Richard W. Unger

Ships, shipping, technological change and global economic growth, 1400-1800

1. General purpose technologies

Not all technical changes are created equal. Some have greater impact on the economy than others. Some have more influence on the pace, character and extent of other technical changes. Some, though very few, have shaped entire periods in history of not just the economy but the shape and character of society, politics and thought even globally. Paolo Malanima, Paul Warde and Astrid Kander, in their 2013 book *Power to the people: energy in Europe over the last five centuries,* talk about technical blocks, that is a group of innovations which defined long periods in the historical sources and uses of energy. Coal, steam and iron was a development block of the First Industrial Revolution. The internal combustion engine and petroleum formed a block in the late nineteenth century and electricity formed another in the twentieth (Kander, Malanima and Warde 2013, 159-60; 287-88; 303-05). Within each of those blocks they isolate what they call macro innovations which created the blocks dominated by the use of specific sets of energy carriers, Joel Mokyr, in his economic history of technology *Lever of Riches,* also identifies a small number of significant macroinventions (Mokyr 1990, 24-25).

The identification of certain innovations that had extensive and lasting effects on productivity and, therefore, economic growth, at least in English, may well have started with Francis Bacon in his *Novum Organum* of 1620. The context was his programme for thinking about knowledge, how it could and should be created as part of a genuine and rigorous reformation of the study of natural history which he called the *The Great Instauration.* His work encapsulated an interest in and a growing enthusiasm for technology which concentrated on the virtues of advances. In praise of technical change, he talked of:

> [...]the force, effect, and consequences of inventions, which are nowhere more conspicuous than in those three which were unknown to the ancients; namely, printing, gunpowder, and the compass. For these three have changed the appearance and state of the whole world. No empire, sect, or star, appears to have exercised a greater power and influence on human affairs than these mechanical discoveries (Bacon 2014 [1620], 105).

The compass he used as a symbol of a complex of innovations in navigation, ship design and shipping.

Richard W. Unger, University of British Columbia, Canada, richard.unger@ubc.ca, 0000-0002-8798-0843

Referee List (DOI 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

Richard W. Unger, *Ships, shipping, technological change and global economic growth, 1400-1800*, © Author(s), CC BY 4.0, DOI 10.36253/979-12-215-0092-9.22, in Giampiero Nigro (edited by), *L'economia della conoscenza: innovazione, produttività e crescita economica nei secoli XIII-XVIII / The knowledge economy: innovation, productivity and economic growth,13th to 18th century*, pp. 373-393, 2023, published by Firenze University Press, ISBN 979-12-215-0092-9, DOI 10.36253/979-12-215-0092-9

In the same spirit and part of an effort to formalize thinking about such macro inventions Dick Lipsey and Kenneth Carlaw discuss what they call «General Purpose Technologies». They followed Timothy Trajtenberg and Manuel Bresnahan who coined the term, discussing the concept in a 1995 article, and Elhanan Helpman who edited a 1998 volume that explored the effects of GPTs on economic growth (Lipsey, Carlaw and Bekar 2005: Carlaw and Lipsey 2006: Bresnahan and Trajtenberg 1995: Helpman 1998). Lipsey and Carlaw try to offer an abstract model that describes how GPTs work and what their findings might imply for research and development expenditure (Carlaw and Lipsey 2006; Lipsey, Carlaw and Bekar 2005, 371). They define the GPT as:

> A single technology, recognizable as such over its whole lifetime, that initially has much scope for improvement and eventually comes to be widely used, to have many uses, and to have many spillover effects (Lipsey, Carlaw and Bekar 2005, 98).

The examples they offer include recognizable technologies like the automobile, the railroad and electricity. The frequency of appearance of GPTs has been increasing over time. While the nineteenth and, even more, the twentieth centuries offer a number, the period from the thirteenth to the eighteenth century offers few cases. The only two they find which qualify are printing and the three-masted sailing ship (Lipsey, Carlaw, Becker, 168-75; Mokyr 1990, 68). The latter, a product of a complex of advances in shipbuilding, qualified as a GPT because it continued to have widespread effects and had extensive spillovers and encouraged further endogenous change in newly emerging practices and improvements or adaptations of existing practices. GPTs offer opportunities for the greater use of other technologies and can even force changes in those interrelated methods of production. They also create new fields for profitable investment in varied technologies, possibly even in different fields entirely. The impact of the GPT can continue, in some cases over centuries (Lipsey, Carlaw and Bekar 2005, 98).

One of the facts if not the most important one that set a technical change apart and placed it in the exclusive category of GPT was that it generated economic growth. Any improvement in the efficiency of moving people and goods promotes trade, exchange of information and specialization in production. In short cheaper transportation generates what has come to be called, perhaps unjustly, Smithian growth (Kelly 1997, 939-52). Adam Smith gets the credit since he argued emphatically at the beginning of his *...the Wealth of Nations* that the division of labour generates economic growth and that the extent of the division of labour depends on the extent of the market. For him, writing at the beginning of the Industrial Revolution, «water carriage» was the greatest source of that division of labour and so improvement of skills and specialization in production (Smith 1937 [1776], 3-21). The three-masted sailing ship, through the mechanism Smith described, offered a wide range of new opportunities for economic growth.

The standard pattern of the evolution of GPTs historically in terms of adoption and impact has followed a logistic function. It is both the way to view the typical pattern of adoption of almost anything new but also the typical pattern of diffusion where there is a limit on capacity. GPTs begin as crude adjuncts to existing practices and so in their early stages are of sharply restricted use. Experiments and elaboration of the potential creates a wider range of characteristics and, with that, more uses. The spread of knowledge of the new method involves more users and so more improvements which in turn makes the GPT more efficient and more sophisticated. The advantages and greater use means a greater impact on other technologies which adjust to exploit or supplement the GPT. At the same time new activities become possible. The impact depends, then, on any interaction with other technologies which includes the decline in use of predecessors since the new way or ways of doing things are superior. The pace of adoption and hence the slope of the logistic curve depends on a number of factors, not least of which is who controls knowledge of the GPT. If no centralized control exists then there can be easy access to the GPT and more rapid recognition of complementarities with other methods. The scale of efficiency improvement introduced leads to changes in the political and economic circumstances, so easing the adoption of the new GPT. More than that, there is a greater impact on social and economic structures and more rapid adoption of other related technologies. In the entire process along with potential limits to the spread of knowledge and restrictions to adaptation of the GPT and related developments, there is always an assessment of risk that all those involved must make. The novelty or difference from past practice the harder it is to identify the level of risk (Lipsey, Carlaw and Bekar 2005, 379-80; 409-10; 432-34).

The concept of general purpose technologies has the advantage of pointing to certain critical factors in the development of technology and the economy. It draws attention to why certain technological changes are more important than others. It suggests where to look for forces restricting or directing patterns of technological development over the long term. It indicates what to look for in examining the history of technology. It points to risk that is always important to innovators though sometimes can be difficult to calculate or assess. In addition, with all technologies there is constant uncertainty with the potential for exogenous events to destroy any sensible predictions. Uncertainty prevails and pervades all aspects of technical change and with GPTs that is especially true because of the scale and range of their impact. If nothing else, there is the threat of the emergence of a new, competing, superior GPT.

The pattern is one of slow adoption at the start with prototypes or early versions able to compete only to limited degree with existing technology, probably in certain niches in the economy. There is then rapid adoption over relatively short time along with long term spread of the new method. Then there is a levelling off as practice becomes so widespread that the users and producers of the GPT come closer to the limits of what it can do and what related technologies can do to supplement or aid in its use. At that point typically if not before another new GPT or GPTs appear to supplant the original one. The pattern applies in many ways to the three-masted ship, a congruence that unfolds in a description of the character, the pace and extent of adoption and the impact of the general purpose technology in terms of the three phases of the logistic curve. The role of seaborne transportation improvements in the general development of the economy becomes more transparent by following the central features of what Lipsey and his co-authors called a general purpose technology.

2. The First Phase: foundations for expansion of the scope and volume of trade

The first phase stretched from the fourteenth century to the early decades of the sixteenth. It was marked by what, some years ago, this Canadian medievalist called «the great invention» of medieval and Renaissance maritime history: the emergence of the three-masted ship (Unger 1980, 216-30). The development of the design led over time to dramatic changes in the world economy and in geopolitics. As always, it seems the historian writing now has predecessors. The English entrepreneur and explorer Sir Walter Raleigh, in about 1605, talked of the invention of ships along with other sea-faring technologies as critical to the power of states and to economic well-being. For him:

> [...]whosoever commands the sea commands the trade; whosoever commands the trade of the world commands the riches of the world, and consequently the world itself (Raleigh 1829 [1605?], 325).

A new design for sailing ships emerged in the fourteenth century which evolved over the next one hundred and fifty years, coming over time to dominate long-distance seaborne transportation. There were precursors. The ability to power a vessel on water by using a sail was known for millennia and the ability to do that over open seas was known at least by 12,000 years BP. By the thirteenth century there was a range of existing technologies for shipping under all kinds of conditions and on all types of waters around the world. The melding of varied practices in different places proved to be a slow process.

The sailing ship inherited in the Mediterranean from the Roman Empire had undergone a dramatic change in hull construction in the early middle ages. The shipbuilder in charge determined the shape of the hull by the design of the principal frames. Set on the keel at the start of construction, carpenters shaped the hull planks to fit those frames. The smooth surface created lowered resistance. Carvel-built hulls with strength coming from the internal framing saved on labour inputs and very probably on quantities of wood required. Repairs were easier relative to other types of construction. Power to move the ship came through triangular or lateen sails, another inheritance from the classical world. The rig made sailing closer to the direction of the wind easier and decreased delays from contrary weather. The principal disadvantage was the sizeable crew needed to handle the sail type and the need, when coming about to sail in a different direction, to carry the whole sail and its long mast over the masthead. The need for that manoeuvre limited the size of the mast. The sail could not be shortened or extended. The only way to change sail area was to use a different sail and yard so ships had to carry differently sized sails or accept the limitations of having only a default sail available. By 1300 the Mediterranean sailing ship could make trips from Iberia to the Levant without stopping.

They could carry hundreds of passengers from Italy to the Holy Land. For some purposes shippers used galleys which had the advantage of being able, at least for short periods of time, to rely on oars for propulsion. That was especially helpful in getting in and out of port. The vessels had low freeboard so had trouble in the open ocean in any storm. Only the largest of galleys could survive a trip from Italy to the Low Countries. Their greatest shortcoming was the high cost created by the relatively massive size of the crew (Pryor 1994; 1988, 25-86).

Northern Europe had followed a different path. There galleys had all but disappeared by the fourteenth century, especially for commercial voyages over seas. Outside the Mediterranean, tubby sailing ships powered by a single square sail dominated seaborne commerce. Shipwrights built the hull up from the keel piece by piece, overlapping the planking to assure watertightness and strength. The clinker-built hull was heavy and required extensive skills on the part of each shipwright (Adams 2002, 53-58; Crumlin-Pedersen 2009, 148-60; McCarthy 2005, 55-81). The rudder was fixed to a straight sternpost, not to the side of the ship as in the Mediterranean. The cog is the best-known type of the northern European ship, coming to take a major role in shipping in the Baltic and North Seas (Crumlin-Pedersen 2000; Ellmers 1994; 2010: Jahnke 2011: Jahnke and Englert 2014; Paulsen 2016, 122-37).

In the late thirteenth and early fourteenth century there was increasing contact between northern and southern Europe by sea, contact that led directly to the development of the full-rigged ship. Mediterranean shipbuilders redesigned the cog, giving it a carvel-built hull. They then added a small lateen sail near the stern. This two-masted carrack had all the advantages of the northern cog with the additional attribute of being able to sail closer to the wind because of the triangular sail near the stern. The vessel was better able to hold a course and also could manoeuvre more easily. The last touch was to put a small mast near the bow and put a square sail on it to balance the lateen on the mizzen mast aft. The master of the ship had even greater control as a result. The exact date and location of the combination of earlier technologies is not known but already by 1400 builders knew the essential components. The Atlantic coast of Iberia is the most likely site for the earliest full-rigged ships.

While it existed by 1400 the design was still not able to compete with many other more traditional forms and the full potential of the full-rigged ship was not yet explored. The potential for saving labour took time to realize. The lateen sail and the still large size of the single square sail on the mainmast kept crew size up. Over the following two centuries builders divided the sail plan. The total sail area stayed the same or increased while the number of sails grew with each smaller than the typical sail of high medieval European ships. With smaller sails crews handled them one after the other and so fewer men were needed for a vessel of the same size. Smaller crews meant greater range over the oceans of the world. Over time shipbuilders developed different designs for different purposes. Carracks were tubby with a deep waist and high castles at bow and stern. Galleons, which owed features to galleys, had straight gunwales and were narrower which increased speed, eased handling of cargo and improved ability to control the vessel (Phillips 1994; Unger 2019, 44).

It is hard to measure the improvement in safety that full-rigged ships brought.1 Similarly it is hard to measure any change in the cost of transport the full-rigged ship might have brought because so many factors determined the price shippers paid at any time. At least there are measures of labour productivity, though with their own flaws. They show improvement over time, however slow, in the early days of full-rigged ships (Lucassen and Unger 2011). The limited data suggest that single-masted ships in the Baltic had manning levels that it took full-rigged ships more than another 100 years to match. The figures are solely for Europe, the only part of the world that knew full-rigged ships in the fifteenth century. That situation changed when, exploiting the greater range of the type thanks to its potential higher carrying capacity and declining crew sizes, Europeans in full-rigged ships travelled across oceans down the coast of Africa, to the other hemisphere and to and through the Indian Ocean in the late the fifteenth century.

Important to the development and success of any technical innovation is, at the least, government indifference and at best government support. The full-rigged ship, after an initial period of experimentation, enjoyed positive institutional promotion. Various states subsidized the exploitation of the design in voyages to distant and even unknown regions. In the first half of the sixteenth century there was an arms race among northern European states with kings paying for the construction of ever bigger naval vessels. The kings of France, England, Scotland and Denmark all found that there were limits to how big such ships could be. It was expensive to build the giants and also costly to find and maintain the massive crews that the vessels needed (Unger 1980, 234-35). Realizing the advantages of the type, governments also built ships which were of little use for carrying cargo but were effective as fighting platforms. Light fast galleys had long qualified as specialized warships. Through the sixteenth century governments increasingly used full-rigged ships to fight at sea, in the process exploring effective changes in design and construction (Unger 1981). In promoting voyages of exploration and, from the early sixteenth century, voyages to carry emigrants to the Americas as well as Asia governments expanded the use of full-rigged ships and also increased the numbers built. They gave shipbuilders more opportunities to hone their skills in producing the type while also giving occasions to try variants. All the time through the first phase down into the sixteenth century the design became better known, the ability to create examples of the type spread and the use of the vessels that fit the description increased not just on the open ocean but also in the Baltic and North as well as the Mediterranean Seas.

[1] The McCormick et al., *Geodatabase of Shipwrecks* ends in 1500 and shows a maximum of 23 cases in the century after 1400 and 20 for the century after 1200. In both cases some of the ships may have gone down in the following century. While the figures are suggestive, the small sample size and the lack of certainty about date of loss or the design of the ships involved, among other things, drawing any conclusion would be overly ambitious.

3. The Second Phase: improvements and impact of the general purpose technology

From the mid sixteenth century to the early years of the nineteenth use of full-rigged ships expanded. The areas of the world where the type was found and built increased to encompass all of the oceans of the world. The variants continued to grow with some standardization in subcategories of the full-rigged ship. Designs took advantage of the qualities of the essential features of the type while adjusting features to suit specific trades. Shipbuilders throughout Europe learned to produce full-rigged ships, in some cases hesitatingly staying attached to older practices which gradually faded away (Unger 1985; Maarleveld 1994a; 1994b). By the eighteenth century, methods of building were consistent everywhere with variations dictated by the trades, functions and places where the ships would find use. The sailing ship was a lumpy investment and while land had the greatest share of total investment it was highly divisible. The risk of loss of such a valuable capital good, a risk that was in large part determined by conditions at sea, was a brake on the pace of technological advance. Buyers of ships and so shipbuilders were leery of novelty. If that was not enough the general uncertainty which accompanies all technological change, the ability of exogenous political and social developments and spillovers from existing technologies to have an impact on the shipping sector as well as the economy at large always served as deterrents to experiment for investors and shipbuilders.

To counteract misgivings there was a varied collection of changes in full-rigged ships in the sixteenth and seventeenth centuries which improved their performance and so promoted the adoption of the type. The continuing success with dividing the sail plan along with the addition of sails of different types, while somewhat increasing the levels of skill needed for crew members, did improve speed, safety and efficiency. Hull shapes continued a process of increasing length relative to width. That made it possible for ships to be larger but also more seaworthy. Builders overcame the tendency of long ships to hog, that is for the ends to sag, not quickly nor completely but enough to improve efficiency in shipping. Greater use of block-and-tackle on board to handle sails and widespread use of capstans to handle anchors and in the loading and unloading of heavy cargo helped in lowering crew size. Perhaps most effective in lowering costs was the emergence of vessels with features suited to one trade or one set of trades. The growth in certain exchanges of goods meant building specialized vessels with designs to suit those trades paid off for both the shipbuilder and the shipper. The Dutch fluyt which emerged in the last years of the sixteenth century was perhaps the outstanding example, at least in northern Europe. Used extensively in the grain trade to the Baltic and to southern Europe, it was longer relative to its width than its predecessors and had a simple sail plan so crew size was kept low. The type could deliver improvements on the best manning ratios of the best-performing competing designs of the end of the middle ages and so replaced them in many northern European trades while being able to compete in transoceanic ones. Dutch builders produced other specialized types and the general development extended to vessels for the fisheries and, in time, to warships (Wegener Sleeswyk 2003b).

The size of individual ships did grow though sailing vessels do not obviously or immediately benefit from increases in scale. The benefits of size may disappear if there is greater danger of loss since bigger ships increase the concentration of whatever loss occurs. It was difficult to know a priori the range of the scale economies and dis-economies, in part because of the inability to accurately assess potential for loss and in part because of the potential impact of constraints such as depth of waterways and ports. Larger ships might mean savings when holds were full but there were no guarantees that vessels would frequently if ever be at maximum cargo. In the trade to the East Indies, because of the considerable profitability, ships were full and even overloaded much of the time. Errors in shipbuilding, such as using wood not properly aged, could generate massive losses as Portuguese shippers learned in the years around 1600. Those same shippers and their government identified the problems and reduced their losses to the norm for their competitors. For all trade around the Cape of Good Hope finding the optimal ship size was something worked out through experiment. A bigger ship almost always meant greater carrying capacity. It also meant a greater investment since big ships cost more to build and apparently more per ton as well. They were often faster and had a lower ratio of crewmen per ton so there were benefits from larger ships under certain circumstances (Wegener Sleeswyk 2003b). Larger vessels required adjustments in building and in some of the materials used which helps explain the higher construction costs. There were significant changes to handling qualities and ways to sail a vessel as size grew suggesting that there was an optimal size above which returns to investment declined, a discovery made in the East Indies trade and in others over the course of the second phase (Lipsey, Carlaw and Bekar 2005, 390; 396).

Technological improvements in the second phase were subject to constraints, some internal to shipbuilding and others external. As anticipated the gains were less dramatic than in phase one and the pace of efficiency gains went down over time in phase two. The greatest added value with general purpose technologies and very probably with any technology comes from the replacement of existing methods with the new ones. In the case of the full-rigged ship the efficiency improvements came from replacing the capital good, that is the ship itself. Over time many types such as cogs in northern Europe to lateen-rigged feluccas and xebecs in the Mediterranean became smaller and their use more circumscribed. The numbers of full-rigged ships rose in the new trades created by their versatility and efficiency but also rose in traditional trades. The use of newer technology spread as shipbuilders modified and improved their products. An obvious result was gains in labour productivity in shipping during the seventeenth and the eighteenth centuries which were higher than in almost any other sector (Lucassen and Unger 2011, 17-22). The potential gains attracted capital investment which also fuelled the replacement rate in ships. It also meant producing vessels that could operate in previously under-developed trades. The addition of gunpowder arms and the improvements in hulls so ships could carry artillery, made lighter by the end of the sixteenth century because of the introduction of iron guns on board, opened operations in dangerous trades and the possibility of intimidating competitors around the globe. Other increases in the capital invested in certain ships had less dramatic effects on the spread of full-rigged ships, though, reinforcement of hulls made possible operation in Arctic waters which opened a number of sites to whale fisheries and, in the late eighteenth century, the addition of copper sheathing among other improvements promoted longer life and higher speeds for ships operating in tropical waters in the East and West Indies (Kelly, Ó Gráda and Solar 2021; Solar 2013; van Zanden and van Tielhof 2009; Rönnbäck 2012).

3.1 Spillovers

One obvious spillover from the more extensive use of full-rigged ships, their growth in size and the prosperity of shipbuilding was the scale and stability of construction sites. Where in the middle ages there were few permanent shipyards, certainly in Europe, and what few there were served for the construction and repair of galleys in the Mediterranean. Starting at about the same time as full-rigged ships some towns in northern Europe set aside land for shipbuilding. Through the sixteenth and seventeenth centuries the number and size of those sites increased considerably (van der Vliet 2006). The choice was recognition of the expansion of the industry and also recognition of the greater needs of craftsmen. The greater efficiency in shipbuilding also depended on improvements in related technologies in shipyards. The use of cranes made moving timber easier but they and the greater size of the varied shapes of pieces of wood increased the space requirement. Improvements in metallurgy made the tools in use more durable. The number and variety of tools along with the permanence of sites translated into more storage space on the wharves.

The greater demand for information about places throughout the world and how to get there generated pressure for improvements in navigation. By the thirteenth century cartographers in the Mediterranean had pieced together data on compass readings and distances from port to port along with sailors' sketch maps of local areas to create large impressive portolan maps of the Mediterranean. While those valuable maps indicated the potential of cartography it was smaller and rougher maps along with books with sailing directions that made their way to sea, serving there as aids for working seamen. By the sixteenth century printed maps in collections, charts of various regions large and small as well as instruction manuals appeared and enjoyed wide circulation (Lang 1968; 198; Schilder 2017; Waghenaer 1965). There was an increasing market for the materials among students going to the navigation schools which began to spring up in port towns (Burger 1908; 1909; 1910; Craig 1982; Schotte 2019). Port towns became home to the makers of nautical instruments who improved the quality and availability of their products. The combination of better devices to measure the position of the sun and the stars and useable and increasingly accurate charts made it much easier for pilots to fix the position of their vessel at sea. Governments took an interest in tracking the latest information about distant sailing routes in the sixteenth century as Iberian sailors ventured to seas in many parts of the globe previously out of the reach of Europeans. State offices gathered the information both for the safety of ships at sea and to establish territorial claims. The commissioning of cartographic surveys and the production of maps may have had political motives but those efforts that, by the eighteenth century, stretched from the Mediterranean to the eastern Baltic were the foundation for government hydrographic offices which emerged in the early nineteenth century (Lang 1968, 50-66; Unger 2010, 76-78; 99-102).

The full-rigged ship generated spillovers to the handling of cargo in port towns. Facing increasing volume of trade and larger ships, civic authorities improved the organization of handling cargo on the wharves. They established institutions to organize teams of experienced longshoremen available to handle cargo when needed. They made provision for storage on wharves and for easier access to the docks for the carts and wagons that took away cargoes. Wharves increasingly had cranes of growing size to ease the work and increase the scale of moving goods from ship to shore (Lucassen 2011; Stern 1960). All those improvements were responses to the changes in ship design. So too were the many cases of towns moving docking facilities further downstream if they were on rivers to be closer to open waters. Larger full-rigged ships with deeper draft needed more space to manoeuvre and for lighters to reach them (Unger 2006b).

The spillovers from port improvements and better navigation promoted more regular trades carried out more quickly which in turn improved communication and also promoted the development of other designs of smaller ships to supplement the long-distance trades using full-rigged ships. While sending information overland was always faster than travel by ship, in cases such as contact between the Americas and Europe or islands around the world the full-rigged ship was an invaluable source of connection. The frequency of voyages over shorter distances might not speed the transfer of urgent information but the volume and range of news expanded along major routes. Advances in specialization of ship design were already underway before the full-rigged ship emerged but the new design accelerated the process as the three-masted. and for a short time four-masted, ship took over an increasing share of longer distance trade. Those smaller boats and ships, some with only one or two sails on a single mast, served to distribute good to and from major ports to lesser ones. In some cases those craft of different design or variants on the full-rigged ship could find use in long distance trades (Unger 2019). Gains in efficiency from technical change in smaller vessels in the second phase and beyond was considerable, advances promoted by the success of long-distance commerce. The pattern of trade reorientation enhanced the tendency toward specialization in design but also among ports. The marshalling of goods at a single site shortened turnaround times and improved utilization of carrying capacity. It also meant that certain centres grew more quickly and so promoted communication and with that the potential for technological advance.

The spillovers and the effectiveness of the full-rigged ship generated a range of connected changes in commerce and settlement. The opening of new trades and trade routes led to an increase in production and also to redistribution of settlement in Europe and in many other parts of the world. It was in long distance seaborne trade where the impact was most obvious. By the early seventeenth century Dutch shippers had found ways to sail between Europe and the East Indies on a more regular basis and in shorter times. Their success and that of their English counterparts sailing to India led directly to a sharp increase in the volume of trade between Europe and Asia and the erosion of overland exchange across Eurasia (Bruijn 1990;

Steensgard 1990; Lane 1940). By the 1620s, for example, Venice had surrendered the role as distribution point for Asian spices to Lisbon and Amsterdam. Spanish navigators learned enough about prevailing wind patterns in the Pacific to establish somewhat regular contacts between Mexico and the Philippines. Volumes might have been small, though, it was a novel trade and a source of the growth of Manila as a port (Giraldez 2015, 101-59).

Already in the sixteenth century exchange of goods carried in full-rigged ships led to reorientation of the trading networks of Indigenous Peoples in North America (Trigger 1986, 111-63). Over time in the Americas the arrival of migrants from Europe and Africa, often sponsored by governments in one way or another, led to implementing new agricultural practices. The trade with more distant places, at first with Europe and increasingly with other sites in the Americas, promoted specialization in crops raised. The settlements of the migrants were largely along or very near the sea coast so easily serviced by sailing ships that, for Atlantic crossings, were largely three-masted vessels. Throughout the world and especially in Europe cities on the oceans saw faster growth than those in the interior. The most prominent examples were ports in Europe such as Seville, Lisbon, London and Amsterdam (Bairoch, Batou and Chèvre 1988, 130-33; 176-88)

The development and continued elaboration of fill-rigged ship design led to spillovers in the organization of the industry that produced the capital good. The great majority of building and especially the building of smaller vessels was in the hands of private investors. By the seventeenth century, though, a few private shipbuilders were moving toward operations on a larger scale with investment in permanent yards and tools and equipment, investments made possible by the volume and value of ships built along with the rise in orders for larger ships. Dating from the late middle ages guilds of independent producers, organizations given legal status by towns, brought together the owners of wharves who were skilled labourers. Not common in areas outside northern Europe, those institutions oversaw training in the techniques of the trade and offered a rudimentary system of grading levels of accomplishment. The guilds then gave shipcarpenters an easier path to move to other towns and in the process increase their own knowledge while disseminating information more broadly. By the seventeenth century the role of those institutions decreased in importance, in part because the need to spread technological innovations declined and the scale of construction grew. The concentration of authority in the hands of the designer of the ship led to a deskilling of workers on the wharf and reduced the need for training.

That tendency was most notable with the rise of government-owned and managed shipbuilding facilities. Such yards predated the full-rigged ship with examples in the Mediterranean, most notably in the Arsenal of Venice. There were also yards in which the state had an interest in China as well in the sixteenth century and before (Moll-Murata 2008, 182-83; Lane 1973, 361-64). The expansion of the responsibilities of governments and the appearance of monopoly trading companies in northern Europe, both in part due to the changing technology of shipping, centralized work for larger ships. They also created pressure to increase the size of ships. The resulting yards, like that of the Dutch United East India Company (VOC), were among the largest industrial enterprises in the world.

4. The Third Phase: flattening the curve and decline, still with technological advances

The rate of adoption of the full-rigged ship levelled off in the eighteenth and nineteenth centuries. The prevalence of the type was so great in most parts of the world that the functions for which it was best suited were overwhelmingly dominated by vessels of that design. There may have been a slight erosion in the number of full-rigged ships in use in the part of the world where it was first developed. Newer versions of other types, influenced by the hull design, rigging and construction methods of full-rigged ships, found certain trades and uses where they could supplant the dominant type. The larger size of two-masted ships and their greater sail area along with greater ease of handling sails was a case in northern Europe where, in some trades, full-rigged ships were replaced. Ultimately it was the emergence of a new technology for the propulsion of ships at sea that led to the fading in importance of the GPT with roots in the fourteenth century.

There continued to be improvements in technology of sailing ships though they were not on a scale or of the complexity of the advances in phase two. The addition of small studding sails on extensions to the now many yards that decorated taller masts, set only in good weather, could mean some greater speed. More important was the gradual change from a lateen sail on the mizzen mast to a gaff sail, called a spanker or a driver, which eased handling of that fore-and-aft sail and made possible its increase in size. There were more staysails to take advantage of the presence of standing rigging from which those sails hung. In general, the maximum quantity of canvas on a full-rigged ship went up (Unger 2011). The greater source of energy was especially valuable with warships as they grew in size (Glete 1993). The wars among states in western and northern Europe generated something of a naval arms race to gain some control over the seas which translated into bigger ships to fight in pitched battles as well as into faster, more versatile warships of middling size (Unger 2006a). The importance of naval conflict also created government interest in finding out what the competition was doing, in acquiring the latest technology through importing shipyard workers from regions that led in naval architecture to using spies to report on how other states built their warships (Harris 1998, 25-26; 425-52; 523-39; Ferreiro 2007, 63-68). Even stretching back into the seventeenth century the armed full-rigged ship with higher costs of construction, fitting out and manning, had forced evolution on governments. Just as the growing sizes of armies and their increasing costs in the sixteenth century had placed greater burdens on governments so too did navies. What historians have called the fiscal-military state which emerged in the period, devoted to finding income sources to finance forces for war, was to a significant degree a result of technological developments in shipbuilding. While there were signs of that evolution of European states before the eighteenth century the increasing size of warships, the larger crews, the permanent bases for them all combined in the eighteenth century to expand the scope of government action, the range of activities of states and make the protection of seaborne commerce a principal goal of government action in both war and peace time (Bonney 1999; Glete 1993; Unger 2015).

New technologies began to have their effect on the full-rigged ship. Metallurgical advances made it possible for shipbuilders to turn to iron supports in place of wooden ones to reinforce the heavier hulls. As iron and then steel production rose in the nineteenth century builders built entire hulls from metal instead of wood. The new general purpose technology with extensive and long-term impact, the steam engine, had a lasting effect on sailing ships. By the third quarter of the nineteenth century the majority of the tonnage of western Europe merchant marines was powered by steam. Faced with competition from steam power, through much of the third phase the pace of technological advance in sailing ships grew, the improvements following the earlier paths toward labour saving and lowering risk (Rosenberg 1972, 26-8). The impact of steam engines already came early in the century, though, and provided a significant advantage for sailing ships. Getting in and out of harbours was always a problem no matter the sail plan. The vessels had to wait for favourable tides and winds and, in extreme cases such as the monsoons winds in the Indian Ocean, delays that could last months. Steam-powered tug boats could tow sailing ships to open water where they could operate freely, cutting down on travel time and making the timing of departures and arrivals more reliable.

The transfer of the sailing-ship technology first developed along the Atlantic Ocean coast of western Europe in the late middle ages started in phase two as full-rigged ships travelled to sites around the globe. The sharing of the design and construction methods became more obvious, however, in phase three. The extent of that transfer was slow, a reflection of the lack of institutions to carry out dissemination and of the quality and character of existing technologies in other parts of the world. The gains from switching to the imported design were in Asia too small to convince builders in India, China, Japan, southeast Asia and the islands in the Pacific to take on what was an unfamiliar type of construction requiring, in many instances, skills different from those they had (Lewis 1994). In Australia, southern Africa and the Americas the full-rigged ship was so different from the existing vessels that entirely different forms of transportation continued to operate in their own spheres. The great difference in technologies made any bridging of the gap impossible and so the full-rigged ship dominated long distance transport and the carriage of large quantities of goods. In China and Japan traditional vessels remained in widespread use, preferred over full-rigged ships. Junks built in Chinese shipyards proved to be as effective as full-rigged ships in many trades, so much so that Europeans used them on occasion as well (Manguin 2010; Unger, 2013, 164-87). In India there was more borrowing of imported technology in the overall design of seagoing vessels and in the specific methods of fastening. Nails replaced tying planks one to the other, though, the cost of iron slowed the transformation (Manguin 2019, 401-03; 407-12; Staples and Blue 2019; Vosmer 2019). In the islands of southeast Asia full-rigged ships operated alongside smaller vessels of designs familiar in Europe alongside those of traditional local design, both used by the dominant European trading company. Europeans, in some cases, found locally-built large trading vessels to be as useful as ships of their own design (Manguin 1993, 265-74). Some cross fertilization existed though that was more obvious in and around the Arabian Sea. There shipwrights maintained the general principles of traditional construction though they added features borrowed from the full-rigged ships operated by European traders, a practice which gained ground during the second phase. One obvious example was the *baghla*, a large ship from 200 up to 1000 tons that below the waterline was shaped like a traditional Arab vessel but which above had many European features (Agius 2008, 153-67; 310-48; Agius 2002, 34-70; 133-87; Al-Salimi and Staples 2019, 45-46).

Maritime states on the European Atlantic front established shipbuilding yards at strategic sites for warships and also for cargo ships in many parts of the world. The principal function of the facilities was the repair of vessels after the implied long voyages from Europe. The presence of those yards from Batavia in present Indonesia to Elmina in west Africa to Paramaribo in present Surinam and many places in between those sites offered examples of how to repair and build ships of European design, full-rigged but also smaller ones. Often the shipwrights brought from Europe had to use local materials and so in the process gained an appreciation of the value of different kinds of wood, for example. The yards typically employed local workers who were often the unskilled labourers there but they had opportunities to learn about full-rigged ships. The imported carpenters learned about local designs and practices as well. The transfer of information was not just in one direction (Antunes et al. 2019). Still through the third phase while any exchange of knowledge of the technologies was limited, it was the development and articulation of the full-rigged ship that created any opportunity for learning. It was in the nineteenth century when the new technology of steam power replaced sails for propulsion that the distinctions among different designs and building practices around the world slowly faded away.

In the third phase, as the influence and importance of the full-rigged ship was declining, the art of ship design and shipbuilding became more formalized, standardized and institutionalised. Methods of knowledge transfer become better. The structure of knowledge about practices in the trade expressed in written works over time improved, at least within the region where the full-rigged ship began. Still, the relationship of the advances made in ships with the institutions, formal and informal, set up to administer shipbuilding in different parts of the world, illustrates the minor role of written works on the topic and the lack of any systematic objective discussion of the practice of the trade until the eighteenth century. Already in phase one, in the fifteenth century descriptive works about shipbuilding and work in shipyards started to appear (Michael et al. 2009). Such books changed over time to careful descriptions of types of construction, works that could be sources of guidance for practising the trade or for apprentice shipbuilders. They became more detailed and came to adhere more closely to practices of the day. They indicate exchange of knowledge and the growth of building traditions (Cazenave de la Roche 2020, 7-22). By the end of the seventeenth century such works, still limited in number, appeared in many parts of Europe. In the eighteenth century, authors tried increasingly to give ship design a more rigorous method through the use of mathematics. It was another case of science having an impacr on technology. In the spirit of Newton, the books on shipbuilding were filled with formulæ and geometric drawings. Controlled experiments with types of ships were rare but they did exist. The texts were required reading and their contents the basis for instruction in the first and short-lived schools for shipbuilders in the second half of the eighteenth century (Ferreiro 2007; Mokyr 2018, 15-17). Through into the nineteenth century the works of mathematicians meant to bring order to the understanding of shipbuilding. Their ability to summarize the technology in a consistent manner indicates a certain ossification of methods and practices. Even so knowledge of how to get the most from the hull of a sailing ship increased dramatically in the nineteenth century, illustrated in published theoretical works on what had become a science of shipbuilding (Ferreiro 2020, 23-55). One remarkable result was the fastest full-rigged ships ever built.

With the full-rigged ship productivity gains came as it supplanted the types that had carried on local and regional shipping tasks, first within Europe and then around the world. While the development of new all-sea routes connecting the varied parts of the globe might have been more dramatic and imply some of the greatest impact of the new technology, the economic importance through the second phase came more from replacement of the range of sailing ships that was in use. As builders refined the design of full-rigged ships and found ways to produce specialized vessels the new type invaded more of the established trades. That importance increased through the second and into and through the third phase. The shipping patterns that the full-rigged ship opened and the shifts in production and populations as a result of the development of the full-rigged ship made possible a sharp increase in global commerce and so a sharp increase in the total number of full-rigged ships in service. European merchant marines grew dramatically through the eighteenth century and hardly flagged in that growth, it seems, in the nineteenth (Unger 1992). Almost contrary to expectations, it was then in the third phase, with established routes and rising populations made possible by trade, that the economic effects as well as political and military ones of full-rigged ships were greatest.

5. The long tail of the logistic curve

Just as with the emergence of the full-rigged ship in the fourteenth and fifteenth centuries the decline and replacement of the type took a considerable time. There were precursors that paved the way to the «great invention» just as there were various successors in the nineteenth and the twentieth century to the full-rigged ship. Even though builders found ways to power river-going craft with steam engines in the first years of the nineteenth century, the sizeable fuel requirements and uncertainty about stability, apprehension created by having a very heavy engine on board, limited the scope of use. In its first stages the new technology required a number of improvements and refinements to compete with existing vessels. Steamship use began with tugs and river craft. This spread to ferries inland and then to short distance services on the sea. Over time the length of voyages increased and steamships replaced sailing ships on ocean going routes. The process was a slow one, however. It was not until the 1870s that the majority of tonnage in the British and the Dutch merchant marines was steam powered. It took that long before steam engines were efficient enough and for spillover effects in the facilities in ports and the opening of new waterways made the choice of steam the logical one. As important were the continuing improvements in speed and manning requirements of full-rigged ships and their impressive descendants which kept them competitive. On some routes where the winds were reliable and commodities established, such as from Europe to the west coast of South America going around Cape Horn, sailing ships remained in use well into the twentieth century.

For millennia sailing ships provided a way to use the wind to move goods and people. In a world where kinetic energy in any form was rare, those vessels going over water opened an otherwise impossible range of possibilities. It was only in the late eighteenth century that the steam engine offered an alternative on land and on water. The low energy levels demanded by sailing ships, the free availability of power and no need to carry their fuel with them gave those craft reasons to continue in use for decades after the new general purpose technology appeared. Steam engines and especially the inefficient coal fired ones of the early years of their use had negative environmental effects but at a scale so limited as to be unrecognized. In the absence of a tax on carbon dioxide emissions the advantage that sailing ships had in their minimal impact on the natural world did not affect decisions on whether to use sails or steam to move ships.

The advances in shipbuilding, including the improvements in design, along with the related developments in various shipping technologies, made a considerable contribution to the long-term growth of the world economy between the fourteenth and the nineteenth centuries. The lowering of transport costs and the opening of new avenues for trade laid the groundwork for specialization in production and as well as the introduction of new goods to otherwise unreached markets. Technological changes also led to better preservation of the capital good and so decreased losses and increased returns to investment, valuable in a capital-poor world. Because of the impact of more efficient and more versatile ships, new forms of organization emerged in shipbuilding with large scale durable facilities and in commerce with joint-stock monopoly trading companies in Europe. In the early phase and in the era of dominance of full-rigged ships the shipping sector offered sources of growth and resilience for the economy. That attribute was especially obvious in the face of serious threats from environmental factors in the fourteenth and again in the seventeenth century. That was even more true over the long term for certain parts of the world where the technology came early and was best exploited. The three-masted ship and the multitude of spillovers from that development of a more efficient variant of an established technology, one using wind as a source of kinetic energy, qualifies and, indeed, almost defines not only for the late middle ages and the Renaissance but also for the history of the last dozen or more millennia what a macroinvention or a general purpose technology was and is.

BIBLIOGRAPHY

Adams, Jonathan, and Johan Rönnby. 2002. "Kuggmaren 1: the first cog find in the Stockholm archipelago, Sweden." *International Journal of Nautical Archaeology* 31, 2: 172-81. doi: 10.1111/j.1095-9270.2002.tb01412.x

Agius, Dionisius A. 2002. *In the wake of the dhow : the Arabian Gulf and Oman*. Reading, UK: Ithaca Press.

Agius, Dionisius A. 2008. *Classic ships of Islam: from Mesopotamia to the Indian Ocean*. Leiden-Boston: Brill.

Al-Salimi, Abdulrahman, and Eric Staples. 2019. *A maritime lexicon: Arabic nautical terminology in the Indian Ocean*, *studies on Ibadism and Oman*. Hildesheim: Georg Olms Verlag.

Antunes. Catia, et. al. 2019. "European shipbuilding and ship repairs outside Europe. Problems, questions and some hypotheses." *International Journal of Maritime History* 31, 3: 456-623.

Bacon, Francis. 2014 (1620). "Novum Organum Or True Suggestions for the Interpretation of Nature," ed, Joseph Devey: Project Gutenberg [eBook #45988]. <https://www.gutenberg.org/files/45988/45988-h/45988-h.htm> (2022-04-10)

Bairoch, Paul, Jean Batou, and Pierre Chèvre. 1988. *The population of european cities data bank and short summary of results*. Geneva: Librarie Droz.

Bonney, Richard. 1999. *The rise of the fiscal state in Europe, c. 1200-1815*. Oxford: Oxford University Press.

Bresnahan, Timothy F., and Manuel Trajtenberg. 1995. "General purpose technologies 'Engines of growth'?" *Journal of econometrics* 65, 1: 83-108.

Bruijn, Jaap R. 1990. "Productivity, profitability, and costs of private and corporate Dutch ship owning in the seventeenth and eighteenth centuries." In *The rise of merchant empires: long-distance trade in the early modern world, 1350-1750*, ed. James D. Tracy, 174-94. Cambridge-New York: Cambridge University Press.

Burger, C. P. 1908, 1909, 1910. "Oude Hollandsche zeevaart-uitgaven." *Tijdscrhift voor boek- en bibliotheekwezen* VI, VII, VIII: 119-37 & 245-61, 1-17, 123-32 & 157-72, 255-62.

Carlaw, Kenneth I., and Richard G. Lipsey. 2006. "GPT-Driven, Endogenous Growth." *The Economic Journal* 116, 508: 155-74. doi: 10.1111/j.1468-0297.2006.01051.x

Cazenave de la Roche, Arnaud. 2020. *The Mortella III wreck: a spotlight on Mediterranean shipbuilding of the 16th century*. Oxford: BAR Publishing.

Craig, Robin. 1982. "Printed guides for master mariners as a source of productivity change in shipping, 1750-1914." *The Journal of Transport History* 3, 2: 23-35.

Crumlin-Pedersen, Ole. 2000. "To be or not to be a cog: the Bremen Cog in perspective." *International Journal of Nautical Archaeology* 29, 2: 230-46. doi: 10.1111/j.1095-9270.2000.tb01454.x

Crumlin-Pedersen, Ole. 2009, "Boat and boat house. The conceptional origins of clinker boats and boat-shaped halls of the fourth to eleventh centuries in Scandinavia." In *Creating shapes in civil and naval architecture: a cross-disciplinary comparison*, ed. H. Nowacki, and Wolfgang Lefèvre, 147-65. Leiden: Brill.

Ellmers, Detlev. 1994. "The cog as cargo carrier." In *Cogs, caravels and galleons: the sailing ship, 1000-1650. Conway's history of the ship*, ed. Robert Gardiner and Richard W. Unger, 29-46. London: Conway Maritime Press.

Ellmers, Detlev. 2010. "Koggen Kontrovers." *Hansische Geschichtsblätter* 128: 113-40.

Ferreiro, Larrie D. 2007. *Ships and science: the birth of naval architecture in the scientific revolution, 1600-1800*. Cambridge, MA: MIT Press.

Ferreiro, Larrie D. 2020. *Bridging the seas: the rise of naval architecture in the industrial age, 1800-2000*. Cambridge, MA: The MIT Press.

Giraldez, Arturo. 2015. *The age of trade: the Manila galleons and the dawn of the global economy*. Lanham, Maryland: Rowman & Littlefield.

Glete, Jan. 1993. *Navies and nations: warships, navies and state building in Europe and America, 1500-1860*. Vols. 1-2, Stockholm: Almqvist & Wiksell International.

Harris, J.R. 1998. *Industrial espionage and technology transfer: Britain and France in the eighteenth century*. Aldershort, England-Brookfield, VT: Scolar Press.

Helpman, Elhanan. 1998. "Introduction." In *General purpose technologies and economic growth*, ed. Elhanan Helpman, 1-13. Cambridge, MA; London: MIT Press.

Jahnke, Carsten. 2011. "Koggen und kein Ende Anmerkungen zu den Thesen von Reinhard Paulsen und Detlev Ellmers." *Zeitschrift für Lübeckische Geschichte und Altertumkunde* 91: 305-20.

Jahnke, Carsten, and Anton Englert. 2014. "Historical research on merchant seafaring in Danish waters and in the western Baltic Sea 1000-1250." In *Large cargo ships in Danish waters 1000-1250 Evidence of specialised merchant seafaring prior to the Hanseatic period*, ed. Anton Englert, 30-75. Roskilde: The Viking Ship Museum.

Kander, Astrid, Paolo Malanima, and Paul Warde. 2013. *Power to the people: energy in Europe over the last five centuries*. Princeton: Princeton University Press.

Kelly, Morgan. 1997. "The dynamics of Smithian growth." *The Quarterly Journal of Economics* 112, 3: 939-64. doi: 10.1162/003355397555398

Kelly, Morgan, Cormac Ó Gráda, and Peter M. Solar. 2021. "Safety at sea during the industrial revolution." *The Journal of Economic History* 81, 1: 239-75.

Lane, Frederic C. 1940. "The Mediterranean spice trade: Its revival in the sixteenth century." *The American Historical Review* XLV: 581-90.

Lane, Frederic C. 1973. *Venice, a maritime republic*. Baltimore: Johns Hopkins University Press.

Lang, Arend W. 1968. *Seekarten der südlichen Nord- und Ostsee*. Hamburg: Deutsches Hydrographisches Institut.

Lang, Arend W. 1986. *Die "Caerte van oostlant" des Cornelis Anthonisz. 1543: arte Nordeuropas und ihre Segelanweisung. Schriften des Deutschen Schiffahrtsmuseums Bd. 8*. Hamburg: Kabel.

Lewis, David. 1994. *We, the navigators: the ancient art of landfinding in the Pacific*. Honolulu: University of Hawaii Press.

Lipsey, Richard G., Kenneth Carlaw, and Clifford Bekar. 2005. *Economic transformations: general purpose technologies and long-term economic growth*. Oxford-New York: Oxford University Press.

Lucassen, Jan. 2011. "Work on the docks: Sailors' Labour productivity and the organization of loading and unloading." In *Shipping and economic growth 1350-1850*, ed. Richard W. Unger, 269-78. Leiden; Boston: Brill.

Lucassen, Jan, and Richard W. Unger. 2011. "Shipping, productivity and economic growth." In *Shipping and economic growth 1350-1850*, ed. Richard W. Unger, 3-44. Leiden; Boston: Brill.

Maarleveld, Thijs J. 1994a. "Double Dutch solutions in flush-planked shipbuilding." In *Crossroads in ancient shipbuilding: proceedings of the Sixth*

International Symposium on Boat and Ship Archaeology, Roskilde, 1991, ISBSA 6, ed. Christer Westerdahl, 153-63. Oxford: Oxbow Books.

Maarleveld, Thijs J., B. Goudswaard, and R. Oosting. 1994b. "New data on early modern Dutch-flush shipbuilding: Scheurrak T24 and Inschot/Zuidoostrak." *International Journal of Nautical Archaeology* 23, 1:13-25. doi: 10.1111/j.1095-9270.1994.tb00435.x

Manguin, Pierre-Yves. 1993. "The Vanishing Jong: Insular Southeast Asian fleets in war and trade (15th-17th Centuries)." In *Southeast Asia in the early modern era: trade, power, and belief*, ed. Anthony Reid, 197-213. Ithaca, NY: Cornell University Press.

Manguin, Pierre-Yves. 2010. "New ships for new networks: Trends in shipbuilding in the South China Sea in the 15th and 16th centuries." In *Southeast Asia in the fifteenth Century: The Ming factor*, ed. Geoff Wade, 333-58. Singapore: NUS Press.

Manguin, Pierre-Yves. 2019. "Sewn boats of Southeast Asia: the stitched-plank and lashed-lug tradition." *International Journal of Nautical Archaeology* 48, 2: 400-15. doi: 10.1111/1095-9270.12367

McCarthy, Mike. 2005. *Ships' fastenings: from sewn boat to steamship*. College Station, TX: Texas A&M University Press.

McCormick, Michael, J. Kirsten Ataoguz, Kelly L. Gibson, Leland Grigoli, Brendan Maione-Downing, Alexander M. More, Robin Reich, Ece Turnator, and Julia Wang. 2013, "Summary geodatabase of shipwrecks AD 1-1500, Status 2008.xlsx." Digital atlas of Roman and medieval civilization summary geodatabase of shipwrecks AD 1-1500, Status 20082013-10-032013V2 Harvard Dataverse. https://doi.org/10.7910/DVN/ZIQPDGdoi/10.7910/DVN/ZIQPDG

Michael, Pamela O. Long, David McGee, Alan M. Stahl, and Franco Rossi. 2009. *The book of Michael of Rhodes: a fifteenth-century maritime manuscript*. Vols. 3. Cambridge, MA: MIT Press.

Mokyr, Joel. 1990. *The lever of riches: technological creativity and economic progress*. New York: Oxford University Press.

Mokyr, Joel. 2018. "The past and the future of innovation: Some lessons from economic history." *Explorations in Economic History* 69:13-26. doi: https://doi.org/10.1016/j.eeh.2018.03.003

Moll-Murata, Christine. April, 2008. "State and crafts in the Qing dynasty (1644-1911)." Habilitationsschrift, Faculty for Cultural Studies, Eberhard Karls Universität Tübingen.

Paulsen, Reinhard. 2016. *Schifffahrt, Hanse und Europa im Mittelalter Schiffe am Beispiel Hamburgs europäische Entwicklungslinien und die Forschung in Deutschland*, *Quellen und Darstellungen zur Hansischen Geschichte*. Köln; Weimar; Wien: Böhlau Verlag.

Phillips, Carla Rahn. 1994. "The caravel and the galleon." In *Cogs, caravels and galleons: the sailing ship, 1000-1650*, ed. Robert Gardiner, and Richard W. Unger, 91-114. London: Conway Maritime Press.

Pryor, John H. 1988. *Geography, technology, and war: studies in the maritime history of the Mediterranean, 649-1571*. Cambridge-New York: Cambridge University Press.

Pryor, John H. 1994. "The Mediterranean round ship." In *Cogs, caravels and galleons: the sailing ship, 1000-1650*, ed. Robert Gardiner, and Richard W. Unger, 59-76. London: Conway Maritime Press.

Raleigh, Walter. 1829 (1605? pub. 1650). *A Discourse, Of The Invention Of Ships, Anchors,,Compass, & C. The First Natural War, The Several Uses, Defects, And Supplies Of Shipping; The Strength And, Defects Of The Sea-Forces Of England,France, Spain, And Venice: Together With The Five Manifest Causes Of The Sudden Appearing, Of The Hollanders.* Vols. 8. Vol. 8, *The works of Sir Walter Ralegh, kt.* Oxford: The University Press.

Rönnbäckk, Klas. 2012. "The speed of ships and shipping productivity in the age of sail." *European Review of Economic History* 16, 4: 469-89.

Rosenberg, Nathan. 1972. "Factors affecting the diffusion of technology." *Explorations in Economic History* 10, 1: 3-33.

Schilder, Günter. 2017. *Early Dutch maritime cartography: the North Holland school of cartography (c. 1580-c. 1620)*, *Explokart studies on the history of cartography,*. Leiden-Boston: Brill, