From Seedlings to Ships: Supply Chain and Production Management in the Venice Arsenale, 1400-1800

INTRODUCTION

Venice was a significant naval power and trading city-state (Crowley, 2011; Faroqhi, 2009; Lanaro, 2007; Norwich, 2003) and its Arsenale, established in 1104, was one of the earliest large industrial complexes, making many of its warships and much of its commercial shipping for the next 800 years. (Bellavitis, 2009; Concina, 2006; Davis, 1991, 1993; Lane, 1934, 1973; Sondhaus, 1989; Ventrice, 2009) Although many commentators (Galloway, Rowbotham and Azhasheni, 2012; Gartman, 1979; Koeningberg and Mackay, 2010; Lambert and Knaak, 2008; Towill, 2005) cited the Arsenale as an early production line none analyze its operations, and all rely on Lane's (1934, 1973) description of Henri III of France's visit to Venice in July, 1574 when the *Doge*, Venice's ruler, showed the Arsenale's capabilities by having a galley converted from a bare hull to a fully complete vessel in just a few hours.

But this was more than a party trick for impressing visiting royalty. This production capability was intimately involved with Venice's strategic needs: state security influenced; and was influenced by, production capabilities. This is an early example that confirms several modern theoretical precepts and practices: First, it shows national security needs promoting production management innovation, as hypothesized by Hounshell (1983). Second, it also illustrates the coordination between stages in supply chains as widely theorized and recommended in practice. Lastly, it reinforces the thinking that supply chain management extends to adapting earlier stages' production processes to integrate with later needs. These historic practices independently confirm the effectiveness of modern theoretical constructs, even suggesting that these might be considered "principles" of supply chain management—ideas of universal applicability.

The Arsenale's continual improvement was stimulated by constant threats and intermittent wars with the Byzantine (subsequently Ottoman) Empire. (Norwich, 2003; Crowley, 2011, 2015) These compelled the Arsenale to expand; and, more importantly, to innovate in its production technology and management. (Lane, 1934, 1973) Military concerns lead to standardized ship designs very early—the best designs were desired for their performance advantages, not only for individual ships but also to facilitate the coordination of fleet-scale maneuvers enabling coherent formations and deployments. Crowley (2011, pp. 267-8) emphases the criticality of coordination for fleet-scale engagements as at the epochal battle of Lepanto in 1571, regardless of the different tactics used by each side.

Given standardized designs, assemblies and components for many ships were built-to-stock and held until hostilities motivated the Naval command to have those assembled-to-order into completed ships. Figure 1 (Roser, 2017) illustrates how their assembly line started a hull in one area, then moved it sequentially to workstations alongside quay-side storehouses from which the necessary components were passed to the workmen and installed. Roser (2017) disputes that this was a production line based on his review of the Arsenale's work in the late 1700s. He uses three rationales: it was not mechanized, or automated, and the volume was too low. This is erroneous since his first two objections anachronistically arise from modern implementations and were not feasible historically. In the late 1700s mechanization was just beginning, with the earliest examples of an integrated mechanized production system being Oliver Evans' fully mechanized American flour mill from 1785 (Bathe & Bathe, 1935), and then Marc Isambard Brunel's Block Mill in Portsmouth, England from 1805 (Wilson, 2019), Neither of those were "automated" since they required human oversight—no mechanized or electronic control systems had yet been invented as Mayr (1970) shows. Furthermore, Roser's objections are theoretically unsound: the sequential arrangement of a series of completely manual operations, such as Adam Smith's contemporaneous example of pin manufacture, or

Ford's first prototyping trial assembly line for flywheel magnetos in 1913 were manually paced production lines. His last objection reflects his focus on the Arsenale of 1797, when it was building a few large ships rather than the earlier periods (as in 1574's demonstration) when larger numbers of more basic galleys were made. We will show the Arsenale could assemble several smaller warships per day using this line-based approach.

A final caveat: although the overall ship designs used standardized assemblies and components, those were not interchangeable. Hounshell (1984) describes this distinction between interchangeability and standardization. The final assembly line took completed hulls for which all this final fitting had *already* been done, and then completed the ship's outfitting with all the other standardized removable components, such as masts, rigging and sails, oars, armaments, and provisions. These components were interchangeable within the tolerances required, and if there were a few larger structural components then they could have been marked and allocated to specific hulls to which they had already been matched. This is analogous with the modern practice of "kitting", in which components are packed together in a "kit" prior to assembly to expedite that process. Haun (2011) describes kits for wood-framed buildings, both standardized and custom designed.

The essential point is that the final assembly stage's volume and speed were critically dependent on earlier production of the components used.

Insert Figure 1 Here

Little is known about the management of early industrial operations and this study provides an insight into them. This research will contribute to knowledge about manufacturing operations before the industrial revolution, and outside the USA and UK. Our notable finding is that forestry practices were coordinated with industrial design and manufacturing requirements—recognizing an integrated supply network. We consider the evolving sophistication and complexity of the Venetian supply chain for wood. These issues are evident in Appuhn (2000, 2010) and Ritter and Dauksta (2013) with their focus on Renaissance forestry. Venice first relied on trees grown in the adjacent coastal region but those were soon exhausted. Italian forests at Montello and Isonzo were used next, and then Croatian forests in Montona. (Appuhn, 2010; Lane, 1934)

Schonberger's discussion (1982) of the motivations for Toyoto's development of Just-in-Time systems emphasizes Japan's resource scarcity: the economic and cultural environment imposed constraints on their production systems. Such constraints were even more stringent for Venetian systems and methods; and compounded by the existential threats posed by the Byzantines and Ottomans. Venice acquired colonies through Machiavellian political-military machinations: The *Doge* agreed to transport the Fourth Crusade's army to the Holy Lands, knowing that the commanders were unlikely to have the funds necessary—of the agreed 85,000 ducats the Crusaders could only pay 35,000 on their arrival. (Norwich, 2003, Phillips, 2004) The *Doge* demanded as payment that they first secure the adjacent Adriatic shore. Venice's Byzantine rivals were then targeted, with Constantinople sacked in 1204. Venice then dominated the immediate area, the Adriatic coast and several large Mediterranean islands. The Crusaders were transported to the Holy Lands only after these strategic areas were captured.

The elimination of Byzantium as a rival proved counter-productive since that weakened regime was replaced by the Ottomans in the mid-1400s. (Mango, 2002) Gugliazzo (2012, p. 26) and Benvenuti (2001) describe the Ottoman's strategy as one that maintained a constant pressure intimidating Venice; exploiting their Christian opponents' intermittent rivalries (e.g., Venice vs Genoa, France vs Italy, Portugal vs Spain, etc.), Strategic demands drove Venice's naval needs: this tiny island city-state opposed an Empire and needed to marshal its resources carefully. The analogy between Venetian military strategy driving its production and supply strategies and policies is comparable to the role of modern corporate strategies in directing operations to enhance competitiveness.

RESEARCH QUESTIONS

The first research question is understanding how supplies of a critical raw material with a long production cycle were managed to support a finished product subject to highly variable short-term demand. Our second question considers how the system reconciled Venice's need for a large fleet with its limited production capacity and strict resource constraints. This study shows how systems evolved over time and stimulated more efficient and effective materials supply, production processes and management.

Content analyses of archival materials shows policies that integrated the management of forest resources with the Arsenale's production needs. Trees needed to be planted many years before they could be used. This necessitated long-term planning in acquiring land or the rights to harvest trees. Each forest area then required the natural seeding or human planting of sufficient numbers of seedlings and then managing their cultivation so that they were most useful for ship building anticipated many years in the future. Figures 2 and 3 illustrate some of the issues concerning the "production" of useful wood products. Figure 2 (Beltrame, 2003) shows a variety of components used in constructing a ship, noting that a wide variety and large number of complex shapes and curved pieces of wood were needed as well as straight pieces and planks; all in differing lengths, thicknesses and widths. Figure 2A (Charnock, 1801-2, p 55) shows an early galley, these were smaller and less complex vessels while the later, round ships shown in 2B (Fincham, 1851, Plate, after p. 113) were larger and more complex structures. (Steele, 1812; Beltrame, 2003; and for later 1700s ships see Desy & Monea, 2016a, Figure titled "U.S.S. *Constitution* Midship Section," Plan 34535, Jan., 1926) Galleys required many curved ribs for their hulls, with other shapes typically used for joints. Round ships were larger and required much more substantial components, with multiple decks requiring more joints.

Insert Figure 2 Here

Purely natural products did not readily conform with the demands of standardization. In the early years, trees might be selected to yield a desired component, but leaving that entirely to natural growth was uncertain and could be wasteful. As supply chain management developed it later dictated not just the types and numbers of trees grown by actively cultivating forests, but also to actively control and modify the growth of individual trees using techniques to form the shapes needed. These shaped trees were illustrated by Vittori (1777) in Figures 3A and 3B: the production of standardized components began in the forests. The caption for 3B is: "Illustration of the cultivation system for growing oak trees, and of the various approaches to pruning them for the use of Venetian navy—an example from Istria."[1] **Living** trees thus became integrated into the production processes. Since oaks take decades to mature the short-term demands of later assembly operations necessitated long-term planning, as we later recognize with a Venetian production plan that assumed wars would occur regularly, and that then dictated continual production at a fixed volume. This stabilized production management and, most importantly for the wood supply chain created a steady, but flexible demand.

Insert Figure 3 Here

METHODOLOGY

The research will use content analysis (Mayring, 2011) of historic archival records (Archivio di Stato di Venezia: *Provveditori e Patroni all'Arsenale* (1715); *Senato Mar, filzas* (1714, 1715), *Senato Rettori, filzas* (1715), *Provveditori sopra Legne e Boschi* (various dates)) supported by

[1] Original Italian: "Illustrazione del sistema di coltivazione per la coltivazione delle querce e dei vari metodi per potarle per l'uso della marina veneziana, un esempio dall 'Istria."

contemporary commentaries and modern secondary sources focusing on the Arsenale's operations and management of wood supplies. Our study uses a positivist theory of history, believing that we can be independent observers and analysts of historic events, documents, graphics and artwork, and contemporary commentaries on them; and that the materials found may be fairly and accurately assessed to develop a fuller knowledge about, and understanding of the Arsenale's operations and its management. But we go beyond simple positivism to use the information found to make justifiable inferences considering the Arsenale as the center of a production system. In this effort we find support for Lane's (1934, 1973) example of a single galley's rapid assembly through an earlier observation (Tafur, 1436; Letts, trans., 1926) of the assembly of several ships, and by Casola's (1493, trans. Newett, 1907; 2020)) observations of semi-finished galleys and facilities for their movement into and out of sheltered storage. These contemporary reports provide a consistent perspective on the Venetian system, that is further supported by internal documents from the Arsenale's staff. From that information we have inferred a model describing the build-up of the warship reserves, their use in war, then their decommissioning and return to reserves; and subsequent repetition.

