**Naval power and textile technology: sail production in ancient Greece**

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> *"It is right that those who work for their living and the common people should have more than the high-born and the wealthy, because it is the common people that set the ships in motion and give the power of the city."*
>
> (*Constitution of the Athenians* 1.2)

*Introduction*

Control of the sea has been fundamental for the rise and maintenance of imperial power through history. Navies were instrumental to imperial expansion, the protection of commercial interests, and the extraction of tribute and tax and other resources for sustained prosperity of the imperial centre. The significance of fleets to ancient empires has been recognised and studied extensively and it is established, particularly with reference to Athens in the 5th and 4th century BCE, that the operation and maintenance of fleets required enormous funds and infrastructure (Gabrielsen 1994). One essential, though little examined aspect, is the role of sails and textile technology in the rise and maintenance of ancient fleets (Spantidaki 2018; Nosch 2014). Hence, the aim of this paper is twofold: to achieve a better understanding of sail production in ancient Greece, taking as a case-study the well-documented Athenian fleet, and in this way to examine the intersections between imperial power and textile technology.

The growth of fleets would have been a major factor driving demand for textiles in ancient Greece from the 8th century BCE onwards. Ships were the *conditio sine qua non* for the expanding trade and migration of the Archaic period. They were also vehicles of war. While oars served for quick manoeuvers and movement upstream, propulsion by wind power was essential for overcoming distances. The growing number of ships would have generated greater demand for sails and cordage and put pressure on the resources and labour involved in producing them. Demand for sails would have continued to grow, perhaps exponentially, with the expansion of commercial fleets and navies during the Classical and Hellenistic periods.

How did the growth of fleets affect textile economy and underlying social relations? In order to address this question, we need to first, consider how many and what kinds of textiles a ship needed; second, reconstruct how they were made; and third, calculate what resources and labour it took to produce them. Then we need to translate how the labour and resource requirements of sailcloth production changed at different scales. Finally, we need to consider how expanding production affected power relations and the social fabric. These steps set the structure for the exploration below.

Quantitative data on the number of ships, labour and resource requirements are critical for this exercise. Because the evidence for them is weaker, agricultural labour and land requirements are beyond the scope of this paper. Information can be extracted from written sources, surviving maritime textiles, historical parallels, and experimental archaeology, and while imperfect, these data provide helpful guidelines and estimates. We have little information about the number of trading ships, but there are written sources and extensive scholarship on the technology and economics of navies, as well as their significant effects on wider society.  Thus, Hans van Wees has argued that naval expansion, and particularly the decision of Greek cities to build expensive warships (*triremes*) in the late 6th century BCE in order to match the naval technology of their adversary, the Achaemenid Empire, played a pivotal role for the development of public finance (van Wees 2013, 30). Considering the need of these ships for sails and the extensive labour, time and resource requirements of textile industry, these policies would have had a dramatic effect on textile and overall economy.

*Equipment*

Most sailboats would have had a single square sail, furled and unfurled using brails, as shown by images and references to ships from the Late Bronze Age onwards (**Figure 1**) (Casson 1971, 36–59). A two-mast ship with two sails was painted on the rim of a krater, found on a sixth-century floor in Corinth (**Figure 2**), but it is a rarity (Casson 1980). Other fore-and-aft rigs were familiar to sailors by the early 2nd century BCE, as tomb stone reliefs indicate (Casson 1971, 243–244).

Records of the 4th century BCE from the Athenian harbour, Piraeus, list the 'hanging' equipment of warships (*triremes*) in detail, including the main sail, a foresail, screens or awnings as well as special bracing ropes that tensed the vessel from prow to stern, and rope tackle for a range of other purposes (Gabrielsen 1994, 227–228; Spantidaki 2018, 77–78).

Further textiles were required for waterproofing the hulls of ships and boats. Ongoing conservation of a Roman barge from the 2nd century CE in Lyon, France recovered 26 $m^2$ of caulking material. Some fragments are identified as recycled sails based on impregnation with ochre and the width of reinforcement strips (Meunier and Guyon forthcoming). Some hulls were sewn together, requiring further lengths of yarn and skilled labour. For the *Gyptis*, a reconstruction of a 6th-century sewn fishing boat, that amounted to about 5 km of linen thread and 3,000 hours of sewing (Pomey and Poveda 2018, 50). Further rolls of linen cloth were used as wadding to waterproof the joints and to protect the stitches (Pomey and Poveda 2018, 46).

