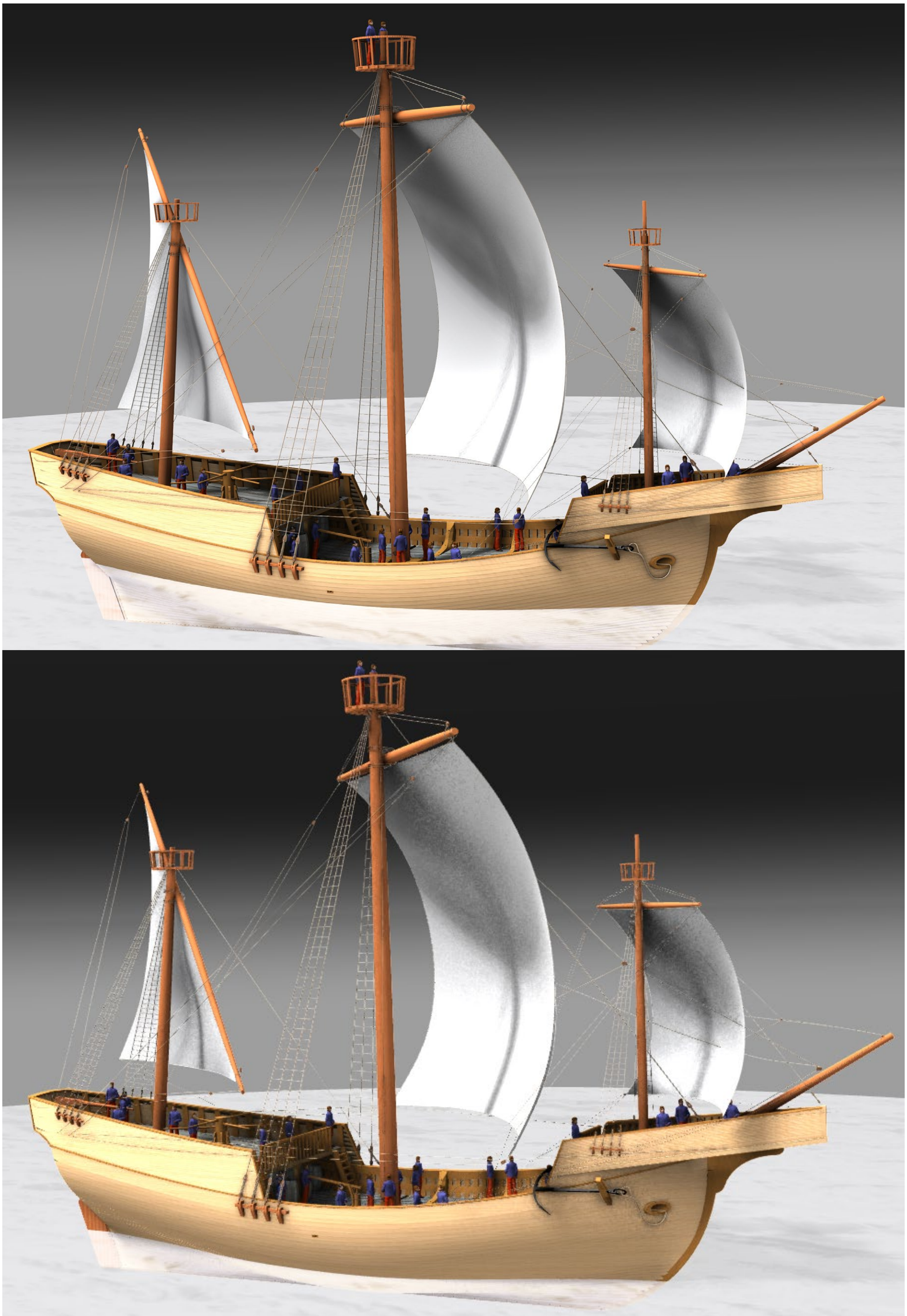

Figure 9-2 Newport Medieval ship – comparison between fully loaded flotation (top) and without cargo (bottom) (Pat Tanner)

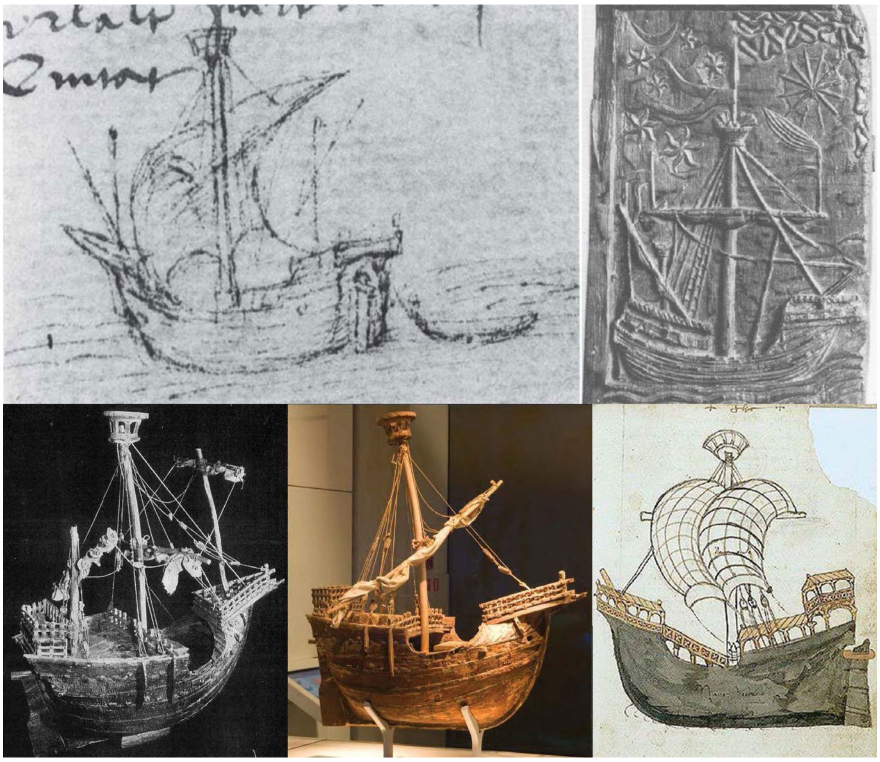

Figure 9-3 Iconography referred to during the minimum reconstruction phase (Top left – a three masted ship from 1409, top right – Kings Lynn circa 1415, bottom left and middle – the Mataro model mid-15th C, and bottom right Michael of Rhodes circa 1450)

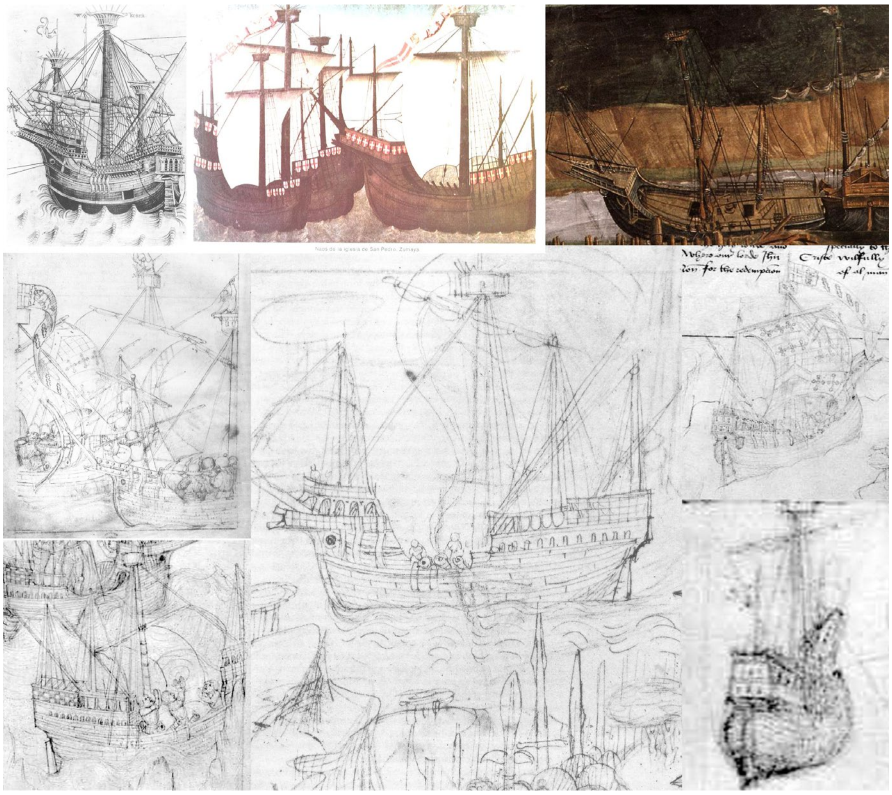

Figure 9-4 Iconography used for further comparisons (top left to right – W A Kraeck 1470, Zumaya tapestry 1475, detail from "The Punishment of Korah" by Botticelli 1482, bottom 5 images from the Beauchamp pageant 1485)

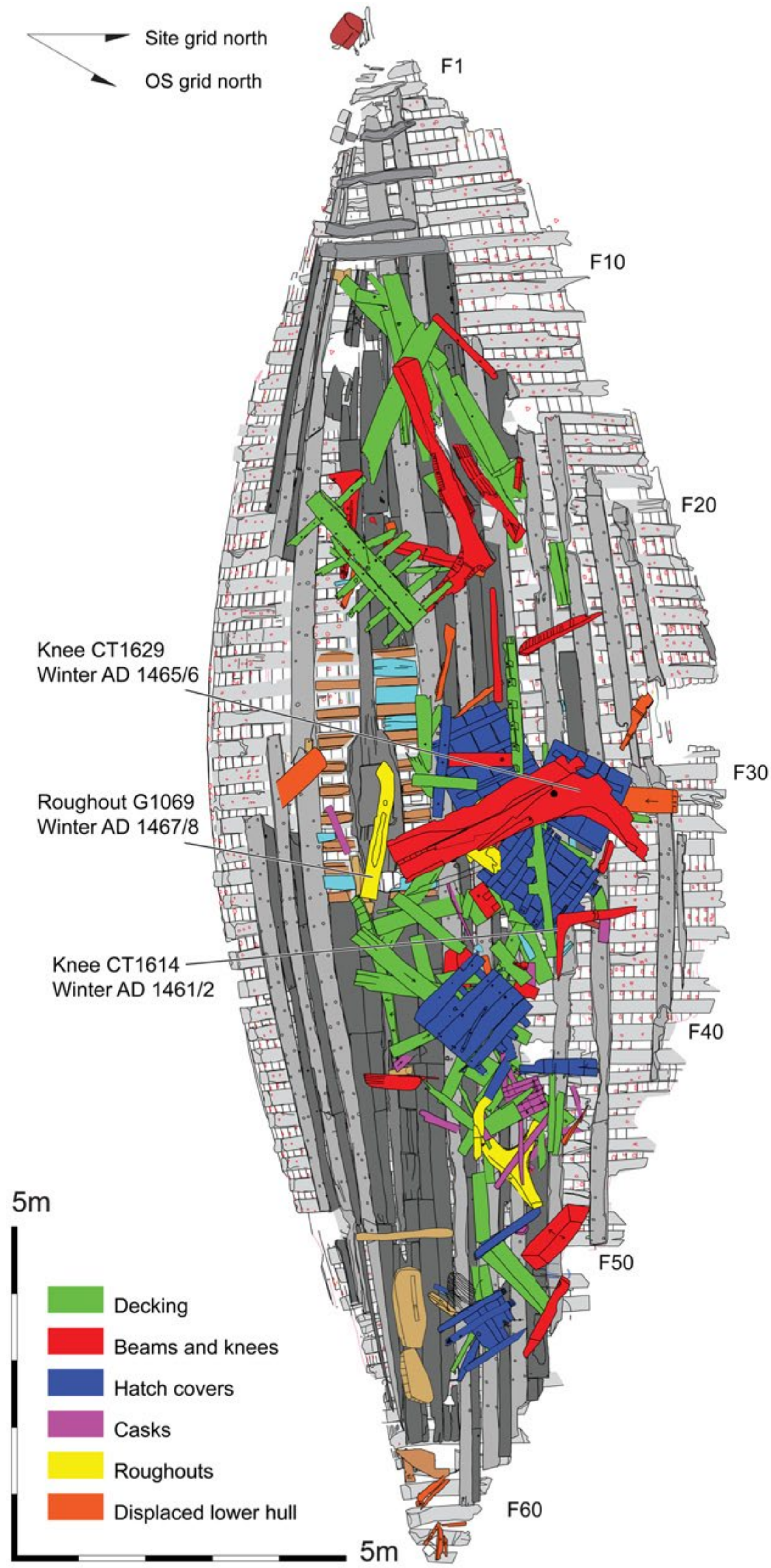

Figure 9-5 Disarticulated timbers lying within the ship, colour coded by major categories. (Nigel Nayling) (Nayling and Jones 2014:9)

9.3 Adding elements for Capital Reconstruction

With the articulated hull remains used to recreate the initial floating hypothesis, and the subsequent hypothetical minimum reconstruction, the next phase was to examine the several hundred disarticulated timbers recovered from within and around the surviving hull area. These timbers were initially categorised by their apparent major categories (Figure 9-5) before being hypothetically placed within the digital model. As the hull form was evolving, it became possible to digitally place more and more of these timbers in their perceived original positions. This hypothetical placement was informed by analysing find location, parallel / comparable archaeological evidence, iconography, and ship building knowledge.

The process of adding these elements to the vessel is set out in detail in the Newport Medieval ship phase two report (Tanner 2020:61–81 see Appendix G). The main categories of disarticulated timbers were elements related to the deck area, such as composite beams and standing knees, deck beams and ledges, carling beams, and articulate but displaced hatch covers. One of the largest disarticulated elements recovered was a composite beam-standing knee assembly (Figure 9-6) which was recovered just aft of midships on the starboard side of the vessel. The outboard end of the lower transverse beam terminated in a dovetail tenon which closely matched the dimensions of the dovetailed mortice rebates on the beam swelling of the articulated seventh stringer (Figure 9-7), thereby indicating the accurate positioning of this element.