Drachio's reports of 1586 and 1596 (Drachio, trans. L Th Lehman, 2001) are the most important discussions of the Arsenale's operations, proposing such radical reforms that murderous threats from outraged *Arsenalotti* (workers) drove him into exile. (Davis, 1993) Never-the-less, working practices and employment relationships gradually evolved, (Davis, 1993) as did management and management control systems (Hoskin, Zambon and Zan, 1994; Zambon and Zan, 1998, 2007; Zan, 2004, 2005, 2016),

This paper's focus will be the Arsenale's development and use of forests to support its shipbuilding. Over time, the Arsenale became increasingly involved with, and sophisticated in its management of this supply chain; with increasing management planning, organization and control asserted over these strategic materials.

Every European naval power: the Spanish and Portuguese (Gomes and Gomes, 2015), French (Bamford, 1956; Boudriot, 1973), British (Charles & Charles, 1984: 40-41; Albion, 1926; Matthew, 1831; Charnock, 1801-3), and even the United States (Wood, 1981; Malone, 1964), became concerned with the now-forgotten industry of "Naval Forestry" and their limited supplies of suitable timber. The U.S. Navy still has a forest at the Crane Naval Warfare (Desy, 2015, 2019) wherein a number of selected trees are reserved for maintaining the USS *Constitution*. There are even raw materials inventories dating from the 1850s kept in ponds in Florida. (Snell, Undated) Our study is relevant to other countries, and to comparable modern supply chains affected by resource supply constraints.

FINDINGS

Venice required wood for competing uses. For shipbuilding it needed different species: Oak, Pine, Larch, and Beech; in a variety of shapes and sizes, for its different applications in building the hulls, masts and spars, oars, and other components. Venice was also particularly reliant on wood for its civil construction; not only for housing but also for maintaining its material existence with pilings and bulwarks needed for constructing and maintaining its canals, and land reclamation. Venice also used significant quantities of wood for fuel. A mix of both publicly owned and private forests were used, and a variety of long-, short- and spot-term contracts and agreements were placed, with implications for how closely these could be managed. Although Venice was wealthy such costs were always a concern, with the lower costs and supply stabilization benefits of long-term arrangements always susceptible to short-term economic pressures.

The Arsenale sourced timber from areas in the north-east of Italy, Croatia and the Adriatic coast, and several Mediterranean islands. (Appuhn, 2010; Candiani, 2009, 2012; Susmel, 1994) The Istria province included several forests, but good quality timber was limited to the Motovun Valley (*Val Montona*), This provided high quality bent and forked oaks needed for hulls. From the 15th century it was a *San Marco* reserve, a publicly owned forest used exclusively for supplying the Arsenale. The Italian Montello Forest was also a *San Marco* reserve, with the management of these reserves given to special magistrates appointed by Venice. (Appuhn, 2009) These magistrates were responsible for periodic inspections and inventories of the trees. Figures 4A and 4B show how areas were divided into sections for closer management. Figure 4A from 1735 shows a forest near Treppo Carnico. It was divided into 20 areas (i.e., the sections below the red line), with the rest unusable. The partitioning process, and an estimate of the number of oaks are described in the oval at the bottom-left. Both maps show natural features such as rivers, streams and cliffs were used to demark sections, with Figure 4A (de Rivo, 1735) seemingly showing trees being grown in rows, implying an active cultivation of those areas. Figure 4B (Venutti, 1763) shows the "Ronchiaria" forest near the village of Imponzo. This is a beech forest divided into 7 areas; inferences from Plot D partially cut in 1759 but with some trees left as shown, but Plot C was apparently clear-cut, with all its trees harvested, and most of Plot D was similarly cleared. This implies a rotating harvest of these areas. Figure 4B also shows the trees seemingly more randomly distributed, suggesting either natural or random seeding, culling, etc. of that area; assuming the artist's renditions are realistic portrayals. Martin (2001) notes that artistic renderings, like other archival materials, should be interpreted cautiously.

Insert Figure 4 Here

Early in the 16th century control systems were instituted. Trees intended for shipbuilding were marked to distinguish them from those for construction or firewood. The first Senate order (analogous to a management directive) referring to the Montona valley is dated 1538; however, Pitteri (2013) maintains there is no evidence of its implementation. Later implementation of these orders seems to have become increasingly effective: in 1568, Niccolo Surian (Pitteri, 2014, p. 146) refers to a 'double stamping' of Montona's oaks following a census of the trees in the area. Trees were often harvested, and the trimmed logs stored in the forest to season into dry wood suitable for use, and to minimize storage requirements within the limited area of the Arsenale. It seems that controls became more effective and consistently employed, and physical control methods were augmented by making individuals and groups responsible for storage as well as tree cultivation and management. The Venetian policy of leaving felled trees in local stockpiles was motivated by the lack of space on the island of Venice itself. A modern analogy would be vendor-managed inventory (Tempelmeier, 2011) in which suppliers (the foresters) hold materials until production requirements pull them into the factory (the Arsenale) for processing or assembly.

Insert Figure 5 Here

Figure 5 (Bergamo, 1672) illustrates how the shaping of individual trees was undertaken. It shows several trees in the process of being bent to shape, along with a forester and his dog in the lower right corner patrolling the area to control wild animals and domestic livestock. The boundaries are clearly shown, along with the nearby villages that helped maintain and exploit the forest.

The first report addressing management of oak supplies in detail was Drachio (1586, trans. Lehman, 2001), He calls for rationalizing the harvesting of oak trees and explicitly recognizes that the common practice of obtaining a single "*stortame*" (i.e., a piece of wood bent to a desired shape) from an entire oak tree would be wasteful and unsustainable in the long run. Instead, he suggested that various pieces could be obtained from the same tree if the woodcutter carefully considered alternative uses for the other branches as components, too. To achieve this, Drachio called for "master woodcutters", with the expertise for managing the logging process efficiently. One important aspect considered working practices: "Masters should be required to bring various '*sesti'* [i.e., templates] that would serve for modelling different oak cuts efficiently."[2]

In his second report Drachio (1596, trans. Lehman, 2001) addressed the scarcity of "*roveri alpestri"* (i.e., "alpine oaks", the term for bent oak trees) needed for the keels and ribs. Drachio warned that these could not be manually planted since they grew only on very dry soils. They also took 50-60 years to grow to a usable size, compared with just 30-35 years for straight oaks. To overcome these difficulties, Drachio suggested that efficient forestry and logging should be complemented with design and manufacturing process expedients. Some were already employed that used straight instead of bent oaks. In one expedient the wood could be heated with steam and mechanically bent to yield desired shapes. In others, for more complex shapes or those with greater deflections in their bends, the piece might be built up by joining and shaping several pieces of wood. Ribs could be formed by bending and gluing several thin boards into a laminate of the desired shape and thickness. Despite these innovations, the naturally formed shapes were considered superior. (Matthew, 1831) Charles & Charles (1984, pp. 39-50) discuss orienting the component to the timber's growth patterns to maximize the strength of joints created. They also note (1984, p. 54) the superiority of timbers split by an axe along the wood's "grain" maintaining its integrity and strength, over those sawn to shape cutting the grain. Splitting wood was less labor intensive than sawing, too.

Drachio (1596, trans. Lehman, 2001) summarizes his views: "you will make your lumber subordinate and you will be freed from being its subordinate, the wood obeys the *sesto* and not the *sesto* to the wood, nature will be subjected to art and not art to nature"[3]. The reference to the "*sesto*" (template) which "obeys to the wood" implies that templates were employed during

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[2] *"andando a far tagli portassero con loro diversi sesti, come diverse sono le opera et con li sesti in mano et il rovere presente cavarono tutta la sostanza"*

[3] *"si fara il vostro legname soggetto et sarete liberi della soggettion di quello, il legno obedira al sesto e non il sesto al legno, la natura sara sottoposta all'arte e non l'arte alla natura"*

harvesting. It thus appears that Drachio's (1586) recommendation had been implemented. This apparently became a standard, on-going practice as Matteo Zorzi (report to the Senate, 1624) confirms that bent wood was regularly harvested using templates and defined dimensional standards. When specifically considering a shortage of bent oaks, Zorzi required a delegate to select trees from Corfu such that: "The supply of bent oaks [has to be] in line with the templates and sizes required [by the Arsenale]."[4]

Effective resource management considered not only issues concerning the use of the wood within the Arsenale's operations and with its harvesting but extended to also consider issues affecting the cultivation and growing of the wood. In Montona these had been:

1. Conflict between different magistrates charged with supplying different applications—firewood, construction, and land-reclamation vs shipbuilding. (Appuhn, 2009)
2. Losses due to negligence and poor land maintenance from frequent floods (Candiani, 2009)
3. Poor husbandry (excessive undergrowth and poor control of livestock) by local district and farm managers (Appuhn, 2009)
4. The colonized workforce resisted direction by the Venetian *angherie* (Appuhn, 2009; Susmel, 1994)

These issues were deliberated in the Senate and directives issued to the regional managers.

The First War of Morea in the late 1600s revealed continuing wood shortages motivating the Senate to order improvements in forest management. The Second War of Morea in 1714 stimulated producing six large "round" ships (Candiani, 2009, p. 506) using a new design requiring more timber than previously. Six months later, less than half of the required straight oaks, around one quarter of the knees and almost all the bent oaks needed had been harvested; but little had been delivered. These shortcomings meant that only two of the six vessels could

[4] *"la provisione del stortame […] conforme alle sagome e misure mandate"*

be finished within the next year. Consequently, there was a preoccupation with the availability of wood (Appuhn 2009; Candiani, 2009; Lazzarini 2013, 2014) and a recognition that although the supplies from Montona were of strategic importance their management remained ineffective (Appuhn, 2009; Candiani, 2009),

The Senate responded by strengthening control by ordering the forest manager to inspect the Instrian dominion. He produced a land register identifying 24 geographic "jurisdictions", classifying each into four quality categories. Forest management afterwards became increasingly finely focused, with different jurisdictions dedicated to producing wood for which their conditions were most favorable. Some poor areas may have been dedicated entirely to producing firewood while other more fertile or favorable areas were used for ship building. This culminated with the identification and marking of specific tress within each forest, and their adaptation to specific purposes in ship building.

The Managerial Imperatives of Supply Shortages

Wood supplies were a perennial concern and motivated Venice to secure new forest areas. The Crusade was the most extreme example for they more typically bought or contracted for private forests. Given the growing periods these relationships were stable. With shortages such a concern the Arsenale was compelled to develop methods that would minimize the wood used through increased efficiency. This involved improved planning and management. Although we found no production plans or forecasts, there are two notable aspects:

Demand Management

The Ottoman threat was significant for they possessed sufficient resources for a large fleet. Peacetime demands on the Venetian navy were discharged using a fleet of only 10 galleys with each having a working-life of about 10 years. A replacement construction program only then needed to supply one ship annually on average. The 1574 demonstration of assembling a galley in just a few hours thus seems irrational: such capacity was far greater than required. Why was so much over-capacity thought appropriate? The peace-time fleet needed to rapidly expand when faced with an impending war. If a 100-ship fleet was kept constantly available Venice would have to build 10 ships annually at a heavy cost and great waste of its limited wood supplies. That approach was neither economically nor environmentally sustainable.

The response was a policy that a modern manager would recognize as a make-to-stock, assemble-to-order approach. In 1545 the Senate determined that a 100-ship fleet was necessary to defend Venice, and it directed the Arsenale to develop methods for achieving that. This was based on strategic necessity: the Ottoman shipyard at Constantinople could build and repair as many as 250 ships simultaneously. (Gugliazzo, 2012, p. 29) The Ottomans enjoyed an "…abundance of materials, money and men which allowed the rapid construction of new fleets." and regularly had "…40 to 60 [hulls] stored in the Imperial Arsenal." (Gugliazzo, 2012, p. 56)

The Venetians needed the capacity to build and store galleys, with storage a priority: for building ships that could not be kept until needed would waste them. Venetian ship builders recognized that ships could be built and then stored **on land under shelter***,* where their life-expectancy was far longer than when afloat, even if not on active duty. More ships could be produced than the base replacement rate needed during peacetime to build up a strategic reserve of semi-finished ships. Those could then be rapidly assembled once hostilities threatened; and subsequently dis-assembled and returned to storage after the threat had passed. The 1574 demonstration shows that the final stage had been achieved, but the evidence concerning the supporting processes is not clear. It seems that different elements of the production system developed irregularly. In fact, the rapid final outfitting of galleys was achieved over a century earlier. Tafur (Letts, trans., 1926, p. 170) in 1436 first described the sequential final assembly process illustrated in Figure 1:

> …there is a great street on either hand with the sea in the middle, and on one side there are windows opening out of the sides of the houses of the arsenal, and the same on the other side, and out came a galley towed by a boat, and from the windows they handed out to them, from one the cordage, from another the bread, from another the arms, from another the balistas and mortars, and so on from all sides everything which was required, and when the galley had reached the end of the street all the men required were on board, together with the complement of oars, and she was equipped from end to end. In this manner there came out **ten galleys, fully armed, between the hours of three and nine**. [emphasis added]

Tafur (Letts, trans., 1926, p. 170) goes on: "I know not how to describe what I saw there, whether in the manner of its construction or in the management of the workpeople…" but recognizes its strategic significance. If Tafur's observations were accurate in 1436 it then makes the 1574 royal display with only a single galley trivial. Casola (Newett, trans., 1907, 2020) in 1494 describes equipment for lifting ships onto land, with covered storage for at least 56 large and smaller galleys; showing that the Venetians understood the benefits of dry storage and already had at least half the called for capacity forty years earlier than the Senate's directive. Also note the 1574 demonstration's implication that at full production Henri III would have seen a sequence of several galleys at different stages of completion being assembled.

It seems that Venice had long before achieved some elements needed for meeting its strategic goals of 1545; but could they all function together for a long enough period to build a sufficiently large fleet? High intensity operations might be possible episodically—but maintaining them consistently was necessary. Candiani (2009) implies that the system could fulfil these objectives in 1602 when a "relazione" by Giovanni Battista Contarini, the "Provveditore alle 100 galee" affirms that the galley reserve is at 109, exceeding the strategic objective; but he also notes that raw materials reserves have been substantially reduced, and need to be restored. Contarini's position was established in 1550 as a kind of program manager to ensure the Arsenale would fulfil its strategic goals. (Zan, 2004, p.152) These reports suggest that before then there may have been some periods where only some processes could meet such demands, or do so irregularly. Tafur's 1436 observation may have been reflecting a single day's efforts, whereas Contarini's report (1602) considers the capability needed by operating over multiple days.

The key recognition is the symbiotic relationship between Venice's grand strategy and the Arsenale's production capabilities: for the Senate's choice of this policy was contingent on believing that it was potentially viable. Realistic understanding of the Arsenale's abilities underpinned Venetian security—those both enabled and constrained the city-state's naval activities. Choosing unrealistic goals would have been potentially ruinous.

Schmenner (2001) prominently mentions the Arsenale as an example of "swift, even flow" but a broader perspective (Randall, et al., 2003) and deeper knowledge of the Venetian system reveals something very different. Schmenner considers only what happened at the final, assembly stage: all the earlier make-to-stock activities, most particularly those in cultivating, harvesting and seasoning the wood almost certainly were not swift, and unlikely to have been very "even". There was no particular need for speed or smoothness provided the average rate sufficed to maintain the reserve stocks at the desired levels—and those reserves de-coupled production from demand by providing an inventory supporting a rapid assemble-to-order final stage. Some years' operational difficulties might require more (or fewer) replacements for the peace-time fleet, or the vagaries of the weather or tree growth may affect supplies; but so long as those variations evened out over time the system was sustainable.

Insert Figure 6 Here

Figure 6 models our hypothesized theoretical stock levels over time: during peacetime a steady production of galleys would service the replacement needs and provide a surplus for the strategic reserve. The excess output for the reserve then gradually accumulates as inventories are kept until the threat of war requires their use in assembling the war fleet. This is identical to modern experience with "smart weapons" during recent wars in the Falklands, 1982; Iraq 1993, 2003 and the Ukraine in 2022. Stocks of those munitions were rapidly depleted after having been slowly accumulated over the previous several years. (Anonymous, 2011; Dunnigan, 2003; Tweedie, 2012; Weisgerber, 2016; Tegler, 2022) Once the war ended the Venetian fleet was de-commissioned with its components returned to the reserves, as shown in the right side of the graphic. Any losses from combat or other causes reduced the reserves; and their replacement provided production targets for subsequent years. The archival records do not show any periodic inventories or detailed accounts as a modern business would since Venetian accounting practices were rudimentary and reports infrequent. This inventory model is then inferred from management policies that dictated a pattern of production with accumulating stock, and then rapid assembly when required.

Specialised Cultivation

The shortages of bent wood were particularly difficult since naturally formed shapes would be formed only randomly. Supplies in those cases were very uncertain. It appears that as early as 1657 that the Cansiglio forest managers began using *curazioni* methods to artificially shape the trees into the forms needed for shipbuilding. These are shown in Figure 4. (Vittori, 1777) There is no discussion of the origins of this innovation, although Pliny the Elder (1982) describes its use for decorative shrubbery in ancient Rome. There are no reports on its spread to other Italian forests, but the practice appears to have become widespread. There is archaeological evidence (Gomes & Gomes, 2015; Grenier, et al., 1994) of cultivation techniques (coppicing and pollarding) used elsewhere that would have been common knowledge and very likely used in Venice too to increase the quantities and quality of the wood grown. The Venetian production line then began in the forests.

We may then conceptualize evolutionary phases in Venetian supply management:

1. RANDOM: Initially, wood was fortuitously harvested with the desired sizes and shapes cut as found. There was much wasted wood and effort searching for desired shapes.
2. PLANNED: Suitable trees or branches were identified before need and marked for later harvesting and use.
3. CULTIVATION: Rather than allow natural growth to dictate the numbers available, trees were identified and cultivated (thinning of seedlings and saplings, pruning and other horticultural work as well protecting trees from animals, erosion, etc.) Other forestry techniques such as coppicing and pollarding that increased production would also have been implemented.
4. MANAGED: Templates were used to match trees to needs, and to maximize the useable material from each one harvested.
5. FABRICATION & ARTIFICIAL SHAPING: harvested wood would be shaped, or unusual shapes constructed from several pieces in the manufacturing processes.
6. SPECIALIZED CULTIVATION: Rather than allow natural growth to dictate the shapes available, foresters could form the still growing tree to yield the shapes required.

Note this hypothesized sequence is an *ex-post* conceptualization, and that the Venetians themselves had no such grand plan; though, as we will show below, this idealization consolidates overall developments in naval forestry and manufacturing seen in other places and times—it is a generalization. This analysis is inductive, building an evolutionary sequence from observations between different countries at different stages of development. In this perspective, some phases were "managerial" dealing with how the trees were used as in the planned and managed phases, while others concerned forestry practices as in the cultivation and shaping phases; and these may have overlapped. These developments progressively improved the volume, quality and usefulness of the wood produced in the forests and the productivity of the manufacturing processes that used it.

SUPPLY CHAIN EVOLUTION & THE ARSENALE

McCarthy, et al. (2016) discuss the evolution of supply chains using several industries as case studies; and the now defunct industry of Naval Forestry may be included. The stages identified above represent a theorized longitudinal perspective based on Venice's usage of a critical forest product, and its attainment of its most advanced stage. This perspective may be generalized using an international cross-sectional study considering other countries' activities. McCarthy, et al. (2016, pp. 1697-8) note that natural resources and "sustainability agendas" may affect supply chains, and this is evident with naval forestry in how different countries managed these resources. Domínguez-Delmás, et al. (2013, p. 133, Figure 12) illustrate the distribution throughout Europe of trees useful for shipbuilding showing some countries were more heavily forested and might then have felt less pressure to intensify their cultivation practices, as will be shown later for the American colonies. Lamond (1959, addendum) maps the similar distribution of forests for Muslim North Africa and the Ottomans. Loewen (1999, p. 143) observes "…a generalized movement toward reserving forests for state ship building…" throughout Europe; and these reserved forests then became a focus for strategic resource management and control.

Venice vis-à-vis Other Ship-building Nations

Our cross-sectional analysis uses Venice as the oldest Naval power achieving its full implementation; with later, but mature industries seen in France and Iberia illustrating the intermediate stages; and the United States, as the most recent developing power showing the earliest stages. Britain also may have attained the final stage, perhaps influenced by its paucity of domestic oaks.

Not every stage in our hypothesised progression was reached, or would be reached by the time iron hulled ships rendered Naval Forestry obsolete. More importantly, the greater areas of other European powers provided more resources domestically and allowed trade with less well-endowed areas. The Ottomans are the most relevant comparator, operating in opposition, in the same area, with the same technologies, but with substantially greater resources. Gugliazzo (2012, p. 40) provides a direct comparison: "the [Ottoman timber] supply was the envy of foreign observers… and did not show signs of exhaustion until the late seventeenth and eighteenth centuries." Gugliazzo (2012, pp. 40-1) then contrasts the "meticulously organized" Venetian "assembly line" with the Ottoman shipyard that operated as a number of "workshops" operating within a larger framework—analogous with what a modern operations manager would consider "job shops". He particularly notes:

> …both the Venetians and Ottomans built the same ships in giant enterprises, yet the organizational logic[s]… differed sharply. The Ottoman[s]… could afford a more flexible organization of production in conformity with the relative ease with which resources could be found in a vast empire [having]… internal connections… facilitated by seaways.

This distinction seems overdrawn, for the Venetian's other production processes operated as job shops, their distinction was the sequential final assembly process. The differences between systems clearly anticipated resource-based strategies that modern businesses employ. These factors may also be seen in other countries' systems at other times.

The Early Stages Shown in the United States

The United States was colonized by the British for many reasons, with obtaining supplies of wood and naval stores a significant strategic objective; replacing supplies from the Baltic States that could be interdicted by their Dutch and French enemies. Malone (1964) describes the difficulties the British had with their American colonies in directing them to producing war materiel for export since local needs dominated. The American producers also suffered high transport costs vis-à-vis their Baltic States competitors. Even in Europe the only truly exploitable forests were in coastal areas or served by river transport. (Domínguez-Delmás, et al., 2013) The earliest American producers also suffered from low productivity and their unfamiliarity with the technologies in growing, harvesting and processing timber.

The first stage of fortuitous harvesting does not appear to have persisted long anywhere. Nevertheless, Fickle (2014, p. 41) entitles a chapter "Cut out and get out" evocative of the period when the forests of America's antebellum southern states (Outland, 2004) were freely exploited. But increasing population cleared land, and industrialization motivated private ownership and control of American forests. With ownership came the second stage wherein forest use became planned, and cultivation with new trees planted and nurtured after older ones were harvested. The American South was dominated by pines, suitably mainly for naval stores. Particularly important were the numbers of Live Oaks that grew in a narrow coastal band from southern Virginia around to the mid-Texas coast. (Wood, 1981, p. 5, illustration) These were quickly acquired by the Navy so that by 1831 the US government owned or controlled almost all live oak forests. (Snell, Undated) Wood (1981, p. 54) notes that the greatest difficulty was harvesting the oaks; and Northerners more used to working with hardwoods were sent South on a seasonal basis when local workers proved inadequate in numbers and skill. (Wood, 1981)

The Intermediate Stages Shown in European Powers

The middle stage, of the managed harvesting of trees for specific applications can be documented by French sources such as Boudriot (1973, p. 54-55, Figure 27), The British and Americans were similarly knowledgeable as shown with Wood's (1981, p. 12) figure that cites a French source as used in the USA; Shown here, with its caption as Figure 7A. Notably, this level of production coordination, where specific parts required in ship building were identified with living trees was formalized. For Iberian ships Loewen and Delhyne (2003, p. 103) observe that archaeological evidence shows that ship's timbers were closely matched to the shape of the trees used, and cite Grenier, et al.'s (1994) supporting archival evidence. In America, a Frenchman, Guillet (1832) produced a guide showing "through its narrative and illustrations, that demonstrated how to maximize the most amount of useful wood" (Desy, 2023) from them as in Figure 7A. He was concerned that the USA would squander its advantageous position and sought to maintain adequate forest reserves, and he made suggestion on cultivation as well as harvesting. (Desy, 2023) Concerning Iberian shipbuilders Loewen (1999, p. 144) maintains: "The archaeology of ships reveals numerous aspects of Renaissance naval forestry…. This art, and its practitioners, fixed the parameters of ship design many years in advance of the shipwright…." He (1999, p. 144) goes on to assert that shipbuilders had an "…ideal supply of ship timbers…." achieved through "…forests that were carefully harvested to meet the specific needs of each shipbuilding project and that cutting timbers was far from being an uncontrolled activity in a virgin forest." Agote and Lopez (2009, p. 17, Figure 67; with English translation, p. 107) and Albaola (2022) illustrate templates used by Basque shipbuilders. Albaola (2014) shows a modern use of templates when harvesting timber.

Figure 7B (Desy & Monea, 2016b) shows the application of a template later in the processing, in this case it is a modern restoration project in which straight timber is sawn into the desired shape. "Because… the work is restoration/rebuilding and not first-time construction … each new piece of structure must fit exactly into a space or onto a particular part of the already-built ship." (Desy, 2023) Loewen (1999, p. 151) makes an observation equally pertinent to Venice: "The Biscayan example, in which an intensive shipbuilding industry existed within severe geographic limits, was obviously unable to expand beyond a certain level of saturation, no matter how efficient the practices of timber growers." The consequence was an incentive to substitute fabricated components for naturally formed ones. These developments also enabled knowledge transfers between European naval powers (and the Ottomans, too),

Calabi (1986) and Charles & Charles (1984, pp. 26-55) discuss the closely related industry of building construction that also used large oaks. Charles & Charles (1984) describe the difficulties in obtaining sufficient quantities of wood and particularly describe the use of a "Cruck System" of building using bent timbers. They note that restoring a building requiring one of these shapes would be very difficult since modern forests might not supply even a single beam with the necessary curvature and size. (Charles & Charles, 1984, p.47 with Figure 44; p. 49 with Figure 46), These all had frames built using trees harvested to specifications—unique and virtually impossible to find now. Campbell (2022) described a Belgian Chateau initially built using curved timbers whose original owners anticipated future maintenance requirements so they themselves planted and started shaping their own oaks in anticipation of needing them for repairs someday—but this was surely an exceptional measure. The archives of the Timber Framers' Guild do not show any recent efforts by modern foresters to shape trees for architectural needs.

Insert Figure 7 Here

Where naturally formed components were not available the Venetians would fabricate substitutes for them. MacDougall (2012) discusses steam processes used to bend components into a desired shape, and these methods seem to have been widely used. Matthew (1831) describes the process. Where more complex shaped pieces were needed, they could be fabricated from several pieces as Figure 8 illustrates how a desired component could be fabricated by joining pieces together. Figure 8A (Trombetta, 1444; from Martin, 2001) shows a Venetian fabrication, circa 1444; with Figures 8B (Steele, 1812) showing eighteen century British practices which are comparable with French methods as Boudroit (1973, Figures 39 and 48) reveals, while 8C shows a more complex modern piece used in restoration (Desy & Monea, 2015),

Insert Figure 8 Here

The final stage, in which living trees were actively bent or deformed to create desired shapes, does not seem widely used by other European powers. It seems the French, German and Baltic states, like the Americans, had sufficiently large forests that these uncommon forms were nevertheless available from natural growth. The Iberians were not so well provided with forests, but we could find no documentation supporting their use of these methods. The exception was the British, as Matthew (1831) demonstrates in Figure 9 and supports with extensive discussion of the desirability of, and methods for shaping oaks into unusual, and complex shapes. Although Venetian shipwrights were employed in England as early as the 1500s (Charnock, 1801) there is no evidence of their influence on British forestry practices there, despite its clear possibility.

Insert Figure 9 Here

VENICE VIS-A-VIS MODERN SUPPLY CHAIN MANAGEMENT

It would be anachronistic to impose modern management concepts onto the Arsenale's operations too stringently. Conceptually, our finding of a make-to-stock, assemble-to-order system simply considers the historical evidence to find it neatly anticipates a modern approach. But as a supply chain the Venetian practices most closely resemble an "internal" supply chain wherein all the buyer-supplier relationships lie within a single organization. This is true for Venice, but only if heroic allowances are made for the very much looser management reporting and control systems found. We observed that these became more rigorous and "modern" over time, but they remained so loose that many of the issues arising with "external" chains (such as trust, reliability, etc.) are noticeably evident. The interrelationships between the Arsenale and the Forests and their "top management" in the Senate are illustrated in Figure 10.

Insert Figure 10 Here

Storey, et al. (2006, p. 761) posed challenging questions for supply chain management in terms of asking whether supply chains are actually managed. Never-the-less, Davis (1993), Storey, et. al (2006), Sweeney (2011), Chen and Paulraj (2004) and Shiau, et. al (2015) identify a set of commonly seen characteristics; and these will serve to assess the Arsenale's management of its wood supplies. The relevant constructs include:

1. **Integrated behaviour**. This was most visible in the Venetian supply chain through the close cooperation between the Arsenale and Forest managers. The Senate acted as the "head" office providing the resources and general direction to two separate "divisions": The Arsenale as the production division and the various forest managers as the supply divisions. The Arsenale managers over time became more involved in communicating their needs to the foresters and eventually came to actively control and participate in their harvesting operations.
2. **Shared Information**. In the absence of formal reporting systems and the paucity of records it is difficult to show how much or what information was shared. However, the Senate's policy establishing a 100 ship fleet stabilized the production system overall; and was communicated to all parties. This was strengthened through the Senate's financing of these activities. There was significant centralization that directed the different activities within the whole system. Non-performance or non-compliance was reported to superiors and could be penalized through the state's power. Although that power was considerable (even physically severe, if criminal behaviour was involved) in theory, and often in practice, too; it was not always effective. The Arsenale's workers and their guilds were themselves political actors

and influential; and Venice's conquered possessions and their inhabitants were not always considered sufficiently deferential or obedient.

3. **Shared and minimized risks**. We've observed that production and supply management effectively improved volume and quality over time by reducing the impact of the natural variation found in the numbers and usefulness of the trees grown. Establishing the 100-galley policy stabilized the quantities demanded and implicitly made Arsenale production and forestry management much easier. Risks from weather and environmental variations (i.e., forest fires, floods) remained, but demand variations were reduced.
4. **Integration of processes**. As noted, the foresters eventually came to artificially create the shapes desired by the Arsenale. This was a slow development for agricultural process innovation took years to come to fruition to complement the relevant industrial processes.

Thinking of the Arsenale and its relationships with its wood suppliers within a supply chain management framework is useful for revealing common issues that persist over long periods.

Serendipitous Innovation

Venice's distinctive final assembly line was widely noticed, but not emulated elsewhere. This is puzzling since it offered significant throughput improvements, but those were seemingly dependant on the Arsenale's physical layout. The canal was not a conscious design feature: it existed before as part of Venice's network of canals used in the normal course of life there. Positioning the Arsenale's assembly process on a canal was natural; and its subsequent exploitation as a means for moving galleys along the storage buildings that were themselves easily sequenced to provide materials when and where required was again quite natural. It was serendipity: the canal existed previously. There were manufacturing and storage buildings alongside it. So, conceptualizing a sequential assembly process was natural. So, the Venetian “flow” shop seems literally unavoidable. A further explanatory factor would be its development and use while Venice produced numerous small galleys suited to that assembly process, whereas later naval powers produced smaller numbers of much larger ships. The British, for example, used a few slipways on which to build their ships even when shipyards were sited on rivers (analogous to Venice’s canals) as at Chatham or Glasgow; as differentiated from shipyards located on sheltered bays as at Plymouth or Portsmouth that lacked any linear flow.

The use of artificial methods for forming the trees used, too, seems possibly serendipitous despite Pliny’s development of topiary in Roman times. Foresters and shipyard workers inspecting trees for suitable components from their trunks and branches could quite easily conceive of artificially recreating the natural forces (e.g., wind) that yielded the desired shapes: simply “helping” nature in making the items required. That process might have begun simply, with trees or branches being pulled to create curved components. Then, more complex shapes might have been attempted. This is seen too, with the common technique of coppicing, in which the stump of a harvested tree is left alive and used to provide an established root system then used to support new growth from grafts or new sprouting side branches. Those side branches could then provide usefully shaped timbers (Agote and Lopez, p. 17, Figure 63) if the foresters cut the stump even shorter.

So, both these notable innovations: the assembly line and purposefully interfering with the natural growth of living trees were neither conceptually nor practically difficult.

FUTURE APPLICATIONS AND DEVELOPMENT

Large-scale Naval forestry has declined after large commercial and warships increasingly relied on iron hulls, and steam power. Nevertheless, there is an on=going demand for smaller wooden ships for fishing and the remaining numbers of wooden ships in operation and requiring maintenance, as well as those still extant as historical artifacts. Modern replicas also require wood supplies in the USA. (Desy, 2023) An excellent example of that is the Basque traditional shipbuilding factory shows templates being used to harvest timbers for current projects. (Albaola, 2014) Despite using a traditional harvesting technique their foresters do not now appear to use methods that actively alter their tree's growth patterns. However, there is some archival evidence that still growing trees in the past were simply trained to shape, though it is unclear whether more complex components were manipulated into shape. (Agote, 2009, p. 17, Figure 63; English translation on p. 107)

During a restoration in the USA Duncan (1925, p. 620) doubted that sufficiently large timbers would be available in the future, particularly noting the difficulties then in finding "knees" and workmen capable of shaping them. He then hoped that "…advance knowledge of the wood requirements of 'Old Ironsides'…" would enable foresters to make timely provision for them. The United States Navy retains a managed forest at Crane, Indiana with selected white oaks committed for future restorations of USS *Constitution*. (Desy, 2019, 2023) But the specialist techniques used for shaping components are not likely to be used because the volumes required are too small, the shapes very application specific, and as noted earlier, advanced woodworking techniques and materials technologies have superseded the need for such naturally grown items.

Nevertheless, the recent fire at Paris's Notre Dame Cathedral has underscored Duncan's point since obtaining sufficiently large oaks for its restoration has proven difficult now. Restoration demands may ensure low levels of demand for the foreseeable future, without also requiring the techniques we found. Even the relatively more frequent restoration needs of historic buildings would not support such dedicated efforts. Charles & Charles (1984) find it virtually impossible to match naturally grown modern trees to specific restoration needs and require fabricated components instead. Our approaches to conservationists (Campbell, 2022) have shown no modern applications of the forestry techniques used in Venice, and the use of cheaper and readily fabricated components instead makes their revival unattractive.

The shaping techniques were uncovered as part of our research on manufacturing operations and considered novel expansions of operations into their materials supply chain. It is commonplace for supply chain management research to suggest such up-stream coordination, so this represents an unusual example of that policy. Having found these practices in Venice we then turned to questions of dissemination: how widely were these used, and how quickly did they spread? Evidence from naval archaeology seemingly shows that hulls were constructed using trees from forests managed for those specific purposes; and although research on relevant historical documents concerning forests as strategic resources there seems little documentation on their operational use outside of the USA. That would be an area for further investigation. Expanding from Venice to other European and American practices revealed that Basque foresters used simple methods to shape trees, and perhaps did more. In Britain, Matthew's (1831) treatise was a comprehensive discussion of the relevant horticultural practices, and their application to naval forestry. Investigations of similar historic documents in languages other than the Italian, French and English known to the authors may be productive.

SCIENCE AND SOCIETY

Of particular scientific interest are the implications for evolutionary theory that Naval Forestry more generally holds; and that these more extreme artificial shaping methods specifically have for Lamarckian evolution as Dempster (1983) assesses. Lamarck theorized that evolution proceeded through organisms interacting with their environment and that such effects during their lives could be transmitted to their offspring. Thus, trees that otherwise would grow straight would, if bent into unusual shapes, yield progeny that would tend to grow in those shapes. These effects were not seen, and foresters had to keep artificially shaping succeeding generations of trees. There was no evolutionary effect from each tree's shaping, their seedlings reverted to previous growth patterns. Matthew (1831) anticipated Darwin's work, and there is controversy (Dempster, 1983) concerning the discovery of natural selection between them.

The general principle of adapting nature to production needs has contemporary applications in the agriculture and food processing industries. Barrangou & Notebaart (2019) describe these developments within a supply chain perspective. Extensive use of fertilizers and pesticides improve yields, and genetically modified plants and animals are becoming widely used. Featherless chickens are an extreme example of an animal specifically adapted to reduce costs and ease processing, as are genetically modified eggs having thinner shells. (Young, 2002)

CONCLUSIONS

The Senate, Arsenale and forest managers acted to use the production facilities and wood available as effectively as possible. The Senate set a long-term strategic demand-driven production plan that stabilized industrial production in coordination with its supporting forestry activities. They developed a make-to-stock, assemble-to-order policy that produced the necessary numbers of ships without unduly burdening the Venetian economy or its forests. The forest managers implemented policies and practices that improved the volume and quality of the wood available, even devising and undertaking their own initiatives in improving the forest and its usefulness. Production needs dictated modifications to living trees to maximize their usefulness. Venice, with very limited resources, used sophisticated production and supply management methods to meet its strategic needs. Venice provides a historical illustration of numerous modern supply chain management concepts and policies—its development reflects McCarthy, et al.'s (2016) evolutionary perspective with characteristics described by Storey, et al. (2006) of increasing integration, improved information sharing and risk management observed. Our finding that the Arsenale's production requirements were accommodated by forester's alterations of living tree's growth patterns is a forceful and novel demonstration of process integration between agricultural and manufacturing operations.

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REFERENCES

Agote Aizpurua, X. and Lopex, J. (illustrator), (2009), *Gure Itsasontziak*, Vol 23, Gipuzkoako Foru Aldundia, Kultura eta Euskara Department, Dostian-San Sebastián, Basque Region, Spain. available from: http://bertan.gipuzkoakultura.net/23/pdf/bertan23.pdf (accessed 14th May 2022).

Albaola: Basque Maritine Heritage Association, (2014), *Comienza la reconstruccion del ballereno "San Juan",* Video, section at minute 4:50 to 5:00. available from: https://youtu.be/PMyUIlu0W4U (accessed 14th May 2022).

Albaola: Basque Maritine Heritage Association, (2022), "Selecting and felling the oak trees", *San Juan Whaleship*, website, available from: http://www.albaola.com/en/site/selecting-and-felling-the-oak-trees, (accessed 14th May 2022).

Albion, R.G., (1926, reprinted 2000), *Forests and Seapower: The Timber Problem of the Royal Navy, 1652-1862*, Naval Institute Press, Annapolis, Md, USA.

Anonymous, (2011), "Logistics: The Great Smart Bomb Shortage of 2011", *Strategy Page: the news as History,* Strategy World, Inc., address unknown, available from: https://www.strategypage.com/htmw/htlog/20,110706.aspx (accessed 27th March 2017),

Appuhn, K. (2000), "Inventing Nature: Forests, Forestry, and State Power in Renaissance Venice", *The Journal of Modern History*, Vol 72 No 4, pp. 861-889.

Appuhn, K. (2010), *A Forest on the Sea: Environmental Expertise in Renaissance Venice*, John Hopkins University Press, Baltimore, Md., USA.

Archivio di Stato di Venezia. (various dates), *Provveditori sopra Legne e Boschi,* Busta 241/II; 218/1; 219/2; 220/3; 221/4; 224/7; 226/9; 228/11.

Archivio di Stato di Venezia. (1715), *Provveditori e Patroni all'Arsenale*, 493, 17/10/1715; 23/10/1715; 31/10/1715.

Archivio di Stato di Venezia. (1715), *Senato Mar*, filzas: 832, 29/12/1714; 836, 11/05/1715, 28/05/1715; 838, 18/07/1715; 841, 12/10/1715.

Archivio di Stato di Venezia. (1715), *Senato Rettori*, filzas: 171, 25/05/1715; 173, 14/12/1715, 18/12/1715; 843, 25/01/1715.

Archivio di Stato di Venezia (1777) *Senato Rettori*, filzas: 133/2.

Bamford, P.W. (1956, reprinted 2014), *Forests and French Seapower, 1660-1789*x, University of Toronto Press, Baltimore, Md., USA.

Bathe, G. & Bathe, D. (1935), *Oliver Evans: A Chronicle of Early American Engineering*, Historical Society of Pennsylvania, Philadelphia, USA.

Barrangou, R. and Notebaart, R.A. (2019), "CRISPR-Directed Microbiome Manipulation across the Food Supply Chain", *Trends in Microbiology*, Vol 27 No 6, pp. 489-496.

Bellavitis, G. (2009), *L'Arsenale di Venezia: storia di una grande struttura urbana*, Cicero, Rome, Italy.

Beltrame, C. (2003), *Boats, ships and shipyards: Proceedings of the Ninth International Symposium on Boat and Ship Archaeology, Venice 2000*, Oxbow Books, Oxford, England.

Benvenuti, G. (2001), *Le Repubbliche Marinare, Amalfi, Pisa, Genova e Venezia*, Newton & Compton, Rome, Italy.

Bergamo, A. (1672), "Drawing of Bosco di Roveri di San Zenone" in *Territorio Asolano*, Archivio di Stato di Venezia, Provveditori Sopra Boschi, reg. 151, pp. 2-3.

Bertoša, S. (2014), "Alcuni Catastici De Boschi Istriani del XVIII Secolo *Atti*", Vol. 43, pp. 533-585.

Boudriot, J. (1973), (Trans. D.H. Roberts, English edition, 1986), *The Seventy-Four Gun Ship. A Practical Treatise on the Art of Naval Architecture; Volume One: Hull Construction*, Collection Archeologie Navale Française, Paris, France.

Campbell, J., (2022), Personal Communication, via Facebook.

https://www.facebook.com/groups/2257795647771395/permalink/3033017213582564/.
Candiani, G. (2012), "Une tradition différente: La construction des navires de guerre à voile à Venise du milieu du xviie siècle au début du xviiie siècle", *Cahiers de la Méditerranée*. Vol 84 No 1, pp. 293-307.
Candiani, G. (2009), "I vascelli della Serenissima: guerra, politica e costruzioni navali a Venezia in età moderna, 1650-1720", *Ist. Veneto di Scienze, Lettere ed Arti*.
Calabi, D. (1986), "Construction history and urban sites: recent work by the Venetian school on the construction history of Venice during the Long Renaissance", *Construction History*, Vol 2, pp. 3-12.
Casola, P. (1493, trans. M.M. Newett, 1907; reprinted 2020), *Canon Pietro Casola's Pilgrimage to Jerusalem in the year 1494*, Manuscript in Medieval Italian, translation published by University of Manchester, reprinted by Alpha Editions. No physical location given, available from: www.aplhaedis.com
Charles, F.W.B with Charles, M. (1984, reprinted 1995), *Conservation of Historic Buildings*, reprinted by Donhead Publishing, Wimbledon, England.
Charnock, J. (1801-2, Reprinted 2017, 3 Volumes combined), *An History of Marine Architecture*. Clerkenwell, England, Bye and Law, reprinted by Forgotten Books London, England.
Chen, A.H. & Calzolaio, F. (2001), *Progetti per l'Arsenale di Venezia*, Grafiche Biesse, Venice, Italy.
Chen, I.J. & Paulraj, A. (2004), "Towards a Theory of Supply Chain Management: The Constructs and Measurements", *Journal of Operations Management*, Vol 22 No 2, pp. 119-150.
Concina, E. (2006), *L'Arsenale della Repubblica di Venezia*, Electa, Milan, Italy.
Contarini, G.B. (1602), *Relazione*. Archivio di Stato di Venezia, Collegio, Relazioni, 57.
Crowley, R. (2011), *City of Fortune: How Venice Won and Lost a Naval Empire*, Faber & Faber, London, England.
Crowley, R. (2015), *Empires of the Sea: The Final Battle for the Mediterranean, 1520-1580*, Faber & Faber, London, England.
Davis, R.C. (1991), *Shipbuilders of the Venetian Arsenal*, John Hopkins University Press, Baltimore, Md., USA.
Davis, R.C. (1993), "Arsenal and Arsenalotti, Workplace and Community in Seventeenth-Century Venice", in Safle, T.M. & Rosenbrand, L.N. (Eds.), *The Workplace before the Factory. Artisans and Proletarians, 1500-1800*, Cornell University Press, Ithaca, N.Y., USA.
Davis, T. (1993), "Effective Supply Chain Management", *Sloan Management Review*, Summer, pp. 35-46.
Dempster. W.J. (1983), *Patrick Matthew and Natural Selection*, Paul Harris Publishing, Edinburgh, Scotland.
Desy, M. & K. Monea. (5th August 2015), Revealing the Cutwater. *USS Constitution Museum Blog*. Available from: https://ussconstitutionmuseum.org/2015/08/05/cutwater/ (accessed 31st Jan. 2022)
Desy, M. & K. Monea. (17th February 2016a), A Bolt from the Past. *USS Constitution Museum Blog*. Available from: https://ussconstitutionmuseum.org/2016/02/17/bolt/ (accessed 31st Jan. 2022)
Desy, M. & K. Monea. (9th June 2016b), The Cutting Edge. *USS Constitution Museum Blog*. Available from: https://ussconstitutionmuseum.org/2016/06/09/the-cutting-edge/ (accessed 31st Jan. 2022)
Desy, M. (9th August 2019), Personal Communication. Historian, Naval Heritage and History Command Detachment, Boston, Mass, USA.

