

THE NAVAL ARCHITECTURE OF *VASA*, A 17TH-CENTURY SWEDISH WARSHIP

A Dissertation

by

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ABSTRACT

The Swedish warship *Vasa* sank in Stockholm harbor after sailing less than one nautical mile (1.85 km) on its maiden voyage in 1628. The hull was raised in 1961, and after a lengthy conservation and reconstruction process, went on display in a state-of-the-art museum in 1990. The hull is estimated to be 98% intact, making it the oldest intact wooden ship recovered to date. The recovery and remarkable preservation of the hull presents unparalleled archaeological research opportunities. This dissertation recovers and analyzes the methods of naval architecture used to design the hull of *Vasa* as evidenced in its intact structure. Digital 3D solid modeling software is used to virtually deconstruct the hull to facilitate a nuanced understanding of the design principles that guided the construction of the ship

Although *Vasa* was a Swedish warship constructed in Stockholm, it was designed and built by Dutch shipwrights. In the early 17th century, the Dutch rose to prominence as the premier shipbuilders in Europe. The quality and character of Dutch-built vessels were renowned and Dutch shipwrights were hired to build the merchant fleets and navies throughout Europe. Limited scholarly attention has been given to the methods of naval architecture by which Dutch shipwrights designed their ships. Dutch shipwrights designed and built ships according to orally transmitted principles of design and therefore left little written evidence for their tradition of naval architecture. *Vasa* presents an unprecedented opportunity to examine the methods used by Dutch shipwrights to design large vessels as they are evident in an intact hull.

The results of the analysis contained in this dissertation suggest that *Vasa* was designed according to proportional and arithmetical methods of naval architecture. The methods are

identical or very similar to those described in Nicolaes Witsen's 1671 treatise on Dutch shipbuilding. While many aspects of *Vasa's* hull appear to be derived according to the tradition of naval architecture described by Witsen, certain significant deviations resulted in an atypically narrow hull. The methods of analysis in this dissertation, which highlight digital 3D visualization, mark an attempt to expand the range of analytic and explanatory tools available to nautical archaeologists in the 21st century.

DEDICATION

To my mother and father, Colene and Robert Rose,
who taught me to always ask questions.

And

To Emily McManus and her endless inspiration.

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This dissertation would not have been possible without the generosity, guidance, and patience of many people. Peter and Nancy Amaral, Patricia Hurley at the Texas A&M College of Liberal Arts, Filipe Castro and Cynthia Werner at the Texas A&M Department of Anthropology, and the Institute of Nautical Archaeology all provided critical financial support for travel, research, and writing. Their generous assistance enabled me to realize the full potential of this project.

From the first day of my first graduate course, ANTH 616: Research and Reconstruction of Ships, Filipe Castro has been a constant source of knowledge, surprise, and inspiration. His courses instilled in me a deep interest in ship construction and a drive to understand how such complex machines were designed and built. Dr. Castro's mentorship, unique wisdom, and enthusiasm have helped shape me into the scholar that I am. Filipe, your wit and hospitality are truly extraordinary and a gift to those around you.

The courses I took from Kevin Crisman helped me to see how sailing ships functioned as a system with thousands of parts and endless combinations of seafaring technologies. These courses also, and perhaps most importantly, put people into these ships. Dr. Crisman has a rare talent for seeing a ship as a whole, which includes not only the nuts and bolts details of the structure, rig, and fittings but also the people who built and sailed them. His rigor and high standards challenged me and elevated my scholarship.

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During a visit to Texas A&M in 2009, Fred Hocker graciously invited graduate students to use *Vasa* material in their theses and dissertations. It was at that moment that the essence of this project was born. Through patient dialogue, Dr. Hocker and I outlined a project that merged my interest in early-modern naval architecture with the remarkable hull of *Vasa*. While on research trips to the Vasa Museum, Dr. Hocker and the devoted museum staff answered incessant questions and granted generous access to archival material, artifacts, point cloud data, and of course the ship itself. Throughout researching and writing this dissertation, Dr. Hocker's scholarly rigor consistently raised the quality of the product.

Guy Thompson II opened my eyes to the power and potential of SolidWorks, which fundamentally shaped the direction of this project. This software, which is an industry standard for mechanical engineers, was a revelation to me.

Without the persistent scholarship of Ab Hoving, current knowledge of Dutch shipbuilding would be dim indeed. His body of work is the basis of my understanding of Dutch naval architecture methods and therefore central to this dissertation. His kind advice and insight helped to further shape this project with specific consideration for the hull of *Vasa*. Likewise, Wendy van Duivenvoorde was a terrific help in providing rare sources that further clarified how abstract Dutch shipbuilding methods and rules were put into practice in the 17th century.

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CHAPTER I

INTRODUCTION

It cannot be denied that the art of constructing ships, which is so necessary to the state, is the least perfect of all the arts.¹

DISASTER AND RECOVERY

Vasa sank to the bottom of Stockholm harbor on the afternoon of 10 August 1628 less than one nautical mile (1.85 km) into its maiden voyage.² Hundreds of onlookers watched in amazement as the most powerful warship in the world filled with water and sank after a gust of wind off the starboard quarter plunged the lowest of the open portside gunports under water.³ 328 years later, on 25 August 1956, amateur archaeologist Anders Franzén and master diver Per Edvin Fälting located a large wooden object on bottom of Stockholm harbor using a drag and a coring device deployed from a small boat. The next week, Fälting and another diver, Sven Persson, dived on the site and found a massive wooden ship, largely intact, with two rows of gunports. Archival research confirmed that given the location and size of the vessel, it had to be *Vasa*.⁴

Almost immediately upon confirming the find, an administrative organization was established to oversee investigation and management of the wreck. One of the first tasks Franzén gave the organization was to determine if it would be possible to raise the wreck and install it in a

¹ Hoste, 1697, i. “*On de peut pas nier, que l’art de construire les Vaisseaux, qui est si nécessaire à l’Estat, ne soit le moins parfait de tous les arts.*”

² Hocker 2006, 36.

³ Hocker 2011, 128.

⁴ Hocker 2011, 174.

museum.⁵ Nothing like this had ever been attempted. Additional dives provided enough documentation and evaluation of structural integrity to determine that the hull appeared sound enough to be raised. Beginning in 1957, Swedish Navy divers began reinforcing the hull and digging six tunnels underneath it to allow steel cables to lift the hull from the water. After years of work under water, *Vasa* was raised. The first timbers broke the surface on the morning of 15 January 1961. In early May, *Vasa* was floated onto a custom-built submersible pontoon which served as a platform for excavation and conservation. It remains atop this platform today.⁶

A team of archaeologists immediately began excavating the interior of *Vasa*. The five month excavation effort recovered more than 30,000 artifacts from *Vasa*'s four intact decks.⁷ Upon completion of the excavation and stabilization of the hull, an aluminum cover was erected over the ship to protect it during conservation. Polyethylene glycol (PEG) was chosen as the conservation treatment for the hull. A sprinkler system was set up in 1962 to deliver a spray of PEG dissolved in water both inside and outside the hull. The hull was treated this way for 17 years, after which it was very slowly dried for 9 more years.⁸

Additional diving campaigns after *Vasa* was raised recovered thousands of timbers, sculptures, and other wooden fragments that fell off the hull – especially concentrated around the bow and stern. The goal was to reassemble the ship as completely as possible. Nearly all of the iron bolts that originally held much of the ship together had corroded away. The structure of the ship was

⁵ Hocker 2011, 174.

⁶ Hocker 2011, 183-186.

⁷ Hocker 2011, 191.

⁸ Hocker 2011, 192.

pushed back into shape using hydraulic jacks and more than 5,000 new mild steel bolts were used to fasten the hull back into something close to its original shape. A permanent steel cradle was built on top of the pontoon to support the ship from below. Over time, much of the hull was reassembled. The hull is now estimated to be 98% complete, as shown in Figure 1.1 and Figure 1.2.⁹

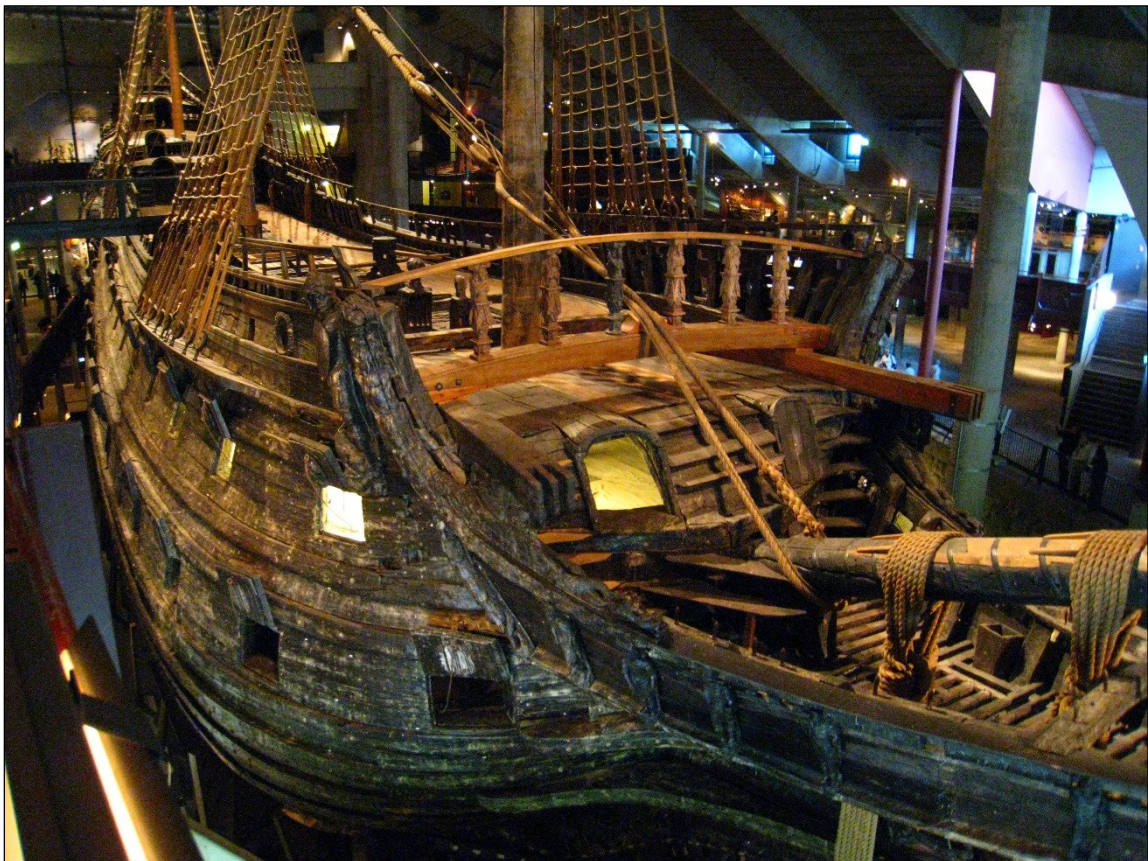


Figure 1.1. The hull of *Vasa* in the Vasa Museum from the bow.

⁹ Hocker 2011, 197.

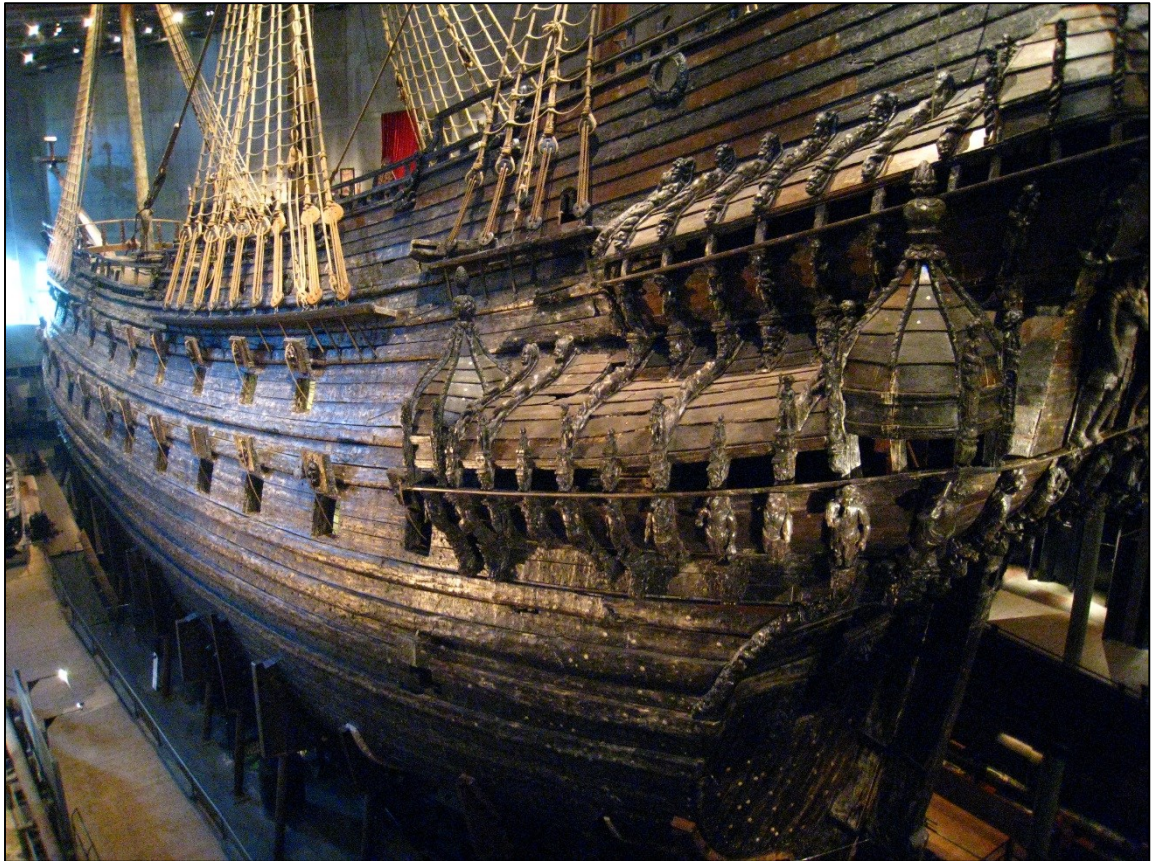


Figure 1.2. The hull of *Vasa* in the Vasa Museum from the stern.

From the moment it was raised, *Vasa* has captured the attention and interest of people worldwide. Public accessibility was a priority from the beginning of the *Vasa* project and the public was granted access to view the conservation and reconstruction of the ship upon completion of the interior excavation.¹⁰ The Wasa Shipyard was built in 1961 and served as a combination conservation laboratory and museum where visitors could see the entire process of conservation and restoration.¹¹ Visitation grew steadily from 250,000 a year in the mid-1960s to more than 500,000 in the 1980s. Construction began on a permanent museum in 1987. In

¹⁰ Hocker 2011, 195.

¹¹ The spelling of the ship's name was later standardized to *Vasa*.

November 1988, *Vasa* made its final voyage as it was floated on its pontoon into the new museum, which had one wall left open to allow the massive ship inside. The Vasa Museum (seen outside and inside in Figure 1.3 and Figure 1.4) officially opened in the summer of 1990.¹² It is now the most visited maritime museum in the world and attracts more than 1,000,000 visitors each year, most from outside Sweden.¹³



Figure 1.3. Exterior of the Vasa Museum in Stockholm. Photograph by Karolina Kristensson, the Swedish National Maritime Museums.

¹² Vasa is not italicized when referring to the Vasa Museum, the proper name of the cultural heritage institution.

¹³ Hocker 2010, 3; Hocker 2011, 196-197.



Figure 1.4. Interior of the Vasa Museum. Photograph by Anneli Karlsson, the Swedish National Maritime Museums.

STATE OF *VASA* SCHOLARSHIP

The archaeological excavation of *Vasa*'s interior yielded a wealth of artifacts depicting daily life in the early 17th century both on shore and at sea. Sea chests packed with personal belongings, cooking and eating utensils, barrels, clothing, and even human remains were recovered from inside the hull. Many ship-related artifacts such as cannon, gun carriages, small arms, rigging elements, intact sails, shipbuilding tools, and of course the hull itself all present a wealth of data unparalleled in preservation and completion. Since it was raised, *Vasa* has been an object of interest for historians, archaeologists, art scholars, economists, politicians, and even children's literature. Recently, master's theses and scholarly articles have examined the historical, archeological, and cultural significance of many aspects of *Vasa*, including several collections of

small finds from within the hull, life on board, and the rigging of the ship. The conservation challenges associated with preserving and maintaining the hull have also received significant recent scholarly attention and are a current priority of Vasa Museum researchers. Despite the wealth of research possibilities *Vasa* presents, a comprehensive study of the ship and its finds was not organized until Dr. Fred Hocker was appointed Director of Research at the Vasa Museum in 2003. The result is a proposed series of six book-length publications intended to be thorough, scholarly, and integrated to examine *Vasa* in its technological, cultural, economic, and political contexts.¹⁴ The first of these volumes was published in 2006, and focuses on the archaeological work on the ship, from sinking through rediscovery, raising, and excavation of the hull. The second volume is forthcoming and examines the sailing and rig of the ship.

Compared to other aspects of *Vasa*, limited scholarly attention has been given to the archaeological significance of the hull itself.¹⁵ This dissertation analyzes the hull of *Vasa* using digital 3D modeling technology to recover the system of logic, rules, and decisions employed by the shipwrights to determine its size and shape – it recovers the hull design method. This is a critical but poorly understood aspect of the ship. To conceptualize the study of shipbuilding from archaeological remains, nautical archaeologists have advanced the notion of ‘reverse naval architecture’. The goal of reverse naval architecture is to define the ship’s principal components and their interrelationship and recover its design method from analysis of the completed structure. Through this theoretical approach, this dissertation discovers and examines the

¹⁴ Hocker 2006, 12.

¹⁵ Currently, the third volume in the *Vasa* series is planned to be a comprehensive study of the hull including its archaeological, technological, and economic significance. The investigation into the hull design methods of *Vasa* contained in this dissertation project will be included in this publication.

proportional and arithmetic relationships between principal hull elements as a means to find the guiding principles used to define its size and shape.

Vasa is the product of an early modern Dutch shipbuilding tradition that produced no technical drawings of vessels and generated only limited written documentation of the design process. Unlike their counterparts elsewhere in Europe who were developing advanced graphical and mathematical methods of naval architecture, Dutch shipwrights built their ships largely by eye according to a tacitly understood system of design. Despite the seemingly disadvantageous conceptual difference between this empirical manner of ship design and the theoretical methods of their contemporaries, the Dutch excelled at shipbuilding during the 17th century and became the premier shipbuilders in Europe. The reputation of the Dutch for producing superior vessels faster and at a lower cost than other shipbuilders was known throughout Europe and made Dutch shipwrights and ships highly desirable. Due in part to the lack of textual evidence, the Dutch shipbuilding tradition is not completely understood. *Vasa* is the only intact readily-accessible example of a ship designed and built in the early modern Dutch shipbuilding tradition and as such offers great research potential.

Although the hull of *Vasa* is complete, it cannot be physically disassembled. This project uses digital 3D solid modeling technology as a tool to overcome these limitations. Based on measurements, total station data, photographs, and drawings, 1:1 digital 3D solid models of *Vasa*'s principal elements have been created. These digital parts can be assembled, disassembled, measured, and modified to allow for detailed analysis of the hull. The models also enable a level of flexibility and precision beyond what would be possible with scale paper

drawings. Despite the power and potential of 3D solid modeling and digital visualization in nautical archaeology, the discipline has been slow to adopt this technology; this dissertation marks a significant methodological step forward in this respect.

The results of this dissertation projects are threefold. First, the analysis contained in this project reveals significant insight into the design methods that produced *Vasa* and promotes a deeper understanding of the ship as an artifact. Second, by virtue of *Vasa*'s position as the only intact and accessible product of the early modern Dutch tradition of naval architecture, this dissertation lends unparalleled insight into early modern methods of Dutch naval architecture – a highly influential but poorly understood shipbuilding tradition. Third, the experimental modeling tools used in this dissertation and their methodological evaluation break new ground in nautical archaeology and enable an unprecedented level of construction and design analysis.

UNANSWERED QUESTION OF DESIGN

Ship design has a particularly interesting role to play in the *Vasa* story. Upon seeing the spectacularly well-preserved and exhibited ship in the Vasa Museum, the most frequently asked question by visitors is ‘Why did it sink?’ There are no simple answers to this question and a combination of factors are likely the cause, however, the design and construction of the hull is certainly a relevant aspect of the discussion. A number of rumors and legends surround the construction of the hull, most focusing on the involvement of King Gustav II Adolf in the design of the ship. Common wisdom states that the king ordered significant changes to the hull during construction and that the result was a faulty combination of features that had no chance of being seaworthy. One of the most persistent rumors is that the king ordered the addition of a second

gundeck partway through construction which created a hopelessly unstable hull.¹⁶ While the king was certainly involved in the initial stages of hull design, there is no archaeological or archival evidence to indicate that the king ordered changes to the hull after construction began.

No contemporary technical drawings of *Vasa* are known and it is very unlikely any ever existed. The two shipwrights responsible for the design and construction of *Vasa*, Henrik Hybertsson and Henrik Jacobsson, were Dutch and there is substantial archaeological evidence to suggest that the ship was designed and built according to the northern Dutch style of shipbuilding. This means that from a small number of primary dimensions agreed upon by the king and the shipwrights, the entire form of the ship could be defined and built following Dutch design principles and the experience and judgment of the shipwrights. This dissertation recovers those design principles as they are evidenced in the intact hull of *Vasa*. The goal is the identification and description of the process of deliberate selection employed by the shipwrights to control the fundamental shape of the hull.

SCOPE OF THIS STUDY

Vasa is a large ship composed of hundreds of timbers. Not all timbers, however, are directly relevant for a study of the hull form. Care is taken in this dissertation to identify and focus on the hull elements of more critical importance for determining the essential shape of the hull. Thus, not all aspects of *Vasa*'s hull are examined. Elements such as the beakhead, upper works, decorations, and rigging are outside the scope of this project. Similarly, minor hull fittings such

¹⁶ Hocker 2006, 44.

as railings, pumps, and capstans are not addressed. The focus is on the overall form of the hull. Analysis proceeds in the same general order as the likely construction sequence of the ship.

METHOD

A detailed analysis of the hull design method used to construct *Vasa* requires a large amount of high-quality spatial data. From 2007 to 2012, the staff of the Vasa Museum and visiting scholars conducted a total station survey of the hull. The result is more than 85,000 data points covering both the interior and exterior of the hull. These points form the core of the spatial data used in this dissertation. To make the best possible use of this data, SolidWorks, a 3D solid modeling software package, is used to create full-size virtual replicas of *Vasa*'s primary hull components. 3D solid modeling enables the creation of digital models with real-world fidelity and enable a range of analytical possibilities. Despite the advantages offered by solid modeling, it has been rarely used in nautical archaeology. This dissertation asserts that the use of 3D solid modeling technology constitutes a methodological advancement for the field. The use of this technology is evaluated for its applicability, advantages, and shortcomings as applied to nautical archaeology.

INTENDED AUDIENCES

This dissertation is written for three intended audiences: those interested in *Vasa* individually, those interested in early modern methods of naval architecture, and those interested in the applications of 3D visualization technology in archaeology. The work can be read with any or ideally all of these interests in mind. This study aims to fill in critical gaps in both the *Vasa*

story and the current understanding of early modern methods of naval architecture through the application of novel methods of investigation.

CHAPTER OVERVIEW

Chapter II places the construction of *Vasa* in its historical and political context. When *Vasa* sailed, it was the most powerful warship in Europe. The early modern period saw dramatic changes in the methods and scale of warfare at sea owing to broad economic, military, and technological developments. This period also saw the transformation of Sweden from a poor, sparsely populated, and marginal country to a powerful player in European politics. The development, maintenance, and use of an efficient and permanent military was a primary reason for this transformation. King Gustav II Adolf, who reigned from 1611-1632 was a champion of military reform and is credited by many as beginning Sweden's Age of Greatness (1611-1718). *Vasa* is a product of both the Swedish fiscal-military revolution and of the technological and military developments that transformed the way warships were constructed, armed, and used.

Chapter III is an overview of the two primary methods of early modern Dutch naval architecture and their chief source material. Neither method used paper plans. Both are essentially identical in the fabrication and assembly of the keel, posts, and transom but the early phases of construction differed significantly. The Northern Method begins planking the vessel in a fundamentally shell-based manner whereas the Southern Method proceeds in a modified frame-based manner. Once the bottom and bilges were planked in the Northern Method, construction proceeded in a generally frame-based manner. Several features in the hull of *Vasa* indicate that it was built according to the Northern Method of Dutch ship construction. Analysis of *Vasa*'s

design methods therefore follows the Northern Method sequence of construction as indicated in archaeological and literary sources.

Chapter IV establishes a methodological context for both the process of reverse naval architecture and the application of 3D visualization technology in archaeology. The hull of *Vasa* is intact and nearly complete. While this presents unparalleled opportunities for research, it also poses unique challenges. The hull cannot be disassembled and therefore full access to every design-relevant timber is restricted. 3D visualization technology is used to overcome these limitations to the fullest possible extent. Visualization technology has been used in archaeology since at least the early 1980s in a variety of capacities. Within the field, however, nautical archaeology has been slow to adopt and apply advanced visualization methods. Low hardware costs and increasingly powerful and user-friendly software enables the creations of high quality scientific visualizations with a range of analytical possibilities. One particularly promising modeling approach, solid modeling, is used in this dissertation to recover and analyze the hull design methods used to create *Vasa*.

Chapter V is a detailed discussion of solid modeling and its application in this project. From a range of available software, SolidWorks was selected as the modeling package to use for the design recovery and analysis of *Vasa*. SolidWorks is virtual prototyping software widely used in mechanical engineering and enables real-world testing of virtual objects; it is also very user-friendly and can be quickly learned by non-specialists. This chapter also provides a systematic and illustrated description of the creation of each *Vasa* hull component used in this project.

Chapter VI is the detailed recovery and analysis of the design methods used to create the hull of *Vasa* as evidenced by the intact structure and current understanding of early modern Dutch naval architecture. The analysis is preceded by a discussion of what little written evidence exists pertaining to the design of *Vasa* – chiefly the contract and correspondence between Henrik Hybertsson and Gustav Adolf regarding the construction of the ship. Although *Vasa* is nearly intact, several processes have acted on the hull that have altered its form to varying degrees. These processes are summarized as they have a direct effect on the recovery and analysis of the hull form design method. The solid models serve as the basis for the design recovery through precise measurement and the discovery of proportional and arithmetic relationships between hull components. Analysis proceeds in generally the same order as the hull's construction. Each primary hull component is measured and examined in relation to other hull components. An interpretation of the particular dimension and configuration of each hull component is derived guided by current understanding of Dutch design methods and factors specific to *Vasa*. The results are insights into the design principles and logic used by the shipwrights to design and construct the hull of *Vasa*, the early modern Dutch shipbuilding tradition, and demonstrate the potential of 3D visualization technology in nautical archaeology.

Chapter VII summarizes the conclusions of this dissertation and critiques the methods used. Particular attention is given to the shortcomings and successes of the modeling methods and their greater applicability to nautical archaeology, both within the academy and without. An appendix defining 3D modeling terms follows.

CHAPTER II

HISTORICAL CONTEXT

This chapter provides an historical context for the construction of *Vasa* within a transformative period in European politics and history. *Vasa* is the product of both a seemingly archaic shipbuilding tradition and a period in European history marked by modernizing movements in governing structures and military innovation. The early modern period (ca. 1500-1800) saw political rulers adopt new administrative systems to more efficiently extract and aggregate resources from society with the goal of building and maintaining permanent armed forces. The establishment of permanent armed forces shifted the balance of power among states. Sweden in particular embraced these reforms and used increasing military might to expand its borders and exert its new-found power throughout the Baltic. *Vasa* is a product of this ambition.

Sweden gained its independence from the Scandinavian Union of Kalmar in 1523 and immediately embarked on a path of military development. A century later, the country was ruled by an aggressive warrior king, Gustav II Adolf. When he came to the throne in 1611, Gustav Adolf inherited a tense struggle with the powerful neighboring kingdom of Denmark and a dynastic conflict with Poland-Lithuania across the Baltic. The young king quickly negotiated a costly peace with Denmark and then focused his attention on hostilities against his cousin Sigismund, King of Poland-Lithuania. During his reign, Gustav Adolf invested enormous administrative effort and capital into the growth and improvement of the Swedish military. The king viewed military strength as a primary tool to advance the position of Sweden within the Baltic and as a defensive strategy against potentially hostile neighbors. Gustav Adolf began a

campaign of strengthening his navy in the mid-1620s, which included the construction of several large and heavily armed warships. The first of these was *Vasa*.

In the early modern period, Sweden developed a close relationship with another emerging power, the Dutch Republic. Trade, religious and political ideology, and mutual enemies brought the two fledgling states together. In exchange for high quality weapons and profitable trade agreements, Sweden gained access to advanced Dutch military knowledge, including weapon manufacturing methods, tactics, and shipbuilding. Dutch ships and shipwrights, which were renowned throughout Europe, were in high demand by emerging military powers in Northern Europe that sought an edge in a growing naval arms race. A number of Dutch shipwrights were hired into the service of the Swedish crown to oversee design and construction of the large warships. Two of these shipwrights, Henrik Hybertsson and Henrik Jacobsson, were directly responsible for the design and construction of *Vasa*. This chapter positions *Vasa* within the complex political and military situation within Sweden, between its neighbors, and the transformations occurring throughout Europe.

EARLY MODERN PERIOD

The early modern period in Europe is defined by a constellation of political and social developments that profoundly influenced Europe and the world for centuries to come. Among the characteristic developments of the early modern period are the emergence of a consumer economy, the free exchange of ideas, religious and social toleration, and the construction of rational unitary states. Despite the scientific and humanitarian advances of the early modern period in Europe, this was also a time of intense conflict, war, and struggle. Many of the most

significant technological developments occurred in arenas with military importance including weaponry, printing, shipbuilding, and navigation.

Prior to the 16th century, European wars were fought by sovereign states as well as various autonomous political entities ruled by the lesser nobility. Military power was largely controlled by local groups who were only conditionally connected to the ruler of a state. The degree of loyalty these groups held toward the ruler directly depended on their interest in the outcome of the war. Management of these groups presented a major challenge and concern of the ruling elites. If these militias did not cooperate with the ruler his authority could be compromised; if they were hostile they might overthrow him; and if they disagreed with each other they could start a civil war.¹ The early modern period saw a fundamental shift in this feudal power relationship with the creation of fiscal-military states and the establishment of permanent state-controlled armed forces.

Broadly, early modern state building is characterized by the process of political elites creating new structures and organization to better regulate behavior and extract resources from society. Often, these new and efficient systems of resource aggregation were intended to establish, maintain, or enhance armed forces. This change resulted in a new kind of state, that historian Jan Glete describes as the fiscal-military state. The enhanced military capabilities of states expanded their resource bases through conquest, increased taxation, and trade duties. An increase in military expenditures also enabled creation and adoption of new military technologies

¹ Glete 2002a, 10.

and tactics, further enhancing military effectiveness in a virtuous cycle. Glete argues that the state formation processes and military revolutions of the early modern period are central to the foundation of the modern world.²

With the shift to fiscal-military states, ruling elites and society entered into a double contractual relationship with a society that more consistently controlled the use of violence. The rulers, or ruling elites, gained uncontested control of permanent and disciplined armed forces through their unique ability to pay them with resources extracted from their societies, which were in turn willing to pay the rulers if they used the armed forces to provide security.³ The creation of standing armed forces wholly loyal to the state made the conditional feudal system of defense obsolete.

Owing to both technological and administrative advances, wars became increasingly expensive, all-encompassing, and brutal. As states struggled for independence, survival, or ideology, an international arms race began that greatly expanded the scale of war in both human and financial terms. Partially as a response to the increased demands of maintaining armies and navies and partially due to an expanding European population, state governing systems grew in size and complexity. This led to an additional, perhaps dubious, feature of the early modern period: the birth of bureaucracy.⁴ With increasing control and monopolization of justice and taxation, centralized bureaucratic governments began to replace feudal aristocracies and local autonomy.

² Glete 2002a, 1.

³ Glete 2002a, 23.

⁴ Cameron 1999, xix.

This resulted in the creation of permanent armed forces under the control of increasingly powerful sovereigns.⁵

The fiscal-military state model of governance made the primary responsibilities of a ruler, enforcement of law and protection against external threats, easier and more efficient. The two centuries from 1500-1700 saw fiscal-military states with large permanent armed forces become the dominant type of European state. A chief concern of many early modern states, including Spain, the Dutch Republic, France, England, Sweden, Denmark, and Poland-Lithuania, was readiness for war. Spain, the Dutch Republic, and Sweden were the first three states to develop strong permanent armies and navies.⁶ The Dutch and Swedish states rose as military powers in response to the rise in power of Spain, Denmark-Norway, Brandenburg-Prussia, and Poland-Lithuania.⁷ Based on the bureaucratic improvements implemented by fiscal-military states, a broad European military transformation began in the late 16th century. This transformation was characterized by a growth in the size of armies and navies, the standardization of armed forces in both training and equipment, strict military discipline, and an expanded state bureaucracy to support these increasingly expensive forces. Military and naval competence was manifested in personnel, weapons, warships, fortifications, and logistics. This knowledge, combined with the ability to plan, direct, and finance major military operations were essential foundations of the early modern state.⁸ Outcomes of wars were no longer decided by the existence of resources, but by how those resources were organized. The proliferation of this type of state created a European power system where the strength of armies and navies became the principal parameter

⁵ Glete 2002a, 1.

⁶ Glete 2002a, 38.

⁷ Glete 2002a, 38-41.

⁸ Glete 2002a, 61.

of diplomacy and international prestige.⁹ Naval operations in particular became especially decisive and expensive, demanding the financial and tactical attention of rulers. *Vasa* was a product of this evolving reality and drew the personal attention of Swedish King Gustav II Adolf.

SWEDEN FROM INDEPENDENCE TO THE REIGN OF GUSTAV II ADOLF

Other powers wage war because they are rich. Sweden, in contrast, must wage them because it is poor, to improve its material condition.¹⁰

When Gustav Vasa established the independent kingdom of Sweden in 1523, it was poor, rural, sparsely populated, and lacked any bureaucratic structure. It existed in the shadow of its more powerful neighbors Denmark, Poland-Lithuania, and Russia. Sweden had been under foreign domination for more than a century and its continued independence seemed tenuous.¹¹ By 1648 Sweden had become the main Baltic power and a guarantor of the Peace of Westphalia, with its ally France.¹²

The election of Gustav Vasa to the Swedish throne broke a more than century-long Scandinavian union between Sweden, Denmark, and Norway and allowed Sweden to embark on an individual trajectory. In 1397, Erik of Pomerania was crowned King of Denmark, Norway, and Sweden, as

⁹ Glete 2002a, 40.

¹⁰ Remark by Swedish Chancellor Johan Adler Salvius at the Polish-Swedish peace talks at Lübeck in 1652; Frost 2000, 114.

¹¹ Lockhart 2004, 5.

¹² Lockhart 2004, 1; This unlikely rise to greatness would not last, however, and by the early 18th century the Swedish empire and wealth had disintegrated.

a product of the Union of Kalmar.¹³ Although the union was intended to unite Scandinavia in opposition to the Hanseatic League, the union was not equal. Denmark, the most highly developed and centralized of the kingdoms, dominated the union to the detriment of the others. In response, separatist movements developed in Norway and Sweden which threatened the stability of the ineffective union.¹⁴

The union struggled on until the early decades of the 16th century. Under Denmark's brutal King Christian II (r. 1513-1523), the 'Stockholm Bloodbath' in November 1520 violently broke the power of the Sture clan, the leaders of the resistance movement in Sweden. Leadership of the resistance fell to a young nobleman named Gustav Vasa. Within a year, the Swedish nobility hailed the new leader as 'Protector of the Realm'. With military aid from Lübeck, Gustav Vasa captured Stockholm in 1523. Shortly thereafter, on 6 June 1523, he was ceremonially elected and crowned King of Sweden by leaders of the Swedish nobility.¹⁵ While Sweden was declaring its independence, the Danish nobility deposed Christian II and his uncle Frederik I (r. 1523-1533) succeeded him. Unlike Christian II, Frederik I had little desire to keep the union together by force, and thus Sweden emerged as a fully independent kingdom.¹⁶

Gustav Vasa secured Sweden's independence, but faced the task of creating a government from scratch. Bolstered by the support of most Swedish nobility, burghers, and peasants, he managed to establish a fledgling governmental structure, aided by German bureaucrats.¹⁷ Despite early

¹³ Palmer 2005, 70.

¹⁴ Lockhart 2004, 5.

¹⁵ Lockhart 2004, 6.

¹⁶ Lockhart 2004, 6; Denmark and Norway would remain united until the Napoleonic War.

¹⁷ Lockhart 2004, 7.

administrative successes, Sweden remained in the economic and military shadow of the other Baltic states, chiefly Denmark, Poland-Lithuania, and Russia. Compared to other regional powers at the time, Sweden was poor and sparsely populated. In 1500, the total population was barely 750,000, mostly peasant farmers. At the end of Gustav Vasa's reign in 1560, the Swedish population had grown to about 1 million, roughly equivalent to that of Denmark but spread across a much larger territory, seen in Figure 2.1. These populations, however, paled in comparison to those of the other Baltic powers. In the first half of the 16th century, Poland-Lithuania's population was approximately 6 million, and Russia's was nearly 10 million.¹⁸

Large portions of Sweden's territory were uninhabited and the terrain made travel difficult. Many of Sweden's ports were ice-bound throughout the long winter, which further hampered overseas trade and naval development.¹⁹ International politics further challenged Swedish independence and prosperity. The decline of the Hanseatic League and the collapse of the Teutonic Order in the 1550s left a power vacuum in Livonia and Estonia that Sweden's powerful neighbors, Denmark, Poland-Lithuania, and Russia, all aspired to fill. An opportunity to capture areas of fertile hinterland along with the valuable ports of Riga and Reval and their growing importance in the lucrative Baltic trade was open to whichever state could claim it first. This instability not only furthered Swedish fears of territorial encirclement by hostile neighbors, it also drew the attention of the major western European powers France and Spain, given the importance of Baltic commerce to their ascending rivals England and the Netherlands.²⁰ Despite

¹⁸ Lockhart 2004, 3; Glete 2002a, 143. Populations: Dutch Republic, ca 1.5 million in the early 17th century. Spain ca. 15 million, France ca. 20 million, England ca. 7 million. Sweden ca. 1.25 million in 1620 rising to ca. 2-2.5 million in 1660.

¹⁹ Frost 2000, 7.

²⁰ Lockhart 2004, 14-15.

the challenges faced by Sweden immediately following its independence, through a wide ranging system of political reforms and ambitious military policies, Sweden would steadily rise to prominence in the Baltic throughout the 16th and 17th centuries.

Sweden was abundant in natural resources, but at the time of its independence, its population had little experience exploiting them. Throughout Sweden's early history, modernization was sought through the importation of foreign entrepreneurs and experts to develop industries. The expansive Swedish territory contained large deposits of iron and copper ore and vast forests that supplied timber, charcoal, and pitch.²¹ The establishment of industries and the resulting trading opportunities were a powerful engine for the Swedish economy. By the early 17th century, Sweden was the leading exporter of iron and held a near monopoly on copper production in northern Europe.²²

²¹ Lockhart 2004, 3. All critical shipbuilding supplies.

²² Frost 2000, 7.

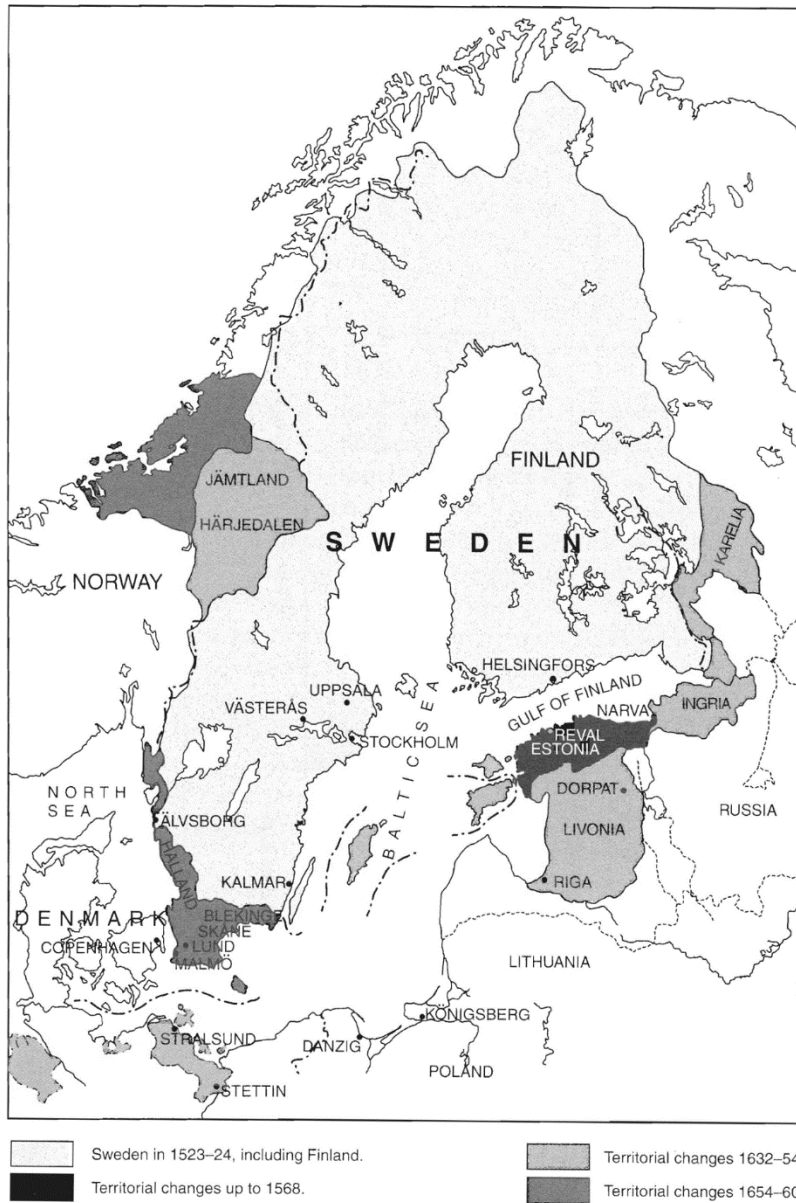


Figure 2.1. Map of Sweden in the 17th century.²³

²³ Lockhart 2004, ix.

The natural resources of Sweden, while not diverse, were abundant and gave the state an advantage in warfare, especially naval warfare. From the early 17th century, Dutch investment and innovation created a profitable arms-exporting industry in Sweden. This partnership supplied the army and navy of both Sweden and the Netherlands with high quality guns. By the 1630s, Sweden was Europe's foremost arms manufacturer, both naval and otherwise.²⁴ While the Swedish state was efficient in resource organization, it left much of the procurement and construction of weapons and, in particular, warships to private enterprise.²⁵ More so than any other early modern state, Sweden was independent of foreign supply of arms and naval supplies. By the early 17th century, rapid economic development, effective governing, and access to high quality military technology positioned Sweden to become a serious European power. All that was lacking was the right leader.

Under Gustav Vasa, Sweden had a strong economic and military start. Politically, however, the early decades of independence were marked by dynastic and religious struggles. Gustav Vasa's son and successor, Erik XIV (r. 1560-1568) proved a much less effective ruler than his father, and was plagued by crippling suspicion and paranoia.²⁶ In 1568, his half-brothers Johan and Karl led a rebellion against Erik and succeeded in capturing Stockholm. Shortly afterward, Johan was crowned as King Johan III (r. 1568-1592).²⁷

²⁴ Cipolla 1965, 54.

²⁵ Glete 2002a, 180.

²⁶ Lockhart 2004, 8.

²⁷ Lockhart 2004, 9.

Johan III was Lutheran, but his wife, Catherine of the Polish Jagiello Dynasty, was Catholic. Johan showed clear Catholic sympathies, which was an unpopular position in the staunchly Protestant state. Christianity came relatively late to Scandinavia, only gaining widespread acceptance and royal approval during the reign of Harald Bluetooth in the late 10th century.²⁸ By contrast, Protestantism was adopted very early, in the 1520s. Gustav Vasa broke with the Catholic church and used the ideals of the Reformation to justify the looting of church holdings and coffers to the extent that he died Sweden's richest sovereign ever in 1560.²⁹ Despite Johan III's efforts in the 1570s, the Vasa house shunned papal authority and firmly embraced Lutheranism.³⁰ The Swedish populace quickly followed.

Johan III's reign was further beset by religious tensions when his eldest son, Sigismund, converted to Catholicism. As a result of the close religious and dynastic ties, Sigismund was elected King of Poland-Lithuania (r. 1587-1632) following the death of King Stefan Bathory in 1587.³¹ Sigismund also succeeded his father to the Swedish throne in 1592 (r. 1592-1599) and faced the impossible task of ruling a state that disapproved of his father and was hostile toward his religion, while attempting to administrate *in absentia* from Cracow. Sigismund only visited Sweden twice during his reign, in 1593-94, and in 1598. In his absence, his uncle, Duke Karl, was able to advance his own political agenda. Fear of Catholicism united Karl, the Lutheran clergy, and the *Riksdag*. Together, in 1594 they began officially limiting Sigismund's authority in Sweden. In 1598, after a series of violent clashes, Sigismund conceded defeat and was

²⁸ Palmer 2005, 33.

²⁹ The wealth amassed by Gustav Vasa effectively made the Swedish crown independent of the Riksdag, the feudal legislature, and ensured that Sweden would continue on as a hereditary monarchy; Palmer 2005, 84.

³⁰ Lockhart 2004, 17.

³¹ Lockhart 2004, 10.

declared officially deposed in 1599.³² The Catholic Vasa and his heirs, however, would not give up claim to the Swedish throne until 1660. Karl accepted the Swedish crown in 1604, as Karl IX (r. 1604-1611).³³

Throughout the dynastic struggles during the reigns of Erik XIV, Johan III, and Karl IX, Sweden confronted its enemies and established an important foothold in the eastern Baltic.³⁴ Investments in economic and military reforms began paying dividends and Sweden was poised to become a major player in European politics. This was to happen, however, at the cost of prolonged bloodshed and toil, as much of Sweden's success was accomplished through war. Five different monarchs would rule during the Swedish Age of Greatness (1611-1718), and four of them would actively seek to expand Sweden's Baltic empire through conquest. All of them would be involved in large scale wars on the Continent.³⁵ Sweden's Age of Greatness came to an end in 1718 following losses in the Great Northern War, but it began in 1611 with the reign of an ambitious young king who was personally involved in the design of Sweden's most famous warship.

GUSTAV II ADOLF

Gustav II Adolf (often Latinized as Gustavus Adolphus) is a pivotal figure in Sweden's rise to power and is revered in Swedish culture as a legendary military leader and one of the nation's

³² Lockhart 2004, 11-12.

³³ Lockhart 2004, 12.

³⁴ Lockhart 2004, 17.

³⁵ Lockhart 2004, 2.

most important rulers.³⁶ Gustav Adolf began his reign at the age of 16, upon the death of his father Karl IX in October 1611.³⁷ Upon coronation, his first military task was to stop the inherited wars with Denmark and Poland-Lithuania. The war with Poland-Lithuania was an ongoing struggle beginning in 1600 stemming from the dynastic conflict between Sweden and Sigismund, and Swedish claim to Livonia. The war simmered on until a truce was signed in 1621.³⁸ The most pressing concern for Gustav Adolf upon his coronation was the war with Denmark. In 1611, Denmark declared war on Sweden in response to an aggressive move by Sweden's Erik IX to claim Danish territory and circumvent the Danish Sound Toll through the Oresund. The war heavily favored Denmark, and Sweden suffered the loss of several fortresses, including the critical port town of Älvsborg. The Peace of Knäred ended the war in 1613, but mandated that Sweden surrender Älvsborg to Denmark, pending payment of a large ransom. Älvsborg was Sweden's only direct outlet to the North Sea and of critical military and economic importance to the kingdom. The terms of the peace agreement stipulated that Älvsborg would remain under Danish control for six years while Sweden paid a ransom of 1 million *riksdalers*. If Sweden was unable to pay the ransom in time, Älvsborg would permanently remain under Danish control. The ransom was such an enormous sum (more than 3 times Sweden's annual revenue) that Denmark's King Christian IV did not expect Sweden would be able to pay it in time.³⁹ The ransom was paid in 1619, though not without nearly bankrupting the kingdom and with substantial assistance from Dutch loans.⁴⁰

³⁶ Subsequently referred to as Gustav Adolf.

³⁷ Lockhart 2004, 23.

³⁸ Hocker 2006, 38.

³⁹ Lockhart 2004, 26.

⁴⁰ Lockhart 2004, 45.

Sweden had a very real fear of territorial encirclement by hostile and powerful neighbors. Denmark, Poland-Lithuania, and Russia all threatened the nation's security. As a response to this threat, Gustav Adolf undertook an extensive military buildup. He continued the practice of instituting bureaucratic reforms that he inherited from previous kings and augmented his reign through appointment of eminently capable bureaucrats, foremost among them chief minister Axel Oxenstierna and Dutch-born finance minister Louis de Geer.⁴¹ By 1621, Sweden was divided into well-defined administrative districts, under the direction of provincial governors. The governors, directly answerable to Stockholm, were employed to effectively extract and organize resources at the local level and ensure their availability to fuel the Swedish military.⁴² Among the other reforms under Gustav Adolf was an expansion of state bureaucracy, the professionalization of military service, the implementation of a successful conscription system, and the recruitment of specialists to oversee technical aspects of military construction – including shipbuilding. The result was a powerful fiscal-military state where nearly all aspects of social and government organization were focused on meeting the needs of the armed forces. Beyond an increase in numbers, Gustav Adolf instituted innovative tactical and equipment improvements that made Sweden's armed forces among the most modern and formidable in Europe. Added to Gustav Adolf's challenges was Sweden's status as a new state, his status as the son of a usurper, and the growing threat of involvement in the Thirty Years' War, which had begun in 1618 as a major conflict between the Bourbon and Habsburg interests in Europe.⁴³ Gustav Adolf unflinchingly sought military power to confront these challenges and assert Swedish authority on the international stage.⁴⁴

⁴¹ Palmer 2005, 96.

⁴² Lockhart 2004, 29.

⁴³ Hocker 2006, 38.

⁴⁴ Lockhart 2004, 40.

During his 21 years as king, Gustav Adolf gained a reputation as Europe's premier warrior king and won numerous important military victories. He was wounded multiple times in battle and during his reign, was constantly directing a military campaign, or preparing for another. The "Lion of the North" favored mobile tactics in war relying on light, flexible, and fast infantry and artillery. This placed great strain on his troops, who often marched more than 320 kilometers in a week.⁴⁵ Unlike his contemporaries, Gustav Vasa preferred to lead his troops in battle, often from the front. He also took a personal interest in military tactics and construction, and personally participated in planning the armament and construction of *Vasa*.⁴⁶

The Swedish Navy lost much of its strength with the capture of Älvsborg. Despite the enormous financial burden of the ransom, rebuilding of the navy began immediately after the Peace of Knäred. The success of this effort was largely due to the fiscal and administrative competence of Admiral of the Realm Karl Karlsson Gyllenhielm and his assistant Admiral Klas Fleming. Together, they vastly improved the quality, discipline, and leadership of the Swedish fleet.⁴⁷

By the end of Gustav Adolf's reign, Sweden possessed a navy that rivaled that of powerful Denmark and an army that equaled the larger continental armies in tactical skill and efficacy.⁴⁸ Built upon the tactical reforms of Maurice of Nassau in the 1590s, the Swedish army emphasized smaller tactical and administrative units, a higher proportion of officers, lighter more mobile formations, and constant drilling.⁴⁹ Gustav Adolf died while leading his troops in the Battle of

⁴⁵ Palmer 2005, 96.

⁴⁶ Hocker 2006, 37.

⁴⁷ Lockhart 2004, 35.

⁴⁸ Lockhart 2004, 33.

⁴⁹ Lockhart 2004, 34.

Lützen in Germany in November 1632. Charles X continued Gustav Adolf's aggressive military campaigns and by the 1660s, Sweden's military reputation was famed throughout Europe.⁵⁰ The meteoric rise to prominence was followed by a series of defeats that permanently reduced Swedish military authority. The debts incurred by Sweden's military combined with a crash in the price of copper beginning in the 1650s, began placing enormous strain on the country's ability to continue such expansive policies. After about 1660, Sweden's military became essentially a defensive force.⁵¹ A defeat by the Danish navy at Køge Bay near Copenhagen in 1677 destroyed much of the Swedish fleet and effectively ended Swedish naval control of the Baltic.⁵² A series of territorial losses in Germany followed, bringing the period of Swedish expansion and predominance to an end.

SWEDEN AND THE NETHERLANDS

An important factor in Sweden's military and political development was the expertise brought to the state by foreign entrepreneurs, craftsmen, and bureaucrats. Sweden and the Netherlands developed a particularly close relationship following Swedish independence. A number of factors brought these fledgling Protestant states together and both profited significantly from the relationship. The primary bond between Sweden and the Dutch Republic was trade. The volume of Baltic seaborne trade surged in the mid-15th century. Raw materials and commodities, including grain, timber, pitch, potash, hemp, flax, wax, hides, and furs were produced in abundance in the Baltic and offered excellent profits if distributed by sea to the rest of Europe, especially to communities on the North Sea, where they were in high demand. Early on, the

⁵⁰ Frost 2000, 200-201.

⁵¹ Glete 2002a, 188.

⁵² Frost 2000, 212.

bulk-goods trade was dominated by the Hanseatic League which controlled a fleet of about 750 merchant vessels by the end of the 15th century.⁵³ The league was led by Lübeck, and formed a trade network of several hundred cities and towns that spanned London to Novgorod. By the early 16th century, however, the Hanse's success in developing the Baltic trade invited challenges to its monopoly. Communities along the North Sea began sending traders directly to the Baltic cities, eliminating the reliance on Hanse trade.⁵⁴ The Dutch pursued this opportunity with particular vigor and found it to be immensely profitable. By 1497, more Dutch ships passed through the Oresund than from any other country. Half a century later, 9 out of every 10 ships leaving Danzig was Dutch.⁵⁵ At the same time that the Netherlands was taking control of the Baltic trade, Sweden was emerging as a new profitable source of bulk goods.

Technical expertise also brought the states together. The importation of experts, particularly military authorities from the Dutch Republic, was critical to the modernization of Sweden and its ambitious pursuit of becoming an international power. Shortly after gaining independence, Gustav Vasa began a massive foundry construction campaign that exploited his territory's rich supplies of iron, copper, tin, charcoal, and water power with the aid of foreign entrepreneurs. Much of the development of Sweden's resources and industry was done by Dutch entrepreneurs.⁵⁶ Particularly critical to both states was the development of an arms manufacturing industry. Many of the guns produced in Sweden, which were among the highest quality available in Europe and built based on Dutch technology, were sold directly to the Dutch for use in ongoing conflicts with Spain. Sweden gained access to high quality weapons for its own military and profited from the export revenue. Building on the success of the early gun

⁵³ The Hanseatic League was formed in the 13th century and held a near monopoly on seaborne trade for nearly 200 years.

⁵⁴ Frost 2000, 3.

⁵⁵ Palmer 2005, 64.

⁵⁶ Lockhart 2004, 45.

founding industry, Sweden became the first state in Europe to become self-sufficient in the production of arms, and by the 1680s was the foremost exporter of iron cannon.⁵⁷ The economic relationship between the Dutch Republic and Sweden benefitted each emerging state as they struggled to gain or maintain independence in a hostile European climate.

The Dutch Republic and Sweden were also united against the threat of Danish naval supremacy in the Baltic. Denmark had long controlled the Oresund, only route to the Baltic from the North Sea and from 1426 had levied tolls against every passing foreign vessel.⁵⁸ The tolls provided a sizeable and reliable income for the Danish crown at the cost of the merchants passing through. As the Baltic trade became increasingly dominated by Dutch merchants, displeasure with capricious Danish monarchs also grew. In 1613, the Dutch States-General signed defensive alliances with Sweden and several Hanseatic cities in fear of an over-powerful and untrustworthy Denmark.⁵⁹ In aid to their ally, the Dutch assisted Gustav Adolf in paying the ransom of Älvsborg with loans, thereby ensuring Sweden had a direct outlet to the North Sea and could maintain a critical naval base. With the rise of Swedish naval power, the Dutch found an opportunity to invest in a counter to Danish Baltic hegemony.⁶⁰ This alliance culminated in the triumph of a combined Dutch-Swedish naval force against the Danish navy in 1644, which effectively dashed Denmark's hope for primacy in the Baltic thereafter.⁶¹

⁵⁷ Hocker 2006, 38.

⁵⁸ Frost 2000, 4.

⁵⁹ Lockhart 2004, 45.

⁶⁰ Lockhart 2004, 45.

⁶¹ Lockhart 2004, 45.

The Swedish crown also sought the expertise of Dutch military commanders to improve the tactical abilities of its armed forces. In 1601, Karl IX recruited John of Nassau, brother of famed tactician Maurice of Nassau, to train the Swedish army.⁶² In the middle of the 17th century, large numbers of Dutch officers were hired into the Swedish navy to improve organizational and operational effectiveness.⁶³ Swedish monarchs, especially Gustav Adolf, admired the Dutch for their triumph against a powerful Catholic foe in their struggle for independence. Encouraged by the Dutch example, Gustav Adolf viewed political unity as a precondition for efficient military power. Later in his reign, he cited the example of the Dutch Republic as an example for how small powers could become powerful through cooperation in an effort to convince German Protestant princes to form an alliance against the Catholics in 1631-1632. The Dutch provinces once faced nearly impossible odds in the struggle against the Habsburgs, but through unity they became a formidable force.⁶⁴ The Dutch Republic also amassed more resources per capita than any other 17th century state, and was able to organize them effectively into large and high quality permanent armed forces.⁶⁵ Gustav Adolf admired this effective management and aspired to do the same with Swedish resources. Through their relationship, Sweden and the Netherlands were among the first European nations to develop strong and modernized standing armies and navies; Sweden through Dutch technology and expertise, and the Dutch with Swedish arms and commerce. It was through this relationship that *Vasa* came to be designed and built by two Dutch shipwrights in Stockholm under the employ of the king of Sweden.

⁶² Frost 2000, 63.

⁶³ Glete 2002a, 201.

⁶⁴ Glete 2002a, 140.

⁶⁵ Glete 2002a, 171-172.

CONFLICT WITH POLAND-LITHUANIA

Following the Peace of Knäred in 1613, the fulfilment of the ransom of Älvsborg in 1619, and the buildup of Swedish military forces, Sweden effectively held Denmark in check until the 1640s. Sweden's military attention then focused on Poland-Lithuania. Karl IX's triumph over Sigismund, and his ouster as King of Sweden, locked Sweden and Poland-Lithuania in a war over control of Baltic ports and dynastic ambition that lasted nearly 30 years, interrupted by short periods of peace. The war was one of creed and greed. Poland and Lithuania were united in a Catholic dynastic union in 1385-1386.⁶⁶ Over the next 250 years, this state grew in power and would come to encompass a vast swath of Eastern Europe. The marriage of Duke Johan (later King Johan III) of Sweden to Catherine of the Polish Jagiello dynasty in 1562 entwined the fates of Poland and Sweden. Their son, Sigismund Vasa, was heir to the Swedish throne and elected King of Poland-Lithuania in 1587. Instead of a powerful union, however, this led to Sigismund being deposed as King of Sweden by his uncle Duke Karl IX (later King Karl IX), and a long series of conflicts between the two branches of the Vasa dynasty between 1599 and 1660.

⁶⁶ Frost 2000, 2.

In the 1610s, however, Poland-Lithuania became the center of papal efforts to re-Catholicize Scandinavia.⁶⁷ As a result, Sigismund's Catholicism threatened the existence of Stockholm's Protestantism.⁶⁸ The added possibility of Habsburg involvement in this scheme added further troubling dimensions to Sweden's fear of encirclement.⁶⁹ This mounting threat prompted Gustav Adolf to begin a massive military buildup and reformation campaign. The Swedish king viewed a powerful offensive strategy as the best defense against an attack on the Swedish homeland. He aimed to capture and hold buffer territories on the Continent. Of particular importance to this plan was the establishment of a powerful navy. Ships were required to transport troops across the Baltic, defend convoys, and blockade enemy ports. *Vasa* was built while the inherited dynastic Polish threat was foremost in the minds of Gustav Adolf and his administrators. This is illustrated in two sculptures on the ship's beakhead, which depict a Polish nobleman crouching under a table in humiliation. The insult was made even more severe by the position of the sculptures, which were only clearly visible when sitting on one of the ships heads, seen in Figure 2.2.⁷⁰

⁶⁷ Lockhart 2004, 42.

⁶⁸ Palmer 2005, 99.

⁶⁹ Lockhart 2004, 43.

⁷⁰ Hocker 2011, 72.



Figure 2.2. Sculpture of crouching Polish nobleman. Visible to *Vasa*'s crew while on the ship's heads.⁷¹

Although dynastic struggle and religious ideology were powerful factors in the conflict with Poland-Lithuania, Gustav Adolf's primary objective was to gain control of the wealthy ports on Livonia's coast. This was a motivation behind many of Gustav Adolf's military campaigns: to capture and hold cities on the southern shore of the Baltic and ensure custom duties imposed on their trade flowed to the Swedish crown's treasury.⁷² After a period of peace, Gustav Adolf renewed the war against Sigismund when he launched an attack against Poland-Lithuania in 1621, focusing on the Gulf of Riga. Sigismund had recently become immersed in a war with the Ottoman Turks in Moldova, and Gustav Vasa took this opportunity to attack. After a decade of

⁷¹ Hocker 2011, 69.

⁷² Palmer 2005, 105.

buildup, Gustav Adolf's fleet contained 148 ships, including 25 warships, 3 pinnaces, 7 galleys, 7 small warships, and 106 transports.⁷³ Poland quickly capitulated and a 4-year truce was signed shortly thereafter ceding Riga and a significant amount of Livonian territory to Sweden.⁷⁴ This action gave Sweden control of the wealthiest port in the eastern Baltic, which had long been a goal of Swedish monarchs. It remained a Swedish possession until 1721.⁷⁵

STATUS OF EUROPEAN NAVIES

When *Vasa* sailed, it was the most powerful warship in Europe. England and Denmark had ships that mounted more guns, or heavier guns, but no other ship could match *Vasa*'s broadside weight.⁷⁶ Although its career was brief, *Vasa* represents an important step in the development of naval technology and organization in Europe. *Vasa* was designed to carry a standardized battery of guns, a new development in naval warfare.

Gunpowder and guns were used in land warfare in Europe from the early 14th century.⁷⁷ Guns on ships, primarily Mediterranean galleys, first appear in the middle of the 14th century.⁷⁸ The first large guns on sailing ships, which would become the standard of naval power for centuries, emerged more than a century later, at the end of the 15th century.⁷⁹ Two rulers in particular were early adopters of this new configuration. Portugal's King João II (r. 1481-95) and England's

⁷³ Frost 2000, 103.

⁷⁴ Palmer 2005, 99.

⁷⁵ Lockhart 2004, 43.

⁷⁶ Hocker 2006, 47.

⁷⁷ Cipolla 1965, 21.

⁷⁸ Cipolla 1965, 75.

⁷⁹ Small guns were used on sailing warships since the 15th century but had little influence on naval design or tactics; Glete 1993, 24.

Henry VII (r. 1485-1509) embraced this idea and sought to make armed sailing vessel the core of their navies. The addition of guns to sailing ships marked the beginning of a major shift in naval warfare but appears to have preceded significant changes in naval construction and tactics. Guns were initially mounted at the bow and stern, inspired by the galley arrangement, or in the waist of the ship and fired over the rail. Deck space limitations meant that early sailing warships could only carry small numbers of guns in this fashion. The technological innovation of creating gunports in the side of the ship to mount more guns occurred in the early 16th century.⁸⁰ This development led to the creation of gundecks in the 1520s and 1530s. Even though warships began to carry increasing numbers of guns mounted on gundecks and fired through gunports, naval tactics still relied on boarding. Toward the end of the 16th century, the conception of naval warfare began to change and warships were increasingly viewed and built as mobile gun platforms, with an emphasis on artillery as the deciding factor in naval engagements.

Until the fiscal-military revolutions of the early modern period, navies, like armies, were temporary. Privateering was the primary way in which actual fighting at sea was conducted. Naval battles were rare and navies were expensive to build and maintain. Until a fiscal apparatus was in place to support a standing navy, rulers favored improvising one in times of need by requisitioning and outfitting merchant vessels. Before the 16th century, purpose-built sailing warships were virtually unknown. Instead, all warfare at sea was conducted using armed merchant ships.⁸¹ This was not especially difficult in many cases, as merchant ships were routinely fitted for defense against piracy and privateering. In the absence of standing navies, piracy and privateering were widespread in the Baltic. Merchants who were able to defend

⁸⁰ Cipolla 1965, 81.

⁸¹ Glete 2002a, 10.

themselves in this climate dominated long distance trade. Early navies emerged mainly on the periphery of Europe in England, Portugal, Denmark-Norway, and Sweden for the purpose of advancing dynastic ambitions. Early mercantile states, including Spain, Venice, Genoa, the Netherlands, and northern Germany were by contrast slow to develop standing navies.⁸²

Sweden's navy began in 1523 when Gustav Vasa purchased a navy from Lübeck to blockade Christian II of Denmark's garrisons in Stockholm and Finland. The Swedish navy could not be built by conscripting and arming Swedish merchantmen, because they did not exist in Sweden. Instead, Swedish kings had to build or purchase specialized warships, which proved to be an advantage over other states.⁸³ From its inception, Sweden emphasized specialized sailing warships armed with guns.⁸⁴ The Swedish navy found early success through the use of naval artillery tactics which were not in simultaneous use throughout Europe. In 1535, Sweden's young navy successfully suppressed Lübeck's navy through the use of guns. The Swedish navy triumphed again with naval gunnery during the Northern Seven Years' War (1563-1570) against the combined forces of Lübeck and Denmark-Norway who emphasized boarding tactics.⁸⁵

Later, the modern Swedish navy played a central role in Gustav Adolf's expansionist plans. The cost of building and maintaining a naval force often forced rulers to decide between a navy

⁸² Glete 2002a, 40; Private trade and shipping interests were not the primary motivators for developing early navies.

⁸³ Glete 2002a, 200.

⁸⁴ Glete 2002a, 180.

⁸⁵ Glete 1993, 113; Naval historians consider the Northern Seven Years' War to be the first modern naval war between sailing fleets in Europe in several respects. Both sides fought for command of the Baltic and control of trade routes and defeat of the enemy through a seaborne invasion via the elimination of the enemy battle fleet.

composed of a large number of small ships of a small number of large ships. Gustav Adolf opted for the large-ship navy. Tasked with modernizing the Swedish navy, chief minister Axel Oxenstierna and Vice Admiral Klas Fleming emphasized the construction of heavily armed 3-masted warships. This was a departure from previous policies that favored many small ships, armed with a single deck of 12-pounder smoothbore cannon.⁸⁶ Gustav Adolf chose to build fewer ships with both more and larger guns. Although his successors would turn away from this policy, four large ships built under his reign, *Applet*, *Kronan*, *Scepter*, and *Gota Ark* (all Dutch designed and built) would form the core of Swedish naval power for a generation. The first ship built under this doctrine was *Vasa*. Gustav Adolf's goal was to build an effective navy for carrying troops across the Baltic to foreign theaters and blockading enemy ports. Line-of-battle tactics had not yet been widely adopted at sea and fleet actions usually consisted of ship to ship artillery duels.⁸⁷ This meant that if Sweden's navy engaged an enemy, its ships had to be strong enough to fight enemy ships one on one. *Vasa* was planned to carry 64 guns with a main battery of 24 pounders. The number and size of guns made it the most powerful warship in the world, for a short time.⁸⁸

VASA'S SHIPWRIGHTS

As states adopted fiscal-military models of governance and evolving naval technology enabled the construction of larger and deadlier warships, navies became a chief concern for many of

⁸⁶ Hocker 2006, 39.

⁸⁷ Hocker 2006, 39.

⁸⁸ Hocker 2006, 52; When *Vasa* was under construction, Gustav Adolf planned on dividing his fleet into three squadrons. One, under the command of Admiral of the Realm Karl Karlsson Gyllenhielm, was to be sent to the Polish coast. A second, under the command of Vice Admiral Klas Fleming, was to be sent to Denmark. A third smaller squadron, commanded by Vice Admiral Eric Jonsson, was to be based at Älvsnabben in the southern archipelago to act as a reserve for deployment to which ever theater may need it. *Vasa* was assigned to the small archipelago squadron.

Europe's rulers. Warships were large, expensive, and had to remain effective under a range of possible conditions. As naval shipbuilding diverged from merchant shipbuilding, specialists were sought out by early modern maritime states, such as England, Denmark, and Sweden, to oversee design and construction of warships. As naval warfare became more decisive, warships were increasingly viewed and used as instruments of political influence.

They also became the expression of a monarch's prestige and tactical doctrine in hardware. The successes or failures of a warship had implications for the reputation and power of a ruler. Thus, shipwrights under the employ of European rulers were under immense pressure to effectively balance the multitude of requirements placed on their designs. Inexperience or too ambitious steps forward created problems, but so too did excessive conservatism.⁸⁹ States responded to different threats with different types of navies. Protection of merchant shipping required a cruiser force, while breaking blockades required a heavy battle fleet. Likewise, attacking merchant shipping required a cruiser force, whereas blockading enemy ports required a high-endurance battle fleet.⁹⁰ National policy aims dictated the strategy under which warships would operate, and these factors together determined the procurement policy (size, number, types) of warships. Thus, warship design was never a purely abstract exercise of the shipwright's skill. The designer of a vessel worked within a framework of specified constraints, including tonnage, cost, seakeeping, range, and firepower.⁹¹

⁸⁹ Glete 1993, 35.

⁹⁰ Glete 1993, 11.

⁹¹ Gardiner 1992, 116.

Knowledge and ability to design ships that responded effectively to these constraints resided within a small population of skilled shipwrights. The technical knowledge, in the form of rules-of-thumb, drawings, or models was inherited. The scarcity of skilled shipwrights turned them, and their knowledge, into national assets that could be transferred from one state to another, regardless of the personal affiliation of the shipwright. States eventually responded to this challenge through the creation of shipbuilding texts, state-owned model collections, and archives of ship drawings. The consequent systemization of warship technology ultimately separated the design and construction processes.⁹² Standardization of warship design and construction was not a concern until the middle of the 17th century. Relatively few warships were built up until this point and the rapid pace of design innovation made centralization and standardization of warship construction impractical. Although states owned shipyards, shipbuilding and design was often decentralized to different shipyards and master shipwrights. This resulted in a diversity of designs and an administrative challenge as the amount of shipbuilding activity increased. As it had happened in Spain in the first decades of the 17th century, from the middle of the 17th century on, the rate and scale of naval shipbuilding grew to the point where the creation of standard designs overseen by a bureaucratic entity became paramount. During the 18th century, standardization of state warship design and construction was typical.⁹³ In the early 17th century, however, outside of Spain naval shipbuilding was dominated by tacit knowledge held by a small number of master shipwrights and functioned in a largely decentralized system.

As part of the Swedish military reforms of the early 17th century, the state sought efficient ways to maintain shipbuilding operations. The solution was sub-contracting operation of state-owned

⁹² Glete 1993, 18.

⁹³ Glete 1993, 44.

shipyard to private entrepreneurs in the *arrende* system. In the early 17th century, the crown owned four shipyards; one in Stockholm on Skeppsholmen, and three others in the towns of Vastervik, Nyköping, and Kalmar.⁹⁴ Although royal ships were built in other shipyards, the large warships were built in these four. Under the *arrende* system, operation of shipyards was contracted to private individuals who were supplied either with raw shipbuilding materials or cash to purchase materials and expected to produce a certain quota of ships over a specified term, usually five years. The shipwrights were also paid a lump sum annually. This system streamlined the process of shipyard administration, a welcome relief to a government undergoing massive bureaucratic transformation.⁹⁵ A state official, most often a senior captain, was posted to each royal shipyard to supervise operations and serve as liaison between the private shipwright and the admiralty.⁹⁶

The first *arrenden* of the Stockholm shipyard was granted to Anton Monier in 1620 and covered the construction of new ships and maintenance of the fleet.⁹⁷ In two separate contracts, in 1621 and 1622, Dutch master shipwright Henrik Hybertsson joined Monier as a partner at the Stockholm shipyard.⁹⁸ Monier's contract was set to expire in January 1626, and negotiations for the next contract began in 1624 without Monier. The new contract with Hybertsson and his business partner Arendt de Groot included the construction of four new warships, the first of which was *Vasa*.

⁹⁴ Hocker 2006, 39.

⁹⁵ Hocker 2006, 39-40.

⁹⁶ While *Vasa* was under construction, Captain Söfring Hansson was posted to the Stockholm shipyard. He later served as *Vasa*'s captain during its maiden voyage; Hocker 2006, 40.

⁹⁷ Hocker 2006, 40-41.

⁹⁸ Hocker 2006, 41.

Despite his pivotal role in the construction of *Vasa* and eminence as a royal shipbuilder, little is known about Henrik Hybertsson. He was born in the Netherlands and records indicate that at various times lived in Rijswijk in the south and Amsterdam in the north.⁹⁹ In the early 1600s, Hybertsson moved to Sweden where he was commonly referred to as Master Henrik.¹⁰⁰ During his tenure in Sweden, Hybertsson maintained his professional contacts in the Netherlands and recruited shipwrights from there. He worked in the royal shipyard at Kalmar for several years during which time he built several large warships, *Maria*, *Gustavus*, *Tre Kronor*, and *Mercurius*. By the time he entered into the Stockholm shipyard contract, he was likely one of the most experienced shipwrights in Sweden.¹⁰¹ In 1609, Hybertsson purchased a flat in the Gamla Stan neighborhood of Stockholm, though he appears to have been still working in the Kalmar shipyard.¹⁰² Hybertsson eventually moved to Stockholm, where he was granted a property near the Stockholm shipyard in 1612.¹⁰³ In 1621, Master Henrik joined the contract held by Anton Monier for operation of the Stockholm shipyard. Along with his partner Arendt de Groot, Hybertsson signed a new contract in January of 1625 that was scheduled to take effect in January 1626.

Hybertsson was likely concerned primarily with organizational and administrative matters of the shipyard and left most practical construction matters to two other shipwrights in his employ, Henrik Jacobsson and Johan Isbrandsson (both Dutch).¹⁰⁴ According to Jacobsson's testimony

⁹⁹ Hocker 2011, 36.

¹⁰⁰ Henrik's surname was likely originally Hubertszoon; Hocker 2006, 41.

¹⁰¹ Hocker 2006, 41.

¹⁰² The Stockholm *tankebocker* (public record) that documents this purchase refers to Hybertsson as 'his Majesties Master of Shipbuilding.' This property was later sold in 1624.

¹⁰³ After his death, the property was sold to Admiral Klas Fleming by Hybertsson's wife, Margareta Nilsson.

¹⁰⁴ Hocker 2006, 41.

after *Vasa* sank and the contract negotiation correspondence, however, Hybertsson was responsible for establishing *Vasa*'s basic dimensions and form.¹⁰⁵ Master Henrik's health began to deteriorate in 1625. In the summer of 1626, he handed practical responsibility for the operation of the shipyard to his chief assistant Henrik Jacobsson who would oversee the completion of *Vasa*. Hybertsson was bedridden by the end of 1626 and died in the late spring of 1627. Due to Master Henrik's deteriorating health, Arendt de Groot had taken over effective administrative duties in the shipyard in 1626. Upon his death, Henrik's wife Margareta Nilsson took over legal responsibility for the fulfilment of the contract and management of the shipyard. Later, Arendt de Groot and *Vasa* captain Söfring Hansson took over official managerial responsibility in the spring of 1628. In 1629, the crown cancelled all *arrende* contracts and resumed direct administrative control over state shipyards. In this new system, Henrik Jacobsson was appointed master shipwright of the Stockholm shipyard.¹⁰⁶

Like his predecessor, Henrik Hybertsson, Henrik Jacobsson was born in the Netherlands. He came to Sweden in 1620 and worked initially in the royal shipyard at Kalmar, though was quickly recruited to work at the Stockholm yard.¹⁰⁷ After completing the construction of *Vasa*, Jacobsson went on to become the leading naval shipwright in Sweden, building three very successful warships; *Applet*, *Kronan*, and *Scepter*.¹⁰⁸ By 1635, Jacobsson was living on a property in Stockholm with *Vasa* captain Söfring Hansson and other ship carpenters. Jacobsson had two sons, Evert and Jacob. Evert would succeed his father as master shipwright in the

¹⁰⁵ Hocker 2006, 41.

¹⁰⁶ Hocker 2011, 140.

¹⁰⁷ Madebrink 2012, 20.

¹⁰⁸ Madebrink 2012, 6.

Stockholm shipyard.¹⁰⁹ A 1634 Stockholm register lists 35 Dutch shipbuilders on Skeppsholmen, but only 3 in 1638. A significant reorganization of royal shipbuilding operations occurred in the early 1630s, which greatly reduced the shipwright's administrative role in operating the shipyards. Likely as a result, Dutch shipbuilders left Sweden to find more profitable work elsewhere. Jacobsson was among these, and moved back to the Netherlands in 1638 either to continue his career as a shipwright or to retire.¹¹⁰

Vasa was designed and built by two Dutch shipwrights who employed a unique method of ship construction. In the early 17th century, at least two distinct methods of Dutch naval architecture were in widespread use; one in the north of the country and one in the south. Although they differed from one another in some key areas, both methods are characterized by a lack of graphic plans or written documentation of the design process. There is substantial evidence in the hull of *Vasa* to suggest that it was designed and constructed according to the northern Dutch shipbuilding method. This evidence and the Dutch shipbuilding traditions as they are currently understood are discussed in the following chapter.

¹⁰⁹ Hocker 2006, 42.

¹¹⁰ Madebrink 2012, 22.

CHAPTER III
EARLY MODERN DUTCH NAVAL ARCHITECTURE

INTRODUCTION

The 17th century is regarded by many to be the Dutch Golden Age. The economic prosperity of the newly independent Dutch Republic made it, for a time, the richest country in the world.¹ Domination of both intra-European and overseas maritime trade was largely responsible for this accomplishment. The quality and economy of Dutch vessels was praised throughout Europe and the heads of state of major European powers sought to incorporate Dutch vessels into their merchant and naval fleets.² The Dutch designed and built their vessels in a unique way, however, when compared with other European shipbuilding nations. The Dutch employed a form of bottom-based construction, which distinguished Dutch shipbuilding among European shipbuilding nations that favored forms of frame-based construction for large vessels.³ The Dutch were further distinguished from many other shipbuilding nations in that they did not use paper plans to design their vessels. This chapter examines the current understanding of early modern Dutch methods of naval architecture and emphasizes the relationship between the well-understood construction process and the more abstract design process. Furthermore, it positions *Vasa* within these shipbuilding traditions and contextualizes Dutch naval architecture within the evolution of European shipbuilding during the 17th century.

¹ Scammel 1981, 373.

² Hoving 1988, 211.

³ Hocker 2004, 82-83.

CONSTRUCTION AND DESIGN

Central to this chapter is a description of the relationship between the construction process and the design process in Dutch shipbuilding. The interaction of these two processes led to what can be called a shipbuilding tradition – a characteristic watercraft production method. An examination of these processes begins with their definitions. In this dissertation, ship construction is defined as the sequence and manner of physically manufacturing and assembling the parts of a ship. Within nautical archaeology, description of the ship construction process aims to identify the constituent parts of a vessel, their characteristics, and the method and order of their assembly. Even if only fragmentary remains exist it is usually possible to recover all or part of the construction process based on the analysis of timber conversion, tool marks, fasteners and fastening pattern, context, and other features.

The ship design process is the intent that guided construction. Here, the design process is defined as the application of a system of rules, logic, and decisions to determine the size, shape, and arrangement of a ship and its constituent parts. The form and expression of this system varies over time and space, though unless the construction of a vessel was a complete accident, design is intrinsic to all watercraft. The design process is the theoretical underpinning for the practical construction process whose physical evidence makes up the archaeological record. In recovering the design process, tangible remains of a vessel are used to reconstruct an intangible system that existed in the minds of shipwrights. Put another way, the construction and design processes are related in the sense that construction is *how* a vessel got to be the way it is and design is *why* the vessel is that way.

An example outside of shipbuilding clarifies this relationship. Take for example the builder and engineer of a modern kitchen table produced by a well-known Swedish furniture company that requires home assembly. In this case, the end consumer is the builder of the table and the construction process is explicitly contained in the instruction booklet that explains how to assemble the table at home. If the table had to be disassembled and reassembled, and the instructions had been lost, the construction process could likely be recovered on the basis of basic knowledge of table structure and furniture building. Conversely, if the table were recovered in an archaeological context, deconstruction and reconstruction of the table may yield insight into basic 21st-century table structure and furniture building methods. In this example, however, the design process behind the finished form and structure of the table is not made apparent to the builder. The engineer of the table applied logic to the design that took into account a variety of factors including weight, strength, taste, utility, and cost of materials – the same factors concerning shipwrights. Although this design process is not made evident to the consumer (builder) of the table, most or all of the underlying design principles are recoverable through careful analysis of the completed structure; this is the same fundamental approach to the practice of reverse engineering. Through analysis, proportional relationships may emerge, for instance, between the height, length, and width of the table. If one were sufficiently interested, a comprehensive explanation of the logic in the design process of the table could be reconstructed. In this case, the reconstructed design process could be checked against the actual design process as recorded by the engineer. No comparable record exists, however, for 17th century Dutch ships.

Things are further complicated in the Dutch shipbuilding tradition as the engineer and builder were effectively the same person. In the 17th century, the master shipwright was responsible for

both design and construction, aided by ship carpenters who worked according to the shipwright's directions. Seminal scholar A.J. Hoving summarizes this phenomenon, explaining "there was no distinction between design and execution. The ship was not designed on the drawing board but was shaped during the building process, not on the basis of an engineer's calculations but through the master shipbuilder's active engagement in the building process on the yard."⁴ Furthermore, Dutch shipwrights operated according to an improvised and oral tradition. The creation of a Dutch vessel began as a contract that defined the basic dimensions of the ship according to their patron's requests. The shipwright then improvised the design of the vessel during the construction process. It is important to note that in this case improvised does not mean accidental or unprepared. Rather, in this context design improvisation means flexibility guided by a set of rules. Dutch shipwrights designed and built their vessels by eye, according to rules of thumb and informed by experience and judgment. Nicolaes Witsen, author of one of two known 17th-century Dutch shipbuilding treatises writes, "Circumstance, and different practices, change the build and shape of ships."⁵ Although successful design features were replicated in subsequent vessels, Dutch shipwrights were continually required to improvise their designs due to variable circumstances such as patron requests and the availability of shipbuilding materials.

This dissertation reconstructs the design process used by the master shipwrights to build the Dutch designed and built Swedish warship *Vasa*. Since no written plans for the construction of

⁴ Hoving 2012, 9.

⁵ Hoving 2012, 35; '*Omstandigheden, en onderscheidelijke gebruiken, veranderen den bouw en vorm der schepen*' Witsen 1671, 262. All translations of Witsen's text come from Hoving 2012 and are cross referenced with the original text. All original language citations come from the 1671 version of the treatise.

Vasa exist, the design process is recovered solely from the physical remains of the vessel, which are estimated to be 98% complete.⁶ Because of the close relationship between the construction and design processes in the Dutch shipbuilding tradition, an overview of current understanding of 17th-century ship construction methods creates a framework in which to identify and extract the key design decisions facing the shipwright.

ORIGINS OF THE DUTCH SHIPBUILDING TRADITION

Currently, the Dutch are thought to be unique in the use of a bottom-based construction method to produce large seagoing vessels in early-modern Europe.⁷ This appears to be an approach shipbuilding that developed as frame-based carvel construction methods were introduced to the Netherlands in the 15th century C.E., where lapstrake shell-based construction predominated.⁸ The result was not a complete replacement of shipbuilding methods, but rather a hybrid method that adopted characteristics of both frame-based and shell-based construction. This hybrid construction method has been termed ‘bottom-based’ due to the important role the bottom planks have in determining the overall shape and character of the completed vessel.⁹ Variations on this method characterized Dutch shipbuilding until the early decades of the 18th century, when frame-based methods became dominant.¹⁰

⁶ Hocker 2006, 17.

⁷ Hoving 1995, 34; Hocker 2004, 82-83; Hoving 1995, 35.

⁸ Hocker 2004, 80; Probst 1994, 143.

⁹ Hocker 1991, 21-22.

¹⁰ Hoving 2006, 105.

Two distinct approaches to shipbuilding existed simultaneously in the Netherlands during the 17th century. The northern method of the *Zaankant* (centered in Amsterdam) typified bottom-based construction. The southern method of the *Maaskant* (centered in Rotterdam), however, emphasized the importance of frames in determining the overall shape of the vessel and is best characterized as early frame-based Dutch construction.¹¹ Although the northern method appears to be older, as indicated by literary and archaeological records, there is no evidence suggesting that one method derived from the other. Both were in use as early as the 1620s and possibly earlier.¹² While there are shared features between the two methods, the most significant similarity is the lack of design on paper, resulting in an unclear modern understanding of the principles that guided design. The northern bottom-based method has attracted the most interest from modern researchers, and is the only 17th-century Dutch method currently identified in the archaeological record. Construction features found in the hull of *Vasa* firmly situate it within this northern tradition. Both methods are described in this chapter.

HISTORICAL SOURCES

Two treatises pertaining to 17th-century Dutch shipbuilding exist, both dating to the second half of the century. Each describes a different shipbuilding method, and consequently each forms the theoretical basis for understanding the two contemporary Dutch traditions. The older of the treatises, which describes the northern method, is authored by an Amsterdam diplomat named Nicolaes Witsen, dates to 1671 and is titled '*Aeloude en Hedendaegse Scheepsbouw en Bestier*' (Ancient and Modern Shipbuilding and Management). In this lengthy work of 574 pages and

¹¹ Hoving 1995, 36.

¹² Hoving 2012, 11.

114 engravings, Witsen endeavors to provide a history of shipbuilding from antiquity to the 17th century. Though the discussion of ancient shipbuilding is largely derivative of other known works, the discussion of early-modern Dutch shipbuilding appears to be original.¹³ Witsen was not a shipbuilder himself but the son of a wealthy merchant, Cornelis Witsen, who had extensive ties to seafaring and shipping. Nicolaes Witsen had a keen interest in shipbuilding and the technical discussions of modern shipbuilding in his treatise are derived from notes passed on by his father, interviews with shipwrights, and shipyard observations.¹⁴ In the course of 4 chapters, Witsen describes the dimensions of constituent parts and method of assembly of a 134-foot armed merchantman, a vessel type known as a *pinas*. The treatise describes the Dutch construction methods in use ca. 1630-1670.¹⁵ Witsen offers a detailed description of the construction process for northern Dutch vessels, but is exceptionally vague when describing the design process, stating simply, “The outward shape of the ship is made with the eye and approval of the master.”¹⁶ Witsen also emphasizes the ambiguous nature of Dutch shipbuilding and cautions his readers to not take his word as law, pointing out, “It is not my intention that one should observe these proportions exactly to absurd precision: think of it as a guideline, from which one is not to diverge too far, and an assurance against awful blunders as long as one follows the rules.”¹⁷ The treatise contains a wealth of valuable information, though the work is written in a chaotic style that makes its interpretation challenging. Despite this, Witsen’s treatise

¹³ Wildeman 2012, 240.

¹⁴ Wildeman 2012, 238-239.

¹⁵ Hoving 1995, 34.

¹⁶ Hoving 2012, 9; ‘*Het uiterlijck beloop der schepen wort onderscheidelijck gemarkt, na het oog en goetkeuren van den meester.*’ Witsen 1671, 265.

¹⁷ Hoving 2012, 9; ‘*Geenzins is mijn meining mede, dat men juist, en op een draet, dees gegevene evenmaet waernemen moet: het diene slechts tot een spoor, om niet te verre afgedwalen, en verzekering, dat zoo men deze wetten volgt, men in het scheeps-bouwen geen zware midgreep zel te vrezen hebben.*’ Witsen 1671, 262.

is the only literary sources dedicated to describing the Dutch bottom-based construction method and forms the basis for understanding the northern method of shipbuilding.¹⁸

The second historical work dealing with Dutch shipbuilding is Delfshaven shipwright Cornelis van Yk's 1697 *'De Nederlandse Scheepsbouwkonst Opengesteld'* (Dutch Shipbuilding Unveiled). Van Yk's work is much more organized than Witsen's and describes the southern Dutch method of construction. Although van Yk was a shipwright, his treatise is less detailed than Witsen's. This has been attributed to the implied or assumed insider knowledge van Yk expected of his readers.¹⁹ Witsen makes no mention of another style of modern shipbuilding, though van Yk acknowledges that two Dutch traditions existed simultaneously. It is clear that van Yk had access to Witsen's treatise and copied several tables from it.²⁰ Van Yk's treatise provides valuable insight into the framed-based method of construction that eventually dominated Dutch shipbuilding in the 18th century.

CONTRACTS AND SPECIFICATIONS

Although the Dutch did not pre-design their vessels on paper, a certain amount of planning did occur before construction. Regardless of whether the vessel to be built was a privately owned merchantman or a state commissioned naval vessel, most ships began as a short written contract.²¹ This contract, called a *bestek* (plural *bestekken*), was both a binding legal document

¹⁸ An annotated English translation of the chapters pertaining to shipbuilding has recently been published by A.J. Hoving, Dutch shipbuilding specialist and former curator of ship models at the Rijksmuseum in Amsterdam: Hoving 2012.

¹⁹ Hoving 2012, 4.

²⁰ Wildeman 2012, 244.

²¹ Hoving 1995, 36.

as well as a list of specifications for the finished product.²² Depending on the size, type, and intended use of the vessel desired by the client, the shipwright employed a set of formulas, basic rules, and intuition to calculate the general dimensions of the hull. Witsen provides many examples of these contracts, which he borrowed from an Amsterdam shipwright. For example, a contract for a ship named *Swol* reads:

A ship named *Swol*, June 20th, 1628. 115 feet long, 27 feet wide, 12 feet deep at the deck, 6 ½ feet high in the sides, the stem 18 ½ high in the square, the sternpost 21 ¼ feet high in the square, the tuck 11 feet above the keel, the wing transom is 16 feet long.

*Een Schip genaemt Swol, Anno 1628 den 20 Juunji. Langh 115 voet, wijt 27 voet, hol op zijn uitwaeteren 12 voet, het bovennet hoogh aen boort 6 voet ½, de voorstevan hoogh in de winckel 18 voeten ½, de achter-stevan hoogh in de winckel 21 voet en ¼, de speigel hoogh van de kiel 11 voet, het hek is lang 16 voet.*²³

Witsen's sample contracts vary greatly in detail. Some provide only the length, width, and depth of a ship while others specify the scantlings of many of the primary timbers – some go so far as to specify the size of the figurehead.²⁴ Witsen does not specify whether the contracts he provides were drawn up in their entirety prior to construction or they are effectively the shipwright's notes on particularly successful ships recorded during or after construction. The contracts provided a starting point for shipwrights and ensured that their clients received a vessel to suit their needs and budget. The specifications, however, were only a framework. Throughout the duration of construction, the experience and judgment of the shipwright was needed to fill in the spaces left in the contract and make decisions that would affect the character of the finished vessel. It is known that shipwrights deviated from the specifications in contracts, and the northern Dutch

²² Hoving 1988, 212.

²³ Witsen 1671, 106.

²⁴ Witsen 1671, 110.

method of construction allowed for flexibility and interpretation.²⁵ For example, the contract specifying the principal dimensions of *Vasa* was negotiated between the initial shipwright Henrik Hybertsson and King Gustav II Adolf, however the final dimensions of the ship vary significantly from what was agreed upon.²⁶ Reasons for deviating from a contract range from personal preference to the availability and cost of shipbuilding materials. Generally, however, the contract specifications were interpreted through a series of rules and proportions developed from experience and passed on orally from one generation of shipwrights to the next.²⁷ One example of a set of these rules is used by Witsen to determine the scantlings of the *pinas* described in his treatise, though Witsen is careful to caution against interpreting his rules too rigidly.

Shipwrights were expected to be able to modify designs in order to fit the needs of their clients and apply shipbuilding principles that produced the best seakeeping qualities. Because of the highly adaptive nature of shipbuilding, shipwrights kept copies of *bestekken* for successful ships, and used these as reference when faced with a similar request in the future. It is likely that, whenever possible, shipwrights and clients would simply agree to copy the design of a vessel that proved to be a successful, perhaps with slight modification.²⁸ While this design process seems relatively straightforward, a lack of substantial documentation and explanation of the rules that guided the hand of the shipwright leave many questions unanswered. The basic steps in the construction of both northern and southern Dutch vessels are described below.

²⁵ Van Duivenvoorde 2008, 34-35.

²⁶ Hocker 2006, 44.

²⁷ Van Duivenvoorde 2008, 35.

²⁸ Hoving 1995, 36.

CONSTRUCTION PROCESS – THE NORTHERN METHOD

The first step was assembly of the keel, stem, sternpost, transoms, fashion pieces, and stern timbers (collectively called the spine), supported by stocks and shoring poles.²⁹ The dimensions and shape of these elements may have been specified in the *bestek*, while others were left to the judgment of the shipwright. Collectively these spine timbers defined the overall size of the vessel. After the spine was erected the garboard strakes were attached, supported by chocks spanning the keel. This completed the first stage of construction, illustrated in Figure 3.1.

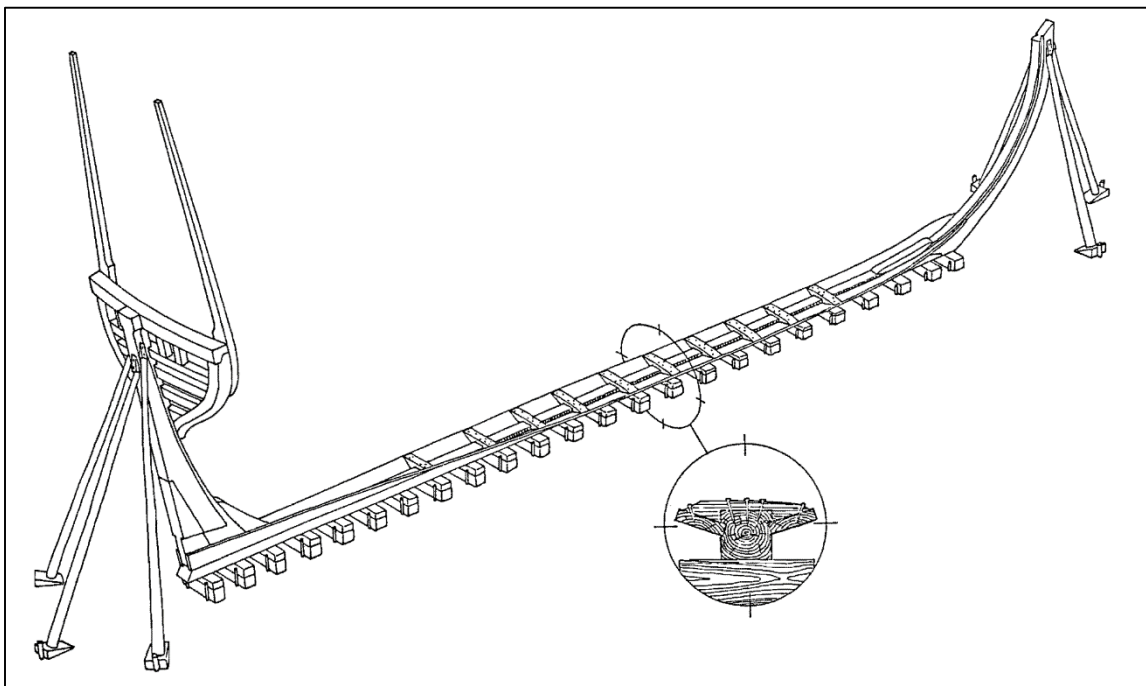


Figure 3.1. First stage of construction: spine and garboard strakes. Drawing by Anton van den Heuvel.³⁰

²⁹ Hoving 1991, 78.

³⁰ Hoving and Parthesius 1991, 5.

Next, additional strakes were added. These were fitted edge to edge and kept in place by temporary cleats that spanned two adjacent planks and were nailed into place to ensure a tight fit.³¹ This is the most characteristic feature of the Northern Dutch method of construction. The shape of the planks at this stage significantly affected the overall shape of the hull and two methods were used to finely control the curvature of this bottom part of the vessel. To ensure a tight fit between planks, a device called a *hel* was used. The *hel* consisted of a hook, chain, and pole that forced the planks together before cleating, to ensure a near water-tight fit between strakes.³² Another device, a clamp-like tool called *boeitangen*, was used to prevent planks from springing free while they were fitted into the hull.³³ Instead of bending the strakes around pre-erected frames, the *hel* and *boeitangen* were used in combination to pull and twist the strakes into the desired shape. This interaction is shown in Figure 3.2. One *boeitangen* was found on board *Vasa* and a replica on display in the Vasa Museum demonstrates how this tool was used. This display is shown in Figure 3.3. Adjustment of the shoring poles supporting the planking from below could also be used to control the shape of the hull. With no rigid internal structure to guide the form of the hull at this point, it was up to the master shipwright to control the developing shape of the vessel by eye. Planks were added until the bottom of the vessel was complete (usually about two-thirds of the total intended breadth) and the shipwright was satisfied with its shape. Though early in the construction process, the shape of the bottom of the vessel was important in determining the overall shape of the hull. This stage of the construction (including the use of *boeitangen* and cleats) is seen in Figure 3.4.

³¹ Van Duivenvoorde 2008, 48.

³² Van Duivenvoorde 2008, 48.

³³ Hoving 2008, 24.

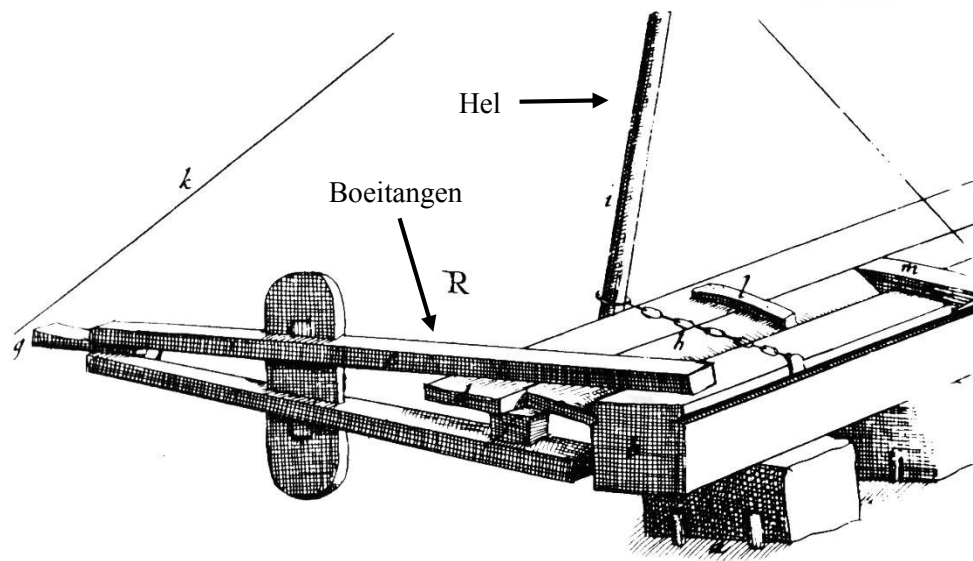


Figure 3.2. The use of the *hel* and *boeitangen* in the construction and shaping of the bottom planking (after Witsen).³⁴



Figure 3.3. Replica of *boeitangen* found on board *Vasa*. Photograph by Kelby Rose.

³⁴ Witsen 1671, 147.

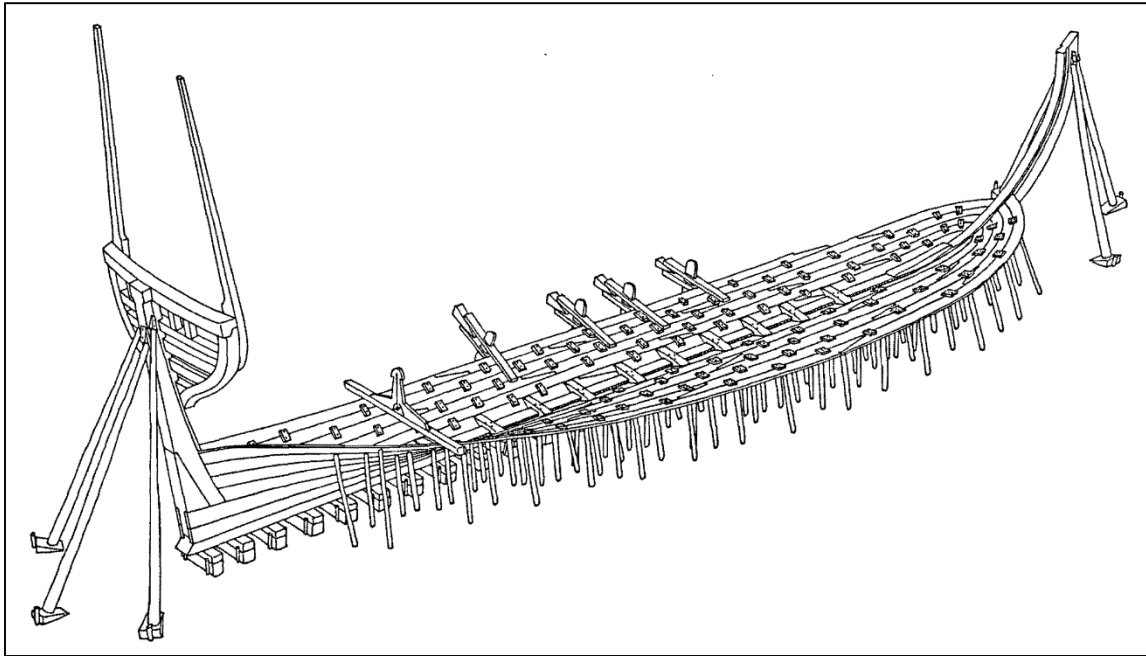


Figure 3.4, Planking continues, using *boeitangen* to guide the shape of the hull. Drawing by Anton van den Heuvel.³⁵

The use of cleats to temporarily fasten planks edge to edge is characteristic of the northern Dutch shipbuilding method and leaves evidence in the archaeological record. Once the cleats were removed, immediately preceding the installation of framing timbers, the nail holes left by these temporary cleats were plugged with small wooden pegs known as *spijkerpennen* (singular *spijkerpen*). These plugs are clearly visible on the inner surface of bottom planking in every archaeologically represented early-modern Dutch vessel where lower planking is preserved. Planks were removed from *Vasa* to test for the presence of *spijkerpennen*. Numerous *spijkerpennen* were discovered and appear as pictured in Figure 3.5.

³⁵ Hoving and Parthesius 1991, 6.



Figure 3.5. *Spijkerpen* as observed on the inner face of one of *Vasa*'s removed planks. Photograph by Kelby Rose.

Once the bottom of the vessel was complete, a single master frame (composed of one floor and two futtocks) was inserted into the empty shell of planking at a location known as the *hals*, located one third of the ship's overall length from the forward edge of the stem.³⁶ Currently, it is unknown how this master frame was designed. The shape of the floor timber was dependent on the angle of deadrise in the bottom planking; however the shape of the futtocks may have been derived from molds.³⁷ Planking continued around the turn of the bilge using the single frame at

³⁶ Van Duivenvoorde 2008, 48.

³⁷ Hoving 2012, 69.

the *hals* to guide the shape of the vessel. Cleats were still used to fasten the planks edge to edge. This stage is seen in Figure 3.6.

Once the bilge of the vessel was planked, the cleats holding the planks together were removed while simultaneously filling the open shell with closely spaced floors and first futtocks. The holes left by the cleat nails were plugged with *spijkerpennen*. The shapes of these framing timbers were dictated by the curvature of the planking shell and roughhewn to shape. Framing timbers were installed quickly with a minimum of effort, which cut down on the cost and construction time of a vessel. This meant that it was not uncommon for gaps between the planking and framing timbers to exist, which were filled with chocks as necessary to ensure maximum contact between the internal framing and external planking of the vessel. Dimensions for Dutch framing timbers are typically consistent in their molded dimension but may vary considerably in their sided dimension – attesting to the Dutch tendency to make best use of whatever timber was available rather than select only choice framing timbers. For a given vessel, the number of floors and futtocks necessary to complete construction was not predetermined, but instead timber was simply added until the shell of planking was filled. Once an acceptable fit between the hull planking and framing timbers was achieved, treenails were used to fasten the planking to the framing, often rather haphazardly. Many of these Dutch framing characteristics are easily identifiable in the archaeological record and Figure 3.7 depicts several as observed in the hull of *Vasa*.

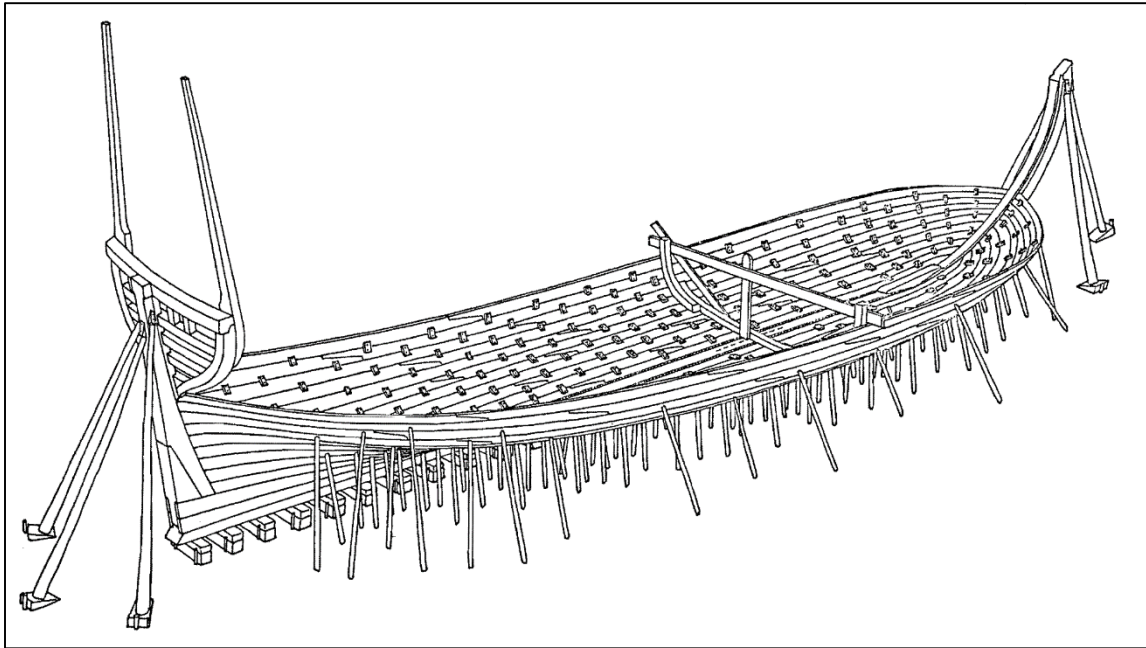


Figure 3.6. The single master frame is installed in the *hals* and planking continues around the turn of the bilge.
Drawing by Anton van den Heuvel.³⁸

In northern Dutch shipbuilding, framing timbers were not fastened to one another – only to the planking. Thus, in this tradition the frames support the shape of the hull, though they are not conceptually the same structures found in frame-based vessels.³⁹ At this stage of construction, framing timbers did not determine the shape of planking, instead the opposite was true.

Investigation with a flexible borescope at several points in the hull found no evidence of fastening between framing timbers in *Vasa*. After the floors and first futtocks were inserted and treenailed to the planking, second futtocks were inserted intermittently along the length of the vessel and fastened to the planking.⁴⁰ A master ribband, called a *scheerstrook*, was then fastened to the tops of these second futtocks.⁴¹ The shape and position of this flexible timber was

³⁸ Hoving and Parthesius 1991, 7.

³⁹ Hoving 2008, 25.

⁴⁰ Van Duivenvoorde 2008, 48.

⁴¹ Hoving 2008, 25.

adjusted according to the eye and judgment of the shipwright. The final position of the *scheerstrook* generally corresponded to the lowest wale or the edge of the main deck in the completed vessel. Its shape and position defined the height of the main deck, the sheer of the vessel, and the height of maximum breadth throughout the length of the hull.⁴² The position of the *scheerstrook* on the second futtock was generally only specified for the frame station at the *hals*, if at all. An illustration of the vessel at this point in the construction is shown in Figure 3.8.



Figure 3.7. Photograph taken in between two of *Vasa*'s floor timbers. The *tingel* (a wedge-shaped timber filling in the space between the garboard and the keel) and chocks can clearly be seen – filling in space left by roughhewn floor timbers. Also visible is the unfinished surface of the floor timber on the right and a carelessly placed treenail. Photograph by Kelby Rose.

⁴² Van Duivenvoorde 2008, 52.

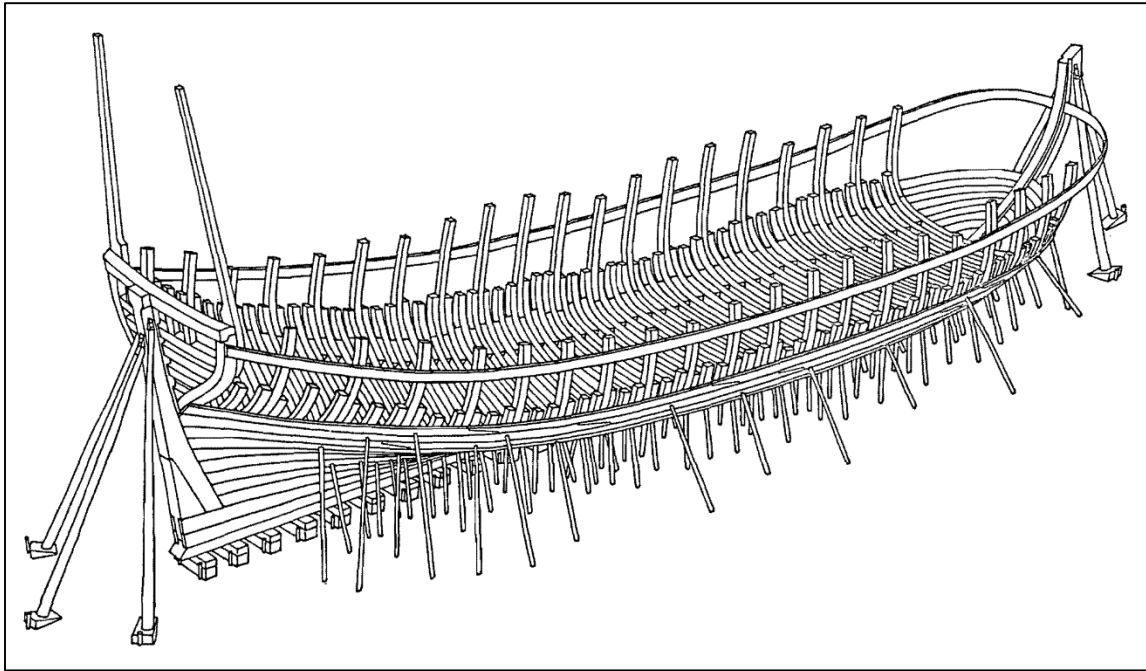


Figure 3.8. The shell is filled with floors and first futtocks. Some second futtocks are installed and the *scheerstrook* is attached to their tops, defining the height of the main deck, the sheer, and height of maximum breadth of the vessel.
Drawing by Anton van den Heuvel.⁴³

Once the *scheerstrook* was fixed in position, the rest of the second futtocks were installed. In most vessels, the majority of these futtocks were the same shape, only slightly modified as needed to achieve desired hull contour.⁴⁴ Intermittent deck beams were then installed, providing ship carpenters a stable platform from which to work on the upper parts of the hull.⁴⁵

Simultaneously, the ceiling planking was installed. After the exterior of the vessel was planked up to the height of the *scheerstrook*, top timbers were installed, followed by the rest of the hull planking. This completed the construction of the overall size and shape of the hull and the vessel

⁴³ Hoving and Parthesius 1991, 8.

⁴⁴ Hoving 2012, 69.

⁴⁵ Van Duivenvoorde 2008, 52.

was launched at this point. Assembly of the upper works occurred while the hull was in the water and was not particularly distinct from well-known methods employed throughout Europe.

From this construction sequence, a number of key decisions on the part of the shipwright can be identified. The first major decision the shipwright made was the breadth and depth of the vessel with in proportion to its length. The overall length of a vessel appears to be the primary characteristic negotiated between the shipwright and his patron. From this measurement, and depending on the intended purpose of the vessel, the shipwright then applied his best judgment to determine the breadth and depth, based on knowledge of how the relationship of these three dimensions interacted to influence the finished character of the ship. In describing his decisions for the design of the *pinas* in his treatise, Witsen writes:

“The ship which is built here in our mind is neither the widest, nor the narrowest; which measure is taken with premeditation, to show a man-of-war as well as a merchantman. Those sailing for freight only, and cannot defend themselves, are narrower above and broader below: those going to war only, are broader at the top and narrower at the bottom.”⁴⁶

Based on the length, breadth, and depth of the vessel, the shipwright set about making a number of other principal decisions that significantly affected the qualities of the finished hull. These include the height and rake of the stem and sternpost, the width of the conceptual bottom of the vessel and its deadrise, the width, height, and shape of the bilge planking, the height and width of the wing transom, the shape of the fashion pieces and stern timbers, the curvature of the first and second futtocks, the shape of the *scheerstrook*, and the arrangement of decks. At present, it

⁴⁶ Hoving 2012, 14; ‘*Het schip hier in gedachten gebout, is noch van de wijtste, noch ook van de naeuwste; welke maet voordacht is genomen, om zoo wel oorlog, als een koopvaerdy-schip te vertoonen. Die alleen op vracht varen, en zich niet denken te verweeren, zijn boven naeuwer, en onder wijder: die alleen ten krijge gaen, zijn boven wijder, en onder nauewer.*’ Witsen 1671, 263.

is not completely clear how these decisions were made. Witsen provides one example in his treatise, but firmly states that it is only one of many possible solutions employed by Dutch shipwrights. The investigation in this dissertation recovers these decisions as they were made to define the hull of *Vasa*, the only intact 17th-century Dutch-built ship.

CONSTRUCTION PROCESS – THE SOUTHERN METHOD

To date, no vessels have been archaeologically excavated that are conclusively attributed to the southern Dutch shipbuilding method. Current understanding of this shipbuilding method is derived from van Yk's treatise and supplemented by limited iconographic evidence. Further insight into this method has been gained indirectly through its similarities to other well-documented contemporary frame-based European shipbuilding traditions. Like the northern method, the southern Dutch shipbuilding method began with the erection of the keel, stem, sternpost, transoms, and fashion pieces supported by stocks and shoring poles. The garboard was also fitted, but this ended the similarities between the two methods.⁴⁷ At this point in construction, two identical pre-assembled frames consisting of one floor, two first futtocks, two second futtocks, and two top timbers each were erected on the keel. The forward frame was placed at a distance from the front of the stem equal to the sum of one half the length of the hull and one half the length of the stem.⁴⁸ The after frame was placed abaft the forward frame at a distance of one quarter of the distance from forward frame to the front of the stem. These two identical frames defined the widest part of the vessel and the shape of the hull did not change between them. This stage of construction is shown in Figure 3.9. Although frames play an

⁴⁷ Hoving 2012, 11.

⁴⁸ Van Duivenvoorde 2008, 54.

important role in the southern method of construction, the sole 17th-century author on the subject, Cornelis van Yk, does not specify how they were designed, only that “I have never found that our shipbuilders have any secure, or fixed rules regarding the shaping of these frames.”⁴⁹ Their form likely depended on the eye and judgment of the shipwright.

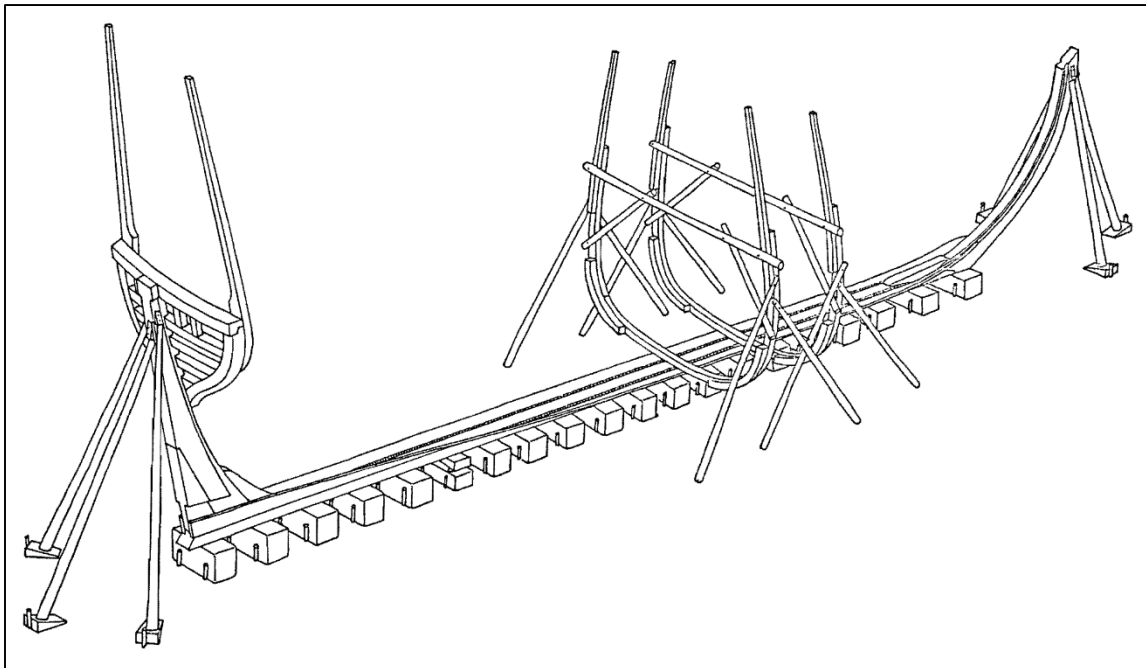


Figure 3.9. Spine and first two master frames erected. Drawing by Anton van den Heuvel.⁵⁰

After the two identical frames were erected, a series of poles were driven into the ground surrounding the hull. These poles were arranged so that they defined the maximum breadth of the ship if viewed from above. A master ribband or *scheerstrook* was attached to these poles and the two initial frames on the keel, and adjusted according to the shape desired by the shipwright.

⁴⁹ Hoving 2012, 18; ‘Noit heb ik konnen merken dat onse Bouwmeesters eenige gewisse, of vastgaande Regulen ontrent het formeeren dezer Spanten hadde.’ Van Yk 1697, 76.

⁵⁰ Hoving and Parthesius 1991, 9.

Like in the northern method, this master ribband defined the height of breadth along the entire length of the vessel and significantly affected the character of the completed ship; its final position was approximately the same as the lower wale or edge of the main deck. Once the position of the *scheerstrook* was fixed, a third pre-erected frame was installed on the scarf between the stem and keel. A fourth frame was installed the same distance from the sternpost that the previous frame sat from the stem.⁵¹ The third and fourth frames determined the longitudinal rising and narrowing of the vessel and their positions at the ends of the hull significantly influenced the hydrodynamic characteristics of the ship; their shape was derived from the shape of the two original frames, according to the tastes of the shipwright.⁵² The relationship between the shape of the spine, the four frames, and the *scheerstrook* defined the majority of the hull shape. This stage of construction is shown in Figure 3.10. Although the primary hull form of southern-built vessels was defined by relatively few elements, van Yk provides little indication about how these were designed.

⁵¹ Hoving 1991, 79.

⁵² Hoving 1995, 36.

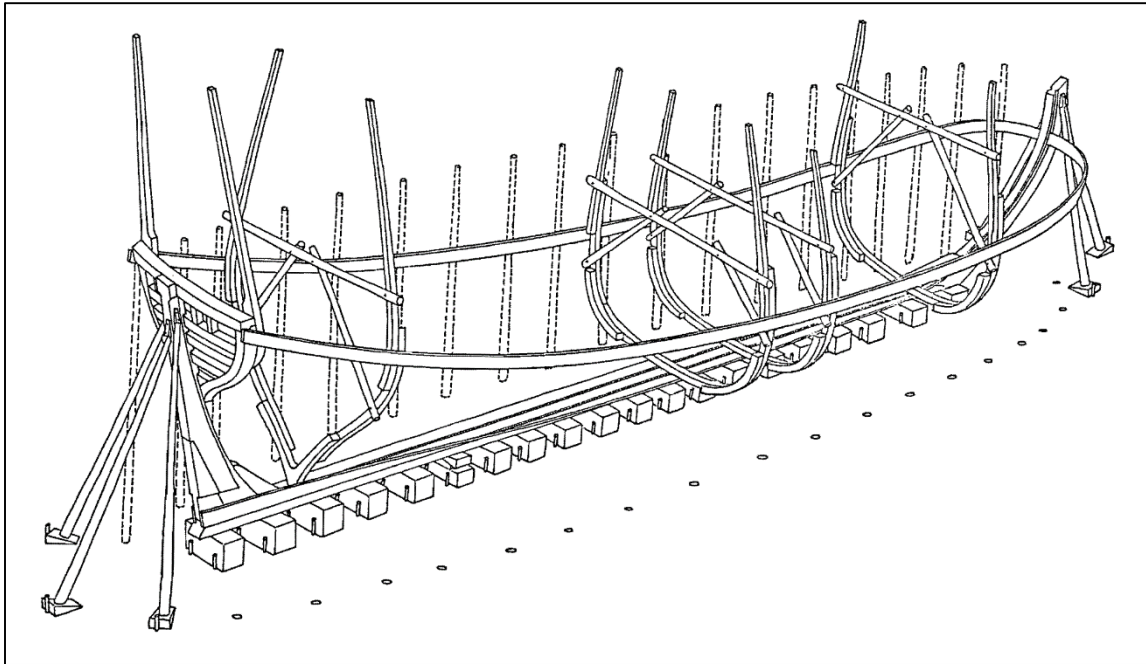


Figure 3.10. All four master frames and *scheerstrook* assembled (Drawing by Anton van den Heuvel).⁵³

Next, the space between the garboard and the *scheerstrook* was filled with a series of thin battens. These battens allowed for further fine-tuning of the shape of the ship and aided in defining the curvature of the lower hull planks.⁵⁴ This stage is shown in Figure 3.11. This basket of battens also served as a guide for cutting the remaining framing timbers which were installed, followed by the beams, and the external planking. Once the hull was sufficiently planked the vessel was launched and finished in the water.

⁵³ Hoving and Parthesius 1991, 10.

⁵⁴ Van Duivenvoorde 2008, 56.

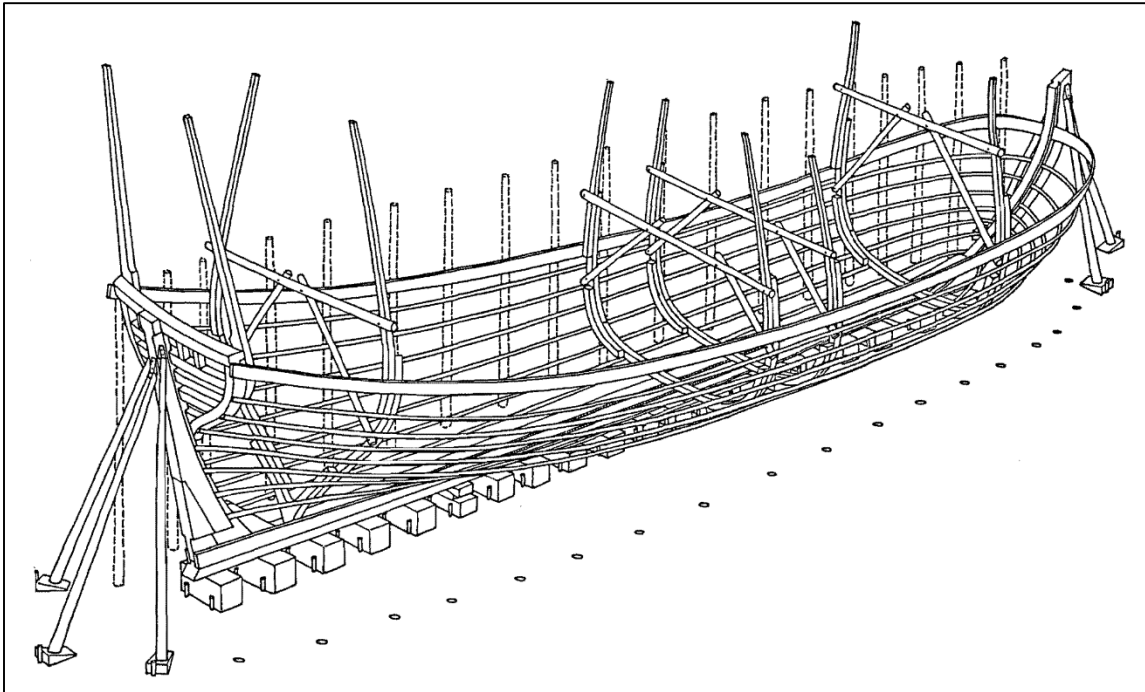


Figure 3.11. The basket of ribbands is ready to be filled with additional framing timbers (Drawing by Anton van den Heuvel).⁵⁵

Like the northern method, the overview of the southern construction method highlights areas in which the design intent of the shipwright is most clearly expressed. Many of these areas are the same for the two methods, but the southern has the added complication of the four control frames. It is clear that these frames were the product of an intentional design process, though at present the details of this process are unknown. Van Yk's treatise provides little insight and no archaeological examples of vessel built according to these methods exist for analysis. While this presents another valuable and interesting line of academic inquiry, it is outside the scope of this dissertation. *Vasa's* position within the northern Dutch shipbuilding tradition necessitates that this particular method be the focus of the present investigation.

⁵⁵ Hoving and Parthesius 1991, 11.

COMPARATIVE NAVAL ARCHITECTURE

Although the term ‘naval architecture’ is frequently used to mean the process of designing and building ships, the term was only introduced relatively late in the history of shipbuilding.⁵⁶ The first known use and definition of the term is found in an unpublished 1610 shipbuilding treatise titled *‘Livro primeiro da architectura naval’* (First Book of Naval Architecture), written by Portuguese engineer João Baptista Lavanha.⁵⁷ In this work, Lavanha defines naval architecture as “that which with certain rules teaches the building of ships, in which one can navigate well and conveniently.”⁵⁸ When Lavanha wrote his treatise, the notion of a system of rules governing the design and construction of ships was not a novel concept; documenting and communicating these systems in writing, however, was a significant departure from older methods. The first known treatise on shipbuilding is the unpublished manuscript of a sailor in the Venetian navy known as Michael of Rhodes, written in 1434 and 1435.⁵⁹ The Michael of Rhodes manuscript marks the earliest known cohesive documentation of guidelines for ship design and construction.⁶⁰ The practice of writing shipbuilding treatises would gain popularity throughout the 16th and 17th centuries. This trend was the first major development in the codification and dissemination of shipbuilding knowledge beyond first-hand master-apprentice experience on the shipyard and the systemization of ship design.⁶¹

⁵⁶ The term would not come into common use in European languages until the 18th century, when it most frequently referred to the application of geometric principles in ship design; Ferreiro 2007, xiv.

⁵⁷ The first published work to use the term was German engineer Joseph Furtenbach’s 1629 *‘Architectura Navalis’* (Naval Architecture); Ferreiro 2007, xiii; Nowacki 2009, 27.

⁵⁸ Ferreiro 2007, xiii.

⁵⁹ McGee 2009, 223.

⁶⁰ This seems to be a practice that began in earnest in Venice and then spread throughout Europe; Alertz 2009, 251.

⁶¹ The first published work on shipbuilding was written by the Spanish government official Diego García de Palacio, titled *‘Instrucion nauthica, para el buen uso y regimiento de las naos su traça, y gobierno conforme á la altura de México’* (Nautical Instruction, for the Good Use and Management of Ships, Their Design, and Conduct in Accordance with the Latitude of Mexico) and published in Mexico in 1587; Ferreiro 2007, 47.

The second major development in early modern naval architecture was the production of technical drawings of ships on paper prior to construction. Up until the late 16th century, the responsibility for both designing and building a ship was combined in one person, the master shipwright.⁶² Although ship construction often required a sizeable labor force, the master shipwright was personally responsible for designing the vessel and overseeing construction. Beginning around 1570, Iberian and English shipwrights began putting their ideas on ship design down on paper in the form of technical drawings. Three of the earliest examples of this practice are found in treatises by Elizabethan shipwright Mathew Baker's well-known ca. 1570 *Fragments of Ancient English Shipwrightry*, and Portuguese Dominican friar Fernando Oliveira's 1570 Latin manuscript, *Ars nautica* and a later Portuguese text, date to ca. 1580 titled '*Livro da fábrica das naus*' (Book on the Construction of Ships).⁶³ In these works the authors offer theories on optimal ship design through the use detailed illustrations depicting vessels in various stages of completion. Several of the drawings are annotated, and the authors offer limited methods for deriving proper proportions, dimensions, and other best practices. While the Baker and Oliveira treatises are some of the earliest known examples of technical ship drawings, they were not meant to be used as construction plans. The images were not always drawn to scale and were often incomplete.⁶⁴ Examples of these early drawings are seen in Figures 3.12 and 3.13. Instead of construction templates, they were illustrations of the authors' personal shipbuilding theories or observations, likely intended as instructional aids to teach methods of

⁶² Alertz 2009, 251.

⁶³ Alertz 2009, 251.

⁶⁴ Another criticism of early shipbuilding treatises is that they too often relied on idealized numbers, which some interpret as dissociation from the reality of shipbuilding. Alertz 2009, 269-275 challenges this assumption by comparing the dimensions provided in various treatises with dimensions recorded in shipwrights' personal notebooks and concludes that even the treatises of non-shipbuilders were probably closer to actual shipbuilding than not.

ship design.⁶⁵ The creation and use of scaled architectural ship plans meant to guide construction would become popular in the early decades of the 17th century.

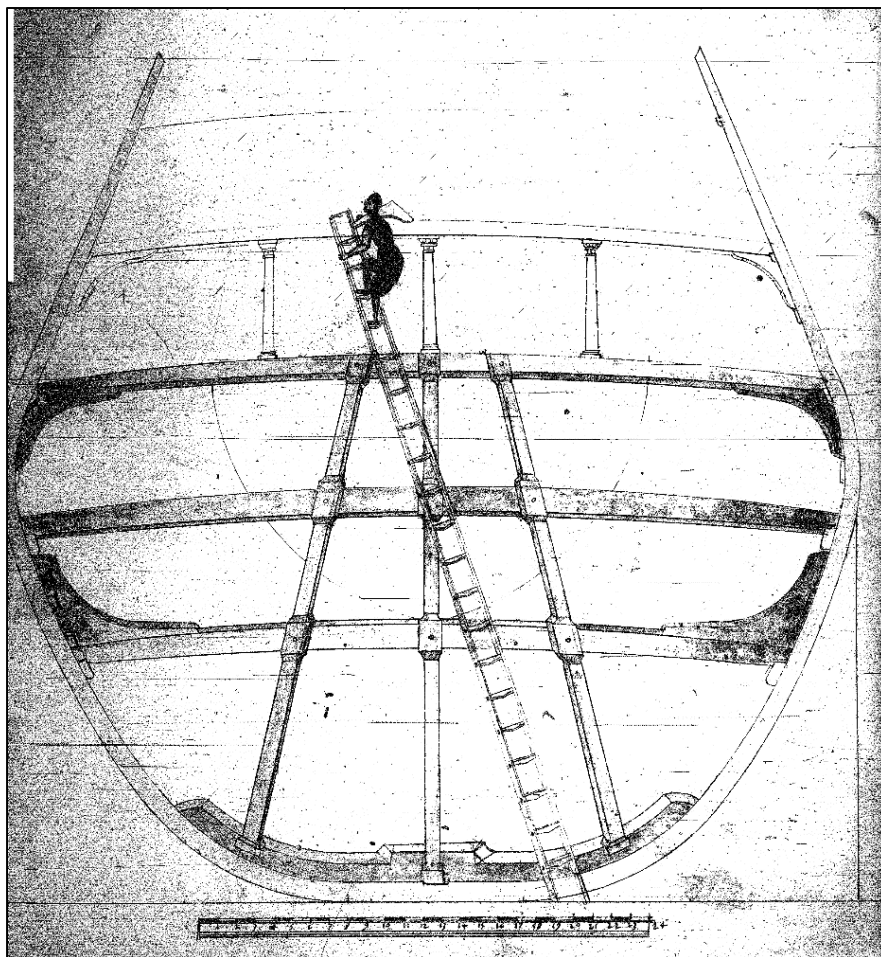


Figure 3.12. Drawing of a frame station, probably the midship frame, of a vessel from Mathew Baker's ca. 1570 manuscript *Fragments of Ancient English Shipwrightry* illustrating the application of architectural drafting methods to ship design.

⁶⁵ Ferreiro 2007, 41; Alertz 2009, 251.

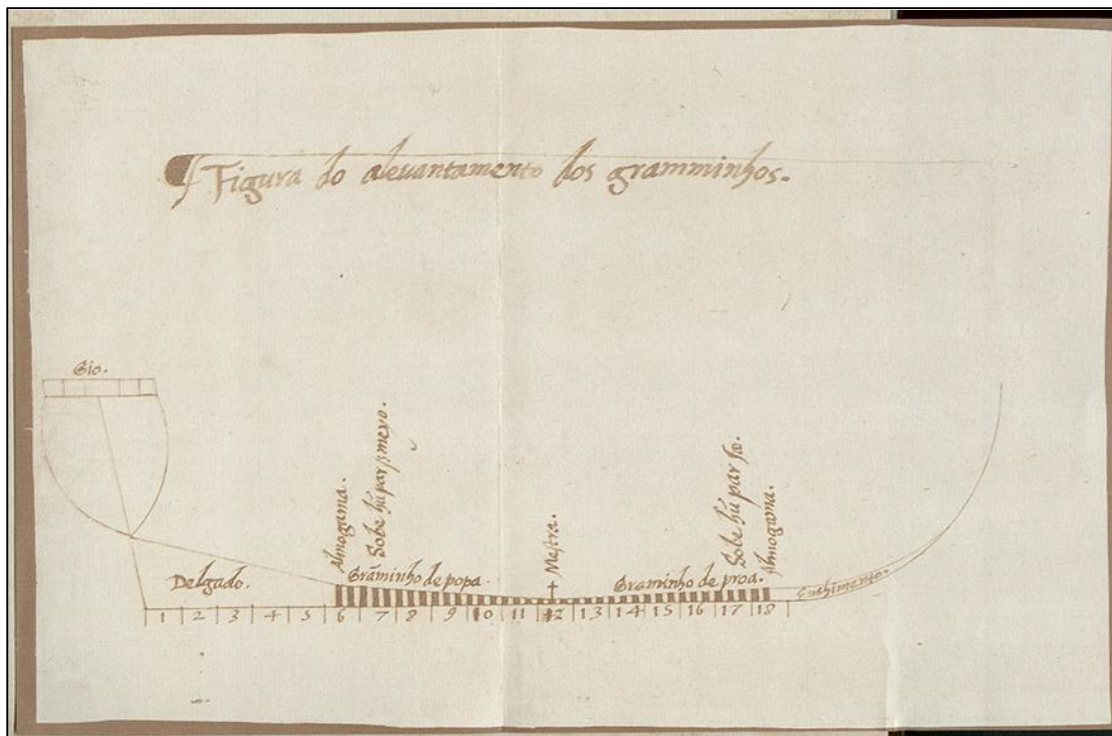


Figure 3.13. A partial architectural plan of a ship from Fernando Oliveira's 1580 *Livro da fábrica das naus* (Book on the Construction of Ships)

In the early 17th century, the use of visual methods and drafting tools to guide the shaping of principal curved ship timbers was well known throughout Europe. Shipwrights often drew, at full scale, the midship frame, stem, and tail frames on the floor of a mold loft or directly on the ground of the shipyard, thereby reducing the complex three-dimensional curvature of a ship to a series of planes.⁶⁶ Using compasses, straightedges, triangles, string, and chalk, shipwrights sketched their desired shapes to be used as guides for cutting and shaping the defining curves of a vessel.⁶⁷ From these designed curves the remaining curves were then interpolated empirically using ribbands in a process called whole-molding.⁶⁸ This method allowed for the controlled

⁶⁶ Alertz 2009, 252.

⁶⁷ Ferreiro 2007, 40.

⁶⁸ For a detailed discussion of history and practice of whole-molding, see Barker 2001.

creation of relatively complex curvatures by a workforce with limited literacy and access to sophisticated geometrical tools.⁶⁹ While this process appears similar to architectural drafting, it was not intended to produce a visual image of a completed vessel. Marking lines on the floor of a mold loft was simply the creation of a guide for cutting timbers, the making of a pattern.

By contrast, drafted architectural ship plans were orthographic projections that included all three dimensions of a vessel. In these projections, the complex curvature of a vessel was calculated and drawn, with particular attention given to the cross sectional shape of the ships mid-body and longitudinal lines of rising and narrowing. English shipwrights seem to have pioneered this method of design and it appears to have been adapted from the practice of whole-molding.⁷⁰ Using this method, the midship curve of the vessel was designed first, using a system of radii and tangent arcs calculated according to the proportional fashions of the day. This midship curve was then modified fore and aft according to the desired amount of rise and narrowing of the cross-sectional form as dictated by the intended size and function of the ship. An early example of this is seen in Figure 3.14, taken from an anonymous manuscript written ca. 1620. The left drawing is the midship curve as defined by the calculated radii and tangent arcs. The right drawing is a section nearer the stern of the vessel, whose radii and resulting arcs have been modified according to the desired amounts of rising and narrowing. These drawings define the shape of the vessel in the plane of breadth and depth. Figure 3.15, taken from the same manuscript, depicts the lines of rising and narrowing, fully defining the vessel by adding the planes of length and breadth, and length and depth. A similar contemporary drawing survived in

⁶⁹ Until the middle of the 18th century, shipbuilding was largely an applied craft – shipwrights often knew basic math and arithmetic but many were illiterate; Ferreiro 2007, 11.

⁷⁰ Lemmers and Hoving 2007, 72.

Denmark, authored by a Scottish shipwright named David Balfour, who worked for the Danish crown in the late 16th and early 17th century.⁷¹

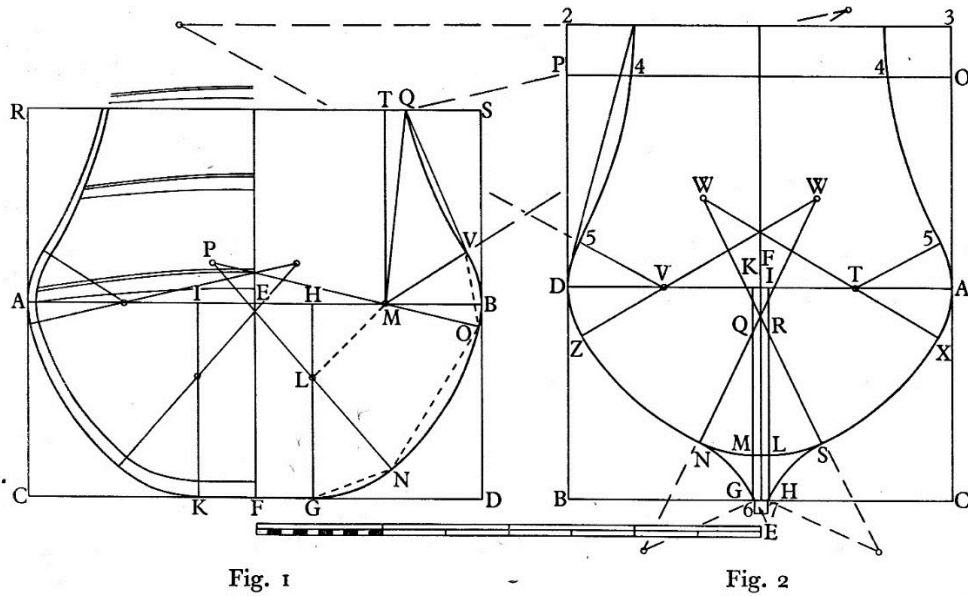


Figure 3.14. Two ship sections from an anonymous early 17th-century English manuscript. The midship frame is on the left, a tail frame on the right. Drawing by W. Salisbury.⁷²

⁷¹ Bellamy 2006, 5.

⁷² Salisbury and Anderson 1958, 17.

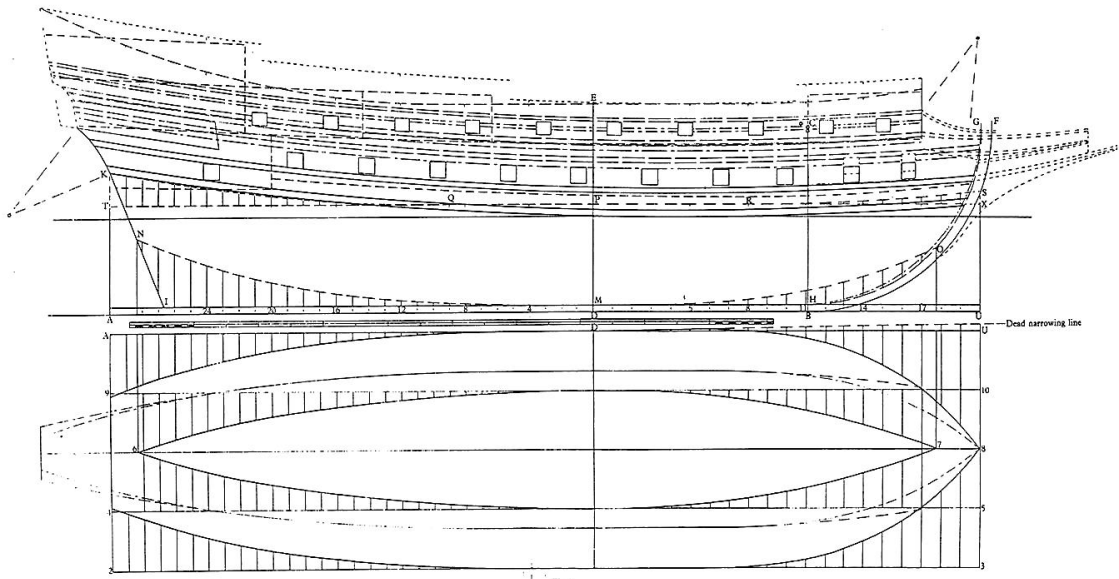


Figure 3.15. A sheer and breadth plan from the same anonymous early 17th-century English manuscript. Drawing by W. Salisbury.⁷³

Throughout the 17th century, this basic method for defining hull shape changed little. Several authors, primarily English, wrote manuals instructing readers how to apply arithmetic and geometric principles to create favorable hull shapes, all employing the same basic method of defining a midship curve, then modifying it fore and aft following lines of rising and narrowing. This method developed rapidly and by the 1670s ship plans were a concise visual record of the overall hull form and appearance of a vessel. These developments are exemplified in English Royal Navy master shipwright Anthony Deane's 1670 *Doctrine of Naval Architecture*. In this treatise Deane carefully explains his graphical methods for designing a third rate warship step by step. This results in a complete draft (Figure 3.16) which also includes decorative details of the sides and stern panel of the vessel, a common feature in drafts from the latter part of the 17th century. This finished draft was both a scaled architectural representation of the ship's hull

⁷³ Salisbury and Anderson 1958, 34-35.

form, which served as the basis for construction, and a presentation-quality image of the proposed vessel. These characteristics offered several pragmatic and administrative advantages over lofting and whole-molding, which led to the eventual widespread adoption of architectural ship drawings throughout European maritime states.

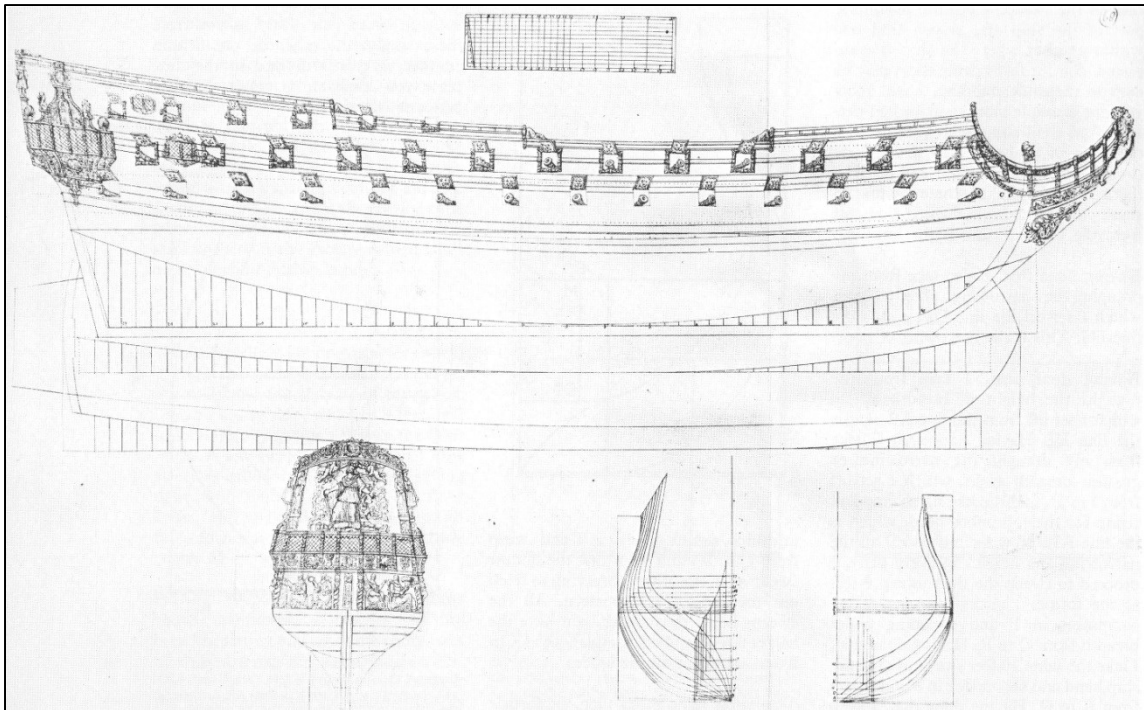


Figure 3.16. A draft of an English 3rd rate naval ship, ca. 1670. Drawing by Anthony Deane.⁷⁴

Drafting vessels on paper allowed for the production of ship plans at a variety of scales, which allowed shipwrights to express their designs at the desk, rather than the floor of the shipyard. Drawing at scale also accommodated more comprehensive design. The practice of drawing ship components at full scale on the mold loft floor was limited both by the size of the available

⁷⁴ Lavery 1986.

drawing surface as well as the tools used to make the sketch. By designing on paper, a shipwright was less constrained by physical parameters and able to design draft the entire length, breadth, and depth of a vessel prior to construction. Similarly, drawing at scale allowed for the easy modification of designs. A shipwright was able to see the complete shape of a vessel before the first timber was cut and able to make modifications as needed. Perhaps most importantly, by its very nature drafting ship plans on paper produced a written record of the design of a given vessel. This made replication of a successful design much more likely. Prior to the drafting of ship plans, if a given ship design proved successful, it was very difficult to replicate it given the nature of mnemonic tools available to shipwrights. Putting designs on paper captured the design of a vessel and facilitated the communication and sharing of successful designs.⁷⁵

The production of a written record for ship designs also allowed naval administrators to begin a process of standardizing designs and creating classes or rates of ships.⁷⁶ As European naval warfare began to favor the line of battle as a tactical doctrine around 1650, standardization of ship size and armament became a logistical necessity.⁷⁷ The drafting of ship plans allowed administrators to review and revise proposed designs. Simultaneously, naval bureaucrats found that standardizing ship designs also made the construction of ships far more economically efficient. These advantages led to the widespread adoption of pre-designing vessels on paper among northern Europe's leading naval nations. By the end of the 17th century, shipwrights in England, France, Denmark-Norway, and Sweden were using paper plans in the design of their

⁷⁵ Nowacki 2009, 12.

⁷⁶ For a discussion of early modern naval standardization, see Gardiner 1992, Glete 1993, Rodger 2005, and Davies 2008.

⁷⁷ Glete 1993, 44.

ships.⁷⁸ The increasing bureaucratization of European navies eventually led to the complete decoupling of the ship design and construction processes. Since designs came to be completely expressed on paper, ships could be designed in an office far from the shipyard and constructed without the architect ever setting foot in the yard.⁷⁹ Whereas at the beginning of the 17th century, it was not uncommon for a single shipwright to be responsible for the design and construction of a given vessel and produce little written record, by the end of the century it was possible for a ship to have been designed by a committee of naval administrators and constructed by a completely separate team of ship carpenters, accompanied by a sizeable paper trail.

The Dutch were an exception to these developments. Dutch shipwrights did not begin designing their vessels on paper until the 1720s, and only then after hiring British shipwrights into their ranks.⁸⁰ Chief among the reasons the Dutch were not early adopters of written ship plans was the decentralization of the navy. In the 17th century, most European naval powers were in the process of creating substantial centralized naval bureaucracies to better manage the financial and logistical challenges of developing a permanent navy. The Dutch took a different approach. Instead of creating one admiralty to oversee all naval operations, the States-General established five separate admiralties, each operating essentially autonomously.⁸¹ This left each admiralty with the responsibility of hiring its own shipwrights and ordering its own ships.⁸² The Dutch also did not undertake massive warship construction campaigns like those in England or later in

⁷⁸ Ferreiro 2007.

⁷⁹ Glete 1993, 18.

⁸⁰ Lemmers and Hoving 2007, 67.

⁸¹ The admiralties were those of Amsterdam, Friesland, the Noorderkwartier, Rotterdam, and Zeeland; Bruijn 1993, 5.

⁸² Glete 2002a, 166.

France; the majority of Dutch shipping tonnage was intended for merchant service.⁸³ The lack of a centralized naval bureaucracy and smaller-scale naval shipbuilding ambitions left the shipwrights of the young Dutch Republic content to carry on building ships by eye, without adopting the latest advances in naval architectural practice. This building scheme served the Dutch navy well for much of the 17th century and it enjoyed several significant naval victories. Toward the end of the 17th century, however, the lack of centralized naval administration and technical design innovation resulted in Dutch vessels being outperformed and outgunned by their English rivals. The Dutch naval supremacy of the 17th century would give way to the great navies of England and France in the 18th century.⁸⁴

SUMMARY

The above Dutch construction sequences highlight the areas in which the discretion of the shipwright had the most effect on the shape of the hull. In both the northern and southern traditions, the overall length was typically specified in the shipbuilding contract and was reflective of the desired capacity of the completed vessel. The breadth and depth of the vessel were derived from the length, but according to accumulated wisdom about the sailing characteristics of particular hull configurations. From these principal dimensions, the shipwrights derived a number of other measurements that defined the character of the vessel. In both construction methods, however, the overall shape of the hull was determined by relatively few decisions on the part of the shipwright. Certain key decisions were important in determining the overall shape and characteristics of the hull. Once in place, these decisions by necessity

⁸³ Glete 1993, 155; Bruijn 1993, 147-148.

⁸⁴ Lemmers and Hoving 2007, 70; Boxer 1965, 108.

determined the shape, size, and configuration of a variety of hull features. Witsen summarized this relationship when he wrote, “No one expects that all part of the ship will be shaped to mathematical detail: this will only be done for those parts, which are the most important in the ship, from which the others will follow without exactness.”⁸⁵ A central task in the recovery of the design method of *Vasa*, then, is the identification and definition of these key decisions.

As indicated by several features in the hull, *Vasa* was constructed according to the northern Dutch shipbuilding tradition. The precise construction sequence can be identified through archaeological analysis of the structural arrangement of timbers and fastening patterns as evident in the hull. The design process of northern Dutch vessels was a product of a dialogue between the shipwright and the vessel during the construction process. While the shipwright certainly had a plan for the vessel in mind, the expression of this plan happened sequentially as he guided the construction and assembly of key hull features. The construction process is easily discernable, according to the principles discussed earlier in this chapter. Due to the close relationship between the construction and design process in early-modern Dutch shipbuilding, the expression of design is recoverable through the close analysis of the completed hull of *Vasa*. Both of the 17th-century Dutch shipbuilding treatises indicate a derivative design process with subsequent design decisions based on those immediately prior. The precise methodology employed for recovering the design, according to a theory of reverse naval architecture, and the visualization tools used are discussed in the following chapter.

⁸⁵ Hoving 2012, 15; ‘*Niemant verwachtte echter, dat alle Scheeps-deelen tot het minste toe, wiskonstelijk zullen warden voorgesteld: zulks geschiet slechts in die gene, welk de voornaemste rang in ‘t schip hebben, d’ overage volgen daer zonder evenmaet uit.*’ Witsen 1671, 54.

CHAPTER IV

METHODOLOGY

This chapter outlines the two major methodological structures that underpin this dissertation: reverse naval architecture and 3D modeling in archaeology. The limitations of studying an intact hull and the approaches and tools use to overcome them are also discussed. The result is a contextualization of the current study within evolving methods of archaeological inquiry.

REVERSE NAVAL ARCHITECTURE

As complex machines produced by societies with distinct shipbuilding traditions, vessels have great potential in revealing the underlying aspects of their creation, and thereby providing a window to the society that created them.¹ Ole Crumlin-Pedersen suggested the phrase ‘reverse naval architecture’ to describe the work of an archaeologist attempting to identify and investigate the primary qualities of a ship based on archaeological remains.² The term intentionally connects the notions of ‘reverse engineering’ and ‘naval architecture’ to mean the recovery and analysis of the underlying components of a ship and their interrelationship based on physical remains.³ Crumlin-Pedersen suggested that reverse naval architecture seeks to identify seven main aspects of the original ship: form, function, concept, construction, materials, dating, and

¹ Adams 2001, 292-310.

² Lemeé 2006, 97.

³ Reverse engineering is a common practice in mechanical, electrical, and software engineering that seeks to understand a system through methodical analysis of its components; to recover the design without knowing the design.

origin.⁴ In cases where only fragmentary hull data remains, the process of recovering these aspects can be quite challenging. For *Vasa*, most of these aspects are well documented. *Vasa* is a large warship (function), built primarily of oak (materials) in Stockholm (origin) from 1626-1628 (dating). The outstanding questions then are those of form, concept, and construction. Since the vessel is nearly intact, recovery of construction details (meaning whether the vessel is carvel or clinker built, fastening methods, evidence for tool usage, etc.) is feasible. The current study on *Vasa* focuses on the *form* and *concept* of the ship. Crumlin-Pedersen defines form as the hull's general shape, and concept to be the methods used in constructing the hull. The relationship of concept to form can be described as 'design' – the shipwrights' intent, decisions, and system of logic that resulted in the finished form of the hull. The particulars of ship design in the case of Dutch-built vessels is discussed in Chapter III. 'Reverse naval architecture' as applied in this dissertation describes this intersection of form and concept with a goal of the recovery and analysis of the design of the ship based on the intact structure.

Rather than reconstructing a complete hull from fragmentary archaeological remains, this project recovers and reconstructs the design process and logic, to the extent that it is possible, as evidenced by the complete hull. Like reconstruction, this is an admittedly speculative process informed by the best current understanding of historical ship design and construction methods. At its core, this study is the identification of deliberate human selection to recover and understand the mental processes of the shipwrights that led to *Vasa*'s finished form.

⁴ Lemeé 2006, 97.

CHALLENGES AND LIMITATIONS

Vasa is the oldest intact ship recovered to date and as such presents unparalleled research opportunities. Along with these opportunities, however, come significant challenges. Most exercises in reverse naval architecture seek to answer fundamental questions about a vessel based on fragmentary archaeological remains. Reconstruction and understanding of vessels through incomplete physical data is challenging and often involves significant conjecture. The disarticulated remains, however, enable a full examination of timbers that can lead to meaningful discoveries. In the case of *Vasa*, the hull cannot be disassembled due to structural concerns for the wood and the public nature of the ship and museum. Thus, some important features of the hull (framing timbers for instance) cannot be fully accessed. Also complicating the recovery of *Vasa*'s design is the distortion of the hull. *Vasa* was on the bottom of Stockholm harbor for 333 years, and although much of the hull remained intact, some structural deformation has taken place. The deformation has been further exacerbated through the conservation of the hull using polyethylene glycol, the subsequent drying of the wood, and the support structure of the hull for display. Current estimates are that hull timbers have suffered 4-8% shrinkage across the grain, with a 6% average, and negligible shrinkage along the grain.⁵ These distortions have been taken into consideration during the design analysis of the hull. A more comprehensive discussion of these factors occurs in Chapter VI.

In an attempt to overcome these limitations, digital 3D modeling is used to virtually construct and deconstruct key features of the hull. A series of models have been built based on data collected by myself and the staff of the Vasa Museum. These models form the foundation of the

⁵ Fred Hocker, pers. comm.

reverse naval architectural analysis of *Vasa*. The models allow both the visualization of spatial data recorded on *Vasa*, and the hypothesizing of internal arrangements and features that are otherwise inaccessible. In this study, digital modeling enables a level of rigorous analysis that would otherwise be impossible without 3D visualization tools. A detailed description of the model creation process follows in Chapter V.

3D VISUALIZATION

Whereas once ‘visualization’ referred to the act of picturing something in the mind, it has more recently come to mean something closer to a *graphical representation of data or concepts*.⁶ The term came to have scientific connotations in 1987, when the National Science Foundation published a report titled *Visualization in Scientific Computing*.⁷ Since then, scientific visualization has taken many forms which can be broadly described as the visual interpretation of data through modeling and display of diagrams, solids, surfaces, properties, and animations through the use of computing hardware and software.⁸

Supporters of scientific visualization define the goal of creating images from numbers as the harnessing of the considerable potential of human perception and cognition to recognize patterns and discern relationships in data that may not otherwise be apparent.⁹ We gather more information through vision than through all other senses combined. The billions of neurons

⁶ Ware 2004.

⁷ McCormick et al. 1987.

⁸ Reilly 1992, 147-173.

⁹ Aldenderfer 2010, 53-68.

devoted to processing visual information provide for the greatest bandwidth of incoming data.¹⁰

The human visual apparatus is adept at data analysis such as pattern recognition and form estimation. These attributes make human vision very adaptable to abstract forms visualization, including microscopy, X-rays, computed tomography, and digital 3D modeling, all of which are characteristics of modern science.¹¹ Information scientist Colin Ware suggests that visualization of data can encourage understating in at least five ways:

1. Visualization provides the opportunity to comprehend large amounts of data
2. Visualization facilitates the perception of patterns or properties that were not initially anticipated
3. Visualization frequently highlights problems with the data itself or the way in which data was collected
4. Visualization enables understanding and analysis of both large-scale and small-scale features of data simultaneously
5. Visualization promotes the formation of hypotheses¹²

One particular type of visualization is of interest here, digital 3D modeling of archaeological data. Computer visualization of scientific data consists of four basic stages: the collection and storage of raw data, preprocessing the data into something more easily understood, the production of an image from the data via display hardware and graphics algorithms, and finally the human interaction with the displayed data.¹³ Multiple types of computer visualizations are possible, but digital 3D modeling is especially well suited to use in archaeological investigations of complex structures such as ships. The reasons for this and an historical context for the

¹⁰ Ware 2004, 2.

¹¹ Kemp 2000.

¹² Ware 2004, 3-4.

¹³ Ibid.

development and adoption of digital 3D modeling are discussed below. The three primary types of digital 3D models are detailed in Chapter V.

Digital 3D modeling is an evolutionary step in the long human history of schematic model making. Examples of architectural models and drawings have been found throughout the ancient Mediterranean, depicting structures ranging from common Greek houses to New Kingdom Egyptian tombs. The tendency to draw or model structures continued into the Middle Ages as structures became increasingly complex. Many examples have been found in Italy, where models of sophisticated cathedral architecture are well documented.¹⁴ An elegant expression of the human inclination toward modeling as means for understanding complex structures comes from the work of Italian Renaissance architects and visualization pioneers Filippo Brunelleschi, Leon Battista Alberti, and Michelangelo Buonarroti. For these architects, models served several purposes. Models were used to persuade clients or guide workmen in construction. Models were also seen as a critical tool for developing and understanding an idea and thus played a vital role in the design process. To Renaissance architects, an idea of a structure in the mind was imperfect, it needed to be modeled so that it could be examined, critiqued, and improved to approach a fuller and more perfect embodiment of the idea.¹⁵ The ability of a model to evaluate, improve, and ultimately realize an idea is what makes them a useful tool for design and evaluation. Modeling is now a regular part of mechanical and architectural design processes. Advances in technology have enhanced this process to the point where computer modeling now

¹⁴ Millon and Lampugnani 1994, 19.

¹⁵ Millon and Lampugnani 1994, 22-24.

easily facilitates the creation of highly realistic models which allow for a faster and more faithful evaluation and realization of an idea.

COMPUTER GRAPHICS

Computer graphics is a broad field that crosses disciplinary boundaries and is evolving at a rapid pace. The term *computer graphics* originated around 1960 and was first used to describe the creation of simple vector images with a digital computer.¹⁶ Since then, ever advancing computer technology has enabled the creation of increasingly complex, detailed, and realistic computer models, while simultaneously becoming more accessible. Of specific interest here is the branch of computer graphics that deals with the production, application, and analysis of mathematically accurate and precise models. This branch, often called CAD (Computer Aided Design, or Computer Aided Drafting), has been part of computer graphics since the inception of the field.¹⁷

CAD systems, which today are routinely used in industrial design and manufacturing, were born out of the convergence of several technologies in the 1960s. Starting in the 1940s, mathematicians working with automotive and aeronautics companies in Europe and the United States began working on streamlining the design and manufacturing process by harnessing the power of analytical geometry. One significant step in this development was the translation of traditional drafting blueprints into computer-generated numerical algorithms.¹⁸ This process, pioneered by North American Aviation during World War II, ensured the precise reproduction of

¹⁶ Graphics based on geometric primitives, such as points, lines, curves, polygons, mathematical solids, or functions.

¹⁷ Farin et al. 2002.

¹⁸ Bézier 1998.

designs and eliminated the risk of varied drawing interpretation.¹⁹ Computers became further involved in the design and manufacturing process in the 1950s when they began to be used to drive milling machines in the fabrication of parts, though manual input of design parameters as expressed in physical blueprints, was still necessary.

In the early 1960s, mathematical principles of design and machine control were paired with graphical input technologies to create completely digital and interactive design systems thereby eliminating the production of physical blueprints.²⁰ Designers and engineers began designing objects entirely in a computer which made the process more efficient and enabled new analytical possibilities. Suddenly, routine but time-consuming processes, such as producing a new view of a wireframed object – which could take a draftsman a week or more – could be accomplished in seconds by a computer.²¹ Automotive and aeronautics companies, including General Motors, Ford, Renault, Citroën, Boeing, and Dassault, began developing propriety CAD systems in the 1960s and 1970s that took advantage of the increasingly advanced digital design workflow.²² Dramatic increases in the power of computer hardware throughout the 1970s and 1980s allowed the creation of models driven by increasingly sophisticated geometry. What had started as computerization of manual drafting methods (based on splines) evolved into digital geometry definition which enabled the creation of complex digital surface and solid models.²³ Draftsmen were no longer constrained by relatively simple geometric constructions. These new capabilities

¹⁹ Farin 2002, 1-21.

²⁰ A foundational event in this pursuit was the development of the Sketchpad system at MIT by Ivan Sutherland. This system, which debuted in 1963, allowed for the direct human input and manipulation of vector images by means of a light pen.

²¹ Farin 2002, 3-4.

²² Bézier 1998.

²³ Nowacki 2010, 956-969.

sparked interest in creating photo-realistic algorithms that could be used to simulate the real appearance of objects.

Over time, individual companies abandoned proprietary CAD systems in favor of more powerful commercially available programs. By the early 1980s, CAD systems had spread beyond automotive and aeronautics companies and were in widespread use in mechanical and manufacturing engineering.²⁴ In the mid-1990s, CAD and CAE (computer aided engineering) software was integrated for the first time and allowed design and analysis to be conducted in the same software program.²⁵ Today a range of CAD products are available, many of which offer functionality tailored to particular industries such as architecture, automotive and aerospace design, and mechanical engineering. Several of these programs are approachable by non-CAD specialists and have modest hardware requirements. Since the early 2000s, hardware capabilities, software efficiency, and the development of easily accessible data standards have created a hospitable environment for the adoption of computer visualization by non-computer scientists.²⁶ CAD systems have developed to the point where the creation of precision models of nearly any object is possible. This ability has attracted the attention of many outside the manufacturing and design fields, and has numerous advantages for the physical and social sciences.

²⁴ Amirouche 2004.

²⁵ Amirouche 2004, 14; CAE is the use of computer software to simulate the physical performance of models. Applications include stress testing, thermal and fluid dynamics, and kinematics.

²⁶ Addison and Gaiani 2000, 26-31.

VISUALIZATION IN ARCHAEOLOGY

The early 1970s were the dawn of computer visualization in archaeology. The first meeting of a new professional organization, Computer Applications and Quantitative Methods in Archaeology (commonly known as Computer Applications in Archaeology or CAA, now the most important professional organization devoted to the topic) was held in 1973 and marks a turning point in the archaeological use of computer technology. At this inaugural meeting, computer scientist and archaeologist John D. Wilcock articulated a vision for the future of computing in archaeology. He predicted four main uses: data bank and information retrieval, statistical analyses, fieldwork data recording, and the production of diagrams and illustrations.²⁷ Wilcock also included a miscellaneous category of uses, which included computer-aided archaeological reconstruction.²⁸ Most archaeological applications of computing in the decade that followed the first CAA meeting fell into one of Wilcock's first three categories. Initially, computers were used to organize and store large amounts of archaeological data, record data collected in the field, and perform statistical analyses on these data sets.²⁹ Graphics were not a concern of early archaeological computing users, only more recently have computers been used to produce technical illustrations (diagrams) and reconstructions.

Mathematician and computer scientist James Doran challenged early adopters of archaeological computing to look beyond computers as tools used solely for the curation of archaeological data, and instead explore their potential to generate explanations of the archaeological record. In Doran's view, computer systems could be supplied with large amounts of raw archaeological

²⁷ Wilcock 1973, 17-21.

²⁸ Ibid.

²⁹ Frischer 2008, v-xxiv.

data and a set of rules or limitations, expressed as algorithms based on observations and hypotheses, formulated by the archaeologist. The computer could process this data and generate possible explanations of all relevant factors and their interaction. This output would then be interpreted by the archaeologist, who would modify the rules, limitations, or other parameters as dictated by the developing hypothesis. Doran likened the process to ‘reconstructing the events at the scene of the crime’ with computers doing the tedious tasks of moving the ‘actors’ and ‘scenery’.³⁰ Although computers could be used to generate statistical explanations and aid the archaeologist in formulating and testing hypotheses, only rudimentary graphics (primarily maps) were used. The visual aspects of computers in archaeology came later.

The first major article that paired 3D visualization and archaeology came in civil engineer Leo Biek’s 1985 paper on the use of stereo photography to document sites and artifacts.³¹ Stereo photography was seen as a powerful new method for easily capturing detailed visual and spatial information and harnessing the acumen of human vision. The jump to 3D computer modeling occurred shortly after Biek’s paper. The first digital 3D archaeological models created manually (as opposed to automatically via stereo photography or similar techniques) emerged in the late 1980s, and tended to focus on reconstruction and analysis of sites or large buildings.³² Roman architecture was an early focus, and several research groups produced reconstruction models that showcased the benefits of computer visualization in archaeology.³³ Digital 3D archaeological

³⁰ Doran 1970, 289-298.

³¹ Biek 1986, 1-35.

³² Arnold 1989, 147-156.

³³ Wittur 2013, 9-10.

reconstruction gained momentum and several papers were published in the early and mid-1990s that focused on the emergent visualization technology.³⁴

One characteristic common among many early 3D models is that they were not created by archaeologists, but rather by computer professionals often working for private companies. The models were created in consultation with archaeologists, but non-archaeologists did the actual modeling. Commercially available modeling programs were difficult to use and many projects resorted to developing their own proprietary modeling systems. Falling computer hardware and software costs and increased user-friendliness of modeling programs, however, meant that by the late 1990s this situation had changed. With access to powerful modeling tools and the skills to use them, archaeologists began building their own digital models ensuring full control of the visualization.³⁵ This trend has continued and currently many digital models are built by archaeologists, rather than by computer scientists. Fruitful partnerships between these disciplines, however, continue to expand the range of available digital research tools.

A digital reconstruction is a theory expressed in a geometric language. Because archaeological data is always incomplete, any reconstruction can only be a best guess. Regardless, when viewing an incomplete artifact or structure, the human brain is capable of filling in gaps, based on prior knowledge, to create a mental image of the complete object. Computers are capable of significantly augmenting this process.³⁶ A great benefit of creating 3D reconstructions, is that they force the modeler to ask and answer questions about features and aspects that might

³⁴ See: Chalmers and Stoddart 1996, 85-93; Reilly 1992, 147-173; Wood and Chapman 1992, 123-146.

³⁵ Frischer 2008, v-xxiv.

³⁶ Barceló 2002, 21-28.

otherwise go unnoticed, for instance the lighting conditions inside the room or a temple or the hold of a ship. This can result in more detailed and comprehensive reconstructions that make greater contributions to archaeological science.

One digital visualization technology that was not predicted by early computing archaeologists was the use of GIS (geographic information systems).³⁷ Since its initial use in the mid-1980s, GIS has seen large scale acceptance by the archaeological and historical community.³⁸ Similar to 3D computer modeling, GIS was adopted in the early 1990s, and by the end of the decade was quickly becoming a commonplace archaeological tool. GIS has proven useful in integrating large amounts of archaeologically significant datasets, including artifact provenance, environmental data, and many others. GIS saw immediate adoption in the creation of site plans and was seen as a significant improvement over earlier techniques of drawing site maps by hand. GIS allows for both the accurate visualization of 3D data (including topography, geology, find location, and features) and the inclusion of metadata beyond what is possible on a hand-drawn 2-dimensional map. Early criticisms of GIS in archaeology, however, accused users of simply creating highly detailed, but still 2-dimensional, maps.³⁹ Projects now routinely integrate 3D models with GIS data to create comprehensive and detailed virtual site plans that can be shared with other archaeologists and the public, inviting individual exploration and interpretation of a site.⁴⁰ The integration of many types of data into one map is not only a triumph of data management, it also facilitates analyses of object-space-time relationships that would otherwise

³⁷ GIS lives up to most of Wilcock's predictions – it combines curation of archaeological data with analysis and visualization.

³⁸ Wilkinson 1996, 271-281.

³⁹ Barceló and Pallarés 1996, 313-326.

⁴⁰ Apollonio et al. 2012, 1271-1287.

be inaccessible.⁴¹ The analytical advantages of GIS in are now widely recognized in both academic and applied archaeology.

An evolution of GIS in archaeology is the reconstruction of ancient and historic landscapes. As early as the mid-1990s large scale digital reconstructions had been paired with emergent virtual reality technology to begin exploring the potential of archaeological simulations. Virtual reality reconstructions create an immersive, interactive, and real-time environment that allow archaeologists to bring their hypotheses about the past to life and test them by virtual interaction and artificial intelligence.⁴² Simulation in archaeology has been used for at least three distinct purposes: testing hypotheses, supporting theory building, and developing methodologies.⁴³ Combining archaeology, paleoclimatology, paleobotany, geology, and other sciences with GIS and virtual reality technology has created compelling reconstructions of ancient landscapes and has proven useful as a research and education tool.⁴⁴ Virtual reality reconstructions of the past have the potential to evoke a strong sense of place, owing to their immersive nature. One avenue of analysis virtual reality has enabled is the reconstruction and testing of the visual aesthetics of the ancient world. Attempts have been made to replicate ancient lighting conditions inside structures and environmental conditions such as fog or smoke.⁴⁵ This type of modeling has been especially effective in testing notions of visibility and sightlines surrounding ritual buildings and landscapes. The use of virtual reality in archaeology continues to be refined as more analytical and explanatory tools are developed.

⁴¹ Arroyo-Bishop 1996, 15-26.

⁴² Frischer et al. 2002, 7-18.

⁴³ Lake 2010, 12-20.

⁴⁴ Winterbottom and Long 2006, 1356-1367.

⁴⁵ Chalmers and Stoddart 1996, 85-93.

Archaeological excavation is necessarily a destructive process. Digital modeling tools have proven to be highly effective in collecting a greater range of high-quality excavation data to mitigate the controlled destruction of a site. Registration of archaeological material has become increasingly digitized, but still presents data with a fundamentally 2-dimensional bias.⁴⁶ One of the greatest benefits - being able to record a 3D excavation in 3D, rather than reducing it to 2D plans and drawings – is being increasingly realized by the archaeological community. This has the added advantage of being easily sharable, which enables other archaeologists to review excavation data and add interpretation or formulate alternative hypotheses.⁴⁷

One form of site documentation tool that has gained traction with archaeologists is photogrammetry, which now allows the rapid production of 3D surface models of archaeological artifacts or sites. Broadly defined, photogrammetry is the process of obtaining mathematical measurements from photographs. More recently, however, photogrammetry in archaeology usually means the creation of measurable 3D models from photographs. Many photogrammetry programs are widely available that require no specialized equipment beyond a DSLR camera and proper software and feature automated or nearly automated production of 3D models from photographs. Photogrammetry programs such as PhotoModeler, developed by Eos Systems Inc., now offer automatic texture acquisition. This feature can apply surface texture and color, as captured in digital photographs, to the 3D models. The results are high quality photorealistic measurable 3D surface models. They do not, however, provide any information

⁴⁶ De Reu et al. 2012, 1108-1121.

⁴⁷ A well-illustrated overview of early landscape reconstructions is Forte and Siliotti 1997.

about the inside of the objects (aside from limited volume estimations) and thus are of limited use to archaeologists interested in the structure or composition of artifacts.

CAD systems began to be adopted by the archaeological community in the early-mid 1990s.⁴⁸ CAD systems were first used to create site-level visualizations. One popular program, AutoCAD, published by Autodesk, saw early use as a means for creating 3D site plans of excavations and reconstruction of archaeological sites. Although use of CAD in archaeology was initially met with praise as a method for more efficient, accurate, and compelling archaeological documentation and reconstruction, it is currently used by a minority of archaeologists. Instead, many archaeologists continue to rely on recording three dimensional sites and artifacts by reducing them to two dimensions on paper or a computer screen. Widely available CAD systems now enable users to create realistic models using a variety of data sources and conduct sophisticated material evaluations with ease.

VISUALIZATION IN NAUTICAL ARCHAEOLOGY

Since the emergence of the sub-discipline in the 1960s, nautical archaeologists have adapted archaeological tools and research methods to investigate the development of human seafaring through a focus on the remains of ships and boats. At times the methodologies of nautical archaeology have paralleled those of the broader archaeological community, and at other times they have diverged. One such divergence is the use of digital 3D modeling. Whereas the broader archaeological community has embraced computer visualization methods as powerful

⁴⁸ Messika 1996, 951-954.

tools for the generation of new data and analytical possibilities, the nautical archaeology community has been slow to adopt such methods in some key areas. 3D visualizations in nautical archaeology have largely been limited to documentation and presentation tools, rather than being regarded as research tools. To date, applications of 3D visualization in nautical archaeology have been concentrated in five key areas, outlined below.

3D Site Plans

To date, the most popular application of 3D visualization in nautical archaeology has been in the creation of underwater site plans. Since the first scientific underwater excavation of a shipwreck at Cape Gelidonya, Turkey, in 1960 nautical archaeologists have sought solutions to the challenges of working in an underwater environment. Locating and accurately mapping underwater sites efficiently is often difficult due to many factors including variable sea conditions, underwater visibility, bottom composition, current, and depth. Since at least the mid-1980s, vessel-deployed underwater remote sensing instruments (primarily sidescan sonar, sub-bottom profilers, and magnetometers) have been standard tools for underwater archaeological survey and documentation.⁴⁹ Improvements to these technologies, as well as the use of additional instruments (including multibeam sonar and 3D seismic scanning) have enabled archaeologists to collect large amounts of highly quality data about archaeologically significant material on or below the sea floor.⁵⁰ The use of ROVs and AUVs have further expanded the capabilities for underwater archaeological survey, documentation, and excavation.⁵¹ Recent

⁴⁹ Redknap and Emptage 1986, 49-58.

⁵⁰ Mueller et al. 2013, 326-336.

⁵¹ Murray 2012, 28-31. A recent project demonstrated the ability to create textured 3D surface models of underwater structures using ROV captured video, see Sedlazeck et al. 2009, 1-10.

applications of these bathymetric tools have demonstrated the ability to create detailed underwater site overviews without putting divers in the water. 3D reconstruction of site plans from this data creates a detailed and mathematically accurate picture of the sea floor and its contents which is useful for archaeological documentation, target identification, and site management.⁵²

Where greater level of detail is required, diver-deployed technologies enable high resolution data capture of individual wrecks, features, and artifacts. Underwater photogrammetry has proven useful as an archaeological documentation method. Using readily available photographic hardware and software in combination with 3D modeling and mapping software, precise 3D site plans can be constructed rapidly with a high degree accuracy. Several projects have demonstrated many benefits of photogrammetry applied to underwater sites. Directors of the Mazotos shipwreck excavation in Cyprus used photogrammetry to create a dynamic 3D site plan to guide excavation progress.⁵³ Photogrammetry has been especially useful at deep sites, where diver bottom time is limited. In the summer of 2012, under the direction of Pierre Drap, the Images and Models team (I&M) from the Laboratory of Sciences of Information and Systems (LSIS) at Marseilles, UMR CNRS 7296, used a new photogrammetric recording process developed at CNRS. This method used three cameras mounted in tandem and produced tremendously promising results, including efficiently assembling extremely accurate 3D mosaics.⁵⁴ During the excavation of the 5th century BC shipwreck at Tektas Burnu in Turkey (38-42m deep), photogrammetry was found to dramatically increase mapping efficiency and

⁵² Bates et al. 2011, 404-416.

⁵³ Demesticha 2011, 39-59.

⁵⁴ Radić-Rossi and Castro 2013, 365-376.

produce a more accurate site plan than traditional multi-tape trilateration or DSM.⁵⁵ At the excavation of the Roman wreck at Kizilburun in Turkey (ca. 48m deep), it was found that the entire site could be photographed for mapping purposes by two divers in a single 20-minute dive.⁵⁶ Recent advances in underwater photogrammetry have resulted in further automation of 3D site plan documentation. A partnership between researchers in underwater archaeology and robotics has paired SLAM (Simultaneous Localization and Mapping) technology with stereovision photogrammetry to automate the creation of a fully georeferenced 3D mesh and texture map.⁵⁷ Other diver-deployed 3D scanning technologies, including ultra-high-resolution multibeam imaging sonar, have been used to capture underwater data.⁵⁸ These devices create high-density measurable point clouds of data and have proven particularly useful in recording structures that stand above the sea floor.

Although useful in documentation, 3D site plans have seen limited use in site analysis. Applications have largely been limited to investigation into the site formation processes and environmental conditions.⁵⁹ While advocates have encouraged further analytical applications based on 3D site plans, most have been slow in their progress.⁶⁰ Future uses of 3D site plans may also include increased collaboration and communication both within the academic archaeological community and with the public.

⁵⁵ Green et al. 2002, 283-292.

⁵⁶ Catsambis 2007, 611-615.

⁵⁷ Henderson et al. 2013, 243-256.

⁵⁸ Thomas 2011.

⁵⁹ Green et al. 2002, 283-292.

⁶⁰ Gibbins and Adams, 2001, 279-291; Chapman et al. 2010, 245-250.

Traditional GIS packages have not seen widespread adoption by the nautical archaeology community.⁶¹ Several programs have been developed, including Site Recorder 4, WEB, and Site Surveyor that offer the benefits of other archaeological GIS systems but also add enhanced underwater-specific capabilities. For example, Site Recorder 4, published by 3H Consulting Ltd., works simultaneously as a mapping tool, artifact database, dive log, and image manager. The ability to integrate and visualize large amounts of spatial and artifact data from an underwater site is very useful and most underwater excavations use some form of this software. Other efforts to use GIS or an equivalent system in nautical archaeology have focused on integrating terrestrial data with maritime data to create a more comprehensive picture of maritime cultural heritage.⁶²

3D Documentation of Hull Timbers

Hull timbers, both intact and fragmentary, are preserved at many shipwreck sites. These timbers are generally recorded in situ along with other artifacts and features through sketching, measurement, and photography. If the timbers are raised, they are usually documented in greater detail before, during, or after conservation.⁶³ By their very nature, hull timbers are irregularly shaped – even more so post deposition. Traditionally, documentation of hull timbers is done in 2 dimensions.⁶⁴ The result is a 2-dimensional record of a complex 3-dimensional artifact that leaves present and future researchers with a faulty dataset.⁶⁵ An example is seen in Figure 4.1.

⁶¹ Groom and Oxley 2002, 50-57.

⁶² Groom and Oxley 2002, 50-57.

⁶³ Steffy 1994, 199.

⁶⁴ Drawings and measurements are usually recorded on a diving slate, then transferred to a paper site plan. Photographs are generally 2D, though 3D photogrammetry is changing this. Detailed hull timber drawings usually record the timber in multiple views, but still only represent two dimensions.

⁶⁵ De Reu et al. 2012, 1108-1121.

Besides being extraordinarily time consuming, the flattening of spatial data places limitations on further analysis, especially if the reconstruction of a complete vessel from fragmentary hull remains is the goal. Over the last decade, archaeologists have sought ways to overcome these limitations and document 3-dimensional timbers faithfully in all three dimensions. Although 3D models of timbers can be generated based on two dimensional drawings, several projects have demonstrated the benefits of full 3D documentation.⁶⁶ The Newport Medieval Ship Project in Wales has embraced 3D timber documentation and produced impressive results. An example is seen in Figure 4.2. Apart from the underwater documentation methods discussed above, the 3D timber documentation methods used in nautical archaeology require timbers to be above the surface of the water, though they do not need to be dry.

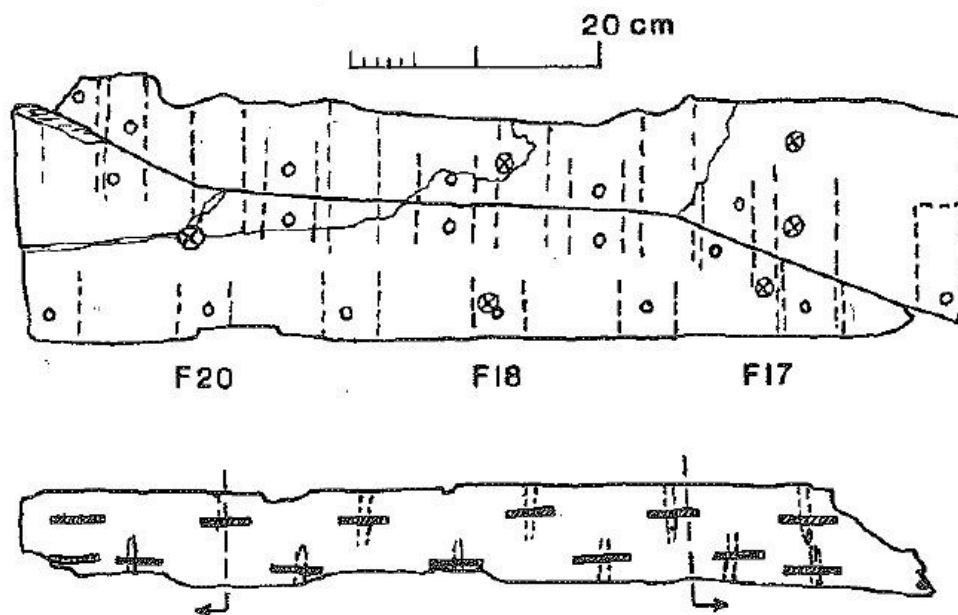


Figure 4.1. Section of wale recovered from the Kyrenia shipwreck. Drawing by J. Richard Steffy.⁶⁷

⁶⁶ See Sasaki 2005, Castro et al., 2011.

⁶⁷ Steffy 1994, 51.



Figure 4.2. 3D laser scan of a block recovered during excavation of the Newport Medieval Ship. Image by Toby Jones.⁶⁸

The capabilities of data-capture equipment, such as laser scanners, now offer major improvements in documentation efficiency and fidelity. Three tools in particular have proven useful in nautical archaeological documentation: wide-area laser scanners, coordinate measurement devices, and total stations. Wide-area laser scanning technology has been used in cultural heritage documentation from at least the early 1990s, when museums began developing and adopting the technology to aid in conservation.⁶⁹ Wide-area laser scanning captures large amounts of spatial data quickly (up to 1 million points per second), in the form of high density point clouds, which form an accurate three dimensional record of the scanned object.

Photographic data can be used to texture the three dimensional geometry to create a fully

⁶⁸ Jones 2009, 114.

⁶⁹ Baribeau et al. 1996, 199-209.

measurable photorealistic documentation of the artifact. Wide-area laser scanners are portable and able to be used in the field (though not underwater). Projects that have used laser scanning focus on the documentation of large structures, including intact or partially intact vessels.⁷⁰

On an individual timber scale, coordinate measurement devices have been used to document hull timbers post-excavation. Exemplified by the pioneering efforts of the Viking Ship Museum in Roskilde, Denmark, on the remains of the Skuldelev vessels and the Newport Ship Project in Wales, archaeologists have used these devices (primarily the FaroArm made by FARO Technologies) to create detailed three dimensional records of individual hull timbers.⁷¹

Coordinate measurement devices use either a contact probe or handheld laser scanner to collect point data on objects which are then imported into a 3D modeling program. Unlike the wide-area laser scanners described above, coordinate measurement devices are not automated.

Archaeologists using these tools must scan or record every edge, facet, and feature of each timber individually. In this way, recording timbers with coordinate measurement devices is more similar to traditional 2-dimensional archaeological recording as it requires close inspection to ensure complete documentation of relevant features. With these devices, archaeologists are able to create detailed digital wireframe or surface models of timbers that capture every feature in three dimensions. Timber features (for example holes or tool marks) are sorted and stored as layers that can be turned on or off to facilitate various types of visual analysis. These digital records are used in reconstruction and analysis of the ship and serve as guides for physical

⁷⁰ Two examples of laser scanning are the *Sub Marine Explorer* project in Panama, which laser scanned a submersible in situ, and the laser scanning of the *Charles W. Morgan*, the world's only remaining wooden whaleship.

⁷¹ The Skuldelev ships and the Newport ship in Wales are the most well-known examples of this documentation method. For additional examples see Ravn et al. 2011 232-249.

modeling or replica construction.⁷² Furthermore, digitized timbers can be examined using a range of computer analytical tools.

The third system of recording hull timbers in 3D is the use of a total station, first used to document to eight large wrecks at the B&W site in Christianshavn, Denmark, from 1996-1997.⁷³ On this project, nearly 100 tons of timbers were recorded in advance of their removal for a construction project. Total station recording has been used on several subsequent projects where large amounts of timber exist in a dry or semi-dry environment.⁷⁴ Total station devices pair an electronic theodolite with an electronic distance meter to capture X,Y,Z point coordinate data. Total station recording does not collect the same level of detail as wide-area laser scanning or coordinate measurement devices, but it does collect spatial data quickly and accurately. On the B&W wreck project, archaeologists found the best results were obtained by using a hybrid timber recording method. To record large vessel fragments quickly and accurately, total station data spatial data was imported into a CAD system (which offered fast and accurate timber modeling) and was paired with hand drawn artifact images (that captured archaeological details) to create complete timber models. The total station data provided both a detailed site plan and valuable three-dimensional timber data. The hull of *Vasa* was recently recorded by total station surveys and the results of this effort form the basis of the modeling contained in this dissertation.

⁷² Jones 2005, 12-15., Ravn et al. 2011, 232-249.

⁷³ Jensen and Lemeé 1999, 85-88.

⁷⁴ Notably on the Yenikapı project in Istanbul, the Utrecht ship, and *Vasa*.

3D Documentation of Artifacts

Nautical archaeologists have recovered an enormous array of artifacts, other than hull timbers, from sites underwater and on land. These objects, like hull timbers, almost never lend themselves to full documentation in two dimensions due to the shortcomings of plan, profile, and section views and archaeologists have sought more accurate ways of documenting complex shapes in 3D. Recent projects have further demonstrated the analytical benefits of 3D imaging, particularly when internal data is combined with surface data. A multi-disciplinary consortium of scholars recently published the results of a range of analyses conducted on the Belgammel Ram, a bronze Hellenistic-Roman *proembolion*. As part of their analysis, the group of scholars combined three visualization technologies to gain insights into the structure and casting of the ram. First, the ram was laser scanned using a coordinate measurement device fitted with a laser scanner to create a high-resolution surface model. Second, polynomial texture mapping was applied to the surface model.⁷⁵ Third, 3D computed tomography (CT) was used to image the inside of the ram. The internal CT data was combined with the textured surface model to create a complete virtual model of the ram. The completed model was then sectioned to reveal details about the casting of the ram and used in finite element analysis for structural testing.⁷⁶

A second artifact analysis, that of a 17th-century pocket watch from the wreck of *Swan* off the coast of Scotland further demonstrates the analytical capabilities of 3D visualization. Due to the fragile nature of the artifact, no conservation treatment was applied. Instead, 3D computed tomography was used to image the internal structure of the watch non-invasively. The resolution

⁷⁵ Polynomial texture mapping is the combination of several photographic techniques to create an enhanced view of an object's surface.

⁷⁶ Adams et al. 2013, 60-75.

of the 3D-CT images is such that the entire internal mechanism can be seen in great detail and the makers engraved signature can be clearly read on the inside of the back cover.⁷⁷ X-ray tomography is not new to nautical archaeology. The combination of advanced methods of tomography with 3D visualization and modeling, however, is an exciting new horizon of artifact documentation and analysis. Like 3D timber documentation, however, advanced 3D artifact visualization has seen only limited use despite the increased analytical possibilities it enables.

3D Ship Reconstruction

In 1994, J. Richard Steffy defined three types of ship reconstructions: graphic, three-dimensional (digital), and physical.⁷⁸ Despite the advantages of three-dimensional reconstructions suggested by Steffy, most subsequent reconstruction projects have tended to favor either graphical or physical modeling, or a combination of both. Reconstruction of complete hulls from fragmentary remains is a difficult process that often involves significant informed speculation. Archaeologists combine archaeological data with historic texts, iconography, and other data sources to arrive at a best guess for a complete reconstruction. Traditionally, this process has been carried out largely in two dimensions, with help from scale wooden or cardboard models. Two dimensional and scale model reconstruction have two main shortcomings – they either reduce a complex three dimensional structure to two dimensions or they do not allow fully detailed reconstruction and analysis free from scaling errors. Despite the advantages offered by digital 3D modeling for overcoming these limitations, 3D visualization technology has seen limited use in reconstructing vessels from archaeological remains. When they have been used,

⁷⁷ Troalen et al. 2010, 165-171.

⁷⁸ Steffy 1994, 214.

3D visualizations of reconstructions are generally enhanced illustrations of reconstructions conducted on paper or through physical modeling.

At least one recent project has highlighted the advantages of using 3D modeling is the reconstruction of a 16th-century Portuguese nau from the text of shipbuilding treatises. In his dissertation project, Alex Hazlett analyzed the text of three late 16th-century Portuguese shipbuilding treatises and attempted to construct a ship based on the guidelines found within them. Rather than construct a vessel on paper or using a scale physical model, Hazlett used Rhinoceros 3D modeling software. Several benefits were identified as a result of this modeling approach. First, digital 3D modeling allows rapid fabrication of individual ship timbers. Second, these timbers were easily modified, moved, or otherwise altered as was necessary to test construction hypotheses and seek the best solution. Third, digital 3D modeling enables the user to view the model from a multitude of angles and a level of detail that paper or physical modeling do not allow. Finally, 3D modeling allowed Hazlett to define the units of measurement used to build the model and consequently the model was constructed entirely using late 16th-century Portuguese units. The main shortcoming identified by Hazlett was the limitation of choosing a surface modeler to create the model. Hazlett suggested that a solid modeling program would have enabled a greater level of realism in model construction, on account of the ability to replicate actual material behavior.⁷⁹

⁷⁹ Hazlett 2007.

Few other examples of ship reconstruction through digital 3D modeling exist. In rare cases, 3D models have been used in guiding the construction of scale physical models or replicas, such as the Newport Ship project in Wales.⁸⁰ Up to this point, 3D modeling in nautical archaeology has largely been an afterthought. Most models are based on 2D data. Introducing 3D modeling at a much earlier stage in the project, such as integrating it with initial site and artifact documentation, can enable new avenues for data interpretation.⁸¹ This dissertation project seeks to evaluate the applicability of 3D modeling in naval architectural analysis.

Analytics Based on 3D Models

As with use in reconstruction, the analytical possibilities of digital 3D models have seen limited exploration in nautical archaeology. The best documented case is the ongoing analysis of the *Nossa Senhora dos Mártires*, also known as the Pepper Wreck, a Portuguese *nau* that sank in 1606. The vessel was reconstructed on paper based on archaeological timber remains, but subsequent analyses of the hull have utilized a variety of digital 3D technologies. Among these have been advanced hydrostatic, hydrodynamic, and seakeeping analysis using digital models of the hull and modern naval architecture evaluation tools.⁸² The application of modern naval architecture methods has produced a more nuanced understanding of sailing characteristics of early modern Portuguese east Indiamen. The ‘Virtual Nau’ project saw the creation of a virtual reality model of the ship, which when displayed in a CAVE (cave automatic virtual environment) created an immersive visualization of the reconstruction.⁸³ Cargo loading analyses

⁸⁰ Jones 2005, 12-15; Ravn et al. 2011, 232-249; Smith 2005, 7-11.

⁸¹ Reilly 1992, 147-173.

⁸² Similar 3D analytical studies have been conducted on medieval Viking vessels based on scale physical models; Indruszewski et al. 2004.

⁸³ Wells 2008.

were conducted using the virtual model to test and refine hypotheses about how large seagoing vessels were loaded for long voyages.

Similarly, a computer simulation has been used to reconstruct, load, and analyze the sinking process of the 4th century BC Kyrenia ship.⁸⁴ These types of complex reconstructions and evaluations are examples of analyses that are only possible using digital 3D modeling. Other projects have begun to explore novel 3D visualization analytical possibilities, such as the recent publication on the Gurob Ship Cart Model by Shelley Wachsmann. In addition to a comprehensive archaeological documentation and analysis of the ship cart model, a virtual reality model of the artifact was published online. The virtual reality model lets users examine and manipulate the pieces of the ship cart model to attempt alternate reconstructions and evaluate the author's conclusions in an exercise in interactive publishing.⁸⁵ These examples of digital 3D analytical tools rely at least in part on documentation or reconstruction done in two dimensions on paper or using physical scale models. Despite the demonstrated advantages of moving to a more fully digital process, the nautical archaeology community has yet to see a project take full advantage of digital modeling.

Evaluation of Modeling to Date

3D visualization has seen increased use in nautical archaeology, however many opportunities remain to better utilize these technologies. One of the many advantages of 3D visualization technology in archaeology is the opportunity to examine multiple levels of data at once. Most

⁸⁴ Bawaya 2006, 1106-1107.

⁸⁵ Sanders 2012, 209-218.

applications in nautical archaeology have focused on visualizing macro-level archaeological data – primarily underwater sites. Limited work has been conducted on micro-level (individual artifacts and timbers) analysis and even less on vessel reconstruction and analysis. Very limited work has been done to integrate these levels of analysis.

Digital 3D modeling technologies enable the integration of many of the primary goals of archaeology, including reconstruction, testing, analysis, collaboration, and dissemination. The ability of 3D modeling to enhance archaeological inquiry and analysis and explain the significance of archaeological work cannot be overlooked. Digital tools offer a fuller, more realistic, and more accurate avenue for interpreting and reconstructing past human activities.

Digital modeling tools enable reconstruction at every level of archaeological interest. From the molecular composition of artifacts to the reconstruction of entire vessels to the environments the vessels operated in, digital tools allow archaeologists to aim higher with reconstructions to create a more comprehensive interpretation of the past. Archaeologists are now presented with opportunities to capture more and better data than ever before, much of it digital. The increased adoption of 3D modeling technologies will continue to expand on and utilize this increase of data collection.

ETHICAL CONSIDERATIONS

As computer modeling in archaeology became more popular in the late 1990s, focus shifted from simply the creation of models to developing standards of best practice. These included

providing greater transparency for the driving scientific data behind models, developing ways of distinguishing hypothesized parts of models, and metadata standards.⁸⁶ The ethics of computer visualization came into question, and is still an active arena of debate today.

While three-dimensional visualization technology can significantly enhance the work of archaeologists, these powerful tools require ethical consideration. A visualization consists of two primary components: observable real-world data and a theorized interpretation of that data. As computer models continue to gain credibility and authority in their ability to communicate complex data in an ever more image-dominated world, archaeologists must take care to be transparent and thoughtful in the creation and presentation of their models. As with all archaeological reconstructions, digital models are a best guess, not an objective scientific truth. By nature, the archaeological record is incomplete and all archaeologists strive to achieve the best possible understanding of a fundamentally unknowable past.⁸⁷ In seeking to reconstruct and interpret this past, archaeologists fill in gaps through the formulation and testing of hypotheses. When these hypotheses are represented as three-dimensional virtual reconstructions, the archaeologists must make clear what part of the model is founded on archaeological fact and what is a product of hypothesis.⁸⁸ This is especially critical as advancing visualization technology enables the creation of increasingly realistic reconstructions, which are often interpreted as being more scientifically accurate because they appear completely rational.⁸⁹

⁸⁶ Frischer 2008, v-xxiv.

⁸⁷ Lock 2003.

⁸⁸ Barceló 2002, 21-28.

⁸⁹ Winterbottom and Long 2006, 1364.

Virtual reality archaeological reconstructions have been especially criticized as misleading because they present a seemingly ‘whole’ picture of an ancient landscape or site.

These challenges can be overcome by addressing two main underlying concerns; making explicit the data upon which the model is based, and allowing room for alternative reconstructions and interpretations.⁹⁰ Whereas once computer models were not capable of easily differentiating data from hypothesis in a reconstruction, nearly all three-dimensional modeling and rendering programs in common use provide the option to clearly distinguish parts or features of a model. This means that archaeologists can easily indicate which parts of a model are hypotheses, and which are archaeological fact, similar to mending or reconstructing pottery using a distinct color of plaster or clay to indicate reconstructed portions of the vessel. As with any archaeological reconstruction, the archaeologist must be careful to not claim his or her reconstruction to be definitive truth but simply a best guess based on the available data. Academic debate and multiple interpretations are fundamental to modern archaeological theory and practice and digital models should reflect this aspect of the discipline. This is particularly important when using digital models, as the technical nature of this modeling technique can artificially introduce authority and finality into a hypothesis, especially when using three-dimensional models to communicate archaeological findings to the public.

A virtual model should be understood for what it is – a model. It is a set of observations, interpretations, and testable hypotheses expressed in images that can be tested.⁹¹ Digital models

⁹⁰ Niccolucci 2002, 4.

⁹¹ Barceló 2002, 27.

do not provide definitive answers to archaeological questions, they simply define a narrower context within which to speculate.⁹² The advantage that digital models provide is their ability to communicate complex ideas, ease of dissemination, modifiability, and ability to harness powerful analytical tools – including human visual perception.

VIRTUAL ARCHAEOLOGY

‘Virtual archaeology’ is a term used to encompass the methods discussed above. Broadly, virtual archaeology is concerned with the application of 2D and 3D models in archaeological analysis. Initially, the aim of virtual archaeology was simply to use computer visualization to aid in interpretation of archaeological data. The term was later expanded to mean creation and dissemination of the most faithful and realistic archaeological reconstructions possible, with presentation of scientifically sound archaeological data.⁹³ New analytical and presentational dimensions have been added to studies in virtual archaeology over time including interactivity, computer simulation, and data mining. In the last two decades, as computer technology has become widely accessible, exercises in virtual archaeology have explored a variety of applications. Projects have included the automatic classification of artifacts, production of interactive games, facial reconstructions, digital gardening, and CT scanning mummies.

Visualization methods have gained general acceptance in the archaeological community and are a powerful new asset in the archaeologist’s tool kit. In archaeology as a whole, 3D modeling has become more than a method of illustration or teaching aid and is now considered to be a

⁹² Winterbottom and Long 2006 1356-1367.

⁹³ Forte and Siliotti 1997, 10; Reilly 1989 569-579.

powerful research tool capable of generating novel data. Moving forward, additional dimensions and tools will be integrated into 3D visualization to make them even richer representations of the past and enhance their analytic capabilities. Aspects may include haptic tools to handle objects and further facilitate physical intuition, 3D printing technology to reproduce artifacts, audio evaluation tools to populate reconstructed buildings and landscapes with sound, increased physical property evaluations, and further development of artificial intelligence to model the behavior of humans, animals, and artifacts.

One facet of digital visualization that has thus far been under-utilized in archaeology is 3D solid modeling. Solid modeling builds digital models with real-world physical fidelity, not just appearance, as the goal. This type of modeling has been widely adopted by mechanical engineers, aerospace engineers, architects, and other engineering-based fields concerned with the production of mathematically accurate computer models of real world objects. The models created by solid modeling programs are actual size, easy to manipulate, and behave as their real-world counterparts. Most importantly, solid models have mass, a key property that most archaeological models to date lack. As a result, material properties, such as density, compressive and tensile strength, and shear modulus, can be applied to the models to make them as close to physical reality as possible. Furthermore, working assemblies of many parts can be created and operated with realistic performance. This enables a range of simulation and testing possibilities, including finite element analysis which can evaluate models under operational conditions. Despite the accessibility of solid modeling software, it has seen little adoption by the

archaeological community since it was first experimented with in the early 1990s.⁹⁴ The following chapter details the use of solid modeling to construct structural models of *Vasa*.

⁹⁴ Steckner 1996, 923-938.

CHAPTER V

MODEL AND VISUALIZATION

As discussed in previous chapters, 3D modeling is proposed as a means to overcome the challenges of recovering the design of *Vasa*'s intact hull. For this dissertation project, 3D solid models of key parts of *Vasa*'s structure were constructed to facilitate analysis.¹ This chapter details the modelling software and procedure used to produce these models. Like any technical skill, digital modeling is described using specialized terminology. Because many of these terms may be ambiguous or redefined in the future, care is taken here to define the terms most relevant to the discussion of the creation of the *Vasa* models.

SOLID MODELING

Three basic types of computer models are widely used in 3D digital imaging: **wireframe**, **surface**, and **solid**.² To highlight the differences in model types, the same object was modeled 3 times in SolidWorks. The wireframe version of this model is seen in Figure 5.1, the surface version in Figure 5.2, and the solid version in Figure 5.3. Wireframe modeling is the simplest form of digital 3D modeling and is the least demanding of computer software and hardware. Most 3D modeling and CAD packages allow users to easily create wireframe models. In this type of model, 3D entities are defined by **points** in 3-dimensions space and interconnected **lines**. While wireframe models are simple to construct and manage, they contain very little information

¹ Because not all of *Vasa*'s structure is relevant to the design study, modeling focused only on the elements of the hull that are directly related to and evident of the design process.

² Bolded modeling terms are defined in the Appendix.

about object surfaces and volumetric data. Wireframe models display only the sharp edges of an object as lines in space and cannot define complex curvatures; therefore, they incompletely describe an object.

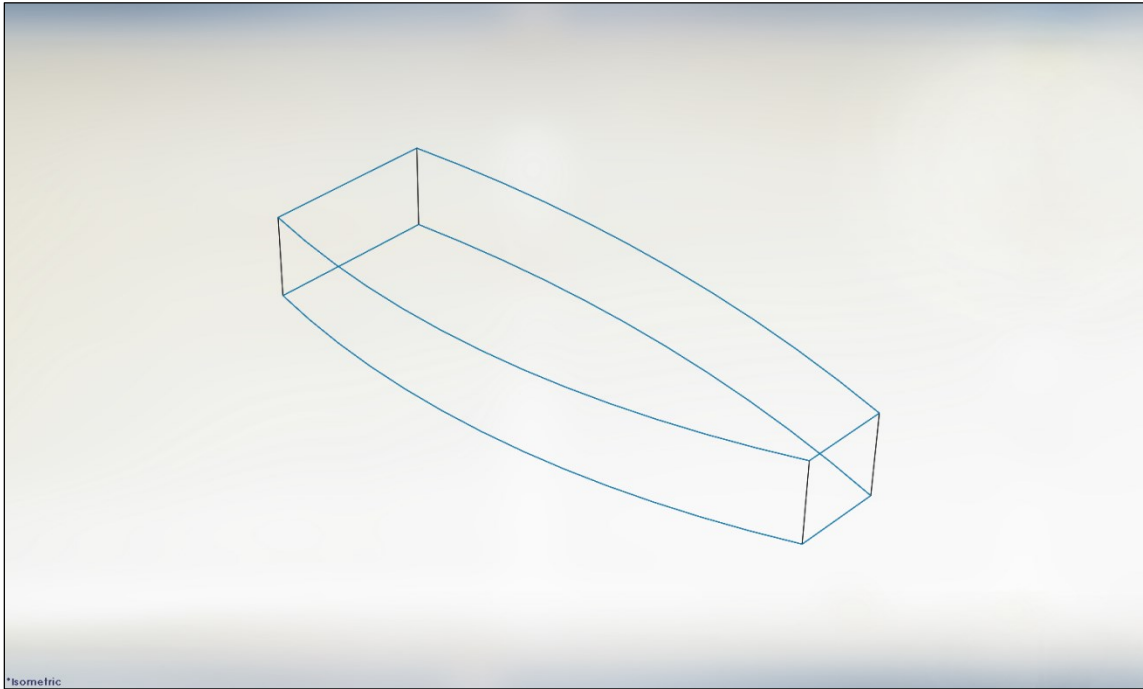


Figure 5.1. A wireframe model.

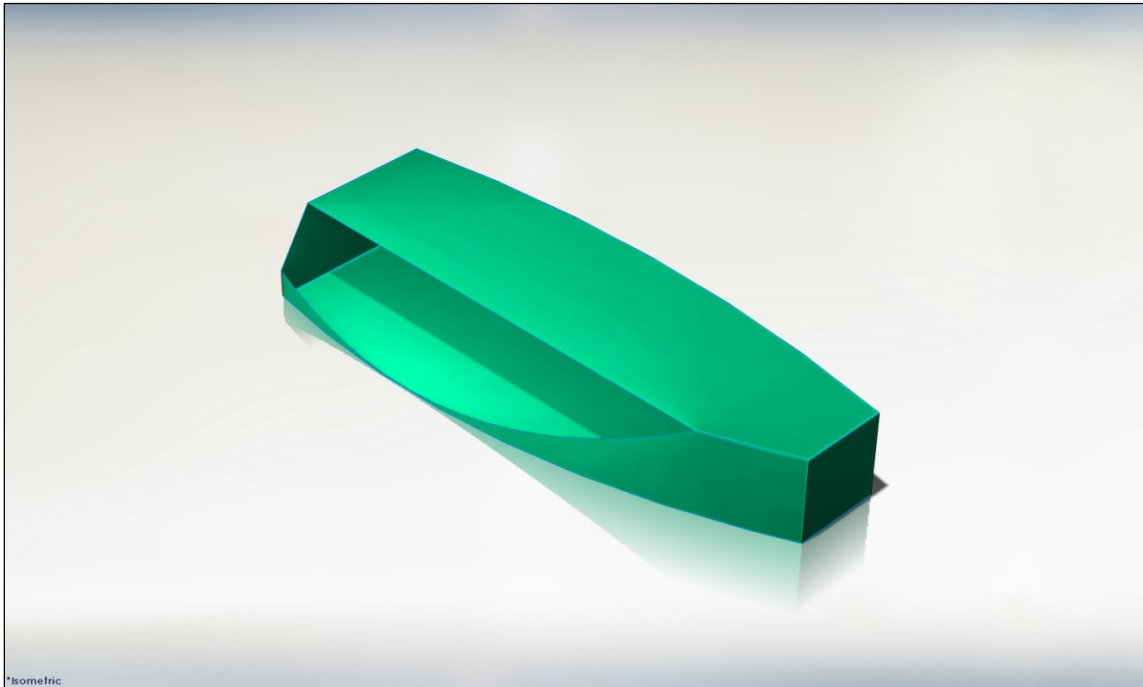


Figure 5.2. The same object as Figure 5.1 as a surface model cut to show the model is hollow.

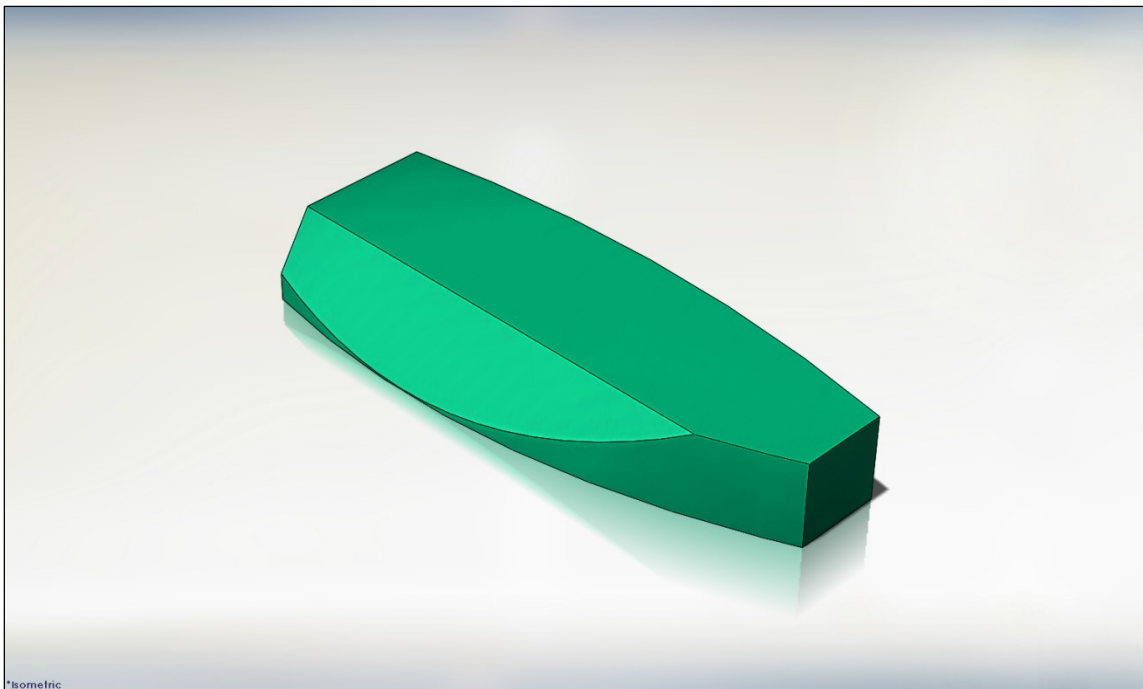


Figure 5.3. The same object as Figure 5.1 and Figure 5.2 as a solid model, with the same cut as Figure 5.2.

The ambiguities inherent in wireframe modeling are overcome by defining the surfaces of an object using surface modeling. In this modeling approach, surfaces are used to fill in the spaces between the edges of a wireframe model and are capable of defining complex curvatures (curvature in more than one direction). Surfaces are infinitely thin boundaries between the inside and outside of an object.³ Two main types of surfaces allow for a wide range of shape creation. Algebraic surfaces, such as planar, cylindrical, spherical, and conical, are defined by simple mathematical expressions and are easy for computer software to calculate. They are, however, limited in the types of shapes they can create and not suitable for construction of complex shapes. NURBS (non-uniform rational basis spline) surfaces allow for the creation of virtually any shape, regardless of the complexity of its curvature. NURBS uses calculations to interpolate points on **curves** and surfaces to enable highly flexible shape creation.⁴ NURBS modeling is also highly precise, and allows the creation of models accurate to 0.000001 inch.⁵ Surface models provide information about discontinuities in the surfaces of objects, differentiate between the inside and outside of an object, and allow for **texturing** to create more realistically rendered models. Although surfaces do not have any volume themselves (they only have the property of area), if they form a closed object they can be used to define volume. They do not, however, provide any information about the internal structure or physical properties of a model. The NURBS-based software Rhinoceros, developed by Robert McNeel & Associates, has seen the most widespread use among digital 3D modeling projects in nautical archaeology.

³ Lombard 2008, 10.

⁴ Lombard 2008, 17-18.

⁵ Lombard 2008, 24.

Solid modeling is the most precise and accurate way to describe mechanical objects in a computer. Solid models fully define the geometry and volume of an object, provide detailed information about the internal structure of an object, and provide the accuracy needed for detailed mechanical design.⁶ Solid modeling is routinely used to construct and define objects in CAD software for analysis and manufacturing. Generally, solid modeling requires less specializing computer expertise and is an easier and more intuitive process, especially for novice users.⁷ A solid model has three main requirements: its faces form a fully watertight boundary with no gaps or overlaps, it is composed of a single body, and all surfaces clearly distinguish the inside of the object from the outside.⁸ This produces a digital object that can be cut in any direction and still remain a solid. Solid modeling is the least ambiguous type of 3D computer modeling and produces models that are suitable for precision manufacturing and engineering. Despite the physical fidelity solid models are capable of and the significant advantages they offer to archaeologists, they have been rarely utilized to this point.

SOFTWARE

From a range of 3D CAD software packages, SolidWorks, developed by Dassault Systèmes SolidWorks Corp., was selected for this project. SolidWorks was initially released in 1995 and is one of the first solid modeling programs to be written exclusively for the Microsoft Windows operating system. To date, when digital 3D modeling has been applied in nautical archaeology, nearly all projects have relied on wireframe and surface modeling. The selection of a solid

⁶ Amirouche 2004, 37-38.

⁷ Lombard 2008, 9.

⁸ Lombard 2008, 16.

modeling approach to this project is an effort to evaluate the applicability of solid modeling to nautical archaeology and expand the range of CAD software used in the discipline.⁹

SolidWorks is virtual prototyping software that is widely used in mechanical engineering.

Virtual prototyping is the creation of digital models that represent their physical counterparts in the most realistic way possible. Mechanical engineers use this process to drastically reduce design and production cycle time and to perform physical validation of parts or products without the need to fabricate tangible objects. Virtual prototyping allows for rapid modification and real-world evaluation of objects without the need to build and rebuild physical prototypes. This approach has numerous benefits to archaeological work, which often seeks to reconstruct and evaluate incomplete artifacts.

SolidWorks employs a parametric feature based modeling approach, meaning that models generally begin as 2D **sketches** (in SolidWorks, sketches are the most basic part of a 3D model). Sketches are two dimensional profiles created on a plane composed of points, lines, curves, and arcs. Sketches can also be made in three dimensions, where they are not tied to a plane, and are especially useful in working with point cloud data. Sketches are given **parameters** to control their geometry (eg. side A will always be twice the length of side B, regardless of the actual length of side B). The parametric design aspect of SolidWorks allows a user to define a set of geometric constraints for creating the geometry of an object. The geometric constraints describe the basic dimensions and arrangement of object components and act as a set of instructions for

⁹ Although solid models are the focus of SolidWorks, it is a hybrid modeler and takes advantage of both surface and solid modeling approaches. There are examples of surface only modelers such as Rhino, and solid only modelers such as Alibre; Lombard 2008, 14.

creating the desired geometry.¹⁰ This design approach creates relationships between entities, which governs the interaction between elements when one dimension or variable of a design is changed. For example, a user could define parameters for a given timber such that its molded dimension was one eighth of its length, regardless of the sided dimension. Processes called **features** are applied to sketches to create a fully defined 3D model.¹¹ The resulting solid model can continue to be modified through the application of more features. This is an advanced type of solid modeling software, and offers significant advantages over **B-rep** (boundary representation) or **CSG** (constructive solid geometry) modeling – which historically have been the primary methods of solid modeling. Despite the sophistication of this modeling method, feature based modeling is simple for users to learn and allows intuitive shape creation.

The basic model unit that SolidWorks is intended to recognize is the **part**, a distinct solid body, and saved as a separate file. Parts can be created individually or built as an **assembly**, but each part is recognized as a separate unit. SolidWorks features associativity between parts and assemblies, meaning that if a change is made to a part, the changes can automatically be applied to every drawing and assembly that part is included in. This feature streamlines the process of editing models and is especially helpful if large assemblies are created. Associativity is also useful for testing reconstruction hypotheses. When creating assemblies, SolidWorks offers automatic interference and collision checking. These features ensures that models are assembled and function in a realistic way. SolidWorks offers a number of simulation packages that provide tools to test and validate models. A variety of factors can be tested, including structural, nonlinear, motion, flow, thermal, and finite element analyses. The range of simulation packages

¹⁰ Amirouche 2004, 40-41.

¹¹ Lombard 2013.

available make SolidWorks an appealing tool for archaeologists who wish to test reconstructions of artifacts or structures under real world conditions without the time, expense, or logistical difficulties of building a physical replica.

DATA COLLECTION

The data used to create the 3D solid models used in this dissertation came from a variety of sources, collected both by myself and the staff of the Vasa Museum. The primary data set is the series of point clouds collected via total station and compiled by the staff of the Vasa Museum. From the time the wreck of *Vasa* was positively identified in 1956, it has been the subject of various archaeological documentation efforts.¹² This has resulted in a considerable body of data that includes drawings, notes, photographs, and observations made by many researchers over more than five decades since *Vasa* was raised. Access to much of this information was generously made available for this dissertation by the staff of the Vasa Museum, in particular by Dr. Fred Hocker, Director of Research. In addition to the data compiled by the Vasa Museum, I have added personal notes, photographs, measurements, and sketches during two research trips (summer 2010 and summer 2011) at the Vasa Museum. I focused my attention on collecting data specifically pertaining to design and filling in gaps in the otherwise extensive structural data on the hull of *Vasa*. During the summer 2011 research trip, I brought a portable borescope, loaned to me by conservator James Jobling at the Texas A&M University Conservation Research Laboratory, to aid in viewing inaccessible or difficult to access structures of the hull, including the inboard faces of the stem and keel.

¹² Cederlund and Hocker 2006.

The point clouds consist of total station data collected by survey teams of Vasa Museum staff and visiting scholars from 2007 to 2012 in an effort to collect detailed spatial data on the entire hull. The teams used three different total station devices, a Leica TS06 reflectorless unit, a Leica TDA 5005 reflective target, and a Topcon GPT-3000 LW. Data from the Leica units was processed first in Leica Survey Office software, and then imported to Microsoft Excel and then finally used to create 3D point clouds in Rhinoceros. Data from the Topcon unit was processed in TOPSURV 8 software before moving to Excel and Rhinoceros.¹³ The environment inside the Vasa Museum remains a constant 18 degrees C +/- 1 degree and 53% humidity +/- 2%; no environmental corrections were necessary for the survey units. Repeatability for all three instruments has been found to be +/- 5mm over the length of the ship. Reference control was established by backsighting to fixed reference prisms with known locations accurate to 0.5mm. In total, approximately 85,000 points were recorded.

CREATION OF THE *VASA* SOLID MODELS

The reverse naval architectural analysis of *Vasa* in this dissertation is based on 3D solid digital models created using SolidWorks 2012 and SolidWorks 2013. Four separate model files were constructed, each focusing on a key component or structure critical to design analysis: the keel, stem, sternpost, and planking. Each file contains multiple timbers. A key feature of SolidWorks is the creation of complex assemblies composed of many individual solid bodies. Individually modeled parts were assembled to create a composite model as needed for analysis.

¹³ Fred Hocker, pers. comm.

All models were created following the same basic procedure, outlined and illustrated below. The first step in creating the models was to crop the point cloud data to focus only on areas of interest for design analysis. This was necessary to reduce the number of points and more clearly view the areas of interest. Cropping the point clouds also reduced the file size and made the files easier for SolidWorks to process. The point cloud files were supplied by the Vasa Museum in .3DM format, the native format of Rhinoceros modeling software, and thus cropping occurred in Rhinoceros. Once files were cropped, they were exported from Rhinoceros as .IGES/.IGS (Initial Graphics Exchange Specification) files, a vendor-neutral 3D modeling format that allows for import/export among many CAD packages.¹⁴ Screenshots of a point cloud before and after reduction are shown in Figure 5.4 and Figure 5.5.

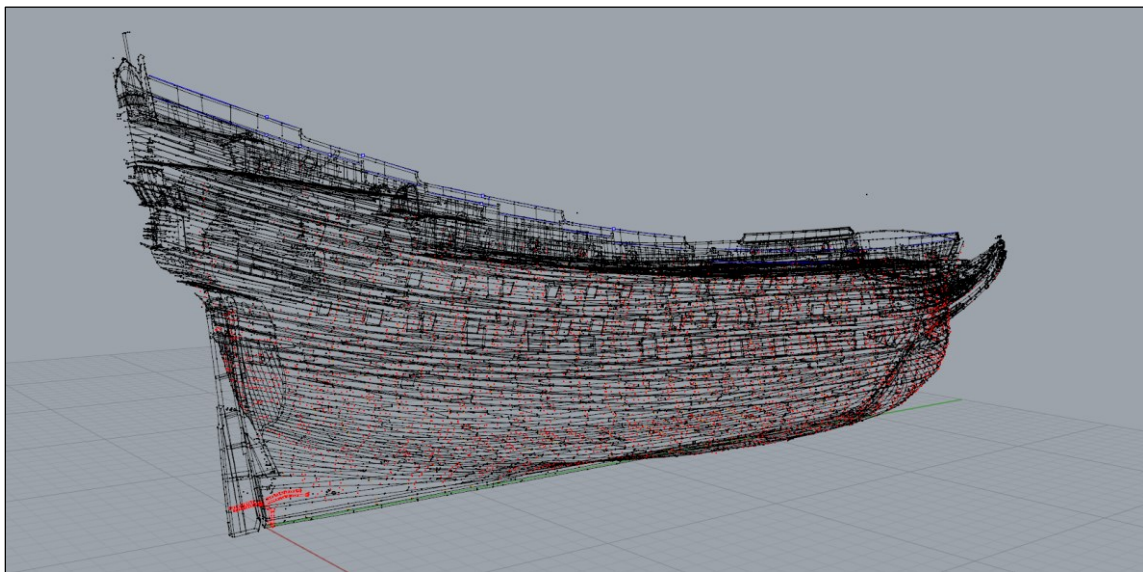


Figure 5.4. Point cloud of *Vasa* in Rhinoceros before cropping. More than 5,000 curves and 27,000 points.

¹⁴ The “SolidWorks solids” IGES type was selected when exporting from *Rhinoceros*.

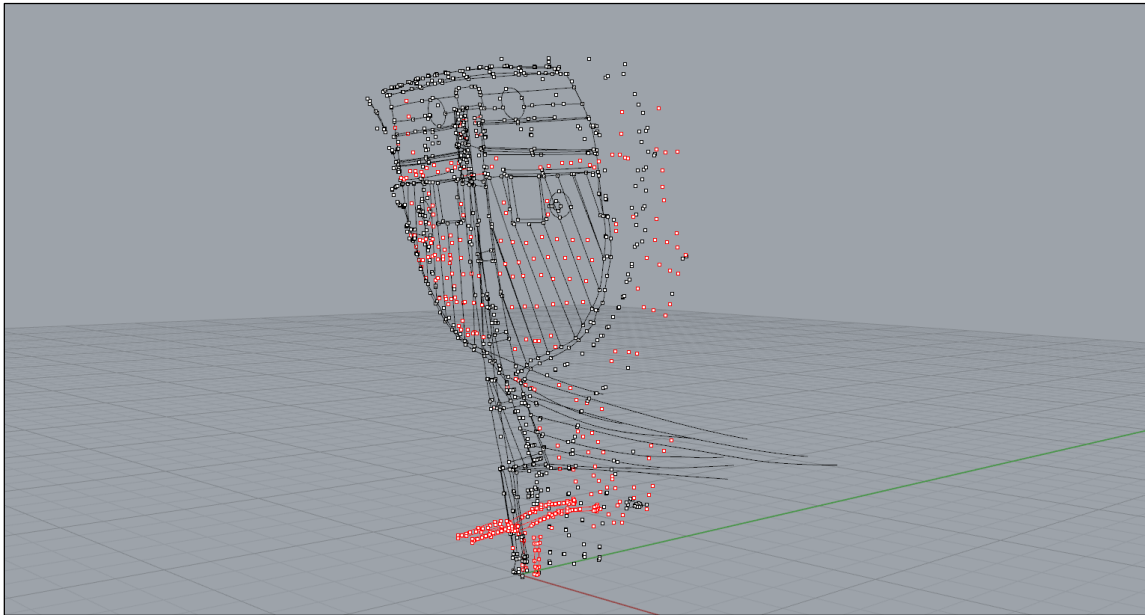


Figure 5.5. Cropped point cloud focused on the sternpost, approximately 300 curves and 1,200 points.

The new IGS point cloud files were then opened in SolidWorks using the default SolidWorks part template and saved as .PRT files, a native SolidWorks format, and the unit standard defined as CGS (centimeter, gram, second). Upon importation, SolidWorks recognizes two types of entities: the points in the cloud, and the curves connecting select points. The floor of the model was defined as the X/Y plane in SolidWorks to ensure each model was created in the same orientation. The same point cloud appears in Figure 5.5 (Rhinceros) and Figure 5.6 (SolidWorks).

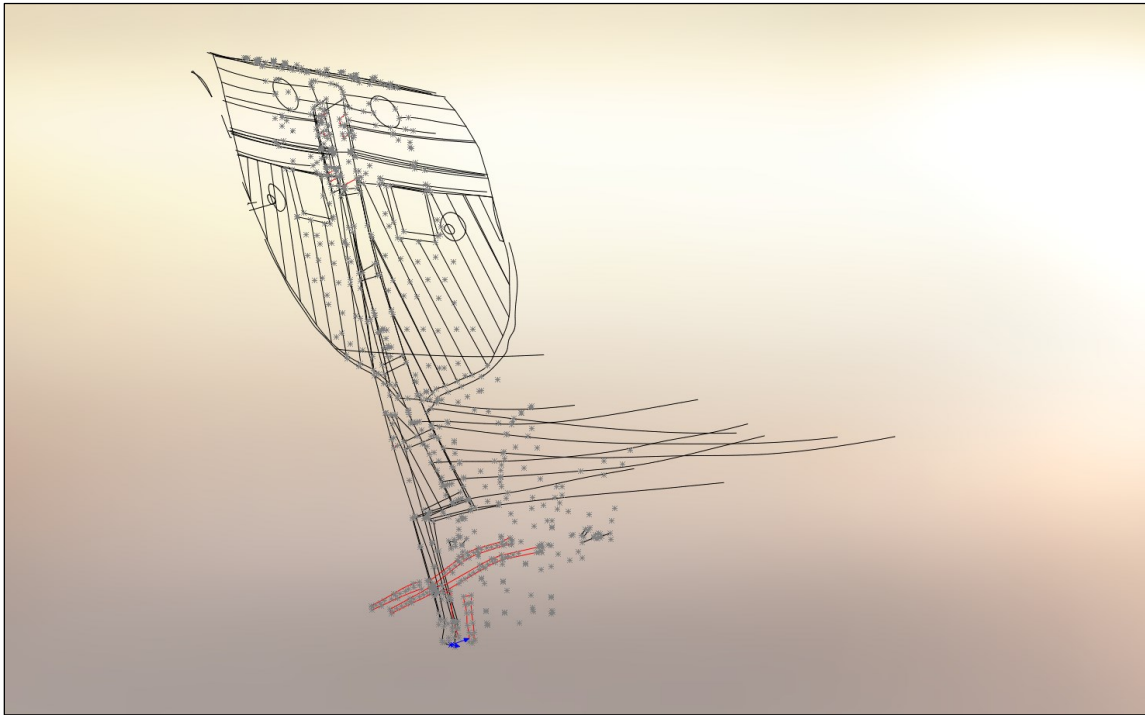


Figure 5.6. Imported point cloud and curves for sternpost in SolidWorks.

SolidWorks offers multiple ways to approach the creation of a solid model. For the models in this dissertation, two main modeling approaches were taken. The first, used to create the keel, stem, and sternpost, employed lofting two or more profile sketches to create a solid. These models were then trimmed, cut, and adjusted as needed to accurately represent the structure of *Vasa*'s timbers. The second approach, used to create the planking, used thickened surfaces to model the complex curvature of *Vasa*'s hull planking. These processes are detailed below.

Broadly, the modeling processes followed a point-sketch-surface-solid progression. Points in the cloud were used as a guide for lines and splines which defined a closed sketch. This process is similar to creating a wireframe model in other programs. In SolidWorks, both 2D and 3D sketches can be created, enabling the definition of complex shapes. Closed sketches were then

filled with a **surface**.¹⁵ This surface could be thickened (given volume) to create a solid if no other parameters were needed. In most cases, however, at least two surfaces were needed to accurately model a timber or timber section. Two surfaces can be used to define a solid by filling in the space between them. In SolidWorks this is called **lofting**; the progression of this process is illustrated in Figure 5.7, 5.8, and 5.9. Most timbers in this study were created by first defining at least two surfaces and then lofting them, creating a solid bounded by the surfaces and controlled by **guide curves**. At this point, models could be further shaped as needed by applying a variety of cuts or by being combined with other models. The specific modeling procedure for each hull timber is detailed and illustrated below.

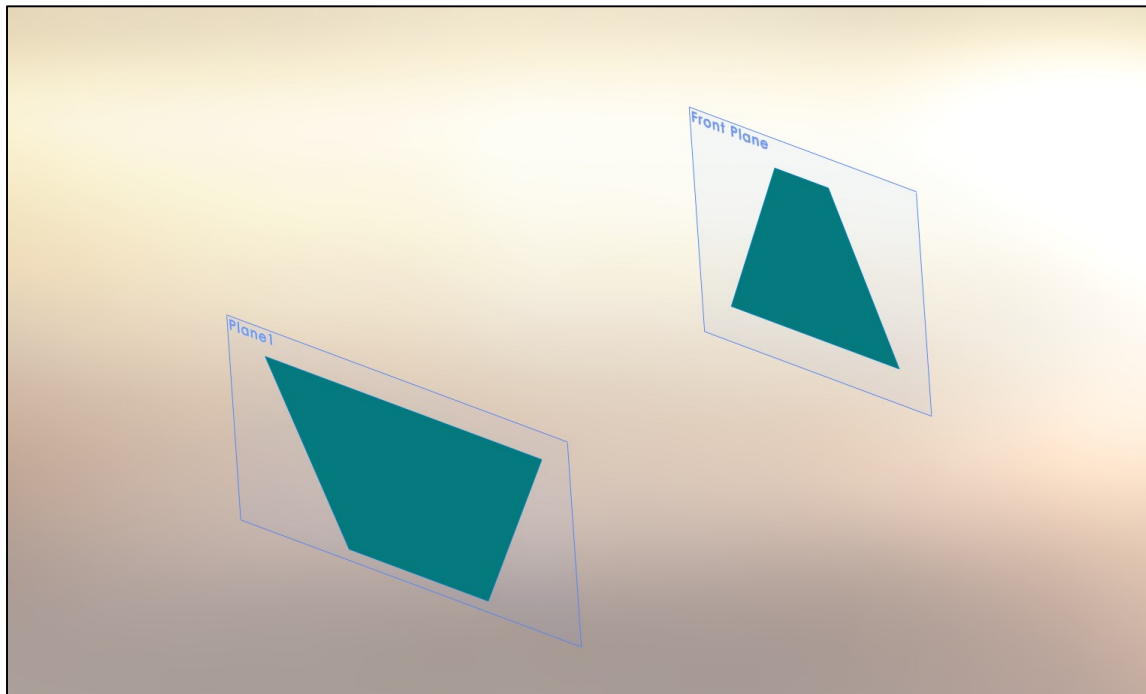


Figure 5.7. Two planar surfaces.

¹⁵ A closed sketch contains no exposed endpoints, both ends of lines are connected to other lines.

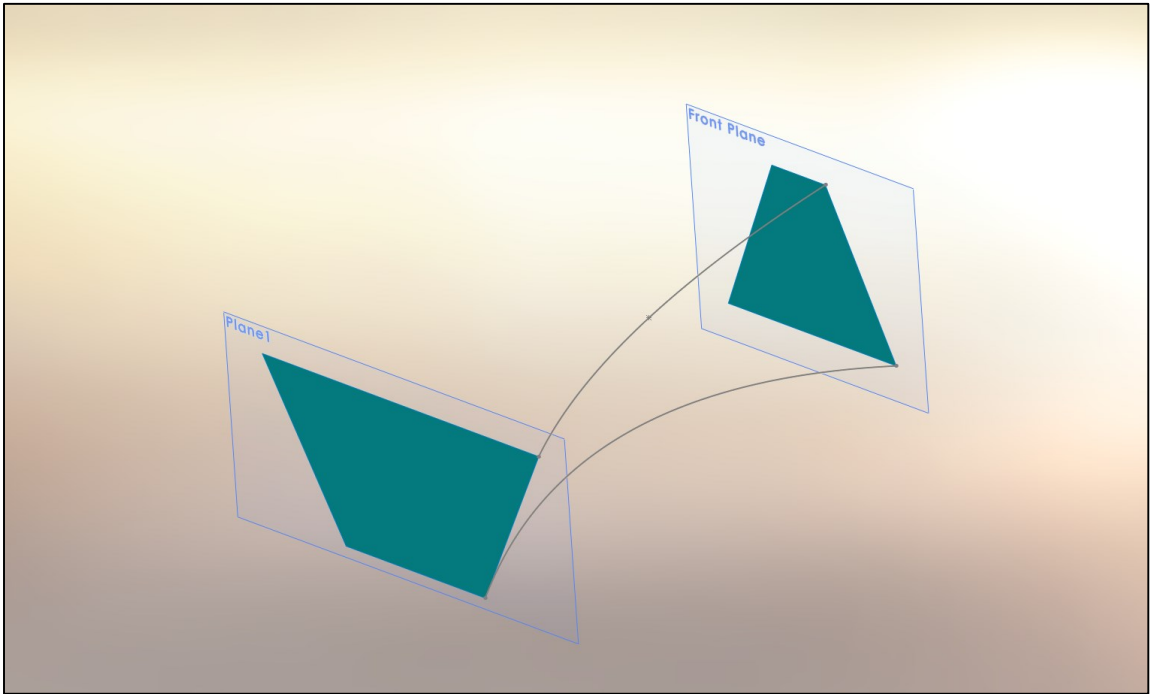


Figure 5.8. Guide curves connect surface vertices to define the contour of the resulting solid.

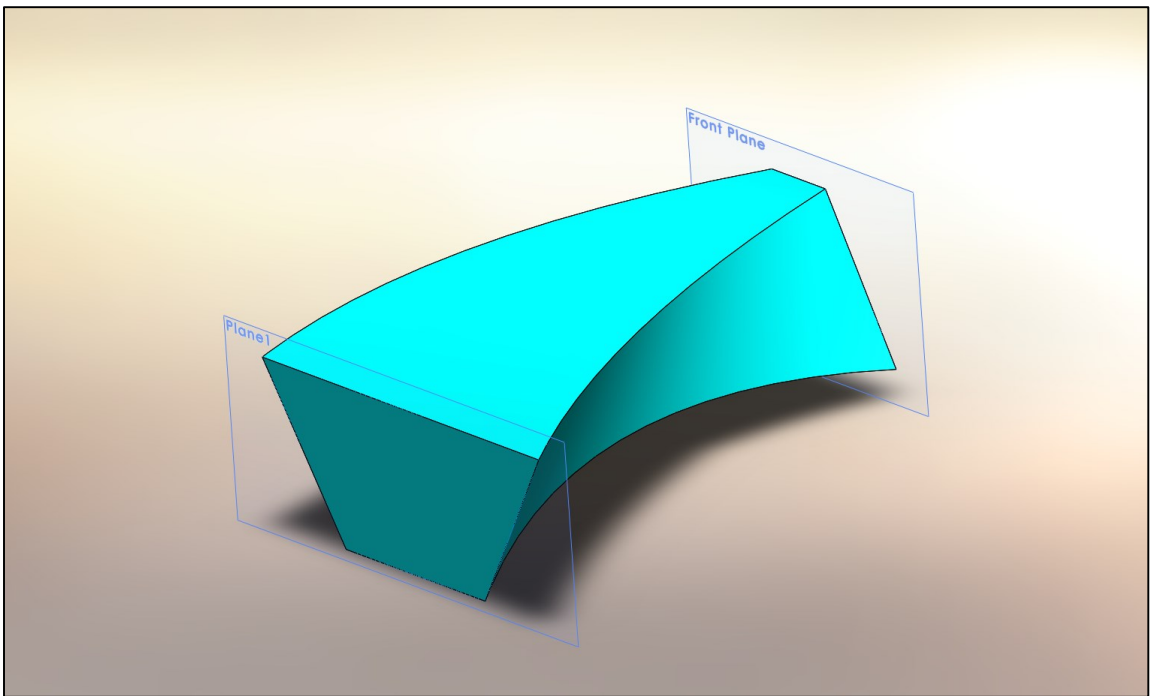


Figure 5.9. The resulting solid, lofted between the two surfaces and shaped by the guide curves.

KEEL MODEL

The first hull element to be modeled was the keel. As described above, the point cloud was cropped in Rhinoceros, imported into SolidWorks, oriented, and saved as a .PRT file, as shown in Figure 5.10. The keel of *Vasa* is composed of four timbers and so the model was built one keel timber at a time.¹⁶ Each section was built using two rectangular profile sketches, one at each end of the timber. While the ends of the keel are clearly visible from outside the ship and are accurately recorded in the point cloud data, the full inboard dimension of the keel is not. The profiles were made to reflect the fact that the keel has its greatest molded dimension toward the middle of the keel and tapers toward the ends. The space between was then lofted, creating a solid. This process is illustrated in Figure 5.11 and Figure 5.12. Creating a solid in this manner roughly defines the volume of the keel section but lacks all other features including scarfs, tapering, and the rabbet. These elements were added by applying features to the model.

¹⁶ Keel sections were numbered 1-4, from bow to stern. Keel section 4 was the first section modeled and is used in the illustrations of the keel modelling process. The same procedure was used for each section.

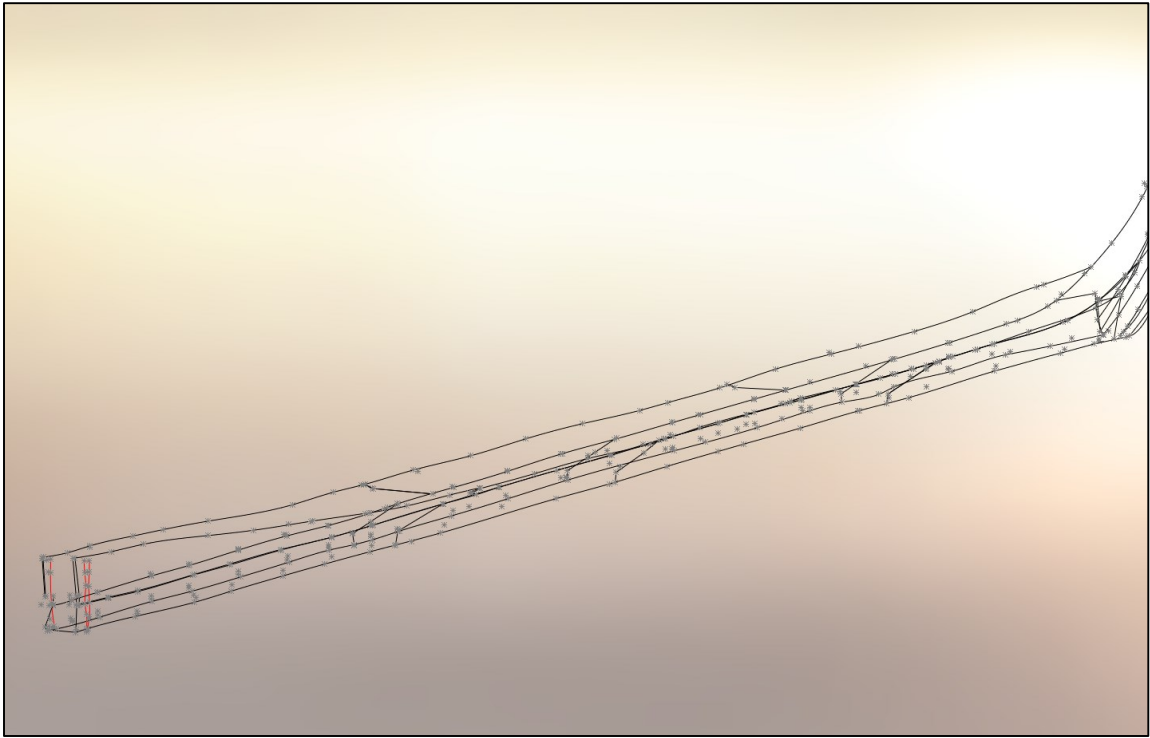


Figure 5.10. Cropped and imported point cloud for the construction of the keel models.

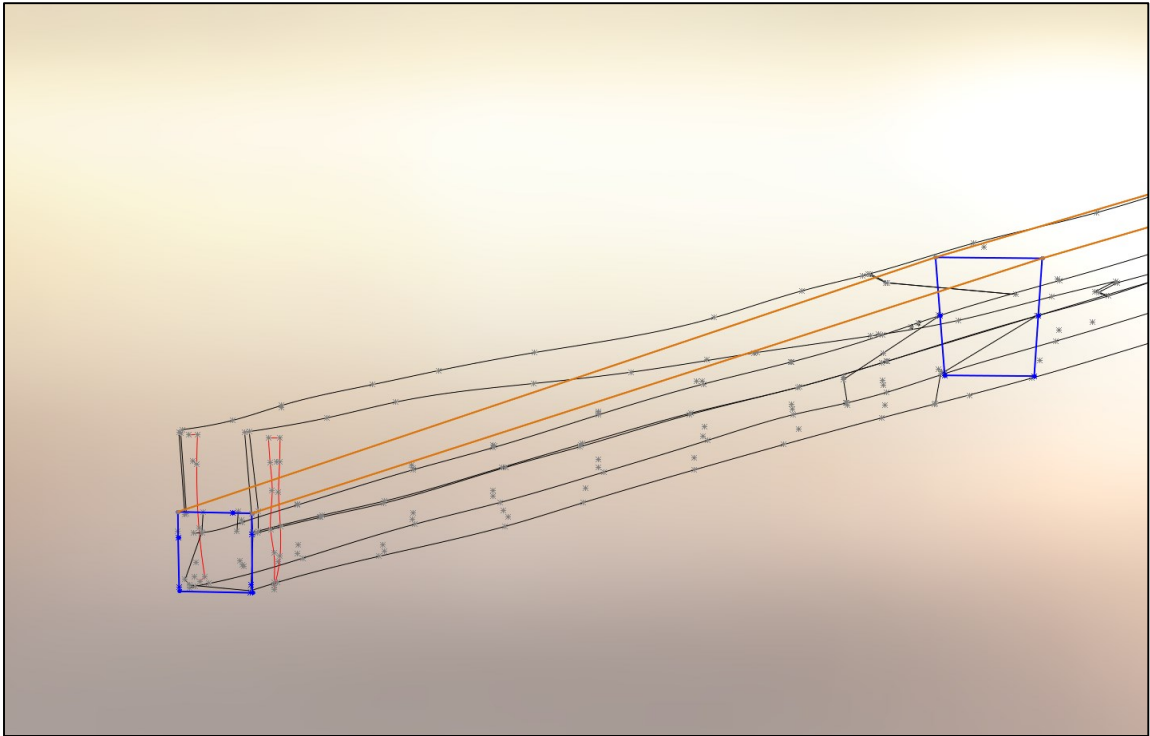


Figure 5.11. Profile sketches (in blue) and guide curves (in orange) for the construction of the aft-most keel section.

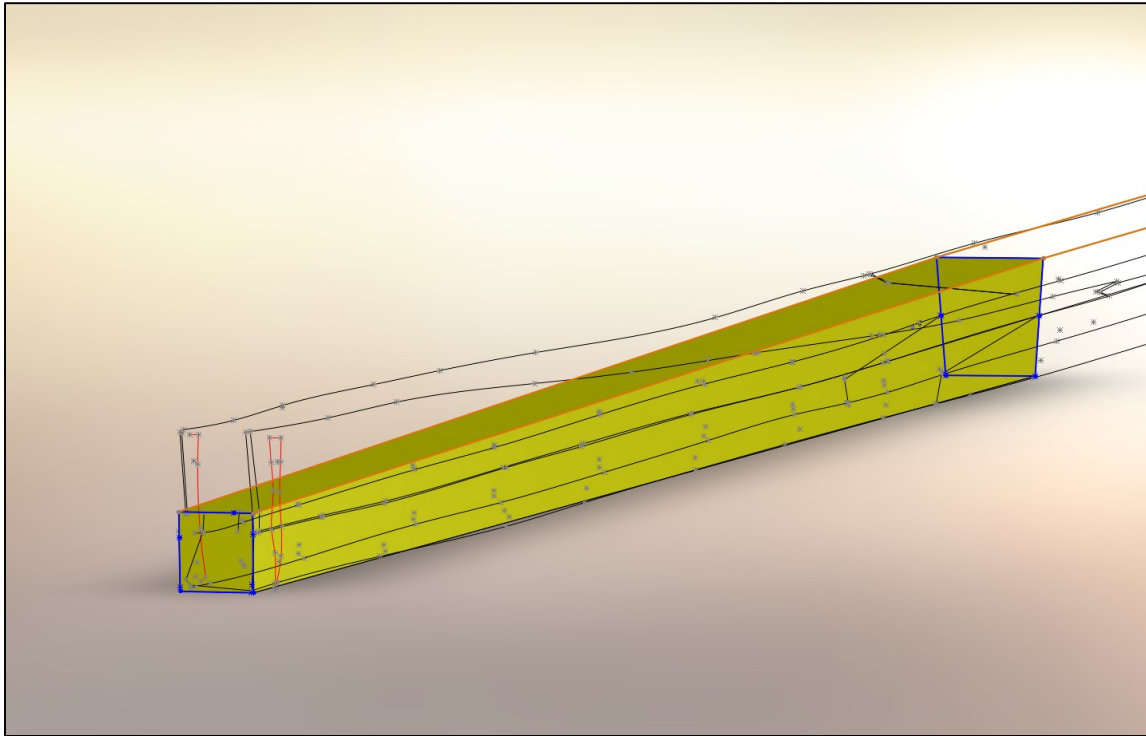


Figure 5.12. Lofted solid body of the after keel section.

The first feature applied to each section was the rabbet. To create the rabbet, a sketch approximating the profile of the garboard was made on a plane coincident with the after face of the keel section. A **sketch path** was then made following the bearding line, which is recorded in the point cloud data. This process is shown in Figure 5.13. Using the **swept cut** feature in SolidWorks, the garboard profile was swept along the bearing line and rotated along the path as indicated by the back rabbet line in the point cloud data. The result is illustrated in Figure 5.14. This process was repeated for each section of the keel and on both sides of the model. Figure 5.15 shows the fully rabbeted keel.

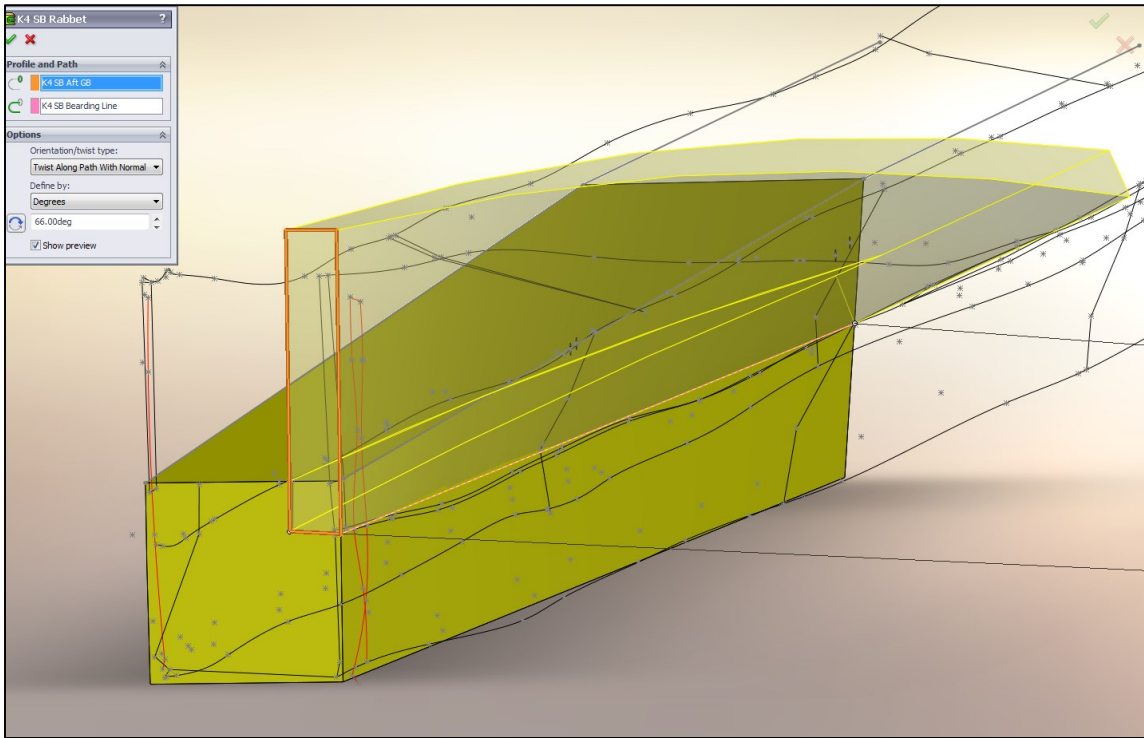


Figure 5.13. Creating the rabbet. The garboard profile (in orange) and bearding line (dotted) are used to define the profile and path of the swept cut.

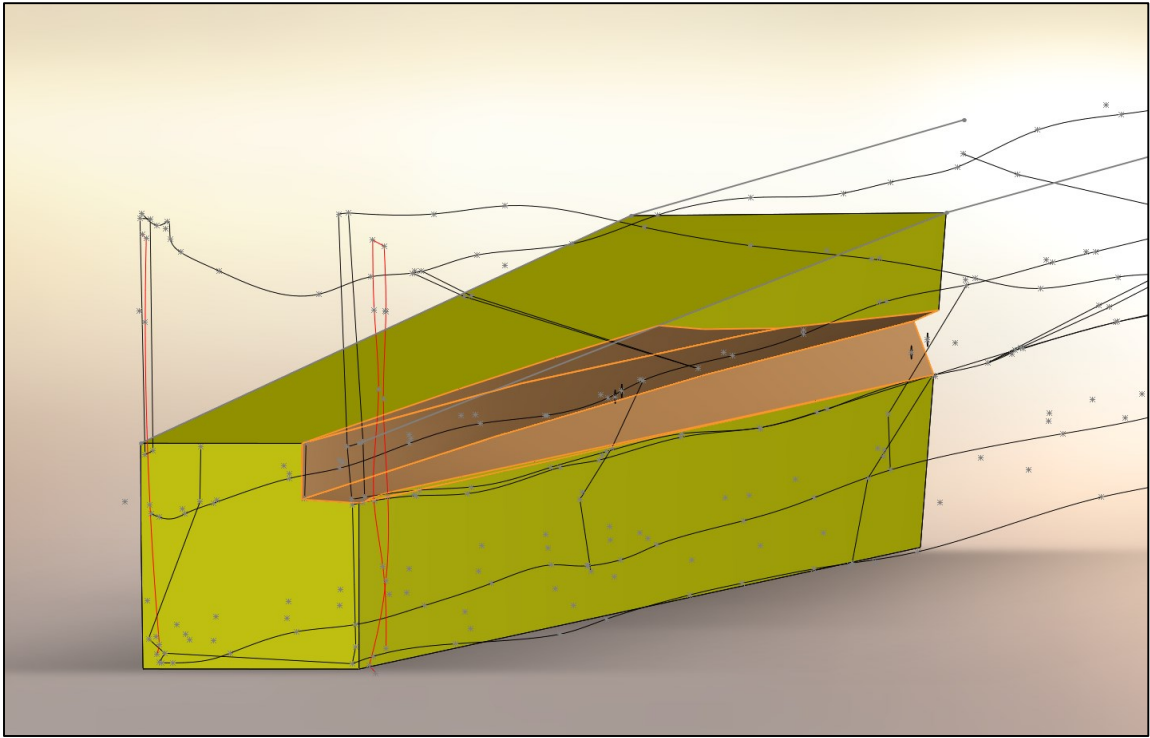


Figure 5.14. The finished starboard rabbet, the result of the swept cut.

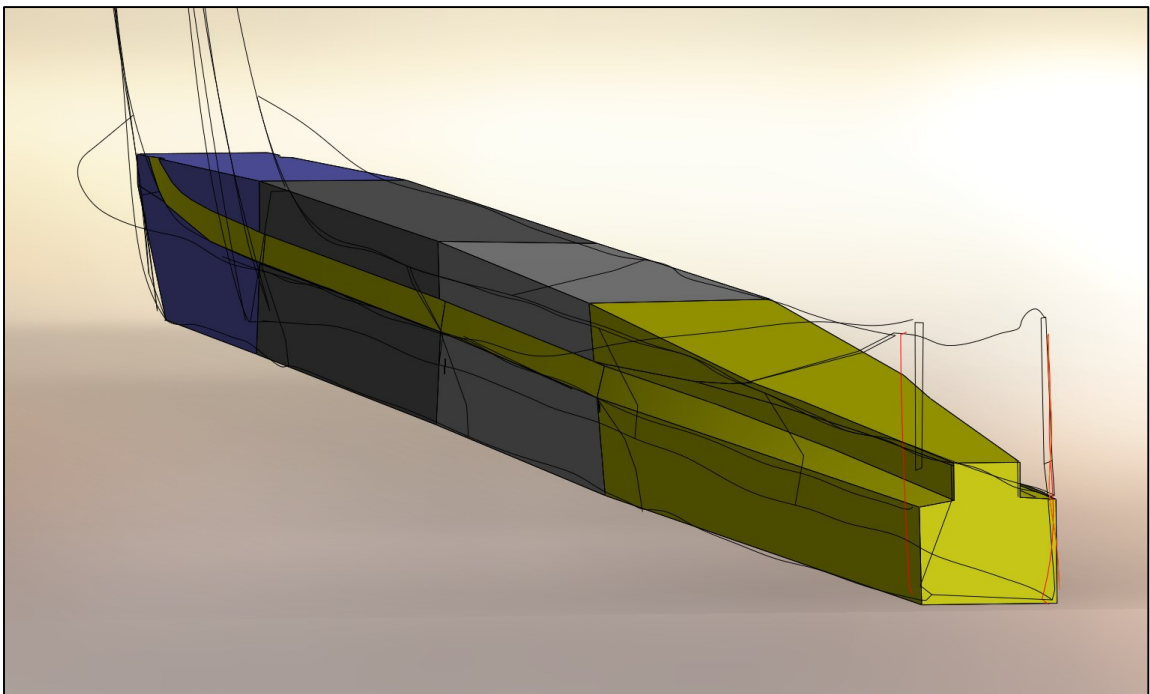


Figure 5.15. Complete rabbeted keel.

Once the four sections of the keel were modeled and the rabbet was cut, scarfs were created between the keel sections. To do this, two parallel **planes** were created on either side of the keel. The profile of each scarf, as indicated by the point cloud data, was sketched onto these planes.¹⁷ Then, using the **boundary surface** tool, these sketches were used to create a surface that projected through the solid keel as illustrated in Figure 5.16. This was done for each of the three scarfs between keel sections. The **split** tool was then used to split the solid keel sections using the surfaces that defined each scarf. This tool enabled the definition of distinct solid bodies on either side of the sketch, plane, or surface used for the split. The fully split keel is seen in Figure 5.17.

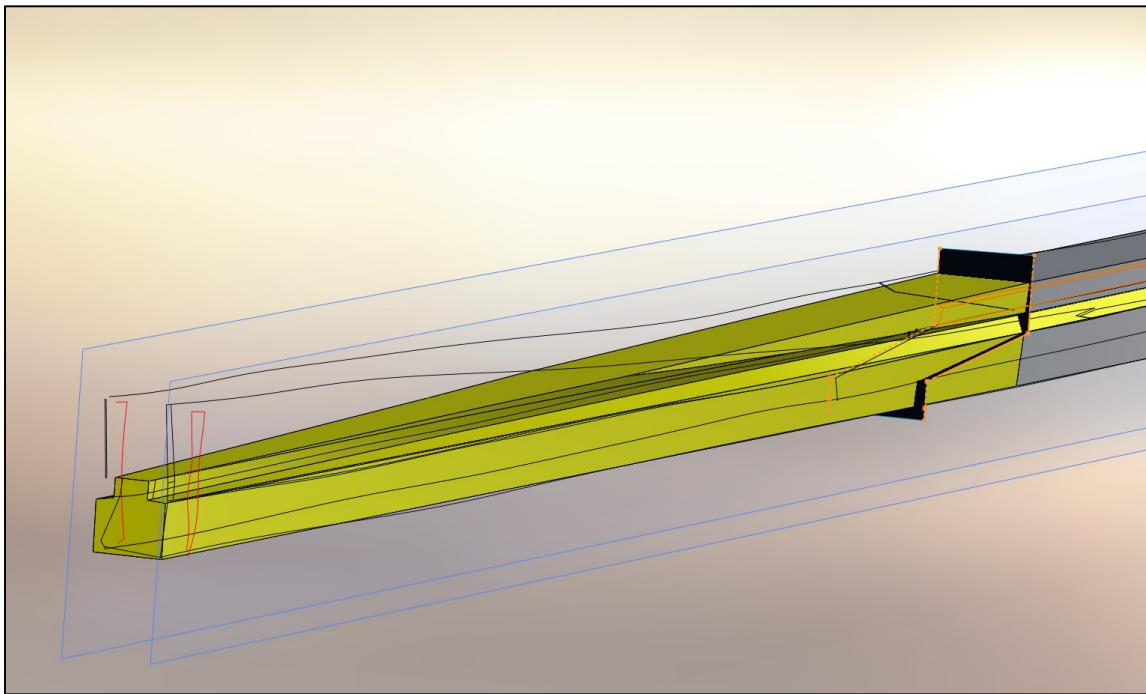


Figure 5.16. The creation of the keel scarfs. The planes (light blue), scarf profile sketches (dotted orange), and surface (black).

¹⁷ The inboard portion of the keel scarfs was estimated based on point cloud data, technical drawings, and observations where the inboard surface of the keel was accessible.

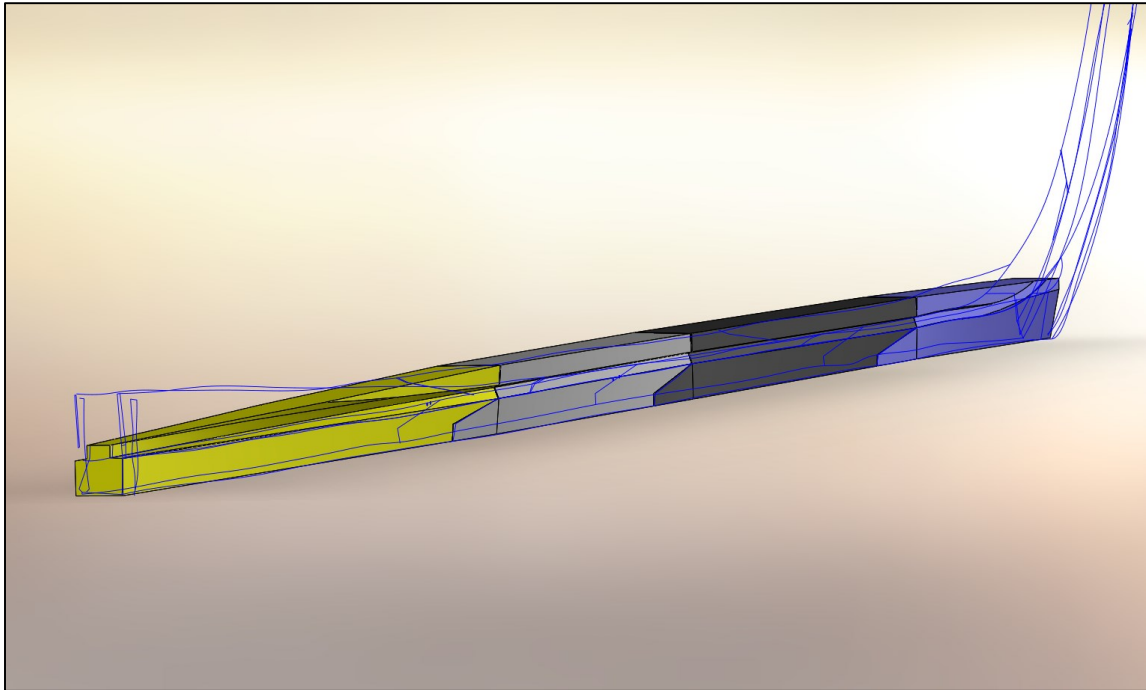


Figure 5.17. Fully split keel, composed of four separate solid bodies separated by scarfs that reflect the configuration of the keel as indicated in the point cloud data.

The final step in the creation of the keel was trimming the ends of the keel to accurately model the skeg and boxing scarf with the stem. To create the skeg, two planes were made using the total station data as reference points. The **surface cut** tool was then used to cut the solid keel along these planes as illustrated in Figure 5.18. To create the boxing scarf with the stem, a plane was created parallel to the top face of the keel at the bow. A profile was sketched onto this plane that approximated the dimensions of the boxing scarf. The **extruded cut** tool was then used to cut the keel using the sketch. The result is seen in Figure 5.19. This completed the construction of the keel model, the complete model is shown in Figure 5.20.

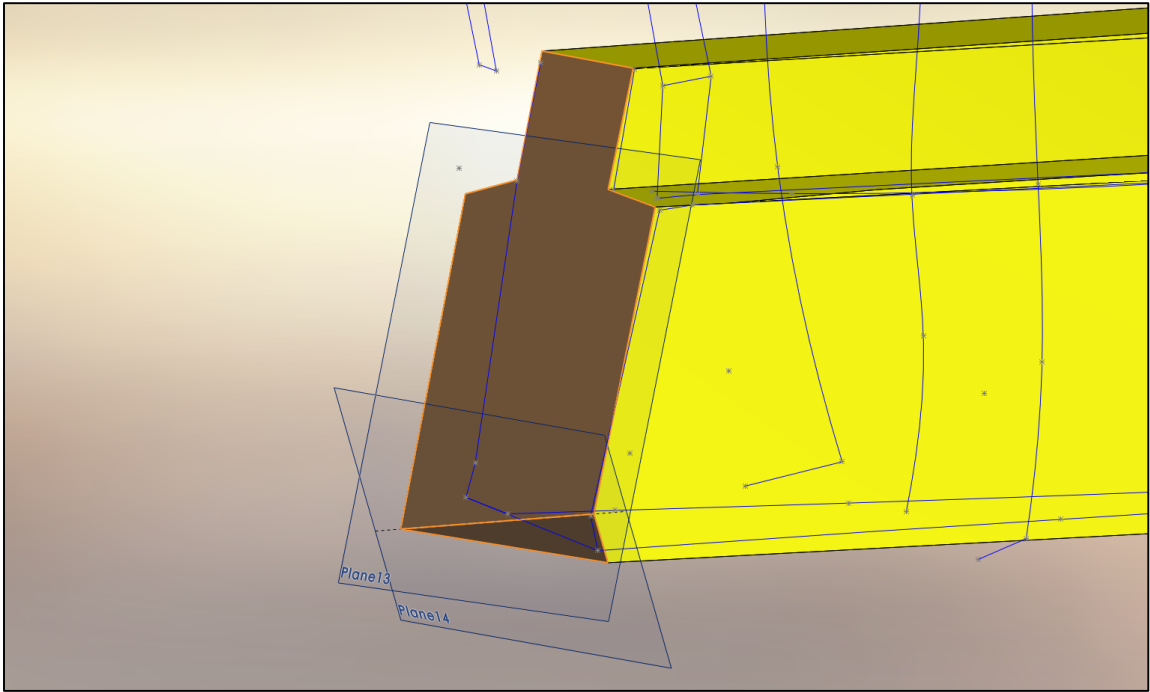


Figure 5.18. The surface cuts creating the skeg of the keel.

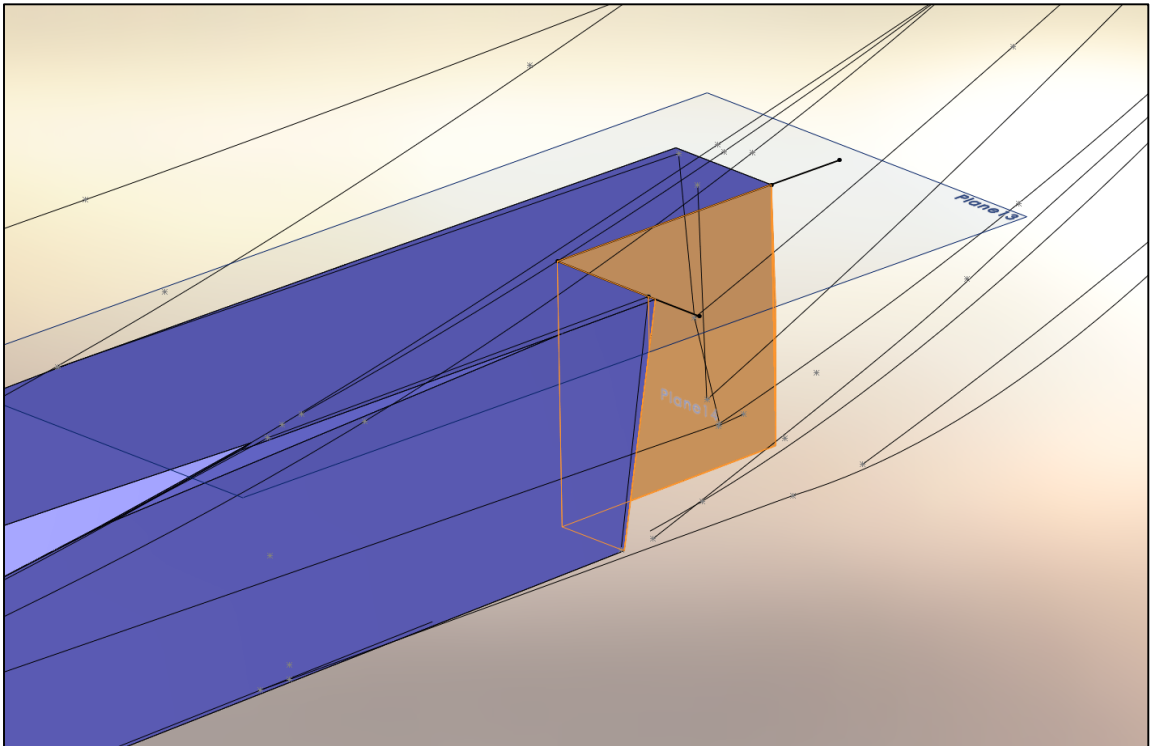


Figure 5.19. Creating the boxing scarf of the keel.

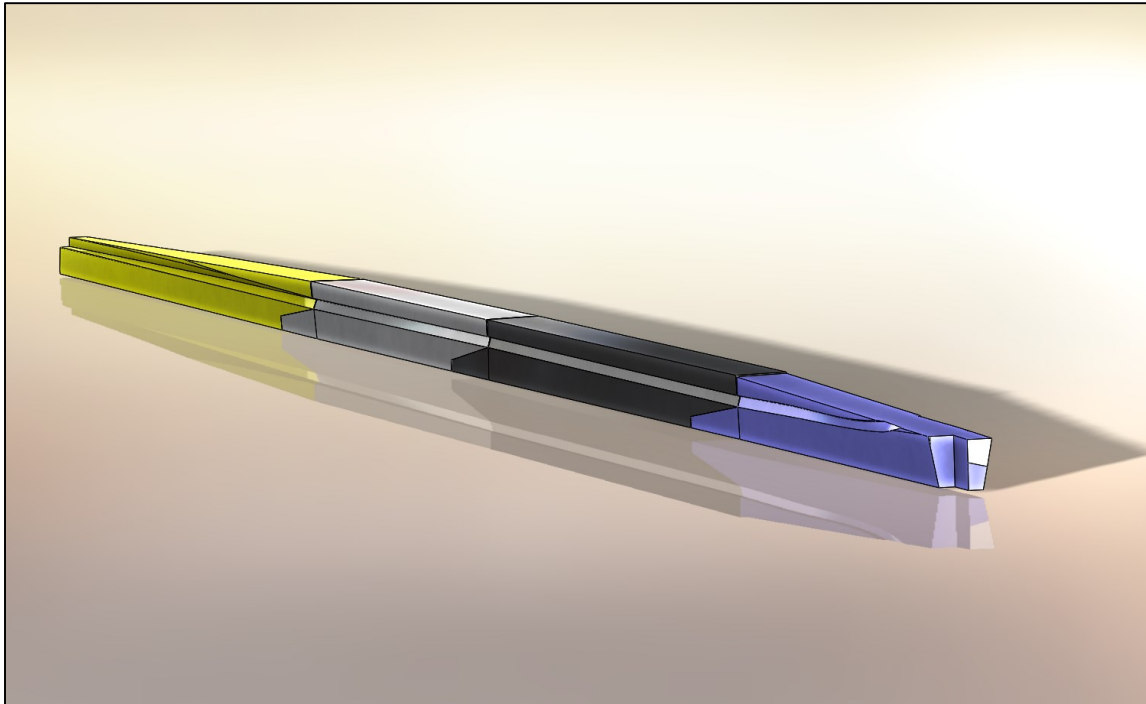


Figure 5.20. Complete keel model.

STERNPOST MODEL

The sternpost was the second hull feature to be modeled. Modeling began as above, with cropping and importing the point cloud data into SolidWorks. The imported data is seen in Figure 5.21. Similar to the keel model, lofting was used to create much of the sternpost model. Due to the irregular shape of the sternpost, however, modification to this procedure was necessary. *Vasa*'s sternpost is three separate pieces: main body, an extension at the top, and what Witsen called the skeg.¹⁸ An illustration from Witsen's treatise of the sternpost is seen in Figure 5.22. Planking overlaps the bottom portion of the sternpost and also obscures the forward face of the sternpost, as shown in Figure 5.23. Therefore, the total station survey was not able to

¹⁸ Witsen refers to this section of the sternpost as the "*achter-scheg*." This particular timber does not seem to have a term in English. In Dutch shipbuilding, the skeg of the keel is referred to as "*kielhak*."

record points capturing the full volume of the sternpost. Supplemental data, including photographs, direct measurements, and in-person analysis facilitated modeling of the full sternpost.

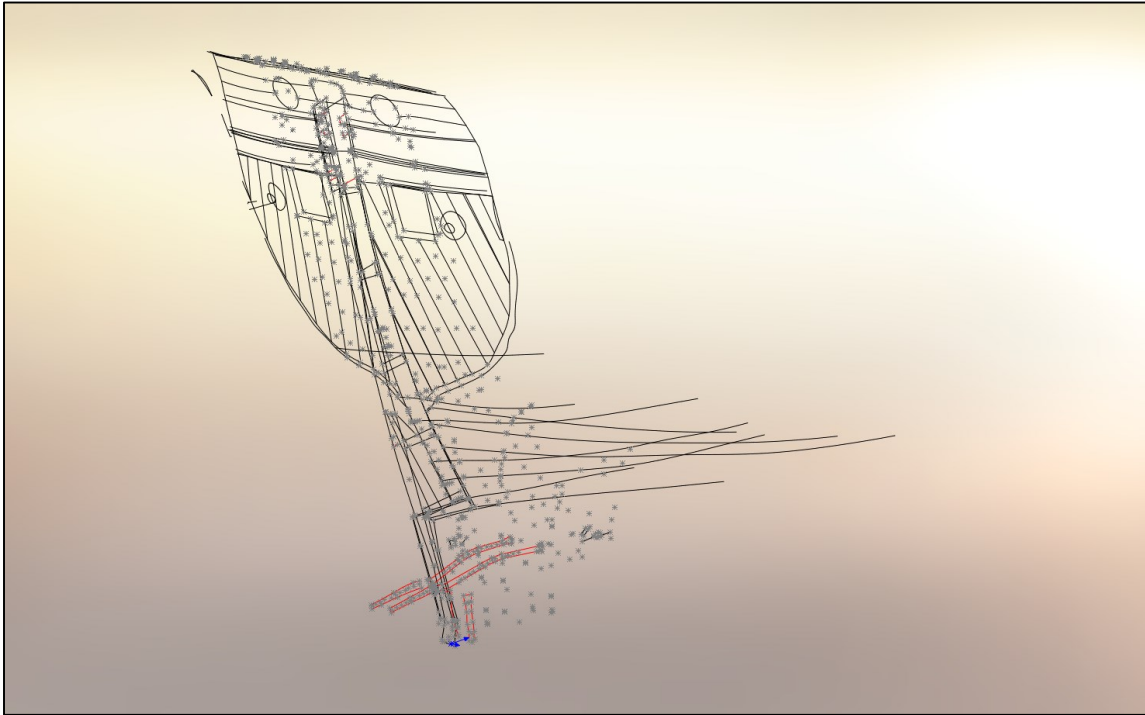


Figure 5.21. Imported point cloud data.

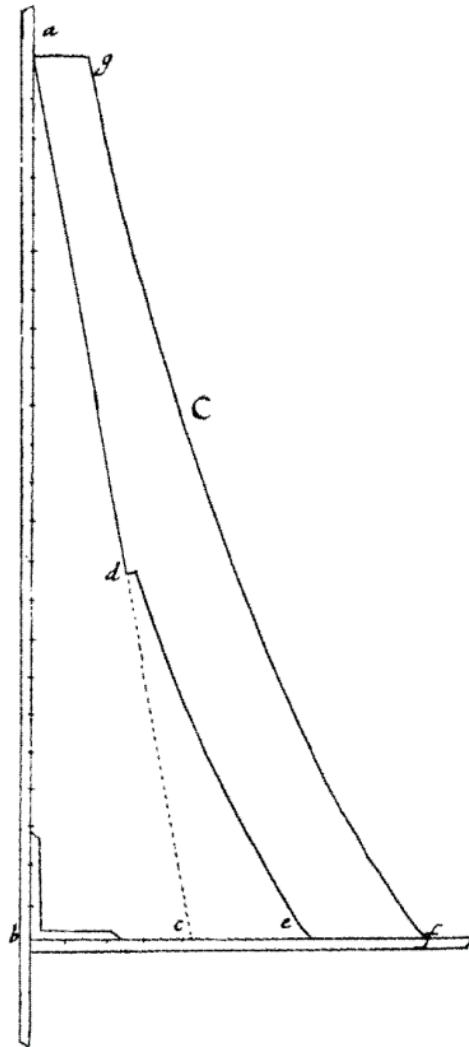


Figure 5.22. Illustration of a sternpost from Witsen's treatise. The small timber c-d-e is referred to as the "*achterscheg*."¹⁹

¹⁹ Witsen 1671, Plate XLVIII.

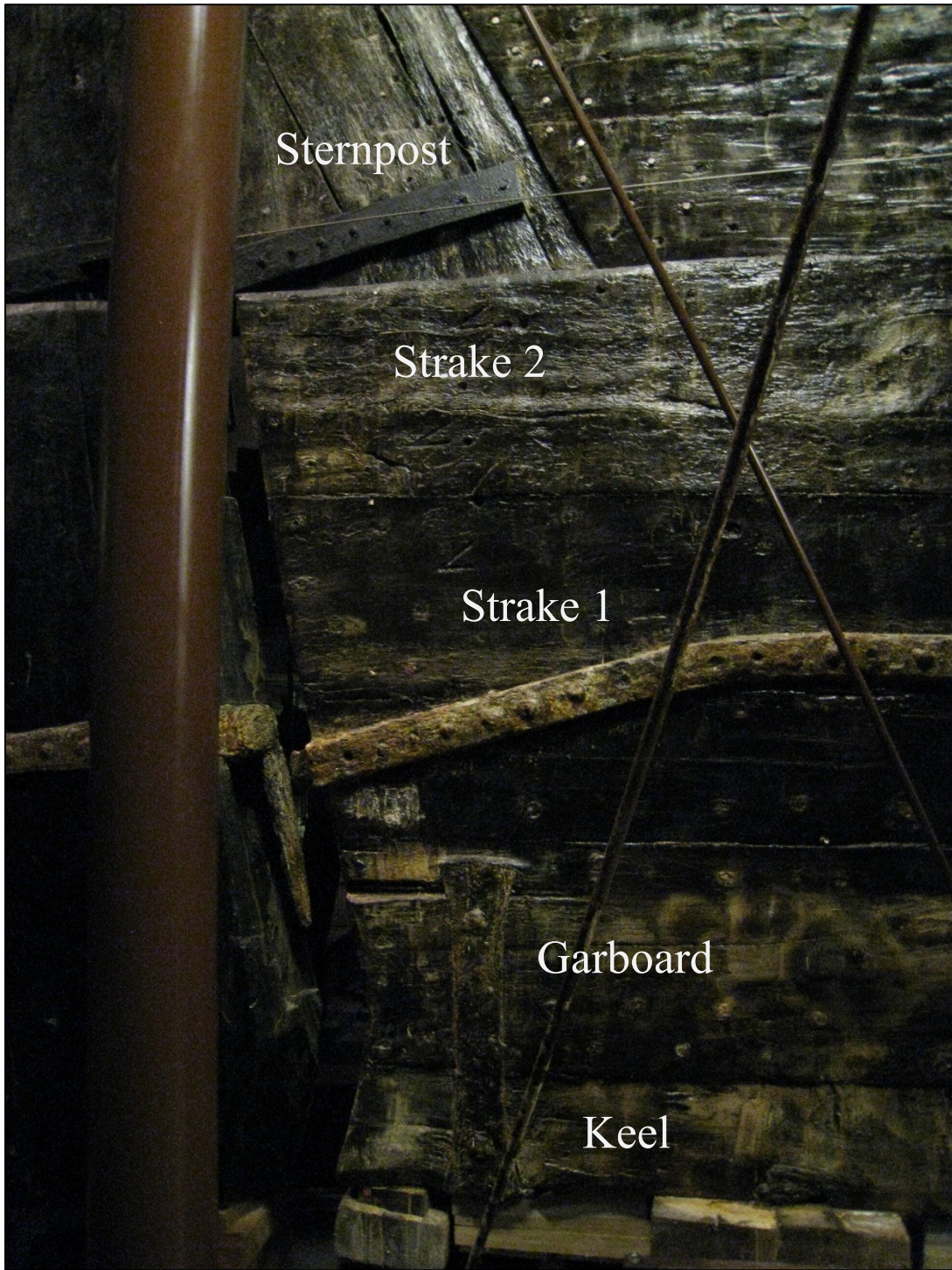


Figure 5.23. The base of *Vasa*'s sternpost, showing overlap of first three runs of planking.

Vasa's sternpost is composed of three timbers. The decision was made to model the sternpost as one body and then split it into three parts to accurately reflect the configuration of the timber and hull. Due to the shape of the sternpost, the distribution of data points, and accessibility, it was necessary to model the sternpost in stages. Modeling began with a focus on the midsection of the sternpost where the majority of the timber is visible and its shape changes evenly. A plane was created at the bottom and top extents of this section. Guided by the point cloud data, sketches were created on these planes that corresponded to the profile shape of the sternpost as shown in Figure 5.24. SolidWorks provides tools to create lofted bodies that change in profile without the need to create a large number of section sketches. The tool used in the case of the sternpost was the use of guide curves. Guide curves enable the user to connect vertices of two or more profile sketches, which the software then uses to interpolate the change in profile between those sections. For the sternpost model, guide curves were created that connected the four corners of each profile sketch. A solid body was then lofted between the profiles using the guide curves to define its contour. The resulting model is shown in Figure 5.25.

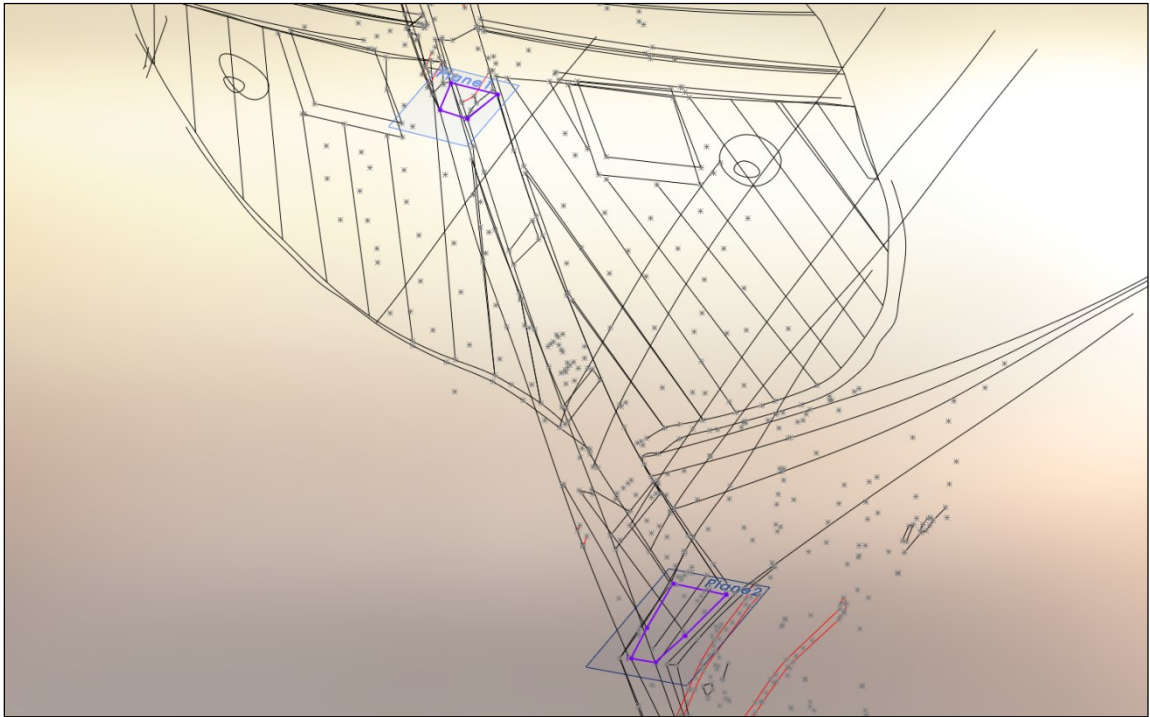


Figure 5.24. Construction planes, upper, and lower sketches (purple) for main sternpost body.

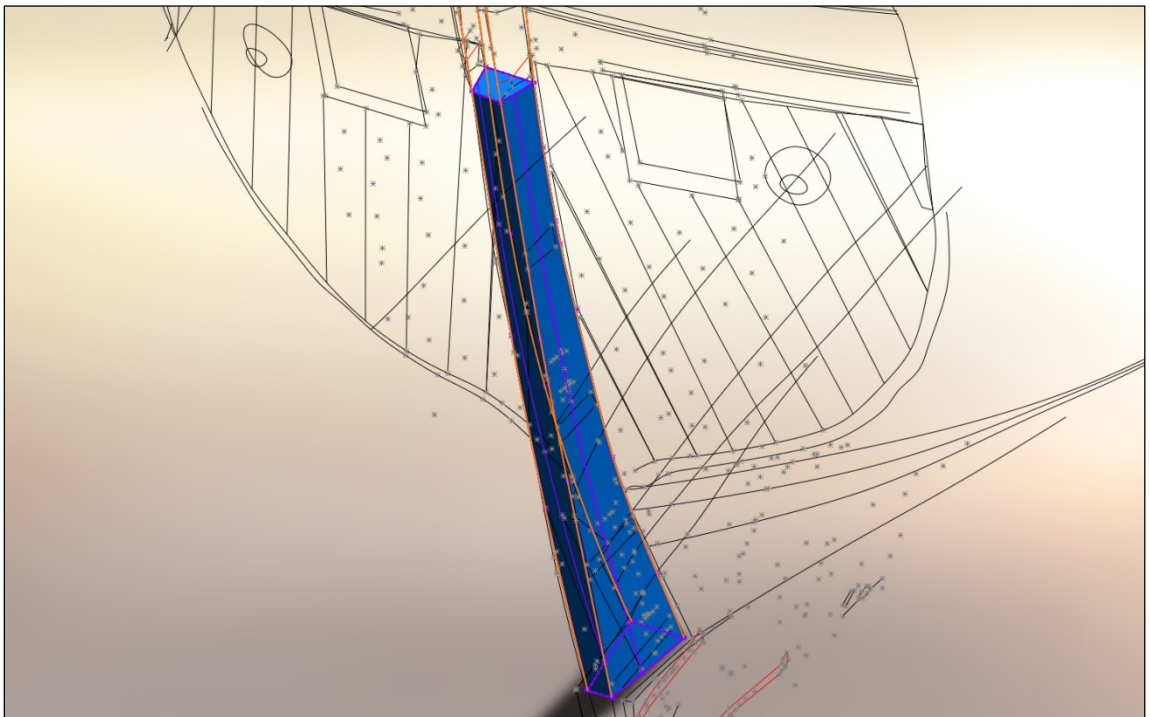


Figure 5.25. Lofting the main sternpost body using upper and lower sketches and guide curves (orange).

The head of *Vasa*'s sternpost widens and is hexagonal in cross section. The decision was made to model the head in three sections. The first section was lofted using the top profile sketch of the main sternpost body, and a hexagonal profile sketch positioned where the sternpost head achieves its full width. The second section used the top profile sketch from the previous section and an additional profile sketch approximately halfway up the sternpost head. The final section was lofted in the same manner. As each of the sections was created they were merged with the other bodies, to form a continuous solid body. This modelling progression is illustrated in Figures 5.26, Figure 5.27, and Figure 5.28.

The lower section of the stern post was made in a single loft, using the bottom profile from the midsection and another profile sketch where the sternpost meets the keel. This lower section was merged with the rest of the sternpost as seen in Figure 5.29.

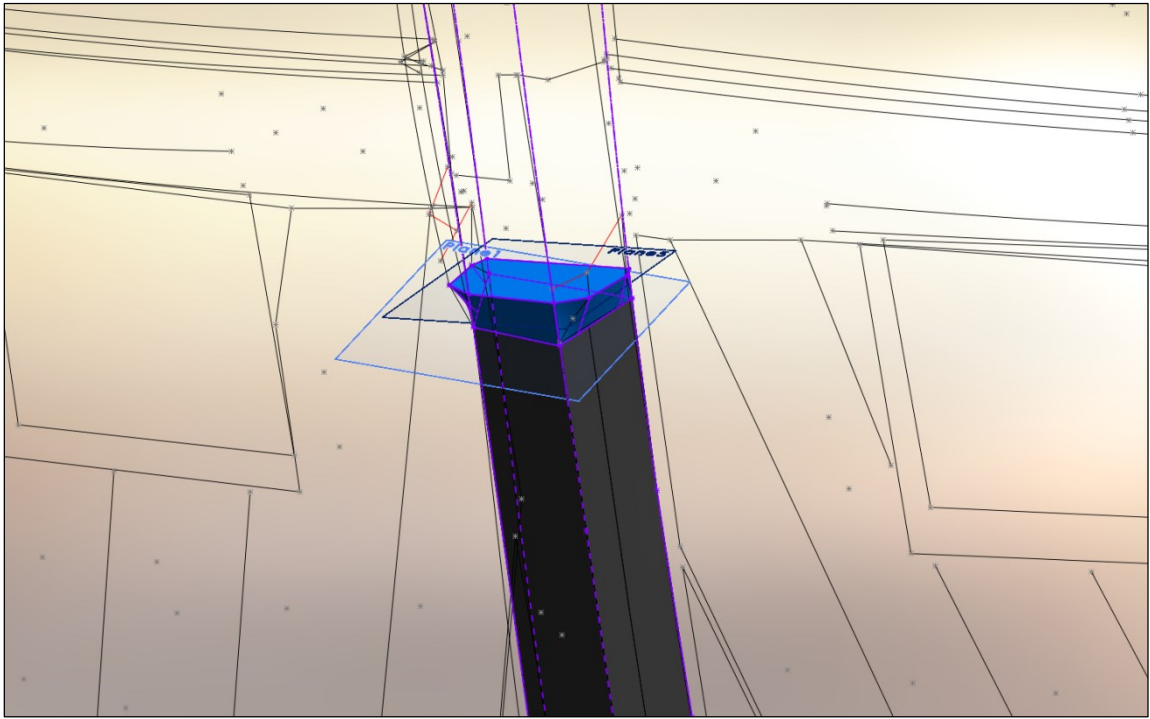


Figure 5.26. Lofting the first section of the upper sternpost.

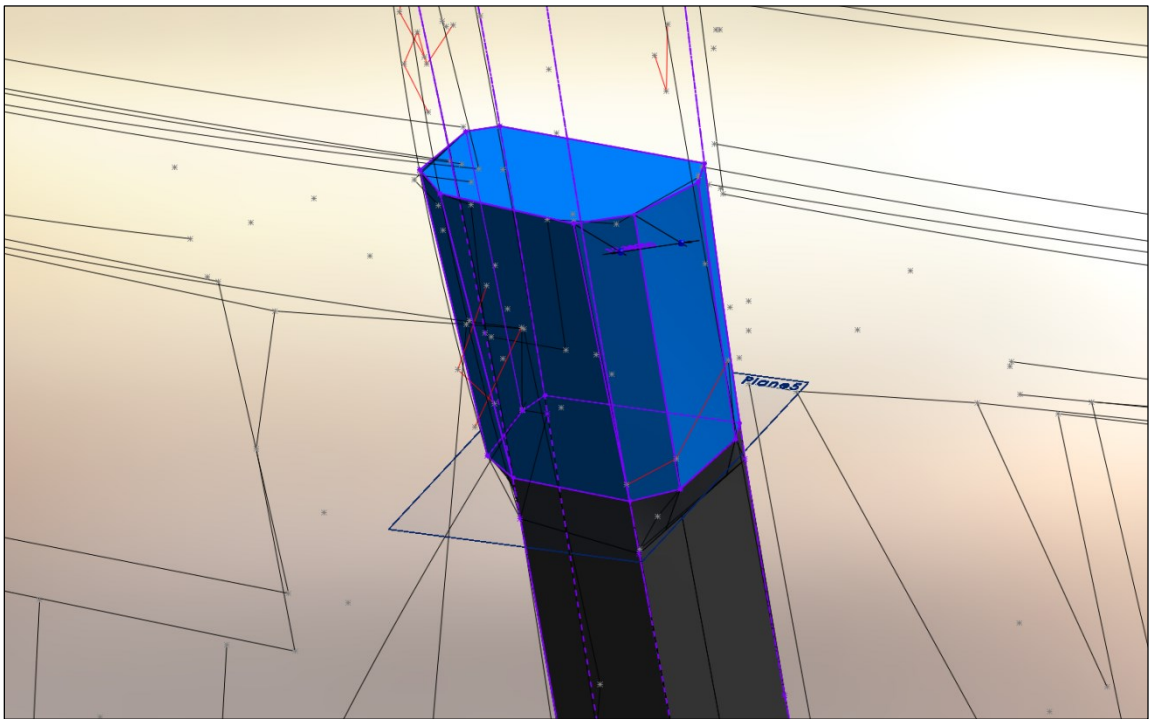


Figure 5.27. Lofting the second section of the upper sternpost.

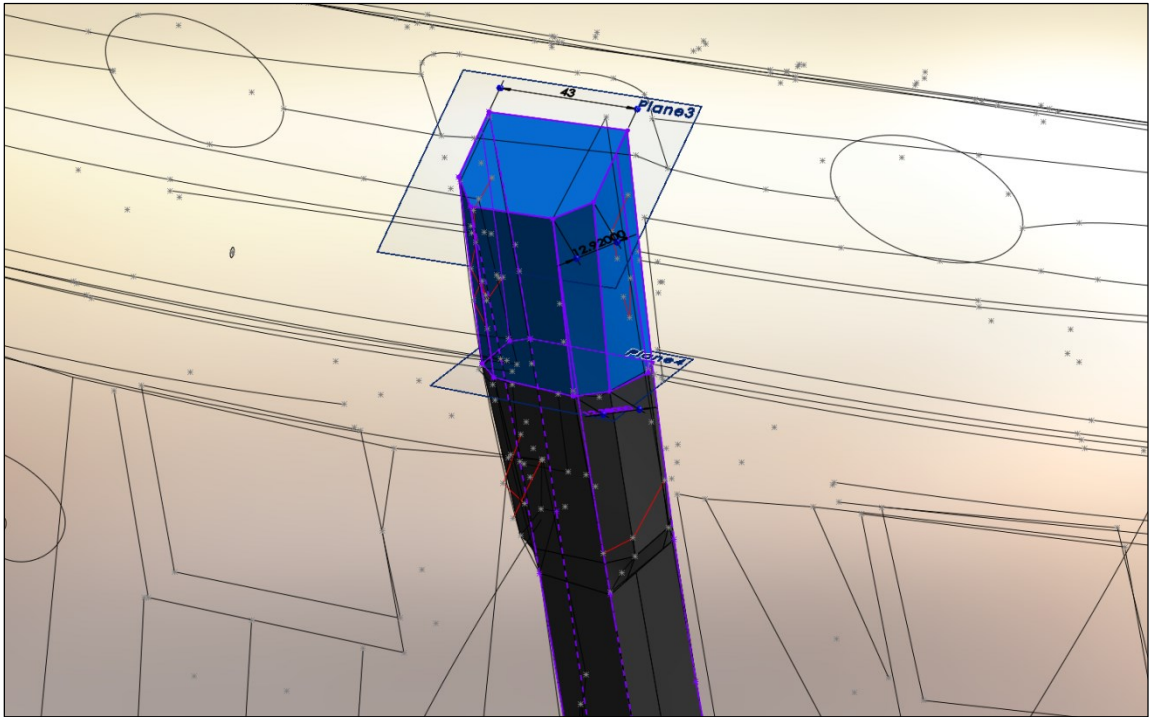


Figure 5.28. Lofting the final section of the upper sternpost.

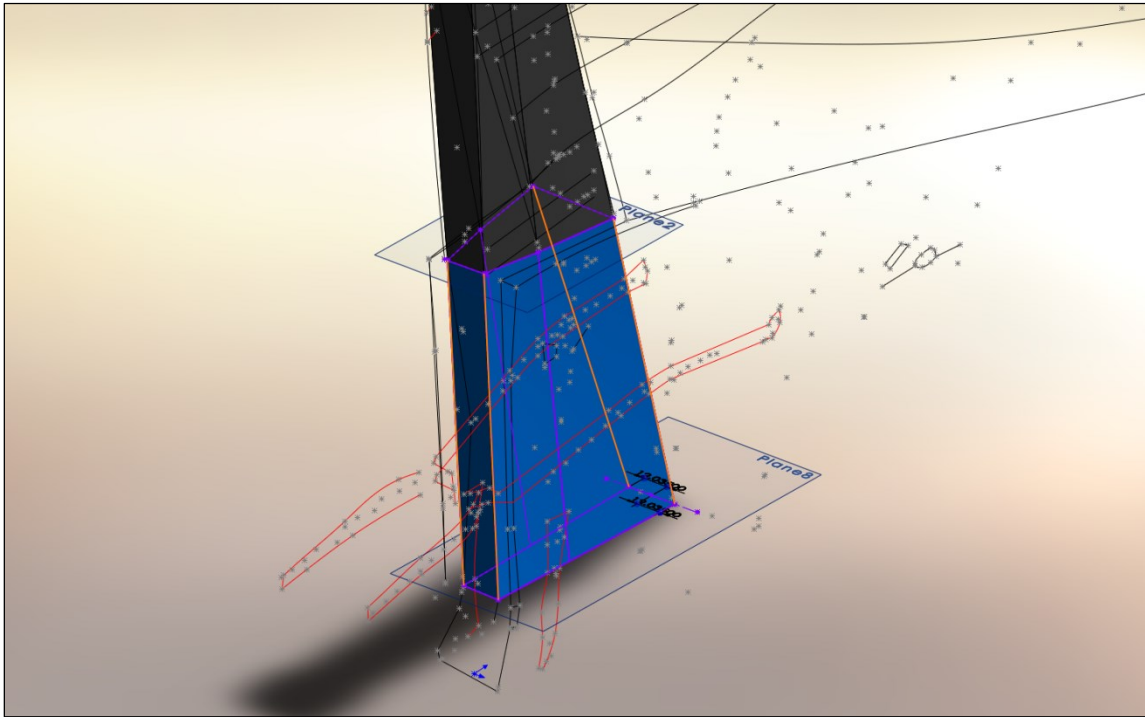


Figure 5.29. Lofting the lower section of the sternpost.

The point cloud data collected by the Vasa Museum focuses on the exterior of the ship. As a result, where timbers extend inside the hull, data for constructing the remaining parts of the timbers must come from other sources. To model the full molded dimension of the *Vasa*'s sternpost, measurements were taken by hand at the head of the sternpost where the timber is easily accessible. Based on the dimensions collected, the model was thickened appropriately, by offsetting the inboard face of the upper sternpost, and lofting the space between as seen in Figure 5.30. The inboard extent of the lower sternpost was estimated based on the position of fasteners at the hood ends of the lower strakes and lower gudgeon. The model was thickened accordingly, following the same procedure as above, shown in Figure 5.31.

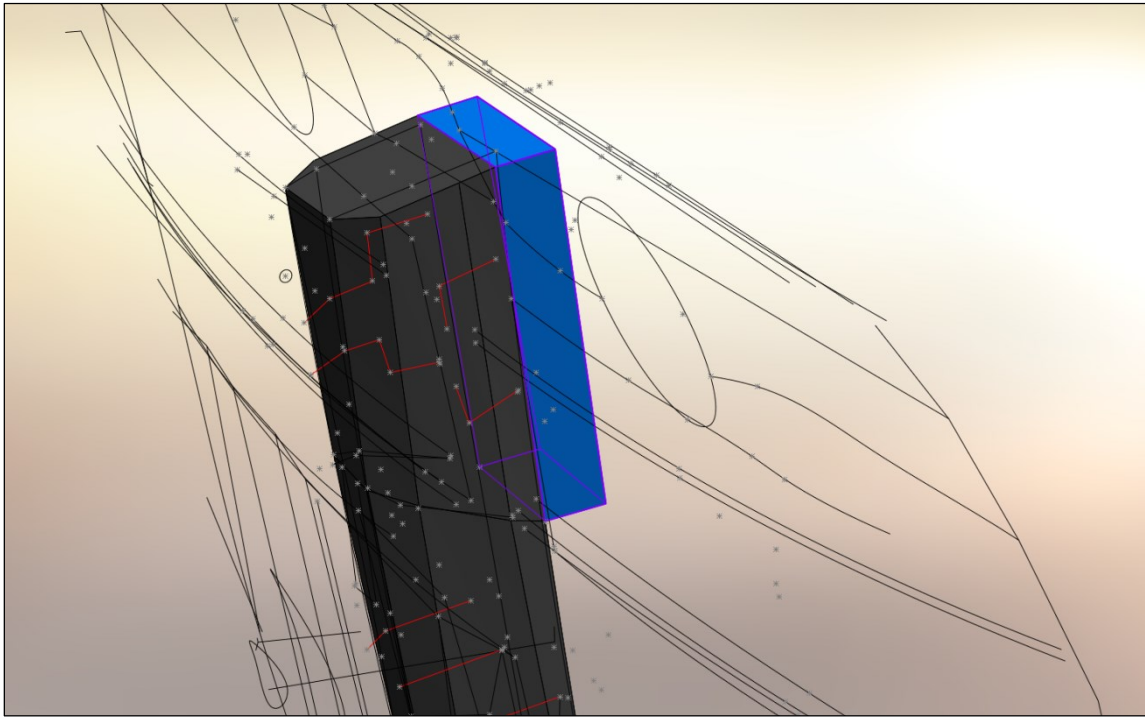


Figure 5.30. Thickening the sternpost extension.

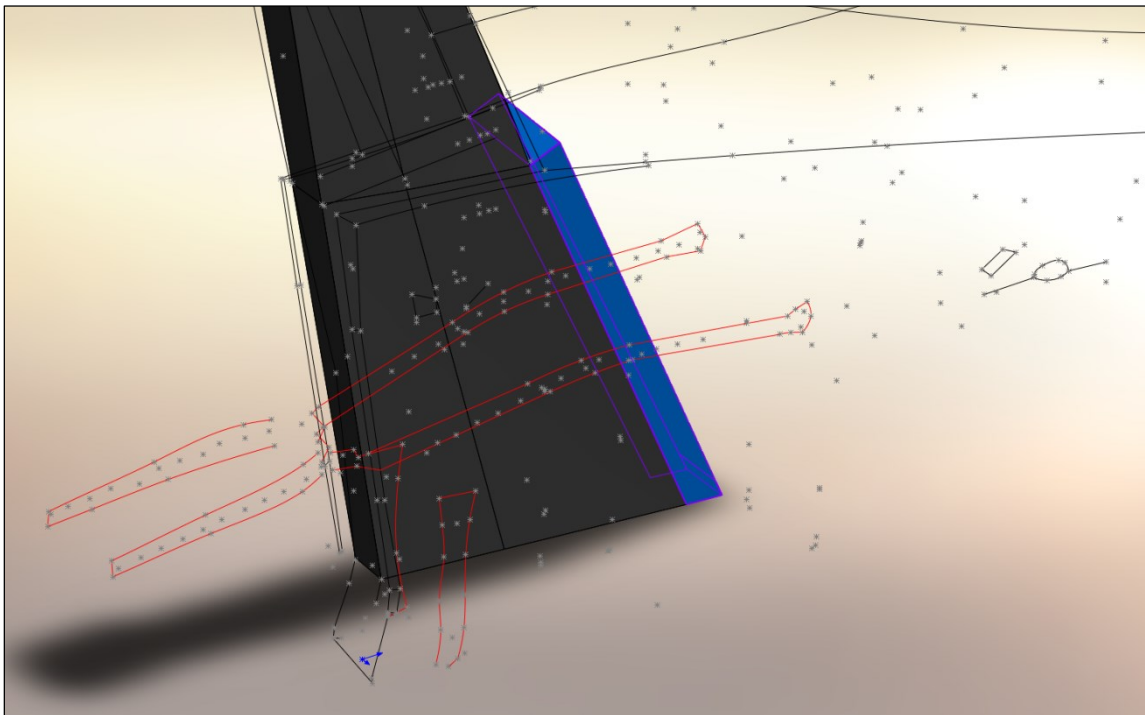


Figure 5.31. Thickening the lower sternpost.

Based on the dimensions indicated by the inboard edges of the sternpost extension and lower sternpost, the main sternpost was thickened in the same manner, seen in Figure 5.32. The approximations made in this process do not affect the design analysis of the hull.

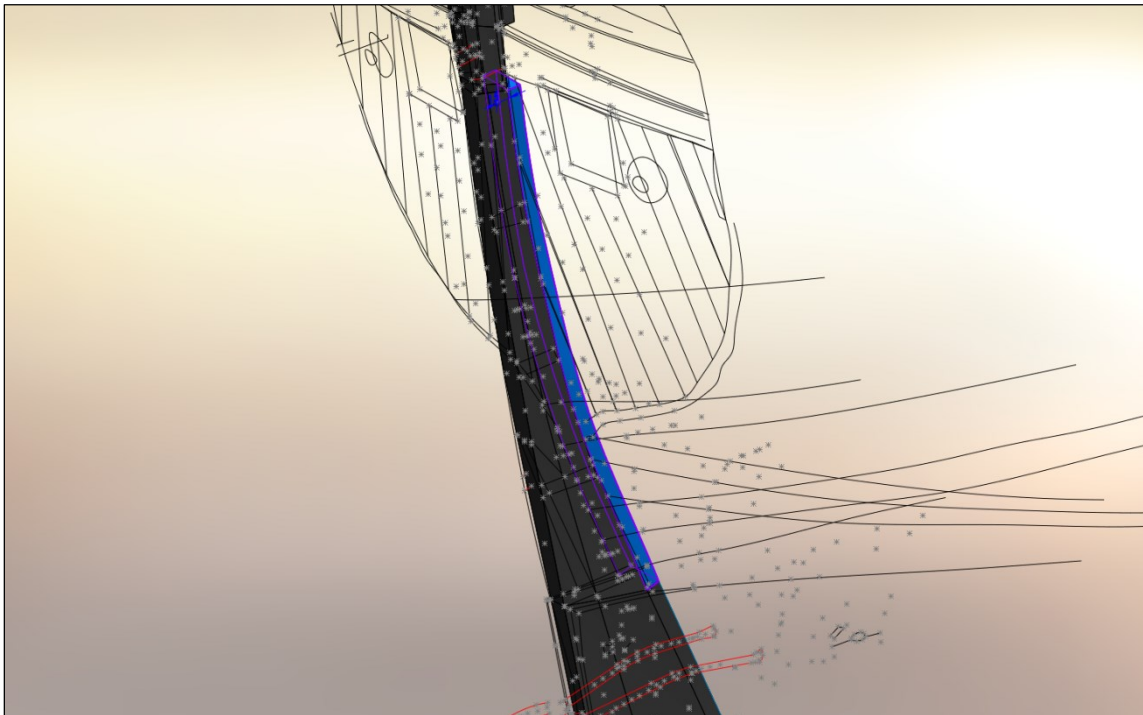


Figure 5.32. Thickening the main sternpost.

Vasa's sternpost is composed of three separate pieces.²⁰ To this point in the modeling, all sternpost entities were merged into a single solid body. Two splits were required to bring the digital model into agreement with the actual hull structure. The first split separated the lower sternpost from the main sternpost so that SolidWorks recognized them as separate solid bodies.

²⁰ A stern knee also joins the sternpost with the keel. The stern knee is not necessary for the analysis of *Vasa*'s design, however, and was not modeled.

The split was accomplished by creating a sketch on a construction plane parallel to the sternpost and then projecting that line through the sternpost to split the solid into two bodies, seen in Figure 5.33.

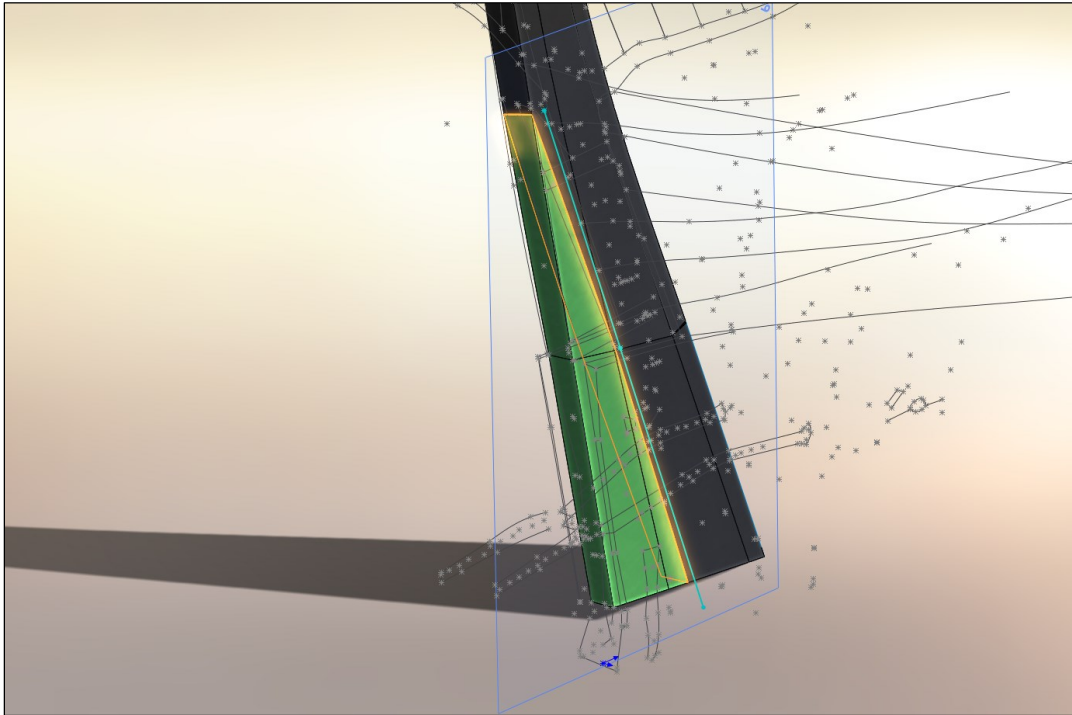


Figure 5.33. Splitting the main sternpost.

In order to separate the sternpost extension from the main sternpost body, a construction plane was created perpendicular to the desired direction of the cut, as indicated by the point cloud data and visual inspection of the sternpost. A sketch was made on the plane, using the point cloud data captured at the joint. The sketch was then projected through the sternpost, separating the sternpost extension from the main sternpost body, as seen in Figure 5.34.

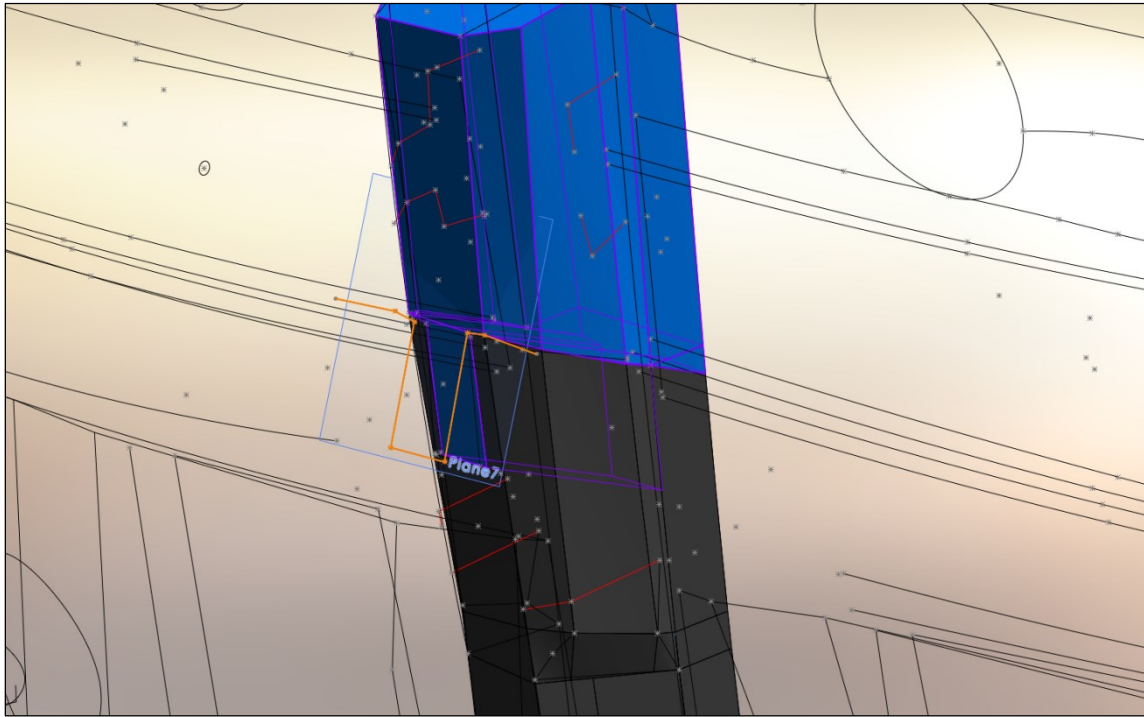


Figure 5.34. Splitting sternpost extension from main sternpost.

The final step in modeling the sternpost was to cut out the area on the sternpost extension where the sternpost and upper transom meet. To do this, a construction plane was made parallel to the sternpost, and a sketch made on the plane with the desired profile. The sketch was projected through the sternpost extension, cutting away the desired material. This process is seen in Figure 5.35. The finished sternpost model, as seen in the exploded view in Figure 5.36 and Figure 5.37, accurately depicts the properties of *Vasa*'s sternpost that are relevant to hull design analysis. Photographs of the head of *Vasa*'s sternpost are shown in Figure 5.38.

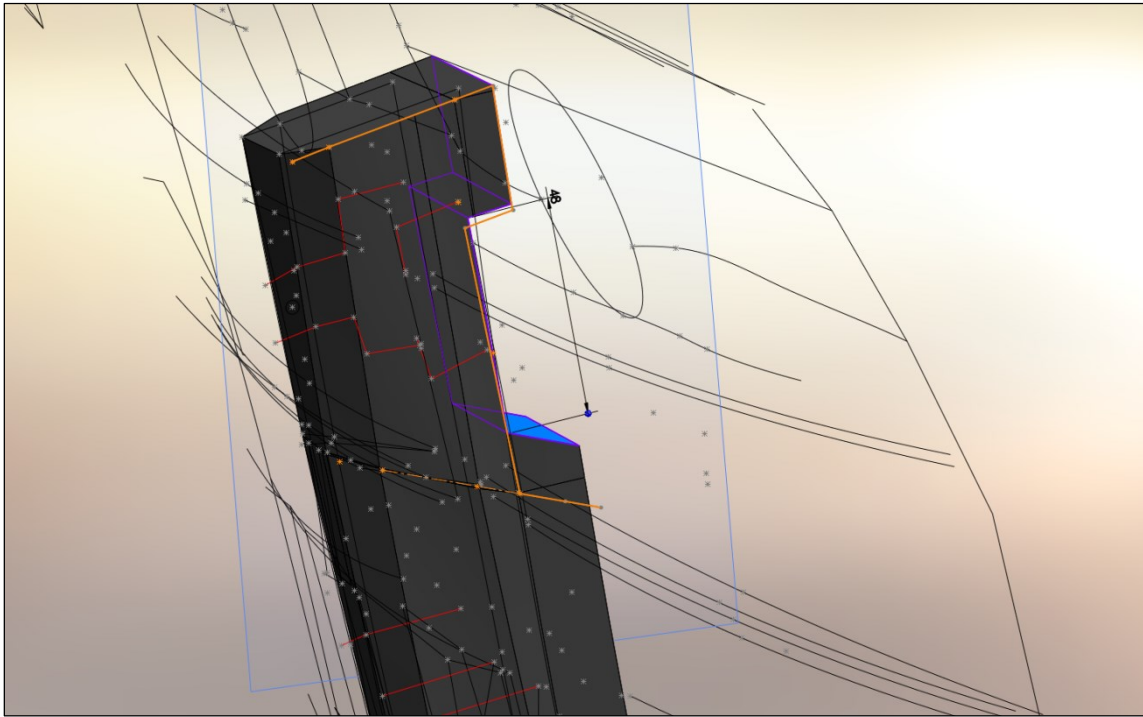


Figure 5.35. Cutting the sternpost extension.



Figure 5.36. Exploded complete sternpost.

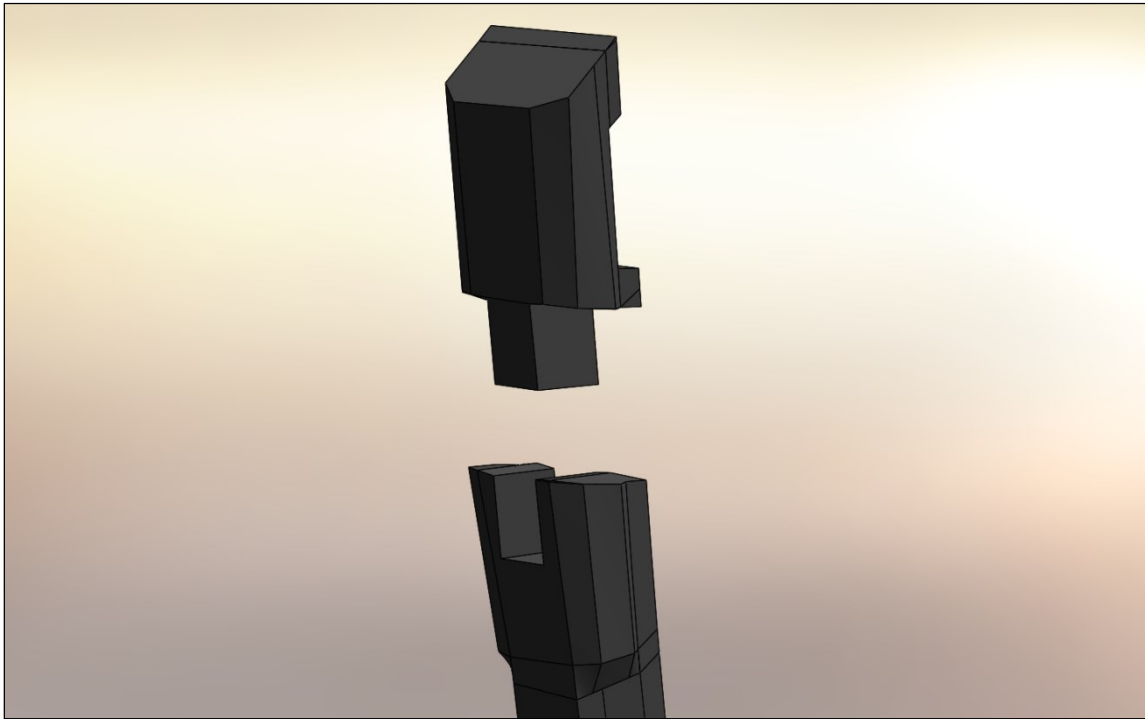


Figure 5.37. Close up view of exploded sternpost.

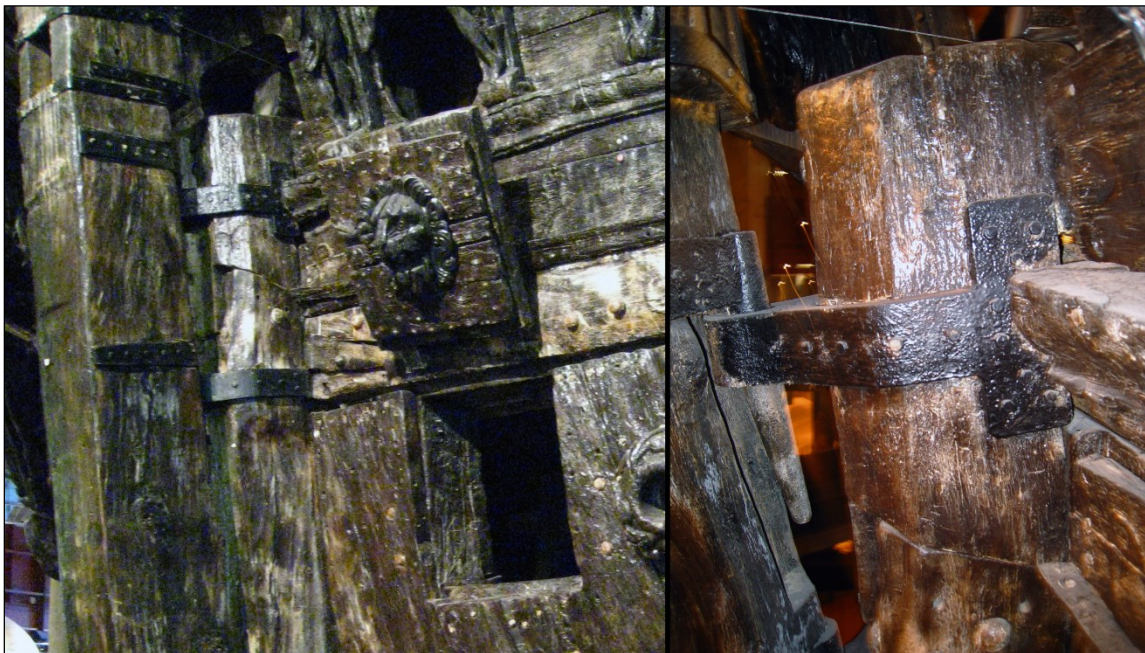


Figure 5.38. Photographs of the head of *Vasa's* sternpost.

STEM MODEL

The model of *Vasa's* stem is made of four timbers; three timbers of the stem and the gripe. Like the sternpost, the inboard face of the stem is inaccessible and not captured in the total station survey. Unlike the sternpost, the stem displays complex curvature which proved to be a modeling challenge. Several attempts were required in order to find a modeling approach that worked.

After cropping and importing the point cloud, the model of keel section 1 was imported to the stem model to serve as a reference for construction, as seen in Figure 5.39. The initial approach to modeling the stem was to model each of the four timbers separately. This began with creation of the gripe. Port and starboard 3D profile sketches and surfaces were made of the gripe, corresponding to the outside port and starboard faces of the timber, seen in Figure 5.40. The initial intention was to simply create a lofted solid between these two profiles. A problem arose, however, when attempting to loft the profiles which contained a different number of vertices. The port gripe profile contained four vertices, whereas the starboard only contained three. This is due to the asymmetry introduced into the lower stem by the boxing scarf with the keel. SolidWorks was unable to produce a solid loft between these two profiles because the result would produce zero thickness geometry.²¹ The solution to this problem was to add an additional sketch on the port side that made the two profiles agree with respect to the number of vertices, seen in Figure 5.41. These surfaces were then lofted to create the solid body of the gripe, shown in Figure 5.42. The compromise of adding an additional sketch to the port side of the gripe

²¹ This is a software error produced when the vertices of a solid model do not properly connect with adjacent geometry. Every edge of a solid must have two adjacent faces. Attempting to loft between a profile with four vertices and a profile with three vertices violates this rule.

resulted in the solid body of the gripe and keel section 1 intersecting. This intersection was later remedied by using the split tool to remove the overlapping material. Figure 5.43 shows the finished gripe model.

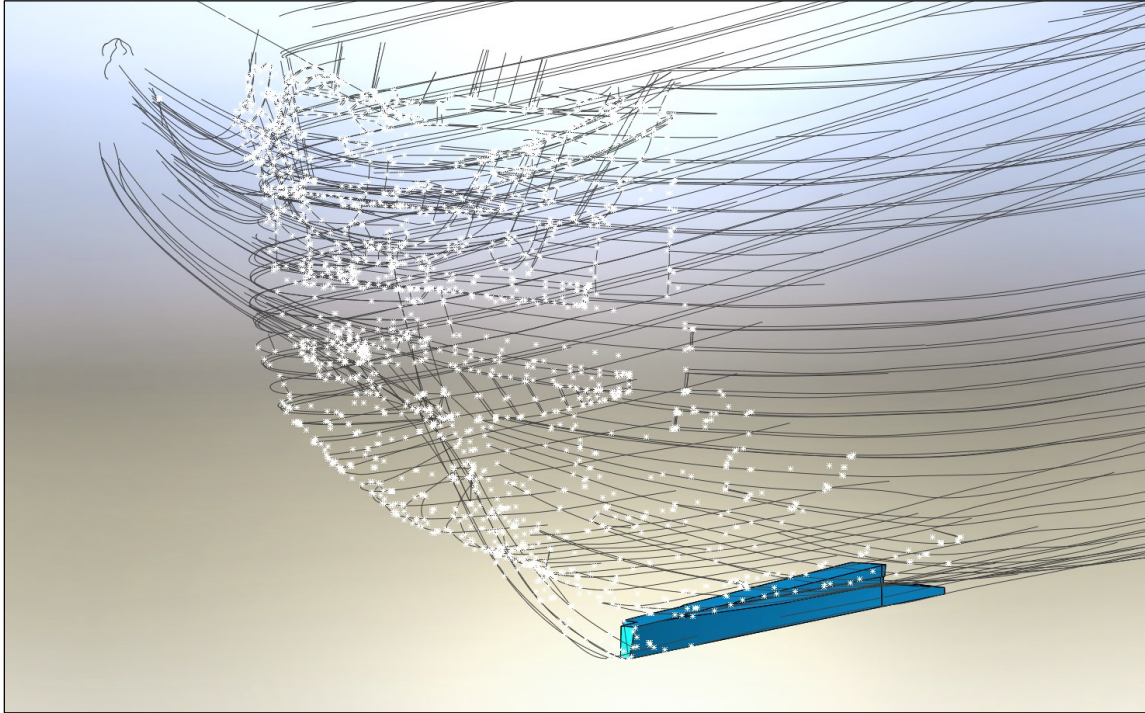


Figure 5.39. Cropped and imported point cloud data and keel section 1 model for the construction of the stem model.

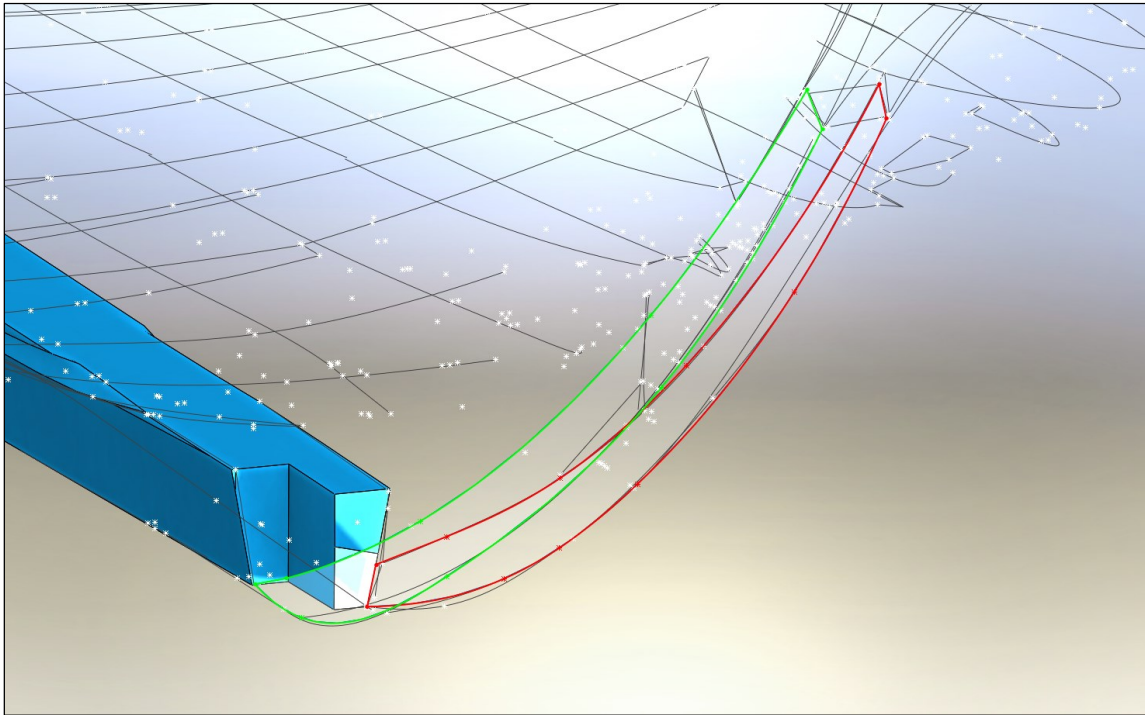


Figure 5.40. Initial gripe profile sketches and surfaces, port (red) and starboard (green). Note the mismatched vertices where the gripe joins the keel (blue).

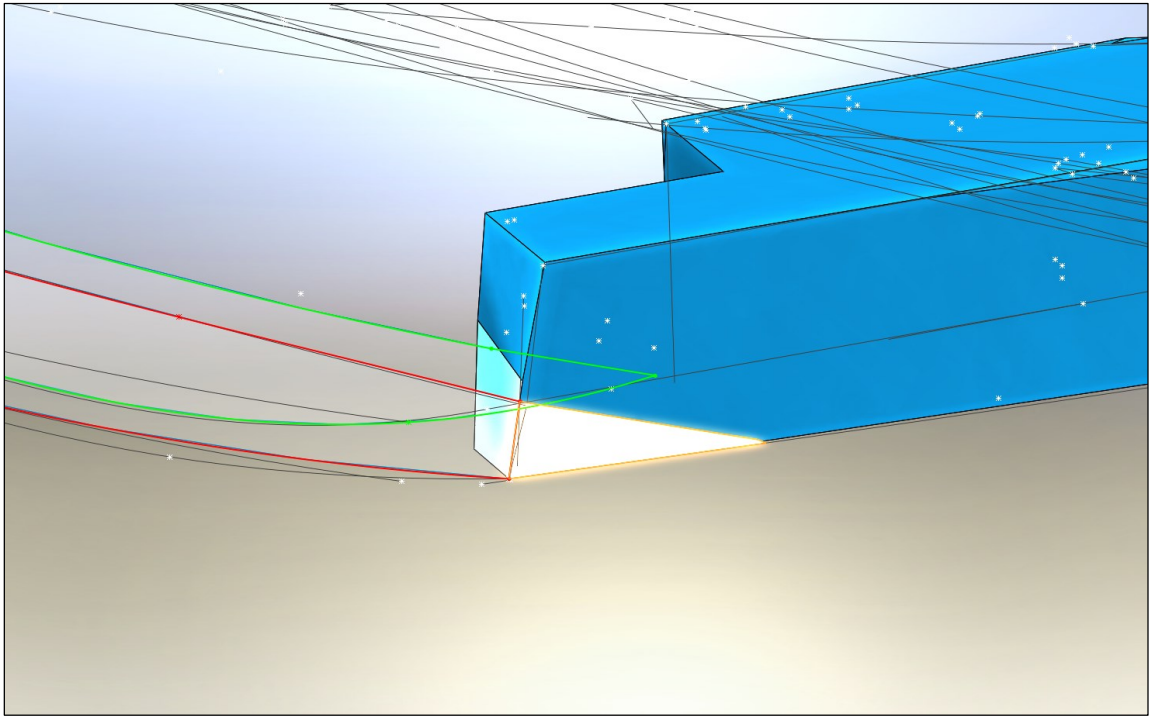


Figure 5.41. The added sketch on the port gripe to correct the mismatched vertices.

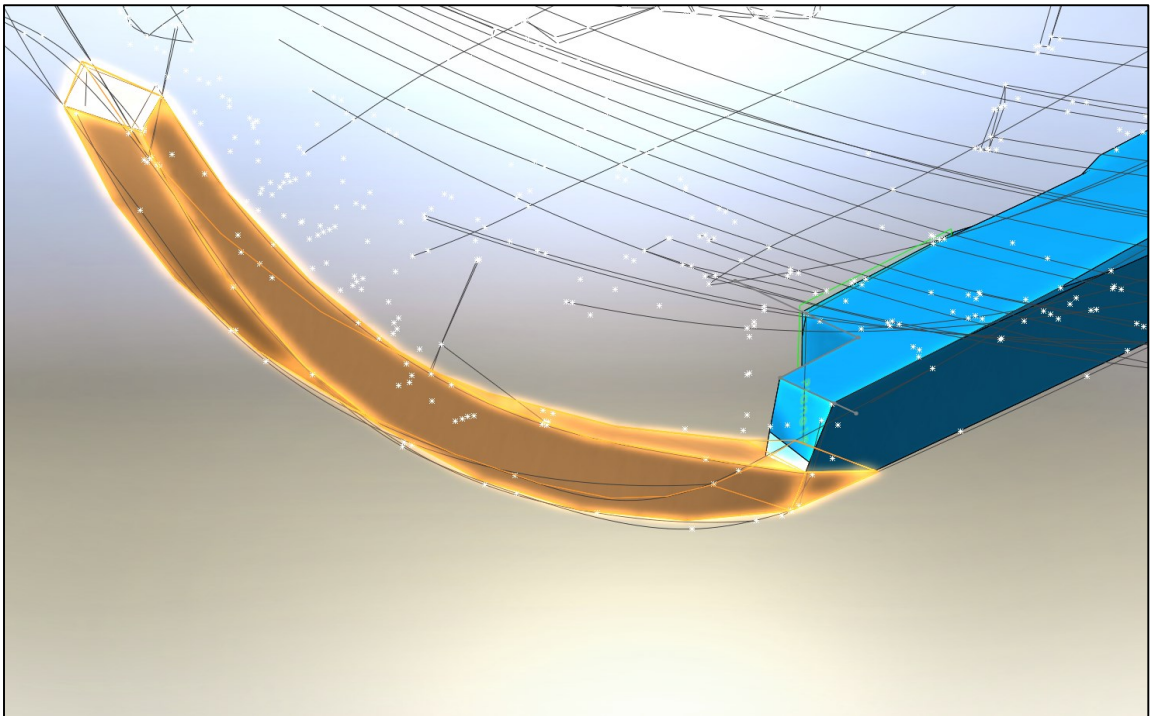


Figure 5.42. Lofted solid body of the gripe.

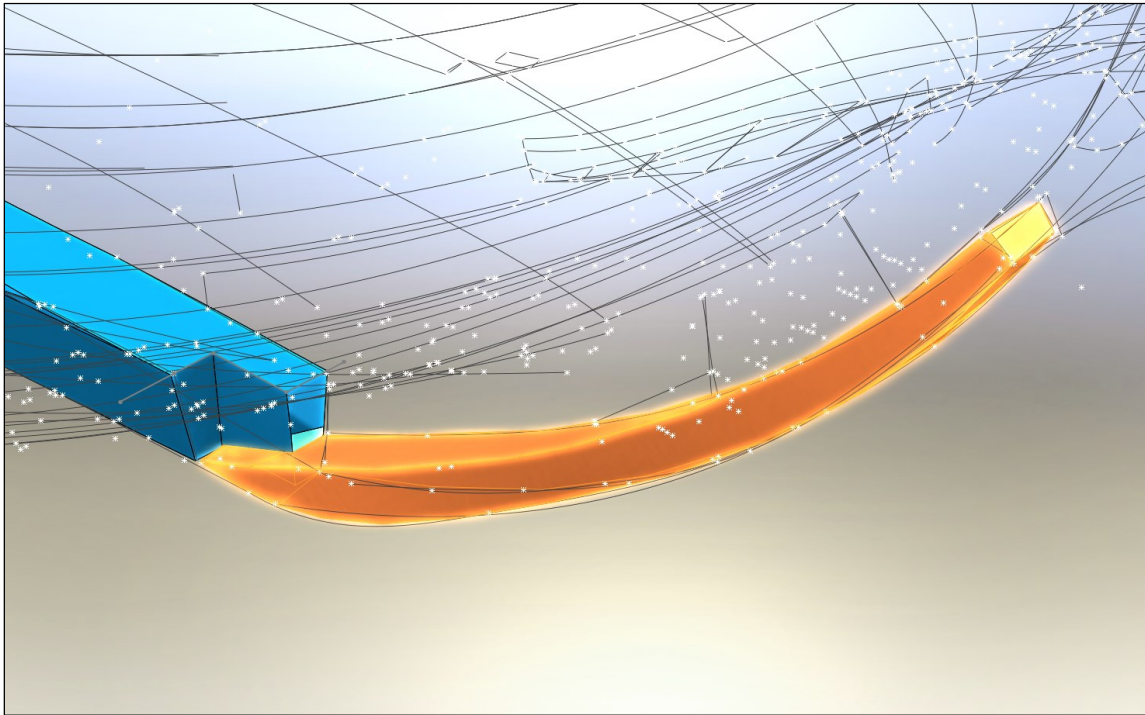


Figure 5.43. Finished gripe model.

The modeling of the main stem timbers built on the lessons learned from attempting to loft the gripe profiles with mismatching vertices. Although the actual stem is composed of three timbers, the stem was modeled as two pieces and then split to accurately reflect the dimensions and shape of the real timbers. For the lower stem model, two 3D profile sketches were made, based on the point cloud data and first-hand measurement and observation. Surfaces were made from these sketches and then lofted to create a solid. Figure 5.44 depicts the lower stem surfaces, and Figure 5.45 the lofted solid body. A projected sketch was used to cut the model to reflect its actual shape, shown in Figure 5.46. The upper stem model was produced in the same way and was made to overlap the lower stem model to ensure the full extent of all three actual timbers were accurately modeled. This stage is shown in Figure 5.47. The same sketch profile

was used to cut the upper stem section to create a tight fitting scarf between the two existing stem sections.

The lower section of the bowsprit was modeled to help with verifying the position of the upper face of the stem. This was simply a lofted body between two profile curves. The schematic model of the bowsprit is shown in Figure 5.48. The upper face of the stem is situated such that the total station survey could not capture points that completely describe its shape. The bowsprit, which was captured in the total station survey, directly overlays the upper face of the stem and therefore aids in determining the precise position of the upper face of the stem. The final step in the creation of the stem model was splitting the upper stem solid into two pieces to reflect the actual configuration of the stem timbers. This was done using the same method as splitting the lower stem model – using a sketch on a plane to create an extruded cut. The complete stem model is seen in Figure 5.49.

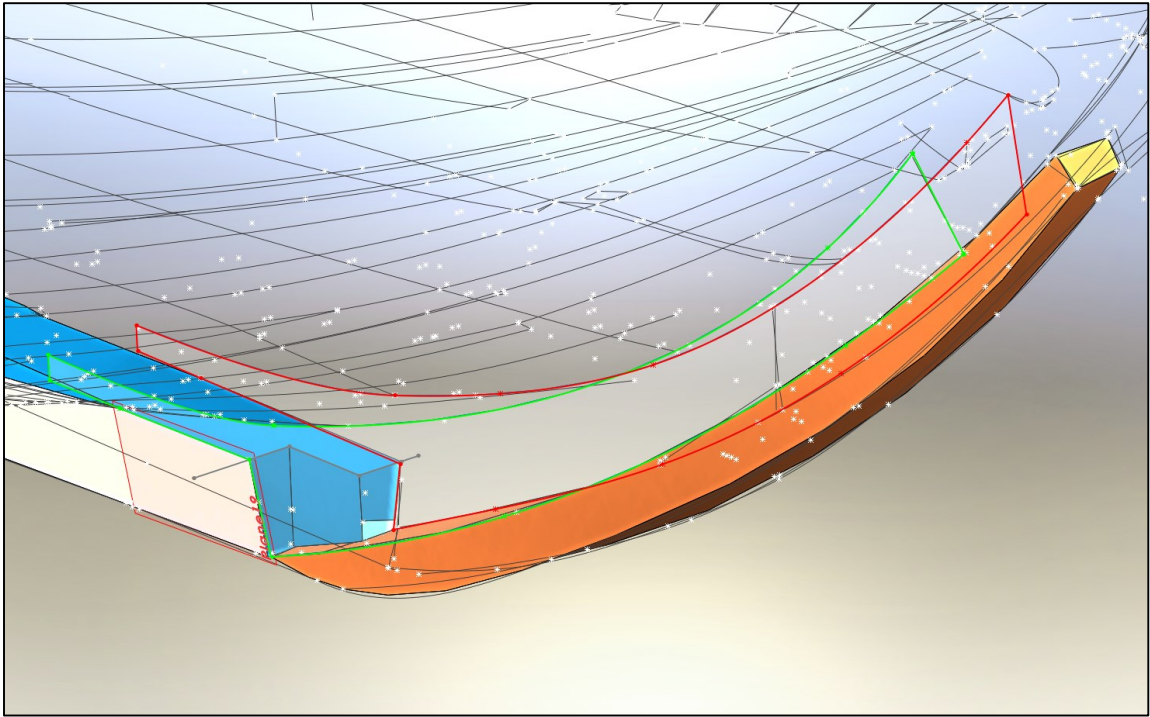


Figure 5.44. Surfaces for the lower stem, port (red) and starboard (green).

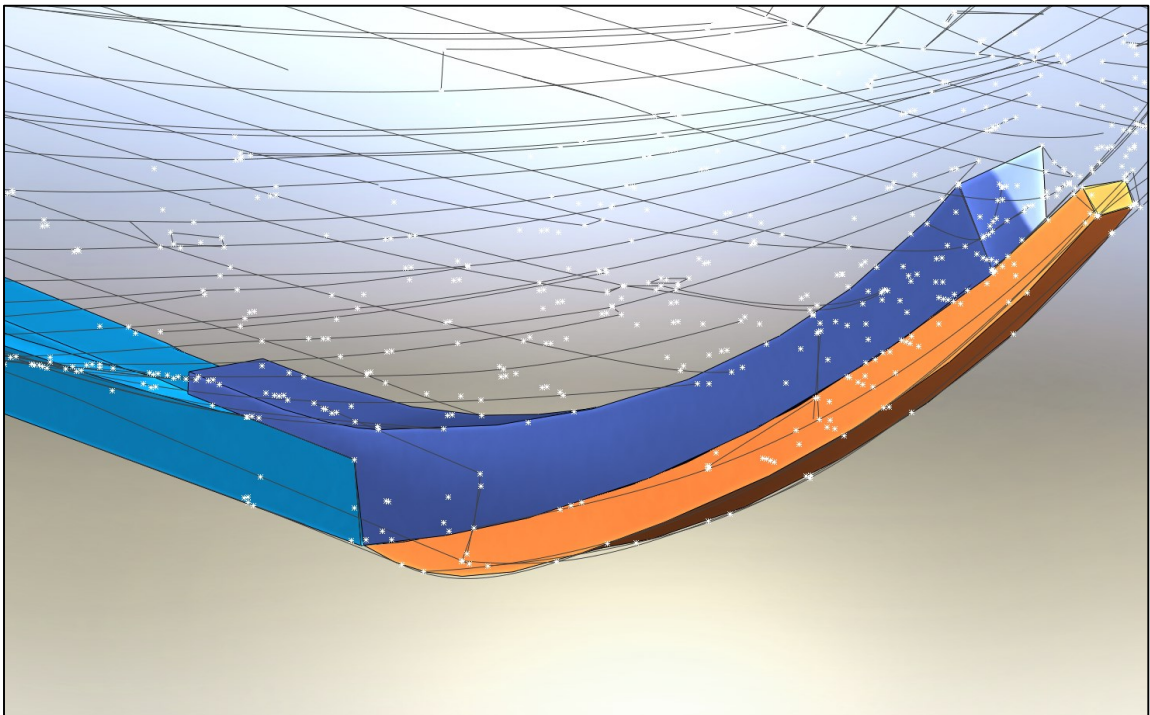


Figure 5.45. Lofted lower stem solid body.

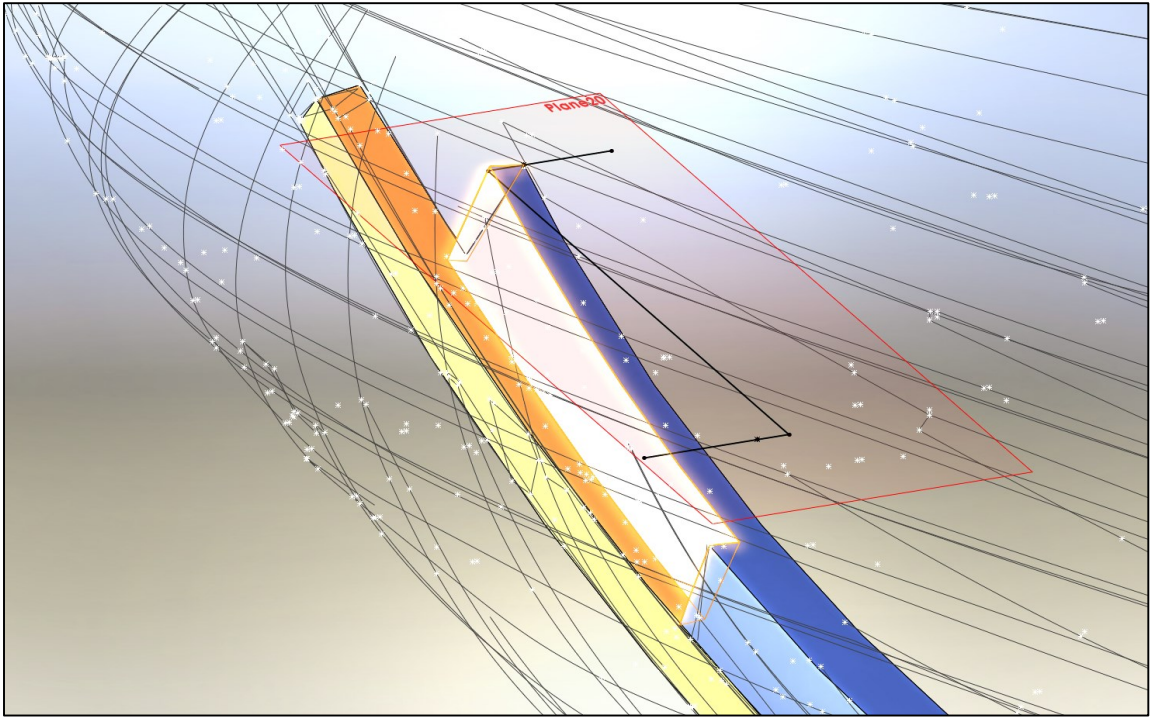


Figure 5.46. Cutting the lower stem.

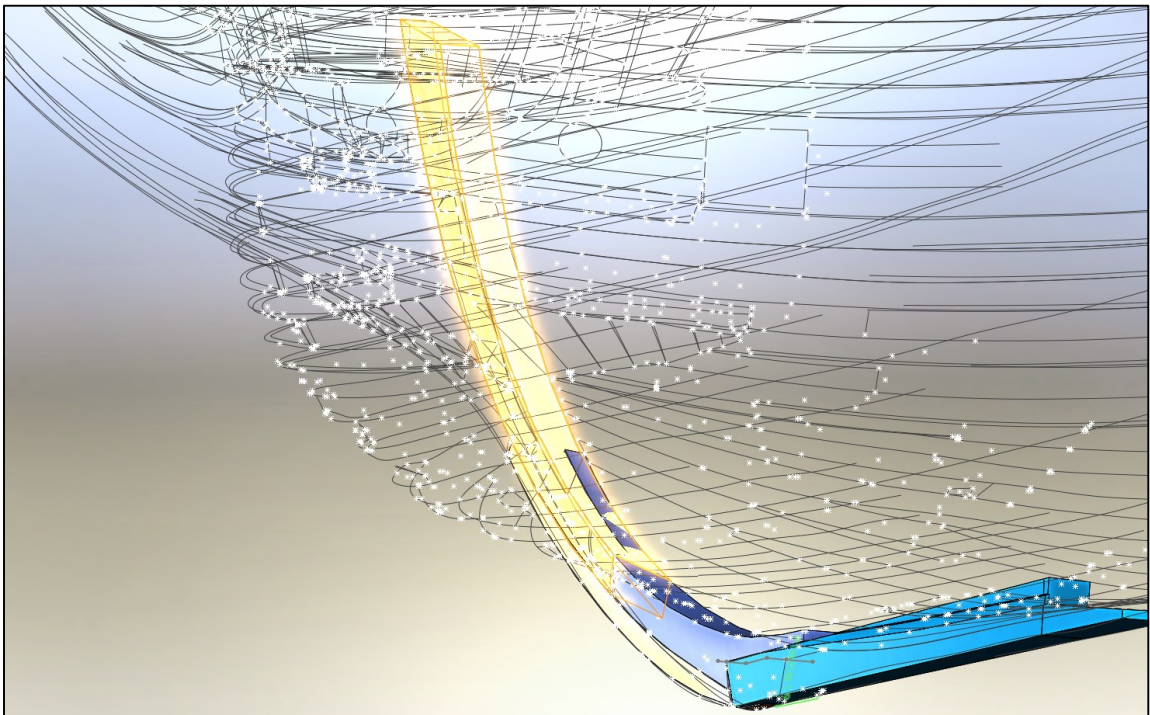


Figure 5.47. Upper stem loft.

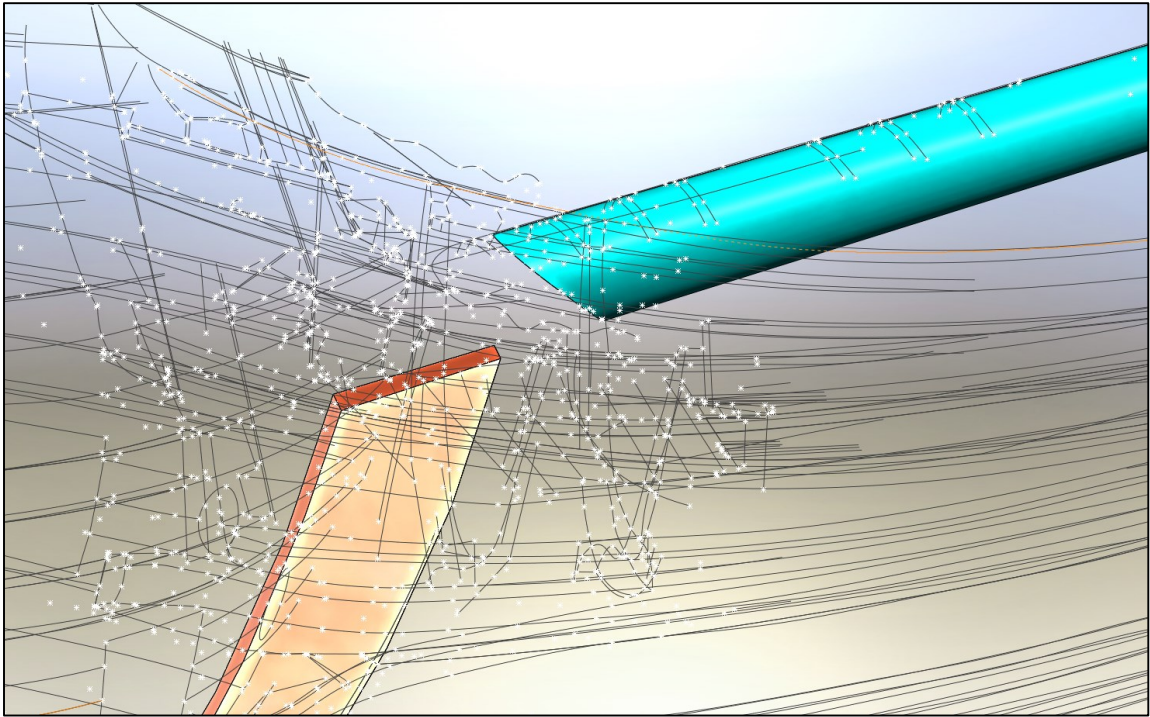


Figure 5.48. Schematic model of the bowsprit. The position of the bowsprit aided in defining the top face of the stem.

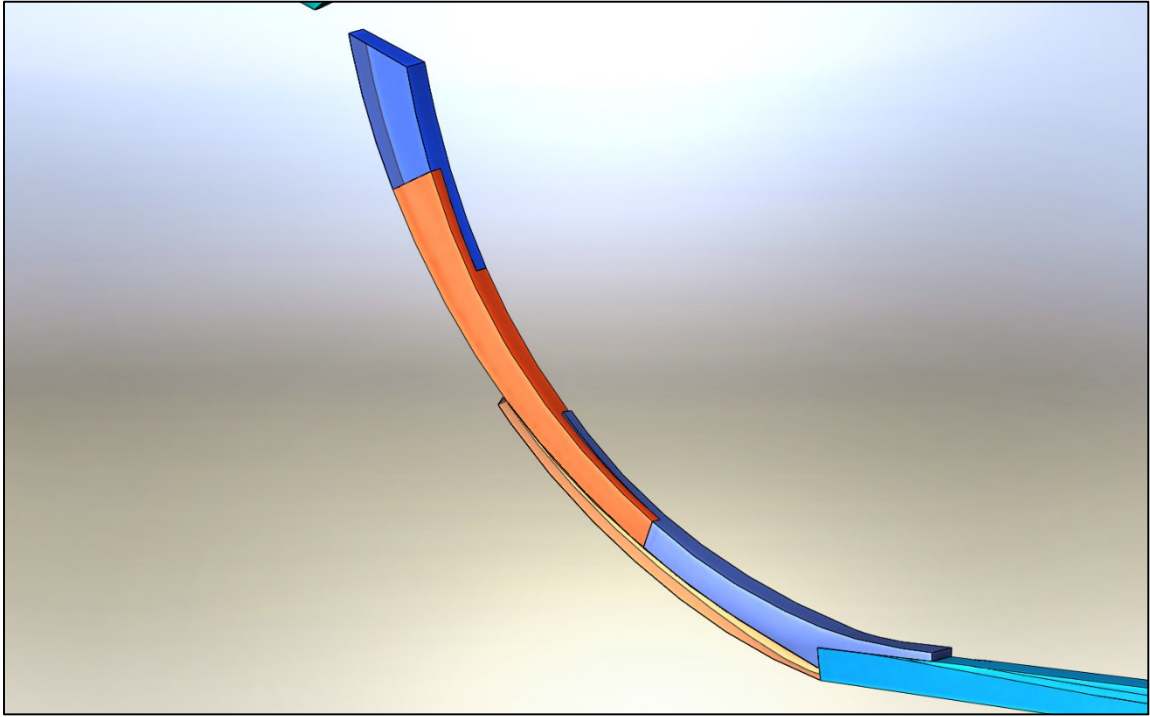


Figure 5.49. Complete stem model.

PLANKING MODEL

The northern Dutch shipbuilding tradition begins construction in a shell-based fashion and the shape and configuration of the planking, particularly the bottom and bilge planking, is an important design component of the overall hull form. An accurate model of *Vasa*'s hull planking is therefore critical to the design analysis. The decision was made not to model all of *Vasa*'s hull planks and instead to focus modeling on the areas of the hull that were most relevant to design analysis.²² Hull planks were modeled individually in most cases. Creating the planking model proved to be the most challenging hull component to model and exposed the greatest limitations of SolidWorks for modeling complex organic curvatures from point cloud data.

The total station survey captured excellent data of the outside surface of the external hull planking and thus a wealth of point cloud data was available to guide modeling. Like the other hull component models, the point cloud was cropped and imported into SolidWorks, seen in Figure 5.50. The method chosen for modeling the planking differed from the approaches taken for the keel, sternpost, and stem. Because point cloud data is only available for the exterior face of the planking, modeling focused on creating accurate exterior surfaces of planks and then thickening the surfaces inward to create solid models of individual planks.

²² Modeling all of *Vasa*'s hull planks would have been unnecessarily time consuming, redundant, and created a much larger and less manageable file size.

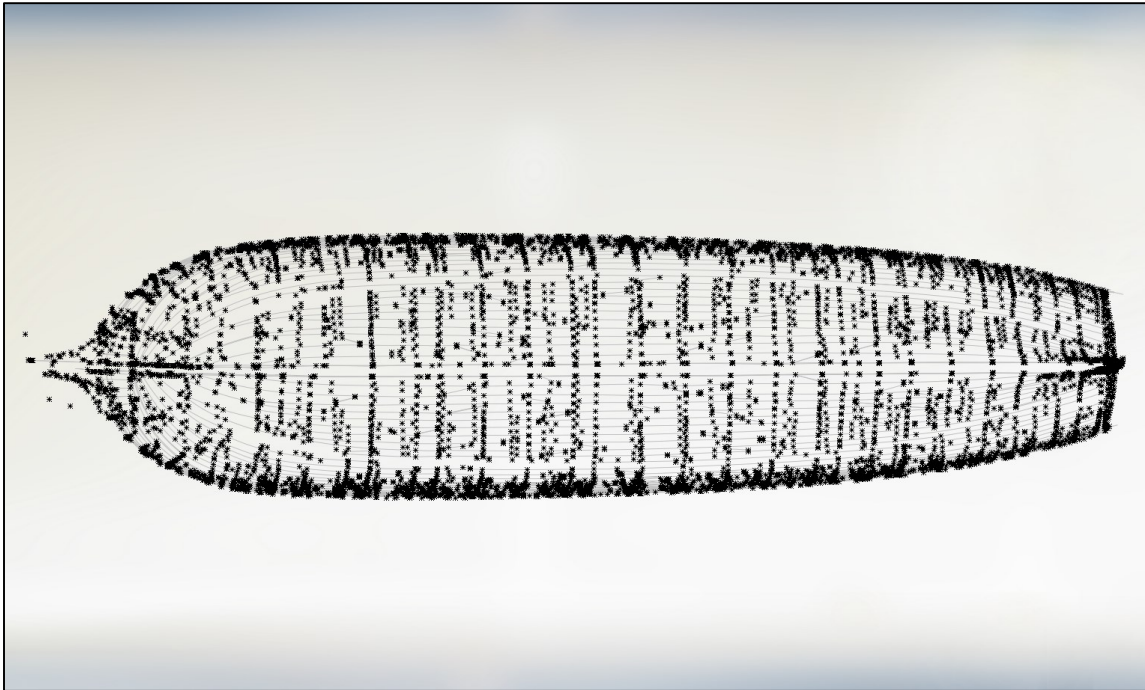


Figure 5.50. Imported point cloud for planking.

The same basic process was applied to modeling each plank. A 3D sketch was made of the plank outline, which was then used to create a surface. The surface was then thickened inboard to 9.9cm. (4in. S)²³, the average thickness of *Vasa*'s planking, and converted into a solid.

Figures 5.51, 5.52, and 5.53 illustrate this progression. This method generally worked well, but in some cases SolidWorks created an abnormal surface from the 3D sketches. Adjustment of the 3D sketch by simplifying the splines of the plank sides occasionally remedied this problem. In situations where the surface still proved troublesome, simplifying the scarfs between planks proved the most useful. Through much trial and error it was found that the flat scarfs between planks were the source of most surface-creation error. Once these flat scarfs were converted to diagonal or butt scarfs, the surfaces behaved as desired and more accurately reflected the shape

²³ A capital "S" is used to denote a measurement in Swedish feet – the unit used in the design and construction of *Vasa*.

of the actual hull planking. An example of this problem and solution is shown in Figures 5.54 and 5.55. Although this created planking models that individually are not replicas of their real world counterparts, the focus of this study is on the hull form. To facilitate better modeling and analysis of the hull form, the decision was made to compromise accuracy on the shape and configuration of planking scarfs, a relatively minor construction detail, which never exceeded a few centimeters. In some cases, mainly in areas of extreme curvature (especially at the bow and stern), SolidWorks was unable to find a reasonable surface solution regardless of how the scarfs and edges of the planks were modified. In these cases, the planking was simply left as a sketch outline and not converted to a surface or solid. None of these planks occurred in areas critical to the recovery and analysis of the hull form design method.

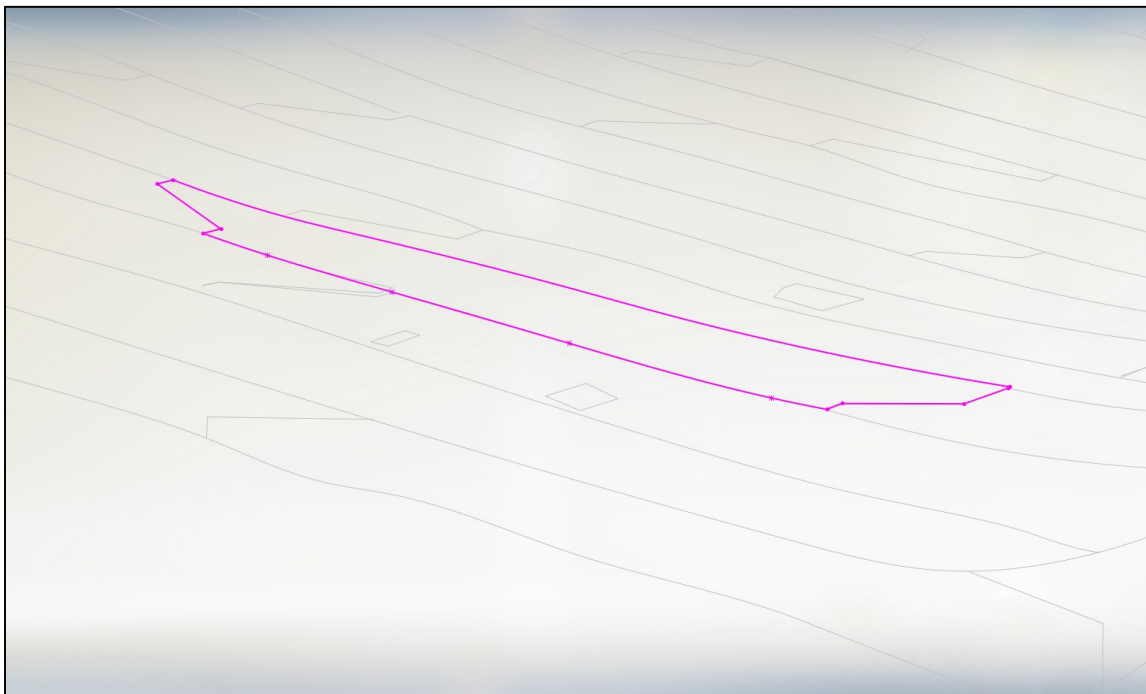


Figure 5.51. Planking outline.

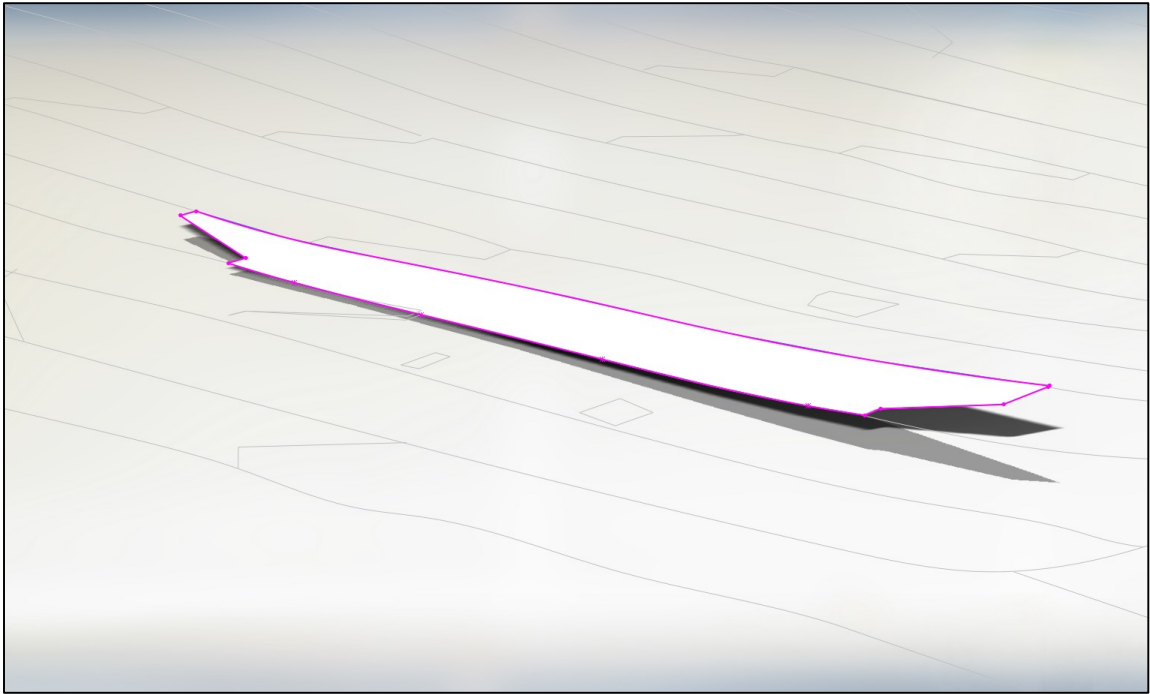


Figure 5.52. Planking surface.

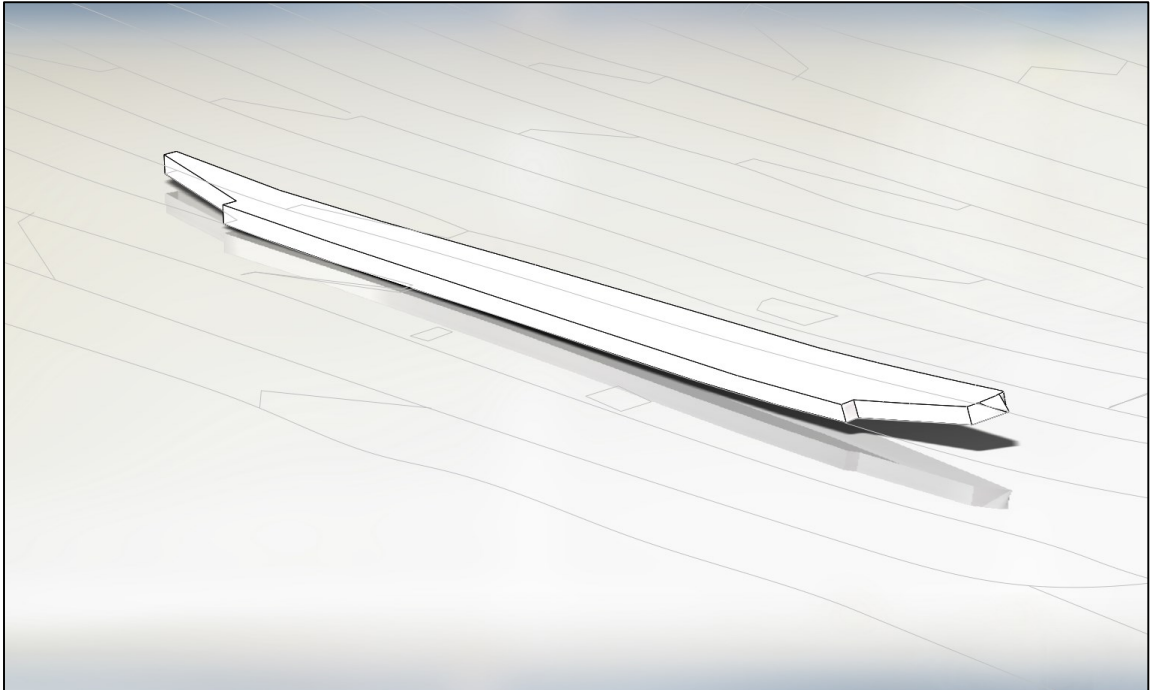


Figure 5.53. Thickened solid plank.

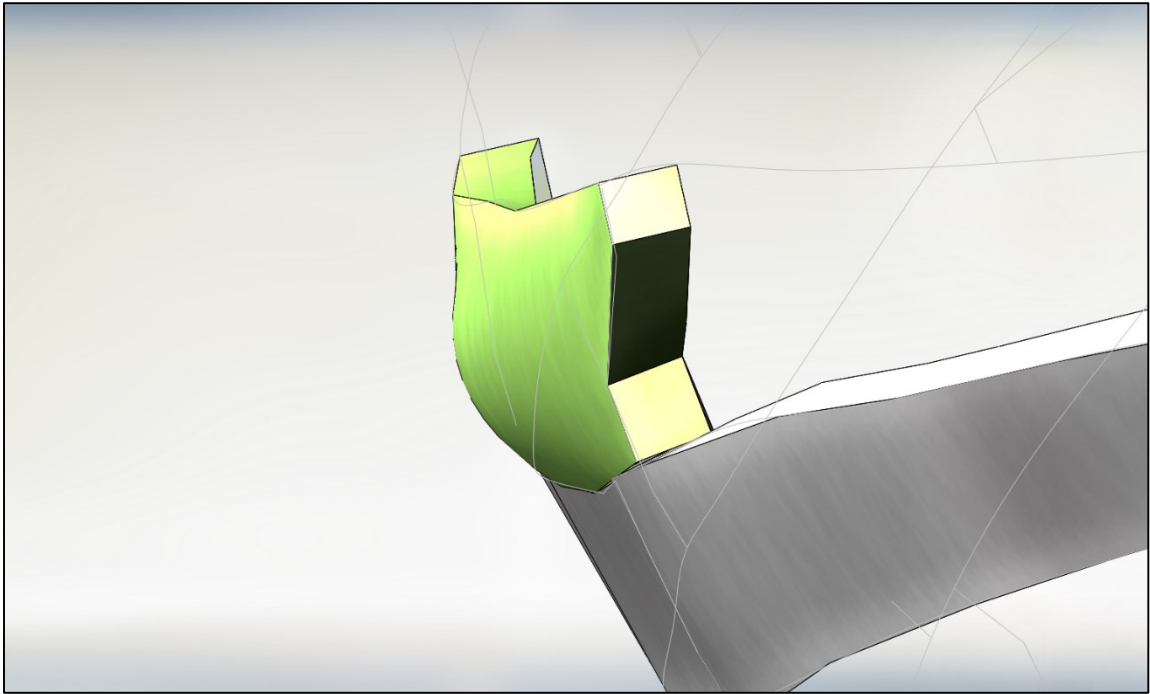


Figure 5.54. End-view of a plank. The surface shows significant bowing outwards.

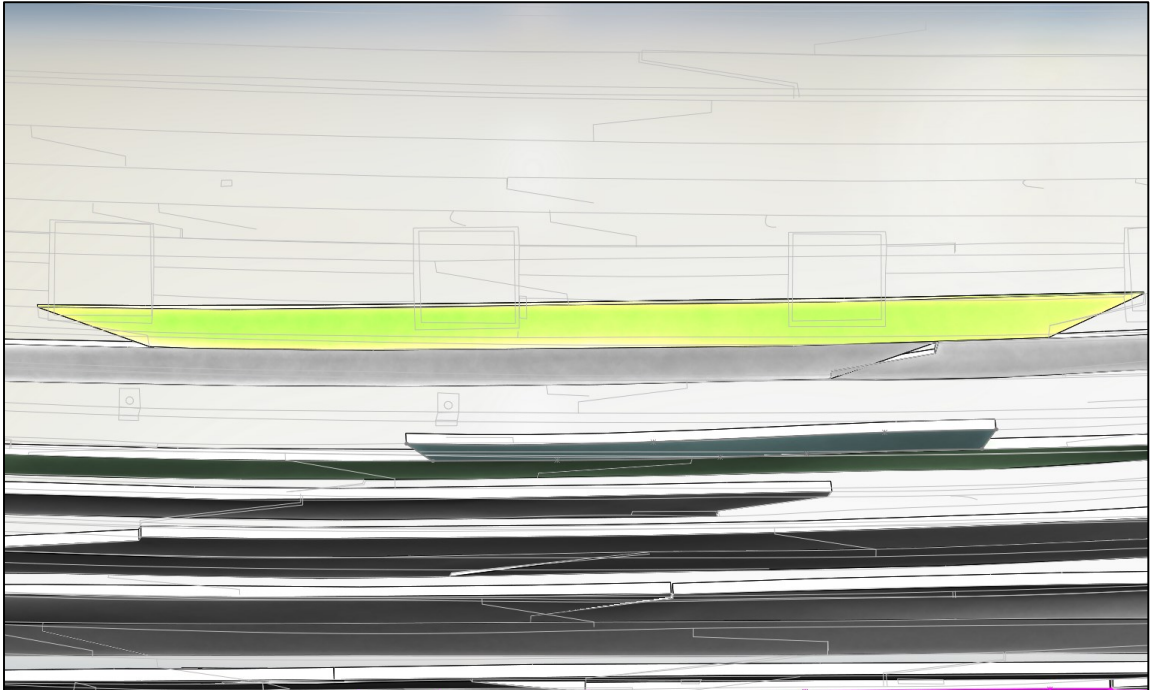


Figure 5.55. The same plank as above with simplified scarfs. This modification eliminated the bowing in the middle of the plank.

A slightly different approach was taken for modeling the wales. A 3D sketch of the wale outline was made, as with the rest of the planking, and used to define a surface. This surface was made at the midplane of the wale, however, and then thickened outwards in both the inboard and outboard directions to a thickness of 19.8cm. (8in. S), the average thickness of *Vasa*'s lower wales. This process is illustrated in Figure 5.56. Modeling progressed from the garboard up to strake immediately below the lower gunports. A limited number of schematic stern planks and upper planks were modeled to aid in the eventual alignment and assembly of hull timbers to create a more comprehensive model, discussed below.²⁴ The finished planking model is shown in Figure 5.57.

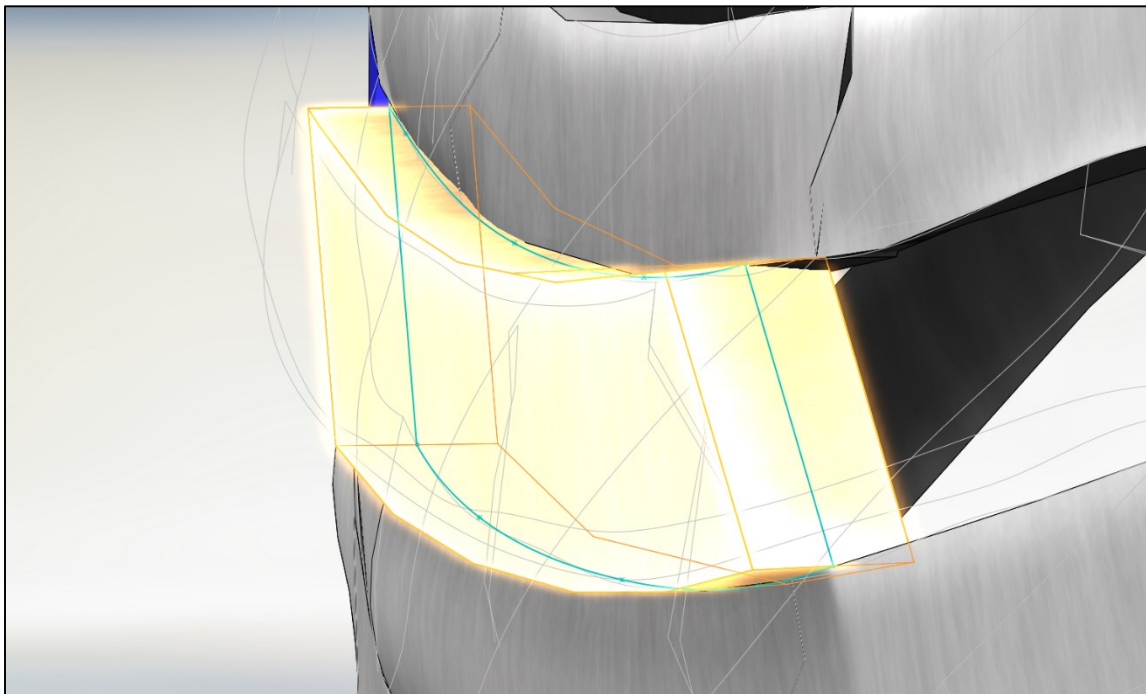


Figure 5.56. Thickening a wale. The wale surface (outlined in blue) is thickened both outside and inside to create a fully defined solid wale.

²⁴ The forward lower gunports were created as 3D sketches for the same reason.

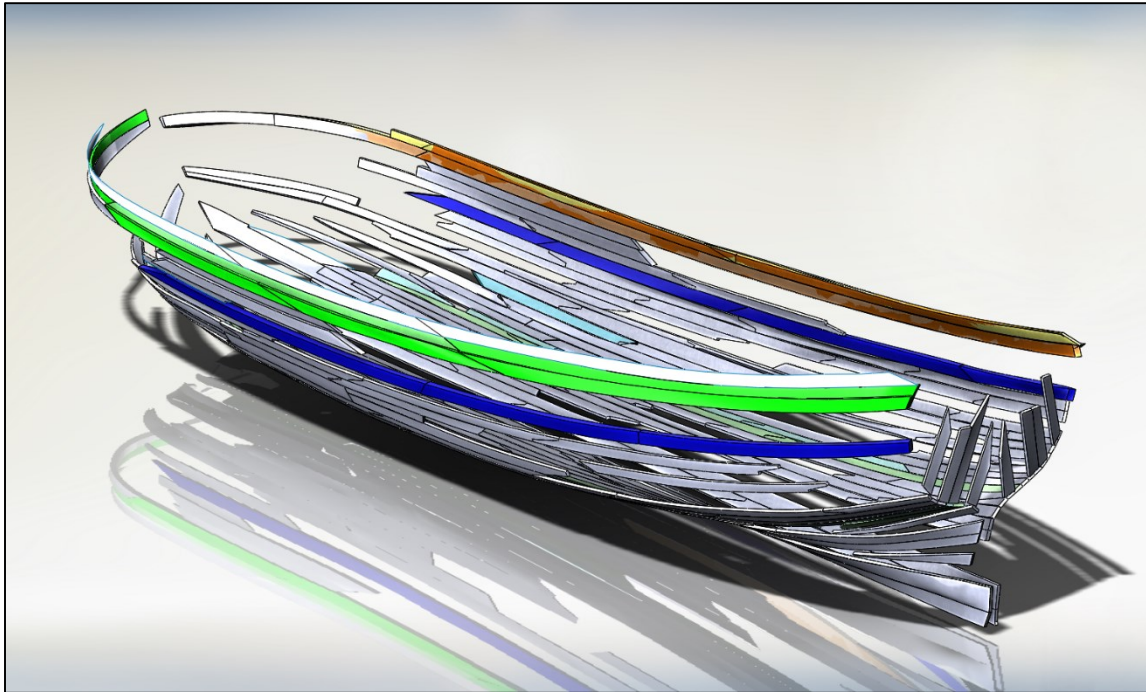


Figure 5.57. Finished planking model.

WING TRANSOM MODEL

Most of the after face of the wing transom is visible and was recorded in the total station survey. The outside of *Vasa*'s wing transom is shown in Figure 5.58. Although much of the timber is inside the hull and therefore not recorded in the point cloud data, it is reasonably accessible from inside the hull. The model was created using both point cloud data and measurements taken with a folding rule inside the hull.

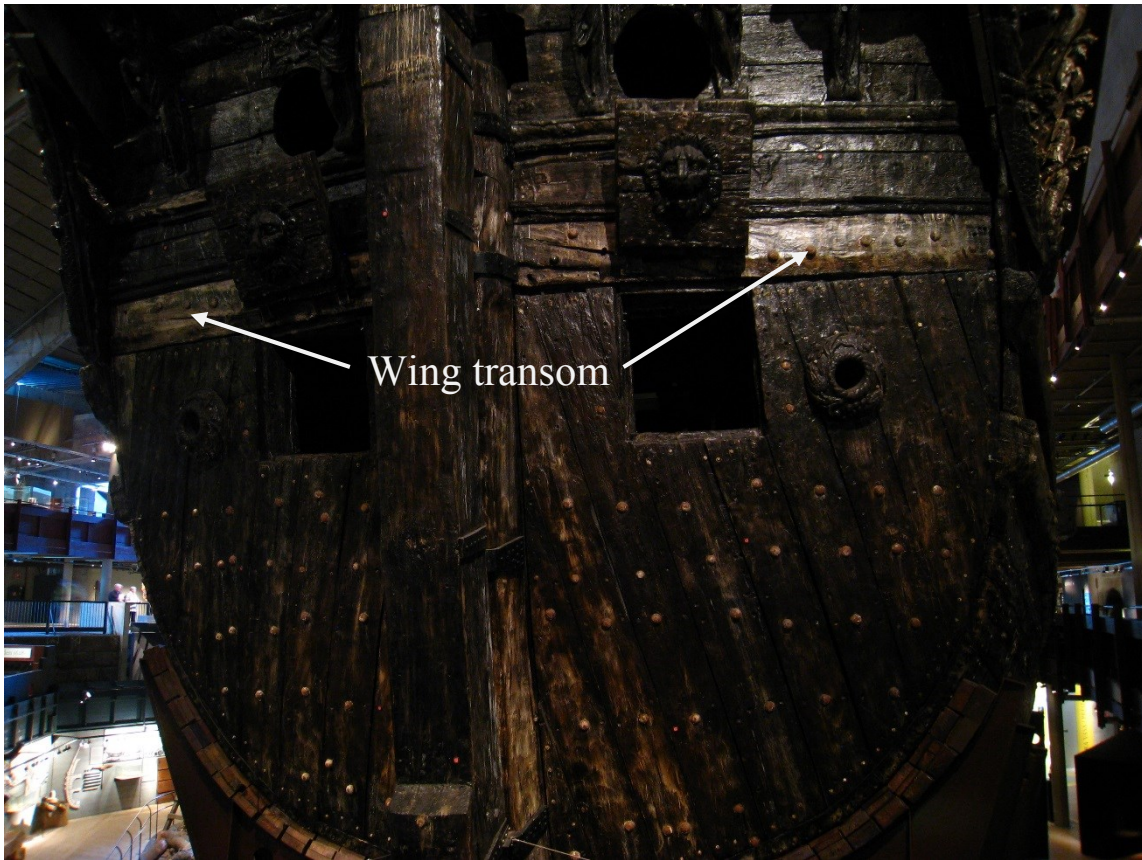


Figure 5.58. *Vasa*'s wing transom as visible from outside the hull.

Instead of starting with a new model, the wing transom model was built within the sternpost model file. After attempting several methods to model the timber, the best approach proved to be creating a central profile of the timber and using the after face outlines as paths to make a swept solid. The central portion of the wing transom is accessible inside the hull on both the orlop deck and lower gundeck, shown in Figure 5.59. Folding rule measurements provide good dimensional data on the timber at this point. Based on these measurements, a central profile of the wing transom was created in SolidWorks that intersected with the after face outline. This profile was then swept along the path of the after face outline in both the port and starboard directions; the two sweeps were then combined to form a single solid body. The finished model

accurately represents the size and position of the wing transom as needed for hull form design analysis.²⁵ The modelling progression is illustrated in Figures 5.60, 5.61, and 5.62.



Figure 5.59. *Vasa*'s wing transom as visible on the orlop deck.

²⁵ Construction details such as bolts or rabbeting for the transom planking are not relevant for the current study and were not modeled.

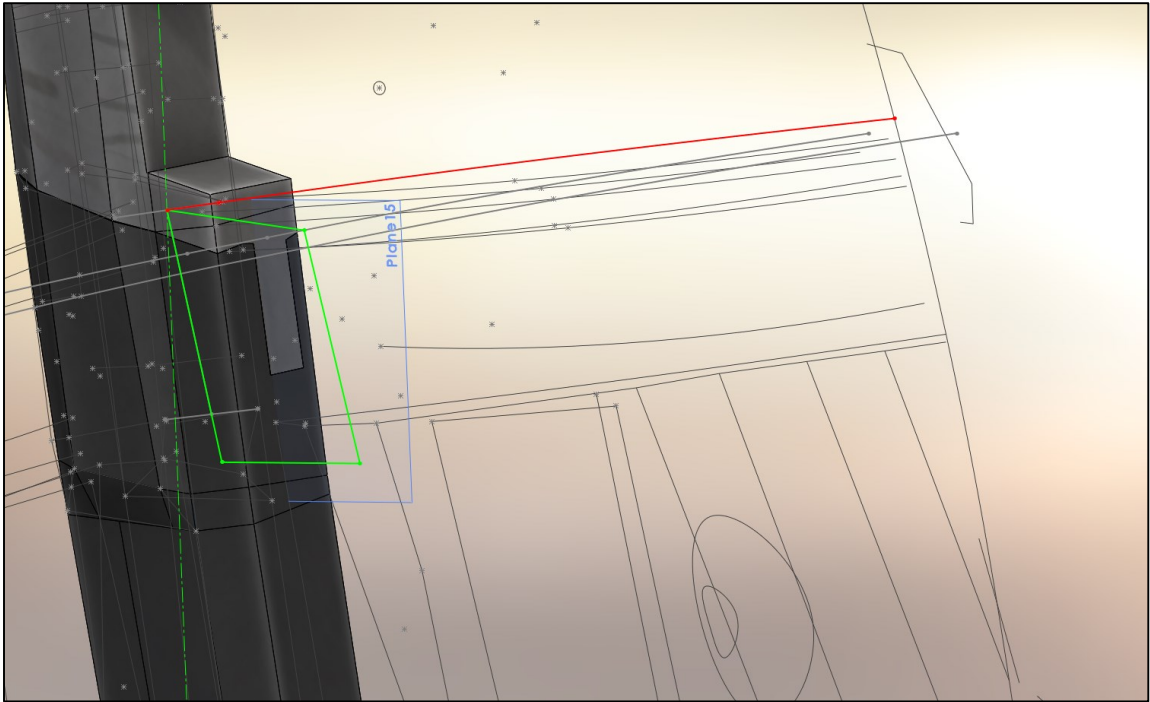


Figure 5.60. The central profile (green) and portside path (red) used to create the port half of the wing transom.

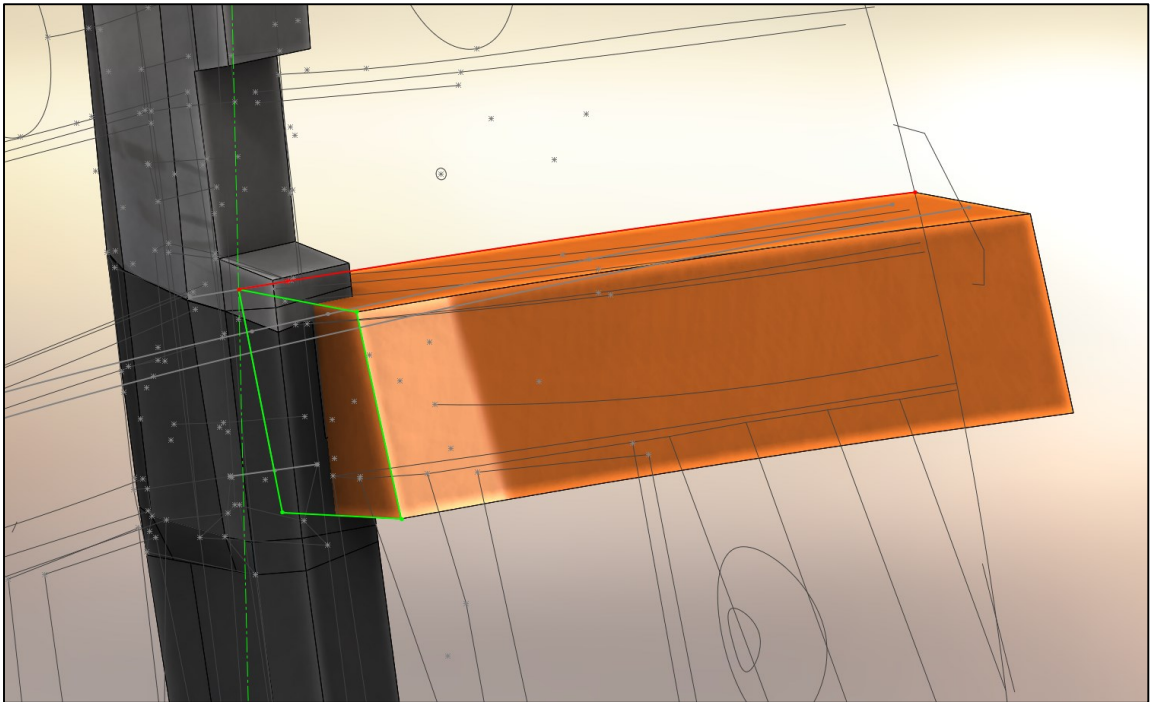


Figure 5.61. Half of the solid wing transom model, created using the central profile and portside path.

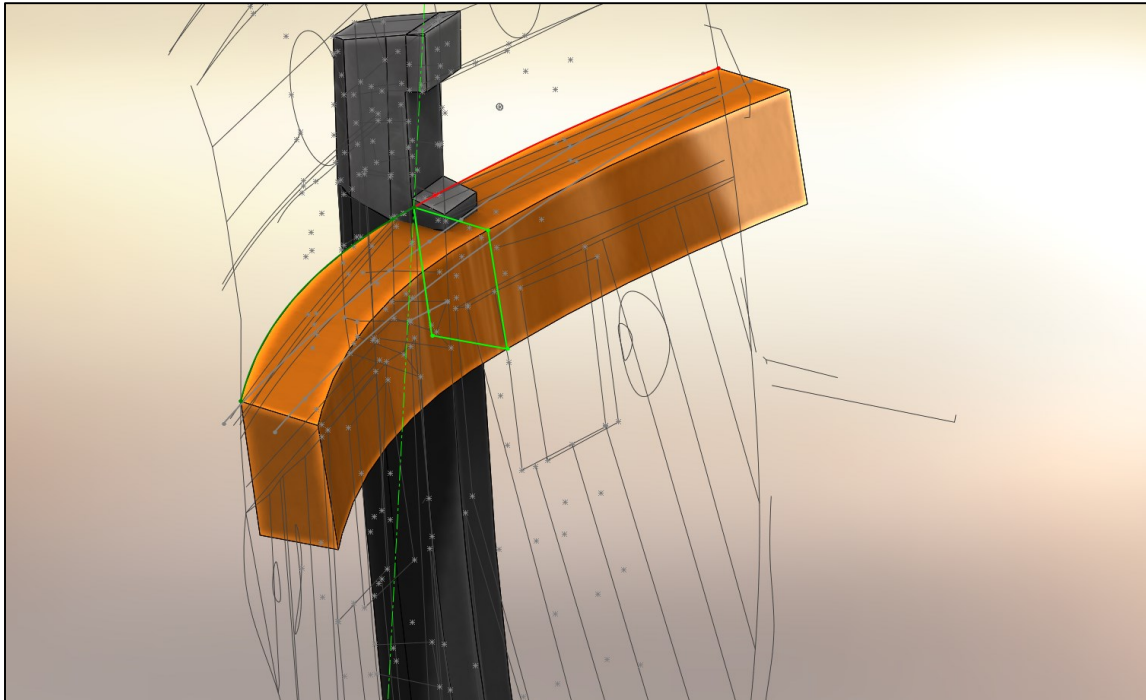


Figure 5.62. The full wing transom model.

FASHION PIECES MODEL

The next timbers to be modeled were the fashion pieces. Like the wing transom, these timbers were created in the same file as the sternpost. The fashion pieces are key timbers in determining the shape of a hull at the stern. These timbers are, however, completely inside the hull and therefore were not recorded in the total station survey. They are only partially accessible inside the hull and measurements of their sided and molded dimensions were taken where possible. A photograph showing the accessibility of the fashion pieces is seen in Figure 5.63. Their general position and outside curvature is evidenced by the lower curve of the stern. The models were created using these data sources.

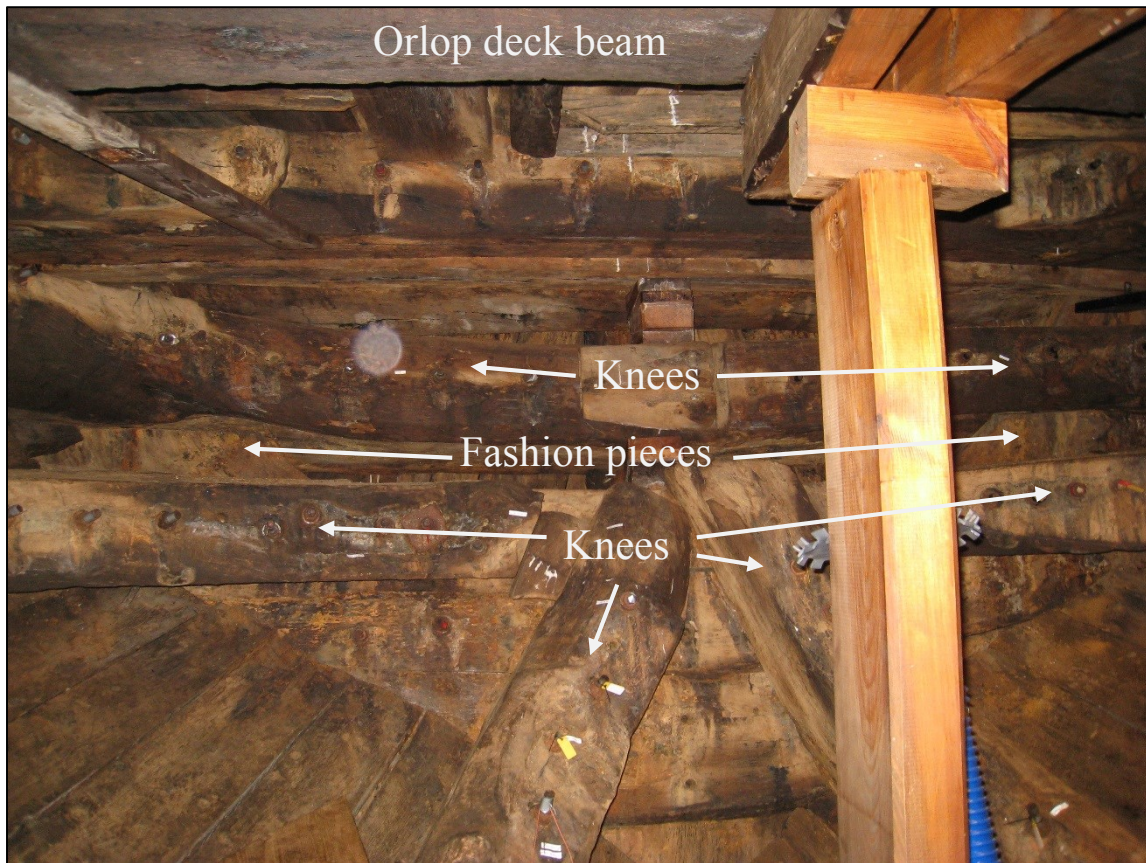


Figure 5.63. Photograph of *Vasa*'s stern construction in the hold. The fashion pieces are only partially accessible.

The fashion pieces were modeled one at a time, beginning with the starboard timber. A plane was created using the lower outboard corner of the wing transom and the estimated position of the inner face of the sternpost as references. A spline that followed the inside curvature of the hull planking was made on this plane to describe the outside curvature of the fashion piece. A second spline was made generally parallel to the first, but adjusted to reflect the measurements of the molded dimensions of the fashion piece. The tops and bottoms of these splines were connected to create a closed sketch describing the outline of the starboard fashion piece. A surface was created from this sketch and thickened on the inboard face to 35cm. (1 ft. 2 in. S), the maximum observed sided dimension of the starboard fashion piece. The timber was trimmed

to eliminate overlap with the sternpost where the timbers meet. The process was repeated on the port side.²⁶ The tops of the timbers were trimmed to be flush with the wing transom. The modelling progression is illustrated in Figures 5.64, 5.65, and 5.66

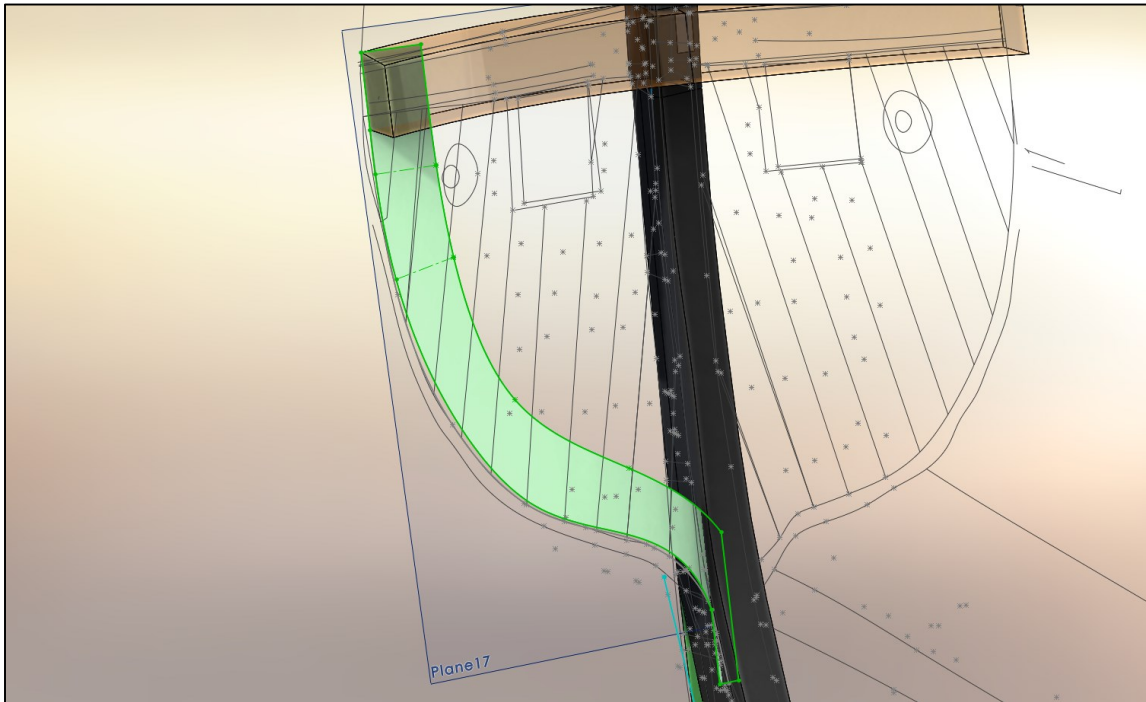


Figure 5.64. The sketch and surface for the creation of the starboard fashion piece.

²⁶ Because the details of these timbers are largely inaccessible, the model is a schematic approximation of the shape and position of the timbers.

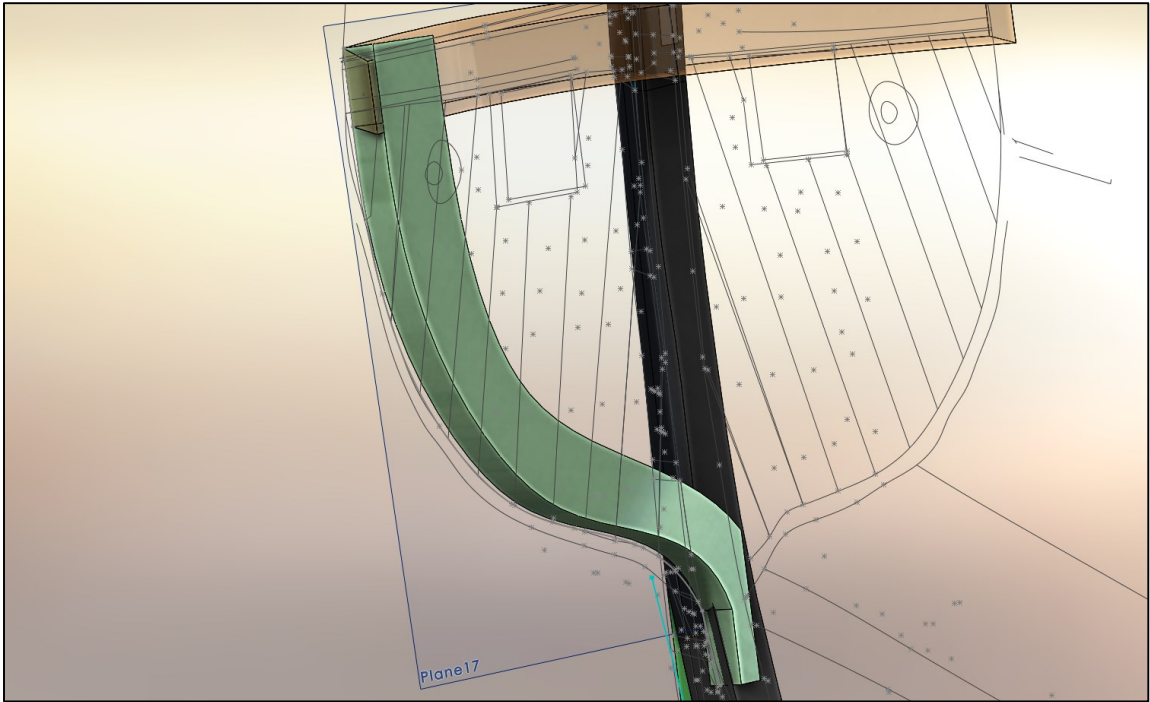


Figure 5.65. Thickened solid body of the starboard fashion piece.

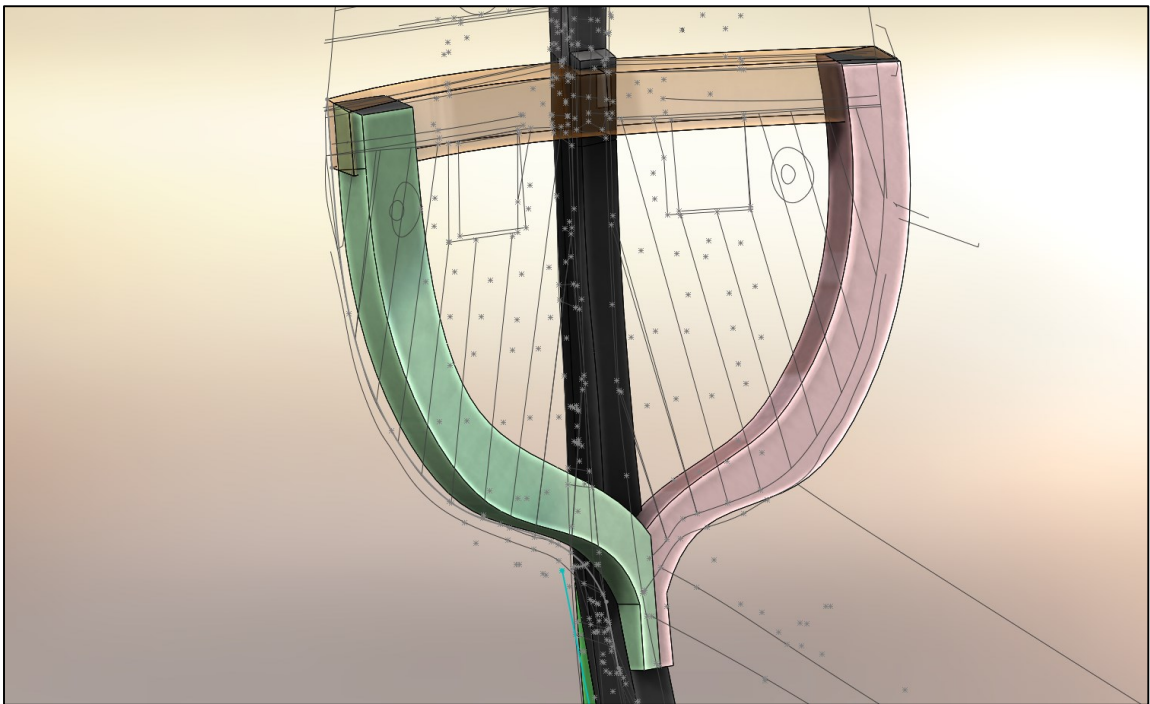


Figure 5.66. Finished port and starboard fashion pieces model.

STERN TIMBERS MODEL

The stern timbers were the final hull element to be modeled and were built in the same file as the sternpost, wing transom, and fashion pieces. Like the fashion pieces, these timbers are largely absent from the total station data because they are almost entirely enclosed within the hull. The total station survey did, however, capture the top ends of the stern timbers where they pass through the roof of the poop deck and support the railing on deck. The top of the starboard stern timber is seen in Figure 5.67. Like the fashion pieces, the stern timbers are not fully accessible inside the hull. Sided and molded measurements were taken with a folding rule where the timbers were accessible. The starboard stern timber as accessible in the great cabin is shown in Figure 5.68. The model was constructed based on these dimensions, the point cloud data regarding the position of the tops, and what is observable about the configuration and behavior of the stern timbers inside the hull.

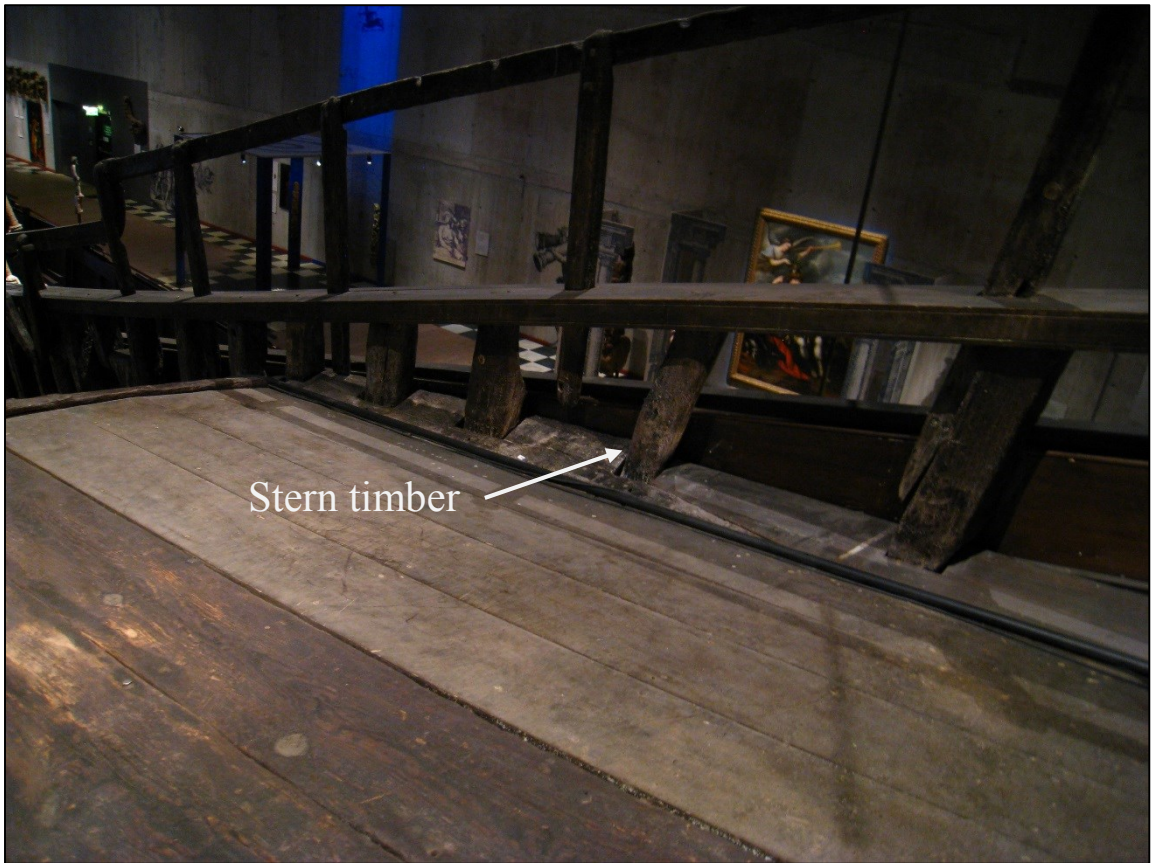


Figure 5.67. Starboard stern timber as seen on top of the poop cabin.

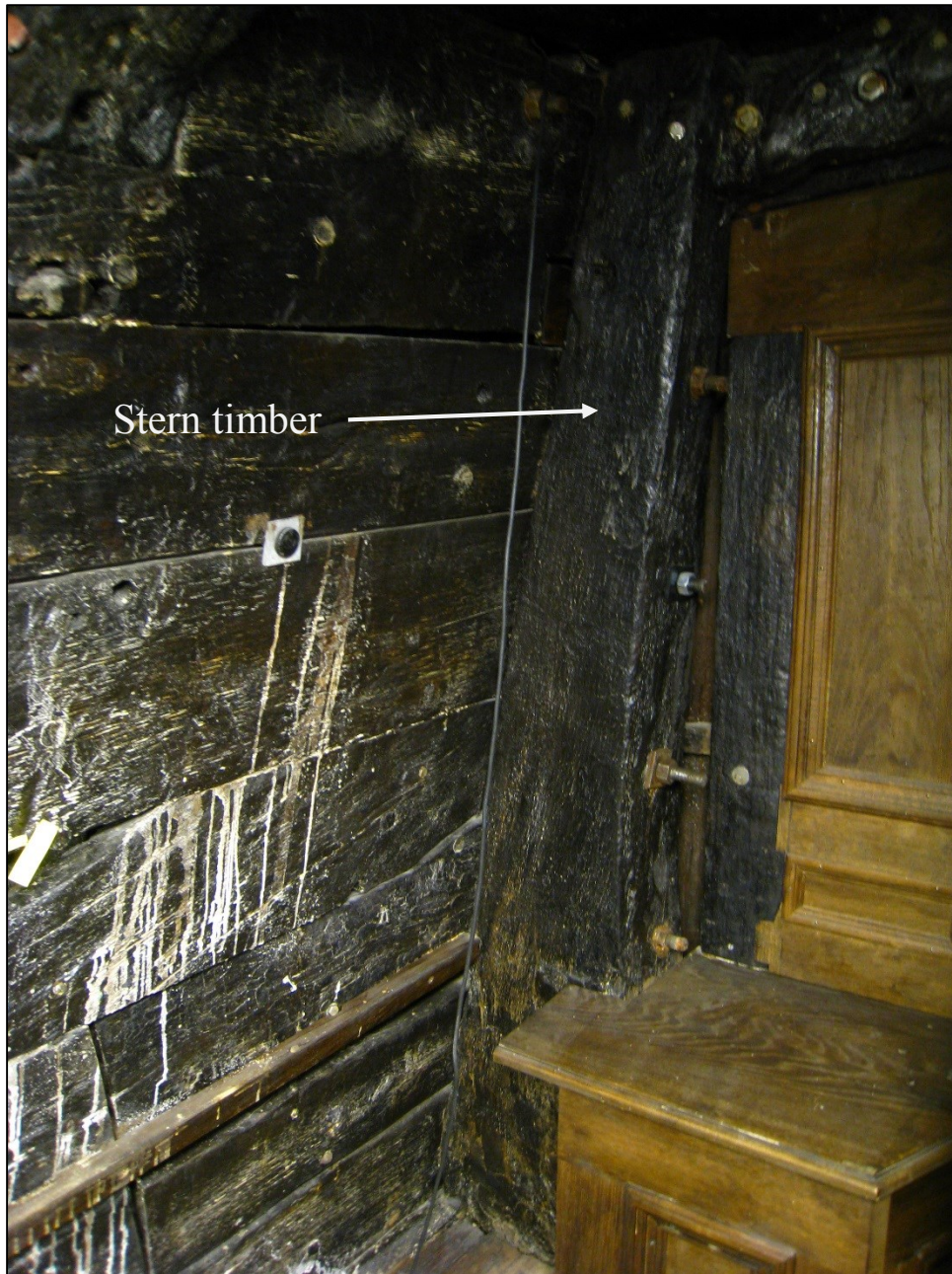


Figure 5.68. The starboard stern timber as accessible in the great cabin.

The first step was to create solids based on the limited point cloud data that was available. Sketches and surfaces were created from the point cloud data and then thickened to create solids based on the dimensions recorded with a folding rule. These solids provided the location and

dimensions of the tops of the timbers. The base of the timbers overlaps the wing transom and fashion pieces. The precise dimensions of this overlap, however, could not be measured. Thus the stern timbers were modeled with their lower extents even with the wing transom and fashion pieces with the knowledge that this does not accurately reflect their precise shape.²⁷ Instead, modeling focused on accurately describing the height and angle of the stern timbers as these are the most relevant factors influencing the shape of the hull.

A surface was created based on the sided and molded dimensions of the stern timbers taken inside the hull on the lower gundeck at the level of the wing transom. A solid was then created by lofting this surface and the bottom surface of the stern timber solid bodies with guide curves connecting the after corners of the solid. The top and the main sternpost body were merged into a single solid. This procedure was repeated to produce the port stern timber. The construction of the stern timbers model is illustrated in Figure 5.69.

²⁷ This is a construction detail that does not have significant influence on the hull form or its analysis.

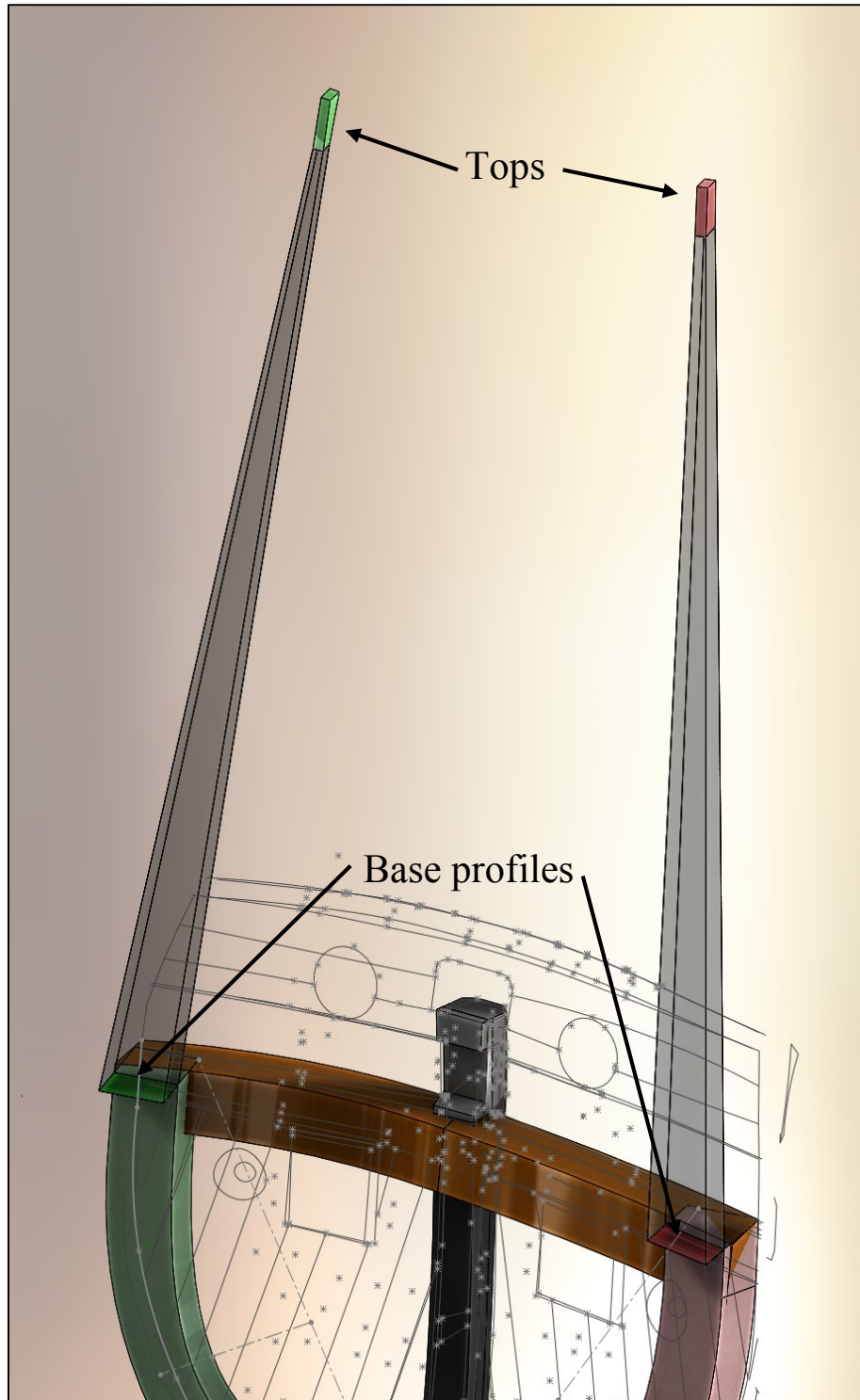


Figure 5.69. The stern timbers model. The tops of the stern timbers (red on port, green on starboard) were made from the total station point cloud data. The base profiles were created based on folding rule measurements. The main bodies of the timbers (transparent grey) were lofted between these two entities.

ASSEMBLY

To this point in model construction, all timbers were contained in four separate files: the keel file which contained the four sections of the keel, the stem file which contained the four stem timbers and bowsprit section, the planking file which contained the hull planking up to the lower gundeck, and the sternpost file which contained the three timbers of the sternpost, wing transom, two fashion pieces, and two stern timbers. To facilitate a full analysis of the hull form design method, it was necessary to assemble all of these timbers into one file. SolidWorks facilitates both top-down and bottom-up construction of large assemblies. Top-down construction enables the user to create a large assembly with many parts in a single file. Bottom-up construction enables the user to create separate parts in different files and then assemble them one by one into a larger assembly file. Each organizational method offers advantages and disadvantages based on the modeling needs and desired outcomes of the user. The approach taken in this dissertation project is a bottom-up approach, with each hull element (although composed of multiple timbers) being modeled separately and then assembled together.

To begin the assembly, a new file was created. Each existing model file was then imported one at a time into the blank assembly. The keel was imported first and served as a reference for arranging the other components, seen in Figure 5.70. The stem was imported next, seen in Figure 5.71. To properly arrange components in an assembly and ensure that they behave in a real-world fashion, SolidWorks allows users to define **mates** between parts. Mates ensure the proper alignment and configuration of parts that were created in separate files when they are

assembled together.²⁸ When importing each timber, mates were defined that established the relationships between the separate hull elements. The sternpost was then added and set on top of the keel, seen in Figure 5.72. Lastly the planking was added and mated to the other hull components. The finished assembly is seen in Figure 5.73. With the assembly finished, analysis of hull form design method could begin. During analysis it was discovered that modeling additional timbers was necessary. These additional models are illustrated at the appropriate points in the following chapter. Since the majority of analysis focuses on the *hals* of the ship, additional timber modeling focused on the area of the hull. Additional timbers include upper hull planks and schematics of floor timbers and deck beams.²⁹ The hull form design analysis based on this model is detailed in the following chapter.

²⁸ Since all parts were created from the same point cloud, the points in the cloud proved to be the most useful mating references.

²⁹ The positioning of the deck beams was most critical to hull design at the *hals* and full solid modeling of the deck beams would have required modeling timbers not directly relevant to the hull form design method, 2D schematic representations of the beams were used instead.

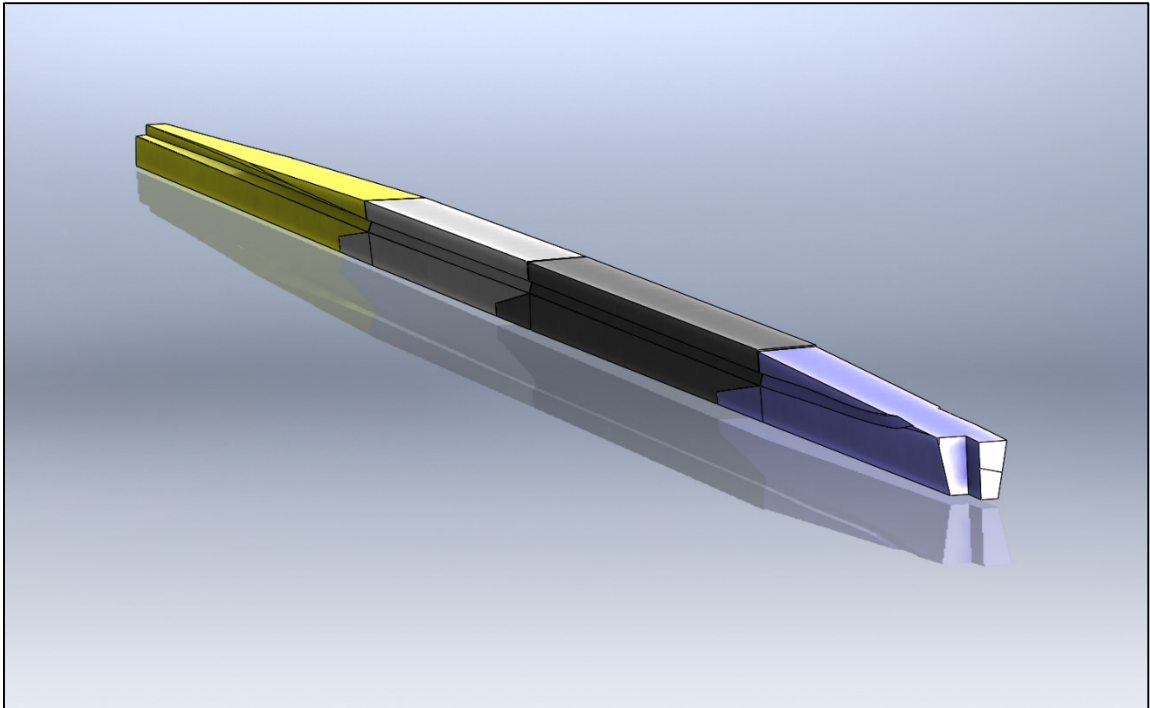


Figure 5.70. The keel imported into the final assembly.

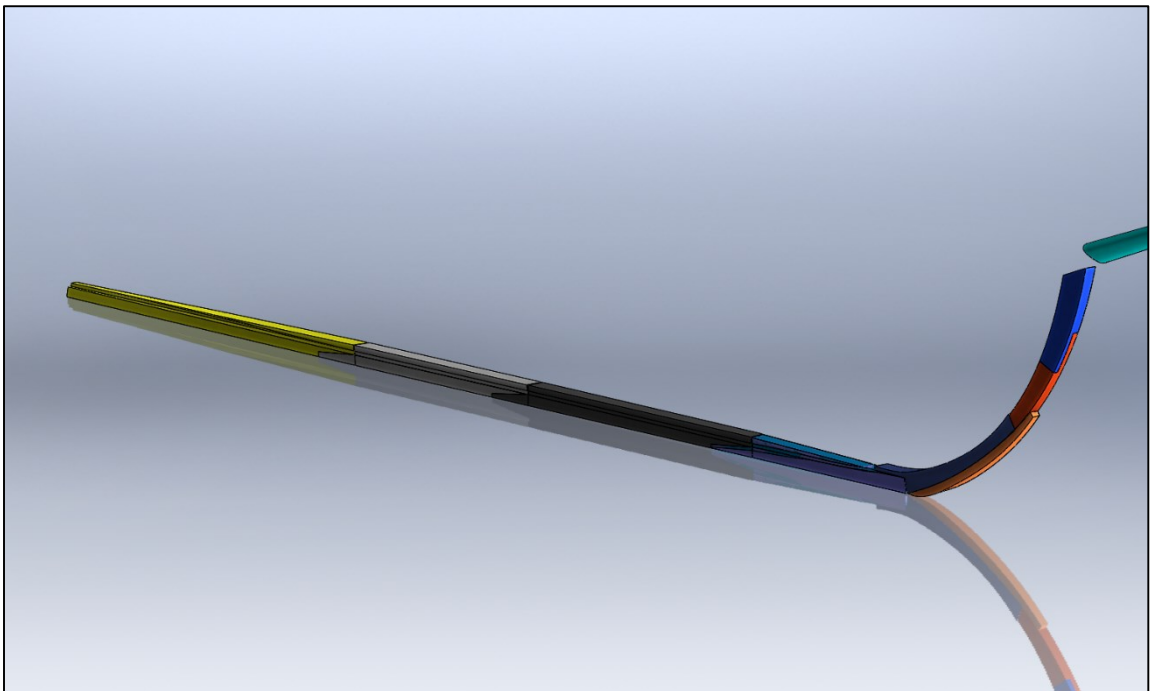


Figure 5.71. The stem added to the keel.

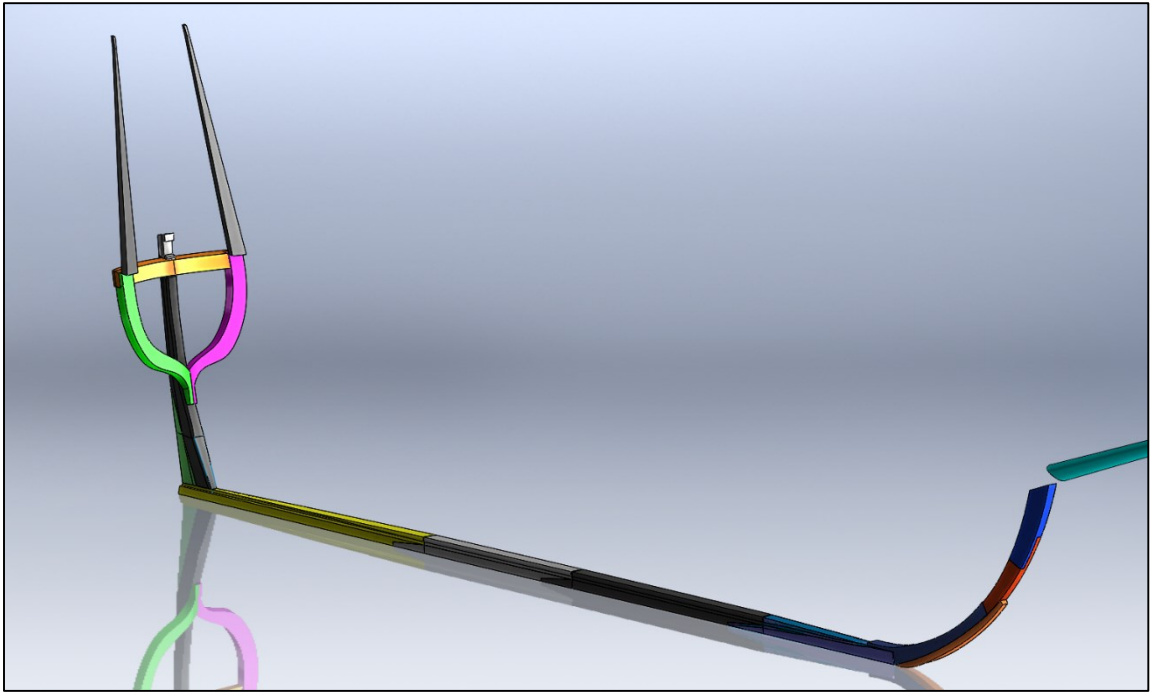


Figure 5.72. The sternpost construction added to the assembly.

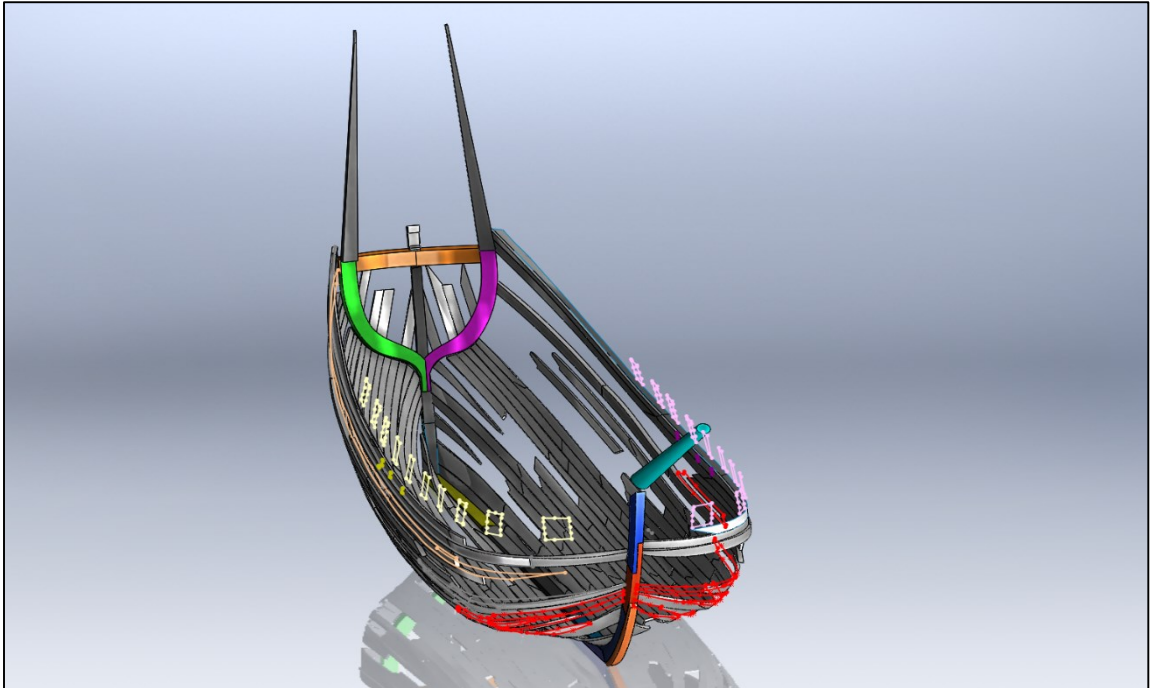


Figure 5.73. The complete assembly.

CHAPTER VI

DESIGN RECOVERY AND ANALYSIS

This chapter details the recovery and analysis of the methods used to design the hull of *Vasa*. Analysis is based on current understanding of Dutch shipbuilding methods and the solid models discussed in previous chapters supplemented by the extant historical documentation relating to *Vasa*'s design and construction. The result is an unprecedented view into early modern methods of naval architecture.

CONTRACT NEGOTIATION AND CONSTRUCTION DOCUMENTATION

Little written documentation of *Vasa*'s design and construction exists and it is unlikely that significantly more records were ever produced. What has survived is a record of contract negotiations and correspondence between shipwright Henrik Hybertsson and the Swedish naval administration, King Gustav Adolf, and his chief naval minister Vice Admiral Klas Fleming. The first surviving draft of the contract was written in 1624 (otherwise undated) and gives Hybertsson responsibility for operation of the Stockholm shipyard for three years. The contract stipulated that during this tenure Hybertsson was to build four new warships in addition to overseeing the maintenance of the existing fleet. The four new vessels were to be two large ships each 136 ft. long over the posts and 34 ft. in beam on the main deck at a cost of 42,000 *dalers* and two small ships to be built to the same specifications as *Gustavus*, each at a cost of 15,000 *dalers*.¹ The second draft of the contract, written on 23 December 1624 and signed by

¹ *Gustavus* was a ship built by Hybertsson as part of a previous contract; Hocker 2006, 42; Glete 2002b, 8.

the Admiralty, increases the term of the contract to four years and specifies that the new ships be delivered in the following order: one large ship in 1626, one small ship in 1627, one large ship in 1628, and one small ship in 1629.² It also lowers the cost of the ships to 40,000 *dalers* for each of the large vessels and 14,000 *dalers* for each of the small. A third draft followed shortly after that simply raised the cost of the small ships back to 15,000 *dalers* each.³

Feature	<i>Tre Kronor</i>	Gustav Adolf's 4 November 1625 Specifications
Keel Length	108 ft.	120 ft.
Keel Molded	21 in.	21 in.
Keel Sided	21 in.	21 in.
Bottom Breadth	24 ft.	Not specified
Planking Thickness	4 in.	4 in.
Wale Thickness	7 in.	7 in.
Keelson Thickness	9 in.	9 ½ in.
Keelson Width	29 in.	29 in.
Ceiling Thickness	3 ½ in.	3 ½ in.
Beams Molded	14 in.	14 in.
Beams Spacing	3 ½ in.	3 ½ in.
Floor Timber Molded	12 in.	12 in.
Rider Molded	16 in.	16 in.

Table 6.1: The specified dimensions for the small ships. Hybertsson's specification (*Tre Kronor*) compared to the king's new specifications as of November 1625.⁴

The final contract was signed by King Gustav Adolf on 10 January 1625 and was intended to take effect in January 1626. The contract still required four ships to be built, two large and two small. The large ships were to be delivered in 1626 and 1628, and the two small ships in 1629.

² Glete 2002c, 19; Hocker 2011, 37.

³ Hocker 2006, 41-42.

⁴ Hocker 2006, 44.

The prices remained 40,000 *dalers* for each large ship and 15,000 *dalers* for each small ship. The two small ships were still to be based on the design and dimensions of *Gustavus*, but modified specifications for the large ships were given. The large ships were to be 128 ft. long on the keel, and 34 ft. in beam.⁵ This change altered the length of the larger ships considerably, though it is uncertain by exactly how much. The previous versions of the contract called for the large ships to be 136 ft. long over the posts, whereas the final version of the contract specifies 128 ft. for the keel length only. A ship with a 128 ft. keel would be considerably longer over the posts than 136 ft. This is discussed in greater detail below, in the section on *Vasa's* keel. *Vasa's* keel (129 ft.) is approximately 4/5 of the length over the posts (159 ft.). Thus, the king's modification to the large-ship specification called for a ship approximately 24 ft. longer than the previous specification with little alteration to other timber or hull dimensions.

In the autumn of 1625, Hybertsson wrote to the king and chief naval minister Vice Admiral Fleming to confirm which ship, either small or large, he should lay down first. In his letter, Hybertsson stated he had the timber to lay down either one large ship or two small ships. He also included a list of dimensions from a ship that was nearly ready to launch (likely *Tre Kronor*) and suggested that it would be a good model for the smaller ships. Although the contract was clear that a large ship should be built first, Hybertsson's inquiry proved fortuitous. On 20 September 1625, ten Swedish naval ships were wrecked in a storm off the coast of Latvia. As a result, Gustav Adolf adapted his short-term naval procurement strategy. He responded to Hybertsson's letter on 4 November 1625, requesting that he lay down two small ships instead of one large as originally planned.⁶ Furthermore, the king provided a list of dimensions for these

⁵ Glete 2002b, 9.

⁶ Hocker 2006, 43.

two small ships that differed only slightly from those suggested by Hybertsson, displayed in Table 6.1. The most significant departure from the finalized 10 January contract is the proposed length of keel. Hybertsson suggested 108 ft. whereas the king lengthened the keel to 120 ft. while keeping nearly every other dimension the same - much like the modification to the large ship keel lengths in the finalized contract. Gustav Adolf also addressed the dimensions for the large ships stating they should be either 128 ft. or 136 ft. on the keel, apparently leaving it the final decision in Hybertsson's hands. On 2 January 1626 Hybertsson wrote back to the king voicing frustration that he had the timber on hand to build a 108 ft. ship but not a 120 ft. ship without wasting a great deal of valuable shipbuilding timber. In early February 1626, Hybertsson wrote again to the king stating he had the timber on hand to build one large ship of unknown specification and one small ship, presumably of the 108 ft. specification.⁷ On 22 February 1626 Gustav Adolf responded instructing Hybertsson to build the two small ships according to the 120 ft. specification, though if he could not or would not, he was to begin construction of a large ship instead. On 20 March 1626 Hybertsson reported to the king that he had begun construction of a ship but it will be slightly smaller than the specification. Unfortunately he does not indicate which specification he was referring to. This is the end of the known correspondence pertaining to the size of *Vasa*, subsequent letters between Hybertsson and the Admiralty dealt with business issues such as payment and schedule for delivery.

The ship under construction in early 1626 would later be named *Ny Wasen* (or *the New Wasa*), its name first mentioned in a rigging contract from 12 August 1626.⁸ Hybertsson, who had been

⁷ Presumably the small ship was of the 108 ft. specification, though he does not explicitly state this.

⁸ Historically, the ship was referred to as '*Wasen*', which translates to 'the *Wasa*'. The 'V' in *Vasa* is a product of the standardization of Swedish spelling that began in the 19th century; Hocker 2006, 15-44.

suffering from an illness for more than a year, died in the late spring of 1627. Even before his death, Hybertsson had turned over much of the shipbuilding operations to Henrik Jacobsson. One of Jacobsson's first executive decisions regarding the ship under construction was to widen the hull. According to his testimony following the *Vasa* disaster, Jacobsson expressed doubt in Hybertsson's original design and claimed to have widened the hull by 1 ft. 5 in., but could do no more.⁹

Construction continued through the upper gundeck at which point the hull was launched, likely in late spring 1627. King Gustav Adolf personally inspected the nearly complete ship in January 1628, the only known time when the king was ever aboard. In the late spring of 1628 the construction of the hull was finished.¹⁰ The ship was rigged, ballasted, and towed to the nearby royal armory where the guns were installed. If Jacobsson's concerns over the dimensional stability of *Vasa*'s hull were not enough, in July of 1628 the ship failed a stability test under the supervision of Vice Admiral Klas Fleming.¹¹ Despite the concerns, *Vasa* set sail for the first time in the afternoon of 10 August 1628. It sank after sailing less than one nautical mile.

CHALLENGES OF THE SHIPWRIGHT

Shipwrights in the early modern period had to balance a number of conflicting factors to produce a successful and effective warship. These diverse factors included capacity, firepower,

⁹ Hocker 2006, 46. Jacobsson began construction of *Applet*, the second of the four ships in the contract, in 1627. He made this hull 5 ft. wider than the specification called for, possibly in response to his concerns over *Vasa*.

¹⁰ Hocker 2006, 46.

¹¹ Hocker 2006, 53.

seakeeping, stability, and resistance to enemy fire. Before standardization in naval construction took over in the 18th century, success in shipbuilding was achieved through a combination of experience and experiment. Countries and monarchs were engaged in a naval arms race and pushed shipwrights to operate on the cutting edge of science and technology. In *Vasa*'s case, the shipwrights, operating under order of the king, were faced with the primary challenge of putting many large-caliber guns on a single ship, while taking advantage of new gun founding technology capable of producing lighter weapons. Gustav Adolf championed standardization in naval weaponry, which was rare in European navies. *Vasa* was the first Swedish warship built with the intention of it carrying a complement of newly founded standardized guns.¹² The king intended *Vasa* to be armed with a main battery of 56 24-pounders split between two full gundecks and supplemented by eight smaller guns on the upper deck for a total of 64 guns.¹³ Although they were both experienced shipwrights, Hybertsson and Jacobsson had limited experience building warships with two full gundecks.¹⁴ This may have been a contributing factor to *Vasa*'s failure, though no single factor can definitively be blamed for the ship's demise. Jacobsson's subsequent warships were all comparable to *Vasa* in size, or larger, and proved to be highly successful.¹⁵

SCOPE OF ANALYSIS

This is a focused study on the methods used by Hybertsson and Jacobsson to design the shape of *Vasa*'s hull. It seeks to answer the question – ‘why is the ship the shape and size that it is?’ The

¹² Hocker 2006, 50.

¹³ Hocker 2006, 51.

¹⁴ Hocker 2006, 59.

¹⁵ Madebrink 2012, 51.

goal is to uncover design intention and the deliberate human selection of dimensions and shapes critical to defining the form of the hull. While the complex controversies, rumors, and legends surrounding *Vasa*'s sinking are interesting topics of debate and interest among museum visitors, the cause of the sinking is ultimately outside the scope of this study. The analysis contained in this dissertation is conducted in order to gain insight into early modern methods of naval architecture through study of a unique and valuable artifact. Although the analysis in this dissertation does contribute to a fuller understanding of *Vasa* as an artifact, it makes no claim to determine why it sank.

In his 1671 treatise, Nicolaes Witsen claims, "To define the proportions of the smallest trifles for the shipwright, would be useless and much too laborious: because they follow automatically when the large parts meet their proportional requirements."¹⁶ This statement reflects the derivative nature of early modern Dutch shipbuilding. Consequently, this study does not cover all aspects of *Vasa*'s hull. Instead, it is limited to aspects of design and construction that most significantly affect the general shape of the hull. Analysis begins with the earliest stages of design and construction and continues to a point in the process where the shape of the hull was largely defined – the erection of the top timbers. At a certain point in the design and construction of a vessel, hull elements are no longer critical design decisions and instead parts begin 'falling into place' – their particular shape, size, and arrangement are already determined by the existing hull structure. This study aims to identify this point in construction and thus the

¹⁶ Hoving 2012, 36. "*Even maet te geven, van d'alderminste kleinigheden des timmermans, in een schip: zoude een on nutte zaak, en can te grooten arbeit zijn: want dees van zelven volgen, als de groote deelen hunnen eysch, en evenmaetige schick bekomen hebben.*" Witsen 1671, 65.

‘filler’ hull elements such as the upper works, rigging, ornamentation, and hull fittings are outside the scope of this investigation.

Because ships are large and complex structures composed of a multitude of irregularly shaped parts, a methodology must be used when attempting to quantify them. For any given timber, there are many possibly ways to approach measuring and understanding its design. The goal of this dissertation is to understand the design of *Vasa*’s hull from the perspective of the shipwrights. Rather than speculate how the timbers and structure of *Vasa* were understood, Witsen’s 1671 shipbuilding treatise is used as a guide to uncover the logic of how early modern Dutch ships were conceived and built. Witsen’s treatise provides valuable insight into the methods and deliberate human selection processes that contributed to the design and construction of a ship. This treatise is quoted throughout this analysis and serves as a guide for how to begin understanding the hull of *Vasa* from the perspective of the shipwrights who designed and built it. It is a useful guide, but presents a clear bias. Witsen was not a professional shipbuilder, though he was well acquainted with the northern Dutch shipbuilding method. Although he endeavors to provide a detailed picture of typical Dutch shipbuilding practice, he regularly points out to his reader that it was a highly variable tradition. He provides suggestions for the design and construction of successful vessels but admittedly leaves much to the discretion of the shipwright. Therefore, Witsen’s treatise serves as a guide but is not interpreted dogmatically.

LAYERS OF UNCERTAINTY

Although the hull of *Vasa* is nearly intact, challenges remain when recovering an historical design method. Ideally, one would be able to analyze an artifact exactly as it was built in order

to recover its design method. In archaeology, however, this is never a reality. All artifacts go through various stages of alteration, degradation, and distortion. Although the hull of *Vasa* is more intact than most archaeologically studied vessels, several layers of uncertainty create barriers to accurate analysis and bear consideration.

Deterioration Underwater

Vasa's hull has existed in a constant state of change following its sinking in 1628. Since that time, there have been two major phases of distortion, each of which has altered the shape of the hull. The first phase began when the ship sank and continued for 333 years while the hull rested on the bottom of Stockholm harbor. Although the wrecking event was not particularly violent and does not appear to have substantially altered the hull form, the processes that followed were not so gentle. Both human and natural forces worked to damage and distort the hull while it was under water, with the most noticeable damage being the collapse of the beakhead and sterncastle. The full extent of the underwater deterioration and distortion, however, is unknown.

The main structure of *Vasa*'s hull is composed of oak, a wood commonly used in northern European shipbuilding and relatively slow to degrade. The water in the area of Stockholm harbor where *Vasa* sank is very cold and low in dissolved oxygen which inhibited the growth of bacteria and fungi that typically attack and rapidly degrade wood.¹⁷ These factors are largely responsible for the remarkable preservation of the hull and the integrity of the wood. Nearly all metal components of the hull and artifacts, however, underwent severe corrosion. For the hull,

¹⁷ Hocker and Wendel 2006, 147-148.

this meant that only the lower pintle and gudgeon and three of the more than 5,000 wrought-iron bolts fastening the structure together survived. All other bolts and hull fittings corroded away completely.¹⁸ While the wood of the structure is sound, the corrosion of metal fasteners inevitably loosened the structure and enabled minor distortions of the hull shape.

Part of *Vasa*'s remarkable preservation and recovery is due to its location in Stockholm harbor. It sank to a depth deep enough that surface ice, storms, and shipping traffic had little effect on the hull.¹⁹ Soundings in preparation for lifting the hull in 1961 measured a maximum depth of 35.8m at the aft end of the keel, 23m on the weather deck, and 15m at the uppermost limit of the remaining sterncastle.²⁰ *Vasa* lay in an area of Stockholm harbor with a slow and steady current. The current carries with it an organic-rich sediment and smaller amounts of clay and silt. This sediment collected on *Vasa* to the point where, when the ship was raised, every deck was covered in a layer of mud a meter or more thick.²¹ This layer of mud helped protect the hull from organisms that would attack the wood, but also caused limited erosion to surfaces and edges of wooden features as it was carried through the hull by current.²² It is unknown to what extent the weight of the sediment may have contributed to hull distortion. Furthermore, the high sedimentation rate and soft bottom of the harbor meant that at the time of excavation, the hull was sunk into the mud nearly to the level of the lower portside gunports.²³

¹⁸ Cederlund and Hocker 2006. A large amount of iron corrosion products leached into the surrounding wood which had the effect of hardening the wood and making it less susceptible to microbial attack.

¹⁹ Hocker and Wendel 2006, 149.

²⁰ Hocker 2006, 62.

²¹ Hocker and Wendel 2006, 149-150.

²² Hocker and Wendel 2006, 150.

²³ The vessel listed slightly to port; Hocker 2006, 62.

Human activity also contributed to *Vasa*'s underwater deterioration. An initial salvage attempt (1628-1629), began shortly after the sinking, and focused on trying to raise the hull. As a result of this attempt, large numbers of anchors and grapnels were hooked into it, causing substantial damage to railings and sculptures, but little damage to the main structure of the hull. Many of the anchors and grapnels used in this failed operation were left behind and later found either on or attached to the hull. The added weight of this equipment may have been substantial and could be a contributing factor to the distortion of *Vasa*'s hull. During this attempt, much of the sailing rig was also removed, leaving only the lower masts and their rigging.²⁴ When *Vasa* sank, much of the ballast shifted to port side causing the hull to rest on the bottom with a list.²⁵ During the attempt to raise the ship, the hull was righted, such that it listed only slightly to port. Based on the apparent lack of disturbance of artifacts inside the hull, this process seems to have been rather gentle and caused negligible damage to the hull.²⁶ Although the righting may not have significantly damaged the hull, the shifted ballast and list of the ship on the bottom may be contributing factors to hull distortion.

A second salvage attempt (1663-1664) focused on recovering the valuable cannon still on board. The method to do this involved tearing through the weather deck in order to access the guns on the upper gundeck. Fortunately, by the time the salvors undertook this operation, most of the iron nails that had once fastened the deck planking had corroded away. This meant that much less force was required to remove the weather deck. The damage from this salvage operation

²⁴ Hocker and Wendel 2006, 151.

²⁵ Hocker 2006, 54.

²⁶ Hocker and Wendel 2006, 152.

was limited to the weather deck planking, hatches, and some deck beams; none of which are relevant elements in this study.²⁷

Much later, when the location of the wreck had been forgotten, *Vasa*'s location in Stockholm harbor became a popular site for dumping blasting rubble and slag from around 1850 until 1956. The divers working on the wreck during the 1956-1961 underwater campaign reported having to remove many tons of rubble and slag from the upper gundeck. The rubble was not distributed evenly over the hull and the greatest concentrations were found on the port side. The added weight of the rubble likely contributed to the eventual collapse of the poop deck and quarter deck.²⁸

Most of the deterioration of the hull is concentrated in three areas: the beakhead, the weather deck, and the sterncastle. Of these three areas, only the deterioration of the sterncastle has direct bearing on the recovery and analysis of *Vasa*'s hull form design methods. Nearly the entire beakhead collapsed due to the corrosion of the iron nails and bolts that were used to fasten it to the hull. Almost all of the beakhead elements were recovered from the bottom sediment during excavation, most in good condition with original faces and crisp edges. The beakhead was subsequently reconstructed using mostly original timbers.

²⁷ Hocker and Wendel 2006, 151.

²⁸ Hocker and Wendel 2006, 151.

As discussed above, the weather deck was the subject of much destruction during *Vasa*'s time on the bottom. Most of the deck planking was damaged or removed during the 1663-1664 salvage operation. What remained was damaged by the many tons of rubble dumped onto the hull beginning in the 19th century. Many of the weather deck beams were broken but almost all were found on the upper gundeck during excavation along with many of the hatch coamings, gratings, and most of the waterways and kingplanks.²⁹

The structure of the sterncastle was very lightly built and one of the most fragile areas of the hull. Three levels of cabins were located above the lower gundeck and their exterior was richly decorated with galleries and sculptures. Both the natural and human destructive forces resulted in the complete collapse of the poop cabin, upper cabin, stern galleries, decorative stern panel, and the collapse of most of the great cabin and steerage. Most significantly for this study, the stern timbers were broken at the level of the deck of the upper cabin.³⁰ The broken portions of the stern timbers, like many of the other timbers from the sterncastle, were recovered during excavation and reassembled into their original position. The reconstructed sterncastle is illustrated in Figure 6.1, and as found in Figure 6.2.

²⁹ Hocker and Wendel 2006, 156.

³⁰ The breaks in the stern timbers are considerably less eroded than the original surfaces of the timbers suggesting that they were broken relatively recently. Hocker and Wendel 2006, 159.

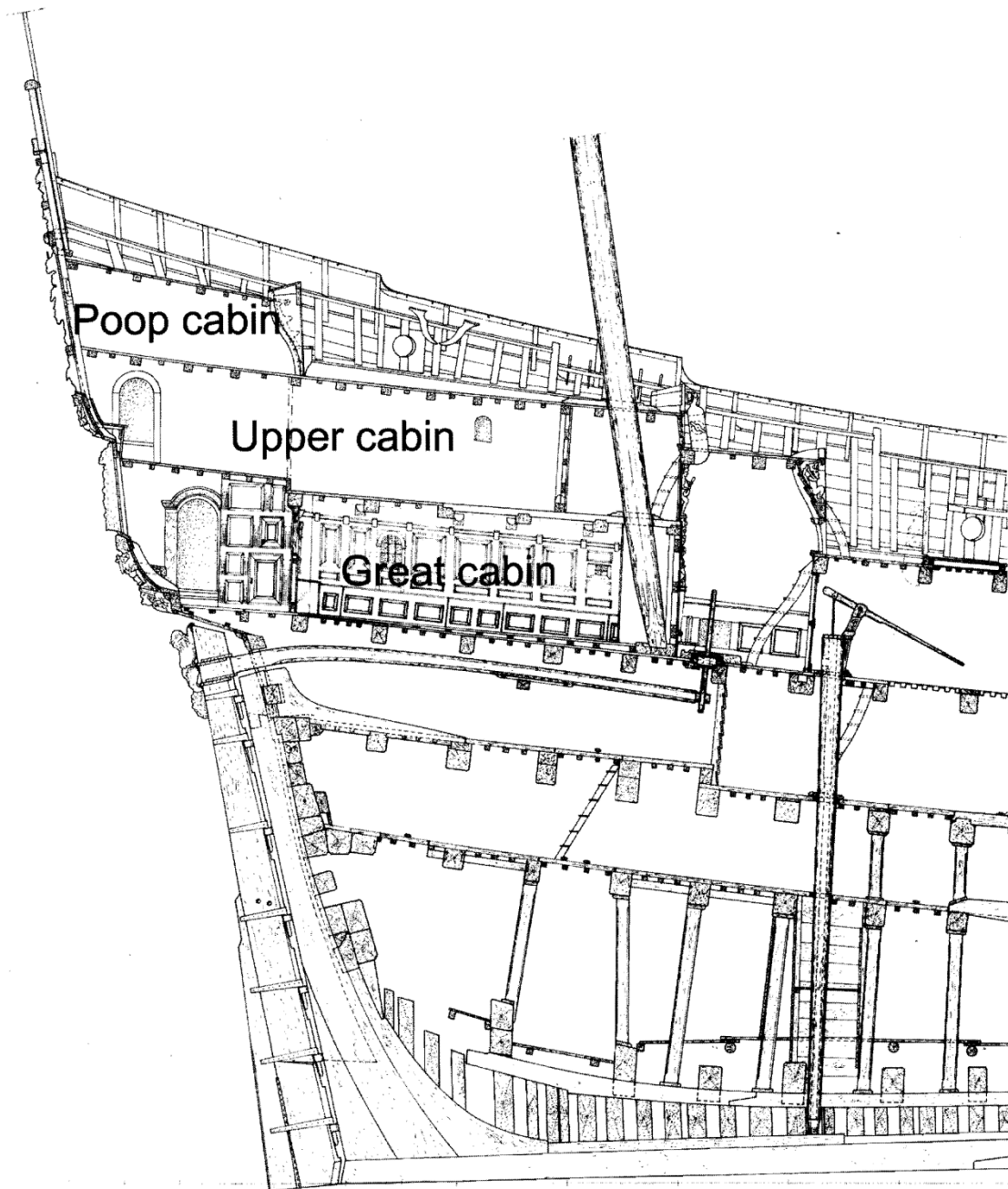


Figure 6.1. The reconstructed sterncastle. Nearly all sterncastle timbers were recovered in or around the hull.
Drawing by Eva Marie Stole and Fred Hocker.³¹

³¹ Hocker and Wendel 2006, 155.

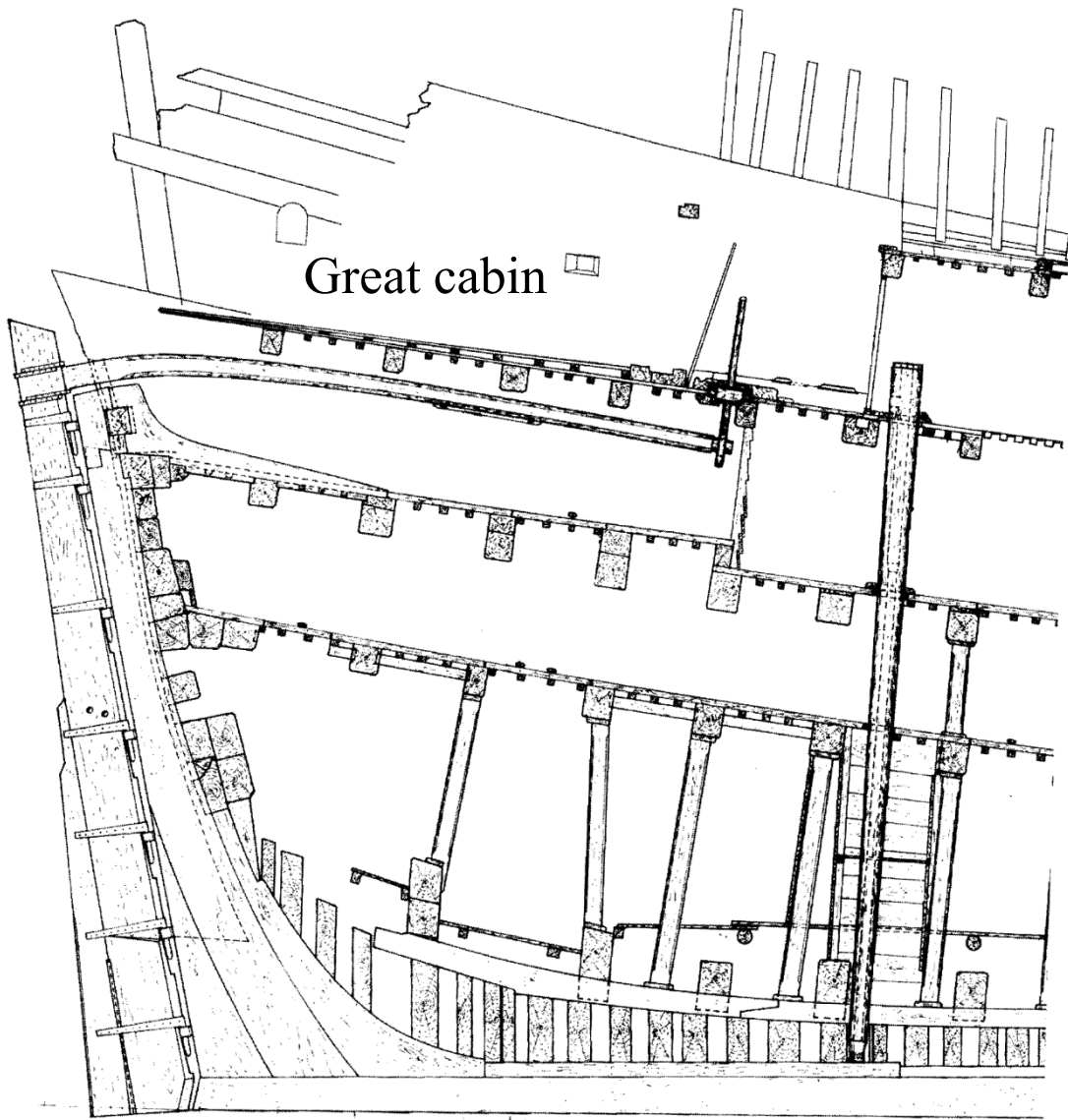


Figure 6.2. The sterncastle as found. Note the complete collapse of the poop cabin and upper cabin and substantial collapse of the great cabin. Drawing by Eva Marie Stolt and Fred Hocker.³²

Hocker and Wendel 2006, 169.

Deterioration on the Surface

When *Vasa* was raised in the spring of 1961, the second phase of distortion began. As archaeologists and conservators are well aware, as soon as waterlogged wood is removed from the water, the surface tension forces resulting from water evaporation causes the fragile cell walls of the wood to collapse, producing permanent damage to the structure and shape of the wood. The goal of most conservation methods for waterlogged wood is the replacement of water in the wood, which is supporting the structure of the wood, with a substance that will not evaporate and therefore stabilize the wood.³³ Following the conclusion of the excavation of the interior of the ship in September 1961, the hull underwent a 26-year long conservation process.³⁴ The hull was sprayed with polyethylene glycol (PEG) for 17 years to impregnate and stabilize the wood. A 9-year period of controlled drying followed in which the relative humidity of the air surrounding the hull was gradually decreased from about 90% to 60%.³⁵ Despite the careful treatment, some wood shrinkage has occurred. It has not occurred evenly in all hull timbers, and the staff of the Vasa Museum currently estimates there is an average 6% shrinkage across the grain, with negligible shrinkage along the grain.³⁶ Due to an unanticipated high level of museum visitation, a new climate control system had to be installed in 2004. Although *Vasa* is inside a closed building sealed with air locks, it is in no way isolated from the air inside the museum. In the 1990s, large numbers of visitors and rainy weather resulted in a dramatic increase in relative humidity within the museum beyond what could be effectively controlled by the original HVAC system.³⁷ PEG is hygroscopic and absorbs moisture from the atmosphere. At high relative humidity, around 70%, this can add a substantial amount of weight to the hull, further

³³ Hamilton 1999, 24.

³⁴ Cederlund 2006, 422; Hocker 2010, 3.

³⁵ Hocker 2010, 3.

³⁶ Fred Hocker, pers. comm.

³⁷ Hocker 2010, 4.

challenging the integrity of the wood and hull form. The increased humidity also facilitates damaging chemical reactions between various compounds in the wood, processes that are still being investigated by museum staff. The improved climate control system maintains a temperature of 17-20C (62-68F) and relative humidity of 51-59% year round in the museum.³⁸ The ship now sits in a stable environment which minimizes further hull distortion and damage resulting from temperature and humidity fluctuations.

While the local climate of the ship is stabilized, the support conditions of the hull are resulting in further distortion. Shortly after raising *Vasa*, a submersible pontoon was placed under the hull to serve as a base to support to the hull.³⁹ Much of the weight of the hull is supported by 28 wooden blocks under the keel which have been in place since the hull was first rested on its pontoon. These keel blocks are seen in Figure 6.3. In 1964, a permanent steel cradle was installed on the pontoon to provide support to the hull and replace the temporary supports that propped up the hull.⁴⁰ The cradle initially consisted of eight pairs of transverse supports spaced approximately 5 meters apart. The supports span each side of the hull from just above the keel to just below the lower wale. The transverse units were connected by longitudinal beams running along the turn of the bilge. Wooden wedges between the cradle and the hull allow for adjustment in response to shrinkage and movement of the hull. In 1990, a second set of ten transverse cradle supports was installed after the bottom of the ship was noticed to be bulging or sagging between the cradle supports. The current support system is seen in Figure 6.4. At the same time, the sides of the ship were also noted to be bulging outwards at the orlop and lower

³⁸ The lower temperature also inhibits the growth of mold or other micro-organisms in the wood. Too low of RH can result in wood shrinkage or warping. Hocker 2010, 6.

³⁹ Cederlund 2006, 275.

⁴⁰ Cederlund 2006, 447.

gundeck. Bolts between the waterways and wales were added to draw the sides back in. Stanchions were also added between the beams of the gundecks and weather deck to transfer some of their weight from the sides, which are not designed to support the full weight of the decks.⁴¹ Despite the improvements to the support system, the hull is still settling and warping slowly. Figure 6.5 illustrates the amount of transverse hull distortion over 40 years on the surface. The staff of the Vasa Museum is currently researching improved support systems which will provide additional support for the heavy decks and better long-term stability for the hull.

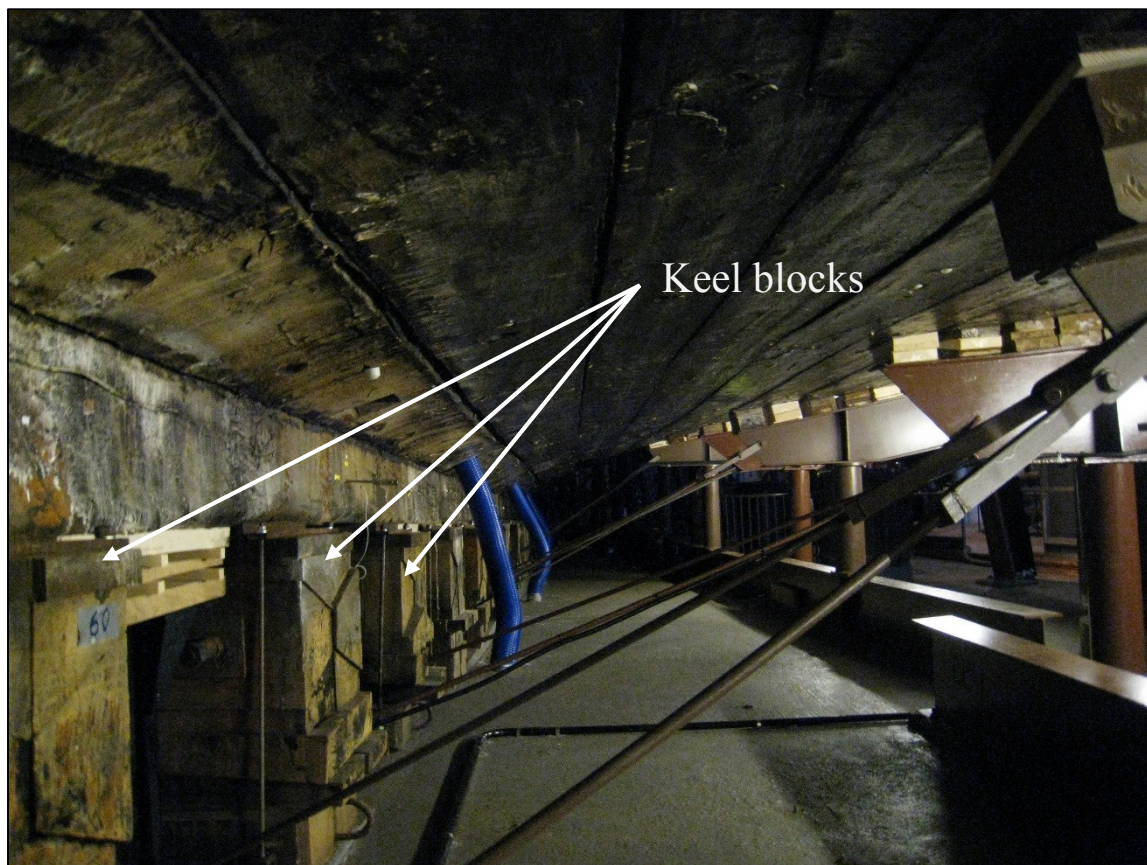


Figure 6.3. Blocks supporting *Vasa*'s keel. Photograph taken approximately at the *hals* on the starboard side looking forward.

⁴¹ Cederlund 2006, 450-451; Hocker 2010, 3.

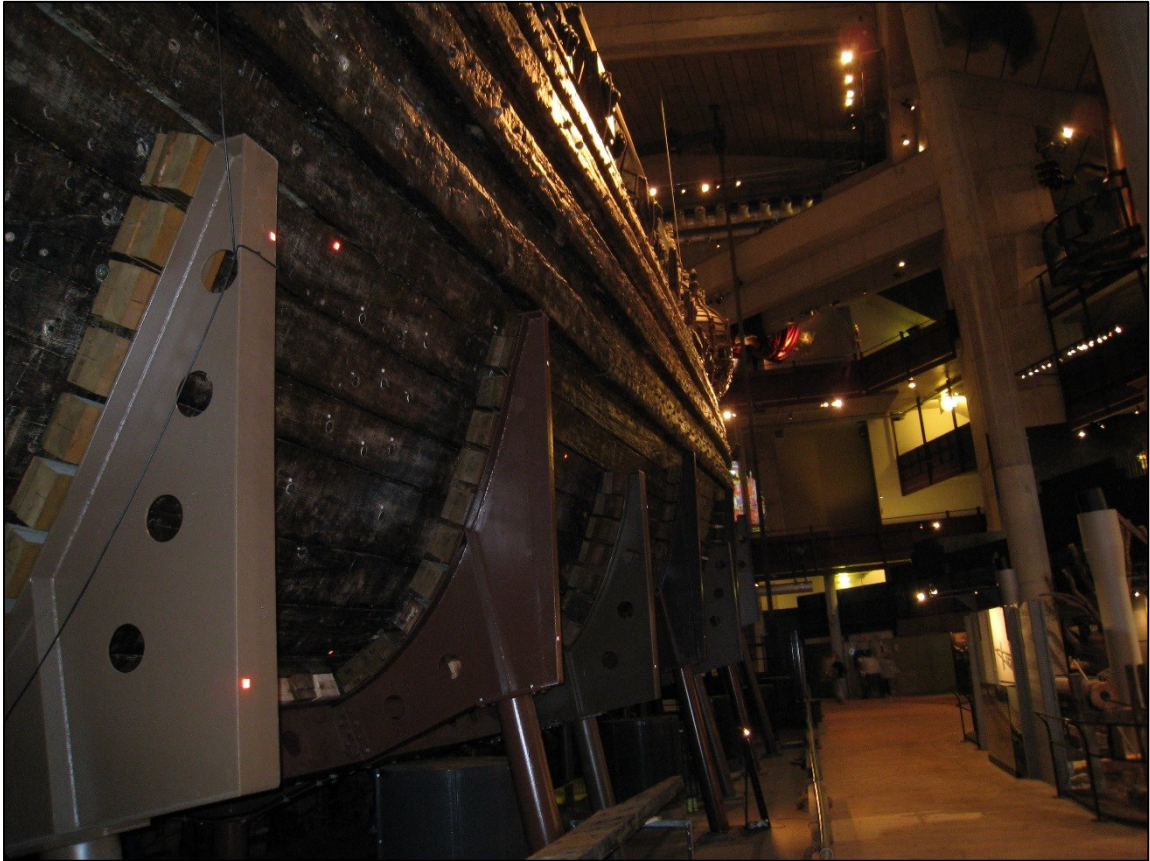


Figure 6.4. Transverse hull supports. Steel braces and wooden wedges.

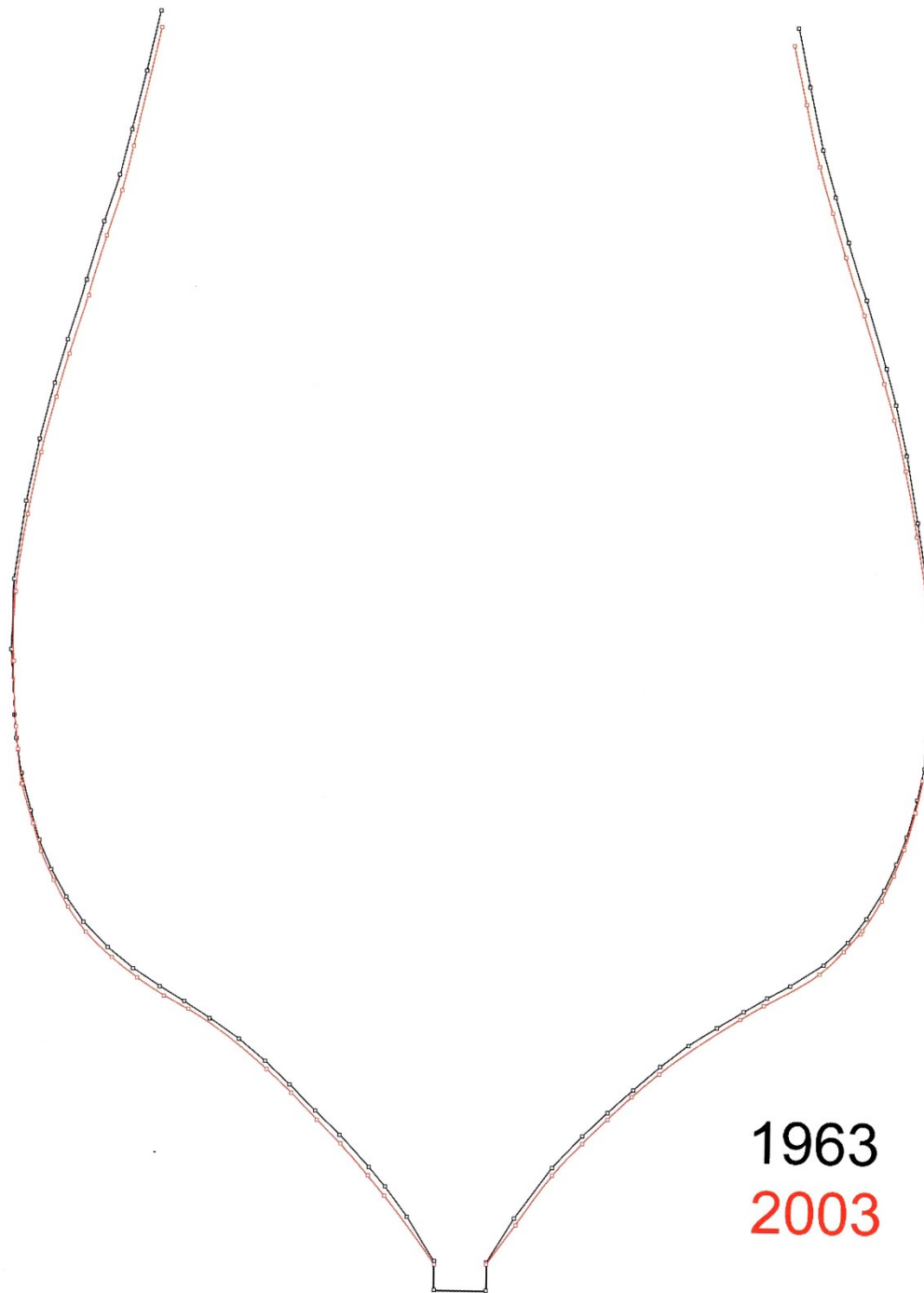


Figure 6.5. Data points taken in 1963 (black) and 2003 (red) show distortion to the hull as it settles and shifts in its supports. Image by Fred Hocker.⁴²

⁴² Cederlund and Hocker 2006, Plate IV-2.

Almost immediately upon being raised, work began to stabilize the hull by replacing the corroded iron bolts with new fasteners. By 1964, nearly 2,500 of the bolts had been replaced up to the level of the waterline. To properly refasten the hull, it was necessary to move the hull back into its original shape to re-align the bolt holes. The complete corrosion of the bolts and the destructive forces while underwater had caused the hull to sag, both on the ends and the starboard side.⁴³ The manipulation of the hull both removed distortions and introduced new ones. The most significant new distortion was the bending of the sternpost which produced large cracks, seen in Figure 6.6 and Figure 6.7.⁴⁴ The full extent of these distortions is not known.

Another factor that obscures recovery of the original intentions of the shipwrights is the issue of historical measuring precision. There is substantial evidence to suggest that *Vasa* was built using Swedish feet as the unit of design and construction, including the spacing of draft marks on the posts and the correspondence of observed dimensions to distances measured in Swedish feet. This does not mean, however, that all shipwrights and carpenters in the shipyard were using identical units of measurement. At least six separate rulers were found on board *Vasa* during excavation, representing a range of units. Two of these are divided into 12 inches and their overall length indicates they are Swedish feet, however, they are not exactly the same length. Another ruler is divided into 11 inches and corresponds closely in length to an Amsterdam foot. The units of the other rulers are unknown.

⁴³ Cederlund 2006, 450.

⁴⁴ The engineer responsible for the documentation of the hull, Eric Hofmann, believed that the deformation of the sternpost occurred because the midbody of the hull had not been returned to its original position and that the bilges needed to be higher. He wrote to the Restoration Council in April 1969, urging that the deformation be corrected, but no action was taken. Cederlund 2006, 450.

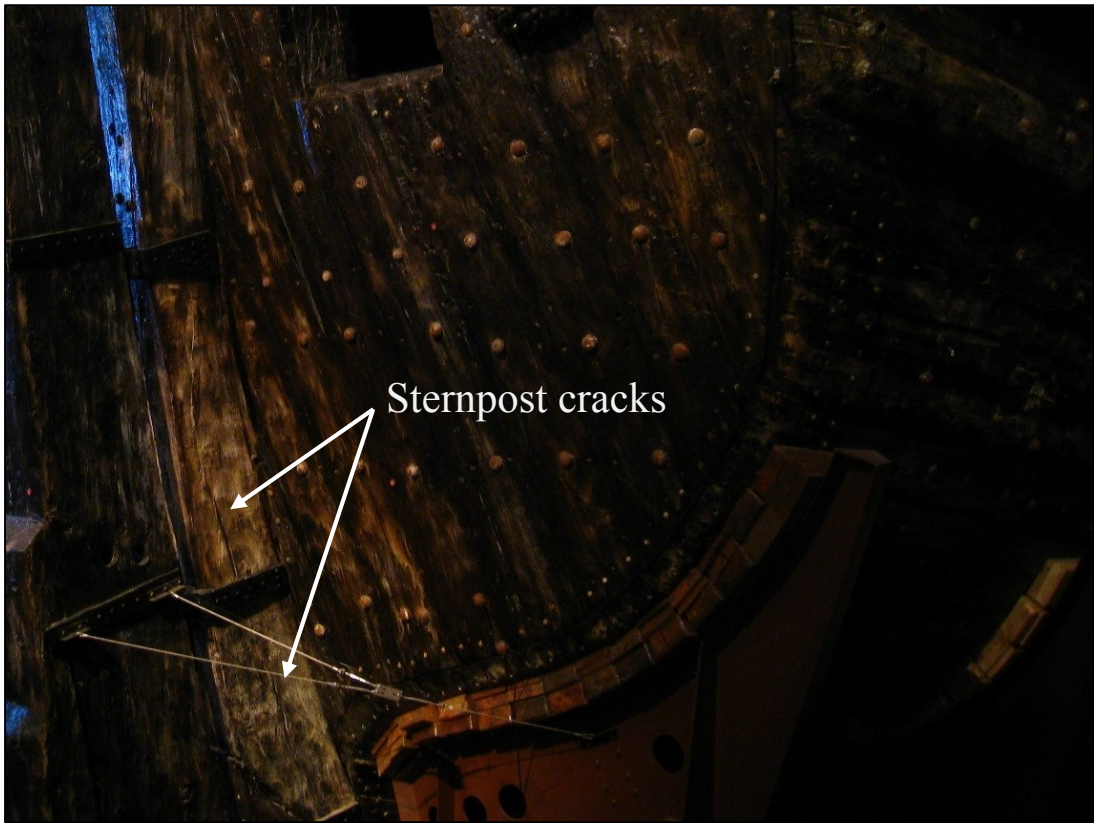


Figure 6.6. Sternpost cracks.

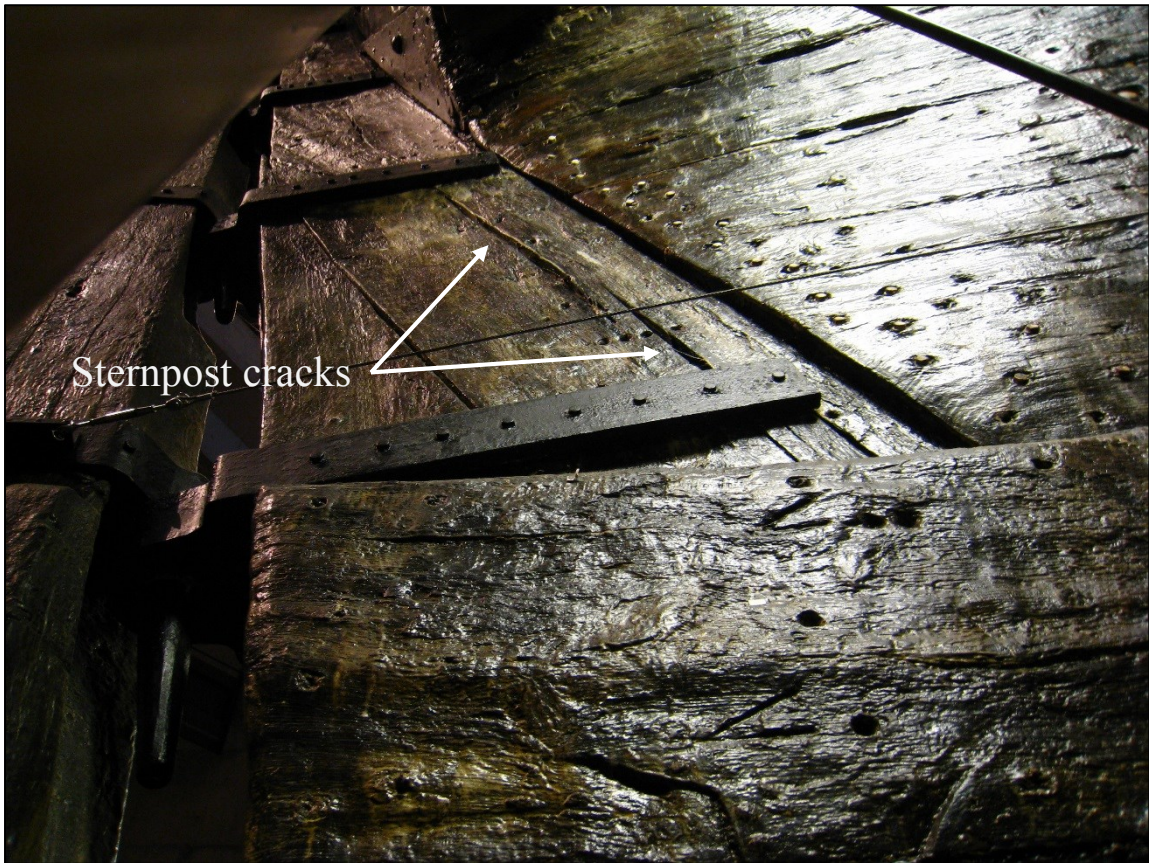


Figure 6.7. Additional sternpost cracks.

The reality that the measuring devices used to design and build *Vasa* did not match one another was not a concern when constructing the ship. Small differences in minor timber dimensions were easily remedied by simply cutting timbers to fit rather than carefully measuring every hull element. This factor means, however, that even though modern archaeologists are able to measure and analyze the hull with units of standard length and immense precision, this is not how the hull was originally measured and quantified. This bias is acknowledged and every attempt is made to interpret the modern measurements within a context that provides for reasonable latitude when considering historical measurement and precision.

Vasa is a large structure made of mostly organic materials and built using hand tools. These factors along with the matter of historical measurement precision mean that it was not perfect even when it was launched. Small imperfections, inconsistencies, and approximations were, and are, the reality of working with such a medium. Furthermore, building a large ship was an expensive endeavor and efforts were made to make economical use of shipbuilding timber, as evidenced by Hybertsson's written protests with the king about timber wastage. Dutch shipwrights, in particular, were known for making very economical use of timber. If a knot or other imperfection was present in a piece of wood, it was used anyway. The knot or imperfection was cut out and replaced with a patch of wood. Many instances of this process are evidenced in the hull of *Vasa*. An example is shown in Figure 6.8. The Dutch were so renowned for their economical use of timber that these patches became popularly known as 'Dutchmen' in woodworking. All of these factors combine to create an artifact that, although virtually intact, differs somewhat in shape from what the shipwrights intended to build. The digital 3D models attempt to visualize the hull as it currently exists and therefore the measurements in this dissertation reflect this current reality. This bias is taken into consideration throughout the analysis and every attempt is made to recover what was originally intended by the shipwrights based on the evidence provided by the intact hull.



Figure 6.8: Dutchman on *Vasa*'s riding bitt.

MEASUREMENTS AND UNITS

Since much of this analysis relies on careful measurement hull elements that are irregularly shaped and form a complex arrangement of parts with multiple orientations, care is taken here to ensure clarity when discussing timber dimensions. The terms *sided* and *molded* are commonly used in shipbuilding and indicate a timber face's relationship to an imaginary point at the center of the hull. The *molded* dimension refers to the dimension measured inward toward the interior of the hull from the outside. It is the face of the timber that is perpendicular to the outside, and

the dimension seen in the sheer and body views of a vessel.⁴⁵ The *sided* dimension of a timber refers to the face of the timber that is oriented parallel or tangent to the outside of the hull and perpendicular to the molded face.⁴⁶ In cases where timbers lie on the centerline of a vessel, such as the keel and posts, the *molded* dimension is the fore and aft dimension, *sided* is the athwartships dimension. *Length* is the long dimension of a timber usually parallel to the wood grain. *Width* is used to refer to large dimensions of features or timbers perpendicular to the keel, for example the ‘width of the bottom’ or ‘width of the wing transom’. *Width* is also used to describe the sided dimension of planks and wales; *thickness* is a plank’s molded dimension.⁴⁷ *Height* is used to describe the vertical dimension of a timber or feature perpendicular to the keel.⁴⁸ Individual timber dimensions and relationships are clearly illustrated below.

All measurements used in this analysis were taken in SolidWorks, using the full-scale solid models built based on total station data, first-hand measurements, sketches, technical drawings, and photographs. The construction of these models is detailed in Chapter V. SolidWorks does not allow for the definition of custom units and so all measurements were taken in centimeters, rounded to the nearest millimeter. Metric measurements were then converted to Swedish feet using the conversion of 1 Swedish foot (12 inches to a foot). = 29.7 cm.⁴⁹ Since the aim of this study is to recover the design methods used by the shipwrights in the construction of *Vasa*, Swedish foot and inch measurements are the dimensions of interest in this analysis. Where

⁴⁵ Steffy 1994, 275.

⁴⁶ For example, the fore and aft distance across an outer frame surface, Steffy 1994, 280.

⁴⁷ Witsen often uses width to refer to the sided dimension of timbers and thickness for the molded dimension.

⁴⁸ For example, the height of the sternpost.

⁴⁹ Alexander 1857, 35.

necessary, converted measurements have been rounded to the nearest whole inch increment.⁵⁰ Dimensions of all timbers and features are reported in both centimeters and Swedish feet and inches, indicated as *X ft. Y in. S* (ex. 132.8 cm./4 ft. 6 in. S). All measurements reflect the hull as it currently exists in the Vasa Museum.

Although this dissertation is organized sequentially, it is unlikely that the initial design of *Vasa* progressed in such a linear fashion. The components of *Vasa*'s hull that define its shape are deeply interrelated and a design choice in one area affected design choices in another. This fact is demonstrated throughout the analysis. As archaeologists studying the remains of this process hundreds of years later, we are predisposed to a careful and methodical analysis. It is important to remember, however, that many of *Vasa*'s features may have been designed more or less simultaneously – not necessarily one at a time as this analysis would indicate. The limits of a written analysis necessitate that a linear progression be followed for the sake of clarity. It is not, however, an accurate reflection of the actual design and construction process.

At many points in the construction, Witsen indicates the need to check the hull for bilateral symmetry. Errors early on in construction would be multiplied throughout the process and could significantly affect the sailing qualities or performance of the ship. Simple tools such as a plumb bob and level were used to check for symmetry at key points in construction. Witsen specifically cautions his reader to check for symmetry when constructing the wing transom, fashion pieces, the garboard, the bottom planking, the *buikstuk*, the bilge planking, the futtocks,

⁵⁰ The focus of this study are relatively large hull elements and thus it is unlikely that fractions of inches were of concern to the constructors of the hull. Furthermore, the variation between measuring devices and consequential (just make it fit) nature of shipbuilding eliminates fractions of inches from the analysis.

and the scheerstrook.⁵¹ It is therefore assumed that timbers and features were built with intended bilateral symmetry at least in dimensions, even if variations in wood, precision, and distortion now cause the halves of the vessel to differ from one another.

LENGTH OVERALL

The length overall, along with the maximum breadth and depth, was one of the three primary dimensions that defined the hull form of a vessel.⁵² The length overall was considered to be the distance between the forward edge of the stem and after edge of the sternpost, measured with a string stretched between the posts. The Swedish navy followed the Dutch method of recording length over the posts and beam inside the planking until at least 1670.⁵³ As the hull currently exists, *Vasa*'s overall length is measured to be 4722.33 cm./159 ft. S including the sternpost extension, illustrated in Figure 6.9.⁵⁴ Without the sternpost extension, the length overall is 4714.4 cm./158 ft. 8 in. S, illustrated in Figure 6.10. The sternpost extension was likely added at a later stage in construction and not part of the original design intent for the hull. Accounting for hull distortion occurring while the ship was under water, during conservation and drying, the variability of historical measurement devices, and the long distance, it is concluded that 159 ft. S was intended as *Vasa*'s length overall.

⁵¹ Hoving 2012, 47-71.

⁵² Although this was not a dimension specified in the contract or correspondence between Hybertsson and Gustav Adolf – keel length was the primary longitudinal measurement.

⁵³ Glete 1993, 71.

⁵⁴ The extension of the sternpost is discussed in the subsection below pertaining to the sternpost.

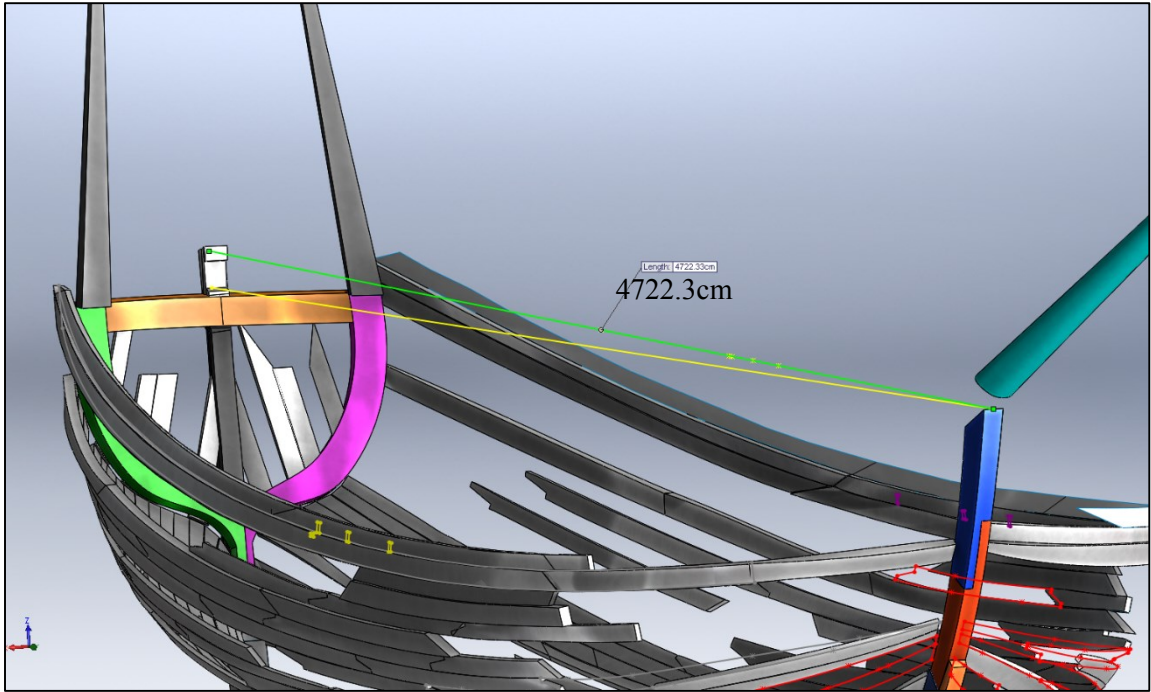


Figure 6.9. *Vasa*'s length overall, including the sternpost extension.

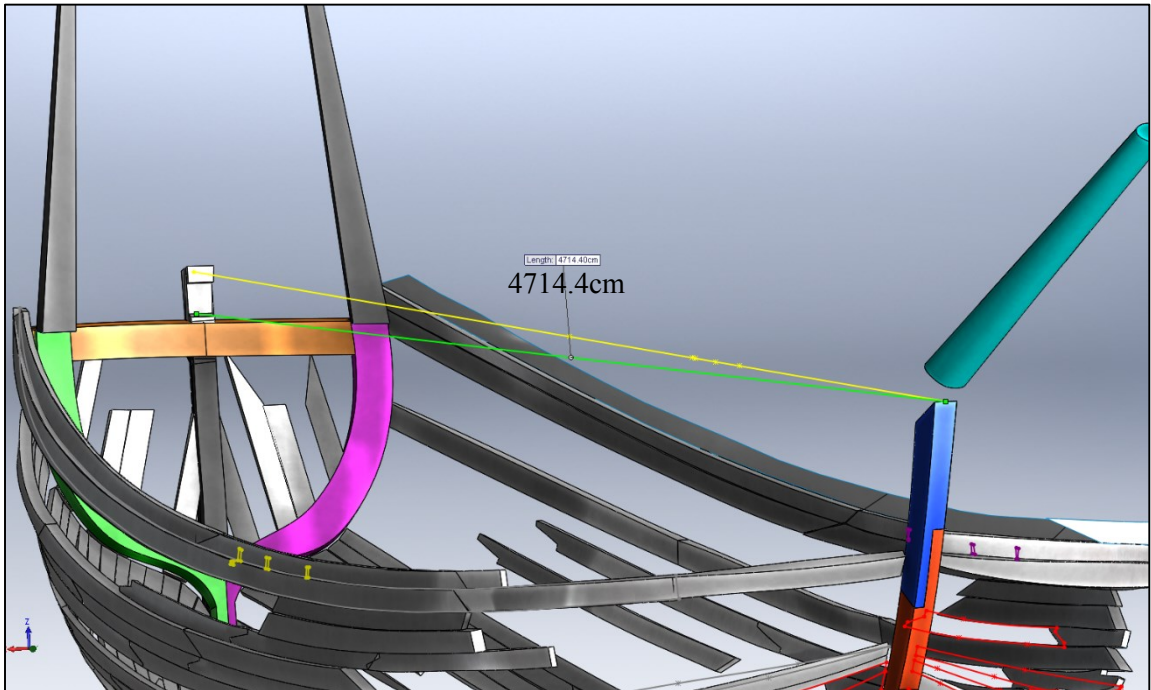


Figure 6.10. *Vasa*'s length overall, without the sternpost extension.

BREADTH

The second of the three primary hull dimensions is the maximum breadth, measured inside the planking. *Vasa's* hull achieves its maximum breadth 1/3 of the length overall 1574.1 cm./53 ft. S from the forward face of the stem, an area of the ship known in Dutch shipbuilding as the *hals*. This location is illustrated in Figure 6.11 and the model sectioned at this point in Figure 6.12. This region of the hull was the focus of cross-sectional design, as discussed in Chapter 3 and below. At this point in *Vasa's* hull, the maximum breadth is 1111.5 cm./37 ft, 5 in. S, illustrated in Figure 6.13.

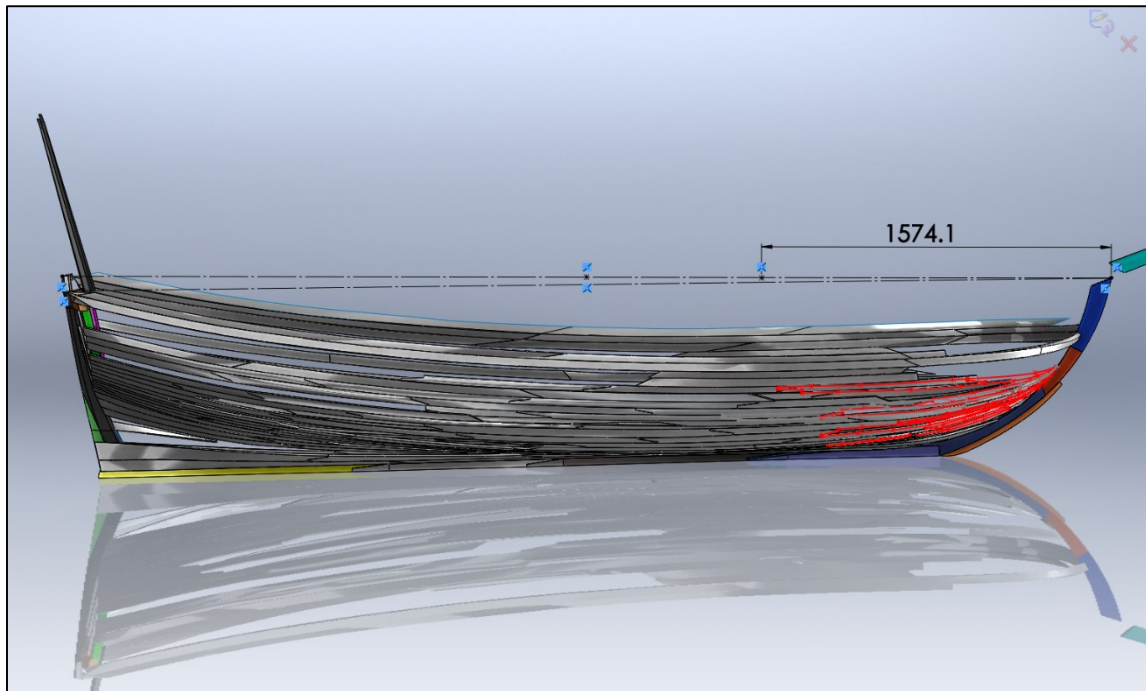


Figure 6.11. The location of the *hals* along *Vasa's* length.

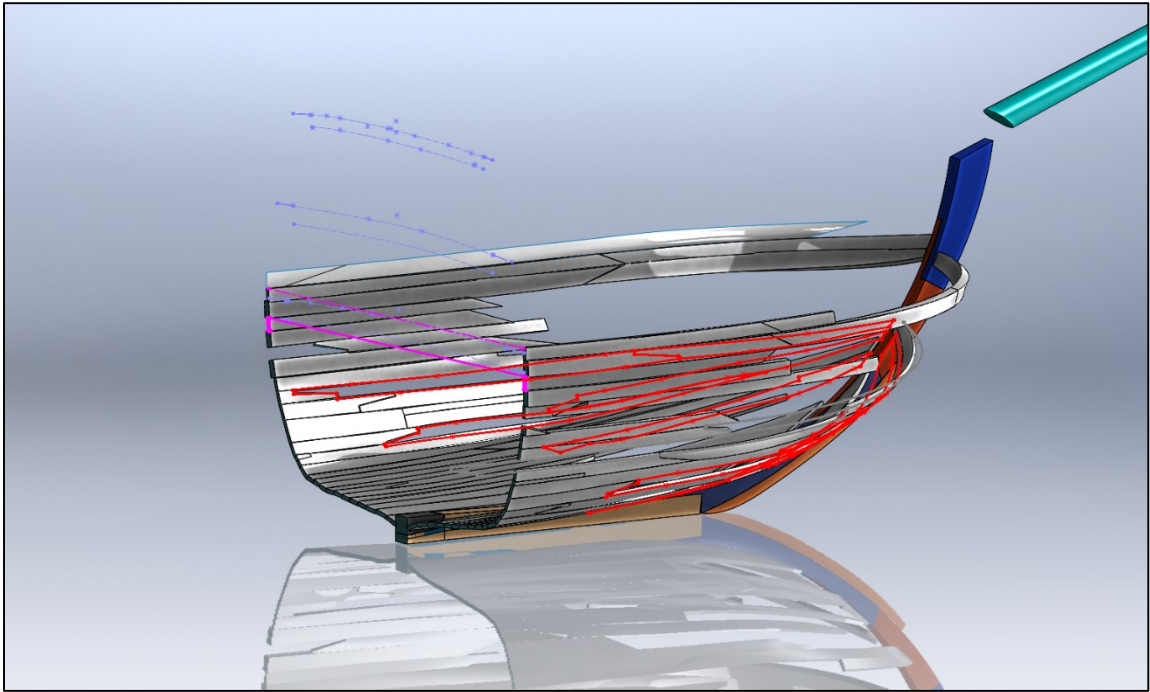


Figure 6.12. The model sectioned at the *hals*.

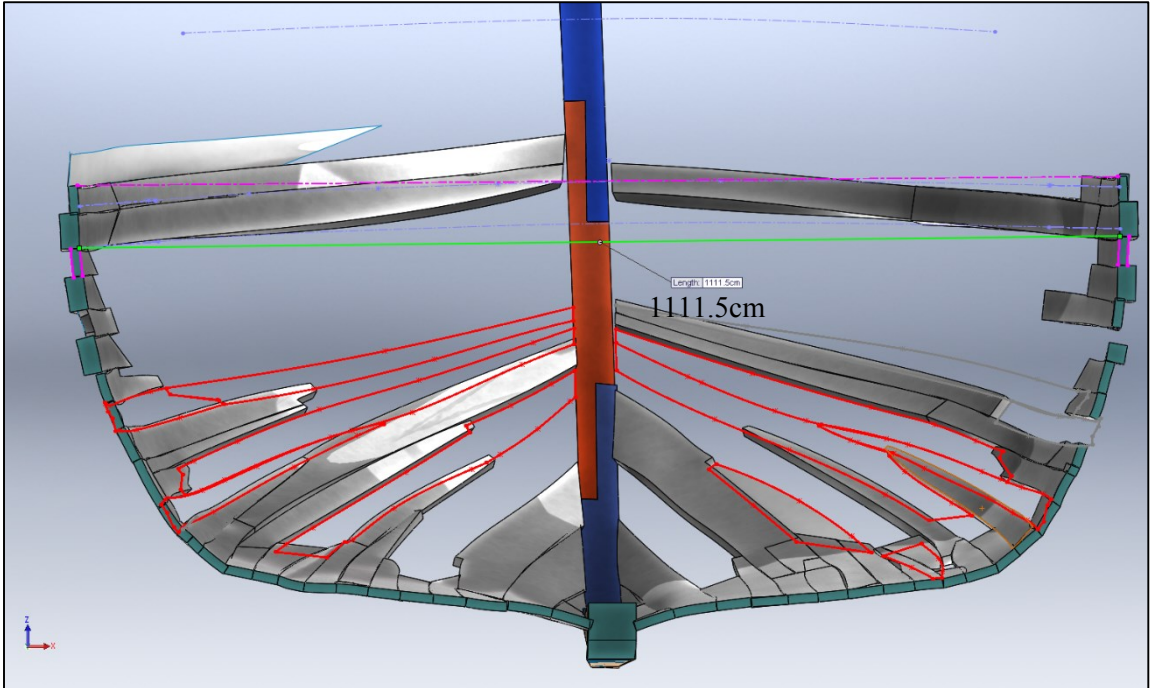


Figure 6.13. The maximum breadth measured at the *hals*.

The length, breadth, and depth of the hull are three of the key defining dimensions for a vessel, and round dimensions would be expected. *Vasa*'s unusual breadth measurement, however, reflects both original design intention and an important event in the construction process. After *Vasa* sank, Henrik Jacobsson testified that although he took over responsibility for *Vasa*'s design and construction following the death of Henrik Hybertsson, he was only able to make minor changes to the hull. The most significant documented change was to the breadth of the ship. Jacobsson testified that he widened the ship by 1 ft. 5 in. but was unable to widen the hull any further.⁵⁵ His testimony, however, does not specify exactly how he widened the hull, or how far along in construction the hull was at the point he made the change. The observed dimension of 37 ft. 5 in. includes this modification, suggesting that Hybertsson originally intended a 36 ft. maximum breadth.

Witsen's treatise indicates that breadth was often derived as a function of the overall length of a ship. Witsen suggests using $\frac{1}{4}$ of the overall length as a starting dimension for the breadth, and adding or subtracting feet as desired by the shipwright to best address the requirements of the vessel.⁵⁶ Applying this formula to *Vasa* ($\frac{1}{4}$ of 159 ft.) would have resulted in a 39 ft. 9 in. original breadth. The measured 36 ft. breadth indicates that Hybertsson desired a somewhat narrower hull than normal. Jacobsson's widening of the hull suggests that he preferred a hull with a length to breadth ratio closer to $\frac{1}{4}$, perhaps indicating a concern for stability.⁵⁷

⁵⁵ Cederlund and Hocker 2006, 36.

⁵⁶ "About the width derived from the length. The length of the ship divided by four, the width is taken as a fourth part." Hoving 2012, 36. "*Van de wijte uit de lengte. De lengte van get schip in vieren gedeelt, zoo neemt tot de wijte een vierde deel.*" Witsen 1671, 65.

⁵⁷ After *Vasa*, Jacobsson went on to build several wider and more successful warships.

DEPTH

The third principal dimension was the depth of the vessel, measured from the top of the keel to the upper face of the lower deck beams. Like the maximum breadth, depth was measured at the *hals*. Measured from the upper face of the keel to the upper face of the lower gundeck beams, the depth of *Vasa* is approximately 450.1 cm./15 ft. 2 in. S, illustrated in Figure 6.14. Witsen suggests beginning with 1/10 of the length overall for the depth of a ship, but that shipwrights frequently deviated from this ratio.⁵⁸ The top of *Vasa*'s keel is difficult to access at the *hals* and the measurement reported here is based on the 3D model. The result is an approximation of the top of *Vasa*'s keel, which was calculated according to the molded dimension of the keel and amount it tapers to meet the stem and sternpost. It is conceivable that the depth measurement may have been intended as an even 15 ft. accounting for hull distortion and the approximation of *Vasa*'s keel position.

⁵⁸ “About the depth derived from the length. To get the depth from the length, take one foot of depth for each 10 feet of length.” Hoving 2012, 37. “*Van de holte uit de lengte. Tot de holte, uit de lengthe, neemt voor 10 voet lengte, een voet holte.*” Witsen 1671, 65.

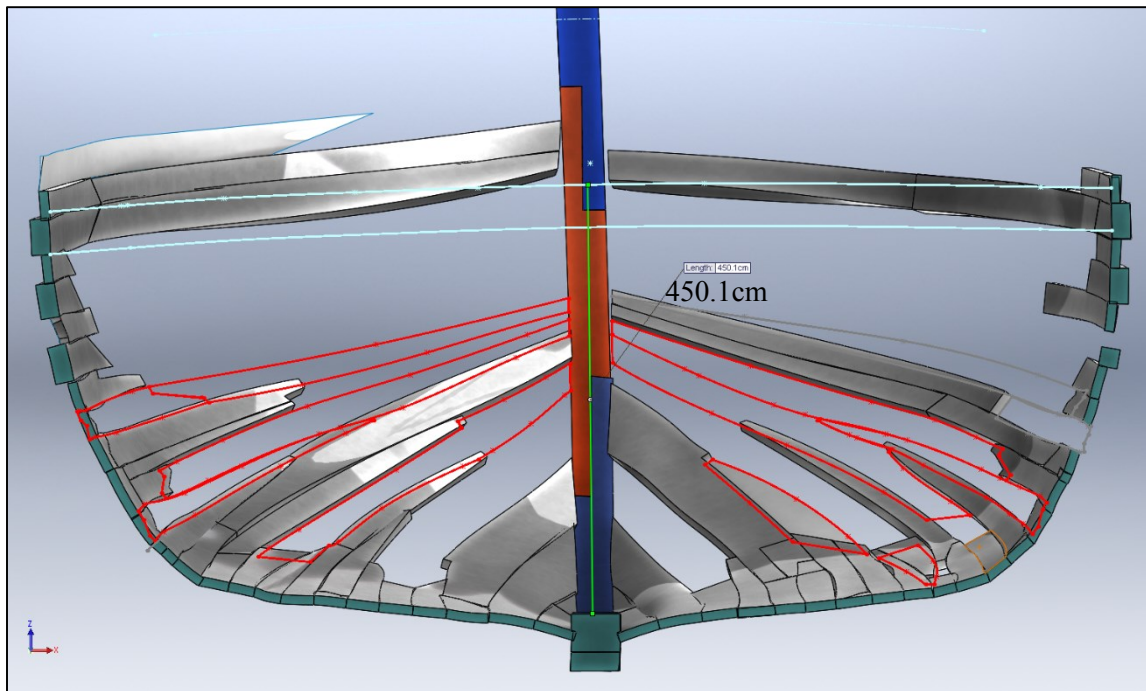


Figure 6.14. The depth measured at the *hals*.

KEEL

Keel Length

The length of the keel is the only longitudinal measurement specified in the contract and correspondence between Hybertsson and Gustav Adolf. In its greatest extent, *Vasa*'s keel is 3830.8 cm./129 ft. S long, as illustrated in Figure 6.15. While there is little documentation of the design of *Vasa*, the proposed length of the keel is one key dimension mentioned in the negotiations between Hybertsson and Gustav Adolf. The version of the contract from January 1625 signed by the king calls for the construction of two large ships measuring 136' on the keel and two small ships measuring 108 ft. on the keel.⁵⁹ The subsequent modifications of the

⁵⁹ The small ships were to be based on *Gustavus*, which Hybertsson indicates measured 108 ft. on the keel.

contract at the request of the king altered this to two small ships of 120 ft. on the keel and two large ships of either 128 ft. or 136 ft. on the keel. In February 1626, the king instructed Hybertsson to begin construction on the two small vessels (120' on the keel) or on one large vessel (128 ft. or 136 ft. on the keel). In March of 1626, Hybertsson testified that he had begun construction on one ship but that it would be slightly smaller than the specifications – though he does not say which specification he is referring to. According to the contract and subsequent correspondence, three possibilities exist for *Vasa*'s intended keel length: 120 ft., 128 ft., or 136 ft. Given *Vasa*'s observed keel length of 129 ft. and Hybertsson's explanation that the ship he laid down was slightly shorter than the specification, it is a reasonable conclusion that he was referring to the 136 ft. dimension.

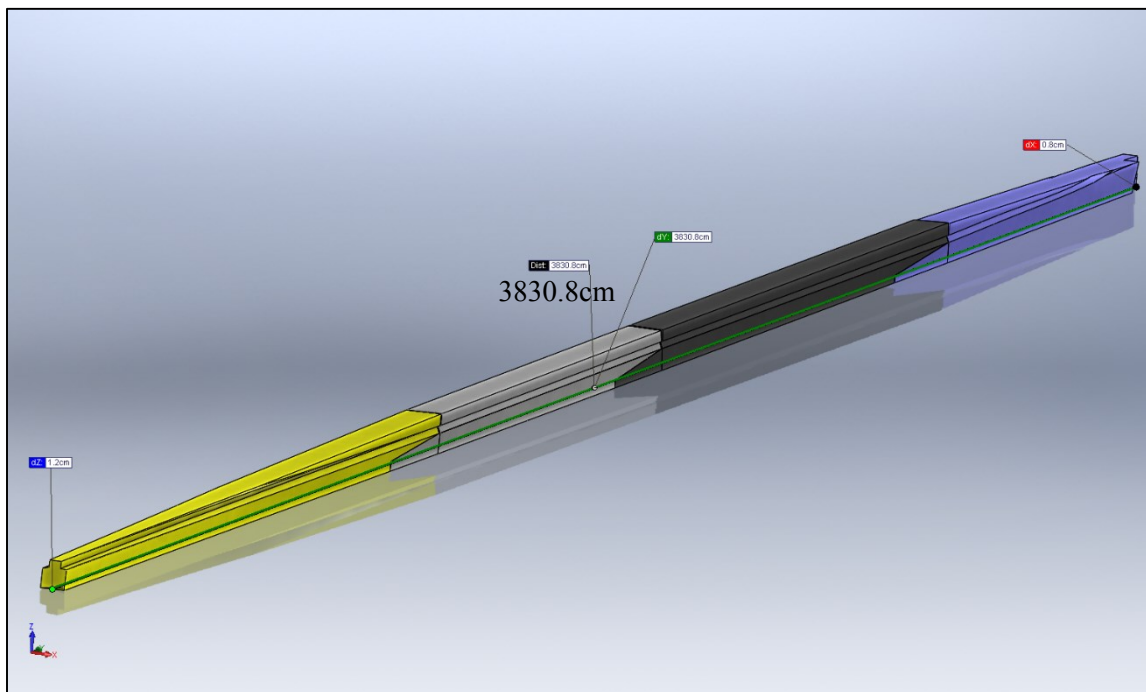


Figure 6.15. The full length of *Vasa*'s keel.

The fact that the length of the keel is the primary longitudinal measurement listed in the correspondence and contract between Hybertsson and the king is perplexing. Generally, one would expect the length overall to be the primary length measurement when discussing the size of vessels. Witsen also indicates that the length overall was the primary measurement from which many other measurements were derived.⁶⁰ The reason for using the keel length as the primary length measurement in the negotiations is unknown.

Comparing *Vasa's* length overall (159 ft.) to the length of the keel (129 ft.) suggests that a relationship may exist. The dimensions differ by exactly 30 ft. and if the keel dimension was in fact decided first, as indicated by the contract and correspondence, then it is possible that the length overall was predetermined to be an even 30 ft. longer. The relationship between keel length and length overall presents an important design consideration for the shipwright. If a shipwright determined the length overall first, then the length of the keel must be determined with respect to the desired rake of the stem and sternpost.⁶¹ Alternatively, if the length of the keel was decided first, then the length overall largely determined the rakes of the posts.⁶² It is significant to note that Witsen is curiously silent on the matter of keel length. He provides many suggestions for the sided and molded dimensions of the keel, discussed below, but no indication of how its length was derived. In the construction of the hypothetical 134 ft. *pinas*, the keel is 104 ft. long, a difference of 30 ft. The relationship between *Vasa's* keel length and length overall may also be explained as a ratio, a common feature in Dutch ship design. *Vasa's* keel

⁶⁰ This is repeatedly demonstrated in the numerous sample contracts he provides; Hoving 2012, 36-37.

⁶¹ No dimensions of the stem or sternpost are featured in the correspondences between Hybertsson and the king.

⁶² It is also possible, though unlikely, that the rakes of the posts were decided independently and prior to determination of the desired length overall and therefore the length overall was simply a function of keel length + rake of posts, each determined without respect for the length overall.

length (129 ft.) is roughly $\frac{4}{5}$ of the length overall (159 ft.). This ratio less closely explains Witsen's keel length, but it is a reasonable possibility for *Vasa's* keel length and may be explained as a function of timber economy or availability.⁶³

Keel Sided and Molded Dimensions

Throughout *Vasa's* 333 years underwater, the lengthy conservation process, and its time on display the keel has undergone crushing and distortion that has altered its dimensions slightly, illustrated in Figure 6.16. The sided dimension of *Vasa's* keel changes significantly over its length. At its maximum, it is sided 54 cm./1 ft. 10 in. S (22 in. S), which occurs just aft of the *hals* on keel section 2. It tapers fore and aft to meet the stem and sternpost. At the bow, the keel is sided 29.3 cm./1 ft. S (12 in. S) and at the stern it is sided 38.8 cm./1 ft. 4 in. S (16 in. S). At its maximum, *Vasa's* keel is molded approximately 60.1 cm./2 ft. S (24 in. S), which occurs at the *hals*. It tapers in its molded dimension to 46.8 cm./1 ft. 7 in. S (19 in. S) at the bow and 41.5 cm./1 ft. 5 in. S (17 in. S) at the stern. Witsen suggests making the molded dimension of the keel $1\frac{1}{4}$ times greater than the sided dimension of the inside of the stem (discussed below), and the sided dimension $1\frac{1}{2}$ times greater than the inside of the stem.⁶⁴ The sided and molded

⁶³ Applying this ratio to the keel lengths proposed in the correspondence between Hybertsson and the king lends further credibility to this conclusion. If each of the keel lengths (120 ft., 128 ft., and 136 ft.) are divided by $\frac{4}{5}$, one derives lengths overall of precisely 150 ft., 160 ft., and 170 ft. respectively. *Vasa's* length overall is very close to the length overall indicated by the 128 ft. keel specification if a $\frac{4}{5}$ ratio was used. Therefore it is also a possibility that when Hybertsson explained that the ship under construction would be slightly shorter than the specification, he may have been referring to the 128 ft. keel specification, which would have resulted in a hull of 160 ft. length overall.

⁶⁴ "The thickness of the keel, is $\frac{1}{4}$ more than the thickness of the inner side of the stem, and the breadth $1\frac{1}{2}$ times the width of the stem, which is at the main frame at one third from the bow, where the ship is at its widest; forward and aft it will meet the dimensions of the stem and sternpost." Hoving 2012, 39. "*De kiels dikte, is $\frac{1}{4}$ meerder als de binnen kant van de steven, en de breedte is $1\frac{1}{2}$ breeder als de steven, namentlijk, op den hals $\frac{1}{3}$ van voorn, daer het schip het wijtse is; achter en voor, accordeerende met de stevens.*" Witsen 1671, 66.

dimensions of *Vasa's* keel does not seem to follow Witsen's method. The sided dimension of the inside of *Vasa's* stem is only accessible directly under the bowsprit, where it is 18 in. S. Following Witsen's method, *Vasa's* keel would be molded 22 ½ in. S and sided 27 in. S, larger than what is observed. The maximum sided dimension of *Vasa's* keel is, however, slightly greater than the maximum molded dimension, which does match Witsen's suggestions. If the sided dimension of the inside stem was used to determine the keel's sided and molded dimensions, the sided dimension is approximately 1 ½ times the inner stem and the molded dimension 1 1/3 times the inner stem.



Figure 6.16. Example of crushing distortion of *Vasa's* keel, on the starboard side near the stem.

Keel Sections

Vasa's keel is made up of four timbers. For this study, the timbers have been numbered 1-4 from bow to stern. Measured along the centerline of the vessel, including the scarfs, the maximum extent of section 1 is 913.9 cm./30 ft. 10 in. S long (Figure 6.17), section 2 is 1171.8 cm./39 ft. 6 in. S long (Figure 6.18), section 3 is 950.6 cm./32 ft. S long (Figure 6.19), and section 4 is 1306.3 cm./44 ft. S long (Figure 6.20). With the exception of the fourth section, the irregular lengths of *Vasa*'s keel sections suggests their dimensions are a function of timber economy. The fourth section, which was the last to be put into place and the longest keel section, exhibits an evenly measured length which may indicate that it was measured and cut first.

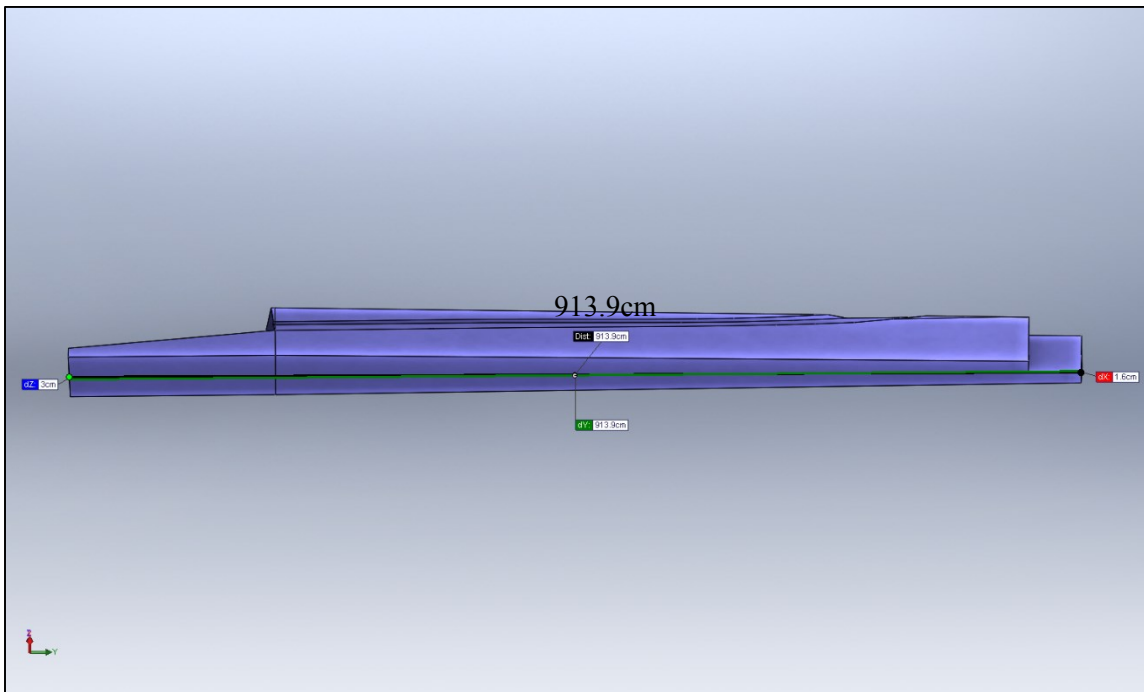


Figure 6.17. Keel section 1.

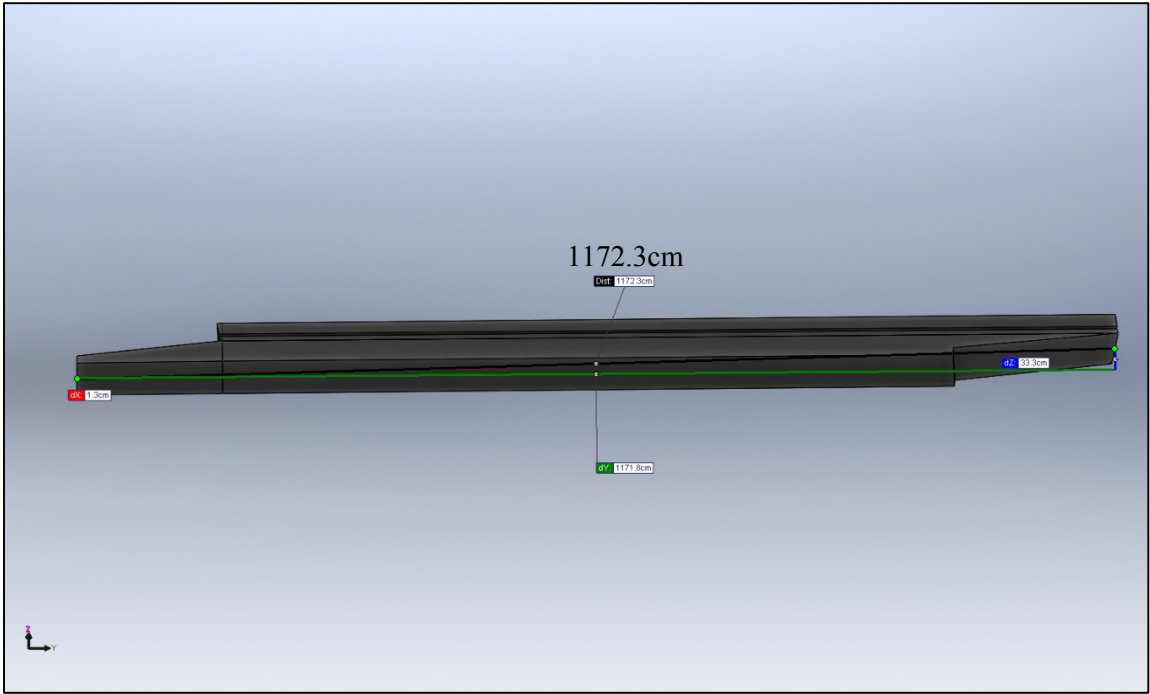


Figure 6.18. Keel section 2.

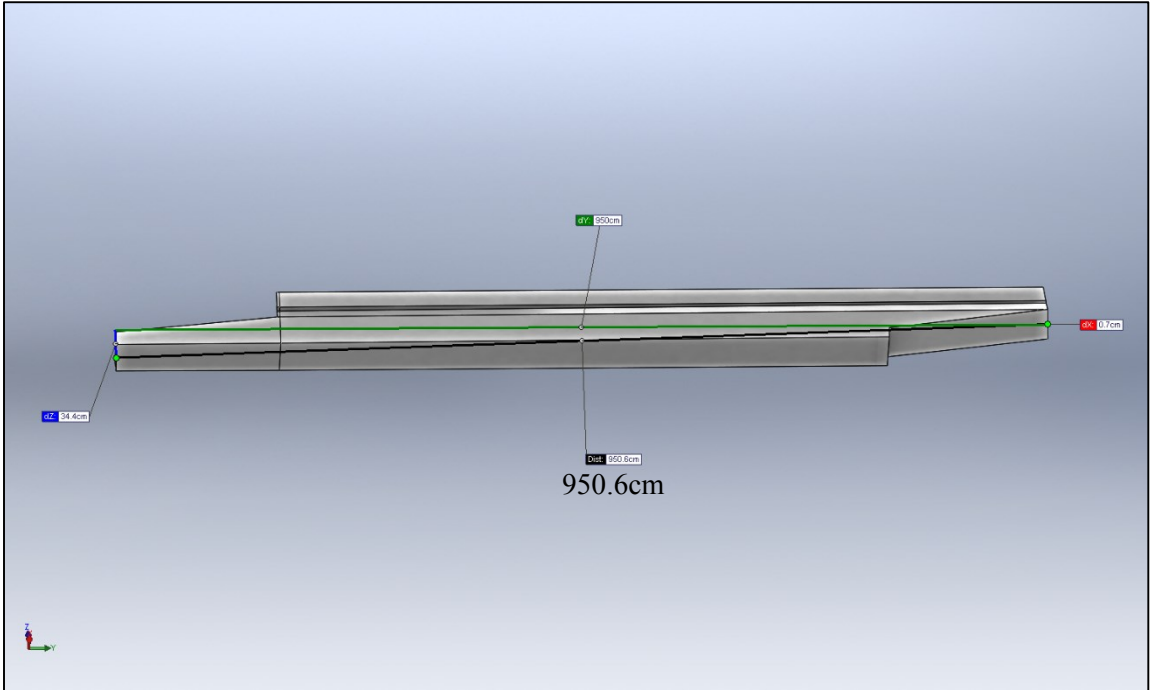


Figure 6.19. Keel section 3.

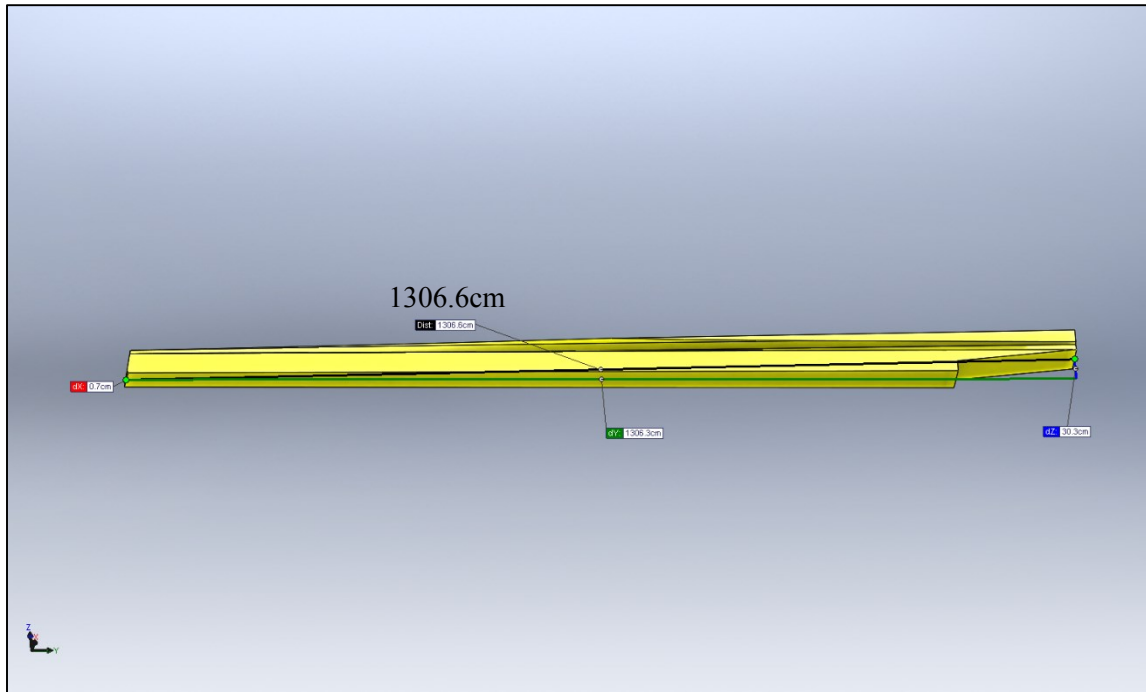


Figure 6.20. Keel section 4.

Together, keel sections 1 and 2 measure 1903.5 cm./64 ft. 1 in. S in length (Figure 6.21).⁶⁵ This is an interesting dimension as it is 1 inch over half of 128 ft., one of the two specifications for the keel length of the large ships in the contract between Hybertsson and the king. In autumn of 1625, prior to beginning construction, Hybertsson indicated that he had sufficient timber on hand to begin construction of either one large ship or two small ships. At the time of Hybertsson's writing, the contract specified that the large ships measure 128 ft. on the keel. Even after Gustav Adolf modified the specification for the large ships (either 128 ft. or 136 ft.), Hybertsson claimed to have the timber necessary to build one large and one small ship in his early February-1626 letter to the king. It is likely Hybertsson chose to construct a large ship, instead of a small ship, to make the most economical use of the timber he had on hand. Another possible explanation is

⁶⁵ As assembled, measured on the port side (the forward-most extent of the keel).

that the shipwrights started out aiming for the 128 ft. measurement but the available timber allowed them to build a keel 129 ft. long. The timber available for the stem and sternpost may have limited the overall length of the hull and therefore Hybertsson was forced to build a hull slightly shorter than the intended length overall.⁶⁶

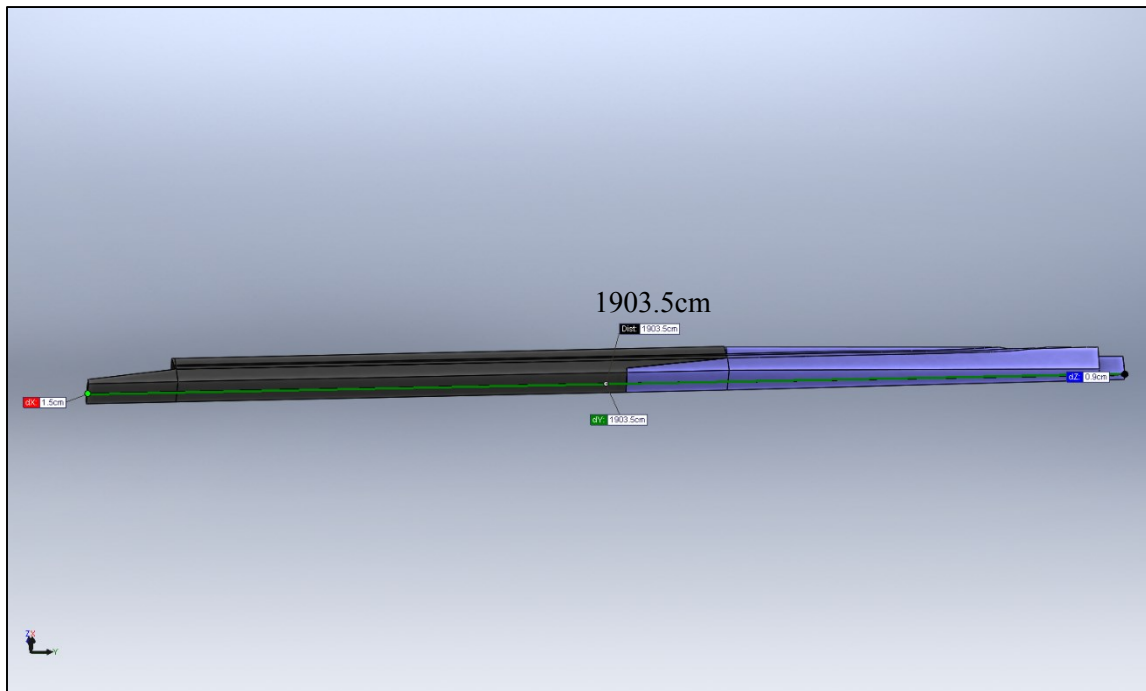


Figure 6.21. Keel sections 1 and 2.

⁶⁶ Alternatively, if the keel was assembled without the third keel section (the shortest section), the length of the keel would be 3211.5 cm./108 ft. 2 in. S – which is very close to the length of the keel for the small ships in the contract.

In general, shipwrights seem to have avoided placing a keel scarf directly under the mainmast.

Witsen specifically cautions against this, writing:

One holds such keels, made of 3 pieces, to be stronger than the ones made of two: because with a such a keel of 3 pieces the scarfs are forward and aft, while in the middle, where the keel has to endure the most pressure from the main mast, it is free of scarfs; which is very good, and makes the ship strong.⁶⁷

The mainmast of *Vasa* is stepped directly on top of the scarf between sections 2 and 3, illustrated in Figure 6.22. It is possible that suitable keel timber was not available to avoid this and instead the keel was made of four pieces, instead of three.

The diagonal portions of the three scarfs that join the four sections of the keel were measured on both the port and starboard sides. The scarf between keel sections 1 and 2 is 178.4 cm./6 ft. 8 in. S long on the port side and 186.9 cm./6 ft. 4 in. S long on the starboard side. The scarf between keel sections 2 and 3 is 165 cm./5 ft. 7 in. S long on the port side and 163.5 cm./5 ft. 6 in. S on the starboard side. The scarf between keel sections 3 and 4 is 167.8 cm./5 ft. 7 in. S long on the port side and 165.5 cm./5 ft. 7 in. S long on the starboard side. Both Witsen and van Yk provide guidelines for determining the length of keel scarfs, each determined as a function of the width (sided dimension) of the keel.

⁶⁷ Hoving 2012, 39; “*Dusdanige kiel van 3 stucken, wordt sterker gehouden, dan of menze van twee stucken mackte: dewijle in een kiel van 3 stucken, de lasschen voor en achter komen te wezen, en in het midden, alwaer de kiel de meeste last heft to lijden, can wegen de groote mast, geheel zonder lasschen komt de blijven; ‘t geen zeer goet is, en het schip stevig maekt*” Witsen 1671, 72.

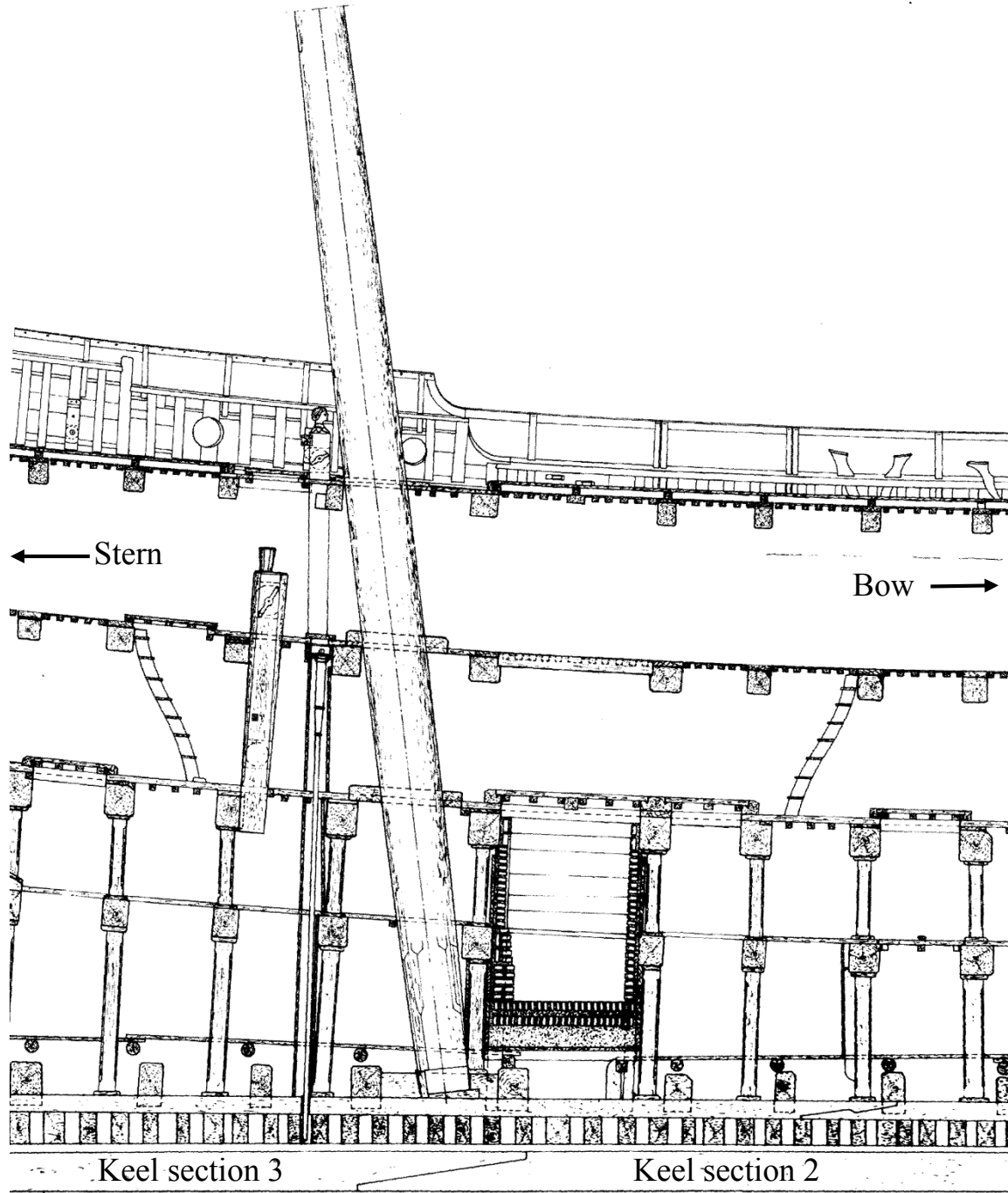


Figure 6.22. The placement of *Vasa's* main mast. Drawing by Eva Marie Stolt and Fred Hocker.⁶⁸

⁶⁸ Cederlund and Hocker 2006, Plan 2.

Although not a critical design element, examination of *Vasa*'s keel scarfs are an opportunity to uncover design logic and deliberate selection by the shipwrights. In the construction of his hypothetical *pinas*, Witsen makes his keel scarfs 4 ft. long for every 1 ft. the keel is wide or a 4:1 relationship. Taking the maximum sided dimension of *Vasa*'s keel (1 ft.10 in. S or 22 in. S), following Witsens formula would yield a keel scarf length of approximately 7 ft. 3 in. S. Van Yk suggests making the keel scarfs 5 in. long for every inch the keel is wide. Following this formula would yield scarfs approximately 9 ft. 2 in. S long. Both of these results are considerably longer than the keel scarfs observed in *Vasa*. Although not a defining design element, and a formula is not required for determining the length of keel scarfs, *Vasa*'s keel scarfs are close to 3 in. long for every inch the keel is wide at its widest point.⁶⁹ The scarf between sections 1 and 2 is approximately 5 in. longer than the other two scarfs and may be a result of the shipwright's concern for a strong supporting joint at the bow where the keel must support a great deal of timber weight.

Keel Marks

During the 2010 fieldwork season, two incised marks were observed on the port side of keel section 2. The first is a series of vertical scratches with a possible circular scratch near the middle that spans most of the visible keel's molded dimension, seen in Figure 6.23. The edges of the scratches do not show the fraying often associated with scratching or damaging waterlogged wood. Solidified PEG is also clearly visible in the scratch grooves. It is possible that this mark was placed on the keel before it became waterlogged and therefore may be a product of the shipbuilding and design process. The position of the first mark was not captured

⁶⁹ 22 in. x 3 = 66 in., or 5 ft. 6 in.

in the total station survey and was instead measured from the forward end of the keel on the port side using a folding rule and later plotted in SolidWorks. This keel mark is 1655 cm./55 ft. 8 in. S from the forward face of the keel on the port side. This mark is located 42.3 cm./1 ft. 5 in. S abaft the midpoint of the length overall, illustrated in Figure 6.24. The location of the mark along the overall length of the vessel suggests that it may have been intended as a construction guide, marking the midpoint of the hull.

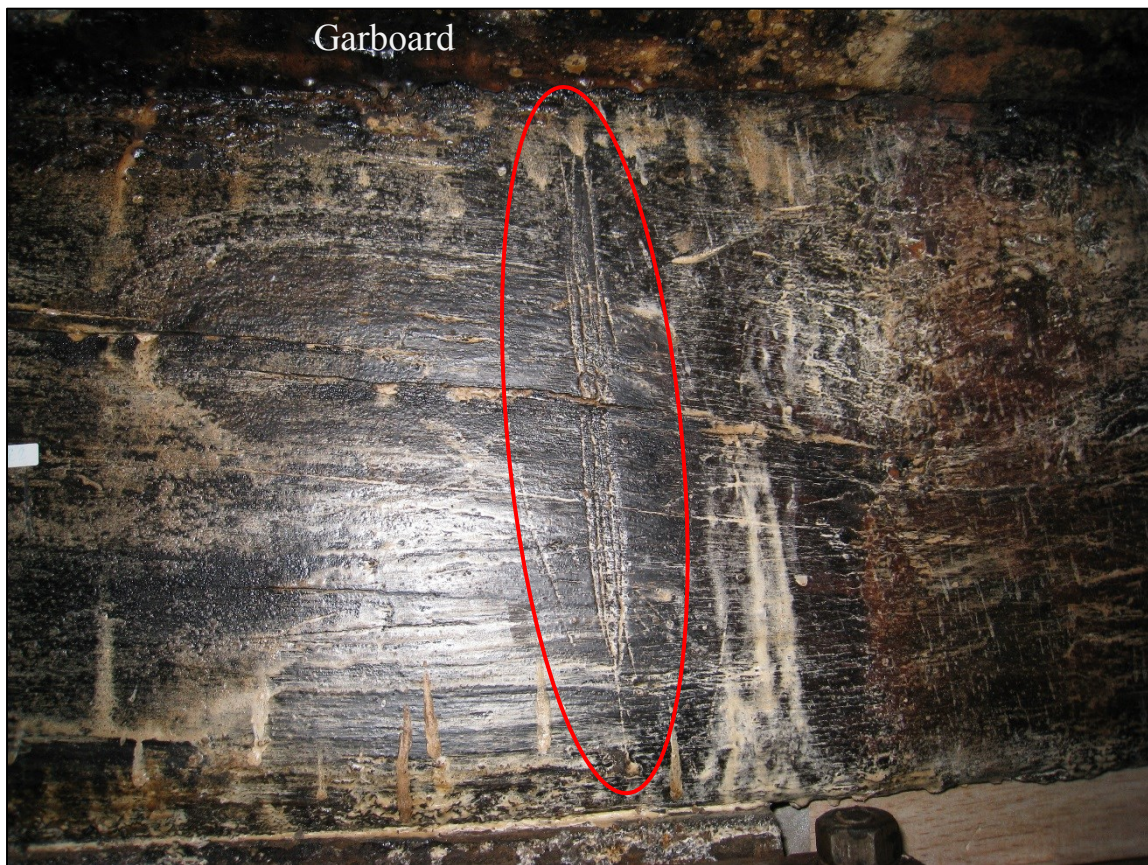


Figure 6.23. Vertical mark on *Vasa*'s keel.

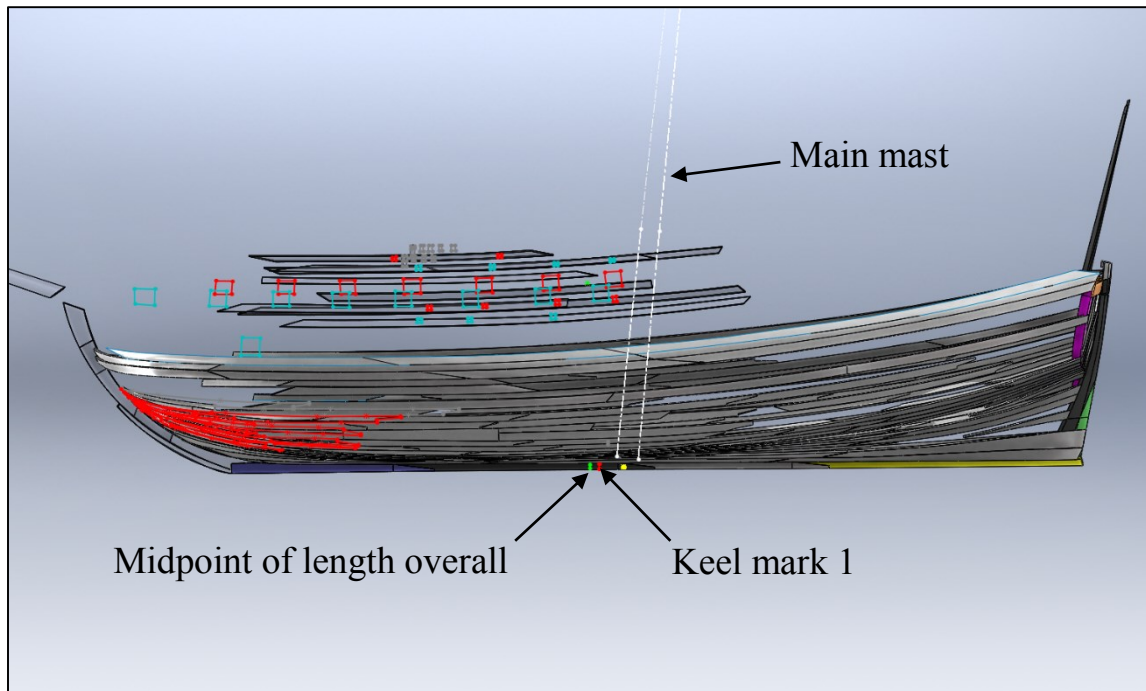


Figure 6.24. The location of keel mark 1 (red) in relation to the midpoint of the length overall (green). The position of the mainmast is indicated by the dotted white lines.

A second mark, consisting of three intersecting lines forming a star, is located abaft the first mark, at a point 1764.4 cm./59 ft. 5 in. S from the forward face of the keel on the port side and 151.6 cm./5 ft. 1 in. S abaft the midpoint of the hull. Like the first mark, the grooves of this star-shaped mark are filled with solidified PEG. The edges of the grooves, however, do show possible fraying or tearing indicating the mark may have been scratched into the wood after it was waterlogged, shown in Figure 6.25. It is possible this mark was made during or after the excavation and does not have any relevance for the investigation of the hull form design method of *Vasa*. It is located under the heel of the mainmast, however, and if it is original, it likely indicated the planned position of the mast early in construction. The position of this mark on the model is illustrated in Figure 6.26.

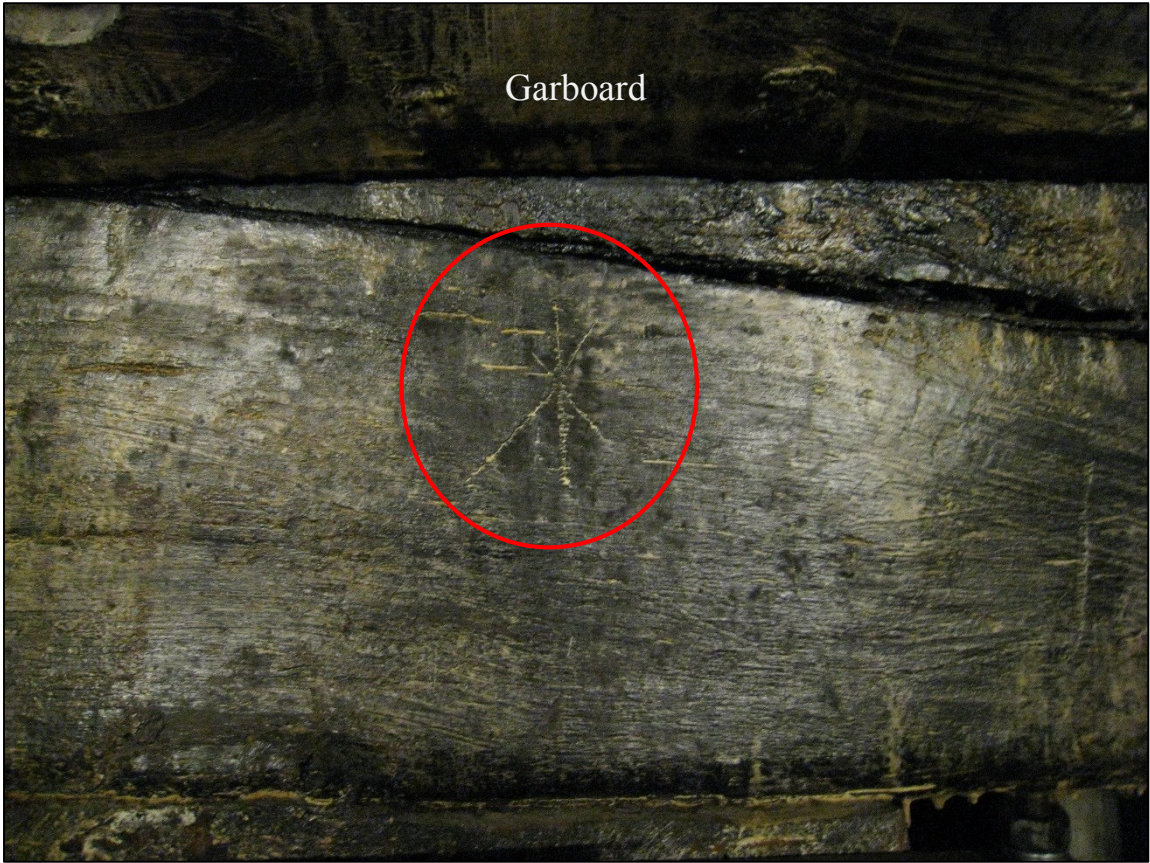


Figure 6.25. Star shaped mark on *Vasa*'s keel.

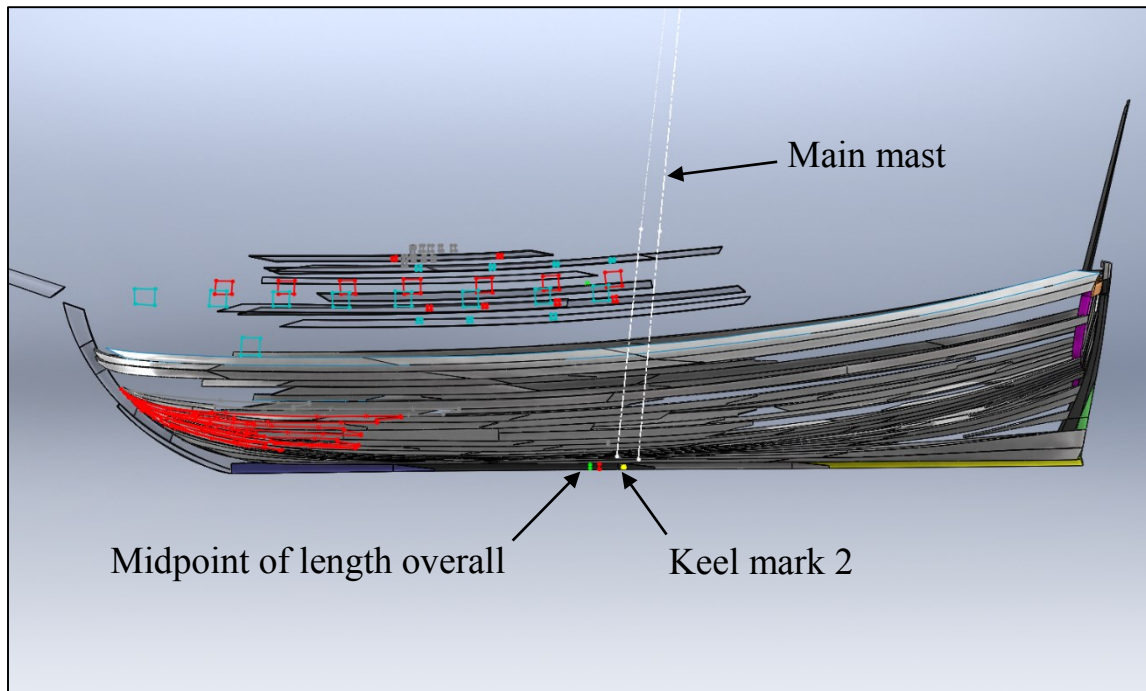


Figure 6.26. The position of keel mark 2 (yellow) in relation to the midpoint of the length overall (green) and main mast (dotted white).

STEM

The stem is one of the most complex, expensive, and distinguishing hull elements. Its shape exerted significant influence over the form of the hull and its hydrodynamic performance.

Vasa's stem is composed of three timbers laminated together with a gripe that spans approximately half of the forward face of the keel. The keel is joined to the stem using a boxing scarf. Although the internal details of the scarf are inaccessible, the scarf measures approximately 47.4 cm./1 ft. 7 in. S alongships, illustrated in Figures 6.27, 6.28, 6.29, and 6.30.

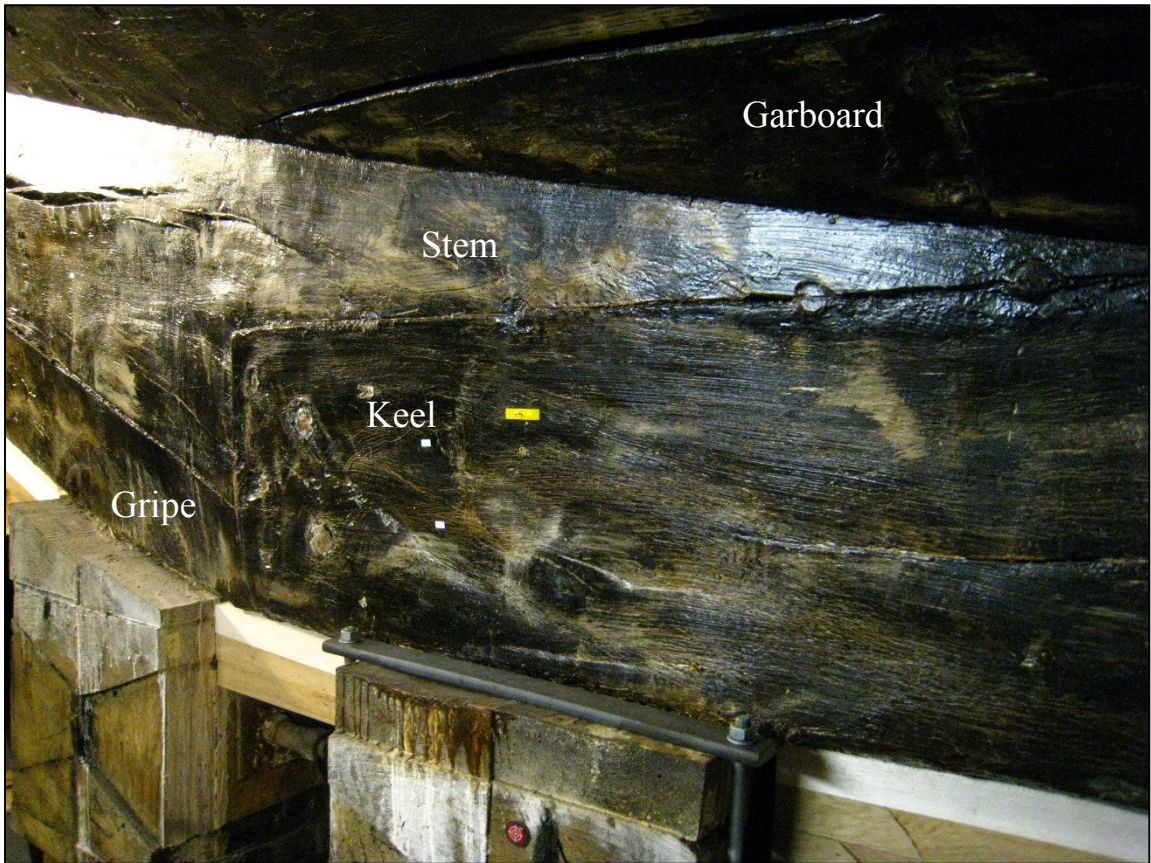


Figure 6.27. Boxing scarf on the port side.

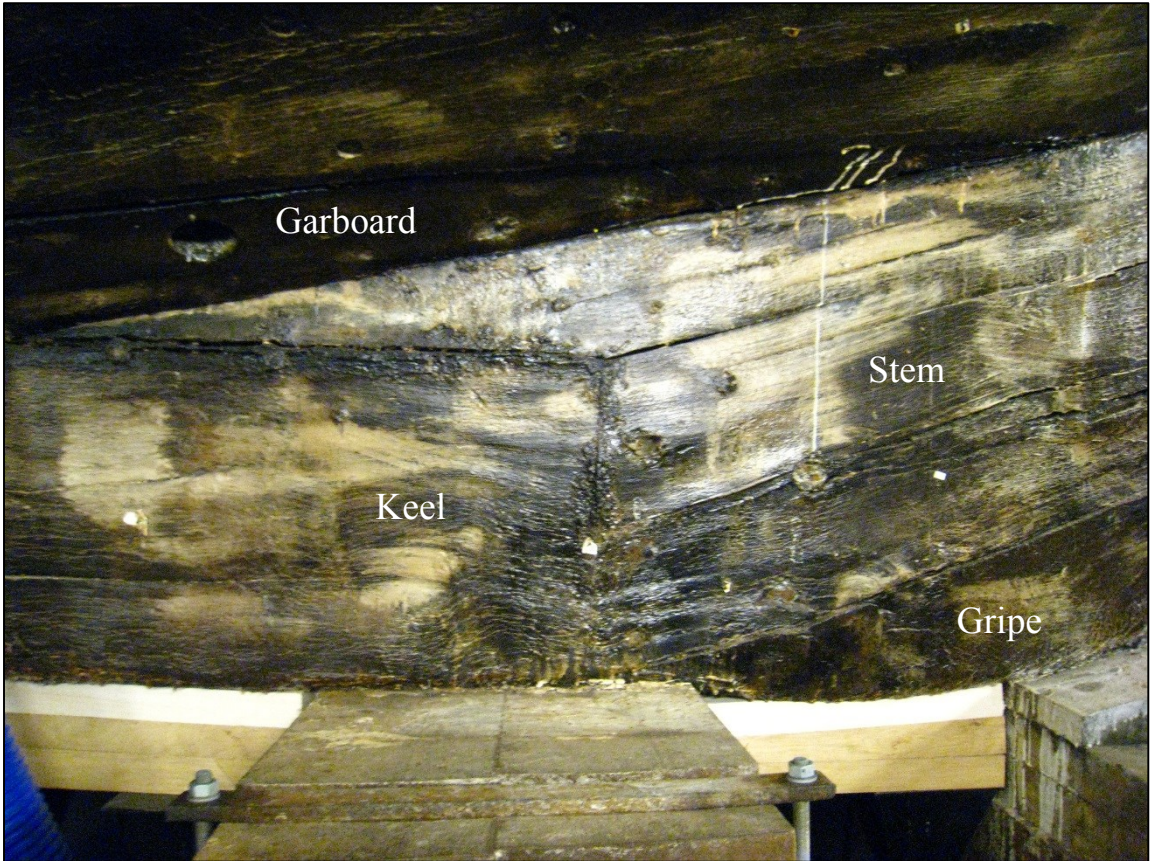


Figure 6.28. Boxing scarf on the starboard side.

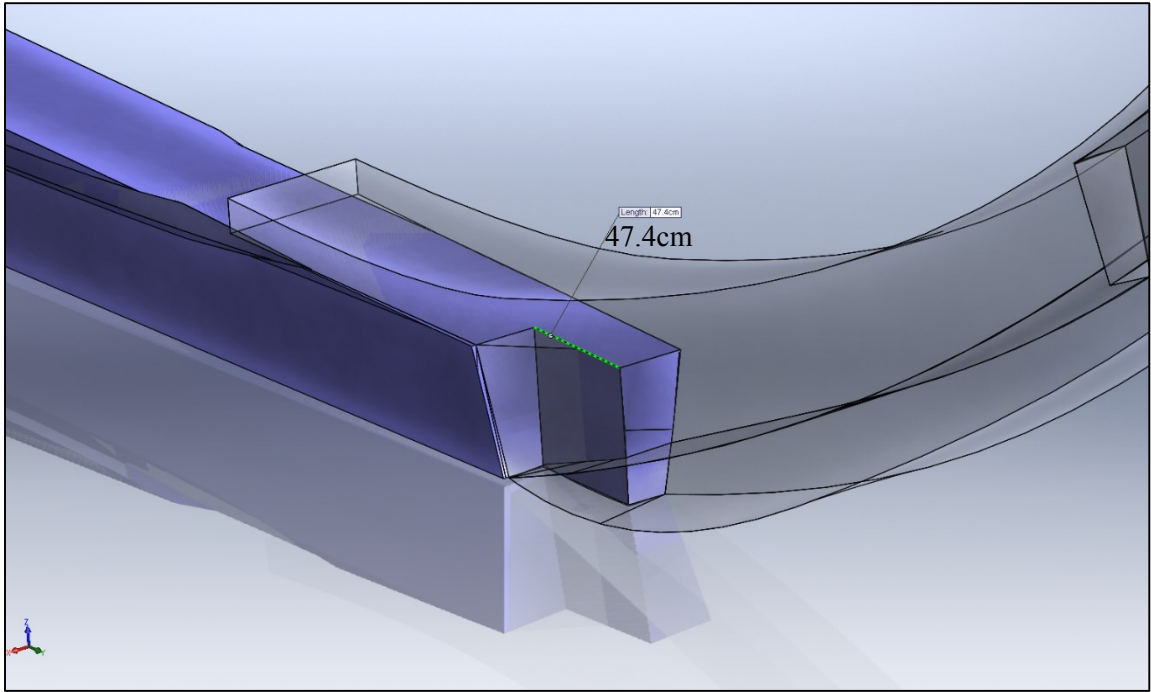


Figure 6.29. Model of the boxing scarf. Keel section 1 (blue) and the stem (transparent grey).

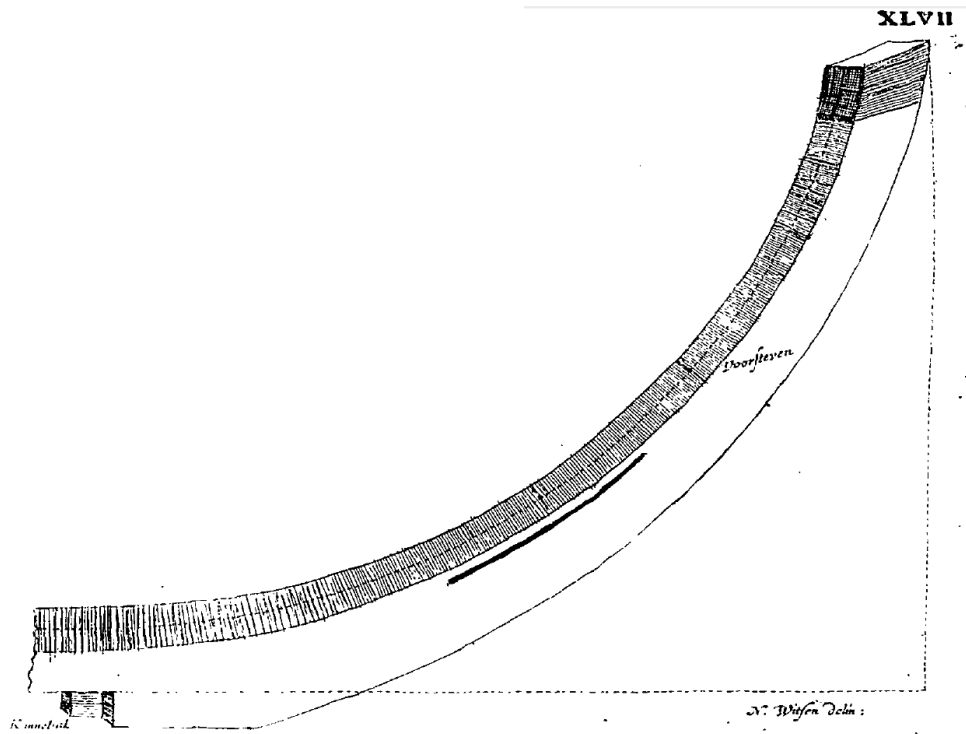


Figure 6.30. Drawing by Witsen showing the boxing scarf of the stem. Also indicating the method for measuring the height and rake of the stem (dotted lines).⁷⁰

Stem Height and Rake

The shape of the stem, especially the relationship of its rake to its height, was a critical design choice that had important effects on the characteristics of the finished hull. In the early 17th century, conventional shipbuilding wisdom held that ships with a dramatically raked stem (relative to the height) made fast sailing ships, while ships with more vertical stems made slower ships with better carrying capacity.⁷¹ Over the course of the century, it was found that in general large ships with modestly raked stems tended to have better sailing characteristics than those

⁷⁰ Witsen 1671, Plate XLVII.

⁷¹ “A fluyt has less rake, a frigate more” Hoving 2012. “*Een fluyt valt minder, en een fregat meerder.*” Witsen 1671, 66.

with dramatically raked stems. The precise relationship of height to rake was up to the shipwright and based on the intended qualities of the vessel.⁷²

The quantification of straight or square timbers is reasonably straightforward. Curved timbers, however, present several possible approaches to measurement. Fortunately, Witsen's treatise provides reasonably clear guidelines for how irregularly shaped timbers, like the stem and sternpost, were measured. To simplify measurement of timbers with complex shape and curvature, their dimensions were calculated using right angles, illustrated in Figure 6.30.⁷³

Witsen's measurements are taken on the port side of the stem at the upper edge of the keel to the upper forward-most edge of the stem, as seen in Figure 6.30.⁷⁴ *Vasa's* stem has the same configuration as Witsen's example, and using this method, the height of *Vasa's* stem is 733.9 cm./24 ft. 8 in. S, illustrated in Figure 6.31. The rake of the stem is 751 cm./25 ft. 2 in. S, illustrated in Figure 6.32.

⁷² Hoving 2012, 43.

⁷³ This is referred to as "in the square", or "*in de winkel*" in Dutch.

⁷⁴ This is the same point that the length overall is measured from.

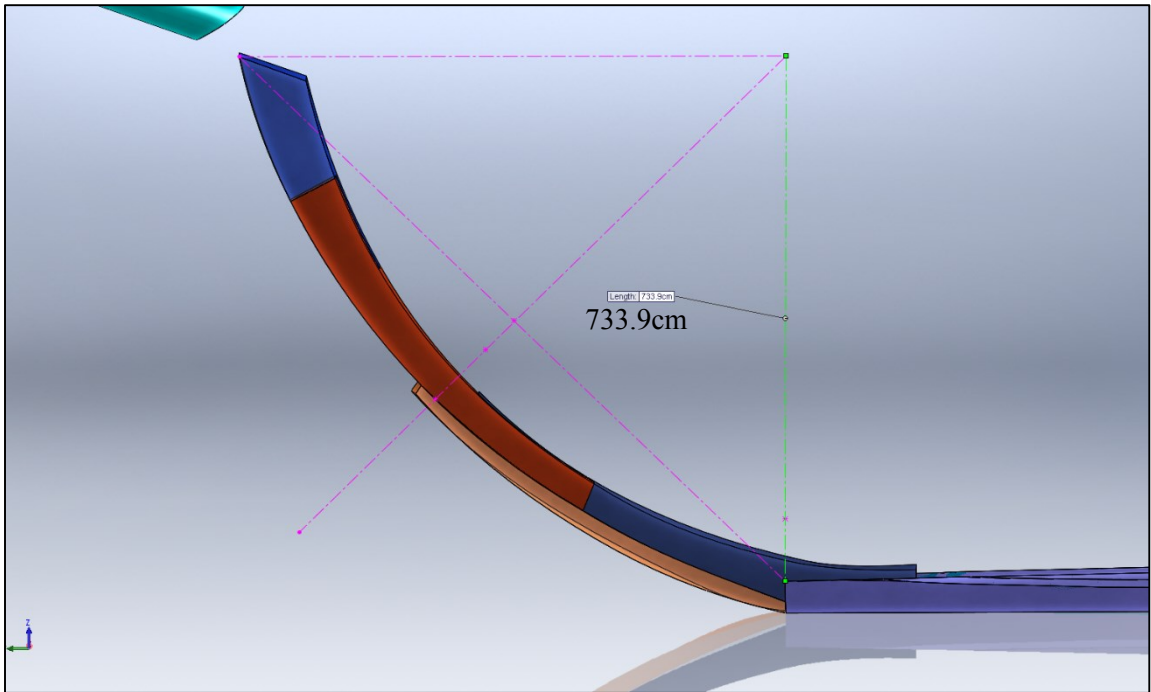


Figure 6.31. The height of *Vasa*'s stem.

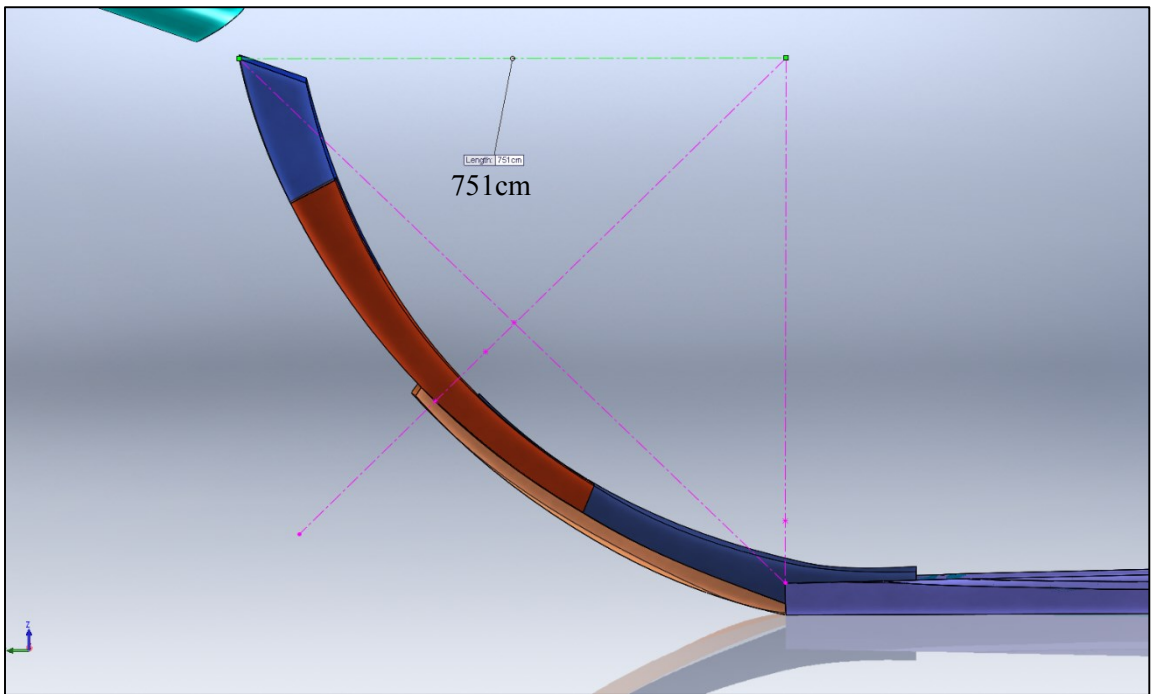


Figure 6.32. The rake of *Vasa*'s stem.

Witsen provides three suggested methods for determining the height of the stem. If the vessel would not have a forecastle, Witsen suggests taking either $2/11$ or $11/60$ of the length overall for the height of the stem.⁷⁵ If the ship would have a forecastle, then Witsen suggests adding together “the depth, the rise of the deck forward, and what is to be above, like the cable tier, the forecastle, etc.”⁷⁶ For *Vasa*, adding the depth (15 ft. 2 in. S), the approximate rise in sheer forward (2 ft. S – discussed below), and the height of the lower gundeck (7 ft. 3 in. S – discussed below) equals 24 ft. 5 in., only 3 in. less than the height of the stem.

Witsen suggests that a shipwright begin by making the rake of the stem $28/29^{\text{th}}$ s of the height.⁷⁷ From this basic relationship a shipwright could increase or decrease the rake according to the desired characteristics of the vessel. In *Vasa*'s case the rake (25 ft. 2 in. S) is only slightly (6 in. S) greater than the height (24 ft. 8 in. S) of the stem and may be influenced by distortion.⁷⁸ This close relationship may be an indication that Hybertsson intended *Vasa*'s stem to be neutral or close to neutral with neither a pronounced height nor rake. For warships in the early 17th century, the primary objective was designing a hull that could effectively support the weight of many (for *Vasa*, 64) guns and create a reasonably stable platform to fire them from. The neutral character of *Vasa*'s stem height and rake relationship may be indicative of conservatism in

⁷⁵ “should there be no forecastle, then the stem should be much longer than the height of the cable tier. Or one takes two eleventh parts of the length of the ship over the stems for the height of the stem in the perpendicular. Others also take eleven sixtieth parts of the length for this.” Hoving 2012, 41. “*zoo daer geen bak opgemaekt zal sijn, zoo moet de steven zoo veel lager zijn, als de hoogte van 't kotis. Of men neemt twee eldfe parten van de lengte over steven, tot de hoogte van de steven, in de winkel. Andere neemen mede hier toe, elfzestighste parten van de lengte.*” Witsen 1671, 66.

⁷⁶ Hoving 2012, 41. “*addeert de holte, 't opzetten, en dat daer boven zijn mote, als 't kot, de bak, &c.*” Witsen 1671, 66.

⁷⁷ “For the rake of the stem one takes 28 twenty-ninth parts, of the height of the stem, in the try square.” Hoving 2012, 41. “*Tot het vallen van de voorsteven neemt men 28 negenentwintigste deel, van de hoogte can de steven, in de winkel.*” Witsen 1671, 66.

⁷⁸ Expressed as a fraction, the height is $49/50$ of the rake, or the rake is approximately $51/50$ of the height.

design regarding large warships and an attempt to balance several desirable qualities of the vessel.⁷⁹

Thickness of the Stem

According to Witsen, the sided dimension (he calls it thickness or *dikte*) of the inboard surface of the stem was a critical dimension from which a number of other measurements were derived.⁸⁰

Nearly half of the timbers or hull elements that Witsen discusses are derived at least in part from the inside of the stem.⁸¹ Without significant disassembly, the inner face *Vasa*'s stem is inaccessible. During survey of the ship, however, it was found to be possible to measure the inner face of the stem under the bowsprit. Measured with a folding rule, the sided dimension of inner stem at this point (the upper face of the stem) is 44.5 cm./1 ft. 6 in. S (18 in. S). Witsen does not indicate the sided dimensions changed along the length of the stem, though it is possible. This is the only point in *Vasa*'s hull, however, that the inner face of the stem is accessible. Witsen suggests making the stem 1 in. thick for every 10 ft. the ship is long, or alternatively $\frac{3}{4}$ of the height of the stem in inches.⁸² If applied to *Vasa*, the first formula results in an inner stem thickness of approximately 16 in.. If one takes only the whole foot measurement of *Vasa*'s stem height (24 ft. S), Witsen's second formula results in 18 in. for the

⁷⁹ "The stem is the guideline from which all proportions in the ship are derived" Hoving 2012, 40. "*De steven is de richt-snoer daer men alle groote, in een schip uit trekt.*" Witsen 1671, 73.

⁸⁰ Witsen more than van Yk.

⁸¹ Hoving 2012, 250.

⁸² "This thickness is found from the length of the ship: example, 10 feet length, 1 inch thick." Hoving 2012, 40. "*De dikte vint uit de length van 't schip: exempel, 10 voet lengte, 1 duim dikte.*" Witsen 1671, 66. " $\frac{3}{4}$ Parts of the height of the stem, in the perpendicular, also gives the thickness of the stem, if one multiplies with the numerator, and divides by the denominator, and takes the result to stand in inches. On ships with forecastles this thickness is made more than on ships without forecastles." Hoving 2012, 41. " *$\frac{3}{4}$ Parten van de voor-stevens hooghte, in de winkel, blijft mede voor-stevens binnenste dikte, als men multiplieert met den teller, en divideert met den noemer, en het zelve dat 'er af komt, voor duimen rekent. Op schepen met backen, maekt men deze dikte meerder, als op schepen zonder backen.*" Witsen 1671. 66.

thickness of the inside of the stem, precisely the dimension observed under the bowsprit, illustrated in Figure 6.33.

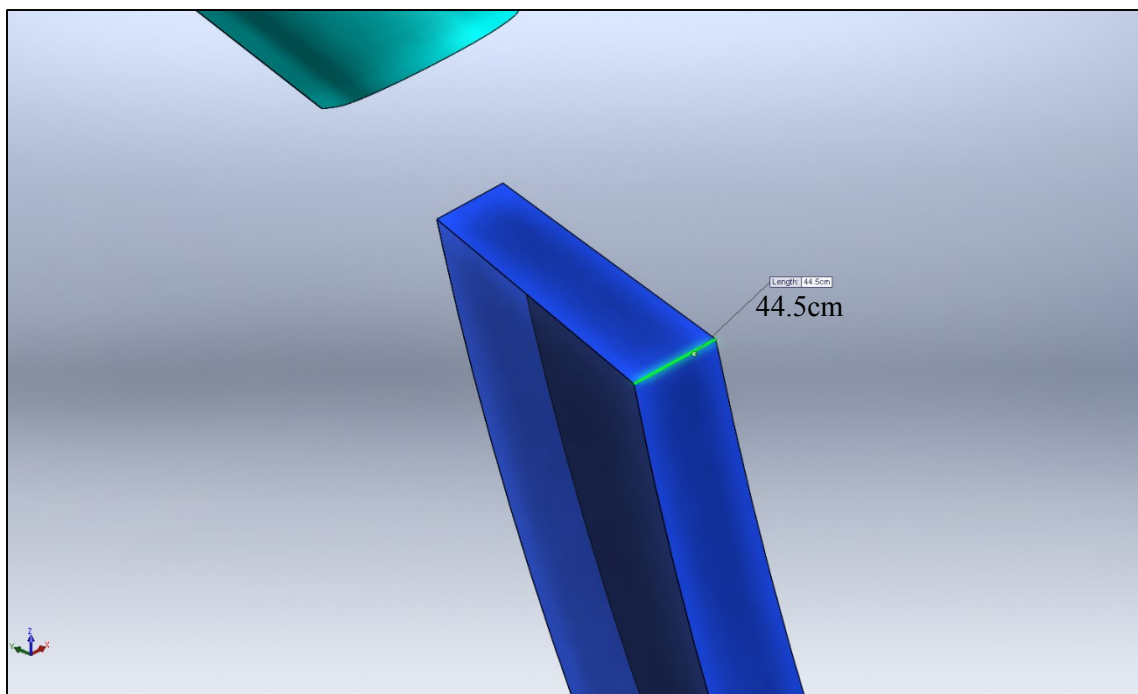


Figure 6.33. The location of the only directly accessible measurement of the inside of *Vasa*'s stem.

The outside of the stem (forward face) is largely accessible and can be measured. Over its length, the outside of the stem changes little in its sided dimension (thickness), from 36 cm./1 ft. 2 in. S (14 in. S) under the bowsprit to 33.2 cm./1 ft. 1 in. S (13 in. S) at its base. Witsen suggests making the thickness of the outside of the stem $\frac{3}{4}$ or $\frac{3}{5}$ of the inside thickness.⁸³ Dividing 13 in. and 14 in. by $\frac{3}{5}$ results in dimensions too large to fit with possible inner stem

⁸³ “The thickness of the foreside is $\frac{3}{5}$ of the thickness of the inside.” Hoving 2012, 41. “*De dikte van de voorkant zy $\frac{3}{5}$ van de dikte der binnen kant.*” Witsen 1671, 66. “And $\frac{3}{4}$ of the thickness of the inside of the stem is the thickness of the outside.” Hoving 2012, 41. “*en voor $\frac{3}{4}$ van de voor-stevens binnenste kants dikte, komt de dikte van de buitenste kant.*” Witsen 1671, 66.

thickness dimensions observed in *Vasa* (21.7 in. and 23.3 in. respectively). Dividing 13 in. and 14 in. by $\frac{3}{4}$, however, provides results that do correlate to the observed inner stem thickness (17.3 in. and 18.7 in. respectively). This also lends confidence to the interpretation of 18 in. as the inner stem thickness. Erosion, shrinkage, warping, and the builders' loose measurement tolerances easily account for the minor discrepancies in dimensions.

Breadth of the Stem

In his treatise, Witsen provides somewhat unclear suggestions regarding the molded dimension (he calls it breadth, or *breed* in Dutch) of the stem and indicates that this dimension changes over the length of the stem. At various points in the treatise, Witsen suggests “In the middle the stem is 3 times as broad as it is thick: above and below it is broader,” “According to some, the breadth of the stem above is twice the thickness inside,” and “The stem should be a little more, than a third broader below than above.”⁸⁴ In the construction of his hypothetical *pinas*, Witsen provides a molded dimension for the stem that is close to 2 times the sided dimension of the inside. A survey of contemporary Dutch shipbuilding contracts reveals that the molded dimension of the stem generally varied between 2 and 3 times the sided dimension.⁸⁵

As it has been noted, much of the inner face of *Vasa*'s stem is inaccessible, thus making a direct measurement of the molded dimension anywhere but under the bowsprit impossible. At this

⁸⁴ Although he does not specify it, it is assumed that the thickness of the inside of the stem was used. Hoving 2012, 41. “*de voor-steven, in de midden 3 mael breeder als de dikte: obdered boven breeder.*” Witsen 1671, 66. Hoving 2012, 41. “*De binnen kants dikte van de steven tweemaal, is de voor-stevens breete boven, volgens eenige*” Witsen 1671, 66. “*De steven onder wat meer, al seen darde breeder also boven.*” Witsen 1671, 68.

⁸⁵ Hoving 2012, 42.

point, the stem is molded 98 cm./3 ft. 4 in. S (40 in. S), illustrated in Figure 6.34. This is roughly twice the sided dimension (18 in.), suggesting a possible relationship between the two dimensions. Although the middle and lower portions of the stem are inaccessible for measurement, it was possible to view the lower stem through a drainage hole cut into the garboard on the starboard side. Based on what is observable through this hole, the lower portion of *Vasa's* stem does not appear substantially greater in molded dimensions than the upper face of the stem. Thus, based on all observable data, the molded dimension of *Vasa's* stem does not appear to change significantly along its length.

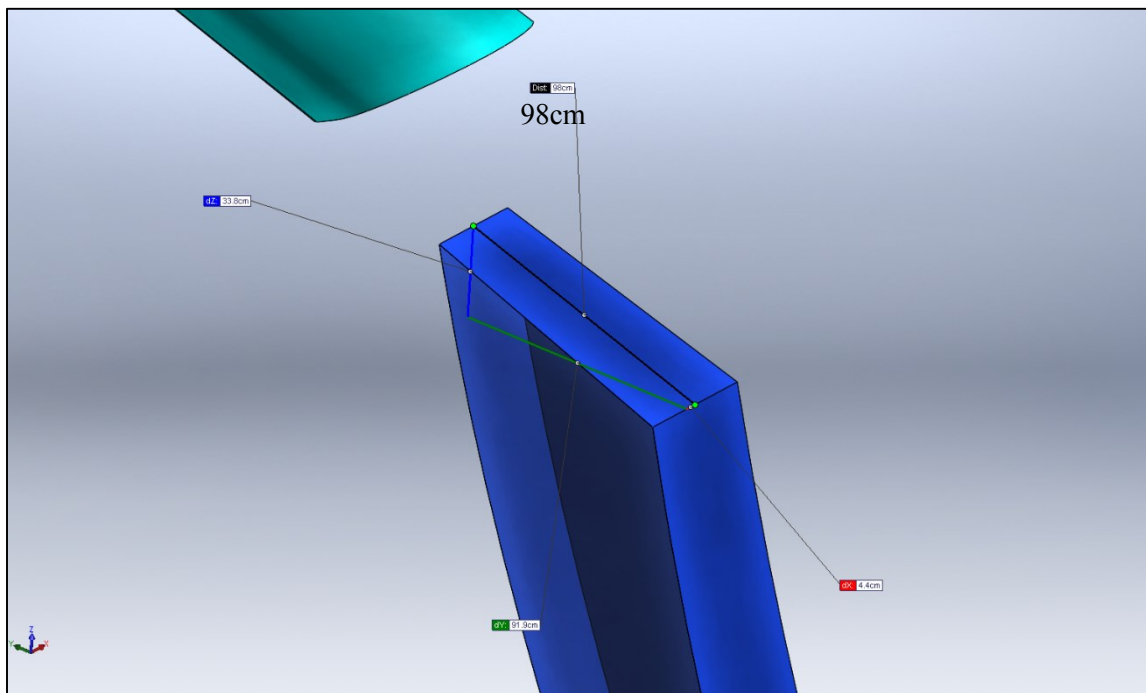


Figure 6.34. The width of *Vasa's* stem measured under the bowsprit.

Curve of the Stem

Whereas the use of compasses and arcs was common among English shipbuilders, these tools seem to be rare in early 17th-century Dutch shipbuilding. According to Witsen and Hoving, the curvature of a Dutch-built stem was likely measured not as a radius but as an offset distance from the midpoint of a line that ran from the lower measuring point to the upper, illustrated in Figure 6.35.⁸⁶ Witsen does not indicate how this dimension was determined. He provides only vague suggestions for the curvature of the stem, such as “When a Stem is made to bear Weight, one may make it two feet higher than its rake, or even 3 or 4 feet, and also a little more curved than usual... The stem of frigates have a large rake, and one tends to make them crooked above and of an easy curve.”⁸⁷ The numerous sample contracts Witsen provides in his text do not consistently mention the curvature of the stem as a significant dimensions and many indicate that the curvature was not consistent along the length of the stem. It is entirely possible that it was not necessary to quantify the curvature of the stem and it was simply constrained by the height and rake of the stem and designed according to the eye and judgment of the shipwright.

⁸⁶ Hoving 2012, 42-43.

⁸⁷ Hoving 2012, 41. “*Wanneer men een Steven toestelt tot een Last-drager, mag men die wel twee voet hoger maecken, als hy valt, of oock wel 3 en 4 voet, mede wel wat krommer als in ‘t gemeen... Fregatten vallen de stevens veel, en men maeckte oock boven wel wat kromen lui van bocht.*” Witsen 1671, 149-150.

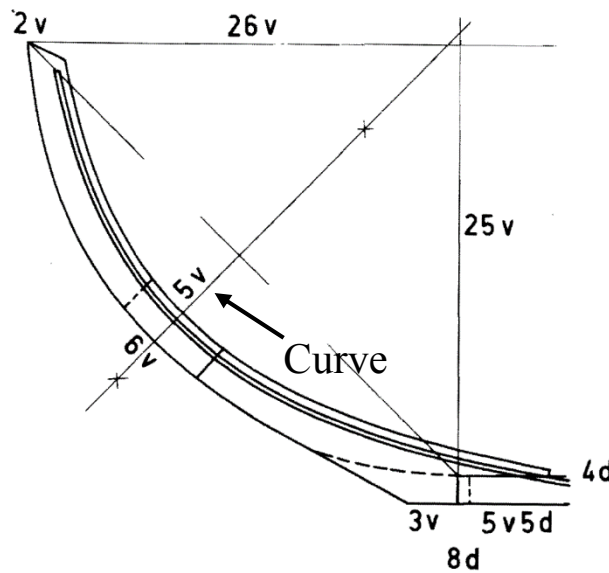


Figure 6.35: The '5v' measurement illustrates how Witsen indicates the curvature of stems was measured. Drawing by A.J. Hoving.⁸⁸

The curve of *Vasa's* stem is difficult to precisely measure because the midpoint of the inner face of the stem is inaccessible. Based on the observed molded dimension (98 cm./40 in. S) of the upper stem under the bowsprit and assuming this dimension remains constant along the length, *Vasa's* stem exhibits a curve of approximately 56.6 cm./1 ft. 11 in. S (23 in. S), illustrated in Figure 6.36. Accounting for distortion, this dimension could have been intended as 2 ft. This is, however, a highly speculative conclusion.

⁸⁸ Hoving 2012, 43.

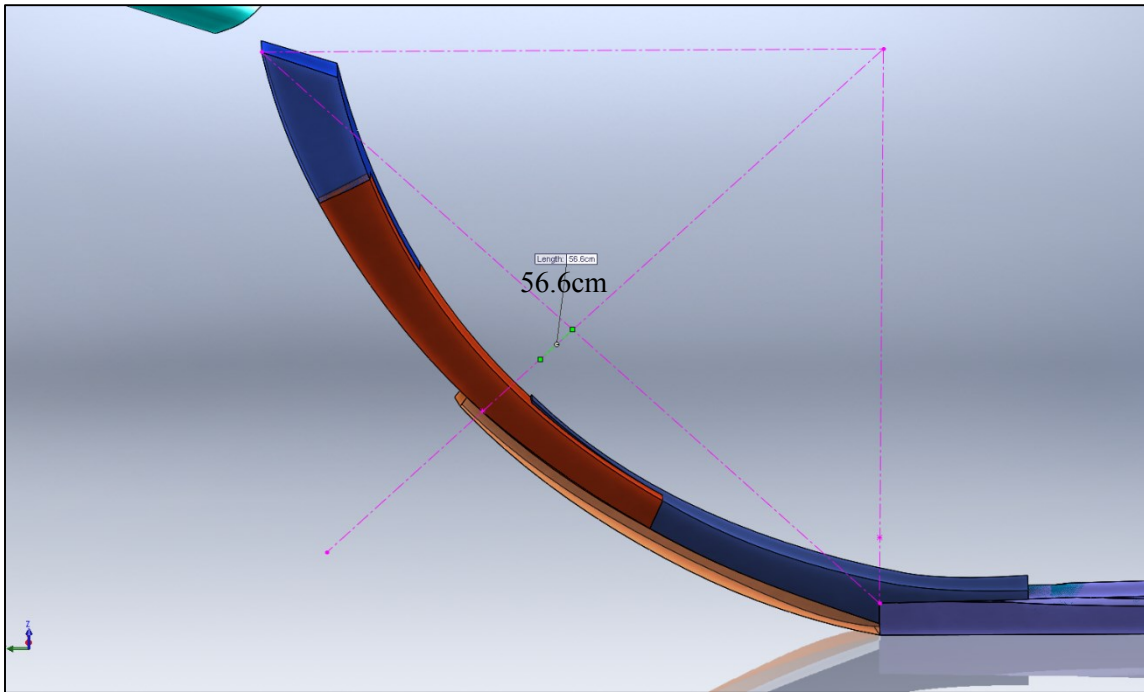


Figure 6.36. The estimated curve of *Vasa*'s stem.

STERNPOST

The sternpost, along with the stem and the keel, was the final major hull component that made up the spine of the ship and together determined much of the longitudinal character of the vessel. *Vasa*'s sternpost consists of three timbers; the main post, the 'skeg' (what Witsen refers to as an *achter-scheg*), and what is here being termed a sternpost extension. At a certain point in *Vasa*'s construction the height of the sternpost was increased with the addition of the sternpost extension timber. It is likely this was done in order to create more vertical space in the orlop gunroom for the operation of the stern chasers.⁸⁹ It is not known precisely at what point in construction the sternpost was extended. Analysis includes measurements for the sternpost both with and without the extension. Emphasis is placed, however, on the dimensions of the post prior to the extension,

⁸⁹ Fred Hocker, pers. comm.

as this is most likely indicative of original design intent. Like the stem, Witsen provides a summary of the method for how the sternpost of a vessel was quantified during design and construction.

Sternpost Height and Rake

The height of *Vasa*'s sternpost in the square without the extension is 807.5 cm./27 ft. 2 in. S and with the extension 873.6 cm./29 ft. 5 in. S, illustrated in Figure 6.37 and Figure 6.38. Witsen's suggestions for determining the height the sternpost is adding together the depth of the vessel, the rise in the sheer aft, and 'what is above that' (*dat daer boven is*) – meaning the vertical space for the gunroom.⁹⁰ Witsen indicates that the amount of rise in the sheer aft was a key variable in determining the height of the sternpost.⁹¹ To calculate the rise in the sheer aft, Witsen suggests a common method was using $\frac{3}{4}$ for every 10 ft. in overall length. For *Vasa*, this results in 11 ft. 11 in. S for the rise in sheer aft.⁹² Measured on the portside third wale, the observed rise in sheer aft is approximately 363.3 cm./12 ft. 2 in. S, interpreted as an intended dimension of 12 ft. S.⁹³ *Vasa*'s depth (15 ft. 2 in. S) added to the rise in sheer aft (12 ft. S) equals 27 ft. 2 in. S, precisely the height of the sternpost without the extension.

⁹⁰ Hoving 2012, 44.

⁹¹ The amount of sheer fore and aft is discussed in greater detail below.

⁹² $(159 \text{ ft.} / 10) \times \frac{3}{4} = 11 \text{ ft. } 11 \text{ in. S.}$

⁹³ The sheer is discussed in greater detail below.

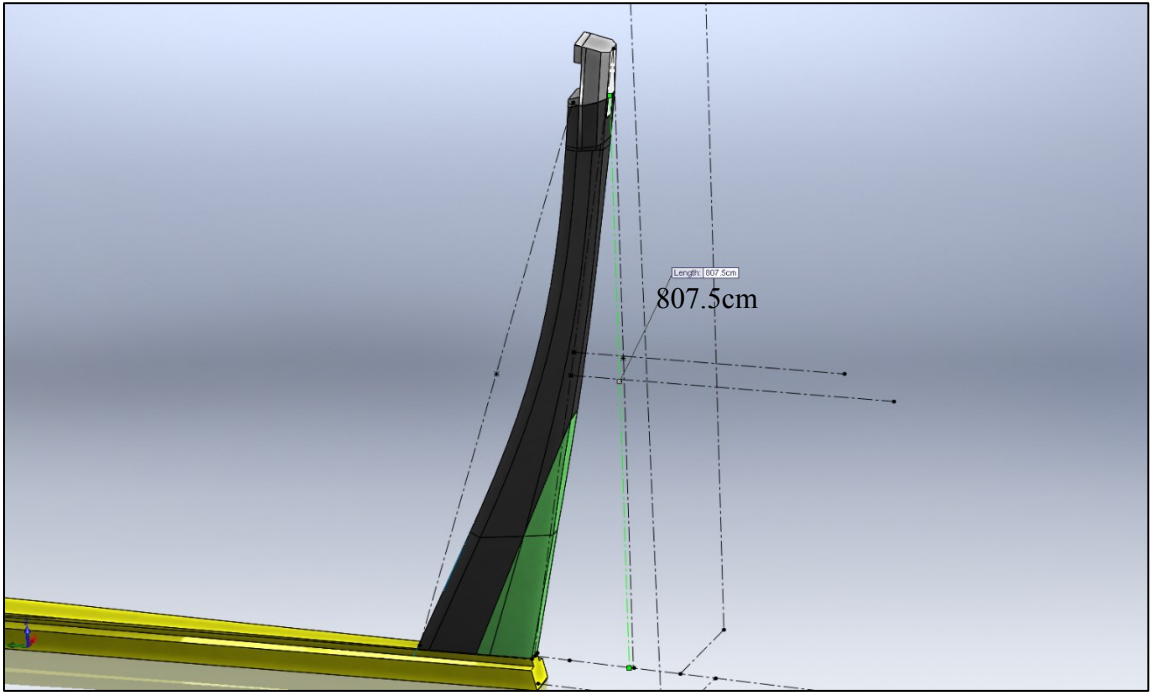


Figure 6.37. The height of *Vasa*'s sternpost without the extension.

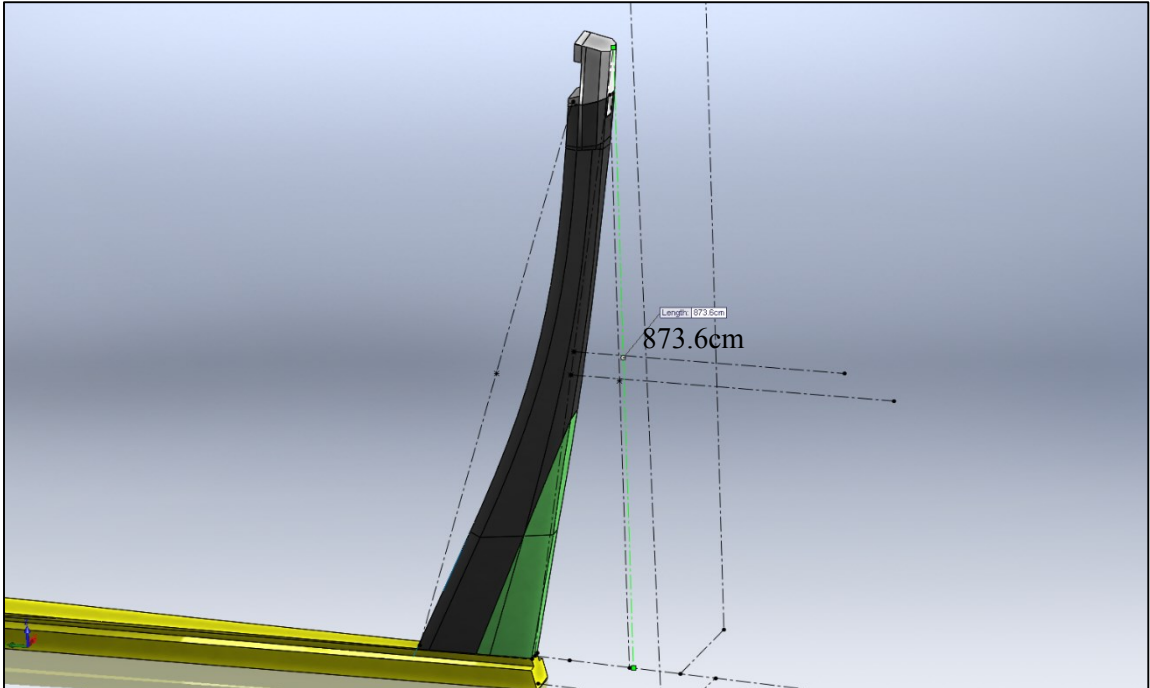


Figure 6.38. The height of *Vasa*'s sternpost with the extension.

Vasa's sternpost rakes 131.9 cm./4 ft. 5 in. S without the extension and 137.5 cm./4 ft. 7 in. S with the extension, illustrated in Figure 6.39 and Figure 6.40. Witsen suggests making the sternpost rake 1 ft. for every 6 ft. the sternpost is high.⁹⁴ When he uses this method to determine the rake of the sternpost for his hypothetical *pinas*, he uses only the whole-foot measurement of the sternpost height.⁹⁵ Witsen's guideline closely describes the relationship of the height of *Vasa*'s sternpost to its rake without the extension; 1 ft. of rake for every 6 ft. of height (27, taking whole ft. only) results in 4 ft. 6 in. of rake, differing by 1 in. from what is observed in the hull. With the extension, this formula results in 4 ft. 10 in. of rake, which corresponds less closely to the arrangement of *Vasa*'s sternpost. It is concluded that the rake of *Vasa*'s sternpost follows the method suggested in Witsen's treatise and rakes 1 ft. for every 6 ft. (whole ft. only) in sternpost height.

⁹⁴ "The Rake of the sternpost is thus, every 6 feet height must rake 1 foot" Hoving 2012, 45. "*t Vallen van deze steven is aldus, ieder 6 voet hoog, moet 1 voet vallen*" Witsen 1671, 66.

⁹⁵ "The sternpost, high 24 ¼ feet; rake 4 feet." Hoving 2012, 46. "*De achter-steven, hoog 24 ¼ voet; valt 4 voet.*" Witsen 1671, 72.

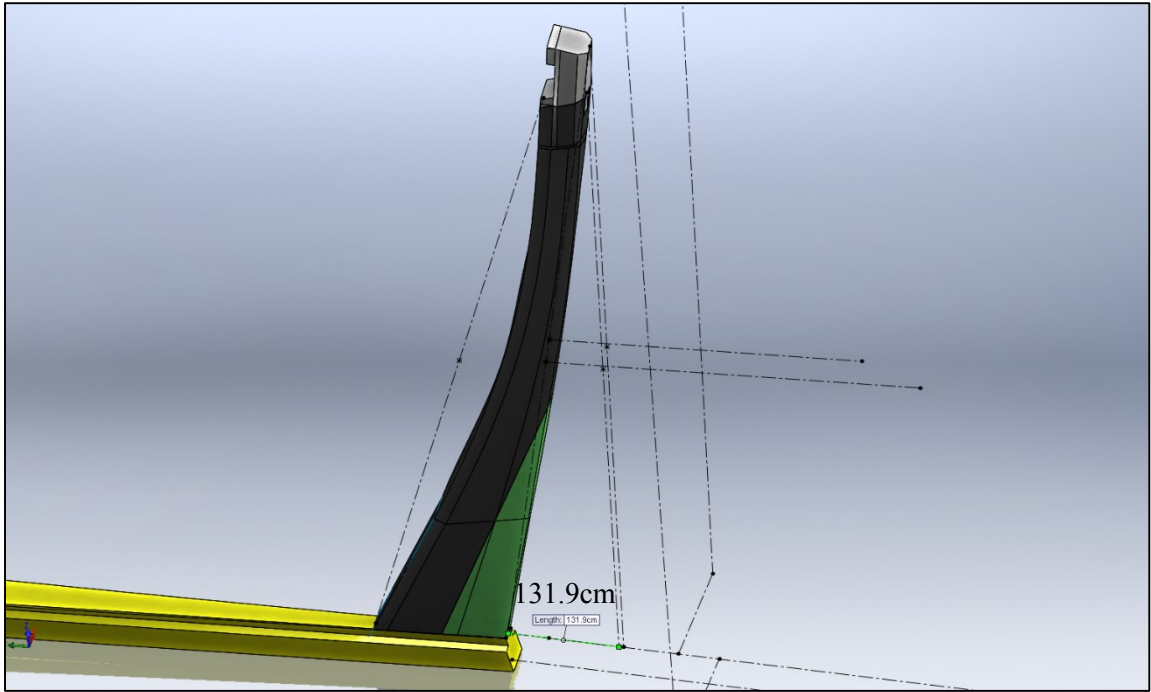


Figure 6.39. The rake of *Vasa*'s sternpost without the extension.

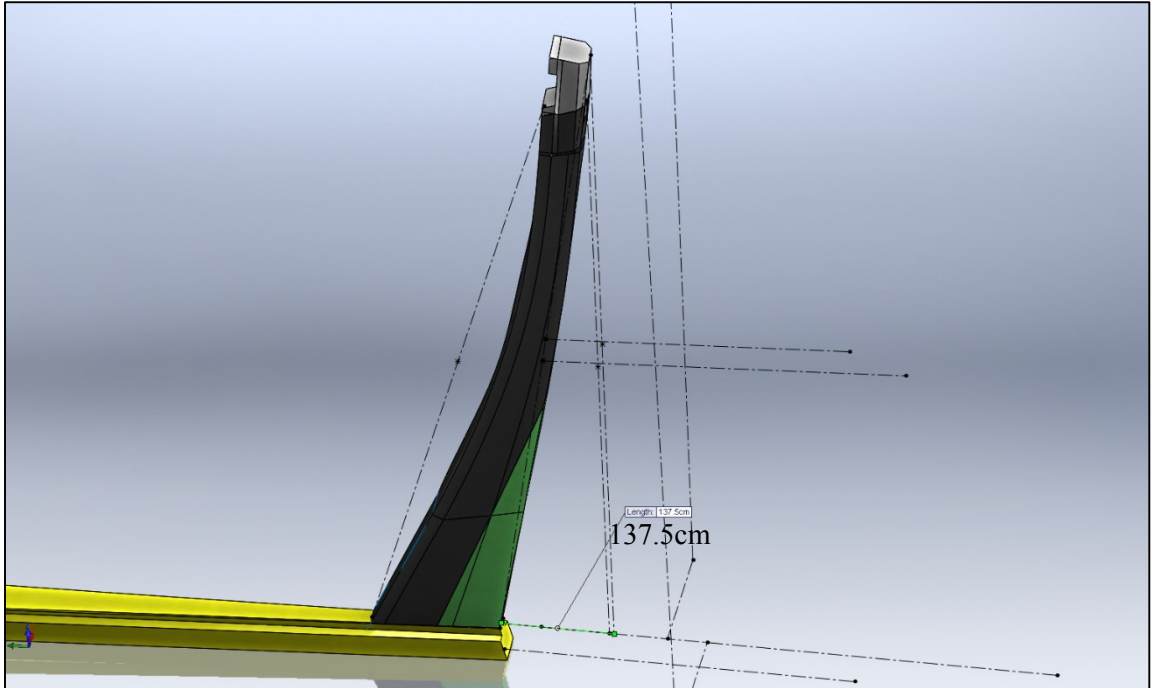


Figure 6.40. The rake of *Vasa*'s sternpost with the extension.

Sternpost Sided and Molded

Much of the base and forward face of the sternpost are inaccessible. The 3D solid model, however, has been used to reconstruct and estimate some of these dimensions. These estimates are based on observable hull data, including the thickness and shape of lower planking runs, position of bolts, and achieving continuity with the rest of the visible sternpost. The estimated molded dimension of the lower face of *Vasa*'s sternpost is 155.4 cm./5 ft. 3 in. S where it meets the keel, illustrated in Figure 6.41. The aft face of the sternpost is visible and is sided 19.4 cm./7 in. S where it meets the keel, as seen in Figure 6.42. At its base, the forward face of the sternpost is inaccessible. A conservative estimate for its sided dimension is 24.6 cm./10 in. S, illustrated in Figure 6.43.

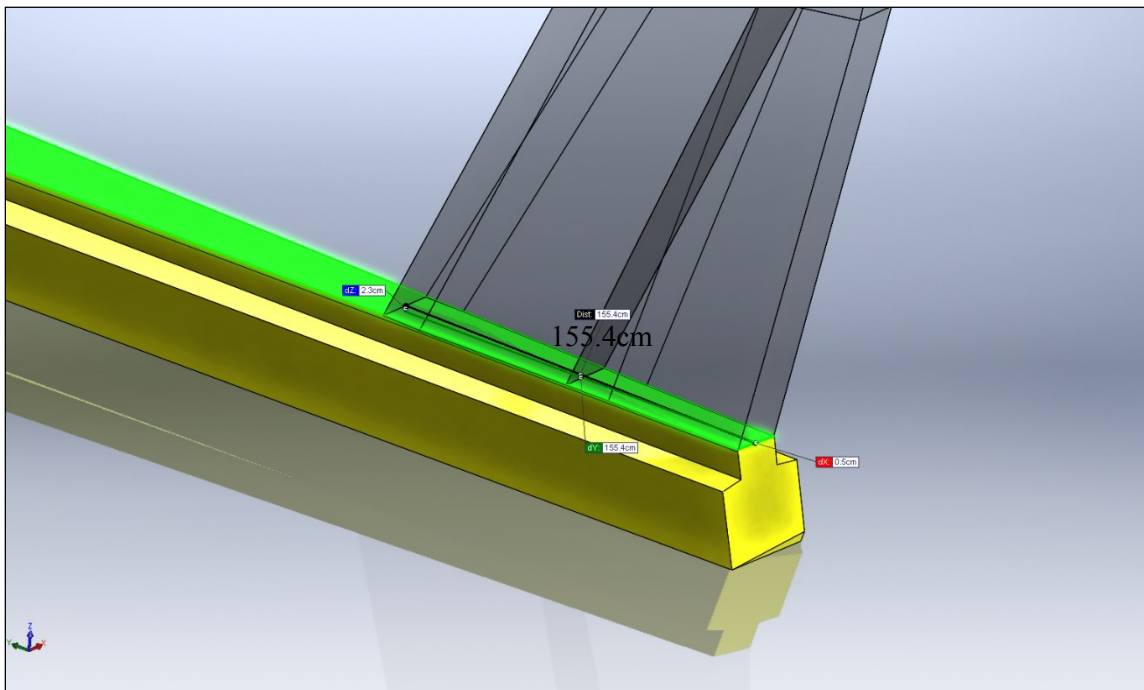


Figure 6.41. Estimated molded dimension of the sternpost where it meets the keel.

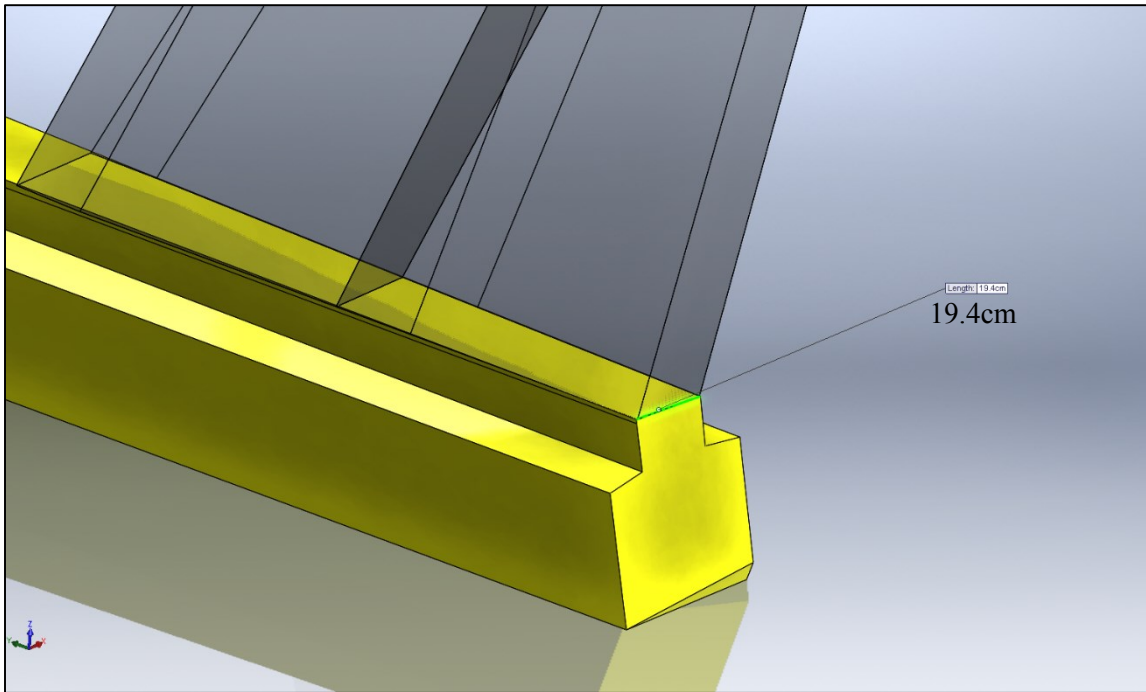


Figure 6.42. The sided dimension of the aft lower corner of the sternpost.

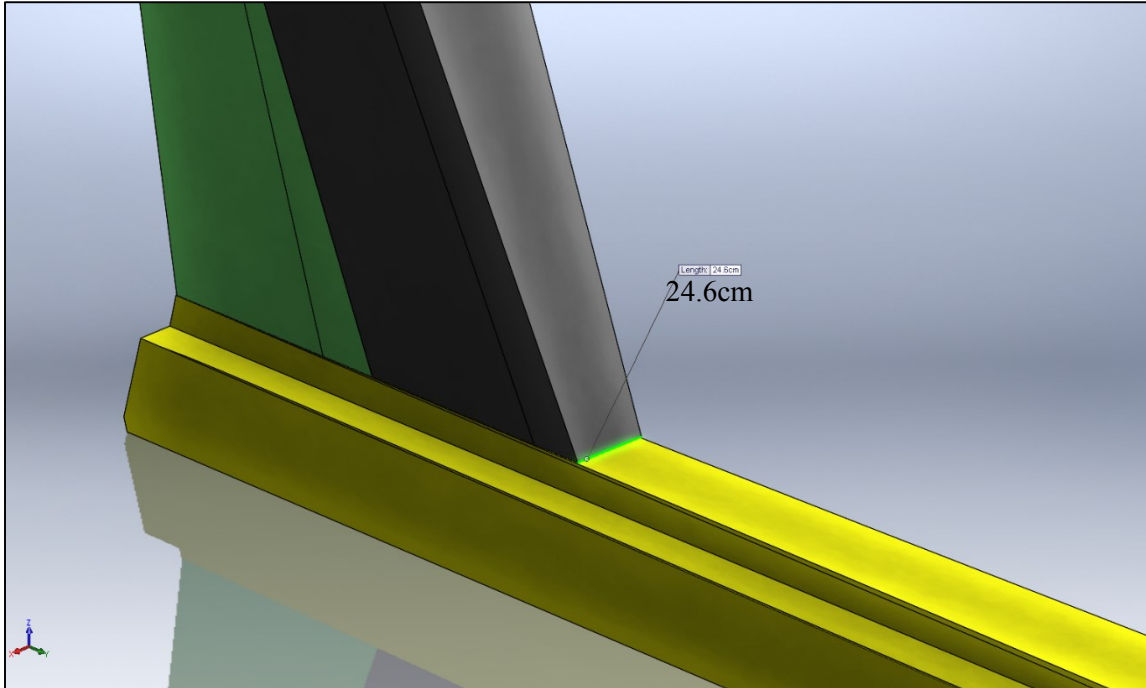


Figure 6.43. Estimated sided dimension of the forward lower corner of the sternpost.

The upper face of the sternpost extension is molded 47.1 cm./1 ft. 7 in. S and sided 43 cm./1 ft. 5 in. S, seen in Figures 6.44 and 6.45. Without the extension, the upper face of the sternpost is molded approximately 57 cm./1 ft. 11 in. S and sided 45 cm./1 ft. 6 in. S, illustrated in Figures 6.46 and 6.47. Between the base and widening at the top, the sternpost changes continually in both sided and molded dimension making quantification difficult. Witsen provides vague suggestions for determining the sided and molded dimensions of the sternpost, a timber which changes considerably in dimensions over its length. He clearly indicates that the forward face of the sternpost should have a larger sided dimension than the after face, which is consistent with what is observed in *Vasa*.⁹⁶ Regarding the particular dimensions, Witsen suggests the sternpost be as thick (sided) as the stem.⁹⁷ He does not, however, state exactly where this thickness should be measured. No correlation between these two dimensions has been found in the hull of *Vasa*. For the breadth (molded dimension), Witsen suggests making the sternpost 1/5 broader than thick at the top, and 5 times broader than thick at the base.⁹⁸ At the top of *Vasa*'s sternpost (without the extension), the sided and molded dimensions do not display this type of relationship and are much closer in dimension to each other than Witsen's treatise suggests. At the base, the relationship of the estimated sided (thickness) dimension (24.6 cm./10 in. S) to the estimated molded (breadth) dimension (155.4 cm./5' ft. 2 in. S) is closer to 1:6, rather than 1:5 suggested by Witsen. With regard to the sided and molded dimensions of *Vasa*'s sternpost, which are not fully accessible and difficult to quantify, there appears to be little correlation between Witsen's

⁹⁶ "The sternpost of a ship of 180 feet, should at the inside in the ship be 5 quarter (of a foot) thick, and at the back side, one foot at the top." Hoving 2012, 44. "*De achterstevan van aen een schip van 180 voet, moet aen de binnen zijde scheepwaert in, wel 5 quaert dik wezen, en aen de achterste zijde, een voet boven.*" Witsen 1671, 73.

⁹⁷ "The thickness is as of the stem, inside and outside." Hoving 2012, 44. "*De dikte is als de voor-stevan, binnen en buiten.*" Witsen 1671, 66.

⁹⁸ "The sternpost, being 1/5 broader than thick above, and below 5 times broader than thick." Hoving 2012, 44. "*De achter-stevan, boven 1/5 breeder als de dikte, en onder vijf-mael breder als de dikte.*" Witsen 1671, 66.

treatise and no other decipherable logic in dimensions. Based on the currently available spatial data, the sided and molded dimensions of *Vasa's* sternpost do not exhibit evidence of proportional or arithmetic design. It is possible that these dimensions were not critical design choices on the part of the shipwrights and possibly determined by the dimensions of the timber that was available. If in the future full access to the entire sternpost is possible, accurate measurement and analysis of all sternpost dimensions may revise this conclusion.

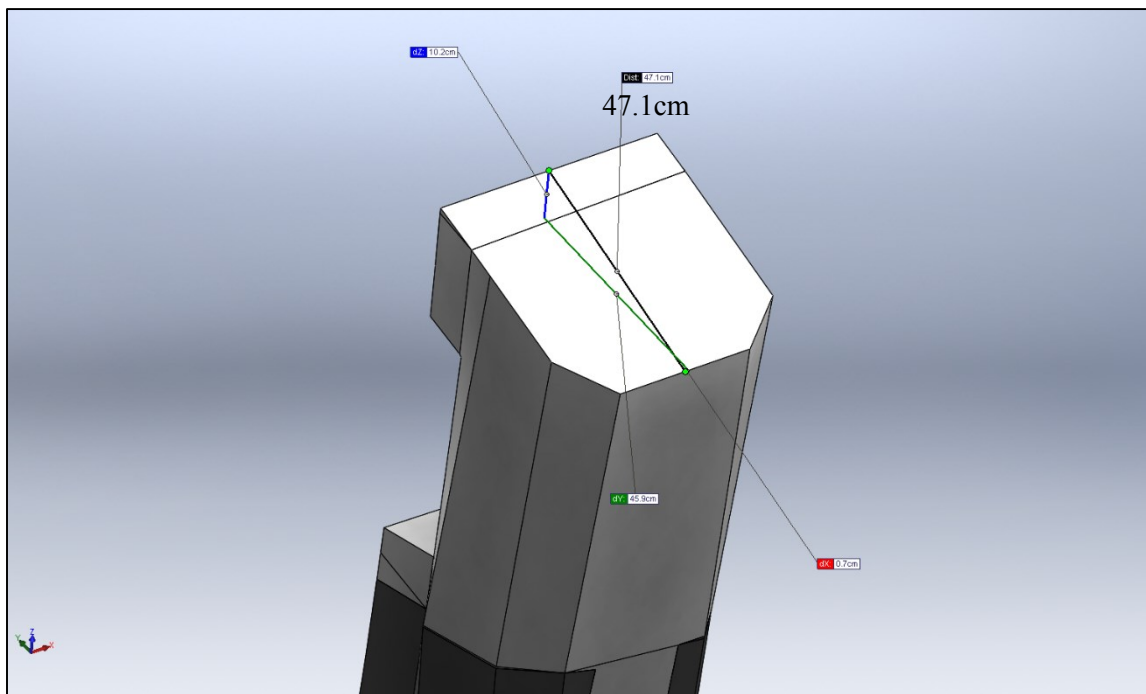


Figure 6.44. The molded dimension of the sternpost extension.

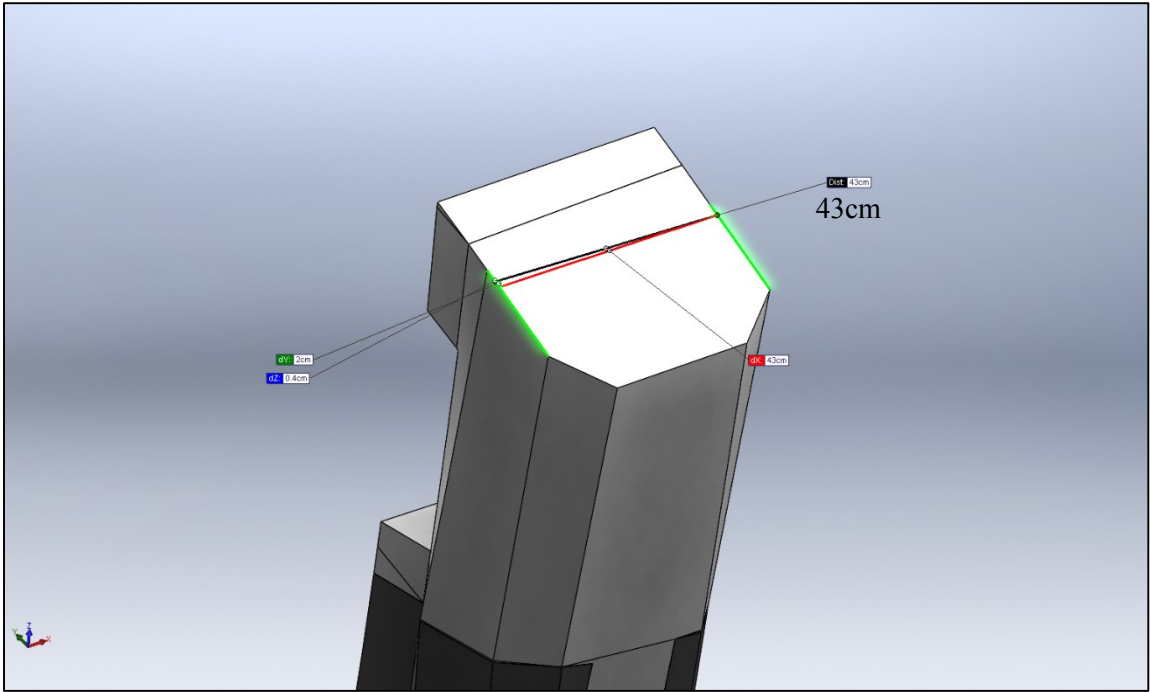


Figure 6.45. The sided dimension of the sternpost extension.

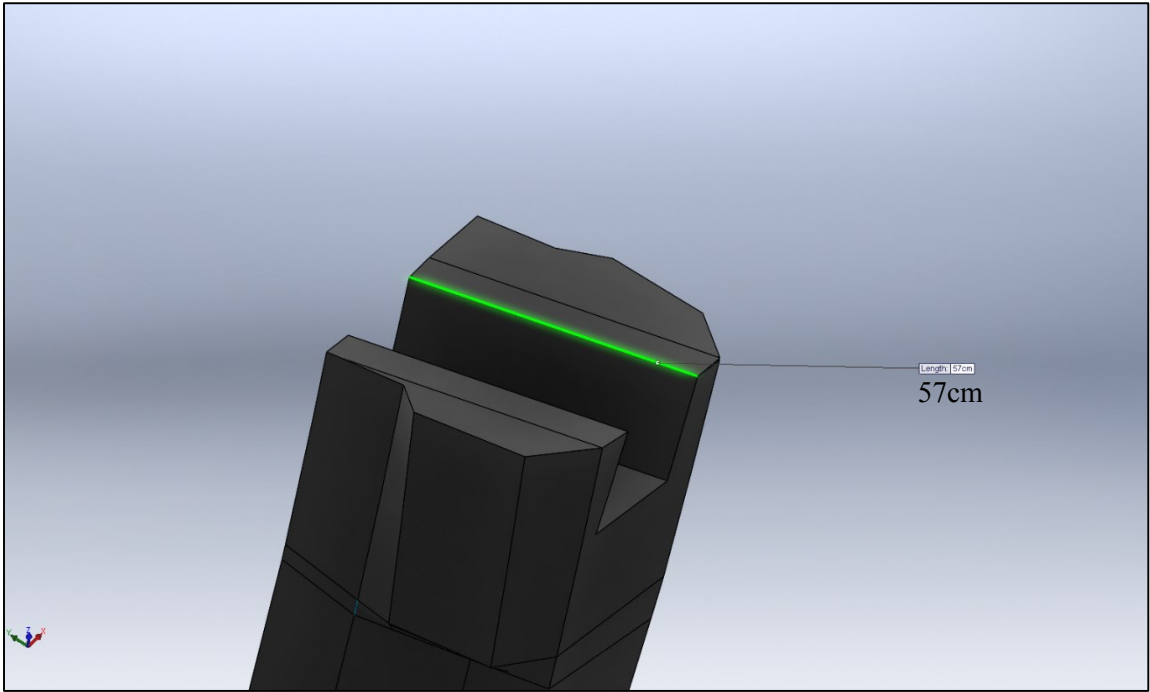


Figure 6.46. The molded dimension of the sternpost without the extension.

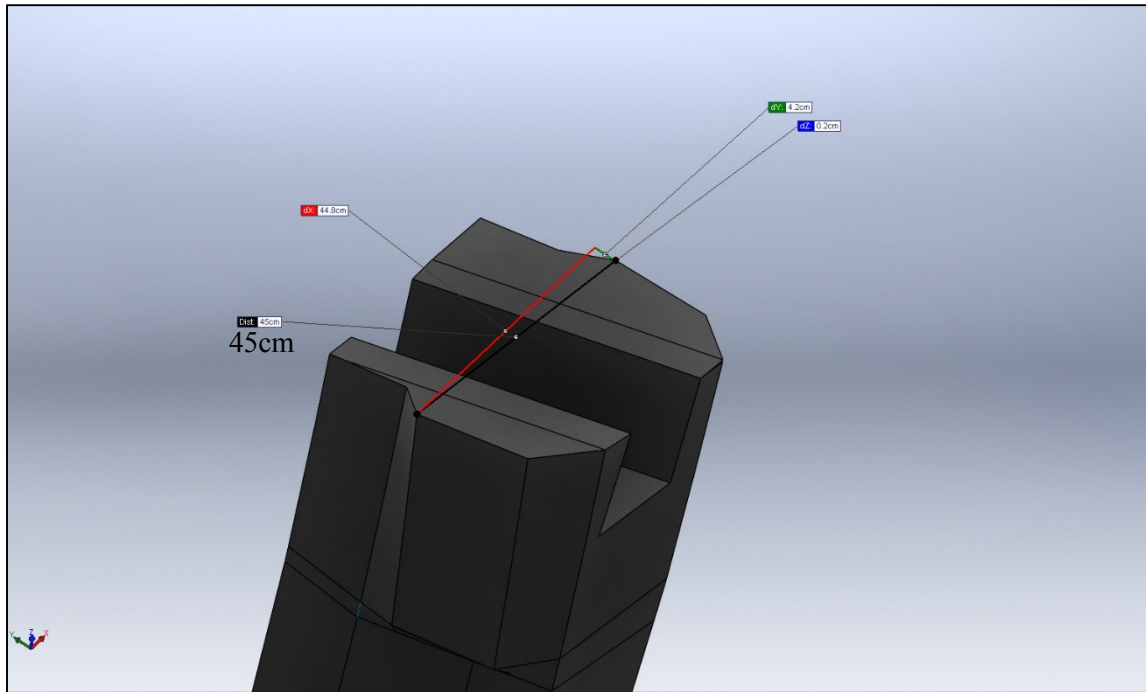


Figure 6.47. The sided dimension of the sternpost without the extension.

WING TRANSOM

The stem, keel, and sternpost provide the framework for defining the longitudinal shape of the hull. Transverse shape definition began with the wing transom, the shape and position of which exerted significant influence on the shape of the hull.⁹⁹ The wing transom is attached at the top of the original sternpost, perpendicular the centerline of the vessel, and defines the height of breadth at the stern. Most of *Vasa*'s wing transom is accessible from either inside or outside the ship (point cloud data only records the outboard face) and the solid model has been built using a combination of point cloud data and direct measurement.¹⁰⁰

⁹⁹ The shape and position of the wing transom affected the shape of the sheer (discussed below), and therefore also had indirect influence on the longitudinal shape of the hull.

¹⁰⁰ The ends of the timber where it is scarfed to the fashion pieces are not completely accessible.

The timber is 582.8 cm./19 ft. 7 in. S long (athwartships direction), illustrated in Figure 6.48. Regarding the length of the wing transom, Witsen suggests using $\frac{2}{3}$ (66.7%) of the breadth.¹⁰¹ Assuming 36 ft. was the original breadth of *Vasa*, $\frac{2}{3}$ of this dimension is 24 ft. As built, the length of *Vasa*'s wing transom is 54.5% of the original 36 ft. maximum breadth. If 37 ft. 5 in. was the intended breadth when making the decision about the width of the transom, the wing transom is 52.4% of the width. *Vasa* exhibits a considerably shorter wing transom and therefore significantly narrower stern, than vessels that used a $\frac{2}{3}$ wing transom to breadth relationship. This is a significant design departure, as most other design decisions up until this point appear to closely follow common methods of Dutch ship design and construction as indicated by Witsen's treatise. The length of the wing transom does not appear to have a logical relationship to any other major hull feature. The particular length of *Vasa*'s wing transom remains the most enigmatic of the primary hull design features and may have contributed to its stability troubles.

¹⁰¹ "In order to obtain the length of the wing transom, one takes $\frac{2}{3}$ of the width of the ship." Hoving 2012, 47. "*Om de lengte, can de hek-balk te bekomen, zoo neemt $\frac{2}{3}$ van de wijte van het schip.*" Witsen 1671, 66.

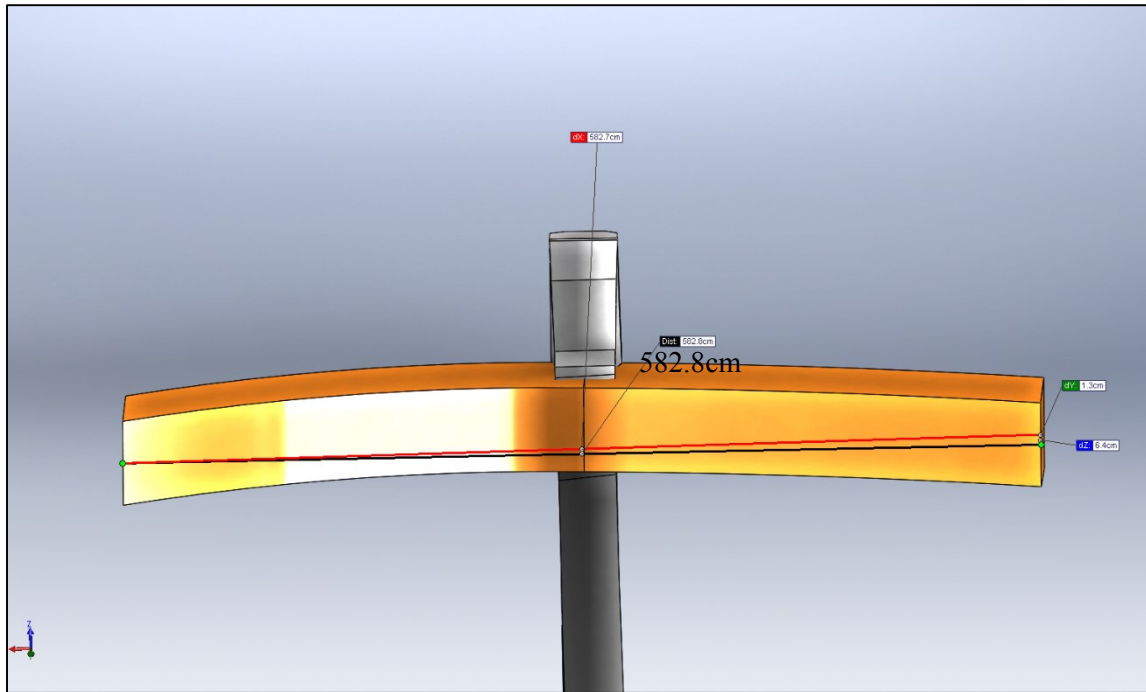


Figure 6.48. The length of *Vasa*'s wing transom.

The wing transom is molded in the center 36 cm./1' ft. 2 in. S (14 in. S), and sided on the inner face 53.7 cm./1 ft. 10 in. S (22 in. S) and approximately 57.9 cm./1 ft. 11 in. S (23 in. S) on the outer face. These dimensions are illustrated in Figures 6.49, 6.50, and 6.51. The ends of the timber are not fully accessible. The timber is curved approximately 36.8 cm./1 ft. 2 in. S (14 in. S) on the outside, illustrated in Figure 6.52. The full inside curvature is not accessible. Witsen suggests making the wing transom thick, broad, and curved as many inches as the wing transom is broad in feet.¹⁰² Using this guideline would result in the thickness, breadth, and curve each being approximately 19.5 in., or 19 in. if only the whole-foot length is taken. Although the wing transom of *Vasa* is roughly square in cross section, it is smaller and does not have as pronounced

¹⁰² "For the thickness, breadth and the curve, take as many inches as the wing transom is broad in feet." Hoving 2012, 47. "*Tot de dikte, breete, en bocht, neemt zoo veel duims als 't hek voeten langh is.*" Witsen 1671, 66.

of a curvature as Witsen indicates was normal. This is another point of departure from what are believed to be common shipbuilding methods, albeit one that does not significantly affect the overall shape of the hull.

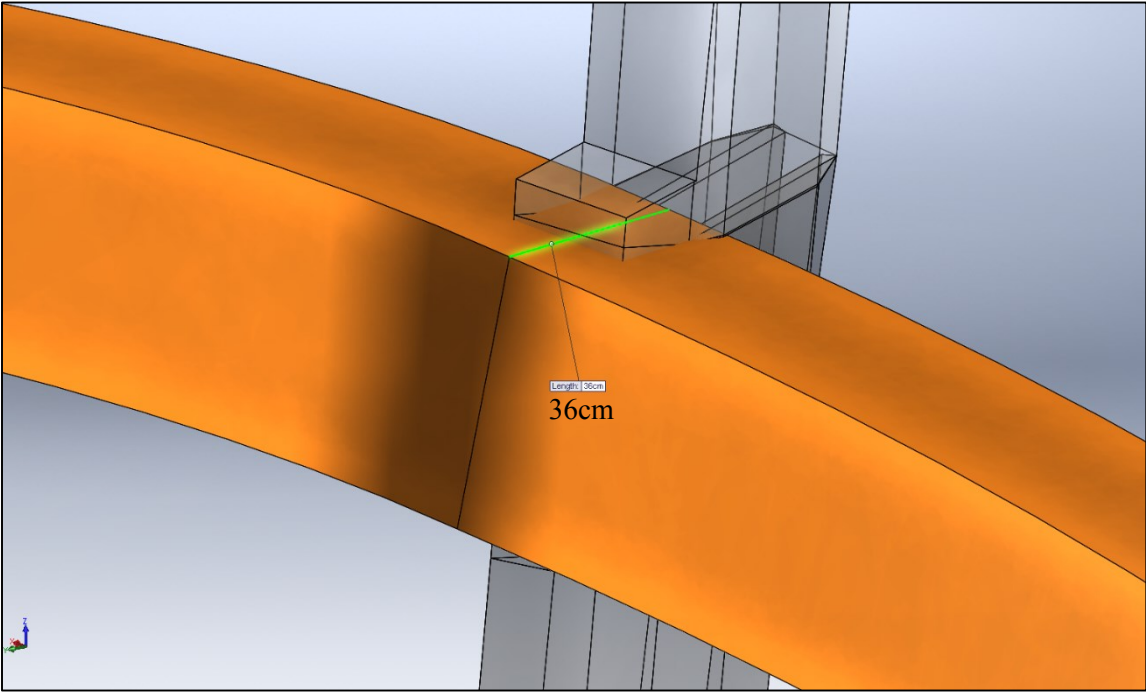


Figure 6.49. The molded dimension of the wing transom in the center of the timber.

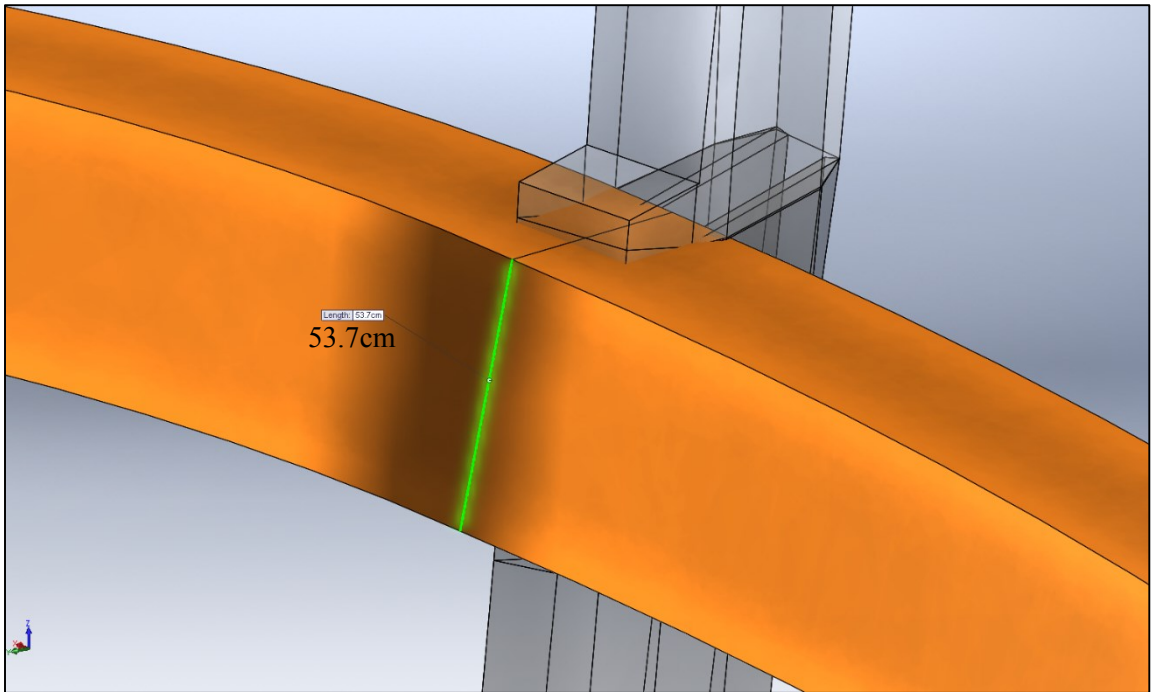


Figure 6.50. The sided dimension of the inside of the wing transom.

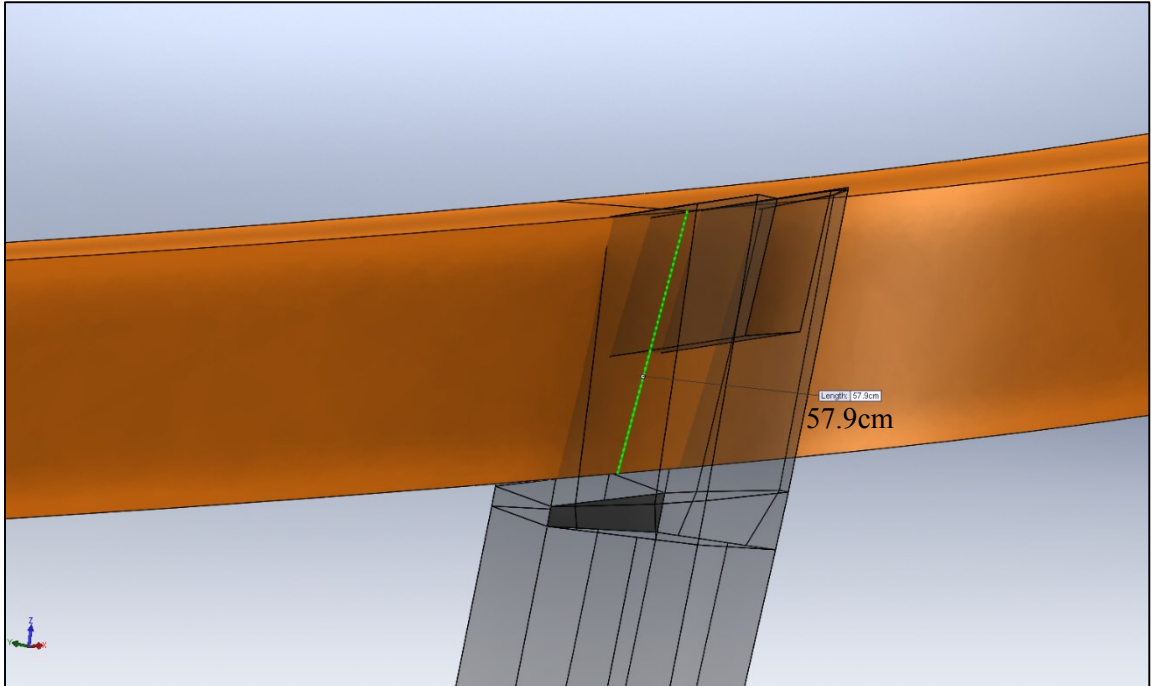


Figure 6.51. The sided dimension of the outside of the wing transom.

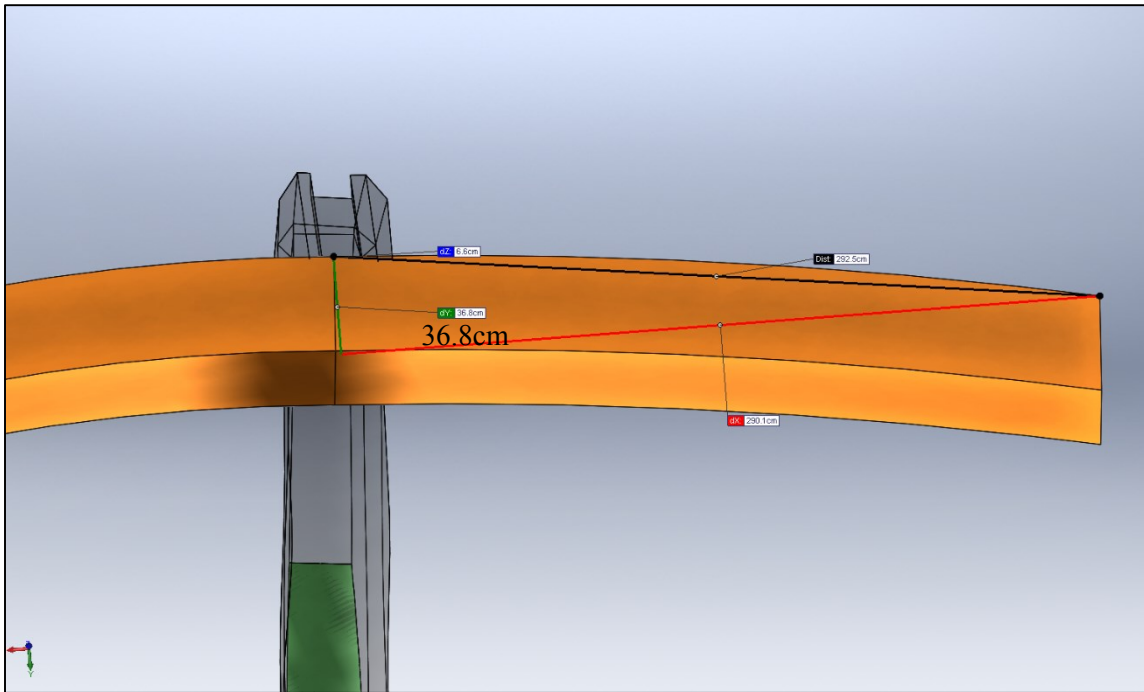


Figure 6.52. The outside curvature of the wing transom.

The position of the wing transom on the sternpost and its height above the keel is a key form-defining aspect of the wing transom. The wing transom is positioned at the top of the inner face of the sternpost (without the extension) and therefore the height of the wing transom (distance above the keel) is determined by the height of the sternpost. Witsen indicates this was a common placement of the wing transom.¹⁰³ The intended height of the wing transom, however, may have been a driving factor in deciding the height of the sternpost. These elements exerted design influence on one another and the decision for each may have been made simultaneously. The center of the aft lower face of the wing transom is 739.4 cm./24 ft. 11 in. S from the top of the keel, illustrated in Figure 6.53. This dimension may easily be interpreted as 25 ft. S. This

¹⁰³ “the back is laid at the inside of the Sternpost, close to the upper end... the sternpost does not protrude above the wing transom” Hoving 2012, 47. “*legth men de achterkant op de binnenkant van de Steven... de steven blijft beheel zonder klep.*” Witsen 1671, 147.

round and logical dimension may indicate an intentional design choice to position the wing transom 25 ft. above the keel, which in turn would have exerted influence over determining the height of the sternpost. Examples of shipbuilding contracts provided in Witsen's treatise indicate that it was common for the height of the wing transom above the keel to be specified, though he does not indicate explicitly how this dimension was determined.¹⁰⁴

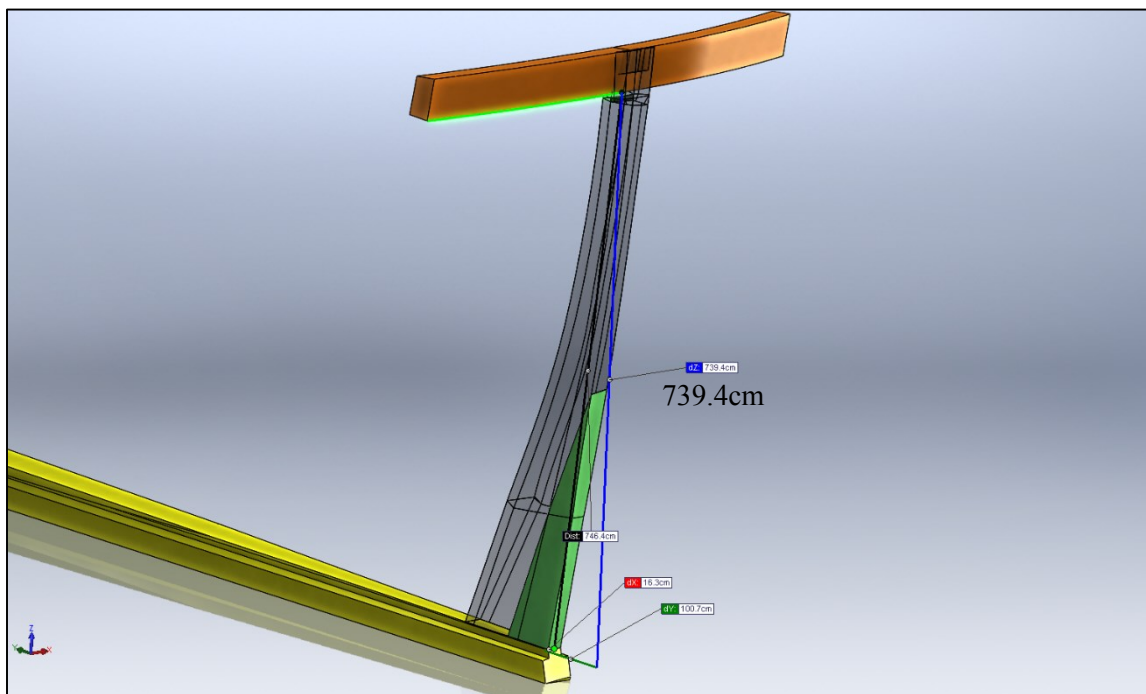


Figure 6.53. The height of the wing transom above the keel.

FASHION PIECES

The fashion pieces define the lower cross-sectional curvature of the vessel at the stern. Their shape and position exert a significant influence on the final shape of the hull. This pair of

¹⁰⁴ Although Witsen does not imply that the intended height of the wing transom was a driving factor in designing the sternpost.

timbers begin on the sternpost and end with a lap scarf on the wing transom. In *Vasa*, they span roughly half of the vertical space of the hold and the entire orlop deck. A drawing of *Vasa*'s fashion pieces is seen in Figure 6.54. Although only parts of the fashion pieces are accessible, from what is visible it is clear that the sided and molded dimensions vary along their length. The irregular dimensions of the timbers suggest that the shipwrights intended to make the best possible use of available timber and create as robust a pair of fashion pieces as their materials allowed. The fashion pieces were largely responsible for attaching the stern panel to the rest of the hull and the strength of these timbers was critical to the integrity of the hull at the stern. Where visible in the hold, the starboard fashion piece varies in molded dimension from 26-29 cm./10-12 in. S; the port molded approximately 30.5 cm./1 ft. 1 in. S. The full sided dimension of either timber is not accessible in the hold. On the orlop deck, the starboard fashion piece is molded 21.5-22 cm./8 in. S and sided 58-58.5 cm./2 ft. S; the port molded approximately 25 cm./10 in. S and sided 57-57.5 cm./1 ft. 11 in. S. Compared to other principal hull timbers, Witsen provides little insight into how the fashion pieces were designed. According to Witsen, the sided and molded dimensions are derived from those of either the wing transom or the sternpost. For the thickness (sided dimension), Witsen's suggestion is either 5/6 the thickness of the wing transom or half as thick as the sternpost.¹⁰⁵ The breadth (molded dimension) is to be 2 times the breadth of the wing transom.¹⁰⁶ From what can be observed in the hull of *Vasa*, the sided and molded dimensions of the fashion pieces do not seem to be related to the dimension of the wing transom.

¹⁰⁵ "The thickness is 5/6 parts of the thickness of the wing transom." "The fashion pieces are thick half the sternpost." Hoving 2012, 48. "*De dikte is 5/6 deelen van de dikte can 't hek.*" "*De rantzoen-houten dick op de helft van de steven.*" Witsen 1671, 67-68.

¹⁰⁶ "The breadth is 2 times the breadth of the wing transom." Hoving 2012, 48. "*De breete komt 2 mael breder als het hek.*" Witsen 1671. 67.

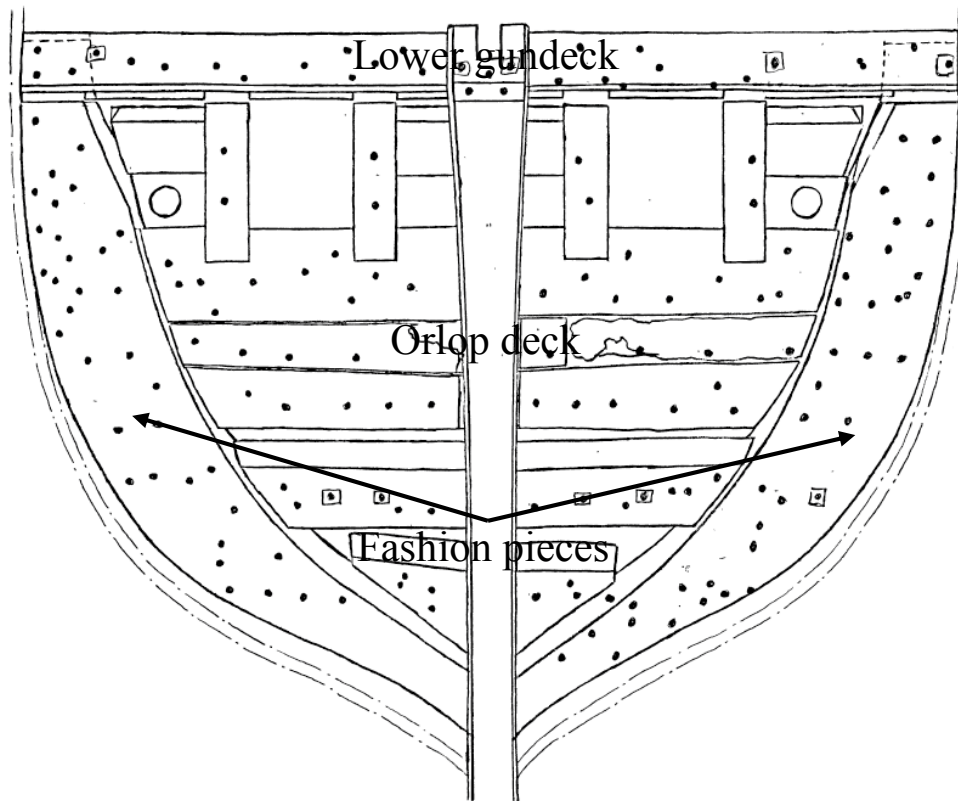


Figure 6.54. Interior drawing of *Vasa*'s lower stern construction, including the sternpost, fashion pieces, wing transom, and filling transoms with deck levels indicated. Drawing after Eva Marie Harms.

Curve

The curve and position of the fashion pieces are the most important factors that influence the shape of the hull. Witsen suggests two methods for determining the curvature. One uses the arc of a circle to approximate the curvature which is then modified as the shipwright saw fit.¹⁰⁷

Witsen illustration of this process is seen in Figure 6.55. Immediately following his description of this method, however, Witsen notes parenthetically "But in general one has molds after which

¹⁰⁷ Witsen also suggests using arcs in designing the midship cross-section of a ship, though there is no evidence that this method was actually employed by Dutch shipwrights. Witsen's suggestions may be a product of an attempt to quantify an otherwise difficult to explain ship design method using the tools and conventions used by shipwrights in other countries, chiefly England.

the fashion pieces are cut.”¹⁰⁸ Analysis of *Vasa*’s fashion pieces yields no candidates for arcs that strongly indicate this was the method used to define their curvature. All arcs that approximate the curvature have centers or radii that do not appear to exhibit a logical design intent.¹⁰⁹ This leads to consideration of Witsen’s other suggestion, that a mold was used to cut the fashion pieces. Hybertsson was a career shipbuilder and experienced in the design and construction of warships. It is entirely plausible, then, that he had molds for timbers (especially those with complex curvature) that were re-used between vessels if they proved successful. Although it is difficult to quantify the curvature of the timbers using an arc, it is possible the curvature was defined using the same offset method used to define the curve of the stem. While the entirety of each fashion piece is not accessible, measuring the modeling estimation shows a possible inner curve of 90 cm./3 ft. S on the port side and 99 cm./3 ft. 4 in. S on the starboard and a possible outer curve of 150.6 cm./5 ft. 1 in. S on the port side and 152.1 cm./5 ft. 1 in. S on the starboard side, suggesting an intended dimension of 5’S. These dimensions are illustrated in Figure 6.56. These are highly approximate measurements due to the difficulty of fully measuring the full dimensions of each fashion piece and uncertainty regarding how or if fashion piece curvature was measured.

¹⁰⁸ Hoving 2012, 48. “*Dog hier toe maectmen gemeinlijck mallen, daermen de rantzoen-houten na hackt.*” Witsen 1671, 147.

¹⁰⁹They are either off the centerline or at an apparently arbitrary position along the centerline.

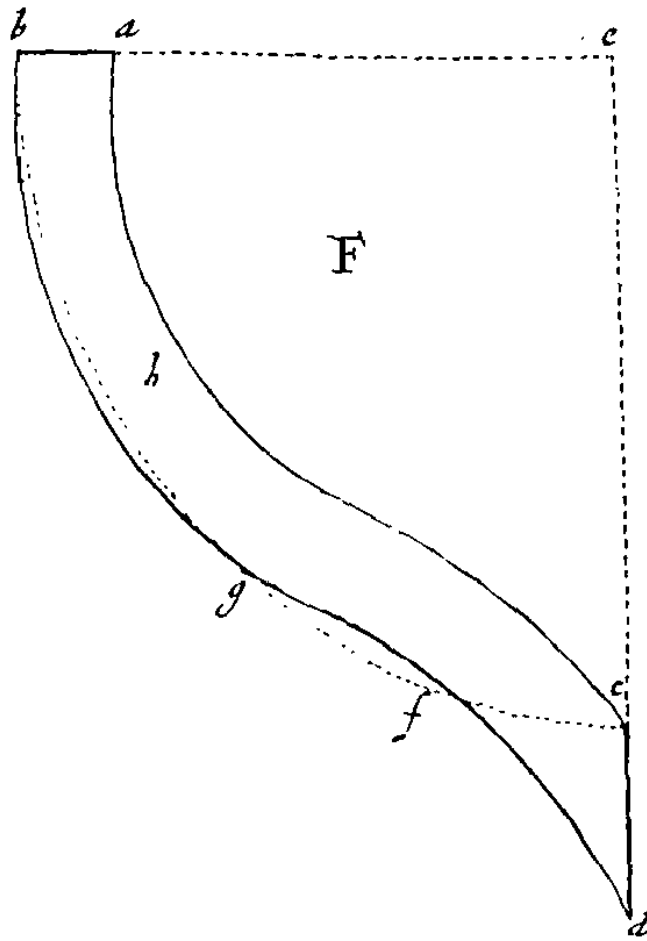


Figure 6.55. Witsen's illustration of defining fashion piece curvature. He suggests beginning with an arc, here shown between points *b* and *c*.¹¹⁰

¹¹⁰ Witsen 1671, Plate XLVIII.

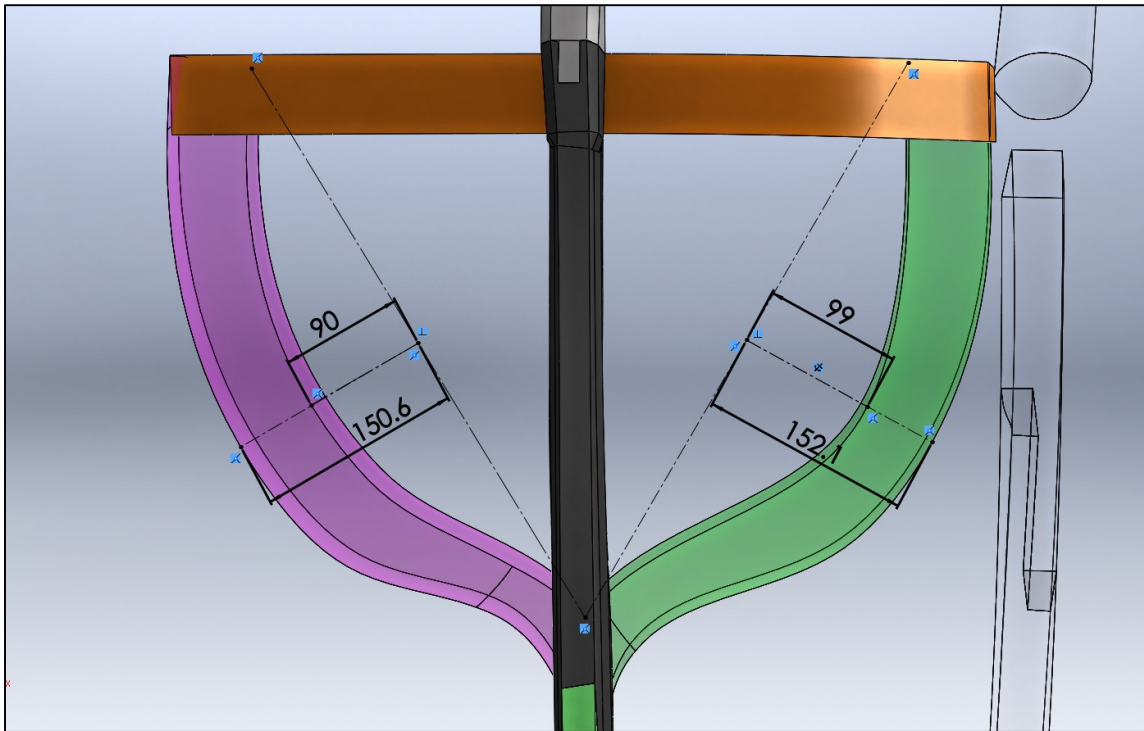


Figure 6.56. Approximate curvature offset measurements of the fashion pieces.

Position

Along with the curvature of the timbers, the position of the fashion pieces along the length of the sternpost was important for determining the shape and characteristics of a hull. Common shipbuilding wisdom of the early 17th century suggested that placing the fashion pieces relatively high along the sternpost would result in a faster ship, at the expense of cargo capacity. Lower fashion pieces increased capacity at the cost of speed. Witsen expresses this writing “With Freighters these timbers come down lower than with Frigates.”¹¹¹ Witsen suggests starting by placing the aft face of their base approximately halfway along the length of the sternpost, a

¹¹¹ Hoving 2012, 48. “*Aen Last-draegers komen deze houten laeger, als aen Fregatten.*” Witsen 1671, 67.

neutral position.¹¹² The precise positioning was left to the discretion of the shipwright and the desired qualities of the finished vessel. Although the lower extents of *Vasa*'s fashion pieces are inaccessible, their position can be estimated using the 3D model. Based on the model, *Vasa*'s fashion pieces join each other on the centerline of the sternpost approximately 395.5 cm./13 ft. 4 in. S above the keel, within approximately 6.4 cm./2 in. S of the halfway mark of the length of the sternpost measured without the extension, as illustrated in Figure 6.57.¹¹³ This suggests that the shipwrights favored a neutral position at the stern.

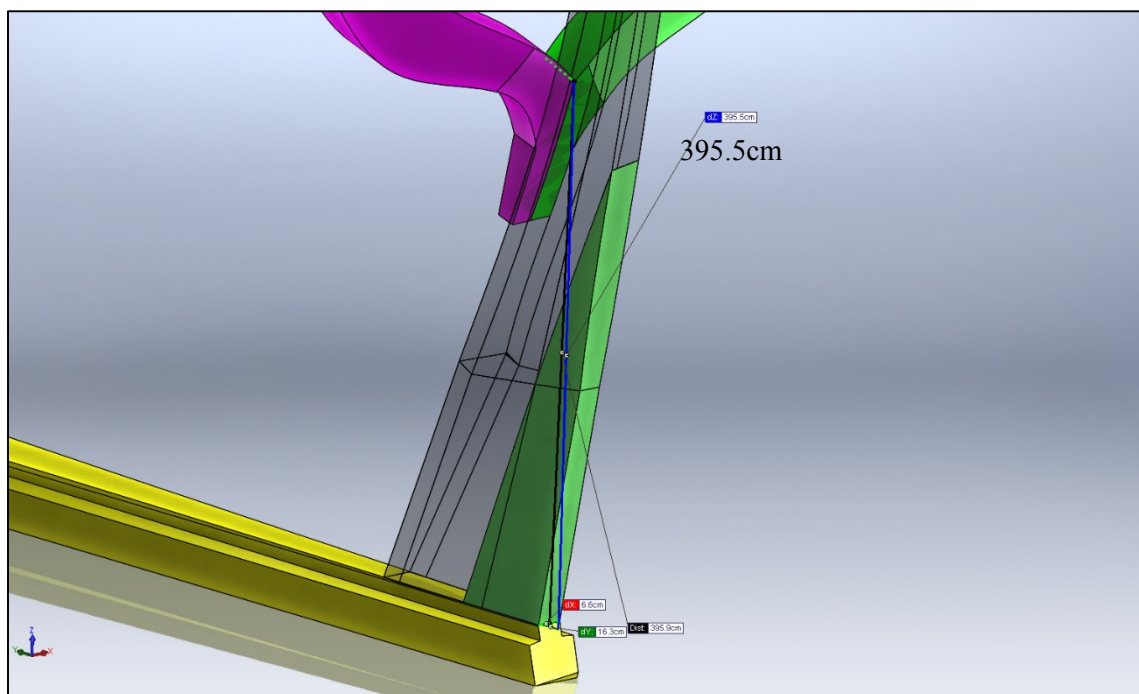


Figure 6.57. The approximate height of *Vasa*'s fashion pieces.

¹¹² “To be sure about the position of the fashion pieces, they are put with their back or outside one foot above half the sternpost.” Hoving 2012, 48. “*Om zeker te gaen, in 't zetten van de rantzoen-houten, zoo stelt die een voet hooger als de helft van de steven, namentlijk met de achter of buiten kant.*” Witsen 1671, 68. “The fashion pieces are put halfway the length of the sternpost at the back.” Hoving 2012, 48. “*De rantzoen-houten, zet op de helft van de lengte van de steven, namentlijk, de achter-kant.*” Witsen 1671, 66-67.

¹¹³ Measured both along the post and in the square.

The fashion pieces were large pieces of curved timber and therefore relatively expensive. Because of their interaction and relationship with the sternpost and wing transom, and their role in defining the curvature of the vessel, it is likely that a high degree of planning went into designing the stern panel of a Dutch-built vessel. It is possible that molds were used to prevent any significant mistakes or deviations in shape that would have dramatically affected the performance of the hull. *Vasa*'s narrow stern may suggest that Hybertsson used established molds for the fashion pieces (from smaller ships, even though *Vasa* is reasonably large). Also, Jacobsson's widening of the hull likely occurred after the fashion pieces and wing transom dimensions were established – perhaps indicating concern about the narrow stern.

STERN TIMBERS

The stern timbers are the final timbers that exerted considerable influence on the hull form at the stern. This pair of timbers defined both the height of the vessel above the wing transom and the narrowing of the sides of the hull. At their base they simply overlap the fashion pieces and are fastened with bolts. They are generally tangent to the curvature defined by the fashion pieces.

Sided and Molded

The stern timbers taper from their lower ends to their upper extents. *Vasa*'s stern timbers are not accessible along their full length but they have been modeled according to measurements taken at intervals along their length where they are visible. Witsen provides limited information regarding the sided and molded dimensions of the stern timbers. He suggests that they are as

broad as the fashion pieces at their base, and 2/3 as thick as the sternpost.¹¹⁴ The sided and molded dimensions of the fashion pieces vary considerably over their length and do not match from port to starboard. At their lowest accessible point, just above their join with the wing transom and fashion pieces on the lower gundeck, the starboard stern timber is molded 54.5 cm./1 ft. 10 in. S and sided 26 cm./11 in. S; the port molded 67.5 cm./2 ft. 3 in. S and sided 23.5 cm./10 in. S. The stern timbers narrow quickly and where they meet the upper gundeck beam, the starboard is molded 35 cm./1 ft. 2 in. S and sided 23 cm./9 in. S and port molded 41.5 cm./1 ft. 5 in. S and sided 26 cm./11 in. S. On the upper gundeck, in the great cabin, the starboard stern timber is molded approximately 29 cm./1 ft. S and sided approximately 20 cm./8 in. S; the port molded approximately 31 cm./1 ft. 1 in. S and sided approximately 19.5 cm./8 in. S.¹¹⁵ In the upper cabin, the starboard stern timber is molded 16 cm./6 in. S and sided 16 cm./6 in. S; the port molded approximately 15 cm./6 in. S and sided 15.5 cm./6 in. S. Their upper faces are visible on top of the poop cabin where the starboard stern timber is molded 9 cm./4 in. S and sided 11.5 cm./5 in. S; the port molded 10 cm./4 in. S and sided 11.7 cm./5 in. S.

Height

How high the stern timbers rise above the wing transom and their inclination toward each other are the most important hull form defining features of these timbers. Regarding their height, Witsen suggests making them as high above the transom as the sternpost is long.¹¹⁶ Measuring

¹¹⁴ “The lower parts of the stern timbers are as broad as the fashion pieces” Hoving 2012, 51. “*De heck-stutten zijn onder zoo breed als de rantzoen-houten*” Witsen 1671, 74. “The stern timbers thick 2/3 the sternpost.” Hoving 2012, 51. “*de hek-stutten dik 2/3, avan de steven.*” Witsen 1671, 67.

¹¹⁵ The timbers are difficult to access on the upper gundeck making these measurements approximate.

¹¹⁶ “The stern timbers as far above the transom as the sternpost is long.” Hoving 2012, 51. “*De heck-stutten zoo verb oven 't hek als de steven langh is.*” Witsen 1671, 68.

their height in the square, the starboard stern timber is 804.3 cm./27 ft. 1 in. S above the upper face of the wing transom; the port 802.9 cm./27 ft. S, effectively identical to the height of the sternpost without the extension. These dimensions are illustrated in Figures 6.58 and 6.59. Measured from the keel, the top of the starboard stern timber is 1603.5 cm./54 ft. S high; the port 1595.5 cm./53 ft. 8 in. S. This indicates an intended total stern height of 54 ft., of which 27 ft. is exactly half.¹¹⁷ The top of the wing transom marks exactly half of the total stern height.

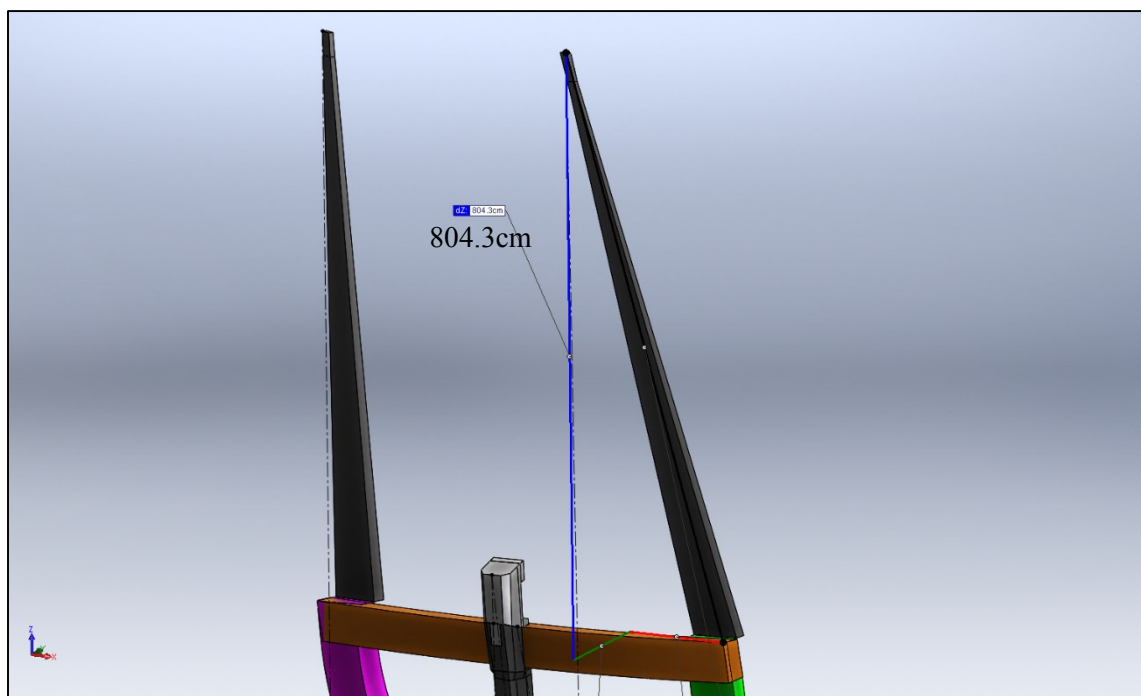


Figure 6.58. The height of the starboard stern timber above the wing transom.

¹¹⁷ The difference between port and starboard may be due to variations in the timber, warping, damage, and distortion from conservation.

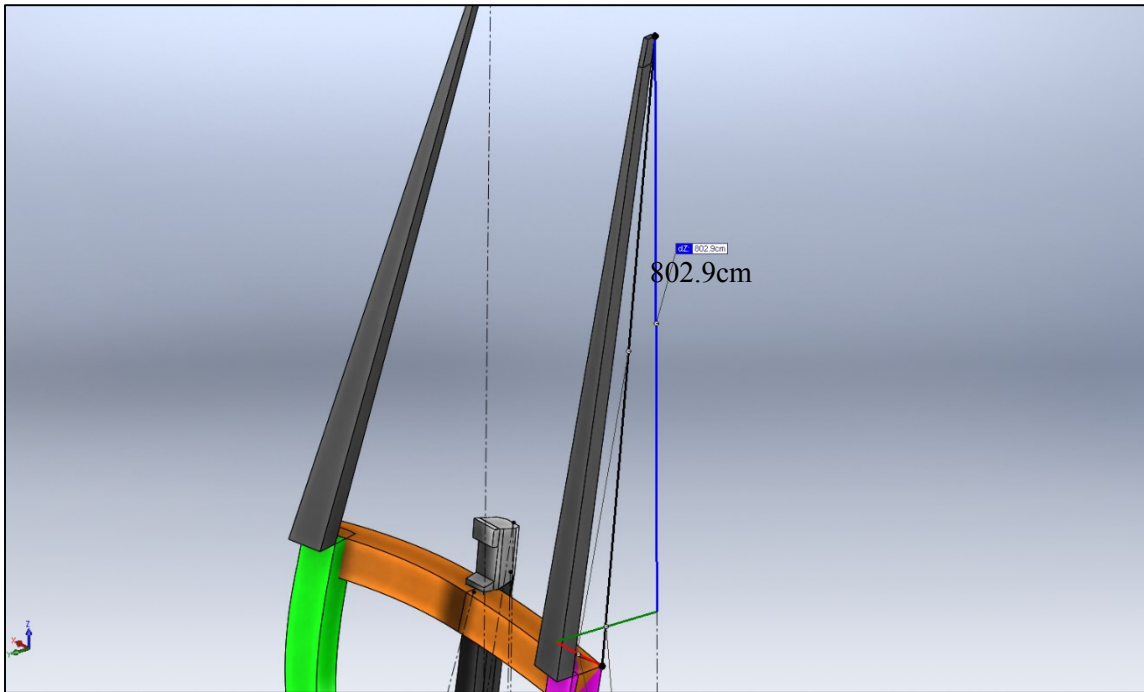


Figure 6.59. The height of the port stern timber above the wing transom.

Inclination

The stern timbers were set roughly tangent to the curvature of the fashion pieces, but their precise inclination was determined by the distance from the tops of the stern timbers from each other. This inclination defined the narrowing of the hull at the stern above the level of the wing transom. Witsen suggests making the spacing at the top “wide $\frac{3}{5}$ the length of the wing transom” or “2 feet broader than half of the wing transom.”¹¹⁸ The tops of *Vasa*’s stern timbers are easily accessible; the outboard edges are 349.3 cm./11 ft. 10 in. S apart, and the inboard edges 330.3 cm./11 ft. 1 in. S apart. Using the outboard edge measurement, Witsen’s suggestion

¹¹⁸ Hoving 2012, 51. “*wijt $\frac{3}{5}$ can de lengthe van ‘t hek.*” Witsen 1671, 67. “*2 voet wijder als de helft van ‘t heck*” Witsen 1671, 74.

of 2 feet broader than half the length of the wing transom precisely describes the distance between the outboard edges of tops of *Vasa*'s stern timbers, illustrated in Figure 6.60.¹¹⁹

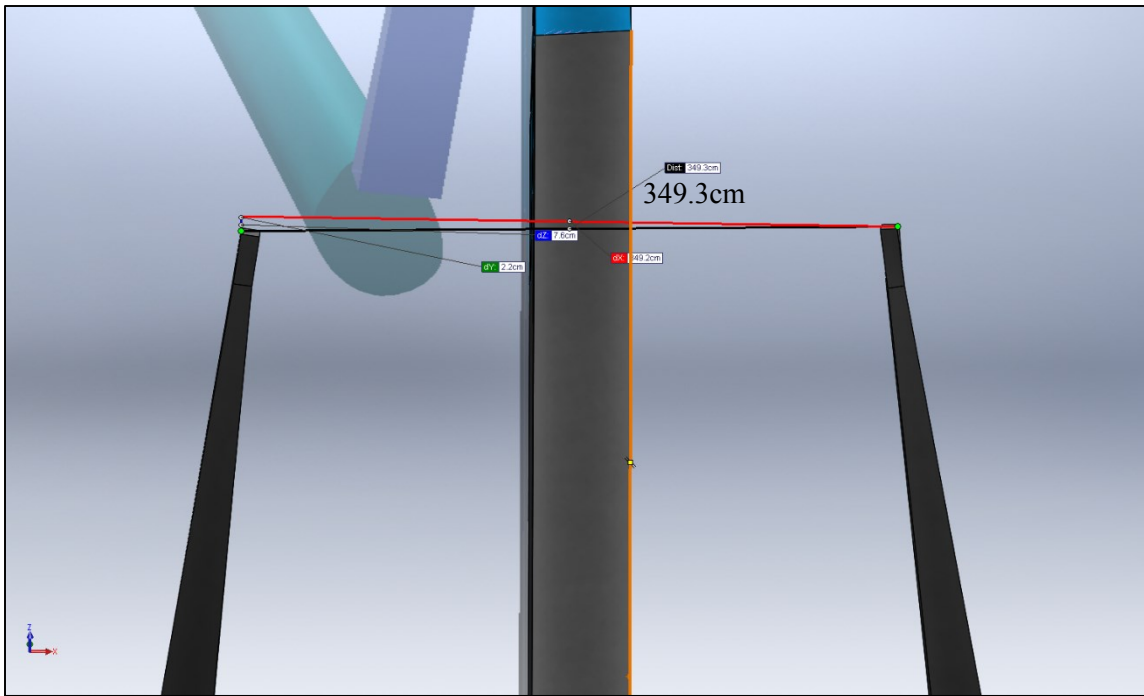


Figure 6.60. The spacing of the tops of the stern timbers measured on the outboard edges.

The full stern panel assembly included the sternpost, wing transom, fashion pieces, stern timbers, and filling transoms, as seen in Figure 6.61. Prior to attaching this structure to the keel, the filling transoms and stern timbers were removed to make the assembly easier to handle. Once the sternpost was affixed to the keel, the filling transoms and stern timbers were reattached,

¹¹⁹ Wing transom is 19 ft. 7 in. (235 in.) long / 2 = 117.5 in. Add 24 ft. = 141.5 in. (Divide by 12) = 11.8 ft., or 11 ft. 10 in. 3/5 of the wing transom (235 in.) is 141 in., divide by 12 = 11 ft. 9 in. Both formulas produce very similar results.

defining the stern profile of the vessel. This marked the last phase of design and construction prior to the addition of planking.

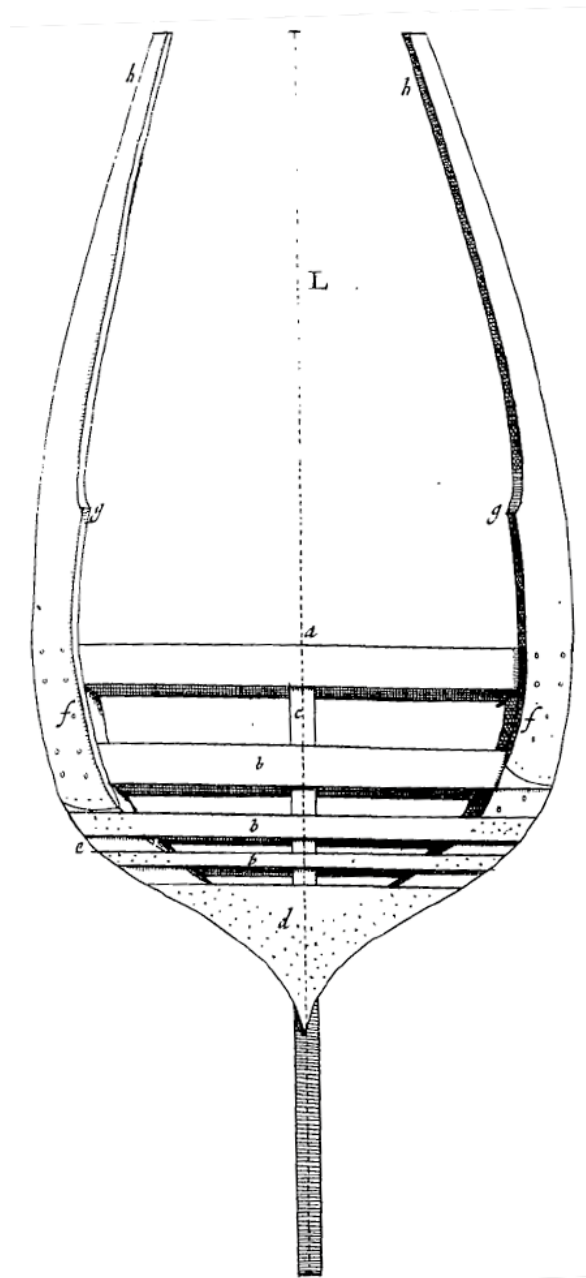


Figure 6.61. The complete stern panel as illustrated by Witsen.¹²⁰

¹²⁰ Witsen 1671, Plate XLIX.

BOTTOM

Once the spine was assembled, installation of the bottom planking began. One of the most defining characteristics of the northern Dutch shipbuilding tradition is that planking began in a shell-first manner. Several strakes were installed before any framing timbers were in place. The planks were temporarily held in place edge-to-edge with cleats until framing timbers were installed. Starting with the garboard, the bottom was planked in this fashion to a desired width and deadrise, determined at the discretion of the shipwright. At this point, the planking transitioned from the bottom of the vessel to the bilge planking, separate conceptual units. This transition is marked by the addition of the *buikstuk*, illustrated in Figure 6.62.

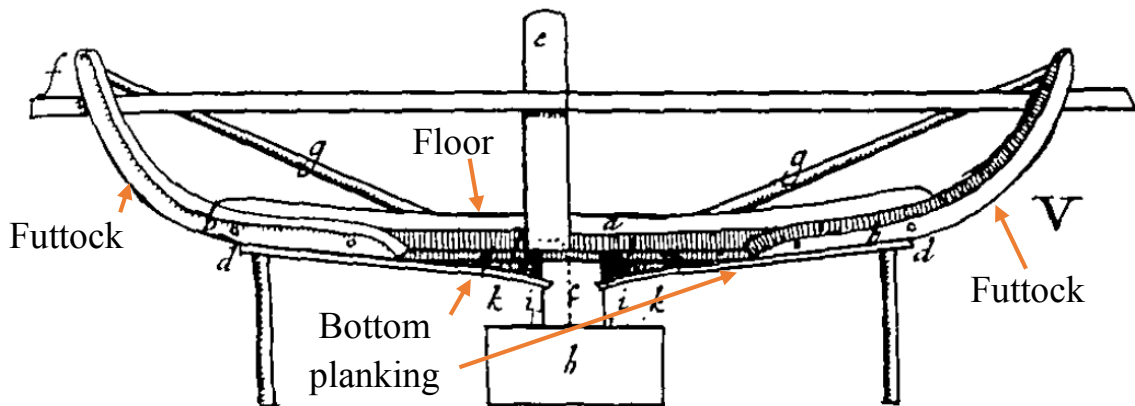


Figure 6.62: Witsen's illustration of the *buikstuk*.¹²¹

Measurements for the width and rise of the bottom planking occurred at the *hals*. In the hull of *Vasa* at the *hals*, it is not immediately clear where the flat of the bottom ends and the turn of the bilge begins. Modeling the planking, however, helps further understand and analyze the extent

¹²¹ Witsen 1671, Plate LII.

of *Vasa*'s conceptual bottom. The planking of the bottom constituted a distinct phase in design and construction that had a clear beginning and end. Since the shipwright had an intended breadth for the bottom, it stands to reason that the outboard edges of the bottom coincide with the edges of planks, one on either side. The distance between the outboard edges of the final bottom planks define the width of the bottom. Thus, the extent of *Vasa*'s bottom should correspond to the edges of two planks, one on either side. The first step in the analysis of *Vasa*'s bottom construction is the identification of the final bottom planks installed in the hull.

Breadth

A cross-section of *Vasa*'s bottom planking does not display a clearly defined flat bottom, but instead reveals two likely candidates for the final bottom plank. Either the 9th or 10th plank from the keel on either side defines the width of *Vasa*'s bottom, illustrated in Figure 6.63. Since it is not immediately clear where the flat of the bottom ends and turn of the bilge begins, each of these planks has been investigated as possibilities for being the final bottom plank. The distance between the outboard edges of the two 9th strakes is 712.1 cm./24 ft. 8, illustrated in Figure 6.64. The distance between the outboard edges of the two 10th strakes is 762.7 cm./25 ft. 8 in., illustrated in Figure 6.65. Witsen suggests that the width of the bottom should be 2/3 of the overall breadth.¹²² If the planking of *Vasa*'s bottom began with the original maximum breadth of 36 ft. as the design intention, Witsen's formula would indicate a bottom width of 24 ft. This matches exactly the distance between the outboard edges of the 9th strakes. Thus, it is concluded that *Vasa*'s bottom planking consists of the first 9 strakes on either side, and constitutes a total

¹²² "For the width of the bottom take 2/3 of the entire width" Hoving 2012, 59. "*Tot de wijte van 't vlak neemt 2/3 van de heele wijte*" Witsen 1671, 67.

width of 24' S.¹²³ The observed dimensions do not indicate that Jacobsson's modification widened the bottom planking.

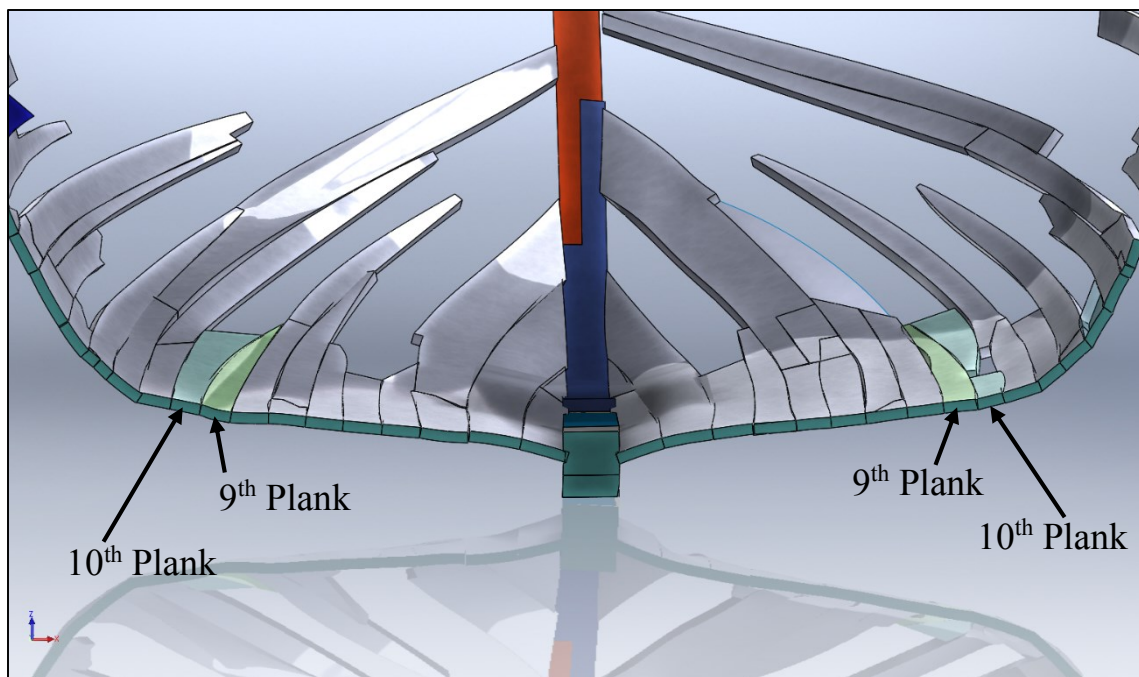


Figure 6.63. Cross-section of the planking model at the *hals*. The 9th and 10th planks on either side are the most likely candidates for the extents of the conceptual bottom.

¹²³ 2/3 of 37' 5" is 24' 11" – which does not closely correspond to either breadth candidate.

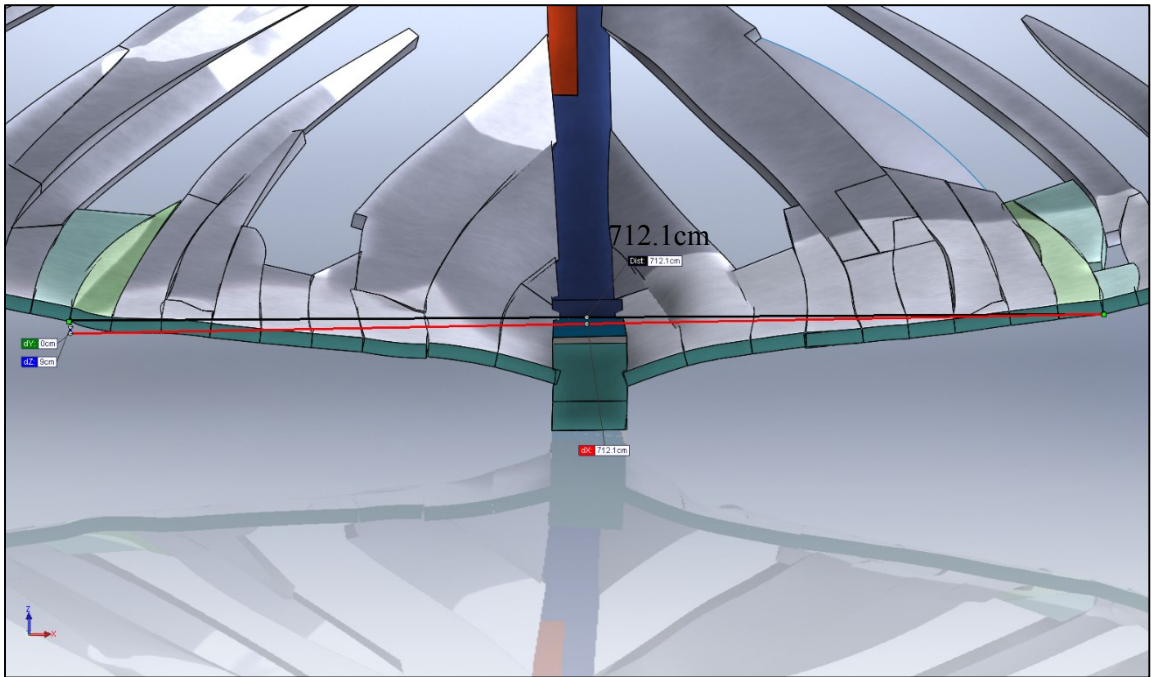


Figure 6.64. Distance between the outboard edges of the 9th bottom planks.

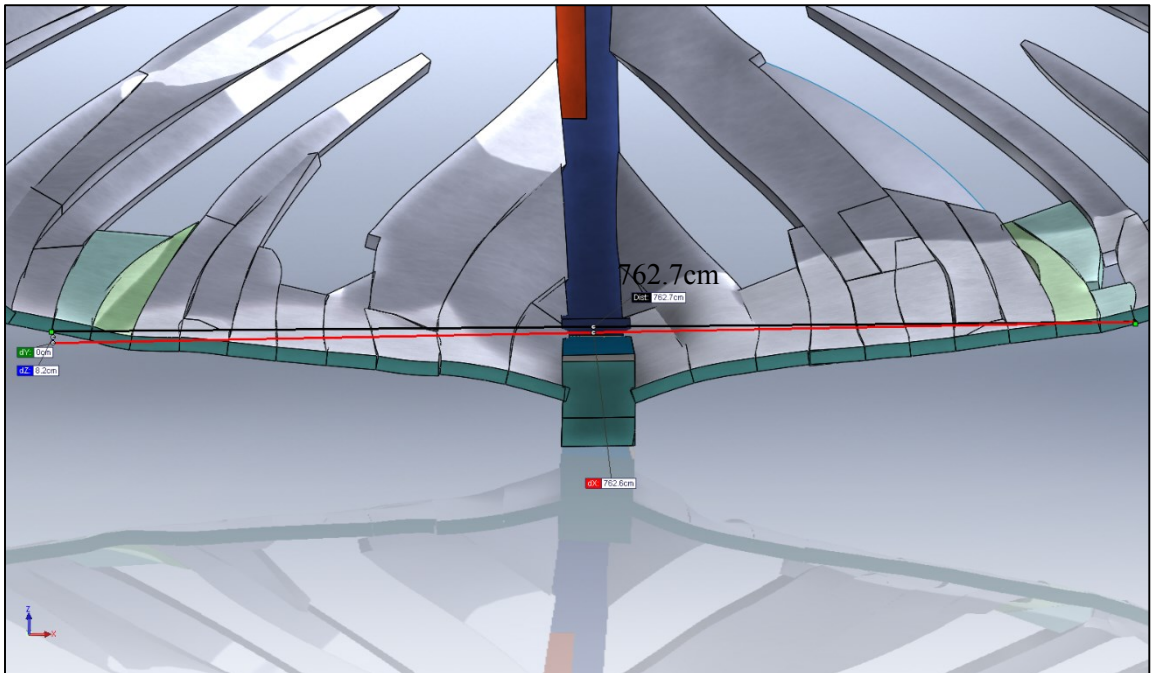


Figure 6.65. Distance between the outboard edges of the 10th bottom planks.

Deadrise

In the absence of framing timbers, shoring poles were used to support the bottom planking from below during this early stage of planking. Anecdotal evidence from the construction of the *Duyfken* replica in Australia showed that use of these poles allowed for the easy adjustment of the curvature and rise of bottom planking simply by moving poles at key locations.¹²⁴ With the plasticity of the bottom planking at this stage of construction, the shipwright was able to exert significant control over the shaping of the bottom planking.

Witsen's suggestions for determining the deadrise of the bottom at the *hals* are imprecise and leave much to the discretion of the shipwright. He recommends "the bottom should rise 1/2 inch to every foot [presumably of width] on the main frame. ... The bottom furthermore, rises and descends, is made sharp or flat, to one's pleasure, and according to the use of the vessel."¹²⁵ The point from and to which rise was measured is not specified.

The angle of deadrise differs between the port and starboard sides of *Vasa*. On the port side it is approximately 8.5 degrees while on the starboard it is approximately 6 degrees. The difference likely results from the distortion the hull has undergone while underwater, through conservation, and while on display.¹²⁶ It is unlikely, however, that an angle off the horizontal was the method

¹²⁴ Leonard 2001, 14-15.

¹²⁵ He does not, however, follow this guideline in the construction of his hypothetical *pinas*. Hoving 2012, 59. "*t Vlak moet ieder voet 1/2 duim op de hals rijze... Het vlak voerdes, doet men rijzen, en daelen, maekt het scherp en plat, nae welgevallen, en na het gebruikt der schepen.*" Witsen 1671, 67.

¹²⁶ Witsen indicates that great care was taken to make the hull, especially the bottom, as symmetrical as possible. "When the bottom is planked, it is hewn off to the well-lined proportion, it is made equal height on each side using a level with a plumb bob and then small shores are placed underneath, for it to remain unalterable." Hoving 2012, 59. "*Als het vlack geboiet is, houtmen het na de welgelijnde evenmaet af,*

the shipwrights used to determine the rise of the bottom. Instead, as indicated by Witsen, the rise was likely expressed as a vertical measurement. This is evidenced by Witsen's indication of a plumb bob as the preferred measuring tool. Although Witsen provides suggestions for determining the amount of the rise in planking at the *hals*, he does not indicate precisely how or where the measurement was taken. Since emphasis was placed on maintaining symmetry between the port and starboard sides of the vessel, it was necessary to be able to easily measure the amount of rise between the sides. A fixed point of measurement would have been necessary. A likely possibility is that this was measured as the vertical distance from the edge of the bottom planking to the ground. The ground is the only fixed point directly below the edge of the planking, and is thus the most likely point of reference for determining planking symmetry. Since the depth of the keel blocks supporting the ship while under construction is not known, it is not possible to measure this dimension in *Vasa* the way it may have been measured in the shipyard.

The overall vertical change in the bottom planking, however, can be measured. Measured from the bearding line to the outboard edge of the final bottom strake (9th on either side) is 43.4 cm./1 ft. 6 in. S (18 in. S) on the starboard side; on the port it is 49.8 cm./1 ft. 8 in. S (20 in. S). As with the difference of deadrise angles, the difference here is likely a result of hull distortion. These dimensions do not conform to Witsen's suggestion of ½ inch for every foot in bottom width.¹²⁷ This is likely one aspect of design and construction that was truly determined by the eye and judgment of the shipwright.

maeckt het met een Water-pas, op verscheide plaetzen waterpas, en zer daer dan paeltjes onder, op dat onveranderlijck blijven mach" Witsen 1671, 151.

¹²⁷ If 18 in. is the intended rise, however, it does correspond to ¾ of the bottom planking width in inches.

BILGE

After the bottom planking was in place and adjusted to the satisfaction of the shipwright, one floor timber, with one futtock on either side, was installed at the *hals*. This temporary structure, called the *buikstuk* and illustrated above, assisted in defining the curvature of the turn of the bilge. Edge to edge planking became much more difficult as the planks started to turn up in the bilge and thus the *buikstuk* provided a mold to help support and shape the bilge planking. The futtocks of the *buikstuk* were cut according the shipwrights specifications for the curvature of the turn of the bilge.¹²⁸

The overall shape of the turn of the bilge was defined by three factors: the width, the depth, and the curvature. Like the conceptual bottom, it is not immediately clear where the bilge of *Vasa* begins and ends. Witsen indicates, however, that like the extent of the bottom, the extent of the bilges also likely corresponded to a plank edge.¹²⁹ Also like the bottom, however, it corresponds to the edge of a plank and can thus be identified through analysis. All measurements for the bottom and bilge were taken at the *hals* using the previous conclusion that the bottom planking extends for nine strakes on either side of the keel.

Regarding the depth of the bilge, Witsen suggests it should be made to 1/3 of the total depth of the vessel.¹³⁰ Like the overall depth, this measurement was taken from the top of the keel.

¹²⁸ Hoving 2012, 64.

¹²⁹ “because the ship is wide 27 feet on the top of the bilges, and wide 29 feet in all, overhanging one foot on each side.” Hoving 2012, 64. “want het schip is wijt tot de kimme 27 voet, en is wijt in ‘t geheel 29 voet, aen ieder zijde een voet overschietende.” Witsen 1671, 60.

¹³⁰ “The depth is one third of the total depth at the place of the main frame.” Hoving 2012, 66. “De holte is 1/3 van de geheele holte op de hals.” Witsen 1671, 67.

Applying this to *Vasa's* depth (15 ft. 2 in. S) yields a bilge depth of approximately 5 ft. S. On the model, this depth does not correspond evenly to the edge of any plank. This measurement is, however, close to the edges of the 15th plank on either side. The inboard edge of the 15th plank on the port side is 10.2 cm. above a line drawn at 5 ft. above the top of the keel. The inboard edge of the 15th plank on the starboard side is 10.8 cm. below this line. This difference could be attributed to hull distortion and the inconsistent width of hull planks. This interaction is illustrated in Figure 6.66. Depth measurements on neighboring planks do not display consistency from side to side or any logical relationship to the overall depth of the hull and thus 5 ft. is concluded to be the intended depth of *Vasa's* bilge planking. Witsen indicates that a beam was laid across the bilge planks to check for symmetry, as illustrated in an image from Witsen seen in Figure 6.67.

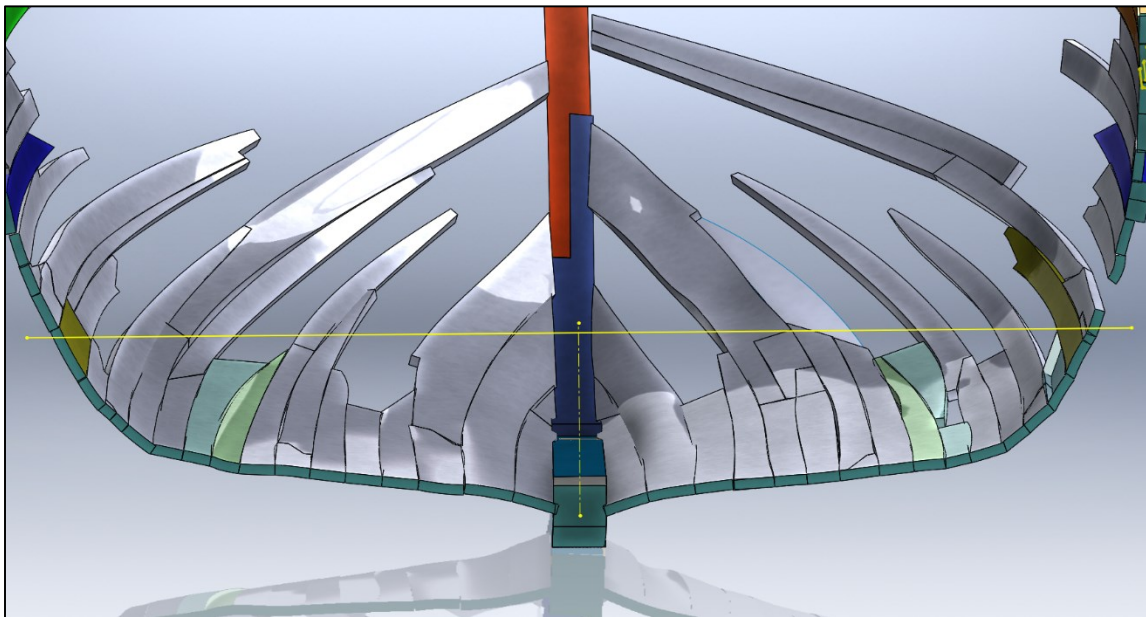


Figure 6.66. The depth of the bilge planking. The horizontal yellow line is equal to 1/3 of the depth (5' above the top of the keel), indicating a possible position for the vertical limit of the bilge planking. The line does not evenly correspond to any plank edges, but is close to the edge of the 15th plank on either side. The inboard edge of the terminal port bilge plank comes 10.2cm above the line, and the inboard edge of the terminal starboard bilge plank is 10.8cm below the line. Distortion is likely the cause of the disparity.

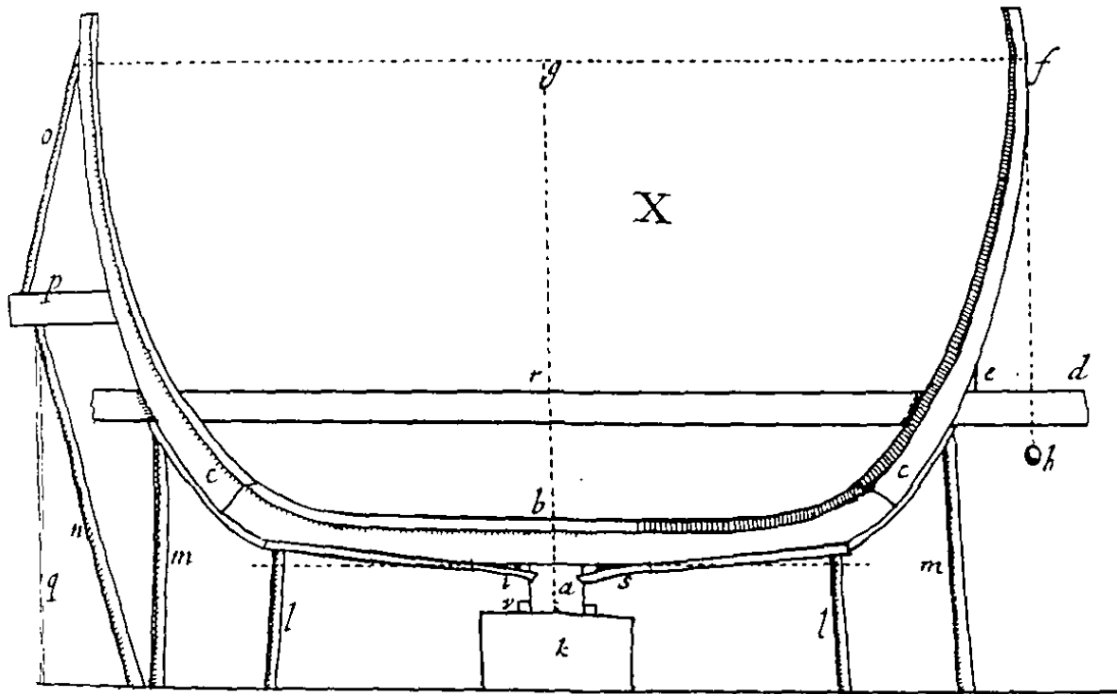


Figure 6.67. Drawing from Witsen's treatise indicating the symmetry checks on the bilge planking and first futtocks.¹³¹

If the 15th planks on both sides of the vessels are accepted as the vertical limits of the bilge, the width between the inboard edges of the planks is 990.6 cm./33 ft. 4 in. S and between the outboard edges 1006.7 cm./33 ft. 11 in. S. For the width of the bilges, Witsen suggests making them 1 inch narrower than the maximum breadth for every 10 feet the ship is long.¹³² The sample contracts provided in the treatise, however, show that this guideline was not consistently used. Applying this formula to *Vasa* results in a calculated bilge width of approximately 34 ft. 8 in. S if 15.9 in. (1 in. for every 10 ft. of length) is subtracted from 36 ft. (original intended

¹³¹ Witsen 1671, Plate LII.

¹³² "About the width of the turn of the bilge, for 10 feet of ship's length make the bilges 1 inch narrower than the total width" Hoving 2012, 66. "*Van de wijte op de kimmen, 10 voet langte van 't schip, doet de kimmen 1 duim nauwer zijn als de geheele wijte*" Witsen 1671, 67.

maximum breadth).¹³³ *Vasa*'s observed bilge widths are considerably less than this. The difference between the bilge breadth and the original maximum breadth is 2 ft. 8 in. if the inboard measurement is used and 2 ft. 1 in. if the outboard measurement is used. These dimensions, however, are within the range of bilge-to-width measurements represented by the sample contracts in Witsen treatise. It is possible that Hybertsson simply decided on making the bilges either 2 ft. or 2 ft. 6 in. narrower than the maximum breadth.

The curvature of the bilge planking is less easily quantifiable. The curvature was determined by the futtocks of the *buikstuk* that were erected once the bottom planking was complete. Although Witsen provides guidelines for determining the sided and molded dimensions of the futtocks, he does not provide guidance on their curvature. These timbers were fabricated before they were installed in the hull and therefore were products of deliberate design on the part of the shipwright. Therefore it is possible that the curve was specified and measurable. The bilge forms the transition between the bottom of the vessel and the sides and significantly affects the transverse shape and underwater surface of the hull. Although Dutch shipwrights in the early 17th century do not appear to have used circles or segments of circles in their design and construction, measurable curvature was nevertheless used in limited situations. One example is that of the stem, discussed above, where Witsen expresses curvature as an offset from a straight line.

¹³³ If 37 ft. 5 in. is taken as the breadth, this formula results in a bilge width of 36 ft. 1 in.

The futtocks of the *buikstuk* extended upwards beyond the bilge planking to an unknown extent. Measured on the plank edge one plank above the extents of the bilge, the outside planking exhibits an approximate curve of 36.6 cm./1 ft. 3 in. S in the port bilge and 33.5 cm./1 ft. 2 in. S in the starboard bilge, illustrated in Figures 6.68 and 6.69. This is the same as the inside curve, assuming a consistent planking thickness. Based on these observed dimensions, it is proposed that Hybertsson, having determined the width and height of the bilge planking, fashioned the bilge futtocks with a curve of approximately 1 ft. to make the transition from bottom to side. This is, however, a highly speculative conclusion.

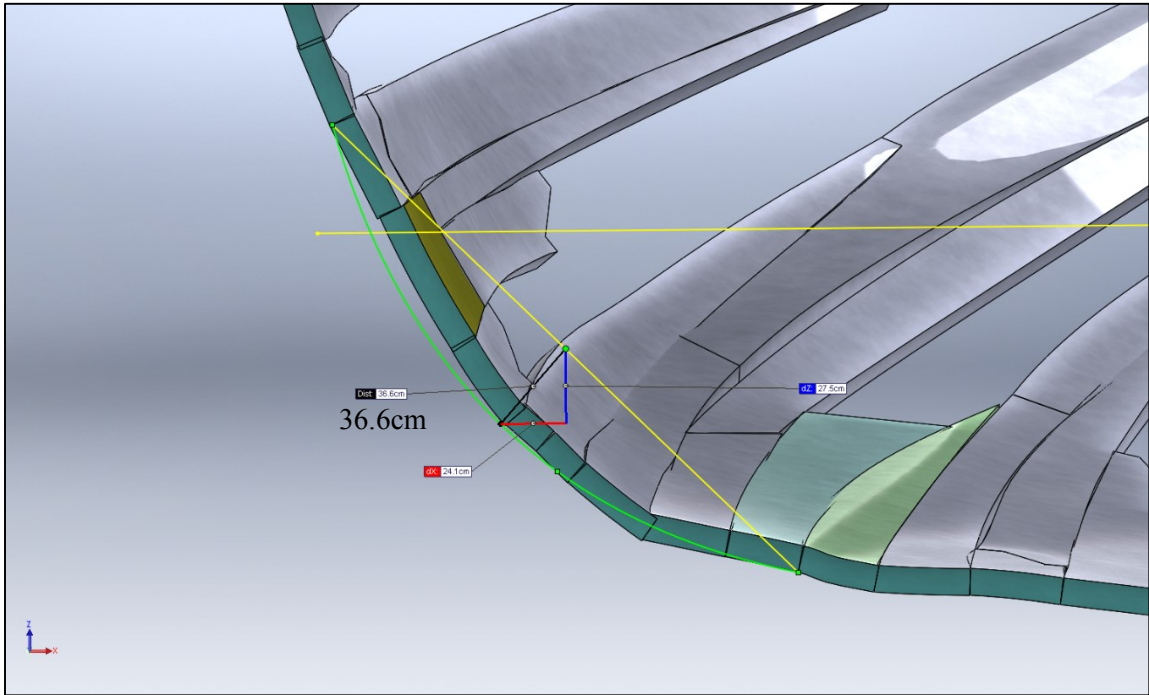


Figure 6.68. Port bilge curvature.

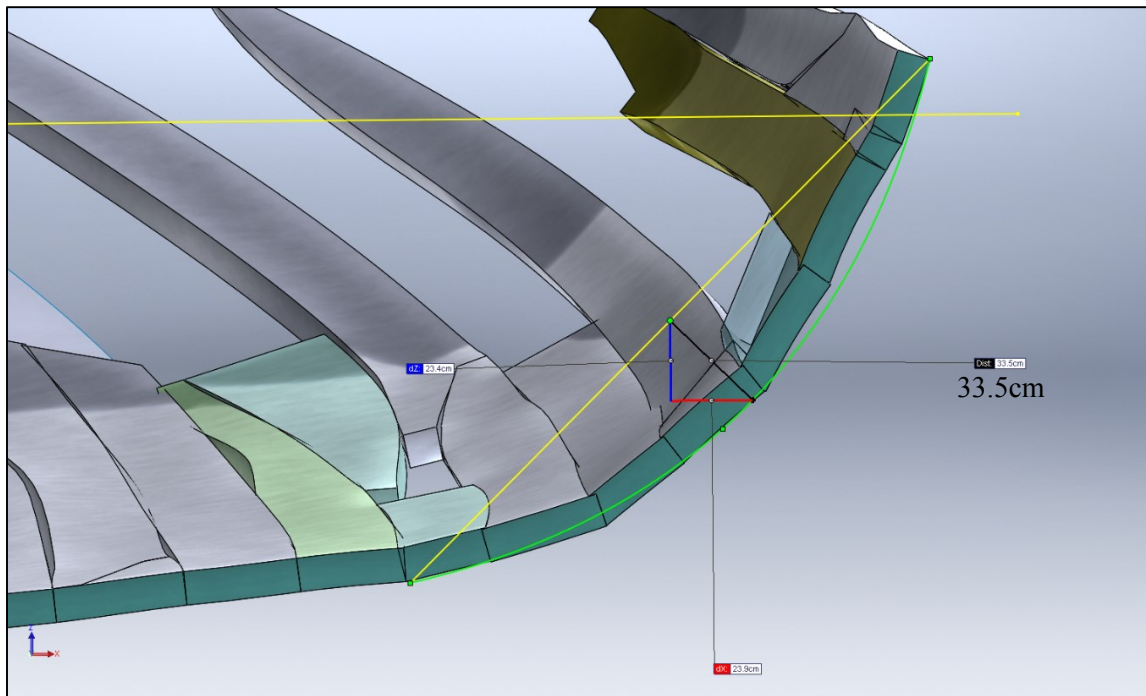


Figure 6.69. Starboard bilge curvature.

SIDE CURVATURE AND SHEER

After the bilge planking was installed, the method of construction shifted from shell-based to frame-based. Floor timbers filled the planking and a small number of first futtocks were raised at intervals along the hull.¹³⁴ Witsen suggests installing a total of eight first futtock stations initially.¹³⁵ Although he writes “No fixed measures can be given of the bends and curvatures in the ribs of the ship, such as the timber, futtocks, etc, because they change according to the use of the ship: they are to be made by eye and should decrease slowly” Witsen provides the curvatures

¹³⁴ The location and spacing of the intervals was apparently left to the discretion of the shipwright. Witsen provides the locations he used in the construction of his hypothetical pinas, but there is no apparent logic to their positions.

¹³⁵ Hoving 2012, 71.

of the initial futtocks used in the construction of his hypothetical pinas.¹³⁶ The curvature of these futtocks range from 3 inches to 7 inches with curvature increasing towards the ends of the vessel. It is likely that most of the futtocks were cut from the same mold, and therefore had the same original curvature, and were adjusted or planed by eye to meet the vision of the shipwright and Witsen sought a means for quantifying this practice even if it was not done so in actual ship construction.¹³⁷ The position of the initial futtocks determined the maximum breadth of the vessel. This is the likely point in construction that Jacobsson took over and made the decision to widen *Vasa*. He likely did so by leaning the futtocks out over the bilges more than Hybertsson intended, continuing a curve more tangent to the bilge curve than originally planned.

After the initial futtocks were raised, the *scheerstrook*, or master ribband, was attached to them. The shipwright used this critical tool to define the sheer and height of breadth of the vessel. The *scheerstrook* spanned the entire length of the hull, beginning on the stem and ending on the wing transom. The position of deck beams, hatches, gunports, and masts were marked on this ribband, which could be save and re-used to build similar vessels.¹³⁸ Witsen provides little information on how the position of the *scheerstrook* was determined.¹³⁹ This was one of the final places where the shipwright could significantly influence the shape of the hull.

¹³⁶ Hoving 2012, 69. “*Van de bochten, en kromten in de Scheeps-ribben als daer zijn stutten, oplangen, &c. en kan geen vaste even maet gegeven werdern, omdat die veranderen nae 't gebruik der schepen: zy moeten op het oogh gebouwt warden, en altans zacht verminderen.*” Witsen 1671, 71.

¹³⁷ Hoving 2012, 69.

¹³⁸ Hoving 2012, 72.

¹³⁹ Like the first futtocks, he provides a list of heights for the *scheerstrook* above the bilge planking at various stations along the hull of his hypothetical pinas. No explanation or apparent logic accompanies these dimensions however. Hoving 2012, 71.

Although it was ultimately removed from the hull, the position of the *scheerstrook* is likely approximated by an existing strake. At the *hals*, *Vasa*'s hull is relatively straight sided for a span of three strakes; the third wale and each adjacent strake. Over this span, the maximum breadth varies less than 1cm. This presents three possible strakes as candidates for the position intended to define the maximum breadth, corresponding to the original position of the *scheerstrook*. Of these three strakes, two are the most likely, as illustrated in Figure 6.70. Initially it was assumed that the *Vasa*'s lower scupper strake, which is at the lower edge of the lower gundeck, was the position of the *scheerstrook*.¹⁴⁰ The lower gundeck beams define the depth of the hull, which also commonly coincided with the maximum breadth of the hull. This strake, however, does not end on the wing transom. A more likely position of the *scheerstrook* was identified as the 3rd wale, which features the scupper channels in its upper face and ends on the wing transom.

¹⁴⁰ Witsen indicates the *scheerstrook* was often placed at the height of the scuppers, "When the Frame timbers have been set, then the Master Ribband is fixed around, at the height of the scuppers" Hoving 2012, 71. "*Als men de SPant-houten heft gezet, zoo brengt de Scheergang om, op de hoogte van de uytwatering*" Witsen 1671, 152.

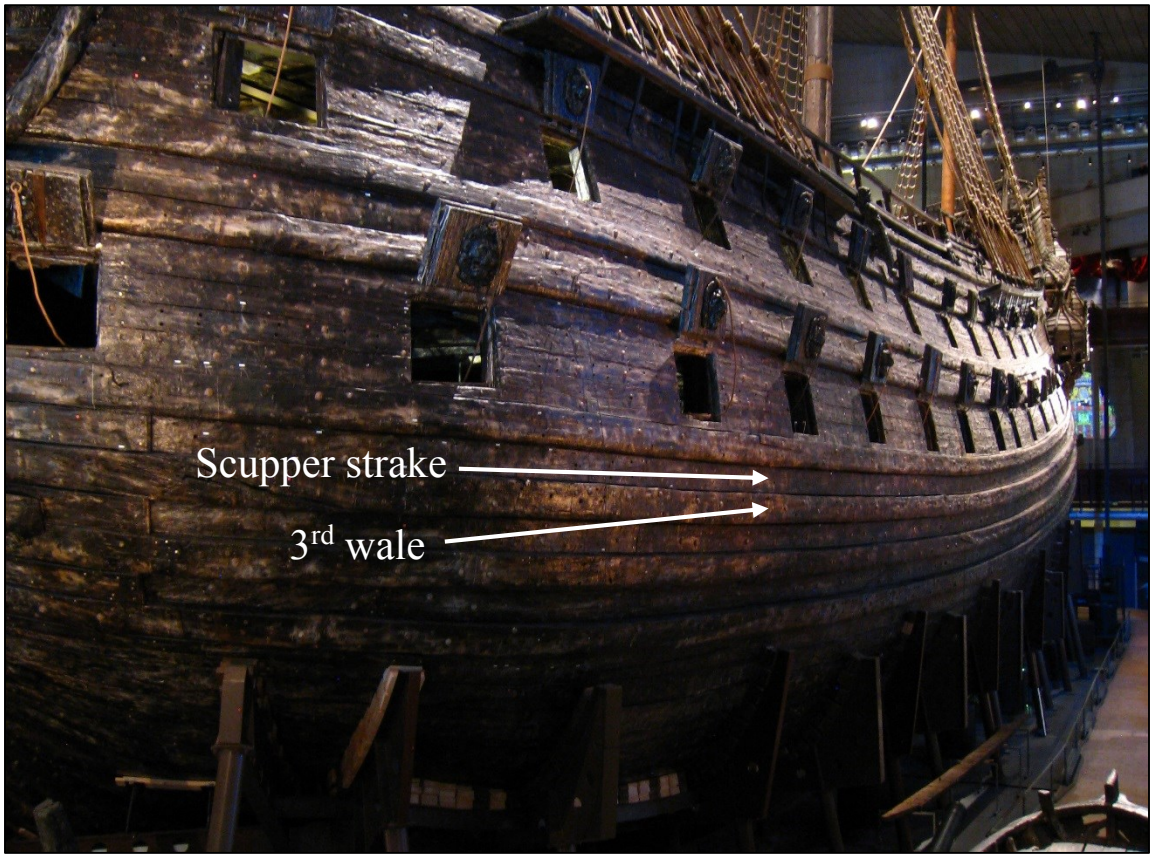


Figure 6.70. The two strakes that most likely indicate the position of *Vasa*'s *scheerstrook*.

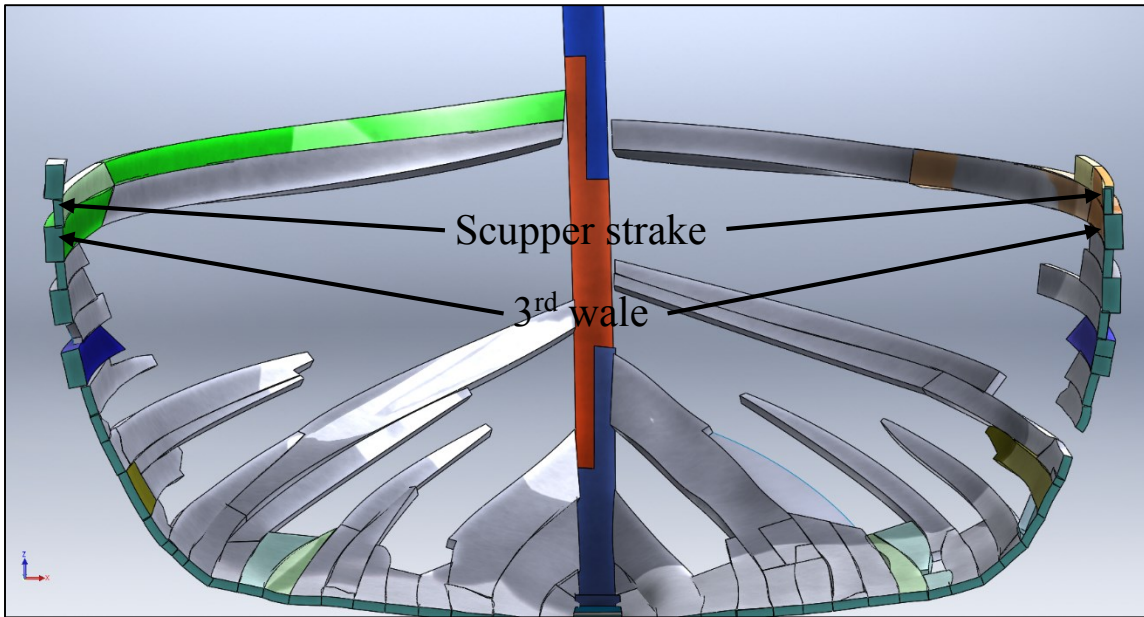


Figure 6.71. The scupper strake and third wale in cross section at the *hals*.

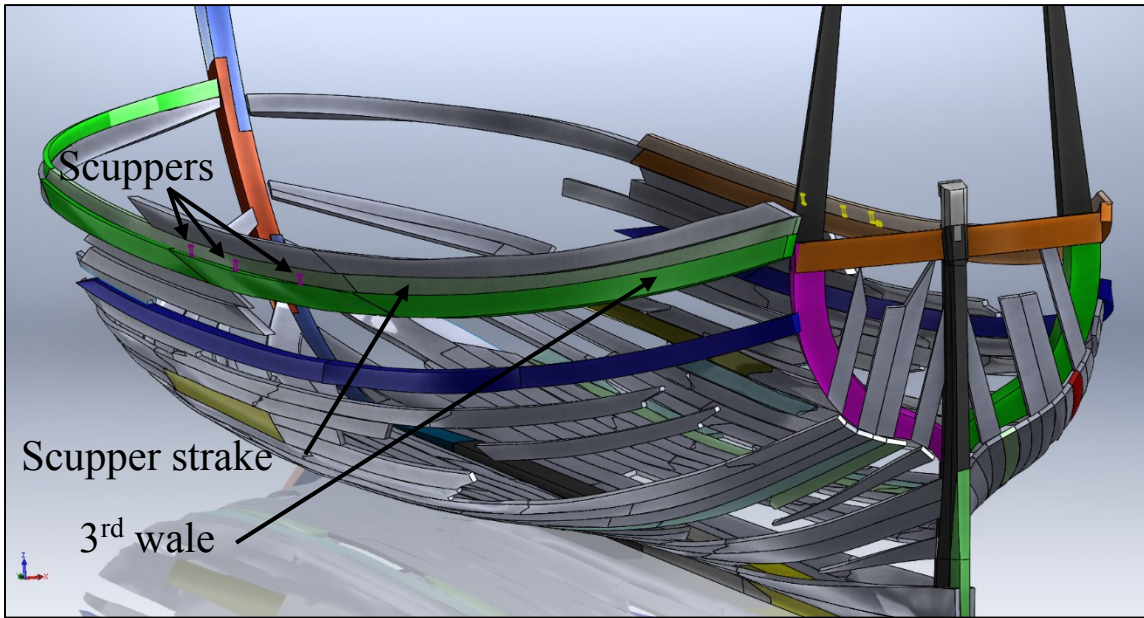


Figure 6.72. The scupper strake and third wale on the port side. Note that the scupper strake does not end on the wing transom but the third wale does.

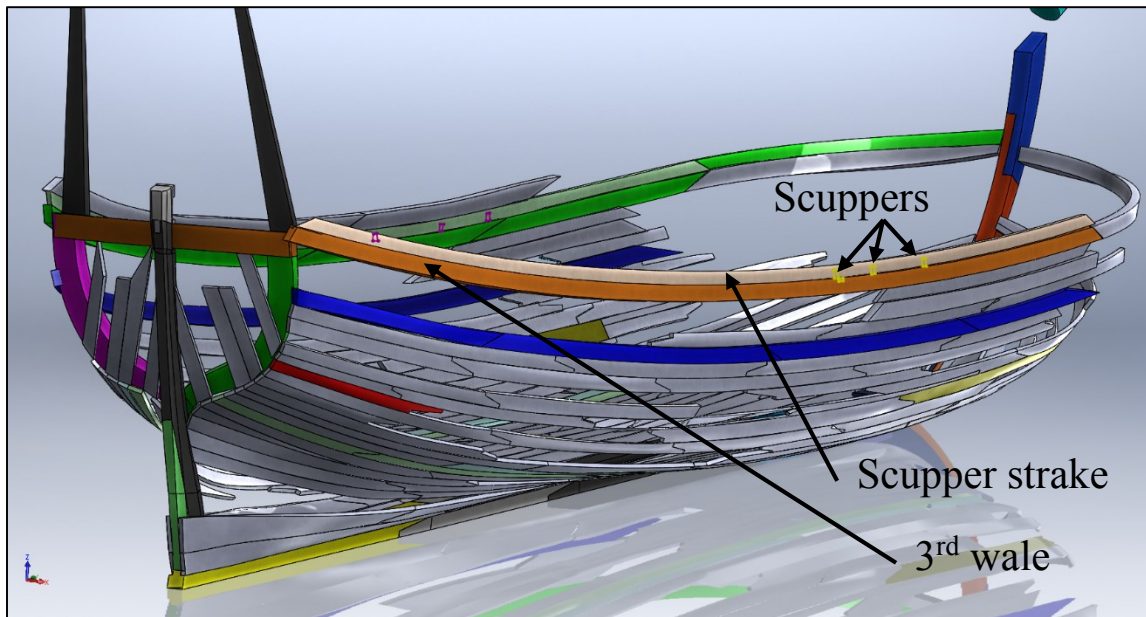


Figure 6.73. The scupper strake and third wale on the starboard side. The strakes show the same arrangement as the port side.

The rise of the *scheerstrook* fore and aft corresponds to the amount of rise in the sheer fore and aft. These dimensions appear to have affected the design of previous hull elements, such as the height of the stem and sternpost, and therefore must have been determined relatively early in the construction process. Measured on the top outboard edge of the third wale (the approximate position of the *scheerstrook*) the port sheer rises 363.3 cm./12 ft. 2 in. S aft and 57 cm./1 ft. 11 in. S forward; the starboard sheer rises 364.8 cm./12 ft. 4 in. S aft and 54.7 cm./1 ft. 10 in. S forward.¹⁴¹ It is likely these dimensions were intended to be 12 ft. aft and 2 ft. forward. These measurements are illustrated in Figures 6.74, 6.75, 6.76, and 6.77.

¹⁴¹ Aft measurements taken from the upper inside edge of the scupper wale at the *hals* to the upper aft corner of the wing transom – which is even with the lower gundeck. Forward measurements taken from the upper inside edge of the scupper wale at the *hals* to the upper inside edge of the scupper wale where it meets the stem.

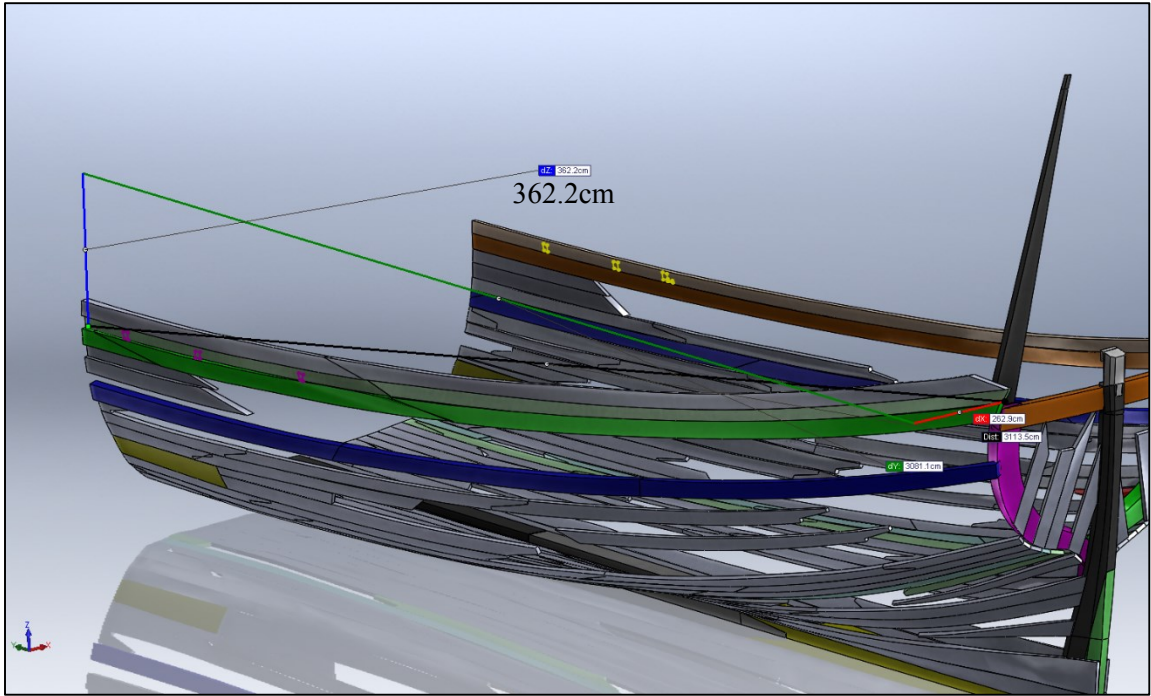


Figure 6.74. The rise in sheer aft on the port side.

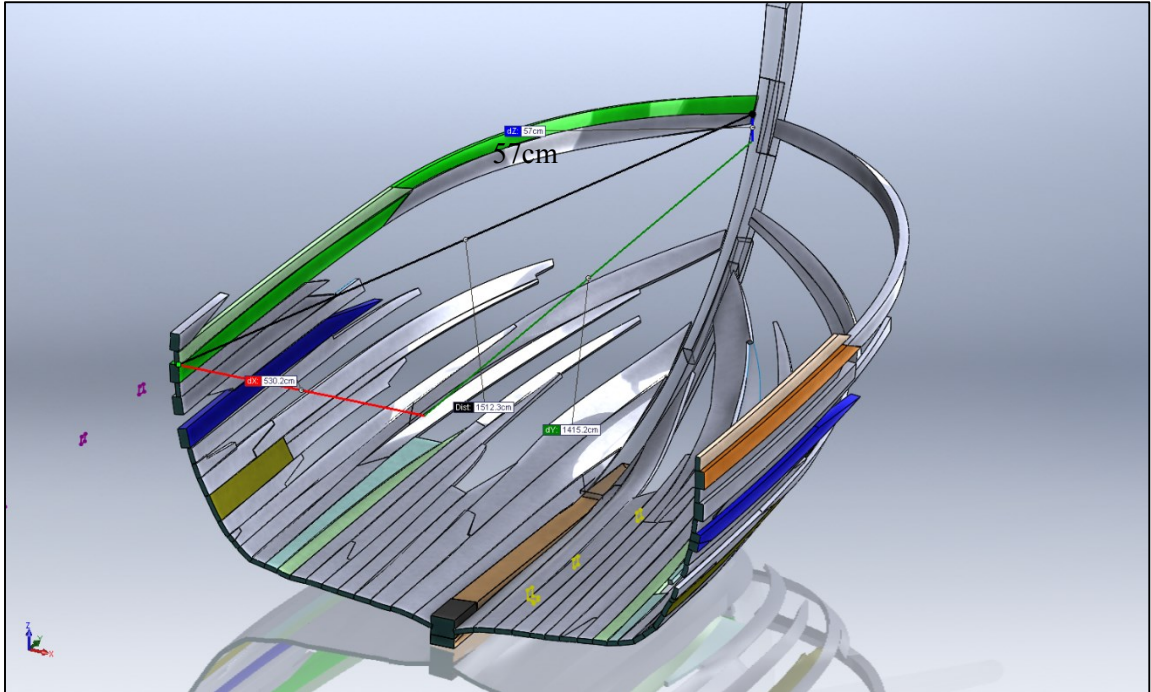


Figure 6.75. The rise in sheer forward on the port side.

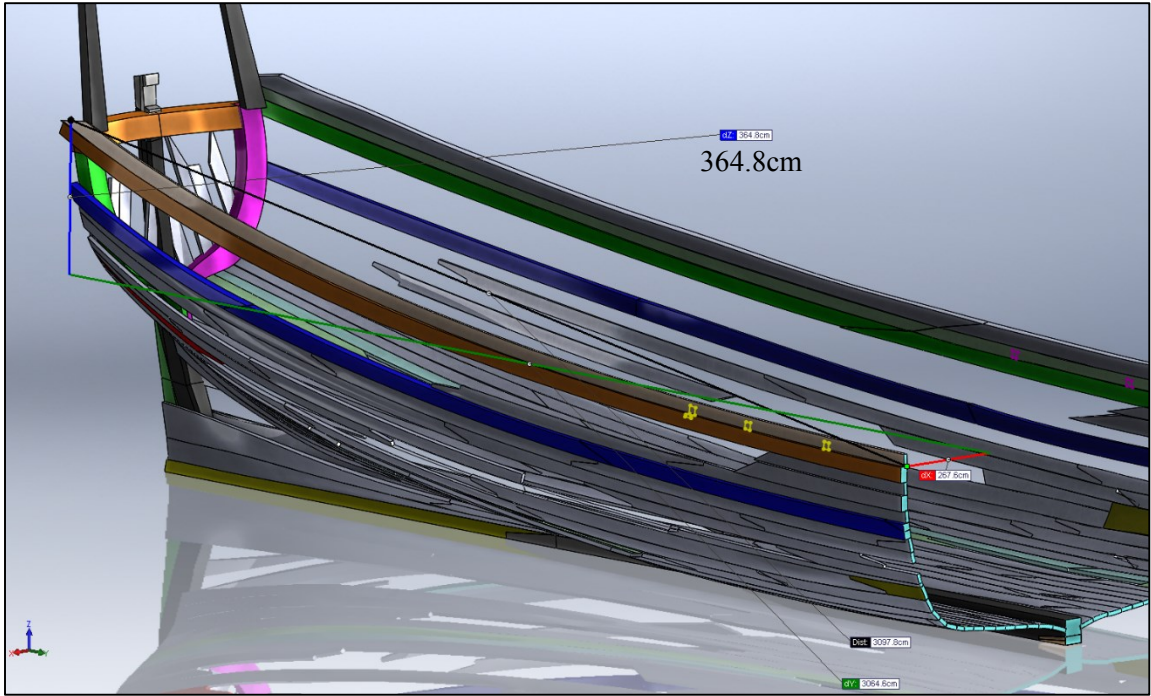


Figure 6.76. Rise in sheer aft on the starboard side.

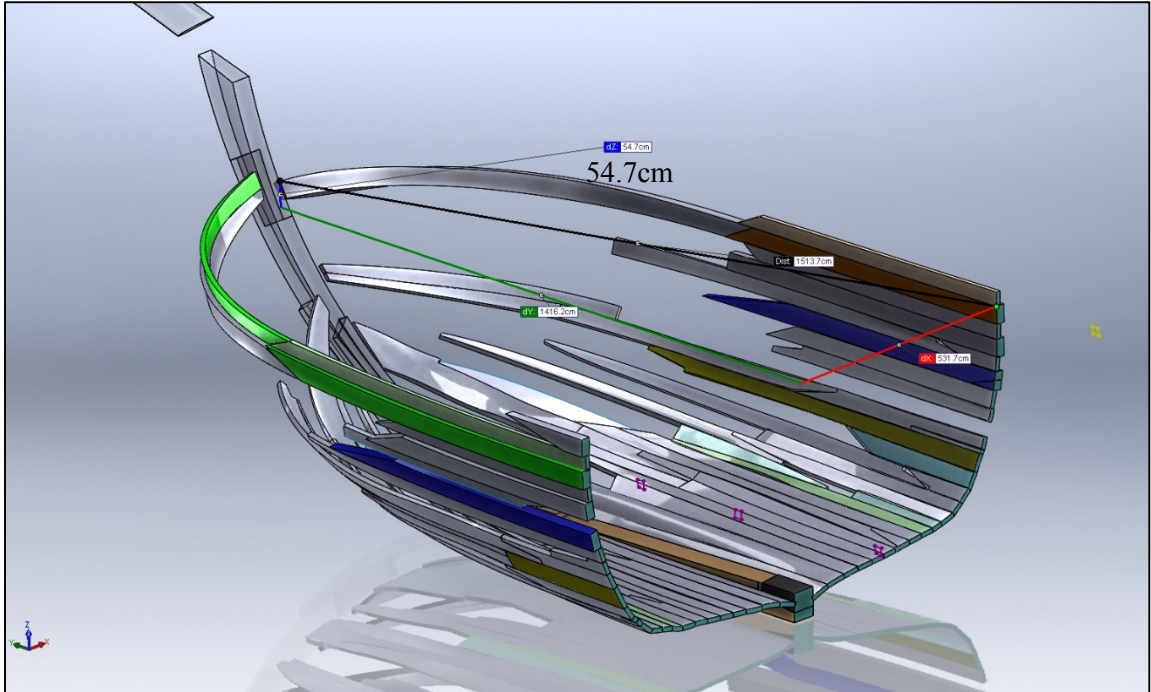


Figure 6.77. Rise in sheer forward on the starboard side.

Once the shipwright finalized the position of the *scheerstrook*, the hull was filled with first futtocks shaped according to the position of the bilge and *scheerstrook*. The first futtocks were responsible for establishing continuity between three key factors in cross-section: the bilge curve, the point of maximum breadth, and the tumblehome of the hull, defined by second futtocks and top timbers. The shape and height of the bilges and the maximum breadth of the vessel have been discussed above. The third main factor in futtock curvature is the desired amount of tumblehome. Witsen suggests that the sides should tumble in from the maximum breadth 1/3 of the height of the upper deck from the main deck, though the actual amount of tumblehome was up to the judgment of the shipwright.¹⁴² The vessel designed in Witsen's treatise, however, only has two decks (a lower deck and a weather deck) and he does not discuss the modifications to design and construction required to build a vessel of *Vasa*'s configuration with two full gundecks and a weather deck.

At the height of the upper gundeck, the hull is 1021.8 cm./34 ft. 5 in. S in breadth and at the weather deck 867.7 cm./29 ft. 3 in. S in breadth, illustrated in Figures 6.78 and 6.79. This represents a narrowing, from the maximum breadth (37 ft. 5 in.), of 3 ft. S on the upper gundeck and 8 ft. 2 in. S on the weather deck. Neither of these dimensions appear to be related to either the heights of the decks (discussed below) or any other design dimension. It is possible that the tumblehome was determined simply by the distance from the tops of the top timbers from each other, similar to how the inclination of the stern timbers was determined. At the *hals*, the outboard faces of the top timbers are 832.8 cm./28 ft. S apart, illustrated in Figure 6.80. This dimension is $\frac{3}{4}$ of the maximum breadth and it is likely that the breadths at the upper gundeck

¹⁴² "The top timbers lean inward, mostly one third of the height of the upper deck." Hoving 2012, 79. "*De stutten komen in, veeltijts een derde van de hoogte van 't verdeck.*" Witsen 1671, 68.

and weather deck were simply results of the dimension. This results in a total tumblehome of 9 ft. 5 in. S (approximately $\frac{1}{4}$ of the breadth) from the maximum breadth of 37 ft. 5 in. S.

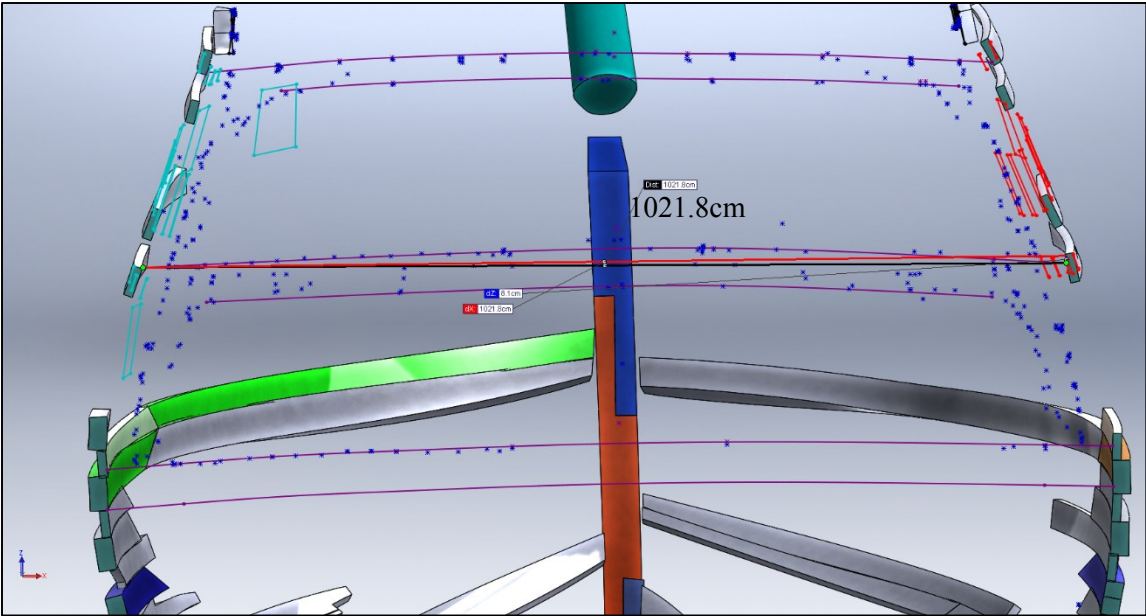


Figure 6.78. Breadth of the hull at the height of the upper gundeck. Beam positions are in purple, the blue points are total station data.

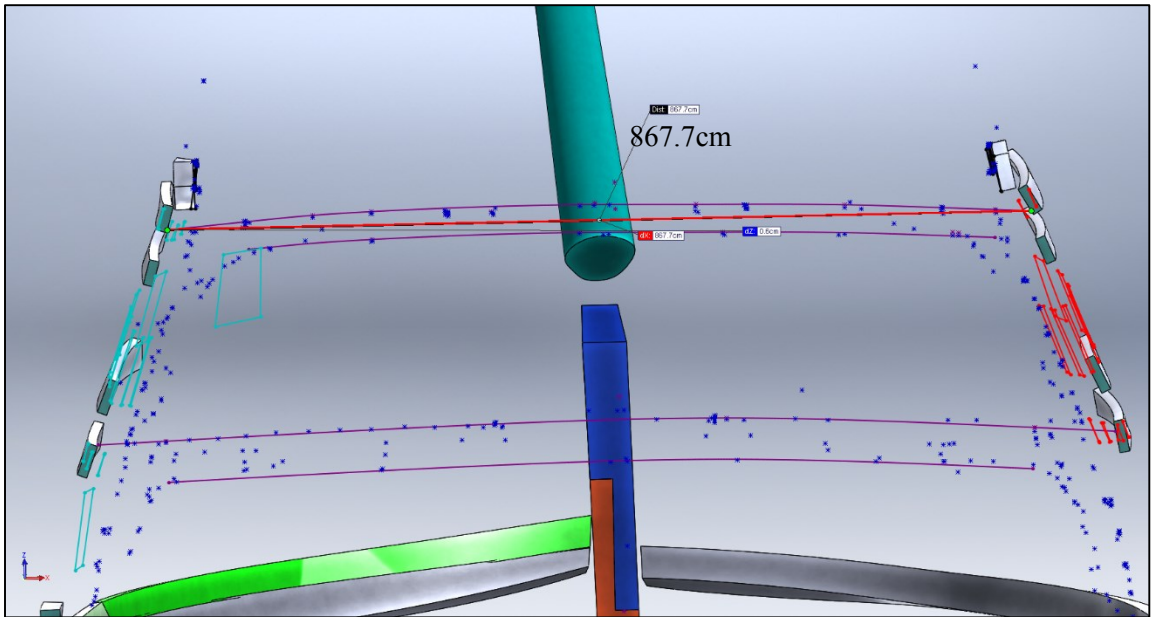


Figure 6.79. Breadth of the hull at the height of the weather deck.

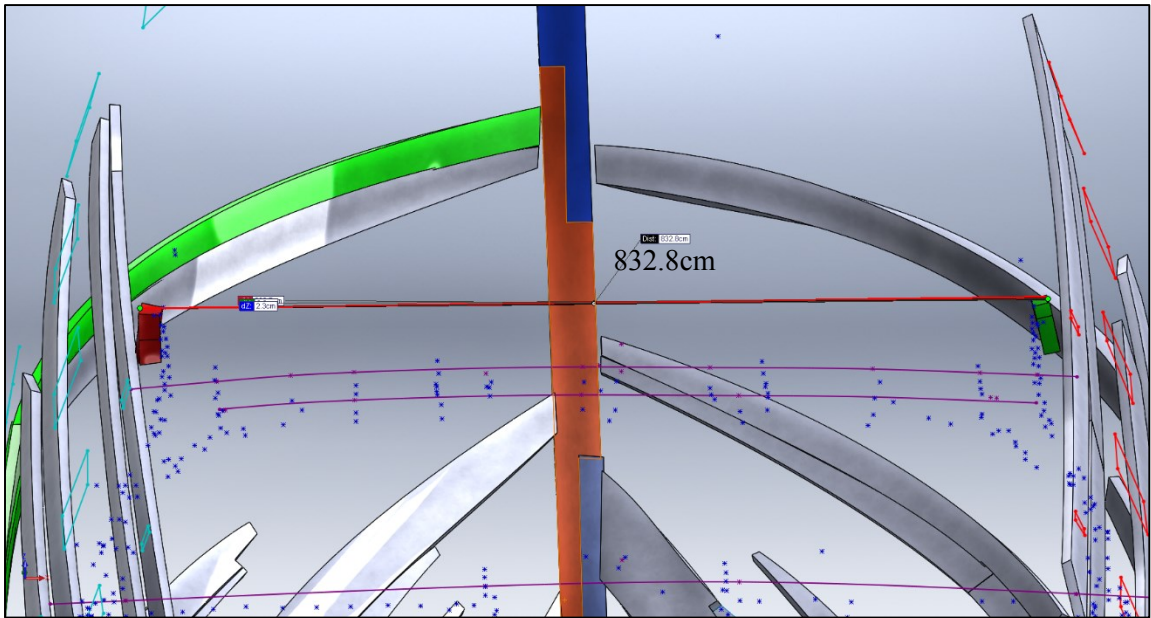


Figure 6.80. The spacing between the outboard faces of the tops of the top timbers (red port and green starboard) at the *hals*.

HEIGHT OF DECKS

The internal volume and shape of the hull was largely defined at this point in construction. The shipwrights, however, were still able to decide how that volume would be divided based on the vertical positioning of decks and deck beams. Witsen provides very little guidance on the placement of decks save for the depth of the ship, and no information at all regarding deck placement in ships with two gundecks. The sample contracts contained in his treatise provide some deck measurements, but do not seem to display any particular logic in their dimensions. The arrangement of decks seems to have been based on rules that Witsen was not aware of or cared not to explain or were solely up to the judgment of the shipwright and escaped explanation.

Witsen does, however, provide some suggestions for the dimensioning of deck beams, which are derived from the length of the ship and have relevance to the measurement of deck heights. His suggestions making the lower deck beams sided and molded dimensions equal to 1 1/8 inches for every 10 feet of ship length overall.¹⁴³ The lower gundeck beams *Vasa* at the *hals* are approximately 44.6 cm./1 ft. 6 in. S (18 in. S) thick (vertical). If Witsen's formula is applied to the 159 ft. of *Vasa*'s length, this results in a beam thickness of 17.9 in. S, very nearly what is observed in the hull. For the upper deck beams, Witsen suggests a thickness of 2/3 of the inside stem thickness (18 in. for *Vasa*). *Vasa*'s upper gundeck beams are approximately 41.5 cm./1 ft. 5 in. S (17 in. S) thick, and do not match Witsen's suggestion. These beams were likely designed to be heavier than usual to support the massive weight of guns on the gundeck. The

¹⁴³ "10 Feet of the ship's length give 1 1/8 inches of the thickness and the breadth of the beam." Hoving 2012, 73. "10 Voet langte van 't schip, geeft 1 1/8 duims tot de dikte en breete van de balk." Witsen 1671, 67.

weather deck beams of *Vasa* are approximately 28 cm./11 in. S thick, and accounting for erosion and damage while underwater, could have easily been originally 12 in. S, equivalent to 2/3 of the inner stem thickness.

With these beam dimensions, the height of *Vasa*'s decks can be measured. As discussed above, the depth of the ship is 15 ft. 2 in. S – the dimension from the top of the keel to the upper face of the lower gundeck beams. Measured from the upper face of the lower deck beams to the upper face of the upper gundeck beams, the lower gundeck is 215.6 cm./7 ft. 3 in. S high at the *hals*, illustrated in Figure 6.81. Measured from the upper face of the upper gundeck beams to the upper face of the weather deck beams, the upper gundeck is 216.5 cm./7 ft. 3 in. S high at the *hals*, illustrated in Figure 6.82. The two gundecks are essentially equal in height. The total height from the top of the keel to the top of the weather deck beams is 882 cm./29 ft. 8 in. S.¹⁴⁴ Together, the lower and upper gundecks are 14 ft. 6 in. S in height, or 8 in. less than half the total height at the *hals*. *Vasa*'s decks show reasonably even distribution over the height of the vessel, with the lower gundeck approximately dividing the vessel in half. The upper gundeck and weather deck are spaced evenly above.

¹⁴⁴ This is 8 in. greater than the breadth at the top of the top timbers.

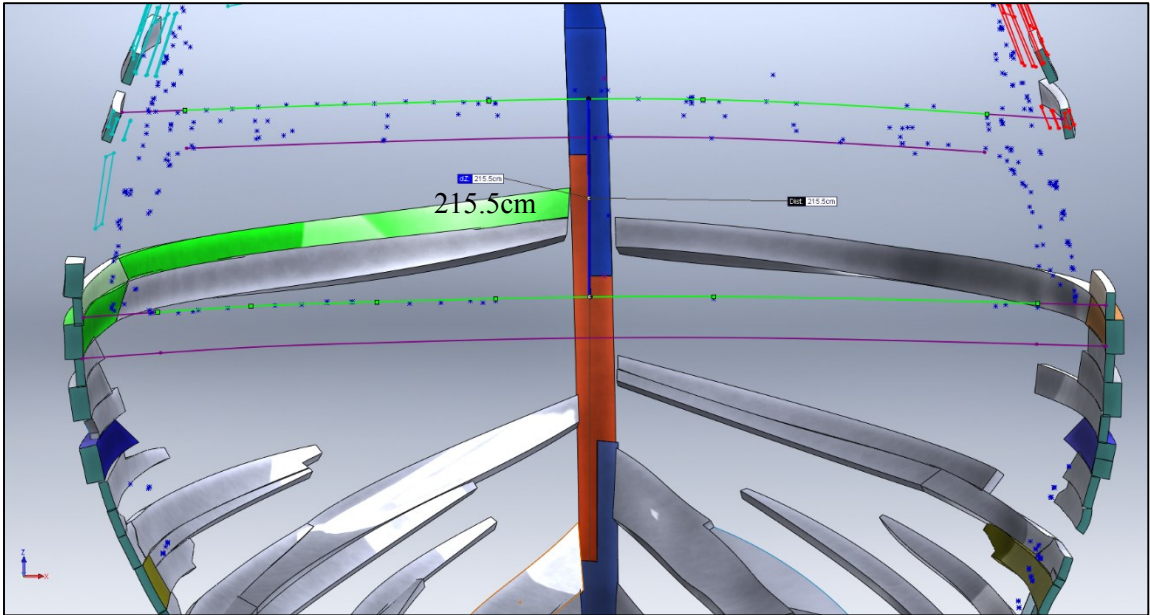


Figure 6.81. The height of the lower gundeck, measured at the *hals*.

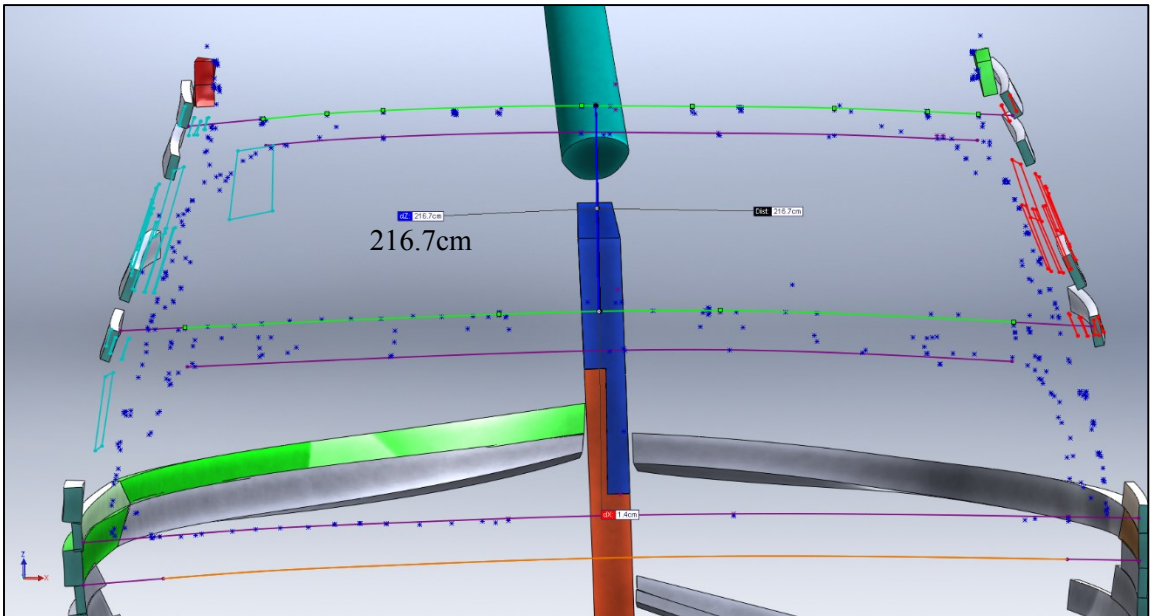


Figure 6.82. The height of the upper gundeck measured at the *hals*.

PLANKING AND WALES

Once the top timbers and deck beams were in place, most of the exterior of the hull was planked. The planking of *Vasa* is reasonably consistently 9.9 cm./4 in. S thick. There is significant variation in plank width. Witsen suggests making the planking approximately $\frac{1}{4}$ of the thickness of the inner stem.¹⁴⁵ If *Vasa*'s inner stem measurement of 18 in. S is taken, this would result in 4.5 in. thick planking, though Witsen clearly states this was not a fixed rule. The thickness of *Vasa*'s planking appears to be within the range of dimensions Witsen indicates was typical.

The lower wales are approximately 19.8 cm./8 in. S thick. They range in width between 37.1 and 37.6 cm./1 ft. 3 in. S (15 in. S) on the starboard side and 36.8 and 38.9 cm./1 ft. 2 in. S-1 ft. 4 in. S (14-16 in. S) at the *hals*. The lower wale spacing varies between 28.6 and 30.8 cm./1 ft. S on the port side and 28 and 31.2 cm./11 in. S-1 ft. S at the *hals*, suggesting an intended spacing of 1 ft. Witsen suggests making the lower wales $\frac{1}{2}$ the thickness of the stem and as broad as the stem thickness.¹⁴⁶ *Vasa*'s lower wales are approximately 1 in. thinner than half of the stem thickness, and 2-4 in. narrower than the inner stem thickness. This is in accordance with the average thickness of the planking, which is on the thinner side of what Witsen indicates was common.

¹⁴⁵ "The planks thick $\frac{1}{4}$ of the stem." Hoving 2012, 59. "*De plancken dick op $\frac{1}{4}$ van de steven.*" Witsen 1671, 68. "More often than not the planks are taken a little less than one fourth of the stem." Hoving 2012, 59. "*De boei-plancken een vierde deel van de dikte van de steven.*" Witsen 1671, 68.

¹⁴⁶ "The Lower wale $\frac{1}{2}$ the thickness of the stem. The breadth, as the stem is thick. The upper wales less." Hoving 2012, 91. "*'t Onderste barghouts dikte op de $\frac{1}{2}$ van de steven. De breete, als, de steven, dick is. De hooger barckhouten minder*" Witsen 1671, 68.

DESIGN COMPLETION

At this point in construction, the majority of the hull shape was determined and the major design choices of the shipwright were over. The hull was planked to about the height of the upper gundeck and then the ship was launched. The rest of construction proceeded while the vessel was afloat. What was left to build was largely determined by the structure already in place.

The focus of this chapter is identification and quantification of the major design choices made by the shipwrights that affected the shape of *Vasa*'s hull. This has not been an exhaustive study. The interpretation of the size and configuration of *Vasa*'s principal design components has been aided by Witsen's 1671 treatise, which provides welcome clarity in some cases and mystifying ambiguity in others. The result of this analysis, however, is a description of the components and features of *Vasa*'s hull chiefly responsible for determining its size and shape. This is similar to the type of quantitative data found in Dutch shipbuilding contracts from the early 17th century, with the addition of the logic and rules shipwrights employed to effectively design and build a large wooden vessel. The particular findings of this chapter are summarized below in Table 6.2 with broader conclusions in the following chapter.

Feature	Observed (cm)	Observed (Swedish feet)	Intended	Relationship
Length Overall	4717.4	158 ft. 8 in.	159 ft.	Keel +30 ft.
Hals	1574.1	53 ft. from stem	53 ft.	53 ft. from stem
Breadth	1111.5	37 ft. 5 in.	36 ft./37 ft. 5 in.	Begin with 1/4 LOA, modified to the desire of the SW
Depth	450.1	15 ft. 2 in.	15 ft.	Begin with 1/10 LOA, modified to the desire of the SW
Keel length	3830.8	129 ft.	129 ft.	4/5 LOA, 30 ft. less than LOA
Keel molded max	60.1	2 ft. (24 in.)	2 ft. (24 in.)	1 1/3 inner stem thickness
Keel sided max	54	1 ft.10 in. (22 in.)	1 ft. 10 in. (22 in.)	1 1/2 inner stem thickness
Keel mark 1	42.3 abaft midships	1 ft. 5 in. S abaft midships		Midship point
Keel mark 2	151.6 abaft midships	5 ft. 1 in. abaft midships		Heel of mainmast
Stem Height	733.9	24 ft. 8 in.	24 ft. 8 in.	Approximately Depth + Rise in Sheer Forward + Height of Lower Gundeck
Stem Rake	751	25 ft. 2 in.	25 ft. 2 in.	Height + 6 in., or neutral
Inner Stem Thickness	44.5	18 in.	18 in.	3/4 of stem height (whole ft. only) in inches
Outside Stem Thickness	33.2-36	13-14 in.	13-14 in.	3/4 on inner stem
Stem Breadth	98	40 in.		Roughly twice inner stem
Curve of Stem	56.6	23 in.	2 ft.	Shipwright's discretion
Sternpost Height (no extension)	807.5	27 ft. 2 in.		Depth + Rise in Sheer Aft
Sternpost Height (extension)	873.6	29 ft. 5 in.		
Sternpost Rake (no extension)	131.9	4 ft. 5 in.	4 ft. 6 in.	1 ft. for every 6 ft. sternpost height (whole ft. only)
Sternpost Rake (extension)	137.5	4 ft. 7 in.		

Table 6.2: Summary of observed and interpreted dimensions of design elements.

Feature	Observed (cm)	Observed (Swedish feet)	Intended	Relationship
Sternpost Molded on Keel	155.4 est	5 ft. 3 in. est		
Sternpost Lower Aft Face Molded on Keel	19.4	7 in.		
Sternpost Lower Forward Face on Keel	24.6 est	10 in. est		
Sternpost Upper Face (extension) Molded	47.1	1 ft. 7 in.		
Sternpost Upper Face (no extension) Molded	57	1 ft. 11 in.		
Sternpost Upper Face (extension) Sided	43	1 ft. 5 in.		
Sternpost Upper Face (no extension) Sided	45	1 ft. 6 in.		
Wing Transom Length	582.8	19 ft. 7 in.		
Wing Transom Molded	36	14 in.		
Wing Transom Sided Inner Face	53.7	22 in.		
Wing Transom Sided Outer Face	57.9	23 in.		
Wing Transom Curve	36.8 est	14 in. est		Equal to wing transom molded dimension
Wing Transom Height Above Keel, Lower Face	739.4	24 ft. 11 in.	25 ft.	
Fashion Pieces Outside Curve	150.6-152.1	5 ft. 1 in. est	5 ft.	
Fashion Pieces Inner Curve	90-99 est	3 ft. -3 ft. 4 in. est	3 ft.	
Fashion Pieces Lower Ends Along Sternpost	395.5	13 ft. 4 in.	13 ft. 4 in.	Halfway up sternpost
Total Stern Height (top of keel to top of stern timber)	1595.5-1603.5	53 ft. 8 in. -5 ft.'	54 ft.	

Table 6.2: Continued.

Feature	Observed (cm)	Observed (Swedish feet)	Intended	Relationship
Stern Timbers Height	802.9-804.3	27 ft.-27 ft. 1 in.	27 ft.	Half of 54 ft., total stern height, equal to the height of the sternpost
Stern Timbers Top Spacing	349.3	11 ft. 10 in.	11 ft. 10 in.	2 ft. broader than half the wing transom
Bottom Breadth	712.1	24 ft.	24 ft.	2/3 original breadth (36 ft.)
Deadrise (from bearding line)	43.4-49.8	18-20 in.		
Bilge Depth	148.5	5 ft.		1/3 of Depth
Bilge Width	990.6-1006.7	33 ft. 4 in.-33 ft. 11 in.		2 ft. or 2 ft. 6 in. narrower than max breadth
Bilge Planking Curve	33.5-36.6	1 ft. 2 in. -1 ft. 3 in.		
Breadth at upper gundeck	1021.8	34 ft. 5 in.		
Breadth at weather deck	867.7	29 ft. 3 in.		
Top Timber Spacing	832.8	28 ft.		3/4 of Breadth (37 ft. 5 in.)
Tumblehome (from max breadth)	278.7	9 ft. 5 in.		1/4 of the Breadth
Lower gundeck beams molded	44.6	18 in.	18 in.	1 1/8 in. for every 10 ft. of length overall
Upper gundeck beams molded	41.5	17 in.		
Weather deck beams molded	28	11 in.	12 in.	2/3 of the inner stem
Rise in Sheer Forward	54.7-57	1 ft. 10 in. -1 ft. 11 in.	2 ft.	
Rise in Sheer Aft	363.3-364.8	12 ft. 2 in. -12 ft. 4 in.	12 ft.	
Height of Lower Gundeck	215.6	7 ft. 3 in.		
Height of Upper Gundeck	216.5	7 ft. 3 in.		
Total Height (Keel to Upper Gundeck Beams)	882	29 ft. 8 in.		
Planking thickness	9.9	4 in.	4 in.	Approximately 1/4 of the inner stem
Lower wale thickness	19.8	8 in.		Approximately 1/2 of the inner stem
Lower wale width	36.8-38.9	14-16 in.		
Lower wale spacing	28-31.2	11 in. -1 ft.	1 ft.	

Table 6.2: Continued.

CHAPTER VII

CONCLUSIONS

The gun room should not be too low; because then the water, which comes over the ship, will come into it and bring much misfortune.¹

VASA DESIGN METHOD

Based on the design analysis of the previous chapter, several conclusions can be drawn about the hull of *Vasa* and the methods used to design the shape of its hull. Broadly, the dimensions of many of *Vasa*'s principal design components exhibit either proportional or arithmetical relationships characterized by even dimensions and simple fractions. The hull exhibits a top-down design approach, with most of the primary dimensions (length, breadth, depth) driving the design of many secondary hull features and timbers. The most significant dimensions for determining *Vasa*'s hull form are the primary dimensions of the length overall, the breadth and depth at the *hals*; and the secondary dimensions of the height and rake of stem, the height and rake of sternpost, the length of the wing transom, the height and spacing of the stern timbers, the shape and location of the fashion pieces on the sternpost, the bottom breadth and deadrise, the bilge breadth, depth, and curve, and the amount of tumblehome at the *hals*.² The particular dimensions of these factors generally describe the shape of *Vasa*'s hull. Nearly all of these elements show evidence of calculation according to proportional and arithmetical means.

Overall, the design decisions in the hull appear focused into three regions: the *hals*, the bow, and

¹ Hoving 2012, 77. '*De konstapels kamer dient niet te laeg te zacken; want dus zal 't water, 't geen over 't schip komt, daer in loopen, dat groot onheil by kan brengen.*' Witsen 1671, 267.

² Curvature is very difficult to accurately quantify in the hull, the northern Dutch shipbuilding tradition did not rely on the use of compasses in ship design.

the stern. For example, the dimensions of the stem do not seem to have had a direct effect on the dimensions of the sternpost, and vice versa, although the length, breadth, and depth measurements of the hull are used to calculate secondary measurements in all three hull regions.

There is substantial evidence to suggest that the hull was designed and built using Swedish feet as the standard unit of measurement for design-critical elements.³ This is based on the rulers found in the hull, the spacing of draft marks on the stem and sternpost, and the degree to which the dimensions and relationships observed throughout the course of this dissertation project align with distances measured in Swedish feet.

Throughout analysis, a pattern emerged that suggests the port side of the hull was the preferred side for taking measurements. This is evidenced in several hull components: the stem, keel, and midsection. The measuring conventions for the height and rake of the stem are based on measurements taken on the port side.⁴ The starboard side of the keel is shortened by the boxing scarf at the connection with the stem and an oblique cut at the skeg. These cuts make the starboard side of the keel 2 ½ ft. shorter than the port side, which has an even measurement of 129 ft. The markings on the keel, which possibly indicate the midpoint of the length overall and heel of the mainmast, are both incised on the port side of the keel. These markings would have only been easily accessible until the bottom was planked, suggesting they may have been marks used when planning the configuration of the ship. A cross-section of the ship at the *hals* shows

³ The presence of rulers of different units suggests it is possible that units other than the Swedish foot may have been used to build contingent hull features. Not all aspects of the hull were investigated in this study.

⁴ Apparently following Witsen's indications, though he does not explicitly state that measurements should be taken on the port side.

the extents of the bottom planking and the bilge planking both correspond with the edges of planks on the portside, but less so on the starboard side. Taken together, this evidence may suggest a preference for taking measurements on the port side while the vessel was under construction. Although Witsen's treatise is not explicit about this, some illustrations indicate that measurements were in fact taken from the port side. Without more archaeological examples, however, it is impossible to say if this is simply a coincidence between the hull of *Vasa* and Witsen's treatise, or a general characteristic of northern Dutch shipbuilding practice.

Witsen

The hull form design analysis of *Vasa* is a unique and valuable insight into an influential shipbuilding tradition. The opportunity to study an intact vessel is indeed a rare archaeological opportunity. As evidenced by the dimensions and relationships of features in the hull, *Vasa* appears to have been designed and built according to an established shipbuilding tradition. This tradition has been represented archaeologically by many wrecks and is most fully described by Nicolaes Witsen in his 1671 treatise. Many key design features of *Vasa*'s hull appear to be derived according to the methods either matching or very similar to those described by Witsen.⁵ Although much of the hull of *Vasa* closely follows the shipbuilding and design practices described by Witsen, there are some significant departures suggesting a degree of innovation or experimentation on the part of the shipwrights. The most significant departure is the length of the wing transom. *Vasa* was built with a much narrower stern than what is described in Witsen's treatise. The maximum breadth and breadth of the bilge planking are likewise smaller than one

⁵ Despite the fact that Witsen was using a foot of 11 inches, and Hybertsson was using a foot of 12 inches, many of the same rules still seem to apply. Guidelines were proportional, rather than absolute, so they could be scaled to the size of the ship, and therefore can function in different units.

might expect, especially for a warship, though in the range of possibilities described by Witsen.⁶ Jacobsson's concern and modification to the hull also speaks to the unusual narrowness of the hull. On the whole, however, when compared with Witsen's description of typical shipbuilding methods in the Netherlands, *Vasa* shows conservatism in design and its dimensions and proportions are generally within the guidelines of what was considered typical of the time, according to Witsen.⁷

Witsen's treatise clearly indicates that in most cases, the length overall would be the first dimension decided upon by the shipwright and his client. Most of the other primary design components of the hull were in turn derived from the overall length. In *Vasa*'s case, however, it seems as though the length of the keel was the first defining dimension. The length overall was likely derived from the length of the keel, as suggested by the even 30 ft. difference between the dimensions. From this point forward in the construction, however, the length overall served as the primary driving dimension. The next most significant dimensions, the breadth and depth at the *hals*, were derived from the length and served as the basis for the calculation of many of the most significant aspects of the hull shape. The formulaic method for determining the shape and size of hull features and timbers based on the length overall ensured that the basic form of a ship that proved successful could be scaled up or down based on the requirements and resources of the shipwright and client.

⁶ It is possible these features contributed to *Vasa*'s demise, however this issue is outside the scope of this dissertation.

⁷ The construction of vessels with two gundecks, however, is not discussed by Witsen.

Witsen places a great deal of importance on the sided dimension of the inside of the stem and derives nearly half of his specified hull components from it.⁸ From what can be observed, there is less reliance on this dimension in the design and construction of *Vasa*. The sided and molded dimensions of several important timbers, including the sternpost, wing transom, planking, wales, and stern timbers, do not appear to be derived from the observed dimensions of the inside of the stem. It is possible, however, that the correct dimension of the inside of the stem is simply inaccessible. Future analysis of *Vasa*'s hull may reveal another design unit used to guide the dimensions in the same way as Witsen's inside stem or that these decisions were simply left to the judgment of the shipwrights. It is also possible that Witsen overstated the importance of the inside of the stem in the design process and it was not as commonly used in practical shipbuilding as indicated in his largely theoretical work.

VASA IN CONTEXT

Vasa is the product of the early modern fiscal-military revolution and an ambitious Swedish king who favored an aggressive form of diplomacy. Yet it was designed and built by Dutch shipwrights according to a unique shipbuilding tradition that made Dutch shipwrights renown throughout coastal Europe. As evidenced by *Vasa*, this tradition was well-adhered to even as Dutch shipwrights worked abroad. Hybertsson and Jacobsson operated within this tradition but were urged by Gustav Adolf to expand the limits of naval architecture and build a powerful new warship unlike any others in the Swedish Navy. They confronted this challenge by employing the well-adhered to methods of Dutch shipbuilding while introducing innovation as necessary. Due to a number of circumstances, the result was not entirely successful but also not entirely a

⁸ Hoving 2012, 250.

failure. Due to *Vasa*'s short voyage, it sank in an environment that kept it remarkably well preserved. It is now the oldest intact ship ever recovered, the oldest intact warship, the only complete 17th-century vessel above the water, the centerpiece of the most visited maritime museum in the world, and a host of other superlatives. It is also a unique window into an exciting and poorly understood chapter of maritime history, architecture, and seafaring.

FUTURE RESEARCH

Avenues of future research include greater comparison of *Vasa*'s dimensions and design to other contemporary vessels, both Dutch built and not, as evidenced in archaeological and archival records. The early 17th century saw rapid growth in the size and firepower of warships. Shipwrights were tasked with putting increasing numbers of guns on ships, while still maintaining a seaworthy hull capable of travelling to theaters of war, making effective use of their weapons, and withstanding enemy fire. Balancing these requirements was challenging and, as *Vasa* demonstrates, shipwrights and naval officials were not always successful.

At the inquest after *Vasa* sank, Hybertsson's business partner Arendt de Groot testified that the design of *Vasa* was based on a large warship recently built in the Netherlands for the French nobleman Charles, Duc du Guise. De Groot claimed to have seen the vessel while under construction and shown Gustav Adolf a picture of this new ship that was to serve as the model for *Vasa*.⁹ There has been difficulty in verifying whether this was actually true or a fabrication by de Groot to shift the blame for the disaster off of the shipwrights. Several scholars have

⁹ Madebrink 2012, 7.

attempted to identify which ship de Groot was referring to with the most likely candidate, identified by Jan Glete, as the *Galion du Guise*, a two-decked warship roughly the same size as *Vasa* built for the French Mediterranean fleet. Although the place of construction for this vessel is unknown, the Netherlands is a likely possibility. The *Galion du Guise* had a successful career until it was wrecked in 1642.¹⁰ Further research into other large warships, particularly those with two gundecks, in the early decades of the 17th century will establish a greater understanding of *Vasa*'s place in the evolution of warship technology.

Although *Vasa* was the largest naval architecture project of Henrik Hybertsson's life, this was not the case with Henrik Jacobsson. Following *Vasa*'s sinking, Jacobsson went on to build at least three more large and successful warships. The keel of *Applet* (the third warship of this name), the first of Jacobsson's ships and the second ship of the January 1625 contract, was laid down in the same shipyard as *Vasa* in 1627 and completed in 1629.¹¹ This ship was generally the same in size and configuration as *Vasa*, but was designed and built to be 5 ft. wider, further suggesting Jacobsson had significant concerns over *Vasa*'s breadth and stability.¹² Jacobsson's subsequent ships, *Kronan* (the largest ship in Gustav Adolf's navy) and *Scepter* (regarded as the best ship in the fleet) were both proportionately wider than *Vasa* and built with increased room for ballast.¹³ All three of Jacobsson's warships had successful careers. The modifications Jacobsson made to *Vasa*'s hull and his subsequent designs speak to concerns over hull stability. Given the nature of *Vasa*'s demise, this is clearly a relevant issue in the debates over the causes for the disaster. Further analysis of the dimensions and proportions of Jacobsson's other vessels

¹⁰ Hocker 2006, 42.

¹¹ Hocker 2011, 145.

¹² Glete 2002c, 20.

¹³ Madebrink 2012, 46-49.

may lend greater insight into *Vasa*'s design methodology. Examining *Vasa* in the broad context of other warships throughout Europe will shed light on both the practical and theoretical approaches of designing and building large warships in the early modern period.

MODELING

In this project, 3D modeling proved an invaluable tool and it is unlikely that an equally detailed analysis of the hull form and its design methods would have been possible without it. The point cloud data was the most valuable source of data regarding the hull. Modelling maximized the utility of this data by creating solids out of what was otherwise a cloud of points and curves. The methodology and software used, however, were not without their challenges and opportunities for continued improvement.

SOLIDWORKS

SolidWorks proved to be an effective software package for completing this dissertation project. Prior to this project, I had very limited experience with 3D modeling and was only acquainted with the wireframe and surface modeler Rhinoceros. Compared to the creation of surface models in Rhinoceros, I found the creation of solid models in SolidWorks to be easy and intuitive. Model creation in SolidWorks is efficient and bears similarity to physical modeling. The feature based modeling approach requires that models are created one step at a time, with a clear record of the progress of modeling. Modeling is very flexible with SolidWorks and the software offers many approaches to the creation of a model, is capable of rapidly manipulating objects, provides many different viewing options, and a wide range of analytical tools. While

there is a learning curve associated with any software package, I believe archaeologists will find SolidWorks to be a very approachable tool. Compared to other 3D modeling and solid modeling packages with similar capabilities, the hardware requirements and costs of the software present a low barrier to entry.¹⁴

Modeling Successes

The study of an intact hull proved challenging. Whereas archaeologists typically have only fragmentary remains of a vessel which allow complete documentation and disassembly of timbers, this is not a possibility with the hull of *Vasa*.¹⁵ The hull is also very large, which creates logistical problems for both measuring the hull by hand and accurately analyzing the hull while not on site. 3D modeling enabled the creation of full-scale models of hull components away from the museum which greatly increased the efficiency of the project and reduced travel and research costs. The models showed great flexibility and the software offered the ability to easily evaluate the physical relationship of individual parts to each other and modify them necessary to bring them into closer alignment with physical reality. 3D solid modeling combined the schematic and large-picture analysis of paper reconstruction with the physical reality of wooden scale modeling. In this project, the hull was built as individual components which were then assembled together in a manner and order similar to how the ship was originally built. Unlike physical modeling, however, a limitless number of views, configurations, annotations, and

¹⁴ The modeling in this dissertation was carried out using free student versions of the software with a time-limited license. Purchasing a full version of SolidWorks, however, is generally much less expensive than comparable products. Many commercially available 3D modeling programs, including SolidWorks, AutoCAD, Autodesk Inventory, Rhinoceros, and Blender, have relatively low hardware requirements meaning they can be run effectively on even modestly powerful desktop and laptop machines. A wide variety of file formats and software standards means that data exchange between programs, and consequently between archaeologists, is easier than ever.

¹⁵ I asked. Museum officials said no.

schematic images can be produced from these visualizations. Images can be easily generated from models that isolate and display clear illustrations and explanations of the structure and arrangement of ships hulls.

Solid modeling both expedited the creation of models but also created more accurate and precise models with many possibilities for expanded analysis in the future. Through the modeling process, I gained greater insight and understanding for both the small-scale mechanics of assembling a ship and the large-scale architectural design of a hull form. The creation of 3D models from total station data, photographs, measurements, and sketches forced me ask questions about the design methods and confront gaps in the data that I may not have encountered if I had not used digital modeling for this project. The subsequent assembly of those models into a more complete hull form prompted further questioning and analysis that led to a fuller and more nuanced understanding of the hull form design methods. The ability to create a model and instantly measure it with precision and accuracy resulted in the discovery of subtle relationships between hull elements that promoted insight into the decision processes and logic of the shipwrights. As a tool for reverse naval architecture and seeking deliberate human selection through quantification, 3D modeling is a powerful and effective tool.

Modeling Limitations

The point cloud data compiled by the staff of the Vasa Museum was central to the creation of the 3D models in this project. However, the point clouds do not supply enough information on their own to enable the creation of detailed solid models. Manual measurements, photographs, and drawings were required to supplement the point cloud data and create more accurate models of

Vasa's hull components. Despite my best efforts, gaps in data were identified throughout the modeling process. Although these gaps were eventually overcome, they did slow down and complicate the modeling process. I did not begin this dissertation project with the intention of using 3D solid modeling as an avenue of analysis. The data collection and modeling could have been more efficient if I had this goal in mind from the beginning. The learning curve, time, and accuracy of implementation of a 3D modeling project could be dramatically reduced if 3D modeling is the goal from the beginning of a project and documentation is carried out accordingly at all stages of an excavation or analysis.

While SolidWorks is capable of applying the physical properties of organic materials to models, software was found to have some trouble modeling surfaces with complex organic curvatures. This was especially true when surfaces had irregular edges as was the case with the Z scarfs between hull planks. In some cases, the modeled surfaces of the planks were dramatically distorted. Through trial and error it was found that many of these aberrant surfaces could be smoothed by altering the scarf edges. This resulted in models that do not replicate their physical counterparts but instead closely approximate their shape and size. These compromises did not have an effect on the analysis in this dissertation.¹⁶ 3D modeling is a skill that is quick to begin using but slow to master. With each part of *Vasa*'s hull, I encountered new challenges and sought different solutions through the software tools and capabilities. The range of tools used in the completion of this dissertation project is only a small fraction of the modeling tools SolidWorks offers to users.

¹⁶ It is possible that the software is perfectly capable of modeling these surfaces accurately, but the operator in this case was not able to make the software comply.

Although the material properties of woods and metals can be applied to solid models to make them behave as their real-world counterparts, the process of building digital models is far removed from the actual shipbuilding process. Archaeologically minded model makers such as J. Richard Steffy, Glenn Grieco, and A.J. Hoving have repeatedly demonstrated the value of building models out of wood and the types of shipbuilding intuition and understanding that come as a result. Digital modeling cannot replace this. It does, however, present a range of other analytical and testing possibilities that wooden modeling does not, and make modeling accessible to those without woodworking tools or skills.

One major aspect of 3D visualization bears consideration particularly in the context of design analysis. Since Dutch shipwrights designed their vessels by eye, shipbuilding was necessarily an iterative process. This means that the shipwright's decisions about the design of a vessel built upon each other, and subsequent design specifications were at least somewhat dependent upon prior specifications. Therefore, the shipwright was never able to view the ship the same way archaeologists can with visualization technology. Modeling software allows users to view objects in nearly any orientation and zoom level, parts of models can be hidden, wireframed, etc. Shipwrights would not have these same options, therefore it is critically important to remember that while advanced technology is aiding in the process, the focus of investigation is still the people who created these ships. Care must be taken to not over-interpret the artifacts through powerful visualization technology but instead maintain focus on the point of view of the shipwrights.

By adopting software built to confront the challenges of mechanical design and manufacturing, archaeologists can easily construct and modify virtual models with real world fidelity, a considerable advantage over costly and time consuming physical modeling. Of the three types of modeling in widespread use, solid modeling has the most to offer archaeologists regarding reconstruction and physical evaluation. Solid modeling, specifically virtual prototyping software, enables types of analyses (FEA and others) that are of considerable use in archaeological evaluation. It has, however, been so far underutilized, particularly in nautical archaeology. Virtual prototyping software has the potential to dramatically reduce the research and reconstruction time, lead to higher quality reconstructions, and achieve greater scientific accuracy. A wide variety of dissemination options are also possible, using compelling illustrations of rendered 3D models.

APPLICATIONS

Within academia, 3D visualizations create valuable opportunities for collaboration among scholars and across disciplines, can facilitate the clear communication of complex ideas, and provide avenues for enhanced dissemination, all of which strengthen and advance the practice of archaeological science. The increased digitization of archaeological and scholarly material facilitates the rapid and large scale transfer and sharing of data. Examples include embedding interactive 3D models in PDF files, using rapid prototyping devices to reproduce artifacts, and making 3D data available via online artifact collections.¹⁷ Digital technology is reaching a point where 3D data of sites and artifacts can replace the need to handle or view the actual object.¹⁸

¹⁷ Rapid prototyping technology, also known as 3D printing, allows production of objects in a variety of media including plastic, wood, paper, metal, and plaster.

¹⁸ Apollonio et al. 2012. 1271.

With a shift to an ever more digital workspace, distance between archaeologists and their sites or material is becoming less important.

3D visualization in archaeology also presents many benefits that extend beyond the walls of the academy. Visualization technologies play a vital role in raising public awareness and appreciation for cultural heritage. 3D modeling of artifacts creates a wide range of potential applications that can engage and educate a variety of audiences. Once a digital model of an artifact is created, a wide range of possibilities exist for its application. Simulations can create immersive reconstructions of historical environments from the same models used for archaeological analysis bringing archaeological and scientific rigor and accuracy to portrayals and representations of the past. Games and other interactive learning and exploration tools are a natural extension of these simulated environments. The digital medium and pervasiveness of mobile internet-connected devices creates a multitude of dissemination possibilities through online channels that are independent of the physical confines of traditional cultural heritage institutions.

Whereas artifacts are often viewed behind glass in sterile environments, digitization and rapid prototyping technologies can bring the physical experience of artifacts into the hands of the public. Replicas of artifacts can be exhibited and used in reconstructed environments, historical reenactments, or practical demonstrations of the artifact's original purpose. In this way, computer modeling technology does not replace physical modeling, but complements and enhances it. Digital visualization technologies have the potential to break down barriers between academia and the public and democratize archaeological research.

Nautical archaeology easily captures the imagination and interest of the public. Too often, however, initial enthusiasm is met with dry technical details or diagrams that alienate non-specialists. 3D modeling and simulation can help to hold public attention without sacrificing scientific accuracy. Simultaneously, increased application of 3D visualization has the potential to be a methodological step forward in the academic practice of nautical archaeology. The adoption of 3D modeling technology should be viewed as another archaeological skill, like artifact illustration, that can remove barriers between the archaeologist, the artifact, and the analytical results. Widespread adoption of digital 3D modeling technologies is a bold step toward bringing the practice of nautical archaeology into the 21st century.

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APPENDIX

GLOSSARY OF 3D MODELING TERMS

Terms are defined with reference to their application in SolidWorks. Unless otherwise noted, definitions are from the SolidWorks help file.

Assembly: A file in which parts, features, and other assemblies are mated together.

Boundary-representation (B-rep): A solid modeling approach that defines solids by their enclosing surfaces or boundaries. Boolean operations, such as union, intersection, or difference are often used to modify the boundaries of an object.¹

Boundary surface: A surface created between two or more bounding sketches.

Constructive solid geometry (CSG): A solid modeling approach that constructs parts through the application of Boolean operations to basic shapes such as cylinders, spheres, cubes, and cones.²

Curve: A non-linear 2D or 3D entity with two endpoints and curvature controlled by one or more control points.

Extruded cut: A linear projection of a sketch profile to remove material from a part.

Feature: An individual shape or modification of a shape that when combined with other features defines a part or assembly.

Guide curve: A curve used to control the contour of a loft between profiles.

Line: A straight sketch entity with two endpoints.

Loft: A solid body created by interpolation between two or more profiles.

Mate: A geometric relationship between two or more parts in an assembly.

Parametric: Values and constraint configurations that control the shape of a sketch or solid body.³

Part: A single 3D object made up of features.

¹ Amirouche 2004, 185.

² Amirouche 2004, 186.

³ Hoffmann and Joan-Arinyo 2002, 519.

Plane: Flat construction geometry used as the basis for a sketch or sectioning a model.

Point: A singular location in a sketch, defined by an X,Y,Z coordinate.

Sketch: A collection of lines and other 2D or 3D shapes on that forms the basis for the creation of features. Sketches can be planar (2D) or non-planar (3D).

Sketch path: A sketch, edge, or curve used in creating a sweep or loft.

Spline: A 2D or 3D curve defined by control points.

Split: The separation of a solid body into two or more distinct entities.

Surface: A planar or 3D entity with edge boundaries that contains no thickness.

Surface cut: A feature that uses a surface to define the region of a solid body to be removed.

Swept cut: A feature that uses a profile sketch and sketch path to define the region of a solid body to be removed.

Texturing: The application of a 2D image to the surface of a 3D digital object. Often used to create models with greater realistic appearance.

Wireframe: A method of modeling that only displays the edges of an object.