*Materials and technology*

Flax was the main material for sails in Greece, according to the written sources (Nosch 2014; Spantidaki 2018). The use of hemp, especially for ropes, is also noted from the 5th century BCE. Surviving archaeological textiles indicate that until the 6th century BCE linen thread was produced by splicing and from then on it was primarily spun – a technological change that may have been prompted by the growing demand for maritime textiles (Gleba and Harris 2019; see **Table 1** and Gleba et al. forthcoming for the chaîne opératoire of linen). Sailcloth would have been woven on the archaeologically-attested warp-weighted loom and other looms that do not typically leave traces, such as the horizontal ground loom or the two-beam loom. Some sails were also dyed in the Classical period (Spantidaki 2016, 80).Sources from 325/4 BCE distinguish between light and heavy sails, tantamount to two qualities of cloth (Gabrielsen 1994, 258 n. 17, IG $2^2$ 1623.368-75; 1629.667-73). The distinction may be echoed in much later periods: the Swedish ship Vasa which sank in 1628 carried two qualities of sails, coarser and finer (Westheden Olausson 1998). In the absence of preserved sails from Classical Greece, we cannot be sure what the terms correspond to. But the average technical properties of sailcloth in the Archaic and Classical period can be deduced with relative confidence because archaeological finds of sails from the Roman and later periods demonstrate limited variation in weave structure and density (**Table 2**). The known examples from the Mediterranean area are plain weaves with 7 x 7 threads/cm to 22 x 12 threads/cm, but most values gravitate towards the median of 10–13 threads/cm.

Once woven, pieces of cloth were sewn together to make a sail. This is how Roman and Viking-age sails were constructed and the practice is reflected in the Greek word *histiorraphos,* 'sail-stitcher' (Spantidaki 2018, 80; Aristophanes *Thesmophoriazusae* 935; Pollux *Onomasticon* 7.160). After an earthquake c. 224 BCE, Ptolemy offered the Rhodians 'gifts' in order to reconstruct their fleet, including timber for ten *triremes* and ten *quinqueremes* and 3,000 pieces of sailcloth (Polybius 5.89), corresponding to 170 pieces for each larger ship and 130 for each of the smaller ones (Morrison and Coates 1986, 185). If this proposition and the sail sizes estimated below are correct, the pieces of cloth would have been 1–2 m² or smaller, possibly woven in narrow strips. Additionally, densely woven webbing bands were sewn in a grid-like pattern to reinforce the sail, as in a linen sailcloth from c. 100 BCE, found in Thebes, Egypt and re-used as mummy-wrapping (Wild and Wild 2001, 216). This case and the example from a Roman barge in Lyon cited above highlight another important factor: textiles, including sails were certainly used for as long as possible in antiquity, then recycled, and repurposed. Parts of a large sail could be used to make a smaller sail or other items. However, it is very difficult to account for this practice in our estimates for demand and supply.

*Sail size*

The size of the sails depends on the balance between the size, purpose, intended speed of the ship and the rigging. War ships were light and fast vessels, which needed large sails to reach the battlefield, after which they would leave the sails and mast ashore and manoeuvre with oars (Casson 1994, 67). Large cargo ships needed even larger sails, in order to move the weight. Smaller boats and ships that did not need as much speed could do with smaller sails.

Reconstructing the exact dimensions of sails is somewhat problematic in the absence of direct evidence for the pre-Roman period, but shipwrecks, ship-sheds, and reconstructions of ancient ships provide some guidelines. The shipwreck evidence shows that small and medium-sized ships were the norm for most trade in the Archaic period and later in history (Horden and Purcell 2000, 145; Schäfer 2012). Ships with a capacity of up to 75 tons or 1,500 amphorae were common throughout antiquity; large commercial ships, reaching 300–500 tons of cargo or 10,000 amphorae appeared late in the Roman Republican period and were rare even then (Greene, Lawall, and Polzer 2008, 112 note 11; Parker 1992, 26). Military vessels before 500 BCE range from boats for 20–30 rowers, such as those mentioned in Homer, to triremes, which were adopted across the Aegean in the 6th century BCE and could carry about 200 crew (Gabrielsen 1994, 6; Casson 1994, 47–77). Judging by iconographic evidence, requirements of the oar system and anatomy, and the sizes of ship-sheds, Boris Rankov estimates that an *eikosoros* was c. 13–16 m long, and a trireme c. 36–41 m in the 5th century and c. 37–42 m in the 4th century BCE and later (Rankov 2013, 90–91).

Several reconstructions of ancient sail ships within this range have been made and have proven sea-worthy (**Figure 3**), so the sizes of their sails give a sense of how much cloth was needed. The *Olympias* was a replica of a 4th-century trireme, 36.9 m long and 5.5 m wide, equipped with a main sail of 95 $m^2$ and the foresail was a quarter of its size, or 119 $m^2$ in total (Morrison and Coates 1986, 223–224). The dimensions of the *Olympias* sail were determined following 19th-century criteria for what was appropriate for the hull. The *Gyptis* is a small sail boat, reconstructed after the mid-6th century BCE wreck Jules-Verne 9 found in Marseille (Pomey and Poveda 2018). The original boat was used for fishing coral, as finds on board show, and probably also light coastal transport of goods and people. The reconstruction was 9.85 m long and 1.88 m wide, with a sail 4.5 m high and 5.5 m wide, totalling 24.75 $m^2$, made of linen and cotton, weighing 410 $g/m^2$. Another small ship, 13.7 m long and 4.4 m wide sunk near Kyrenia on Cyprus c. 300 BCE and was reconstructed with a sail measuring 9.6 x 4.9 m, totalling 47 $m^2$. This reconstruction also used cotton (Katzev and Katzev 1989, 173).

These hull and sail dimensions compare well with the sails made and tested on reconstructions of Viking ships (**Table 3**), which have withstood the test of time and of the sea, having sailed from Denmark to Scotland and Ireland and one of them having been used in twenty sailing seasons (Andersen and Nørgård 2009, 6–7).

In view of the above, we can calculate the labour and materials needed for sails of three sizes, 25 $m^2$, 50 $m^2$, and 119 $m^2$, corresponding to a large fishing boat like the *Gyptis*, a small cargo ship like *Kyrenia* II, and a war ship like *Olympias* (**Figure 4**). The calculations for large sails are obtained by multiplying the amount of time to spin and weave and the material required to weave 1 $m^2$ by the size of the finished sail, although this may be an underestimate.

These calculations are rough approximations, based on the size of reconstructed sails, extrapolations about the properties of ancient sailcloth, and the time required to spin and weave linen with a drop spindle and a warp-weighted loom. Our calculations take into account the main and most readily measurable tasks of producing textiles, spinning and weaving. We recognise that the chaîne opératoire (**Table 1**) included other time-consuming tasks, but we lack sufficient data to factor them in. Hence, the calculations provide a sense of the scale of textile labour, rather than a precise quantification.

*Labour*[1]

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[1] Lise Bender Jørgensen first presented calculations for labour, material, and land requirements for the *Olympias* sail at a conference on held in Cambridge in 2015; Bender Jørgensen forth..

In order to calculate the labour involved in sail production, it is critical to know the yarn requirements, and the speed of spinning and weaving. Yarn requirements depend on the density of the sailcloth. As discussed earlier, the density of sailcloth in historical samples varies between 7/7 and 20/12 threads/cm. This would correspond to 1,400–3,200 m of yarn per $m^2$. A median density of 13/10 threads/cm corresponds to 2,300 m of yarn per $m^2$ (**Table 4**). Weaving would actually require at least 10% more thread to allow for wastage in setting up the loom and allowing the yarn to bend in the weave take up of yarn and shrinkage (Ligon 2000).

Few contemporary flax-spinners use a drop spindle and amateur spinning rates are likely slower than a professional's. There are hardly any historical records on the rate of yarn production with a drop spindle. A professional spinner in Finland could achieve the astonishing 144 m/hour with a spindle (Vallinheimo 1956). Two spinners who participated in experiments for the Centre for Textile Research in Copenhagen, achieved 24 and 31 m/hour each, working with an 8-g spindle whorl on a drop spindle (Olofsson, Andersson Strand, and Nosch 2015, 85). With wool the same spinners managed 50 m/hour. Likewise, few experiments have been done with weaving linen on the warp-weighted loom. Experienced weaver Lena Hammarlund tried to replicate a sailcloth quality and in her fastest samples 2b and 3b, she inserted 86 and 88 weft threads/hour, corresponding to 8.9 and 9.6 cm/hour (after washing) on a web c. 40 cm wide (**Table 4**). (**Figure 5**). This translates to a rate of 25–28 hours/$m^2$. The weaving speed per square meter depends on many factors, including the weaver's experience and skill, the yarn's properties, and the loom setup: the weight and number of loom weights, the width of the cloth, its intended length, as well as the thread count. With 9.6/8.5 threads/cm, sample 3b requires 1,810 m yarn/$m^2$.

At the rate of 50 m/hour, spinning 2,300 m of yarn for one square metre of medium-dense sailcloth would take 46 hours. Spinning 1,810 m, for the 1 $m^2$ experimental sample 3b, would take 36 hours. Weaving it would take at least 25 hours without counting time for setting up the loom, mending threads if they break, and re-knotting the weights. Equipping a ship like the *Olympias* with its 119 $m^2$ of sails would require at least 4,299 hours (18 months) of spinning and 2,966 hours (12 months) of weaving, or 7,265 hours in total. **Table 4** shows the details and variations. This calculation assumes 8-hour working days without rest days; in practice the work probably took longer, interspersed with other activities.

This figure is not far from the time that weaver Anna Nørgård calculated for the 90 $m^2$ woollen sail for the *Ottar*: 4,710 hours of spinning and 3,140 hours of weaving (Nørgård 1999). Nørgård also wove a 25-$m^2$ sail for the *Oselven,* which took an estimated 2,000 hours for spinning and 1,600 hours for weaving (Andersen and Nørgård 2009). The correlation between sail size and labour time is non-linear, because other variables affect working speed, including the type of yarn and weave, the thread count, the width of the cloth, the craftsperson's experience, skill, comfort, and ability to work uninterrupted (Andersen and Nørgård 2009, 50).

*Ship to fleet*

If making sails for the *Olympias* trireme would take one and a half years of spinning and one year of weaving, the labour and resource requirements for larger fleets escalate quickly (**Table 5**). Consider the Battle of Salamis c. 480 BCE. According to Herodotus (7.89, 7.97, 7.184, 8.1, 8.44–48), whose numbers give a sense of scale but are not to be taken at face value, the Greek fleet numbered 387 triremes, while the Achaemenid fleet consisted of 3,000 vessels, including 1,207 triremes followed by pentekonters and support ships. Producing sails for the Achaemenid triremes alone would take 143,331 $m^2$ of sailcloth and almost 3000 years of labour (1,772 years spinning, 1,223 years weaving), without counting time for growing and processing flax, sewing, and without the support ships. Equipping the Greek triremes with sails would require 45,956 $m^2$ of cloth and 960 years of labour (568 spinning, 392 weaving).

Whilst enormous, this task was distributed between the allied cities, which contributed to the fleet and their contributions varied significantly (**Table 5**). According to Herodotus, Athens provided the lion's share, 180 triremes, followed by Corinth with 40 and Aegina with 30, Chalkis and Megara with 20 each, Sparta with 16, down to several cities that sent one or two ships each. With such disparate numbers of ships, the need for sailcloth varied dramatically from city to city. Accordingly, each city would have organised production and supply differently in order to meet demand of different scale.

An earlier case where we know the number of ships in a fleet for a major expedition is the catalogue of ships in the *Iliad* (2.494–759), listing 1,186 vessels. The source is too controversial for our present purposes and we do not know the size of the sails, but it is informative that, like in the Battle of Salamis, the Achaean fleet at Troy is composed of disparate contributors from across the Aegean: from Agamemnon of Myceanae with 100 ships and Nestor of Pylos with 90, through Odysseus of Ithaca – 12, and Nyraeus from the small island of Syme – 3. Whatever the ships, contributions of such different scales would have required different ways of procuring the necessary textiles.

*Effects of scale*

Before addressing production and procurement strategies, let us consider the effects of scale. According to the calculations above, one person could spin and weave sails for a trireme over two and a half years, working eight-hour days every day. Equipping a few ships would therefore have a small effect on a city's textile industry, but producing and maintaining large volumes of sails, especially at short notice, would have been a serious challenge. For example, Athens built 100 or 200 ships between 483/2 and 480 BCE. Making sails for the 180 Athenian triremes at Salamis within one year would require 265 spinners and 183 weavers, working eight-hour days every day. If these 448 people were household slaves, then 149 households with three slaves each could provide for the Athenian fleet within one year. These are not large numbers of workers, spread across a major city like Athens, whose 5th-century population is estimated at over 150,000 people, including tens of thousands of slaves (Akrigg 2019, 84, 91–94, 126). But the growing demand for sailcloth would have been a significant burden for individual workers and households, who had to dedicate more time and resources to weaving for the fleet – whether they were in Athens or elsewhere. Sail-making had to be fitted around already existing economic activities. If the textile workers could dedicate one month to equip the triremes, then 3,180 spinners and 2,194 weavers would be needed. Hence, periodic ship-building campaigns would have put a strain on the economy and would have diverted labour from other productive activities.

*Meeting demand*

One way to mitigate the growing demand for labour was to adopt more time-efficient technologies for various stages of production, particularly for thread-making, which was a production bottle neck. Indeed, as noted earlier, from the 6th century BCE onwards linen textiles across the Mediterranean shift from spliced to draft-spun yarn (Gleba and Harris 2019). The extraction of fibre from the stem by breaking, scutching and heckling in preparation for draft spinning is a mechanised process that can work multiple stems at the same time and was likely more time efficient than stripping fibres from individual plant stems in preparation for splicing.

We may expect similar changes to affect weaving, but this is not the case. Throughout the Archaic and the Classical period textiles were produced primarily by women and slaves within the household (Barber 1991, 283–298; Spantidaki 2016, 9–18). Except the royal palaces in the Homeric poems, the literary and the archaeological record provides no evidence for textile production units larger than an extended household or a household workshop with 10-15 people (Xenophon *Economics* 7.20–23; *Memorabilia* 2.7–9). The largest known concentrations of loom weights come from Houses A v 9 and A viii 7/9 at Olynthos c. 350 BCE, with four looms and two large clusters of tools respectively (Cahill 2002, 250–252), Building Z3 in Kerameikos c. 307 BCE, which had eight clusters of loom weights (Knigge 2005), and a deposit from the Athenian Agora c. 380 BCE which produced over 500 loom weights, corresponding to 5–10 looms (Tsakirgis 2016, 174–175). Larger workshops may have existed and not survived, but the data indicate that most production remained household-based. Yet, this was not an impediment to producing sufficient volumes of cloth to meet the demands of growing fleets. This phenomenon goes beyond ancient Greece: the example of Medieval Scandinavia shows that household production could provide the 1,000,000 m$^2$ of sailcloth needed for the Viking fleet in the 1030s CE (Bender Jørgensen 2012).

A significant amount of labour was required to equip fleets of hundreds of ships with sails, but some of this labour could be economised by adopting new technologies and some could be distributed within communities. The greater challenge therefore lay not in textile production, but in logistics: planning demand, sourcing raw material, co-ordinating production, safeguarding reserves, managing a system for supplying and maintaining sails. How this challenge was met varied over time.

In the Archaic period, members of elite families would have been able to mobilise the necessary labour and resources to make ships and sails. Homer mentions skilled female slaves grinding grain, spinning, weaving, and making elaborate garments for royal palaces (*Iliad* 6.288–95; *Odyssey* 7.103-105); their labour could be directed to make sailcloth. Wealthy elites around the Mediterranean would also have been well-positioned to initiate cross-regional trade and to establish bonds with fellow elites, and develop maritime networks (Greene 2018, 155).