Desy, M. (12th January, 2023), Personal Communication. Historian, Naval Heritage and History Command Detachment, Boston, Mass, USA.
Di Berenger, A. (1863, Reprinted 2012), *Saggio storico della legislazione veneta forestale dal sec. VII al XIX*, Nabu Press, Charleston, SC, USA.
Domínguez-Delmás, M., Nayling, N., Wazny, T., Loureiro, V., & Lavier, C. (2013) "Dendrochronological Dating and Provenancing of Ships Timbers from the Arade 1 Shipwreck, Portugal", *The International Journal of Nautical Archaeology*, Vol 42 No 1, pp. 118-136.
Drachio, B.Q. (1586), *Ricordi*. and (1596), *Pensieri*. trans by LTh Lehman and combined in one book. (2001), *Visione del Drachio*, De Gouden Reaal, Amsterdam, Netherlands.
Duncan, G.A. (1925), "The Wood in 'Old Ironsides'", *American Forests and Forest Life*, Vol 31 No 382, October, pp. 583-613, 620.
Dunnigan, J.F. (2003), "Where Have All the Smart Bombs Gone?", *Strategy Page: the news as History.* Fenrir Industries, Inc. Stamford, Ct, USA. Available from: http://www.fenrir.com/free_stuff/columns/dunnigan/dun-120.htm (accessed 27th March 2017)
Faroqhi, S. (2009), *Artisans of Empire: Crafts and Craftspeople under the Ottomans*, I.B. Tauris & Co., Ltd., London, England.
Fincham, J. (1851), *A History of Naval Architecture*, London, England, Whittaker & Co.
Fickle, J.E. (2014), *Green Gold: Alabama's Forests and Forest Industries*, University of Alabama Press, Tuscaloosa, Al., USA.
Galloway, L., Rowbotham, F., & Azhashemi, M. (2012), *Operations Management in Context*, Butterworth-Heinemann, Oxford, England.
Gartman, D. (1979), "Origins of the assembly line and capitalist control of work at Ford", in A Zimbalist (Ed.), *Case Studies on the Labour Process*, Monthly Review Press, London, England.
Gennaro, P. & Testi, G. (1985), *Progetto Arsenale*, Instituto Universitario di Architettura di Venezia, Cluvia Università, Venice, Italy.
Gomes, R.V. & Gomes, M.V. (Eds.) (2015), *The Management of Iberian Forest Resources in the Early Modern Shipbuilding: History and Archaeology*, Ulzama Digital, Navarra, Spain.
Grenier, R., Loewen B., & Prolx, J.-P. (1994), Basque shipbuilding technology ca. 1560-80, in Westerbrook, C. (Ed.) *Crossroads in Ancient Shipbuilding, Proceedings of the 6th International Symposium on Boat and Ship Archaeology*. Roskilde, Denmark, pp. 137-141.
Guillet, P. (1823; Reprint, Undated), *The Timber Merchant's Guide*, James Lovegrove, Baltimore, Md., USA, reprinted by Pranava Books, Delhi, India.
Gugliuzzo, C. (2012), *Factories of Galleys: Mediterranean Arsenals in the Early Modern Age*, Armando Siciliano, Messina, Italy.
Harbron, J.D. (1984), "The Spanish Ship of the Line", *Scientific American*, Vol. 251, No. 6, pp. 116-129.
Haun, L. (2011), *A Carpenter's Life as told by houses,* Taunton Press, Newtown, Ct., USA.
Hoskin, K.W., Zambon, S., & Zan, L. (1994), "Management and Accounting at the Venice Arsenale in the 16th Century, 1580-1650" presented at *EIASM Workshop on Management and Accounting in a Historical Perspective*, December 16-17th, Bologna, Italy.
Hounshell, D.A. (1984), *From the American System to Mass Production—1800-1932*, Johns Hopkins University Press, Baltimore, Md, USA.
Koenigsberg, E. & McKay, K.N. (2010), "A taxonomy for understanding the origins of production control", *Production Planning and Control*, Vol 21 No 5, pp. 437-451.

Lambert, A. & Knaack, R.K. (2008), *Production at the Arsenal, Venice: Historic institutions for in-line production*. Unpublished Thesis, Universiteit van Amsterdam, Amsterdam, Netherlands.

Lamond, M. (1959), "Une Problème Cartographié: le bois dans la Mèditerrannée musulmane (VIIe-XIe siècles)", *Annales. Historie, Sciences Sociales,* 14e Année Vol 2, pp. 234-254.

Lanaro, P. (ed.), 2007. *At the Centre of the Old World. Trade and Manufacturing in Venice and the Venetian Mainland, 1400-1800*, University of Toronto, Toronto, Canada.

Lane, F.C. (1934, reprinted 1992), *Venetian Ships and Shipbuilders*, John Hopkins University Press, Baltimore, Md., USA.

Lane, F.C. (1973), *Venice, a maritime republic*, John Hopkins University Press, Baltimore, Md., USA.

Lazzarini, A., (2013), "I boschi del Veneto prima dell'unita", *Archivio Veneto*, CXLIV. Vol 6 No 5, pp. 7-18.

Lazzarini, A. (2014), "Boschi, legnami, costruzioni navali. L'Arsenale di Venezia fra XVI e XVIII secolo", *Archivio Veneto*, CXLV. Vol 6 No 7, pp. 111-175.

Loewen, B. (1999), "Forestry Practices and Hull Design", in *Fernando Oliveria and his Era: Humanism and the Art of Navigation in Renaissance Europe—Proceedings of the IX International Reunion for the History of Nautical Science and Hydrography*, Patrimonia, Cascais, Portugal, pp. 143-151.

Loewen, B. & Delhyne, M. (2003), "Oak growing, hull design and framing style, The Cavaliere-sur-mer wreck, c. 1479", in *Connected by the Sea: Proceedings of the Tenth International Symposium on Boat and Ship Archaeology.* Roskilde, Denmark. pp. 99-104.

MacDougall, P. (2012), *Chatham Dockyard: The Rise and Fall of a Military Industrial Complex*, The History Press, Brimstome, Port Stroud, England.

McCarthy, B.L., Blome, C., Olhagar, J., Srai, J., & Zhao, X. (2016), "Supply chain evolution—theory, concepts and science", *International Journal of Operations & Production Management*, Vol 36 No 12, pp. 1696-1718.

Malone, J.J. (1964), *Pine Trees and Politics*, Longmans, London, England.

Mango, C. (Ed.) (2002), *The Oxford History of Byzantium*, Oxford University Press, Oxford, England.

Matthew, P. (1831), *On Naval Timber and Arboriculture: With Critical Notes on Authors who Have Recently Treated the Subject of Planting*, Adam Black Edinburgh, Scotland; Longman, Rees, Orme, Brown, and Green, London, England. Available from: https://ia802608.us.archive.org/1/items/onnavaltimberan01mattgoog/onnavaltimberan01mattgoog.pdf (accessed 31st Jan., 2022)

Martin, L.R. (2001), *The Art and Archaeology of Venetian Boats and Ships*, Chatham Publishing, Rochester, England.

Mayr, O. (1970), *The Origins of Feedback Control*, MIT Press, Cambridge, Mass., USA.

Mayring, P. (2011), *Qualitative Content Analysis: A Step-by-Step Guide*, Sage, London, England.

Norwich, J.J. (2003), *A history of Venice*, Penguin, London, England.

Outland, R.B. (III), (2004), *Tapping the Pines*, Louisiana State University Press, Baton Rouge, La, USA.

Pitteri, M. (2014), Granične oznake Motovunske šume iz 1779, Godine, *Histria archaeologica*, Vol 44, pp.143-160.

Pliny the Elder (trans. J.I. Whalley, 1982), *Historia Naturalis*, Victoria & Albert Museum, London, England.

Phillips, J. (2004), *The Fourth Crusade and the Sack of Constantinople*, Viking, New York, NY, USA.

Randall, T.R., Morgan, R.M., & Morton, A.R. (2003) "Efficient versus Responsive Supply Chain Choice: An Empirical Examination of Influential Factors", *Journal of Product Innovation Management*, Vol 20 No 6, pp. 430-443.

Ritter, E. & Dauksta, D. (2013), "Human–forest relationships: ancient values in modern perspectives", *Environment, development and sustainability*, Vol 15 No 3, pp. 645-662.

de Rivo, B. (1735). *Disegno del Bosco di Siaio e Treppo*, Archivio di Statio di Venezia, Provveditori Sopra Boschi - Reg. 171.

Roser, C. (2017), *Materials Flow in the Arsenale of Venice, 1797*, Web Publication, Available from: https://www.allaboutlean.com/material-flow-arsenal-of-venice/ (accessed 7th July 2021)

Schonberger, R.J. (1982), *Japanese Manufacturing Techniques*, MacMillan, New York, NY, USA.

Schmenner, R.W. (2001), "Looking Ahead by Looking Back: Swift, Even Flow in the History of Manufacturing", *Production & Operations Management*, Vol 10 No 1, pp. 87-96.

Shiau, W-L., Dwivedt Y.K., & Tsai, C-H. (2015), "Supply Chain Management: Exploring the Intellectual Structure", *Scientometrics*, Vol 105 No 1, pp. 215-230.

Snell, C.W. (Undated), *A History of the Naval Live Oak Reservation Program, 1794-1980,* Special History Study, Gulf Islands National Seashore (Florida/Mississippi), National Park Service, US Department of the Interior. Available from: https://www.ltrr.arizona.edu/webhome/cbaisan/seq_nm/Naval%20Live%20Oaks%20Reservation%20Program%20Special%20History%20Study%201794%20to%201880.pdf (accessed 21st Jan. 2022)

Sondhaus, L. (1989), "Napoleon's Shipbuilding Program at Venice and the Struggle for Naval Mastery in the Adriatic, 1806-1814", *The Journal of Military History*, Vol 53 No 4, pp. 349-362.

Steele, D. (1812). *The Elements and Practice of Naval Architecture, or, A Treatise on Ship-building, Theoretical and Practical, on the Best Principles Established in Great Britain*, London, England, Steele & Company.

Storey, J., Emberson, C., Goodsell, J., & Harrison, A. (2006), "Supply Chain Management: Theory Practice and future Challenges", *International Journal of Operations & Production Management*, Vol 26 No 7, pp. 754-774.

Susmel, L., (1994), *I rovereti della pianura della Serenissima*, Cedam, Rome, Italy.

Sweeney, E. (2011), "Towards a Unified Definition of Supply Chain Management", *International Journal of Applied Logistics*, Vol 2 No 3, pp. 30-48.

Symonds, W. (1840), *Correspondence on the subject of the royal forests, and the supply of oak timber for naval purposes*, Geo. Pierce, London, England.

Tafur, P. (1436), translator, Letts, M. (1926), *Travels and Adventures: 1435-1439*, Harper & Brothers, London, England.

Tegler, E. (2022**)**, **"**Russia May Be Showing It's Running Low On Precision-Guided Munitions", *Forbes.* March 24th. Available from: https://www.forbes.com/sites/erictegler/2022/03/24/from-debuting-hypersonic-missiles-in-ukraine-to-hinting-at-chemical-weapons-russia-may-be-signaling-its-short-of-munitions/?sh=7a2224c3632a (accessed 27th April 2022)

Tempelmeier, H. (2011), *Inventory Managment in Supply Networks—Problems, Models, Solutions*, 2nd Ed., Norderstedt, Books on Demand, GmbH, Germany.

Towill, D.R. (2005), "Breaking the china [process flow mapping]," *Manufacturing Engineer*, Vol 84 No 5, pp. 26-31.

Trombetta, Z. (1444), *The Book of Zorzi*, Manuscript MS. Cotton Titus A, XXVI, Folio 43, London, England, British Museum Library. Figure 134 is redrawn from the illustration in

Martin, L.R. (2001), *The Art and Archaeology of Venetian Boats and Ships*, Chatham Publishing, Rochester, England.
Tweedie, N. (28th Dec 2012), "Thatcher's blistering attack on French over Exocets during Falklands", *The Telegraph.* London, England. Available from: http://www.defenseone.com/threats/2016/05/us-raiding-its-global-bomb-stockpiles-fight-isis/128646/ (accessed 27th March 2017)
Venutti, B. (1763). *Disegno del Bosco di Ronchiaria*, Archivio di Statio di Venezia, Provveditori Sopra Boschi - Reg. 171, p. 8.
Ventrice, P. (2009), *L'Arsenale di Venezia: tra manifattura e industria*, Cierre Edizioni, Venice, Italy.
Vittori, G.C. (1777), Illustrations, Folio 133/2, Archivio di Stato di Venezia, Senato.
Weisgerber, M. (May 26th 2016), "The US is Raiding its Global Bomb Stockpiles to Fight ISIS", *Defense One*, Atlantic Media Company, Washington, D.C., USA. Available from: http://www.defenseone.com/threats/2016/05/us-raiding-its-global-bomb-stockpiles-fight-isis/128646/ (accessed 27th March, 2017)
Wilson, J.M. (2019), "Implementing and Operating the Portsmouth Block Mill, 1803–1812", *Business History*, Vol 63 No 5, pp. 795-825.
Wood, V.S. (1981), *Live Oaking*, Naval Institute Press, Annapolis, Md, USA.
Young, E. (2002), "Featherless chicken creates a flap", *New Scientist*. (Issue 2344), downloaded 17th April 2022: Available from: https://www.newscientist.com/article/dn2307-featherless-chicken-creates-a-flap/ (accessed 24th March 2022)
Zambon, S. & Zan, L. (1998), "Cash Flows and Accounting Practices of a Large XVI Century Organization: The Case of Venice Arsenal", presented at *XXI Annual Congress of the European Accounting Association*, Antwerp, Belgium.
Zambon, S. & Zan, L. (2007), "Controlling expenditure, or the slow emergence of costing at the Venice Arsenal (1586-1633)", *Accounting, Business and Financial History*. Vol 17 No 1, pp. 105-128.
Zan, L. (2004), "Accounting and Management Discourse in Proto-industrial Settings: The Venice Arsenal in the Turn of the XVI Century", *Accounting and Business Research*., Vol 34 No 2, pp. 145-175.
Zan, L. (2005), "Future directions from the past: management and accounting discourse in historical perspective", *Advances in Strategic Management*, Vol 22 No 3, pp. 463-496.
Zan, L. (2016), "Complexity, anachronism and time-parochialism: historicising strategy while strategising history", *Business History*, Vol 58 No 4, pp. 571-596.
Zoccoletto, G. (2014), *Il Bosco d'Alpago, Decreti e statuti raccolti dal bellunese Prudenzio Giamosa*, Dario De Bastiani, Vittorio Venetto, Italy.
Zorzi, M. (1624). Relazione dell'Arsenale di questa città presentata dal nobil homo ser Mattio Zorzi, Savio alli ordini, et letta all'eccellentissimo Senato, adi 25 giugno 1624. Archivio di Stato di Venezia (ASV) Senato, Deliberazioni Mar, 49.

FIGURE 1

The Arsenale's Final Assembly

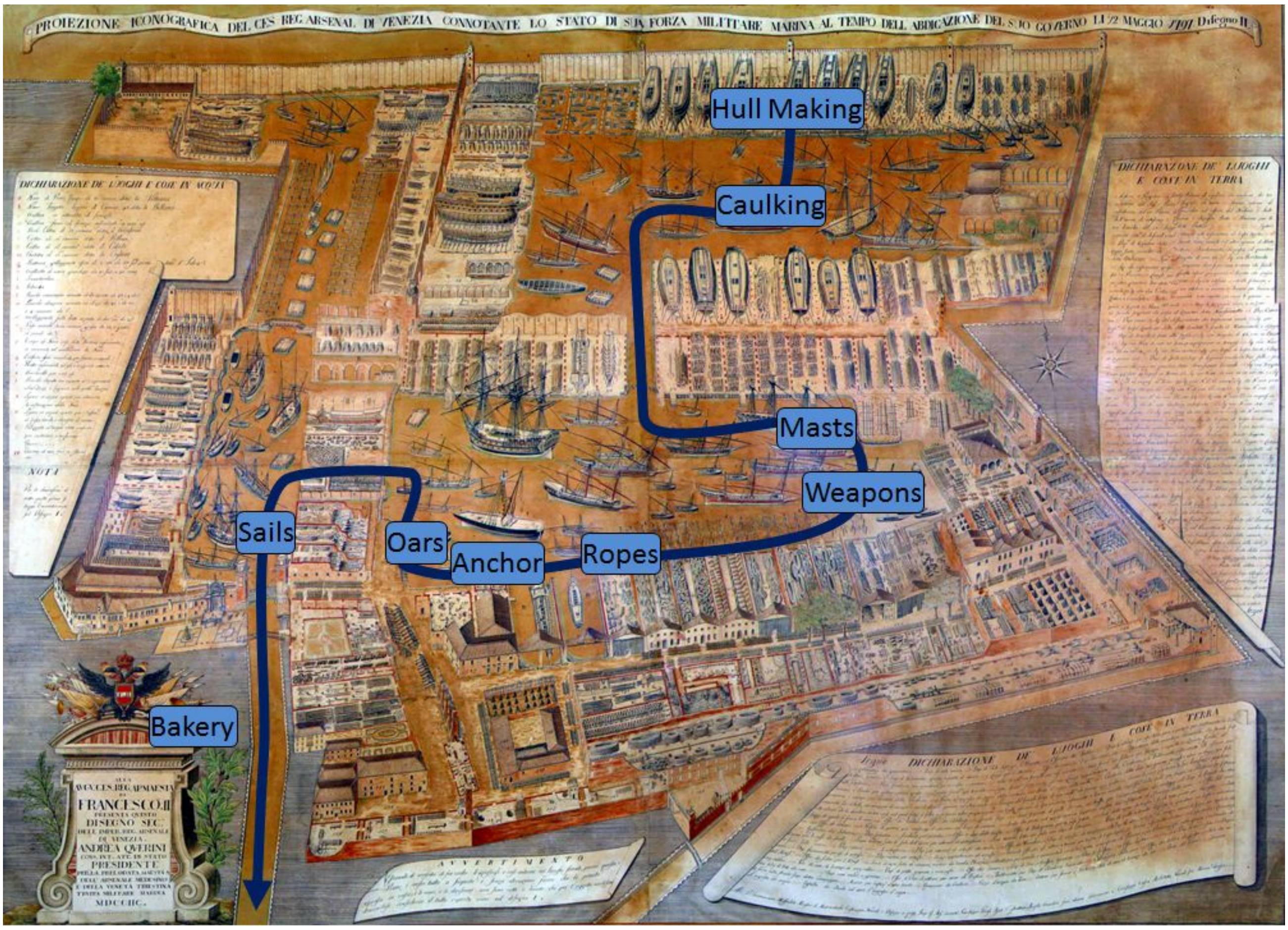


Figure courtesy of C. Roser (2017)

FIGURE 2

Shaped Wooden Pieces Used in Shipbuilding

FIGURE 2A
Galley

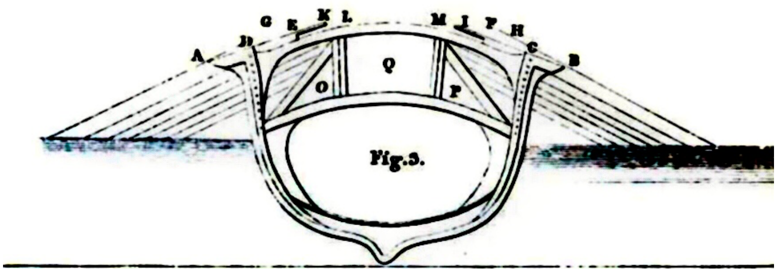


Figure courtesy of Charnock (1801-2), p. 55

FIGURE 2B
Round Ship

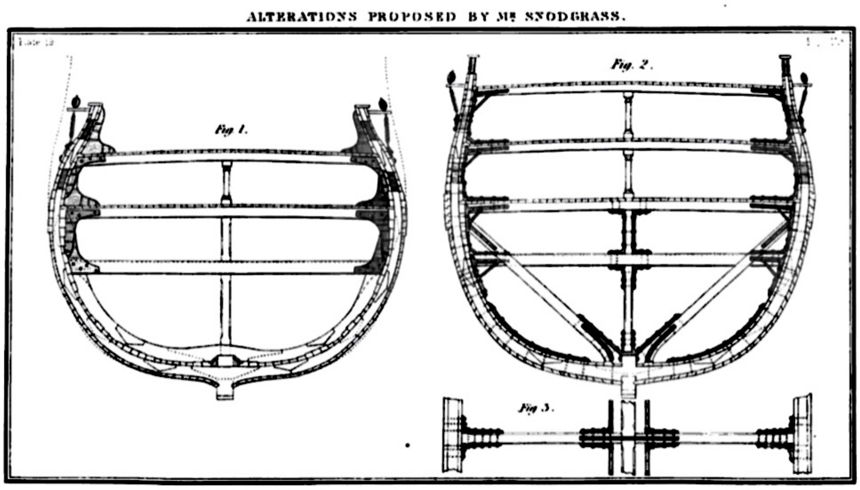


Figure courtesy of Fincham (1851), Plate, after p. 113

FIGURE 3

Arboriculture Practices

FIGURE 3A

Types of trees suitable for shipbuilding:

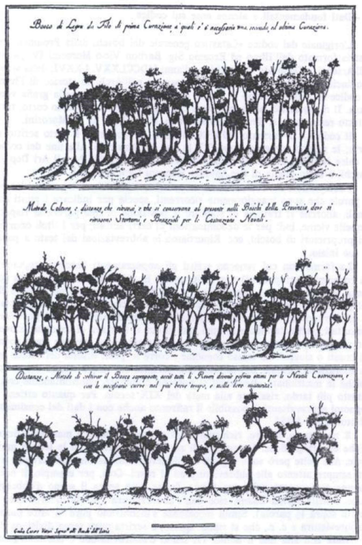


FIGURE 3B

Modifications of trees to improve their use in shipbuilding:

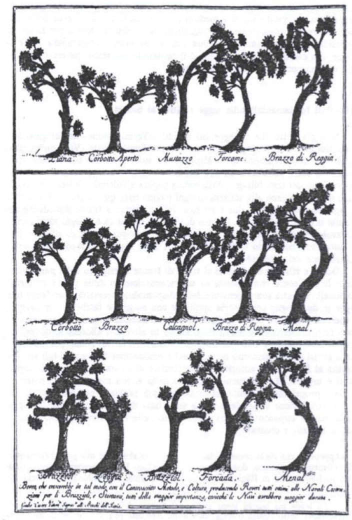


Figure courtesy of Archivio di Stato di Venezia (1777)

FIGURE 4

Forest Management Practices

FIGURE 4A:
Forest Management: Partitioning

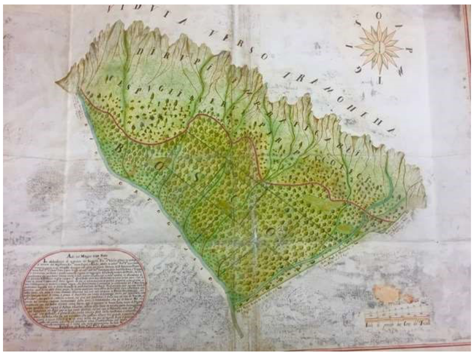
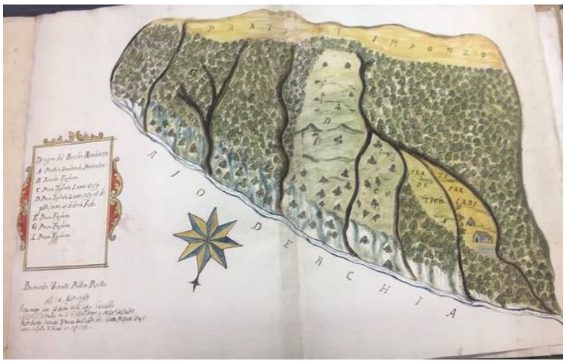


FIGURE 4B
Forest Management: Area Clear Cutting



Fgure 4a courtesy of Archivio di Stato di Venezia, de Rivo (1735)
Figure 4b courtesy of Archivio di Stato di Venezia, Venutti (1763)

FIGURE 5

Map with Illustrations of Trees Artificially Bent into Desired Forms

Figure courtesy of Archivio di Stato di Venezia, Bergamo (1672).

FIGURE 6§

Penultimate Manufacturing Stage Stock Levels during Peace and War

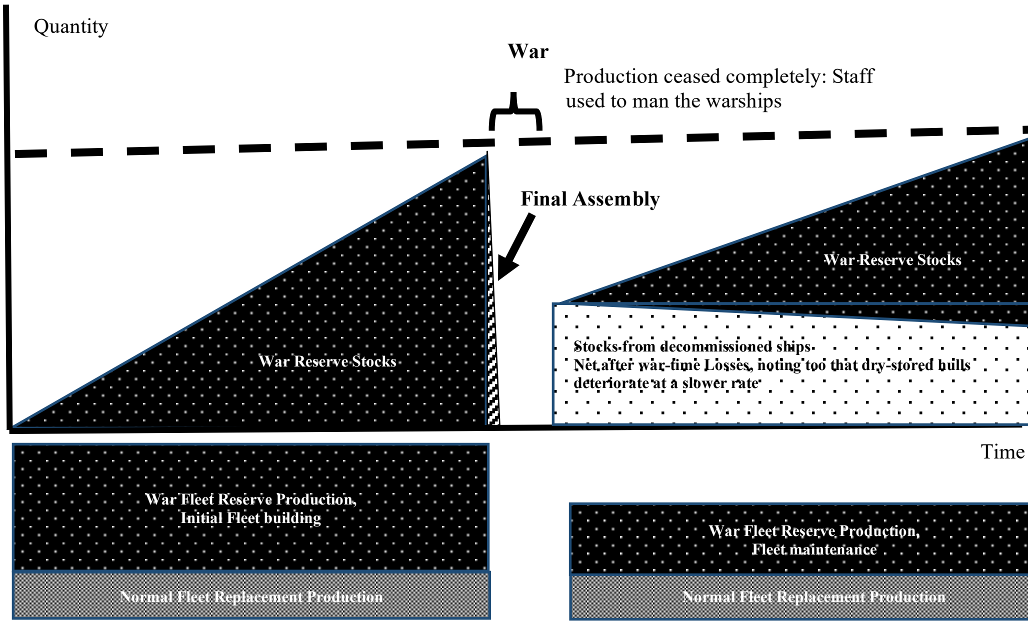


Figure by the authors

FIGURE 7

Templates for Foresters

FIGURE 7A
Templates Matched to Live Trees

Figures of the principal pieces of timber used for shipbuilding in standing trees. This is one of many illustrations from Lescallier's book for French naval architects, published in 1777, and it served to guide shipwrights in choosing which trees to fell. Similar illustrations were published in America during the early nineteenth century.

From: Daniel Lescallier, Planches du Dictionnaire de Marine (Paris, 1797), plate 103.

Figure courtesy of Houghton Library, Harvard.

FIGURE 7B
Plywood patterns outline the shape of a live oak piece for USS *Constitution*'s Restoration.

Figure courtesy of Naval History and Heritage Command Detachment Boston.

FIGURE 8

Fabricated Components

FIGURE 8A
Venetian, circa 1444

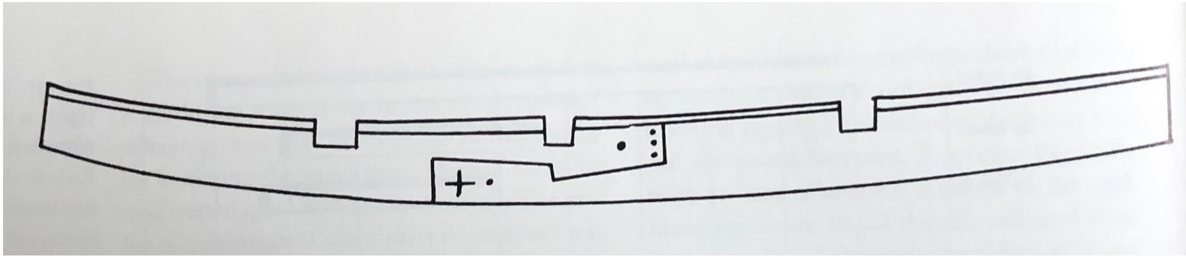


Figure courtesy of Martin (2001) redrawn from original in Trombetta, Z. (1444), *The Book of Zorzi*, Manuscript MS. Cotton Titus A, XXVI, Folio 43, London, England, British Museum Library. Figure 134

FIGURE 8B
British, mid 1700s

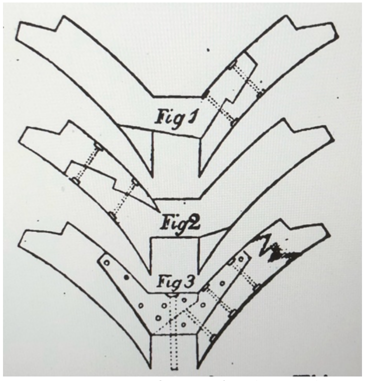


Figure courtesy of Steele (1812), p. 377

FIGURE 8C
"Cutwater Sketch" for USS *Constitution*'s 2015-2018 restoration showing the many pieces of white or live oak that make up the ship's bowhead area.

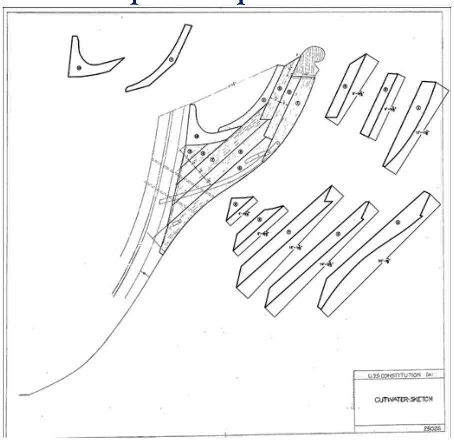


Figure courtesy of Naval History and Heritage Command Detachment Boston.

FIGURE 9

British Methods of Shaping Trees

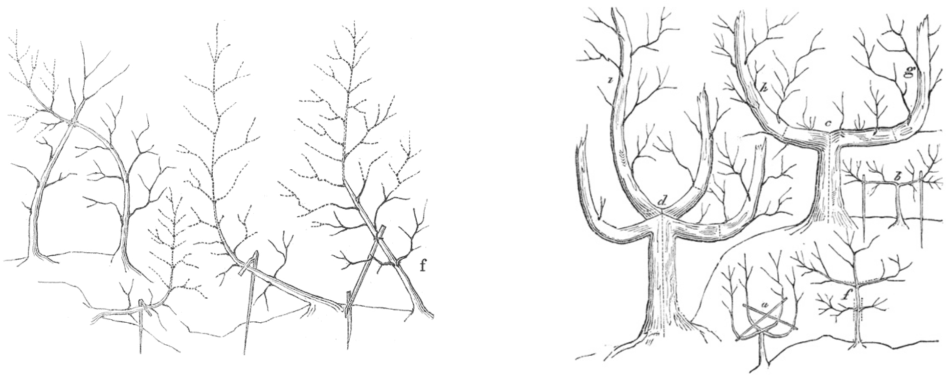


Figure courtesy of Matthew (1831), left: p. 22, right: p. 27

FIGURE 10

Organizational Relationships

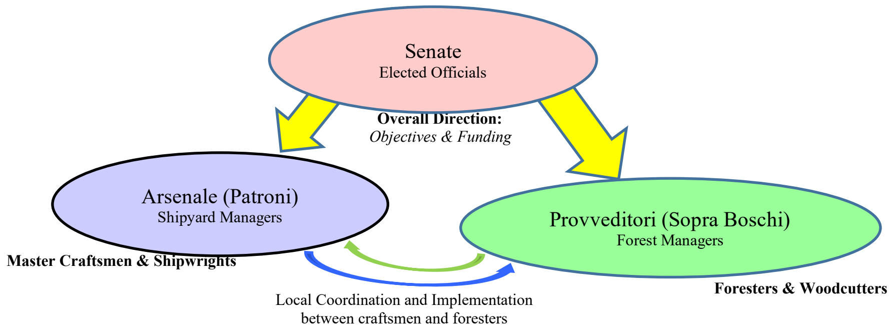


Figure by the authors