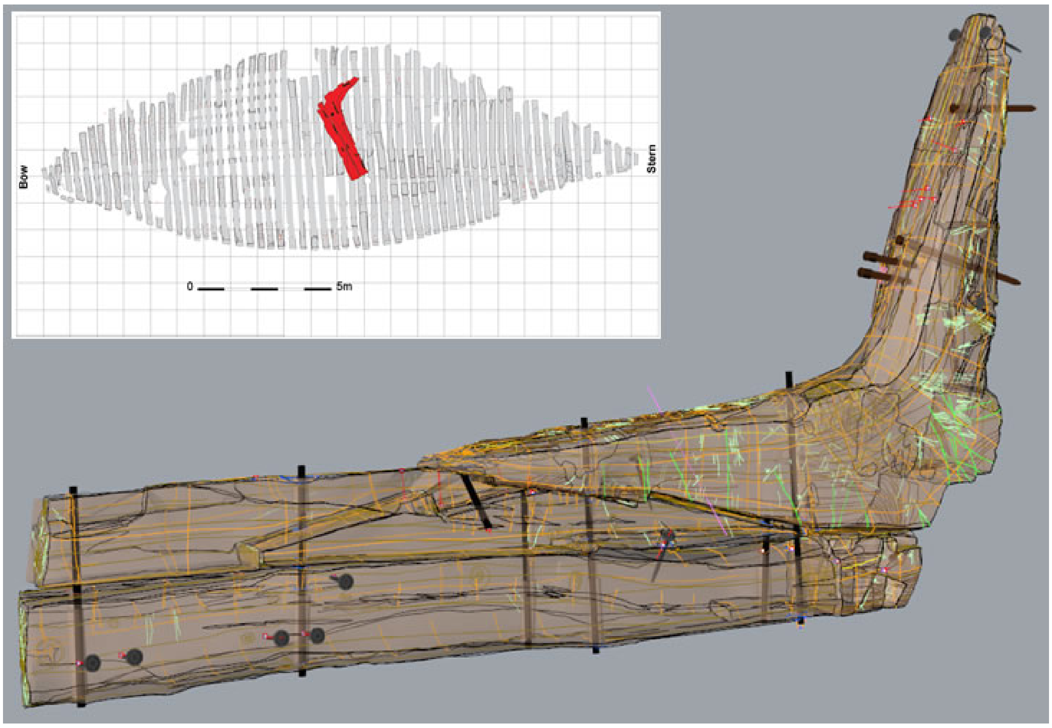

Figure 9-6 Newport Medieval ship Large standing knee and composite beam assembly (Pat Tanner)

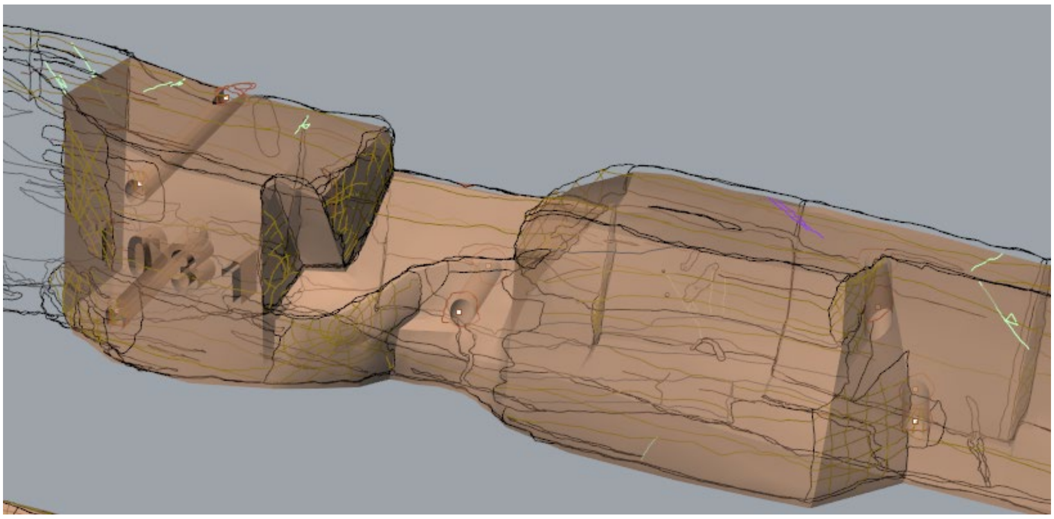

Figure 9-7 Newport Medieval ship, detail of beam swelling on seventh stringer (Pat Tanner)

Initially thought to be associated with the beam swelling located midships between frames 29 and 30, however, closer examination of the outboard end of both the beam and knee revealed the end had not been cut square, but tapered aft, indicating the assembly was located further aft, probably associated with the beam swelling between frames 40 - 41.

The partial beam shelf fragment CT1526 (Figure 8-26 and Figure 8-27) was already fitted to the digital model, and gave an accurate indication of the location, size and spacing of the deck beams. Several disarticulated deck beams were recovered which had average dimensions of 115 mm wide x 95 mm high which matched the deck beam rebates on the beam shelf, and were not straight, typically having a curvature with a rise of 15 mm over 1.2 m distance indicating the deck was cambered (Figure 9-8).

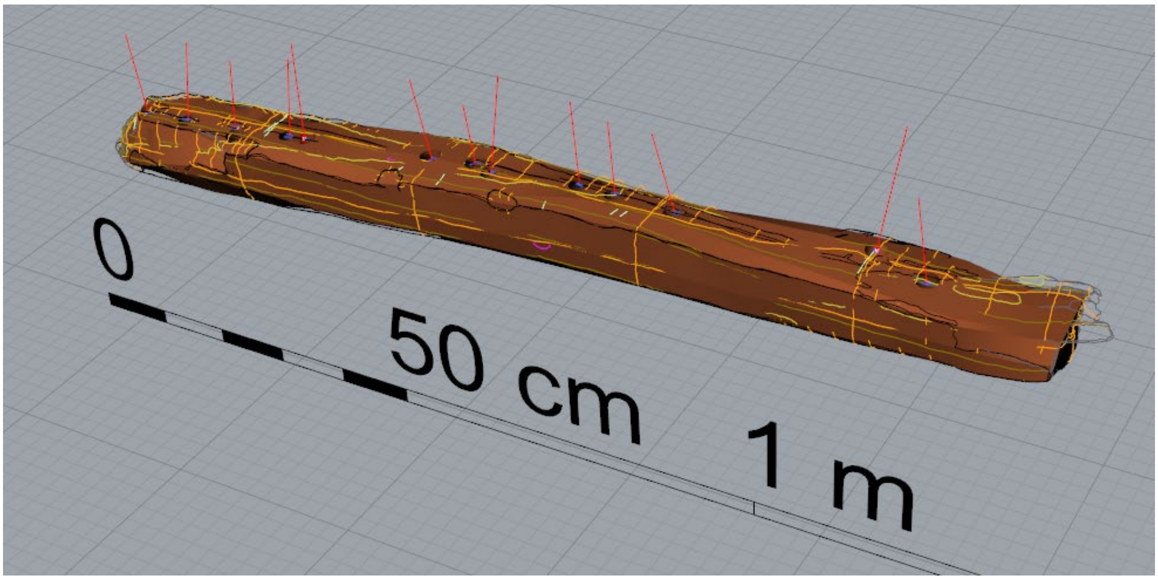

Figure 9-8 Several disarticulated deck beams were recovered such as CT1235 recovered near frame 19 (note the nail angles - red lines - probably for fixing deck planks) (Pat Tanner)

A very significant find was the displaced mast partner fragment recovered from within the vessel, which had been roughly hacked in antiquity, through one of the four iron bolt fastening positions (Figure 9-9). The curved rebate on the aft face, to accommodate the mast indicated a mast diameter at deck level in the region of 815 mm. A rebate of circa 305 mm wide x 135 mm deep on the underside of each end was probably used to clamp over the heavy carling beams either side of the mast. A corresponding rebate on the damaged inboard extremity of the composite beam-knee assembly (Figure 9-6) measured circa 285 mm wide by 95 mm deep on both the forward and aft faces, and was probably associated with same heavy longitudinal carling beams.

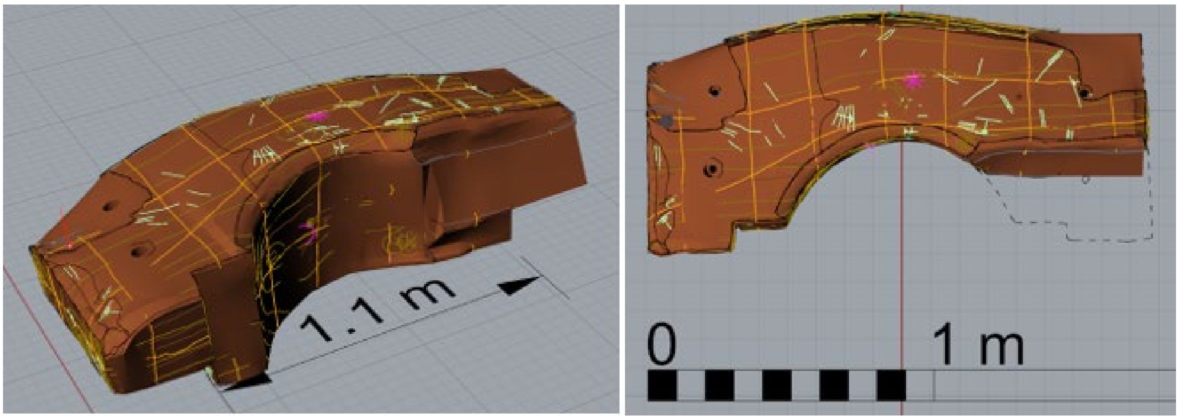

Figure 9-9 Displaced mast partner with presumed extent of the missing portion shown dashed (Pat Tanner)

The heavy carling beams were reconstructed based on the evidence provided by the mast partner, the composite beam-knee assembly, and the near-complete rebate surviving in the fragmentary remains of beam CT1610 (Figure 9-10).

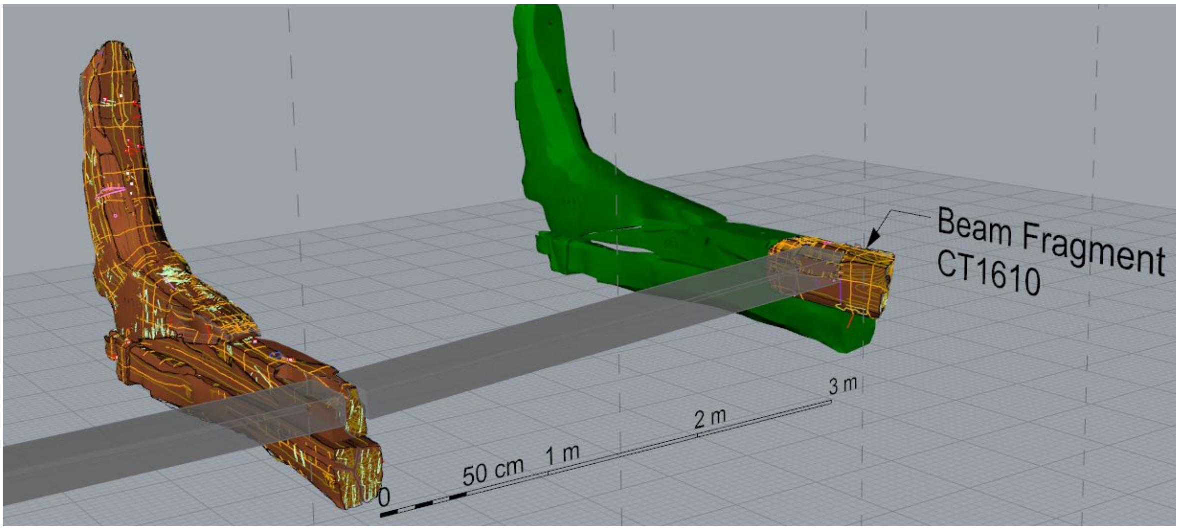

Figure 9-10 Composite beam and standing knee assembly with rebates for heavy carling beams (Pat Tanner)

The transverse spacing between both carlings was 1.1 m, based on the mast partner, which coincided with the two of the five articulated but displaced hatch covers recovered from within the vessel (Figure 9-11). All five of these deck hatches featured caulking between the deck planks, which indicates an attempt at waterproofing and could suggest a watertight deck. Positioning the deck hatches on the centreline of the vessel is logical, and standard practice as it positions the deck opening, a potential cause of flooding, in the safest location, resulting in a significantly higher (safer) downflooding angle. Of the remaining three deck hatches, two were too wide to fit between the heavy carling beams, and the fifth was too narrow, which raises further questions regarding their final position within the reconstruction.

Figure 9-11 Hatch Cover context 143 (Newport Museums and Heritage Service)

The digital reassembly and positioning of these disarticulate but obviously associated ship's timbers allowed for a hypothetical reconstruction of the deck structure (Figure 9-12). The composite beam-standing knee assembly, combined with associated carling beams, the recovered mast partner, and recovered deck hatches, when positioned relative to each other, provided evidence based remains which crossed the vessel's centreline. These were located at a height close to the uppermost extremity of the articulated remains. Mirroring these elements provided a reliable width for the reconstructed hull form, which highlighted that the faired watertight envelope shape was in fact 20 cm too wide and needed to be modified.

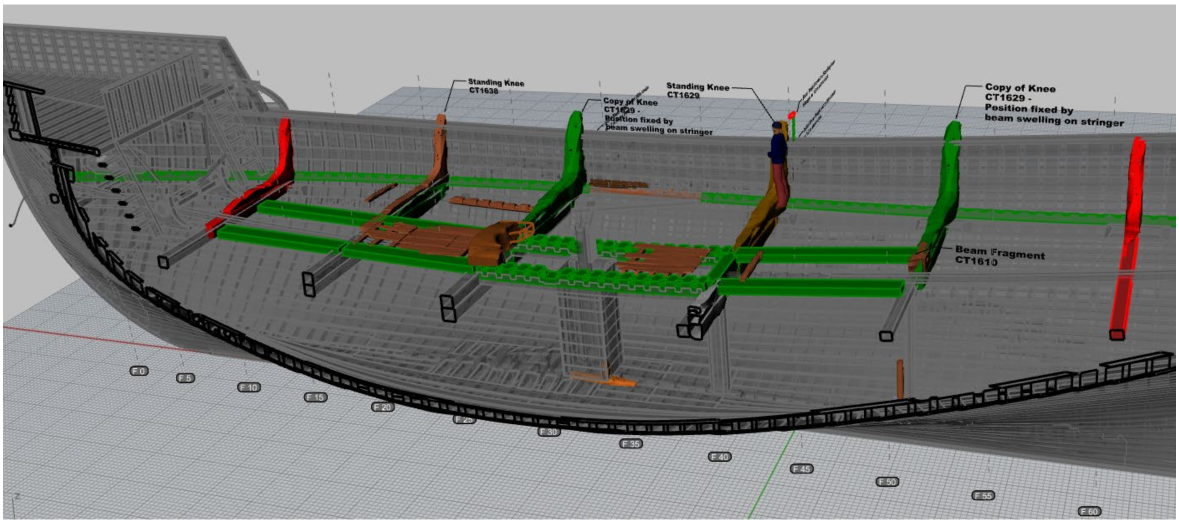

Figure 9-12 Newport Medieval ship reconstructed deck structure based on disarticulated elements (Pat Tanner)

This immediately highlighted two issues with the hypothetical minimum reconstruction. The sheer line, initially set at 1.2 m or elbow height above deck level, was in-fact too low, based on the upstanding leg of the standing knees, and the deck, initially installed as a flat laid deck should be a curved (cambered) deck (Figure 9-13).

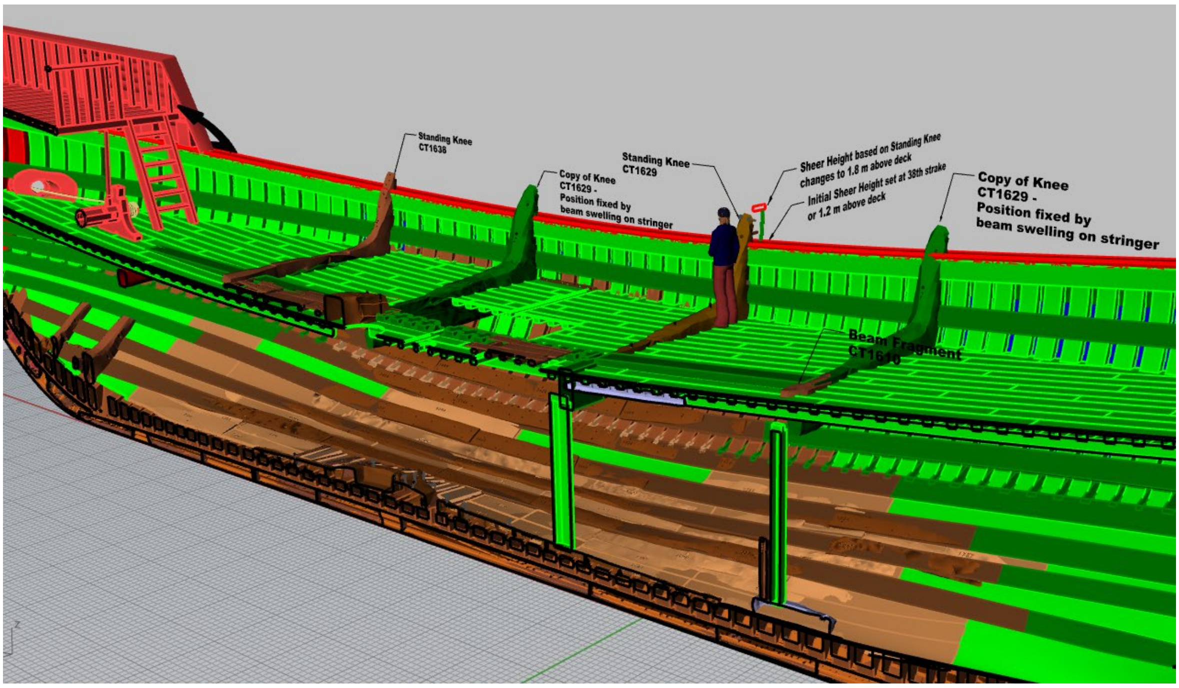

Figure 9-13 Composite beam-standing knee assemblies fitted to the digital model (Pat Tanner)

However, if the sheer height is raised to accommodate the evident standing knee, this results in a height of 1.8 m, clearly not a practical or functional situation for any crew working at deck level (Figure 9-14). This would appear to suggest that the top of this standing knee, causing the hull structure to require at least 41 strakes, did not represent a valid sheer line.