Many warships in Archaic Greece were privately owned or sponsored by wealthy individuals (Herodotus 5.47, 8.17, 8.47). This practice was embedded in a system of values, whereby aristocrats were bound by duty to contribute to the war effort of their city in order to maintain their status. The Battle of Salamis in 480 BCE was one of the last occasions where this system still operated (Gabrielsen 1994, 202, 266).

In the late 6th or early 5th century BCE, Athens developed a state navy, funded through the institution of the *trierarchy,* effectively a wealth tax (O'Halloran 2019, 167–171 with references). Fulfilment of trierarchic duty continued to offer wealthy individuals power and influence over public life, even though some sought to evade it (Gabrielsen 1994, 10–12).

Besides ownership of work force, another way to procure sailcloth in large volumes and to distribute the labour and raw materials is through levying tax in kind. In early modern Sweden, taxes of hemp and sailcloth were increased to equip ships for the war with Russia (Glete 2010, 472). In medieval Scandinavia coastal districts were required to build, staff, and equip a ship, including making the sails, in order to build the Viking fleet; textile manufacture was organised as household industry (Andersson 2003, 56–57). Hans van Wees (2013, 56) has proposed a parallel between this organisation and 6th-century Athens, where a group of 48 officials carried the title *naukraroi*, ship 'captains'. Although their precise function is debateable, these 'captains' held some military power and collected taxes from their districts (*naukrariai*).  (van Wees 2013, 44–61). Athens also levied ad-hoc military taxes when necessary, though usually in cash. Some city-states within the Athenian empire provided ships as tribute (Nixon and Price 1990). Collecting textiles as a form of tax or tribute was documented among Greece's neighbours. The Achaemenid Empire under Darius collected tribute in the local produce of each province, including hair and wool (Strabo 15.3.21) and Seuthes I of Thrace received 'plain and patterned cloth' as 'gifts' alongside taxes (Thucydides History 2.97).

The market would also have played a growing role in supplying sails through the 5th and 4th centuries BCE. Rope, tow, low-quality cloth and perhaps sails were sold and bought in Athens (Spantidaki 2016, 80). Linen was imported from Egypt, Cyprus, and the Black Sea as prepared thread or cloth (Bresson 2007, 160; Nosch 2014, 22–30), i.e. part of the labour was outsourced (see Gleba et al. forthcoming for a discussion of flax cultivation areas). A black market for contraband naval equipment, including 'linen textiles' also existed (Nosch 2014, 36–37; Aristophanes *Frogs* 361–365). Despite the vibrant commerce within Athens and internationally, however, shortages of naval equipment were chronic due to demand exceeding supply and misappropriation of equipment within the navy (Gabrielsen 1994, 147–157).

Linen would have been too important to leave to market forces alone. As Pseudo-Xenophon asks, "if some city is rich in iron, copper, or flax, where will it distribute it without the consent of the rulers of the sea?" (*Constitution of the Athenians* 2,11). The state could intervene in the sailcloth market by obtaining linen through political alliance, diplomacy, force, and regulatory measures, which were applied to other critical resources: timber and grain. To ensure a supply of Macedonian timber, for example, Athens had an agreement with king Perdicas c. 417-413 BCE (Gabrielsen 1994, 140).

Legislative and commercial incentives were combined to ensure a sustained grain supply (Demosthenes 35.51).

*Conclusions*

The methodological exploration of sail production we present has brought to light several significant issues around power relationships in Greece. Returning to the passage quoted at the beginning, *The Constitution of the Athenians* recognises that the power of 'the common people' put ships in motion, alluding to the men in the galleys. This paper has drawn attention to the considerable number of other people who were needed to equip a ship or fleet with sails – the women and household slaves (male, female, children) engaged in textile production. The results of this analysis of time resources draws warranted attention to the underlying power dynamics surrounding multiple sections of society. Sail manufacture was dependent on and enabled many and complex power dynamics: from those of slavery and household relations, through inter-city cooperation and conflict, to war and control of sea routes.

The expansion of commercial and military fleets led to a boom in textile production, according to the calculations presented here. Making sails entailed logistical challenges in managing supplies and reserves, and occupied a significant part of the economy, especially in cities that aspired to naval power. The resulting expansion in textile economy was supported by technological advances in yarn manufacture during the Archaic period, and a variety of distribution and procurement strategies outlined above, but it is striking that textile production could increase in output without changing structurally. This was possible because of the availability of exploitable domestic labour, mainly women, children, and slaves. The power relations, which structured work in the Greek household meant that making textiles was part of the social role of women (Larsson Lovén 1998). As written sources document, making textiles and managing slaves making textiles was considered women's duty in high Athenian society. The association between cloth manufacture and wifely virtue endured in later periods, regardless of whether it was an accurate reflection of who did most textile work. Such norms are internalised as values and, according to Foucault, they structure the agents' possibilities and impossibilities for action. Because they are rooted deeply in the social nexus, power relations cannot be uprooted, which gives them a certain resilience. This is how household-based production can increase its output to meet new needs. Simply put, spinners and weavers worked 'extra shifts' to set the ships in motion. It is this resilience which allowed domestic textile production to absorb more load without changing in structure. This resilience through exploitation may explain partly why textile technology was conservative: although yarn production changed from splicing to spinning, there are no signs of major changes in weaving during the period considered here. This highlights a long-term feature of textile production – an industry that continues to rely on vast amounts of exploitable manual labour, even today.

The study of sail production indicates that domestic power relations, ideas and hierarchies of labour, were among the factors that enabled Athens to rise as an imperial naval power. Athens was not an isolated example, as demonstrated by the example of the Viking fleet of the 10$^{th}$ to 112$^{th}$ centuries CE, which also procured its sails via household production. However, power relations and economy were likely structured differently in these two distant societies. One future direction for research is to compare how different societies addressed the same challenge – equipping fleets with sails – given similar technologies (the warp-weighted loom and drop spindle) but different cultural contexts. The method presented here can be applied to other contexts, where fleets and sails were historically important, if some quantitative data are available, at least for fleet size. Larger experiments, following Anna Nørgård's reproduction of full sails for a Viking ship, would give us a fuller and more accurate picture of the labour, time, and skill involved in sail production in the Mediterranean. Another direction for future research is to consider the limits of domestic production and of the warp-weighted loom as a technology. Fleets grew considerably in the Hellenistic and Roman period, generating greater demand for sails. Perhaps this new scale of demand brought about technological and organisational changes? Roman written sources attest the existence of larger weaving workshops – but domestic production persisted.

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Figure 1. Merchant ship with furled sail (left) under attack from a war galley (right) on an Attic cup found in Vulci, c. 520–500 BCE (1867,0508.963, © The Trustees of the British Museum)

Figure 2. Two-mast ship on a Late Corinthian krater, 6th century BCE (ASCSA Corinth excavations C-1972-38, C-1972-40, photograph: Petros Dellatolas)

Figure 3. *Gyptis*, *Kyrenia II*, and *Olympias* (photographs: Pomey & Poveda 2018; Tzalas 2007, 301; the Trireme Trust)

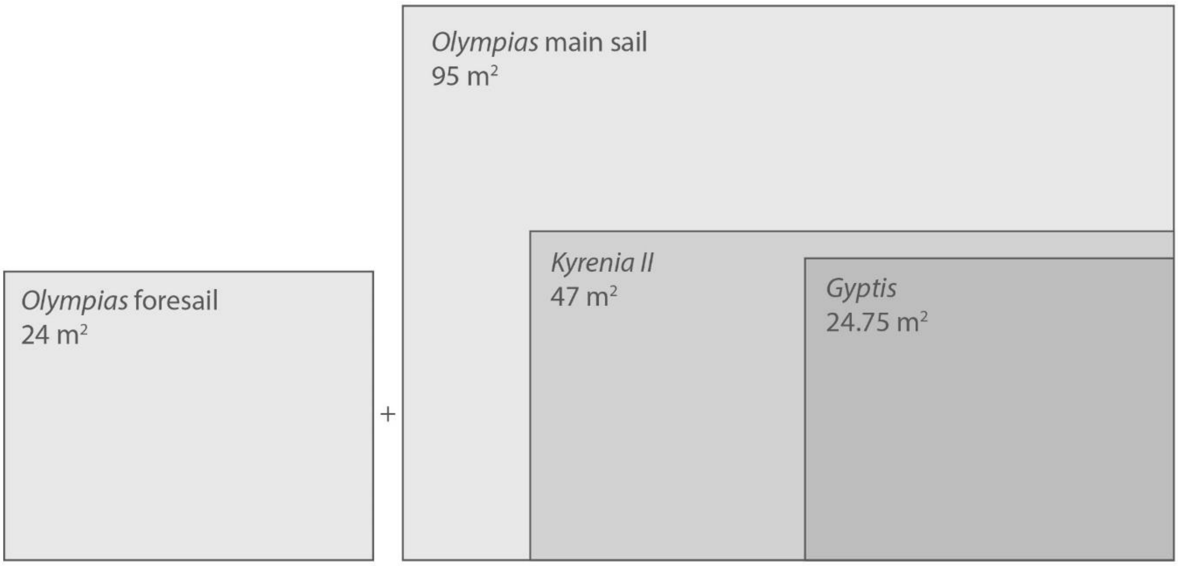


Figure 4. Comparison of sail surface area for *Gyptis*, *Kyrenia II*, and *Olympias*

| Site | Date | Weave | Thread count | Twist | Diameter | Fibre | Reference |
|---|---|---|---|---|---|---|---|
| Edfu, Thebes, Egypt | 100-50 BCE | warp-faced tabby | 22/12 | s/s | | flax | (Wild and Wild 2001, 213; Wild 2002, 13) |
| Berenike, Egypt | 1st c. CE | Tabby | | z/z | | cotton | (Wild and Wild 2001; Wild 2002, 10) |
| Berenike, Egypt | 1st c. CE | Tabby | 12-13/ 9-11 | s/s | | flax | (Wild and Wild 2001; Wild 2002, 9) |
| Myos Hormos, Egypt | 1st-2nd c. CE | warp-faced chevron twill; warp-faced tabby | 7/7 11/5 16/15 20/12 16/12 15/7 | z/z | 0.4-0.7/ 0.6-0.8 | cotton | (Whitewright 2007, 286; Fiona Handley 2011, 325, 327) |
| Myos Hormos, Egypt | 1st-2nd c. CE | basket weave; tabby; warp-faced tabby | 11/8 16/12 14/13 21/6 12/12 10/18 | s/s | 0.4-0.6/ 0.3-0.8 | bast | (Fiona Handley 2011, 327; Whitewright 2007, 286; Fiona Handley 2003, 20) |
| Mary Rose | 1545 CE | tabby | 10-12/8-10 | z/z | 0.2-0.7/ 0.3-0.9 | plant | Gleba, personal observation |
| Vasa | 1628 CE | tabby | 10-12/7 | z/z | | hemp | (Westheden Olausson 1998) |
| Vasa | 1628 CE | tabby | 11-13/ 9-11 | z/z | | flax | (Westheden Olausson 1998) |
| Jeanne-Élisabeth | 1755 CE | tabby | 12/6 | z/z | | hemp | (Bartoš and Sanders 2012) |

Table 2. Sail cloth remains

| Ship size | Mediterranean (6th-4th century BCE) | | Scandinavia (11th century CE) | |
|---|---|---|---|---|
| | Hull | Sail (m²) | Hull | Sail (m²) |
| War ship | *Olympias* (36.9 x 5.5 m) | 95 + 24 | *Sea Stallion* (30 x 3.8 m) | 112 |
| Medium cargo ship | | | *Ottar* (16 x 4.8 m) | 90 |
| Small cargo ship | *Kyrenia II* (13.7 x 4.4 m) | 47 (9.6 x 4.9 m) | *Roar Ege* (14 x 3.3 m) | 45 |
| Large fishing boat | *Gyptis* (9.85 x 1.88 m) | 24.75 (4.5 x 5.5 m) | *Oselven* (10.2 x 2.6 m) | 25 |

Table 3. Sail sizes for reconstructed ships from the Mediterranean and Scandinavia (Data: Roskilde Viking Ship Museum website; Andersen and Nørgård 2009)

| Sailcloth example | Cloth quality Warp th/cm | Weft th/cm | Yarn / $m^2$ Weft | Warp | Yarn/ $m^2$ | Spinning Rate m/hr | Hr/ $m^2$ | Weaving Wefts/ hr | Cm/ hr | Width (cm) | Surface ($cm^2$) | $m^2$/ hr | Hr/ $m^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Low density | 3 | 6 | 300 | 600 | 900 | 50 | 18 | | | | | | |
| High density (Thebes, 100 BCE) | 22 | 12 | 2,200 | 1,200 | 3,400 | 50 | 68 | | | | | | |
| Medium density | 11 | 8.5 | 1,100 | 850 | 1,950 | 50 | 39 | | | | | | |
| LH sail sample 2a | 9.8 | 7.5 | 980 | 750 | 1,730 | 50 | 35 | 88 | 11.7 | 41 | 481 | 0.05 | 20.8 |
| LH sail sample 2b (washed) | 9.9 | 8 | 990 | 800 | 1,790 | 50 | 36 | 71 | 8.9 | 40.3 | 358 | 0.04 | 28.0 |
| LH sail sample 3a | 9.4 | 8.7 | 940 | 870 | 1,810 | 50 | 36 | 86 | 9.9 | 42.5 | 420 | 0.04 | 23.8 |
| LH sail sample 3b (washed) | 9.6 | 8.5 | 960 | 850 | 1,810 | 50 | 36 | 82 | 9.6 | 41.5 | 400 | 0.04 | 25.0 |

* LH = samples, in which Lena Hammarlund achieved her fastest weaving speed with linen on the warp-weighted loom.

| Olympias Sails size: 119 $m^2$ | Cloth quality Warp | Weft | Yarn m | Spinning Hours | Days | Months | Weaving Hours | Days | Months | Total labour Hours | Days | Months |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Low density | 3 | 6 | 106,875 | 2,138 | 267 | 9 | | | | | | |
| High density (Thebes, 100 BCE) | 22 | 12 | 403,750 | 8,075 | 1,009 | 33 | | | | | | |
| Medium density | 11 | 8.5 | 231,563 | 4,631 | 579 | 19 | | | | | | |
| LH sail sample 2a | 9.8 | 7.5 | 205,438 | 4,109 | 514 | 17 | 2,468 | 309 | 10 | 6,577 | 822 | 27 |
| LH sail sample 2b (washed) | 9.9 | 8 | 212,563 | 4,251 | 531 | 17 | 3,320 | 415 | 14 | 7,571 | 946 | 31 |
| LH sail sample 3a | 9.4 | 8.7 | 214,938 | 4,299 | 537 | 18 | 2,827 | 353 | 12 | 7,125 | 891 | 29 |
| LH sail sample 3b (washed) | 9.6 | 8.5 | 214,938 | 4,299 | 537 | 18 | 2,966 | 371 | 12 | 7,265 | 908 | 30 |

Table 4. Calculations of time and yarn required to make sail cloth for the *Olympias*

| Fleet | Triremes | Sailcloth ($m^2$) | Yarn (m) | Spinning (yrs) | Weaving (yrs) | Production time: 1 year | | Production time: 6 months | | Production time: 1 month | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Spinners | Weavers | Spinners | Weavers | Spinners | Weavers |
| Greek fleet | 387 | 45,956 | 9,877,721,484 | 570 | 393 | 570 | 393 | 1,139 | 786 | 6,837 | 4,717 |
| Athens | 180 | 21,375 | 4,594,289,063 | 265 | 183 | 265 | 183 | 530 | 366 | 3,180 | 2,194 |
| Corinth | 40 | 4,750 | 1,020,953,125 | 59 | 41 | 59 | 41 | 118 | 81 | 707 | 488 |
| Aegina | 30 | 3,563 | 765,714,844 | 44 | 30 | 44 | 30 | 88 | 61 | 530 | 366 |
| Chalcis | 20 | 2,375 | 510,476,563 | 29 | 20 | 29 | 20 | 59 | 41 | 353 | 244 |
| Megara | 20 | 2,375 | 510,476,563 | 29 | 20 | 29 | 20 | 59 | 41 | 353 | 244 |
| Spartan | 16 | 1,900 | 408,381,250 | 24 | 16 | 24 | 16 | 47 | 33 | 283 | 195 |
| Sicyon | 15 | 1,781 | 382,857,422 | 22 | 15 | 22 | 15 | 44 | 30 | 265 | 183 |
| Epidauros | 10 | 1,188 | 255,238,281 | 15 | 10 | 15 | 10 | 29 | 20 | 177 | 122 |
| Ambracia | 7 | 831 | 178,666,797 | 10 | 7 | 10 | 7 | 21 | 14 | 124 | 85 |
| Eretria | 7 | 831 | 178,666,797 | 10 | 7 | 10 | 7 | 21 | 14 | 124 | 85 |
| Troezen | 5 | 594 | 127,619,141 | 7 | 5 | 7 | 5 | 15 | 10 | 88 | 61 |
| Naxos | 4 | 475 | 102,095,313 | 6 | 4 | 6 | 4 | 12 | 8 | 71 | 49 |
| Leukas | 3 | 356 | 76,571,484 | 4 | 3 | 4 | 3 | 9 | 6 | 53 | 37 |
| Hermione | 3 | 356 | 76,571,484 | 4 | 3 | 4 | 3 | 9 | 6 | 53 | 37 |
| Keos | 2 | 238 | 51,047,656 | 3 | 2 | 3 | 2 | 6 | 4 | 35 | 24 |
| Styra | 2 | 238 | 51,047,656 | 3 | 2 | 3 | 2 | 6 | 4 | 35 | 24 |
| Kroton | 1 | 119 | 25,523,828 | 1.5 | 1.0 | 1.5 | 1.0 | 3 | 2 | 18 | 12 |
| Kythnos | 1 | 119 | 25,523,828 | 1.5 | 1.0 | 1.5 | 1.0 | 3 | 2 | 18 | 12 |
| Achaemenid fleet | 1,207 | 143,331 | 30,807,260,547 | 1,777 | 1,226 | 1,777 | 1,226 | 3,554 | 2,452 | 21,323 | 14,713 |
| Phoenicia | 300 | 35,625 | 7,657,148,438 | 442 | 305 | 442 | 305 | 883 | 609 | 5,300 | 3,657 |
| Egypt | 200 | 23,750 | 5,104,765,625 | 294 | 203 | 294 | 203 | 589 | 406 | 3,533 | 2,438 |
| Cyprus | 150 | 17,813 | 3,828,574,219 | 221 | 152 | 221 | 152 | 442 | 305 | 2,650 | 1,828 |
| Cilicia | 100 | 11,875 | 2,552,382,813 | 147 | 102 | 147 | 102 | 294 | 203 | 1,767 | 1,219 |
| Ionia | 100 | 11,875 | 2,552,382,813 | 147 | 102 | 147 | 102 | 294 | 203 | 1,767 | 1,219 |
| Phrygia | 100 | 11,875 | 2,552,382,813 | 147 | 102 | 147 | 102 | 294 | 203 | 1,767 | 1,219 |
| Caria | 70 | 8,313 | 1,786,667,969 | 103 | 71 | 103 | 71 | 206 | 142 | 1,237 | 853 |
| Aeolia | 60 | 7,125 | 1,531,429,688 | 88 | 61 | 88 | 61 | 177 | 122 | 1,060 | 731 |
| Lycia | 50 | 5,938 | 1,276,191,406 | 74 | 51 | 74 | 51 | 147 | 102 | 883 | 609 |
| Pamphylia | 30 | 3,563 | 765,714,844 | 44 | 30 | 44 | 30 | 88 | 61 | 530 | 366 |
| Doria | 30 | 3,563 | 765,714,844 | 44 | 30 | 44 | 30 | 88 | 61 | 530 | 366 |
| Cyclades | 17 | 2,019 | 433,905,078 | 25 | 17 | 25 | 17 | 50 | 35 | 300 | 207 |

Table 5. Fleet size in the battle of Salamis, required sail cloth and production time