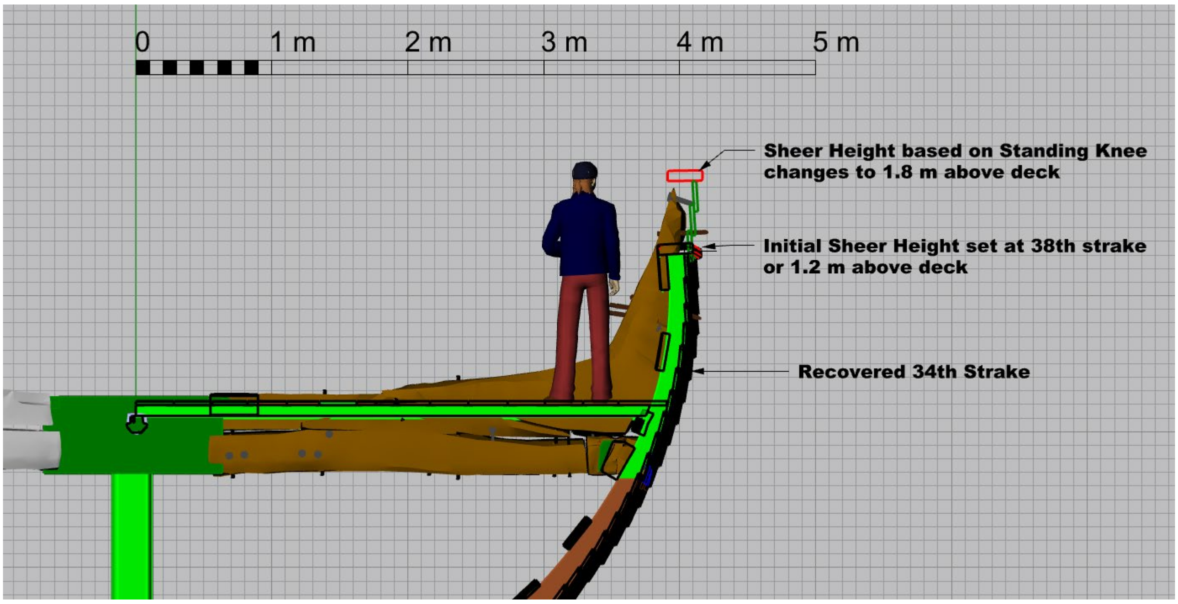

Figure 9-14 Revised sheer height as a result of the Composite Beam and Standing Knee (Pat Tanner)

Additional recovered elements included a standing knee CT1547 and a transverse beam CT1542 (Figure 57) which were both recovered in the vicinity of frame 40. Both are similar in features and shape to the composite beam standing knee assembly, however, the scantling size for this beam of 205 mm sided by circa 175 mm moulded, is significantly smaller than that of the composite beam CT003 at 260 mm moulded by 215 mm sided.

More significantly, while the larger standing knees all showed an outboard angle of circa 7° for the upright leg, the smaller standing knee had an inboard leaning angle of circa 4° for its upright leg. This angle did not match any are of the existing hull geometry. This inboard angle or tumblehome, a common feature higher up in a ship's hull, point towards these elements coming from a second higher level in the vessel, where the hull curvature has transitioned from an outboard flare to a vertical or slight inboard (tumblehome) shape (Figure 9-16).

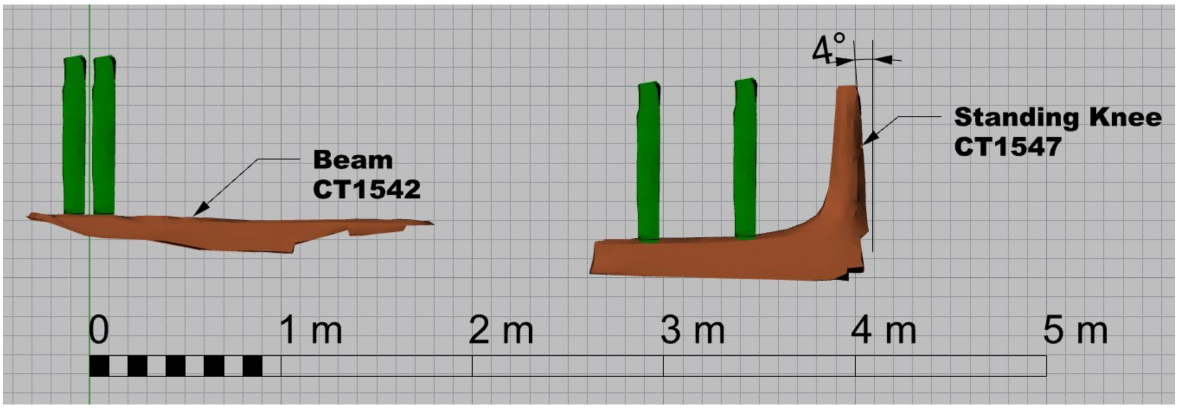

Figure 9-15 Standing knee CT1547 and transverse beam CT1542 recovered near frame 40 (Pat Tanner)

The transverse beam CT1542 was double the scantling size of the typical deck beams, and in addition contained two morticed rebates, presumed to be associated with the base of upright stanchions. Additionally, the horizontal leg of the standing knee CT1547 contained another two morticed rebates, also presumed to be associated with the base of upright stanchions. These were the only recovered features which provided any indication of internal subdivision or compartmentalisation of the vessel. The standing knee CT1547 also has two rebates on the forward face, presumably to accommodate carling beams.

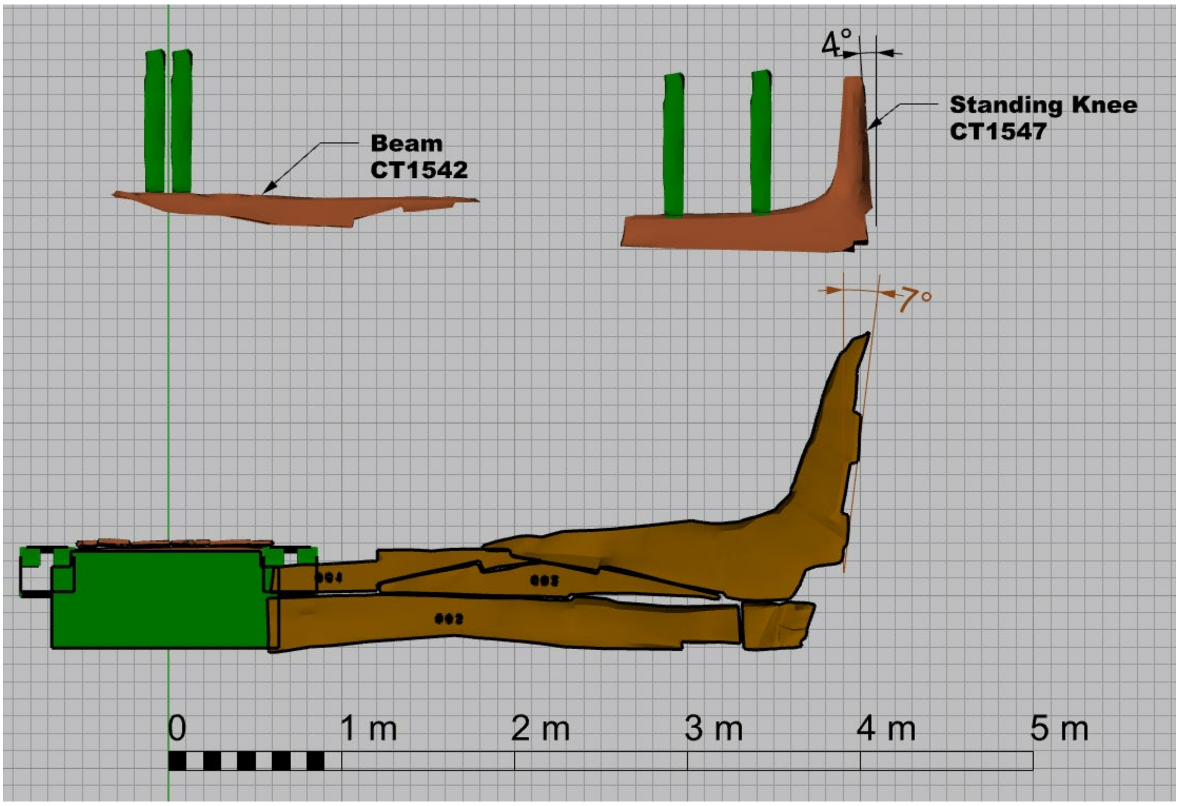

Figure 9-16 Standing knee CT1547 and transverse beam CT1542 fitted to the digital reconstruction (Pat Tanner)

When all this evidence is combined – the reduction in scantling size, the tumblehome angle, the excessive sheer height caused by the vertical height of the composite beam standing knee assembly, and taken together with the three deck hatches which did not fit between the heavy carling beams already installed, this would appear to be a strong indication for the existence of a second deck level. While the upright stanchions may form part of the support structure for a stern castle deck above (Figure 9-17).

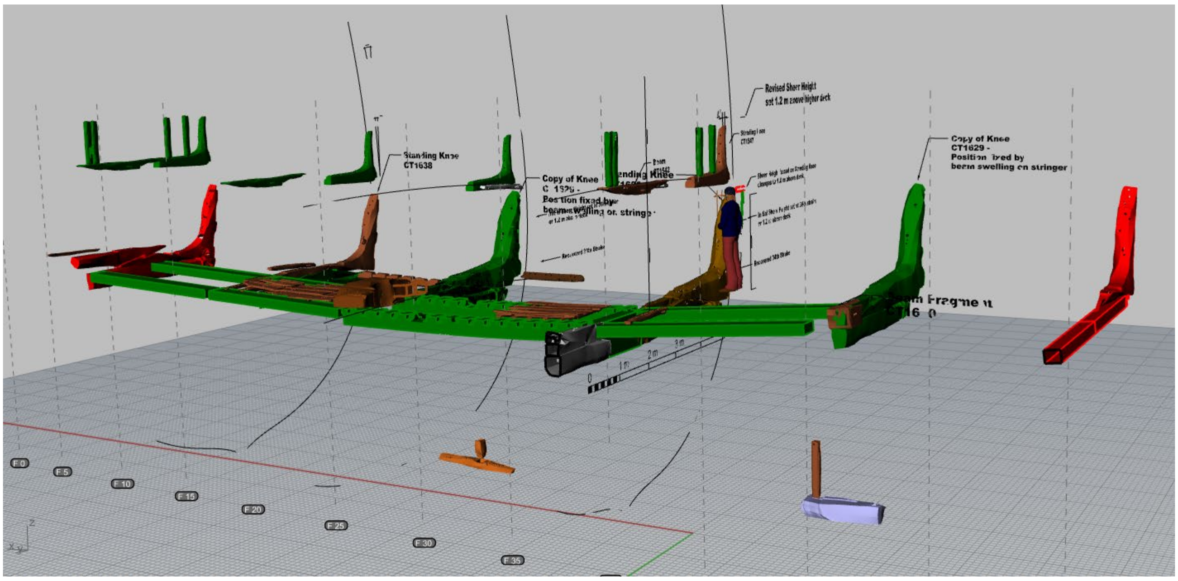

Figure 9-17 Disarticulated deck elements digitally reposition to indicate a possible deck structure (Pat Tanner)

In a further check on the potential of the recovered remains representing a vessel of the scale and proportions emerging from the digital repositioning of disarticulated elements, the surviving futtock dimensions were analysed. Similar to the probability box method used to determine possible strake hood end positions, the shortest and longest surviving futtocks were examined. Evidence from the surviving articulate hull remains indicated that at least three futtocks had been used to for a complete frame assembly. Of these futtocks, the shortest recorded complete length, excluding scarf is 1.6 m and the longest recorded complete length excluding scarf is 2.7 m.

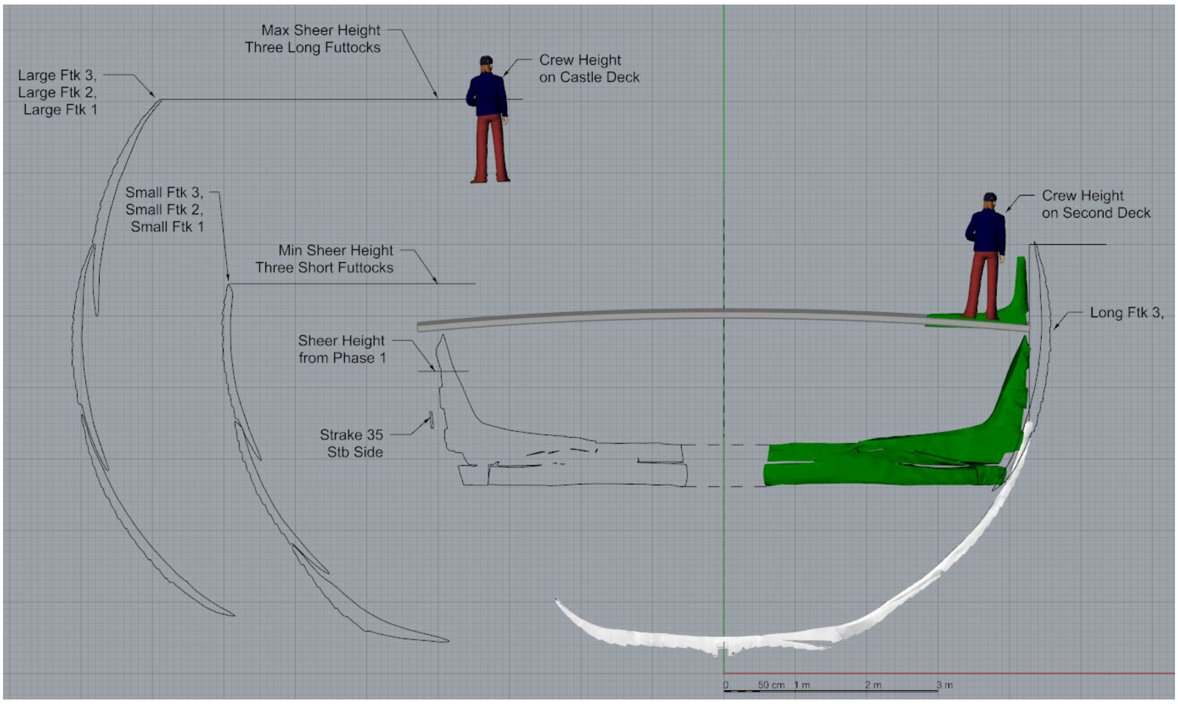

Figure 9-18 Estimating sheer height using a probability box based on surviving futtock heights (Pat Tanner)

Using three of the shortest futtock lengths created a sheer height which was both too high for a single deck, and too low for a two decked reconstruction. A single short futtock combined with two long futtocks created a valid sheer height for a second deck at 1.2 m or elbow height above deck level. And using three of the longest futtocks created a sheer height at elbow level for a man standing on a castle deck, indicating a potential maximum extent for the hull reconstruction (Figure 9-19).

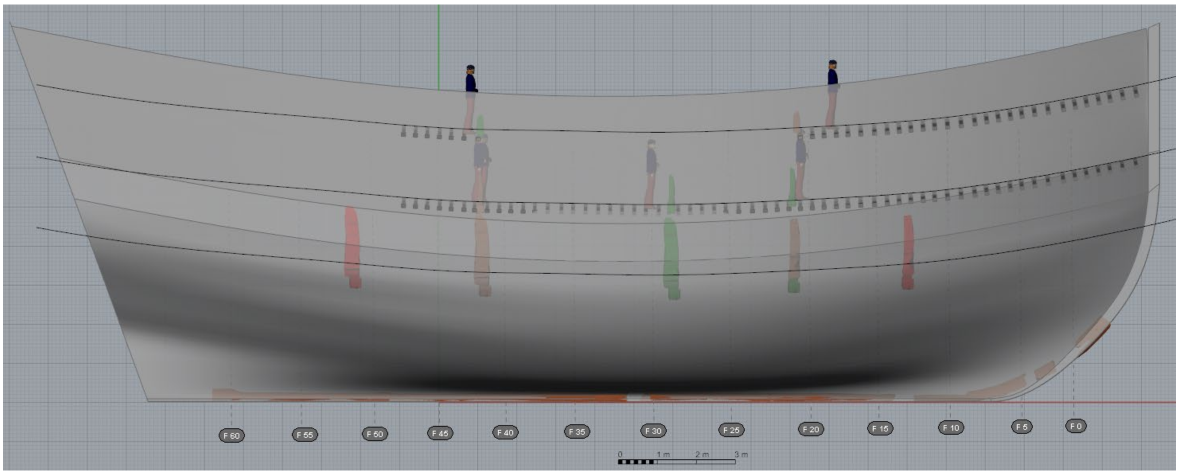

Figure 9-19 Potential maximum extents for the hull reconstruction based on surviving futtock dimensions (Pat Tanner)

Another thought to be considered is the extent of the surviving articulate hull remains, initially thought to be the substantial remains of a large medieval ship. If we consider a vessel which apparently suffered a catastrophic incident while undergoing repair work in the pill and fell over onto her starboard side. There appears to be some evidence for attempted salvage, suggested by the roughly cut bilge pump holes between frames F7 and F8, and also at frame F58 (Nayling and Jones 2014:24–25). Further evidence may include the series of seven drainage holes drilled along strake S19_6 and S19_7, which would have been the lowest point in the vessel after it came to rest on its starboard side. At some point the attempted salvage was abandoned and the work turned to reclamation as evidenced by the hacked extremities with axes in the surviving remains.

In a time when recycling ships timbers for other uses was commonplace, at what point do the reclaimers call a halt to the reclamation process? If you picture the recovered remains laying on its starboard side, as being the last, lower single figure, or low teen percentage of the entire vessel. Being the parts lowest down, in the most difficult area to work, and the most effort required for further reclamation, possibly subject to tidal or continual flooding.

Perhaps the recovered remains represent the point whereby the reclaimers decided they had recovered enough, and what was initially considered to be the substantial remains of a large ship, is in fact the partial remains of a much larger Medieval ship.

Based on the reconstruction work completed thus far by repositioning disarticulated elements, the potential maximum hull extents (Figure 9-19) was then compared with contemporary iconography (Figure 9-4). These images were used to further refine and develop the hypothetical reconstruction by lowering the sheerline in the central waist area to a height commensurate with the second deck level, and the addition of 1.6 m to the sheer would create adequate height for the proposed castles (Figure 9-20). The spars and rigging were then modified to suit (Figure 9-21)

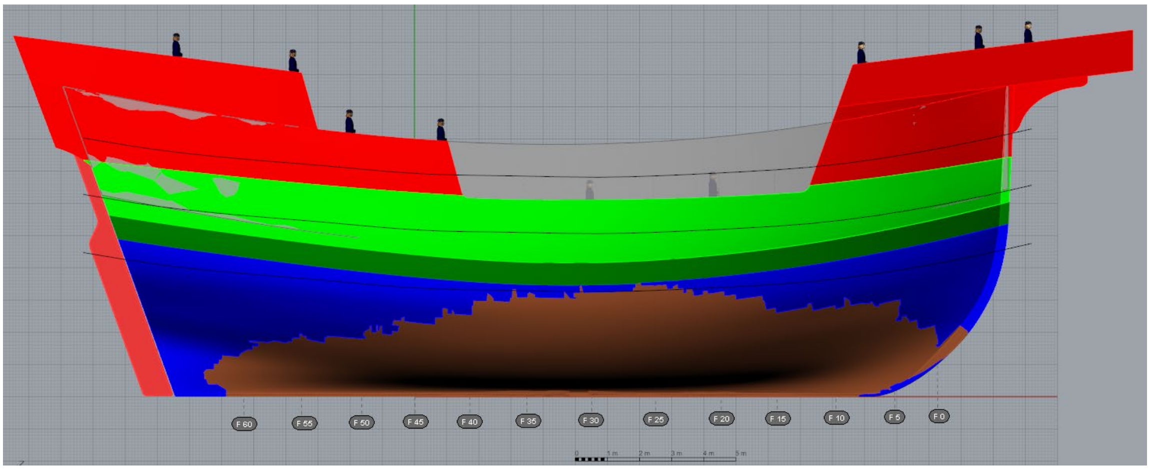

Figure 9-20 Refining the Capital Reconstruction hull extents based on contemporary iconography (Pat Tanner)

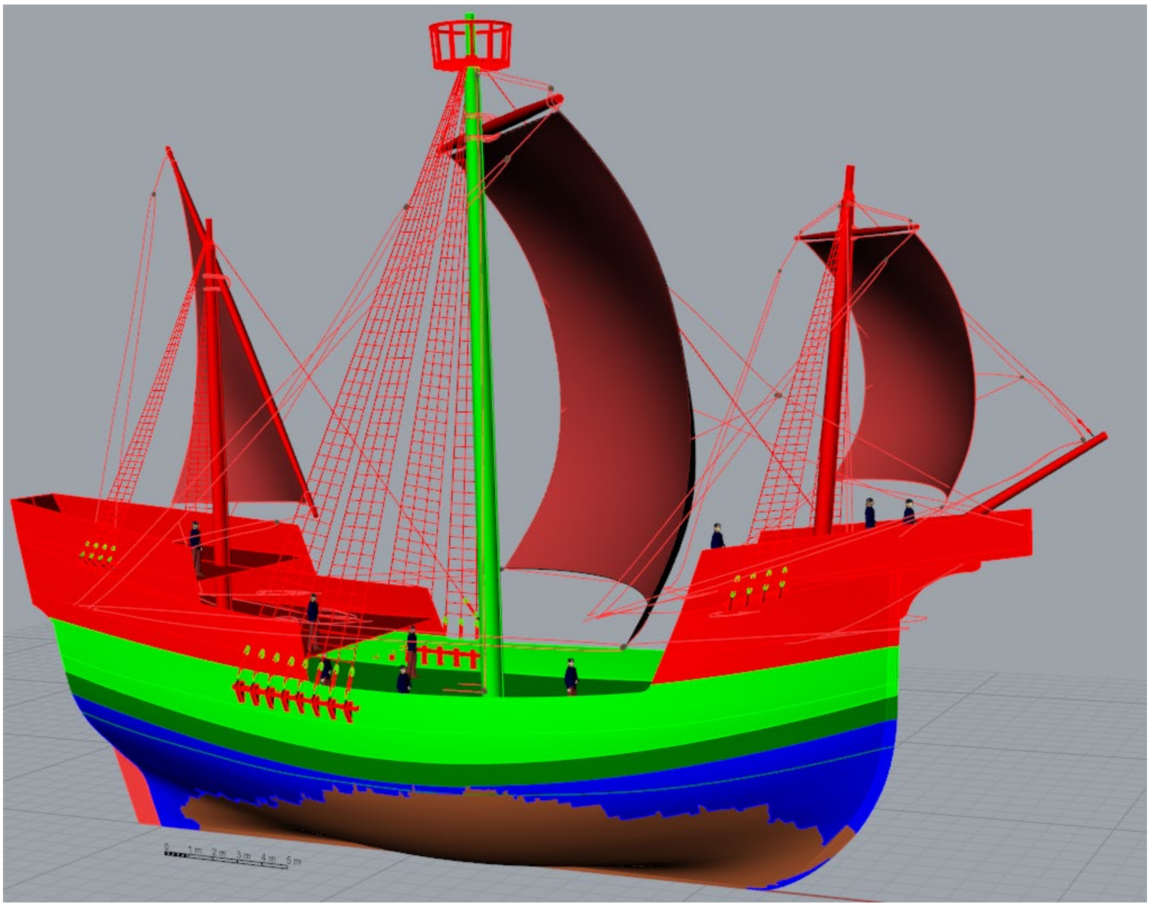

Figure 9-21 The hypothetical Capital reconstruction with rigging adjusted to suit (Pat Tanner)

9.4 Testing and analysis

This hypothetical capital reconstruction (Figure 9-21) was again tested and analysed using Orca 3D. A weight report was generated to include the revised capital reconstruction vessel, complete with the masts and rigging. In this capital construction configuration (Figure 9-21) the vessel's total weight increased from 79.6 tonnes to 131.5 tonnes, and the vessel was again analysed for intact stability.

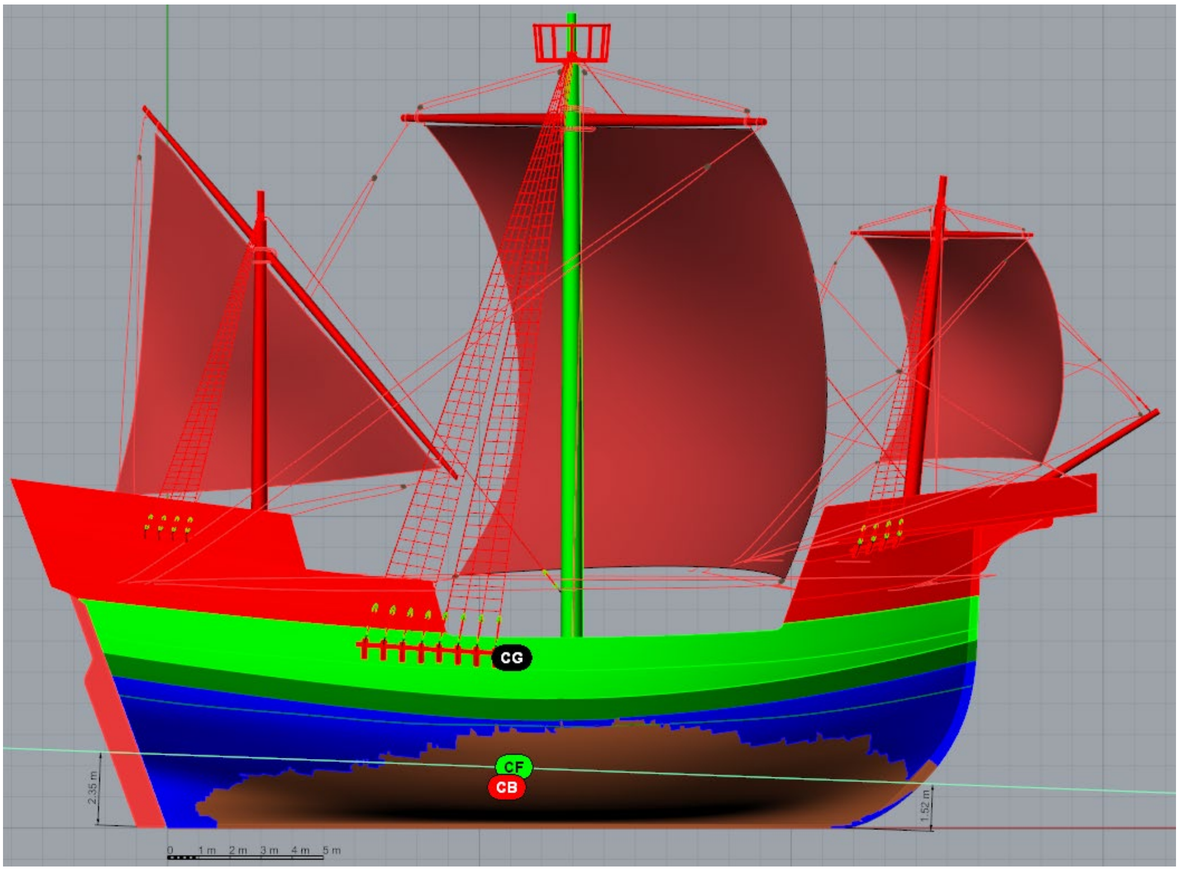

Figure 9-22 The Capital reconstruction flotation condition without ballast (Pat Tanner)

In this configuration, the vessel has a total weight of 131,502 kg, the longitudinal centre of gravity L.C.G. is located 11.04 m forward of the aft end of the keel, the transverse centre of gravity T.C.G. is 0.0 m, meaning it is located on the vessel's centreline and the vertical centre of gravity V.C.G. is located 5.4 m above the bottom edge of the keel. The draft aft is 2.35 m, and draft forward is 1.52 m with a freeboard midship of 4.19 m.

The vessel is clearly floating too high in the water, and with the centre of gravity so high the vessel in this configuration has a negative transverse metacentric height (GMt) of -1.127 m (Figure 9-23). Even with a negative metacentric height, vessels with certain hull forms still find a position of stable equilibrium at an angle of heel that does not immediately endanger them and will remain permanently heeled at this angle called angle of loll. However, as the ship is inclined, negative

Righting Arms (called upsetting arms) are created which tend to capsize the ship (Figure 9-24). It would be impossible for the vessel to sail in this condition without internal ballast being added to lower the centre of gravity and thereby generating a positive metacentric height.

Load Condition Parameters

Condition	Weight / Sinkage	LCG / Trim	TCG / Heel	VCG (m)
Condition 1	131502.466 kgf	11.039 m	0.000 deg	5.431

Resulting Model Attitude and Hydrostatic Properties

Condition	Sinkage (m)	Trim(deg)	Heel(deg)	Ax(m^2)
Condition 1	2.360	-2.202	0.000	9.19

Condition	Displacement Weight (kgf)	LCB(m)	TCB(m)	VCB(m)	Wet Area (m^2)
Condition 1	131502.756	10.880	0.000	1.286	164.227

Condition	Awp(m^2)	LCF(m)	TCF(m)	VCF(m)
Condition 1	122.350	11.109	0.000	1.935

Condition	BMt(m)	BMl(m)	GMt(m)	GMl(m)
Condition 1	3.021	29.395	-1.127	25.247

Condition	Cb	Cp	Cwp	Cx	Cws	Cvp
Condition 1	0.288	0.557	0.646	0.518	2.898	0.446

Figure 9-23 Orca intact stability results for Capital reconstruction without ballast (Pat Tanner)

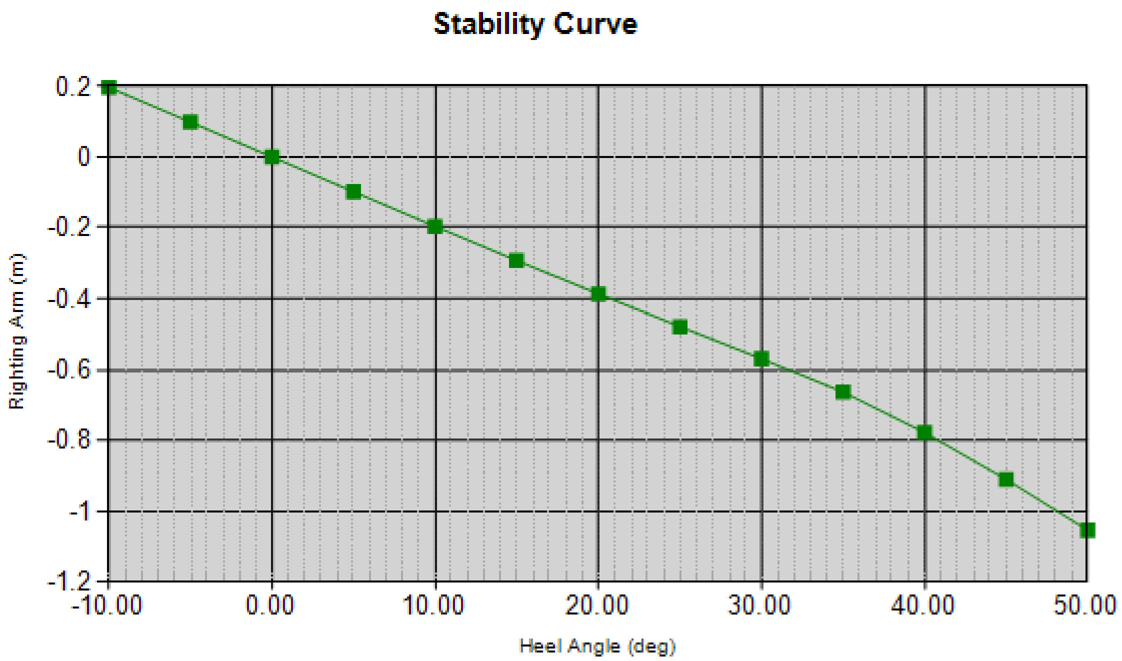

Figure 9-24 Orca stability curve for Capital reconstruction without ballast – note how all the curve is in the negative area of the graph (Pat Tanner)

Just as was done for the minimum reconstruction in Chapter 8.10, several stability criteria were then run with varying quantities of ballast to determine a sufficient or minimum quantity of ballast to enable the vessel operate under full sail in up to 15 knots of wind. Internal ballast of stone was positioned inside the vessel on top of the ceiling planking. The quantity required to allow the vessel to operate under full sail in 15 knots of wind was determined to be a depth of 0.6 m which resulted in 73.8 tonnes of ballast.

In this configuration, the vessel has a total weight of 205,377 kg, the L.C.G. moves slightly forward to 11.4 m from the aft end of the keel, the T.C.G. remains at 0.0 m on the vessel's centreline, but the vertical centre of gravity V.C.G. is significantly lowered from 5.4 m to 3.85 m, creating a positive metacentric height of 0.535 m. The draft aft is 2.7 m, draft forward of 2.3 m and the remaining freeboard midship is 3.6 m. In a 20-knot wind the vessel would heel to 17.6°, the angle of maximum righting moment GZmax is 64.7°, and the downflooding angle is 47°.

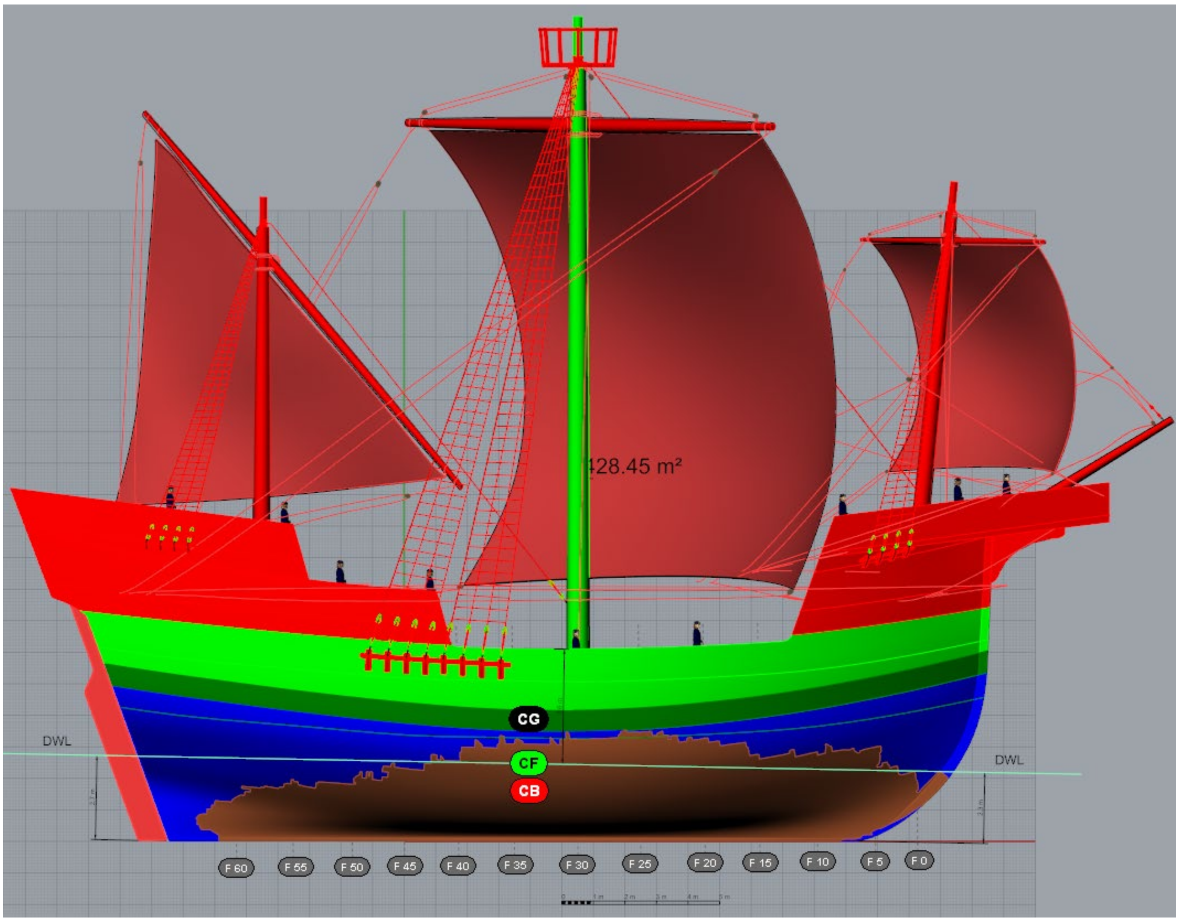

Figure 9-25 The Capital reconstruction flotation condition with 0.6 m of ballast (Pat Tanner)

This would indicate that the capital reconstruction, in this configuration has a satisfactory stability curve (Figure 9-26) and also passes the modern Bureau Veritas intact stability criteria (Figure 9-27).

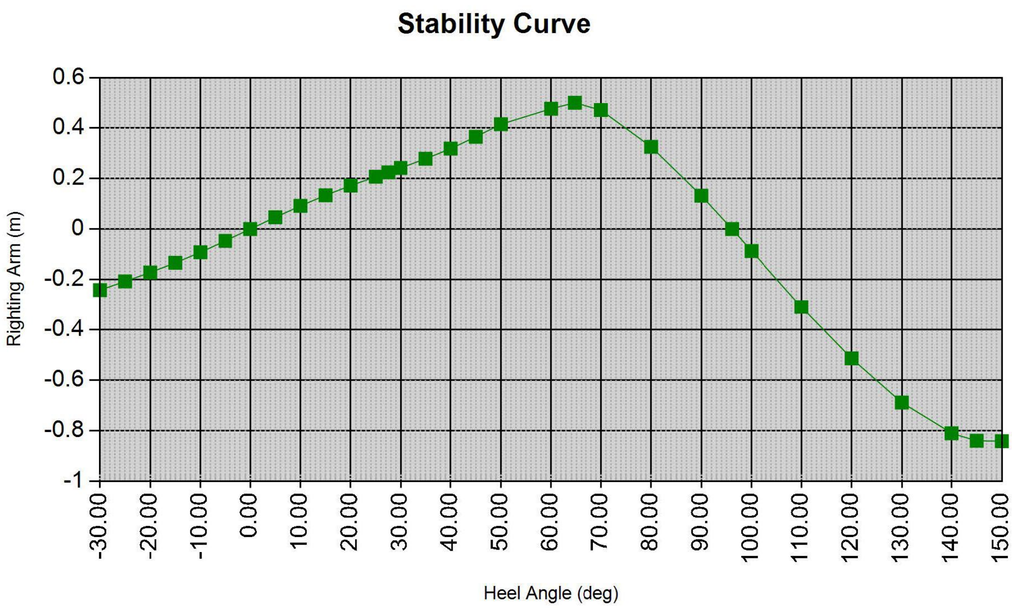

Figure 9-26 Orca stability curve for Capital reconstruction with 0.6 m of ballast (Pat Tanner)

Stability Criteria - Bureau Veritas, Intact Stability					
Name	**Angle 1**	**Angle 2**	**Required**	**Actual**	**Pass / Fail**
Area Between FreeEquil and 30 > 3.151 meters-deg	0	30	3.151	3.8587	Pass
Area Between FreeEquil and 40 > 5.157 meters-deg	0	40	5.157	6.648	Pass
Area Between 30 and 40 > 1.719 meters-deg	30	40	1.719	2.7893	Pass
GZ At 30 > 0.2 meters	30		0.2	0.2416	Pass
Angle At GZmax > 25 deg	64.7245		25	64.7245	Pass
GM At FreeEquil > 0.15 meters	0		0.15	0.536	Pass

Figure 9-27 Bureau Veritas intact stability results for the Capital reconstruction (Pat Tanner)

9.5 Cargo capacity and tonnage

The cargo capacity for any vessel is ultimately the difference between the vessels total weight and the weight of the volume of water that vessel displaces when loaded to a certain freeboard.

In the case of the Newport Medieval Ship the minimum freeboard from the *Grågås Codex (*see Chapter 8.6.2*)* would be F=2 x 6.1 / 5 = 2.46 m. This would result in a draft aft of 3.88 m and a draft forward of 3.46 m. This results in a displacement value of 392.5 tonnes. With a ballasted deadweight of 205.3 tonnes this means the Newport Medieval Ship would be capable of carrying circa 187.2 tonnes of cargo.

A "typical" unit of Medieval cargo was the "Tun", a volume measure of the quantity of wine in a "Tun" cask. Although accurate dimensions for this vary wildly, with the "Tun" sometimes referring to volume and sometimes referring to weight. As noted by Castro (2013) these casks were built by hand, according to tradition, and the external dimensions and capacities of barrels varied considerably. For example, the Portuguese standard tonel had a max height 1.54 m and max diameter of 1.027 m. With differences between elliptical and parabolic sided casks, and base diameters ranging between 80 - 95% of max diameter resulting in internal volumes ranging from 828 to 931 litres.

In Spain, in 1575 Juan Escalante de Mendoza indicated a tonel as 55 arrobas or 632.5 litres. The *Enciclopedia general de la mar* indicates 436 litres as the capacity of a pipa de Castilla, making the Castilian tonel 872 litres. Castro (2013:1138) also notes the English ton of between 240 - 252 gallons gives 910 - 955 litres. This conversion appears to use U.S. gallons and if converted using imperial gallons would give between 1091 - 1145 litres. Tipping (1994:6) states an English Act of 1423 defined the wine "tun" as not less than 252 gallons (1,145.6 litres). Hutchinson (1994:90) notes that Gascon tuns seems to have contained between 750 and 900 litres. Castro (2013:1138) states that in France the Bordeaux toneau was the equivalent of two pipes or four barriques, each barrigue contained 10 pots of 2.265 litres each giving four barriques of 225 litres giving a toneau of 900 litres.

As can be seen a "tun" of wine could contain between 750 and 1,145 litres. With wine having a specific gravity similar to water this results in a weight variation for the wine of between 750 - 1145 kg. With the cask weight adding an additional 8 - 10% the combined weight of the 'tun' is between 810 - 1259 kg.

From the disarticulated remains recovered within the Newport Medieval ship, many cask staves were also recovered. The typical lengths are between 640 - 1060 mm for open casks and between 675 - 1230 mm for sealed casks. The thickness of staves varied between 12 - 15 mm.

From these three typical sizes of Cask were digitally reconstructed:

1. "Wine Tun" with a height of 1,230 mm and max diameter of 1030 mm. With an internal volume of 806 litres. (a 5 mm reduction in stave thickness results in a total of 831 litres internal volume.
2. "Pipe or Butt" equal to ½ "Tun" with a height of 1065 mm and a max diameter of 780 mm. With an internal volume of 422 litres.
3. "Last or Quarter" equal to ¼ "Tun" with a height of 710 mm and a max diameter of 514 mm. With an internal volume 124 litres.

The remodelled casks were then fitted inside the lower cargo hold within the vessel in order to determine a potential loading capacity. One possible loading scenario resulting in 118 "tun" cask, 21 pipe (½ tun) casks and 130 last (¼ tun) casks giving a combined total of 161 "tun" casks. If these casks were all filled with wine the resulting cargo weight including casks would be in the region of 147.17 tonnes. With a total loaded capacity of 187.2 tonnes, this means the vessel could load an additional 40 tonnes of cargo or provisions on the upper deck.

While it is also possible to calculate cargo capacity, based on volumetric calculations, this approach provides less accurate results. For example, the Newport Medieval ship has a total cargo volume of 225 m³. If this total volume were filled with salt carried in bulk (loose) the stowage rate of 1.07 m³ per ton would result in a total cargo weight of 190.5 tonnes which is greater than the vessel's maximum capacity. If the salt were stowed in casks, the available volume would reduce the total cargo to 177 tonnes of salt. If the casks contained alum, a mineral salt widely used in the textile industry, the lighter stowage rate of 1.74 m³ per ton would mean only 117 tonnes of alum could be carried. This variance in stowage rate, volume, and capacity, illustrates the complexity faced by ship owners and captains when taking on board cargo, but it is a complexity that a digital approach can begin to shed some light on.

9.6 Seakeeping and final testing

The final phase in testing and analysis is to examine the vessel's seaworthiness abilities. While the previous tests examined the vessel's intact or static stability, they are a snapshot of the vessel's characteristics at a specific point in time. The term seaworthiness is a very broad one, as it not only includes the physical state of the vessel but also extends to other aspects and factors. Consequently, it is not easy to define seaworthiness in rigorous terms. A 13th century law defined a ship as seaworthy if she did not need to be bailed (emptied of water) more than three times in 24 hours (Christensen 1968,138-9). The Marine Insurance Act (1906) states 'A ship is deemed to be seaworthy when she is reasonably fit in all respects to encounter the ordinary perils of the seas of the adventure insured' (Chalmers and Ivamy 1976). Consequently seaworthiness can be defined as the following: the fitness of the vessel in all respects, to encounter the ordinary perils of the sea, that could be expected on her voyage, and deliver the cargo safely to its destination.

McGrail (2001:6) states that evaluating whether a vessel would have been seagoing is an art as well as a science since a number of interacting factors have to be considered, including the strength, durability and integrity of the hull, the freeboard at operational drafts, the stability and reserves of buoyancy. McGrail (1998b:13) In order to determine seaworthiness, the vessel must be examined in varying floatation conditions. These conditions are suggested as being influenced by the following four main factors

1. Weight and centre of gravity of the vessel,
2. Number and normal station of crew,
3. Bulk density of cargo,

4. Freeboard, the distance between the gunwale or top edge, and the operational waterplane, will need to be examined.

McGrail then recommends the vessel be tested in its various operational freeboard conditions (empty of cargo, fully loaded) to determine the stability criteria.

The hypothetical reconstruction has already been analysed in these operational freeboard conditions and has demonstrated sufficient stability to pass the modern Bureau Veritas stability rules. But again, these tests are simply point-in-time snapshots and prove little in terms of seaworthiness. At the most basic level a vessel must resist the ingress of water in order to remain afloat. As noted in Chapter 7.4, a relatively small hole, just 5 cm diameter, located 1 m below the waterline, has a water flow rate of 31,000 litres of water per hour. That equates to 0.5 tonnes per minute or 31 tonnes per hour. A pierced hull is not the only danger to a sailing vessel, breaking waves on deck can add a significant quantity of water to a vessel. As an example, during the 21 hour leg of its journey from Dublin to Land's End, the Sea Stallion from Glendalough, a replica of Skuldelev 2, took on board over 18,000 litres of seawater, the pumps onboard constantly in use and the crew permanently drenched by waves (Nielsen 2011). If the pumps had failed or the crew stopped bailing, that additional 18 tonnes of seawater would have easily overwhelmed the vessel.

This raises the question of how we determine a vessel's seaworthiness. In Ancient Boats in North-West Europe (McGrail 1987:195–198) the author states the assessment of performance of excavated examples of early boats and ships is difficult, but by making certain assumptions it is possible to give broad answers to such questions as how fast was that boat. And what was her cargo capacity. Suggested approaches include speed estimates based on prismatic coefficient (displacement volume / (cross sectional area x waterline length)) where a lower value of 0.55 to 0.53 indicate low resistance and hence a potentially fast boat. Slenderness coefficient (waterline length / beam) where high values greater than 5 indicate good speed potential. Midship coefficient (cross section area / (beam x draft)) where low values below 0.85 indicate good speed potential. And finally Block coefficient (displacement volume / (beam x waterline length x draft)) where low values below 0.65 indicate good speed potential.

The use of simple form coefficients is suggested by McGrail as a method of determining relative assessments of a boats capabilities such as length to beam ratio, or beam to depth ratio. The use of hydrostatic curves to define the underwater form of a vessel are used to generate coefficients of form which then give forecasts of performance. However, coefficients such as block, prismatic, midship, volumetric and slenderness coefficient are all relative values. They are taken from the realm of naval architecture where they provide initial early approximations of a vessel's potential characteristics relative to other known vessels. While they might prove useful in comparing a particular vessel to several contemporary and similar hull form vessel, they give little information relating to the real-world operation of a vessel – its seaworthiness.

The vessel was again configured in the worst-case scenario condition with regard to wind loading, which would represent a "beam on" wind, with the sails sheeted in tight. This is not a normal sailing configuration but represents a worst possible case scenario. The vessel was then tested in that configuration for varying wind conditions.

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 5kts

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Angle At SteadyEquil <= 16 deg	1.1347		16	1.1347	Pass
ResRatio Between SteadyEquil-25 deg and DeckImm > 1	-23.8653	23.4986	1	0.8022	Fail
ResRatio Between SteadyEquil-25 deg and Flood > 1	-23.8653	45.6671	1	2.9878	Pass
ResRatio Between SteadyEquil-25 deg and 50 > 1	-23.8653	50	1	3.6001	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	1.1347		18.7988	1.1347	Pass

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 10 kts

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Angle At SteadyEquil <= 16 deg	4.5154		16	4.5154	Pass
ResRatio Between SteadyEquil-25 deg and DeckImm > 1	-20.4846	23.4986	1	0.5688	Fail
ResRatio Between SteadyEquil-25 deg and Flood > 1	-20.4846	45.6671	1	2.548	Pass
ResRatio Between SteadyEquil-25 deg and 50 > 1	-20.4846	50	1	3.1277	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	4.5154		18.7988	4.5154	Pass

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 15 Kts

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Angle At SteadyEquil <= 16 deg	10.0707		16	10.0707	Pass
ResRatio Between SteadyEquil-25 deg and DeckImm > 1	-14.9293	23.4986	1	0.2781	Fail
ResRatio Between SteadyEquil-25 deg and Flood > 1	-14.9293	45.6671	1	1.926	Pass
ResRatio Between SteadyEquil-25 deg and 50 > 1	-14.9293	50	1	2.4531	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	10.0707		18.7988	10.0707	Pass

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 20 kts

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Angle At SteadyEquil <= 16 deg	17.5641		16	17.5641	Fail
ResRatio Between SteadyEquil-25 deg and DeckImm > 1	-7.4359	23.4986	1	0.0543	Fail
ResRatio Between SteadyEquil-25 deg and Flood > 1	-7.4359	45.6671	1	1.2737	Pass
ResRatio Between SteadyEquil-25 deg and 50 > 1	-7.4359	50	1	1.7335	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	17.5641		18.7988	17.5641	Pass

Figure 9-28 Bureau Veritas wind and rolling wave stability analysis (Pat Tanner)

The Principal Reconstruction passes the modern Bureau Veritas stability rules for wind and rolling waves in all 5 to 15 knots of wind, except for the stability ratio between -25° and the steady wind heel angle (Figure 9-28). The Bureau Veritas criteria uses a generic wave roll angle of 25° for calculating wave roll stability, however their stability booklet also allows for the calculation of the actual wave roll angle as this is specific to each vessel depending on the underwater profile and position of the centre of gravity. The Angle of roll, in degrees, to windward due to wave action, is calculated as follows:

$\theta_1 = 109kX_1X_2\sqrt{rs}$
Where k, X_1, X_2 and s are coefficients defined in the Bureau Veritas handbook,
r = 0,73 ± 0,6 (OG) / T_1 - where OG = distance between centre of gravity and the waterline, and T_1 = mean moulded draft.

The actual wave roll angle thus calculated for the reconstructed Newport Medieval Ship is 14.59°. For any vessel, its most tender (unstable) configuration would be when it is floating high without cargo. The Newport Medieval ship was again configured to represent this flotation condition, and the rigging configured to represent the worst-case scenario condition with regard to wind loading. A "beam on" wind, with the sails sheeted in tight. The vessel was then retested using the Bureau Veritas stability criteria, but with the actual calculated wave roll angle of 14.6°, rather than the generic 25°. The hypothetical reconstruction satisfies all of the Bureau Veritas criteria in 5 to 10 knots of wind but exceeds the imposed limit of 16° wind heel angle by 1.6° with the sail sheeted in tight. A situation easily remedied by easing the sails. As such the vessel is deemed as seaworthy.

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 5kts

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Angle At SteadyEquil <= 16 deg	1.1347		16	1.1347	Pass
ResRatio Between SteadyEquil-14.6 deg and DeckImm > 1	-13.4653	23.4986	1	2.2623	Pass
ResRatio Between SteadyEquil-14.6 deg and Flood > 1	-13.4653	45.6671	1	8.4361	Pass
ResRatio Between SteadyEquil-14.6 deg and 50 > 1	-13.4653	50	1	10.1629	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	1.1347		18.7988	1.1347	Pass

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 10 kts

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Angle At SteadyEquil <= 16 deg	4.5154		16	4.5154	Pass
ResRatio Between SteadyEquil-14.6 deg and DeckImm > 1	-10.0846	23.4986	1	1.6134	Pass
ResRatio Between SteadyEquil-14.6 deg and Flood > 1	-10.0846	45.6671	1	7.2378	Pass
ResRatio Between SteadyEquil-14.6 deg and 50 > 1	-10.0846	50	1	8.8822	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	4.5154		18.7988	4.5154	Pass

Figure 9-29 Bureau Veritas wind and rolling wave stability analysis (Pat Tanner)

9.7 Conclusion

Steffy (1994:189) defines capital reconstructions as coming from the well-preserved remains of a wreck, resulting in hull lines or elaborate construction plans. Crumlin-Pedersen and McGrail (2006:57) state that where considerable portions of the original vessel are recovered, and full reconstruction appears to be a realistic aim, the problem is to determine one or more minimalistic ways to complete the hull. That problem begins with the archaeological evidence and how it is interpreted. Just as Crumlin-Pedersen (1995:304) noted, a person does not turn into an archaeologist simply by digging into an archaeological site, and no one turns into a maritime archaeologist just by building a boat resembling one from the past. How that archaeological evidence is captured, analysed, and interpreted is set out in Chapter 4 to Chapter 7.

Chapter 8 takes that archaeological data, using the articulated hull remains as the de-facto primary record, and reverse engineers the processes that material has succumbed to, during the many stages between the as-built, and as-excavated shape states. Through an iterative process, of ‘repairing’ and fairing the archaeological evidence, a hull form representing the idealised or design intent shape is recreated in the form of the watertight envelope. That watertight envelope is tested and analysed to establish the flotation condition, and the hypothesis continues until a functioning minimum reconstruction is established. That iterative process employs an overtly scientific approach – mathematically faired curves, detailed weight studies, volume, and displacement calculations, to analyse and test each iteration of the hypothesis. This sets out the process in a clear stepwise manner, where each iteration in the development and its effect on preceding and subsequent iterations is tested to ensure the hypothesis remains tenable. A process employed to develop a more definitive hypothetical minimum reconstruction.

However, as clearly illustrated in the case of the Newport Medieval ship, stopping with the hypothetical minimum reconstruction would only have accounted for half the archaeology, and led to a misunderstood ship. To better understand the vessel, the process, the people and the society involved, we have an obligation to develop that minimum reconstruction to its logical conclusion as a capital reconstruction where the evidence permits.

Chapter 9 builds on the work of the minimum reconstruction, continuing the same iterative process, adding additional disarticulated elements and retesting as necessary. As noted in the introduction to this chapter, capital reconstructions, by their very nature, involve a greater level of interpretation. The further any capital reconstruction proceeds, the more that reconstruction diverges from the direct archaeological evidence that is available, and the more the focus turns to comparative data. Just how that comparative data is employed is also of critical importance. As pointed out by Crumlin-Pedersen and McGrail (2006:55), it is often necessary to add elements to the hull for which no direct evidence has been found. Most reconstructions will require supplementary evidence from other finds, or the use of comparative data, which leaves room for a wide variety of proposals.

Just how we interpret that comparative data is of equal importance to how we interpret the archaeological evidence. Crumlin-Pedersen and McGrail (ibid) state the importance of the comparative data being contemporaneous, and of the same type and tradition as the vessel being reconstructed. The risk of introducing alien elements is highlighted, and the use of circular arguments cautioned against. The issues of reconstructions based on literary or iconographic sources, or ship treatises are discussed in Chapter 2, and it is noted that all of these are interpretations of the original object. An interpretation based on an interpretation is unlikely to yield a more definitive result. The risk of creating a self-fulfilling positive-feedback loop needs to be considered, and reconstructing the archaeology based on a treatise, which is not a set of ship-building instructions, is unlikely to yield the desired result.

Rather than forcing the archaeology to take on the form as represented in contemporary interpretations (literary or iconographic), repair and reconstruct the archaeology, and only then compare the results to validate the tenability of the hypothesis. As Dick Steffy liked to say, "listen to the timber, it will tell you what it wants to do" (F. Hocker 2020, pers. comm., 28th January). To do this successfully we also need to understand what the timber is trying to tell us. Hull planks and framing timbers do not just grow on trees – well in fact they do, just not in a format that is ready to use – off the shelf. Those trees need to undergo some form of timber conversion, whether it be radially splitting logs to produce hull planking, sawn to produce flat board stock, or selecting grown or curved timbers to be hewn into framing elements.

As Muckelroy observed, ships are indeed complex machines. However, the creation of those machines is an equally complex affair, requiring a variety of skillsets. As noted by Friel (1995:39–69) the process of building a ship often involved a large workforce, reports from 1294 of the building of royal galleys at London and York list the number of Shipwrights at 50 and 69 respectively. And Shipwrights are not the only trade to appear in the archives, the Berder (also termed boarder or hewer) was concerned with shaping and fitting timbers, Clenchers and Holders involved with the clenched nails. Carpenters receive specific mention alongside Shipwrights, often involved in the felling of trees, and Sawyers are mentioned as early as the 13th century. Two other major classes of specialist workers are also mentioned, Smiths that produced the thousands of clench-nails, spikes, bolts and other pieces of iron-work, and Caulkers to waterproof the seams are first mentioned in an account for building the galley *Philippe* at King's Lynn in 1377.

In order to better understand the vessel, the people, the process and the wider society, we need to listen not only to the timbers, but to the evidence itself. To understand not just the material, but how that material was created and assembled, which may provide an opportunity to peer inside the mind of the boatbuilders and sailors to comprehend not only the object, but also the how and the why. And it is for these reasons that, as the various disarticulated components are analysed and added to the evolving hypothetical reconstruction, it becomes even more imperative that the iterative process of editing, analysing, and testing is followed. Equal portions of logical reasoning, and common sense will be required, while continuing to view the results, not just from the archaeologist's perspective, but also from the perspective of the boatbuilder and the mariner.

Chapter 10 **Conclusions**

10.1 Introduction

As noted in Chapter 1, ship reconstruction from archaeological remains is almost as old as ship archaeology itself, one of the earliest known publications being the reconstruction of a ship excavated by Reuvens and Glavimans in 1822 (Maarleveld 1997:35). This study set out to investigate how these archaeological shipwrecks are reconstructed.

Chapter 2 and 3 traced the development of archaeological ship reconstruction, highlighting the evolution and development of that process and the perceived goals and challenges. While the 19th century saw mainly an antiquarian interest, where vessels were excavated and the primary focus was on reassembly for public display, the beginning of the 20th century saw antiquarianism evolve into what is now referred to as contextual archaeology. This involved the excavation, cataloguing and slotting into the appropriate timeline each artefact which was excavated. However, in many 'maritime' cases, documentation was often limited to in-situ recording of the vessel, while the primary focus was on identification of the vessel to secure accurate dating such as was the case with the Woolwich ship (see Laughton 1914; Anderson 1959; Salisbury 1961; Glasgow 1971; Anderson 1972).

During the second half of the 20th century, the focus shifted to detailed research in an effort to understand and reconstruct those vessels for the purpose of archaeological interpretation. This gave rise to a significant change in the approach to documentation, switching from documenting the entire vessel as a complete and single artefact, to detailed documentation of the individual timbers. This was seen as critical to understanding the design and shape of the original hull form as well as probable construction sequence. Since the 19th century, and in earnest since the mid-20th century, this gave rise to a mixture of reconstruction processes, from a variety of perspectives, with a range of success and failure.

These reconstruction approaches, or changes in the reconstruction methodologies employed in the various, and varied, practical efforts that have been undertaken to reconstruct ships from archaeological, literary, iconographic, and historical sources were reviewed from a practical point of view in Chapter 2, and from a conceptual point of view in Chapter 3.

Many of the conceptual approaches and classification attempts, focussed on archaeological reconstructions, have developed within maritime archaeology and history, alongside the physical reconstruction work. Much of the conceptual theoretical approaches have developed in the wake of practice, and very rarely has the practice been driven by theoretical ideals. They lagged behind and have not undergone development within academic literature until the 1990's.

As highlighted by Bass (2011:10–11), archaeologists publish only a fraction of the sites they investigate, and the publication of excavation reports which are more than simple catalogues, can often take years or decades. In addition, reconstruction, while not an end of its own, but a seemingly logical continuation of any ship excavation in order to better understand and visualise the vessel represented by the archaeological evidence, has not been a primary goal of many publications. As evidenced by the mere 4 to 8% of the articles in mainstream archaeological journals which specifically deal with reconstruction.

As early as the 1980's McGrail (1984:26) suggested that if standard rules for describing a boat find, based on internationally agreed attribute lists, can be evolved, then comparisons between finds becomes possible. That list has remained an elusive goal, and standardisation has also evaded the maritime archaeological publication format. Details such as location and dating which provide temporal and cultural background, and the vessels characteristics such as length, beam, draft and displacement seldom appear grouped together either in the introduction or the conclusion, but rather are scattered deep within the pages, often requiring their own excavation to be rediscovered.

In many cases it has been necessary to 'reverse engineer' the published material, in order simply to comprehend the published results. While the rapid increase in the number of vessels being excavated during the second half of the 20th century added significantly to the published resource, as noted by Adams (2013:7–13), some criticisms of early maritime archaeology included the work being of an almost totally descriptive nature and orientated towards historic particularism. Adams argues that there are mitigating factors, firstly, in terms of data collection and analysis, most projects were still at a very early stage. Secondly, as many projects were using methods and techniques for the first time, it was inevitable that the authors would discuss methodologies.

This descriptive nature provides a very detailed view of the evolution and development of both underwater in-situ documentation, and the post-excavation detailed documentation of individual components. Unfortunately, from the reconstruction point of view, this descriptive nature did not extend to the process or methodology employed in converting that source data into a hypothetical reconstruction of the vessel.

10.2 Confidence in the source data

As noted in Chapter 4, one of the main themes highlighted in the literature review is that all archaeology is contingent on the source data and everything stems from that. That source data, by its nature, can be difficult to understand due to its damaged, distorted, and often disarticulated nature. While it is acknowledged that there can be no single way to reconstruct a vessel, any reconstruction must be based on appropriate source data in which we have confidence. Past reconstruction projects may have used the source data, but it is not always possible to understand or interrogate how that source data has been used or interpreted.

This source data has often been presented either as McGrail's 'as-found' drawing or as Crumlin Pedersen's 'torso' drawing. McGrail's (2007:255) definition of 'as-found' is a model formed of the boat as found, but with distortions and compressions removed, displaced elements replaced, fragmented timbers made whole, and the hull rotated to its deduced attitude when afloat. Crumlin-Pedersen (2002c:125) describes the 'torso drawing' as a drawing of all the recovered parts for which the original position in the ship could be identified, and is created based on the 'inner-edge lines-plan' drawing. This 'inner-edge lines-plan' drawing is described as being the tracing of the inboard upper edges of each strake as well as the external outline of the keel, once a satisfactory model had been achieved. Neither of which truly represent the actual archaeological evidence. Both represent the evidence as recorded but modified and interpreted in some way.

From the reviews of the practical and conceptual approaches to reconstruction and the key developments in ship/boat archaeology, the main themes that come to the fore are: the object itself (the shipwreck); the person or people who ordered the object; the person or people who constructed the object; the person or people who used the object; how the object performed; and the society in which the object was used.

Consequently, any reconstruction must employ a clear unambiguous approach, which is both methodical and meticulous in terms of the data that is used. In addition, a reconstruction which violates none of the archaeological evidence, in order to know what the ship or vessel looked like, how it was used, and to reconstruct both the object (the vessel) and the process (the construction) in a scientific and repeatable manner. Finally, that reconstruction will need to be analysed and tested in order to support the hypothesis.

Chapter 3 concluded not only with looking at the evidence from the perspective of an archaeologist, but also examining that evidence from the perspective of a boat builder and that of a sailor. This identified a list of up to eleven potential shape states which may be observed in a vessel's life from the initial shape that the customer thinks they want, up to the final full-scale replica produced from the archaeological record. It identified where in that list the archaeological evidence sits, and outlined how those various stages impact on, and affect the potential reconstruction process.

Chapter 4 examined the process of recording and documenting the raw primary data that represents the archaeological record. Beginning with examining how that data was recorded in previous projects and highlighting how the technology used to record site data is not a secondary concern but is central to the activity of site archaeology. The purpose being to transfer the ground-based record into a form accessible not just to the site archaeologist but to all potential users. The development of that technology, and the various methodologies were then analysed and compared. This demonstrated that the capturing of three-dimensional high volume, high quality raw data is now possible, and as such, generates a superior archival record. A record which is stored as a full-sized three-dimensional object, rather than a reduced scale, two-dimensional paper-based interpretation.

10.3 The issues with scale modelling

As discussed in Chapter 5, the majority of reconstruction projects reviewed have involved, or been based to some extent, on some form of three-dimensional scale modelling (with some scale drawings in earlier periods of site analysis such as with Sutton Hoo), and fully understanding that process is therefore critical to understanding the reconstruction process itself. While some work uses scaled timber drawing to inform the scale models, others used 1:1 timber drawings to inform the scale models. However, the question remains, how is the 'as-found' evidence transformed into what McGrail (1992:354) calls the floating hypothesis? How are distortions and compressions removed, the displaced elements replaced, and the hull rotated to its deduced attitude when afloat? Is it an assumption that the hull form is known, is it a case of trial and error, or simply a case of if it looks right, it must be right?

Clearly three-dimensional modelling is without doubt, a valuable and necessary approach in the reconstruction process when dealing with a complex three-dimensional form such as a vessel. However, creating a model at a reduced scale, has the associated issues of model effect, scale effect and measurement effect, and the issues associated with testing scale models have already been identified. The advent of three-dimensional digital modelling means there is no longer any logical reason for this modelling to be carried out at a reduced scale, and full-scale digital modelling produces more assets which allows for increased accuracy in test results.

10.4 The need for hydrodynamic testing

McGrail (1992:355) states that hypotheses must be investigated and tested by experiment, a process which lies at the foundation of all sciences. However, what testing, and experimentation do we use? Do we use the coefficients of form as suggested by McGrail (1987:195–198) and CiFA (2014:21–23), taking the example of the Oseberg ship, as discussed in Chapter 3.9, the 1954 lines drawings were used for analysis by Jensen (1999:216) to determine ratios of form and hydrostatic coefficients. When these were compared to circa 34 other vessels the coefficients were within average parameters, but still the full-scale replica sank.

The Oseberg project (Bischoff 2016:27–29) clearly illustrates how a reappraisal of the hull form, combined with hydrodynamic testing demonstrates that it was the original reassembly and replication, rather than the original vessel which was flawed, and demonstrates that to properly understand a vessel, or at least to properly begin to understand it, you have to do the reconstruction and also the testing. Just doing the reconstruction alone will not provide a complete picture. The reconstruction also requires hydrodynamic testing to validate whether or not the hypothetical reconstruction can actually function as a vessel. As noted by Coates *et al*. (1995:297), no experiment can ever prove a hypothesis: it can either disprove it or produce results in agreement with its predictions. In the latter case, the hypothesis can remain tenable until disproved, or accepted as a theory after having been established as an explanation of the evidence

And *Dronningen,* the replica Oseberg ship is not alone; other examples include both replicas, *Kyrenia II* and *Kyrenia Liberty* which were unable to load all of the cargo suggested by the archaeological evidence (Katzev 2008:77–79) indicating some issue with the proposed hypothetical reconstruction. While unpublished (I believe), Tom Vosmer stated at the Red Sea V conference (Exeter, September 2010) that the Jewel of Muscat replica also could not carry all of the cargo suggested by the evidence excavated from the original site, also indicating issues with that proposed hypothetical reconstruction. All three replicas of the Bremen cog have some significant differences (Tanner 2018:10–12 see Appendix I), and none of these replicas with their waterproof decks, modern safety and navigation systems, internal bulkheads, and engines match the original vessel. *Kraka Fyr* a replica of Skuldelev 6 was built in 1998, but an error in the stem meant a second replica, *Skjoldungen* had to be rebuilt with a different interpretation of the bow and stern design (vikingeskibsmuseet.dk 2018).

In relation to sailing performance, taking the Bremen cog as an example, a plausible reconstruction of the cog's rig was created by Wolf-Dieter Hoheisel, naval architect and technical director of the *Deutsches Schiffahrtsmuseum*. Igo Clausen, a student in ship engineering at

Hamburg University, tested Hoheisel's reconstructed rigging on a simplified model in a wind-tunnel. Results indicated the vessel could tack to windward, but tests were unable to include wave action or seaway. Professor Postel at the Institute for Shipbuilding in Kiel undertook tank-towing tests, and results indicated the model could not come above 90° to the true wind (Hoffmann and Hoffmann 2009:287–89). Hoffman states that the first replica – the *Hansekogge* underwent sea-trials led by a team from the Institute of Ship- and Sea-Technology, Berlin, and the vessel sailed faster than anticipated, averaging five knots on all courses and wind conditions. Though the wind never increased above a Force 7 that summer, the vessel was easily steered by one person, although the slight weather helm meant the helmsman had to remain vigilant as the vessel turned quickly. The angle of heel remained at 15° or less, but in an agitated sea the short roll and pitch periods caused many of the crew to become seasick (Ibid:289-290).

The Ubena cog, another of the Bremen cog replicas, was captained by Hans-Joachim Möller, a time-served master mariner, from ship's boy to captain, who has sailed freighters on every ocean, as well as experience of sailing "square riggers" aboard traditional sailing ships. Möller paints a slightly less optimistic view of the vessel, describing a vessel requiring a minimum of 12 crew, a number which cannot be reduced by training, as it is their physical strength which is required. The vessel he states, rolls awfully, bringing everybody including himself down with seasickness. It can sail in a Force 8 wind, but not directly downwind as the loss of stability on wave crests becomes too dangerous. The vessel simply will not sail in winds less than a Force 4, it just drifts sideways, and requires a Force 5 wind to get moving. In these conditions the vessel carries significant weather helm, requiring up to 20° of correction on the rudder angle. A drift or leeway angle of 10-15° means the vessel cannot make any progress to windward. The high sides and castle mean the vessel is unable to tack through the wind. Möller describes this as more of a chance happening when it does occur, and with sails lowered, the same high sides and castle mean the vessel drifts at 4-5 knots before the wind (Ibid: 292). Hoffmann notes that Baykowski also admits the *Hansekogge* is a similarly clumsy sailing vessel.

If these replicas are such 'clumsy sailors', which appear to function only within a very limited set of ideal conditions, how then, did the cog as a type, become such a ubiquitous vessel?

Is it a case that the replicas are inaccurate? All full-scale replicas are expensive and time consuming to construct, and perhaps some of the issues could have been identified using a digital approach, prior to constructing the full-scale replica. However, because we are not currently recording the replicas to compare or cross reference what is being constructed as a replica, we simply do not know if the issue lies with the replica itself or elsewhere.

Is it a case that our assessment of the performance of such vessels is inaccurate, as suggested at the ISBSA symposium in 2018 by Vibeke Bischoff? Perhaps it is not an issue with the actual replica vessel, but an issue with the manner in which we attempt to operate that vessel.

Or is it a case that the ubiquitous cog simply was a clumsy sailor, clearly our research on the cog is unfinished, and Karel Vlierman's forthcoming *Cogs, small cogs and boats: The thirteenth until sixteenth century Dutch and Flemish archaeological finds from the Hanseatic shipbuilding tradition seen in a broader perspective*, is eagerly anticipated.

As pointed out in Chapter 2, in the case of modern ships, a combination of experiments with scale models, tank tests and full-scale sea trials has made it possible to develop correlation factors that permit reasonably reliable predictions of performance for new vessels of known types. Such work on ancient ships has not been fully undertaken in order to corroborate the results (Crumlin-Pedersen and Trakadas 2003:218).

Chapter 6 presents a case study which proposes a digital approach to this hydrodynamic testing. By taking a known item, in this case a vessel which I have rebuilt and sailed, this allows the establishment of a baseline dataset, which has its basis in a real-world physical object which has clear and measurable characteristics. The 'source data' (the vessel) was recorded and documented using the methodology discussed in Chapter 4 to capture high volume, high quality three-dimensional raw data. That raw data was then analysed from a dimensional accuracy viewpoint, and the result demonstrated an accuracy of between 99.67 and 99.87%. Illustrating that the methodology discussed in Chapter 4, not only produces high volume and high quality, but also highly accurate, three-dimensional raw data.

With source data in which we have confidence, the process of converting that source data into three-dimensional digital solids to enable further analysis and testing is then set out in the remaining sections of Chapter 6. This digital 'reconstruction' is carried out in an incremental process, beginning with the articulated hull structure, before adding additional disarticulated elements such as rigging and equipment. The 'reconstructed' vessel is tested at each incremental stage using Orca 3D to calculate the weight analysis study and determine the actual flotation condition. The results from each incremental stage clearly highlights how the inclusion, or omission of any elements directly effects the final analysis results.

The results of this digital modelling process demonstrated a methodology which has just 1.16% margin of error in relation to the total weight of the vessel, and in terms of the digitally modelled flotation condition, the margin of error is less than 0.1%. Clearly, with source data in which we have confidence, and sufficient evidence surviving within that source data to recreate the shape and form of the vessel, it is possible to create a digital replica of the original to a high degree of accuracy.

10.5 The archaeological evidence

Having examined the development of archaeological ship reconstruction, the evolution and development of that process, and highlighting the perceived goals and challenges, Chapter 7 began the task of demonstrating how to take the methodologies and processes discussed in Chapter 4, Chapter 5 and Chapter 6, and apply them to the archaeological evidence.

The source data is firstly examined to determine what exactly it is that the data represents. Where that data fits into the various potential shape states of a vessel (Table 7-1), and which shape states are to be reconstructed, dependant of the specific objectives of the research project. For example, the post-conservation ‘shape’ of certain frame timbers from the Newport Medieval ship will never be modified to match the original design intent shape as imagined by the builder. Neither may they have ever actually been that design-intent shape, but rather were the as-built shape. This in itself raises the research question – what caused that as-built shape, or what prevented the builder from achieving their design-intent shape? This timber, therefore, needs a target reassembly shape for the purposes of exhibition as it is reassembled together with the other surviving elements. That process of reassembly for exhibition may result in another shape – the achievable shape state, and the difference between the two may help to inform future conservation and exhibition projects.

Next the archaeological evidence is examined from the viewpoint of a complete functioning vessel, and what extent of the complete vessel, the archaeological evidence represents. The concept of a minimum reconstruction is considered, and what would be entailed in transforming the archaeological evidence back to a minimum reconstruction. The first stage in that minimum reconstruction is to establish what McGrail (1992:354) termed the floating hypothesis. That floating hypothesis will represent the vessel in a form whereby it is capable of its intended function. That is a watertight envelope capable of floating, which will allow for some basic hydrostatic calculation to be carried out in order to generate an impression of the vessel’s potential capabilities. This watertight envelope will help to establish the initial bounds of the hull, its overall dimensions in the form of length, beam, and depth, as well as setting out an approximation of the overall hull form, a faired, or idealised hull shape, representing the design intent shape (number 2 from Table 7-1). The important point is that this watertight envelope is an approximation, in an iterative process, which will develop and evolve as the process continues.

With the watertight envelope representing an approximation of the overall hull form, it is then possible to analyse the archaeological evidence in terms of both global and localised distortion. These distortions may have developed either during the use-life of the vessel, or post-abandonment, as a result of the wrecking process, the site formation processes, or distortions introduced during the excavation and documentation phases. The use of this digital approach, at full-scale, combining all available data sets, enables the easy correlation of a multitude of source data. An analytical approach which would be difficult using unwieldy two-dimensional full-scale tracings and resulted in many projects employing reduced scale copies in the past.

On these reduced scaled drawings, the fine details such as wood grain or inscribed marks would be nearly invisible at the reduced scale. In addition, the three-dimensional digital nature of the recorded data allows for readily understandable and convenient comparisons, compared to the dissociative nature of multiple two-dimensional records. This allow the archaeological evidence to be digitally 'repaired', in a clear, accurate, and detailed manner, which is documented to describe and illustrate how the archaeological data has been interpreted and to record where changes have been made along the way.

10.6 The minimum reconstruction

Chapter 8 describes the process used in taking the source data – in which we have confidence (Chapter 4), creating a superior three-dimensional digital archive – Steffy's (1994:198) hull catalogue (Chapter 5), the digital approach for validating the hypothesis (Chapter 6), and the interpretation of the archaeological evidence (Chapter 7), and creating a minimum reconstruction from that source data.

The approach used is the same as that employed in any shipyard when repairing or rebuilding a damaged vessel. It is acknowledged from the outset that there can be no single way to reconstruct every vessel, and as such, the process described is more conceptual or thematic in its nature, with references or examples of specific case studies cited. The process begins, as in the boatyard, with orientating the vessel to a construction baseline as the flotation orientation is as yet unknown. Then, beginning with the foundations, the backbone of keel, stem, and stern post in the case of a vessel, each component is digitally repaired or replaced, based primarily on the archaeological evidence. The process continues to the additional components, a logical progression, following the same sequence as in the boatyard, which by its nature follows the perceived construction sequence of the original vessel.

From the surviving hull structure, the individual planks, and strake runs, are faired where necessary, recreating the idealised hull form or design intent shape, which is then extended or extrapolated to close the ends, and recreate the watertight hull envelope. This watertight envelope is then analysed and tested to establish the initial floating hypothesis. With the watertight envelope, and the flotation condition initially established, the process continues with repairing or placing the individual disarticulated components until all of the archaeological evidence has had its distortion and compression removed, the displaced elements replaced, the fragmented timbers made whole and rotated to its deduced attitude when afloat (McGrail's (2007:255) definition of 'as-found').

This digital repairing of the archaeological evidence served to highlight certain assumptions and erroneous practices, for example the assumption that large heavy timbers, such as stems and frames do not distort. Such an assumption appears to be the case in the hybrid system used in the reconstruction of *Sørenga* 7 (Falck *et al*. 2016), where the strakes were printed onto flat cardboard as done in Roskilde, but the 'four sided timbers' such as keel, stem, stern and frames, were 3D printed in their 'as-found' form, because it was assumed they had not distorted. Similarly, the *Ma'agan Mikhael* (Kahanov 2011:166–167) reassembly, entailed the ship being reassembled 'shell first', on temporary adjustable scaffolding of MDF transverse supports which were cut following the original shape of the frames. The reconstructed vessel was therefore constrained to the unrepaired 'as-found' hull shape. The application of such an assumption has been clearly demonstrated (Figure 2-58) to not be the case in the Newport medieval ship project (Tanner 2013b:33–34), where the relatively massive framing timbers were demonstrated to have become distorted.

Once all of the archaeological evidence has been digitally repaired and replaced, it is then possible to quantify that evidence, and the extent of comparative date required to create the desired functioning minimum reconstruction. It is important to remember that each stage of the process is an iterative one. As each modification is carried out, or alteration made, the consequences of each is examined and analysed, their effect on preceding and subsequent stages is also monitored and analysed. Any one of those stages can then be refined or edited to suit the emerging reconstruction. That iterative process can also alternate between the digital and physical scale models (Figure 10-1).

Figure 10-1 Dry-erase markers were used to draw on potential posts and planking termination points during an early iteration of the process. (Newport Museums and Heritage Service)

The process takes that definition by Crumlin-Pedersen and McGrail (2006:57) of a minimum reconstruction, breaks down that definition into its constituent parts, and clearly defines how each of those constituent parts is created. Thereby creating a more definitive hypothetical minimum reconstruction, using a process which is clearly documented, and is ultimately more transparent in its nature.

10.7 The capital reconstruction

The further any reconstruction proceeds, the more that reconstruction diverges from the direct archaeological evidence that is available, and the more the focus turns to comparative data.

Capital reconstructions, by their very nature, will involve a greater level of interpretation of the available direct archaeological evidence, and a greater reliance on contemporary comparative data, consequently making any such reconstruction even more hypothetical. As such, many capital reconstructions have, at best been contentious, Westerdahl (1992) questioned if a reconstruction based solely on documentary, iconographic and comparative evidence can be a 'scientifically based reconstruction'. I have argued that it can (see Tanner *et al*. 2020). McGrail (1992) states that the Kyrenia replicas are based on well executed and well published excavations, but how the excavated material was transformed into a complete ship has yet to be published in the necessary detail.

Of the two capital reconstructions I have completed – Newport Medieval ship (Tanner 2020 see Appendix G) and the Bremen cog (Tanner 2017b see Appendix H) either one could be used to describe the capital reconstruction process. Bremen cog would have made for a simpler explanation, with the vast majority of the hull surviving, albeit somewhat distorted in its current as-displayed format, but the Newport Medieval ship was seen as being more representative of a typical archaeological ship find, and its several hundred disarticulated timbers makes for a more detailed example of the reconstruction process. In addition, the Newport Medieval ship was the only project to have used every one of the 22 individual stages set out in Table 7 2, from initial site recording to seakeeping and final testing. As such the Newport Medieval ship project represents a potential exemplar for digital reconstruction.

Chapter 9 takes the hypothetical minimum reconstruction, which has been developed through an iterative process, tested in order to remain tenable, and published for peer review. Developing on the feedback received from the publishing and peer review process, the reconstruction is further refined and tested. As the hypothetical reconstruction moves further from the available evidence-based archaeology, the significance of contemporary comparative data becomes more critical.

As the various disarticulated components are analysed and added to the evolving hypothetical reconstruction, it becomes even more imperative that the iterative process of editing, analysing and testing is followed. Equal portions of logical reasoning, and common sense will be required, while continuing to view the results, not just from the archaeologist's perspective, but also from the perspective of the boatbuilder and the mariner.

10.8 Further (potential) advances to the digital testing and analysis

The hydrodynamic testing carried out in Chapter 6, Chapter 8 and Chapter 9 examined the reconstructed vessel from the viewpoint of how it would float in various loading conditions as well as examining the healing moments generated with various wind and wave roll loadings. These results give an indication of the vessels initial static stability and demonstrate how the vessel will float at given cargo loads and various flotation depths and with various wind conditions.

However, each test is a static snapshot and does not consider the dynamic and changing conditions of a body floating in water. Other than the vessel itself, the other major influencing factors on any sea voyage are the weather conditions and the sea state. Both of which are never static. Wind affects the vessel in the form of pressure on the sail area resulting in a heeling moment applied to the vessel, and that pressure is a constantly changing force, as the wind which is never a constant, varies both in direction and strength about a given mean.

Sea state is primarily influenced by waves, which are primarily influenced by wind speed, wind duration, and fetch[85]. These factors work together to create waves, and the greater each of the variables in the equation, the greater the size of the wave (Tanner 2018:48–54 see Appendix I). Within the Baltic and North Sea, the fetch is limited to less than 300 nautical miles, thereby limiting the significant wave heights. Storm waves in the Baltic seldom exceed 2.4 m in height and 30 m in length, while those in the North Atlantic can reach heights of 10.6 m with a length of 304 m. (Marchaj 1964:400–401).

Computational fluid dynamics is a potential approach to analyse both the aero and hydrodynamic interactions with a vessel, however the calculation process is also a static one, and the vessel will require to be re-orientation for each changing environmental factor, and consequently the computing requirements are large.

An alternative approach is to use Unity3D, a real-time development platform which includes a built-in physics engine to handle calculations based on real world physics (Tanner Forthcoming). As each component of the digital model is created using closed three-dimension solids, every part has a solid density based on its relevant material. As a result, the physics engine within Unity3D applies a gravitational force to the vessel. Voxels[86] were used to check whether each point on the hull was submerged (Figure 10-2 top left) and if so, to exert the appropriate upward (flotation) pressure to counteract the gravitational weight thereby causing the vessel to 'float' in a realistic manner.

This process is still in the early experimentation phase, the 'sea' was provided as a third-party asset or plug-in for Unity3D, which reacts and behaves in a realistic manner as the wind force is applied. This was verified by creating reference blocks to measure the resultant sea state in any given wind condition (Figure 10-2 top right). The real-world flotation of the vessel, now controlled by the voxels, was tested by varying the weight of the vessel and comparing the visible updates to known predetermined calculations. This flotation condition was also checked for live updating as the various voxels are either submerged or exposed due to waves (Figure 10-2 bottom left).

At present the Unity3D wind force does not act on the digital vessel, resulting in angles of heel and propulsion, this will require some additional computer coding in order to improve and update the simulation. Currently the speed of the vessel is adjusted to suit each of the relevant wind

[85] Fetch is the distance of open water that the wind blows over.

[86] Voxels represents a single sample, or data point, on a regularly spaced, three-dimensional grid. This data point can consist of a single piece of data, such as an opacity, or multiple pieces of data, in this case each voxel would continually check if it were submerged or not, and if submerged apply the relevant buoyant force to the vessel.

strengths and with the simulation running, the vessel is observed to see if the simulated vessel remains afloat or if any sea water was taken onboard (Figure 10-2 bottom right). Additionally, the water taken aboard, and its subsequent additional weight loading is not tracked in the simulation, and this also requires some additional coding to be added. Consequently, while presently still a visual simulation, the potential for further computational based analysis is clear.

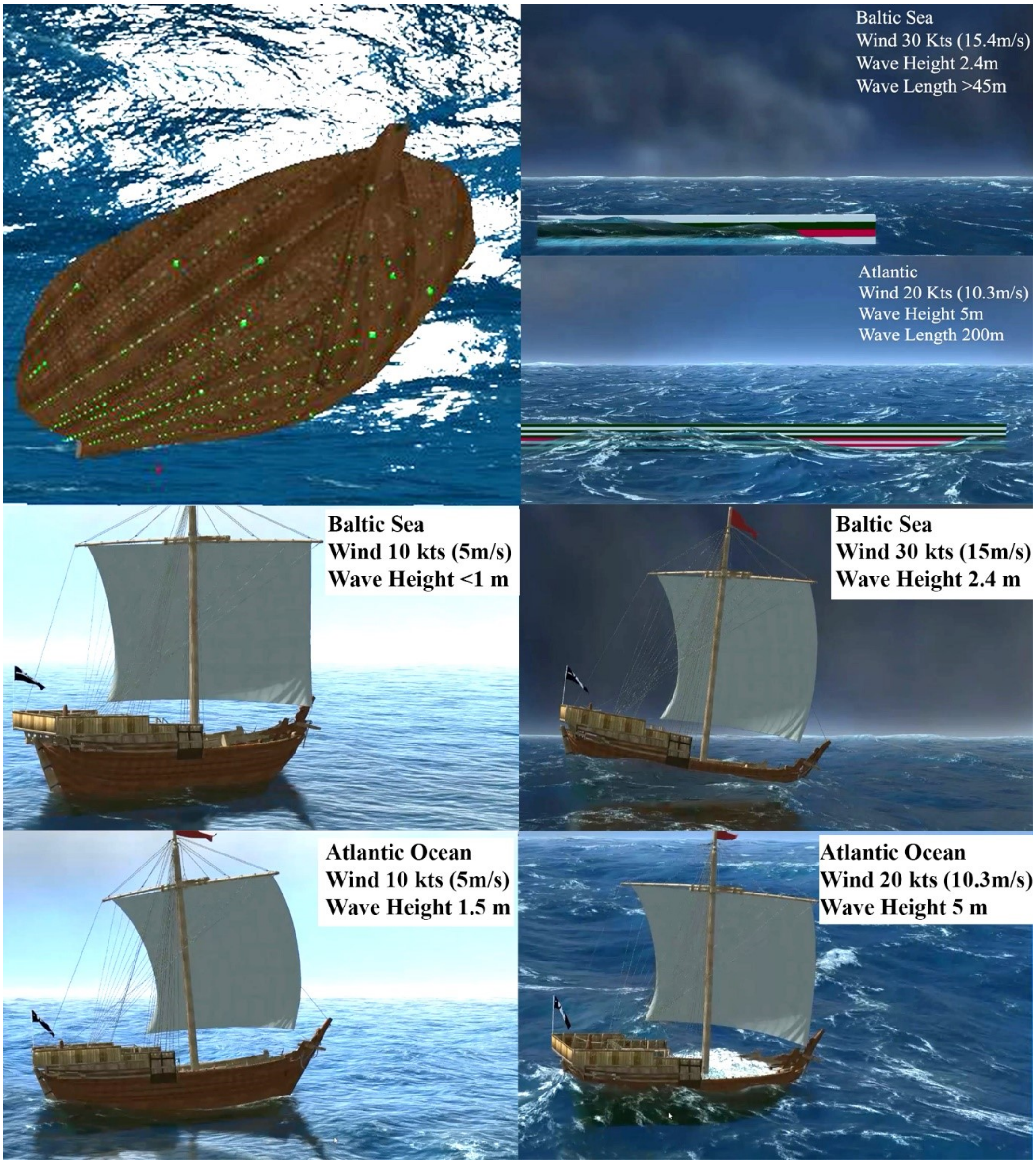

Figure 10-2 Using Unity 3D to simulate real world dynamic sea state conditions[87] (Pat Tanner)

[87] Top left showing underwater hull with voxels, top right showing accurately scaled wave height and length relative to weather conditions. Centre left and bottom left shows the sea state for the Baltic Sea and Atlantic Ocean respectively in a 10-knot wind. Centre right shows the vessel still floating in typical Baltic Sea storm conditions. Bottom right shows the vessel failing in conditions 50% less than that seen in typical storm conditions

10.9 Additional uses for the digital model

10.9.1 Two-dimensional visualisations

The digital three-dimensional model is also used as a base asset for artistic impression work, where the initial point of view of the vessel can often be one of the most significant factors in the initial setting up of the image (Figure 10-3). The ability to rotate and tweak the viewpoint of the digital model allows the artist to easily predetermine the painted scene digitally, prior to paint touching the canvas.

Figure 10-3 Artist's impression of the Newport Medieval ship (Painting: David Jordan)

10.9.2 Interactive three-dimensional digital archives

Augmented reality

Additional hardware such as Microsoft's HoloLens allows for the holographic projection (Figure 10-4) of the digital model directly into any real-world environment, allowing the user to walk around the digital model and view the model from any position. This allows the user to interact directly with the model, taking measurements, or examining areas which are not accessible or no longer exist in the physical world. The technology is also being developed to allow a three-dimensional object, rather than a paper-based barcode like image to be the trigger which activates the augmented display on hand-held devices such as tablets and smart phones. This would allow the physical (incomplete) museum display to be the trigger, with the missing portions overlaid onto the physical object using the device's augmented display.

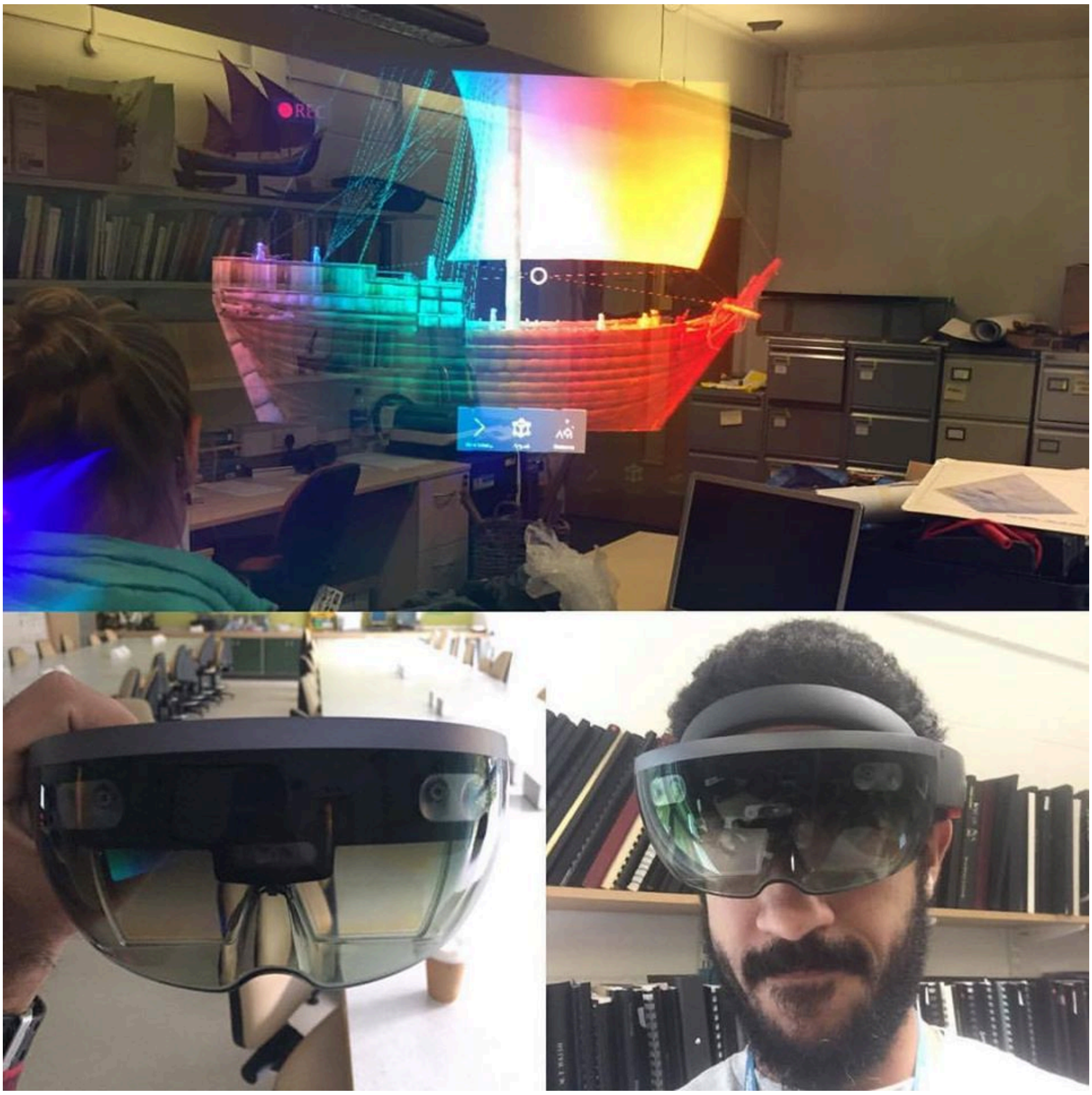

Figure 10-4 Holographic 3D model of the *Bremen Cog* using Microsoft's HoloLens (Pat Tanner)

Virtual reality

Virtual reality headsets allow the user to move around inside a full-scale digital environment (Figure 10-5) interacting directly with the digital data, taking measurements, or examining areas in full scale in three dimensions. No longer is it necessary to try and correlate several two-dimensional images back into a three-dimensional object, the user is actually inside a fully three-dimensional world. Issues such as size and spatial dimensions are immediately obvious, and this is without doubt one of the biggest benefits of the entire digital process.

Figure 10-5 Professor Seán McGrail examining a virtual reconstruction model (Pat Tanner)

This thesis has traced the development of archaeological ship reconstruction, highlighting the evolution and development of that process and the perceived goals and challenges. It is acknowledged that there can be no single way to reconstruct a vessel. However, it sets out a clear unambiguous approach, which is both methodical and meticulous in terms of the data that is used, how that data has been interpreted, and how that interpretation has been developed into a hypothetical reconstruction. It is subsequently tested and analysed, to ensure that the hypothesis can remain tenable. This form of digital data should go a long way towards bridging the gap between the exclusive knowledge of the excavator and the published record. Furthermore, it can allow lots of people to use the data in new and novel ways, while adding to our understanding of the past people and processes involved.

Glossary of Terms

Artemon	(Greek for foresail), a sail set well forward, often on an inclined mast, whose main function was largely as an aid to steering
Downflooding	Means the entry of seawater through any opening into the hull or superstructure of an undamaged vessel due to heel, trim, or submergence of the vessel. Downflooding Angle means the static angle from the intersection of the vessel's centreline and the waterline in calm water, to the first opening that cannot be closed weathertight and through which downflooding can occur.
FP	Forward Perpendicular, the point where the design water line (DWL) intersects with the stem
LCG	Longitudinal centre of gravity
Reconstruction	A thing that has been rebuilt after being damaged or destroyed. An impression, model, or re-enactment of an object or past event formed from the available evidence
Replica	An exact or accurate copy or reproduction of an object.
Sheer clamp	A long board that runs along the inside of the boat along the sheer line. The sheer strake attaches to the outside face of the frames and the sheer clamp attaches to the inside face of the frames. Sometimes also called the Inwale.
Shim	a thin slip or wedge of material, for driving into crevices or gaps, as between machine parts to compensate for wear, or beneath bedplates, large stones, etc. to level them
Shimmed	or shimming, to fill out or bring to a level by inserting a shim or shims
TCG	Transverse Centre of Gravity
Thwart	A thwart is a strut placed crosswise (left/right) in a ship or boat, to brace it crosswise. In sailing vessel often added to support the mast, in rowboats it can also serve as a seat for a rower.

Tumblehome	the term describing the narrowing of a ship's hull as it rises above the waterline
VCG	Vertical Centre of Gravity

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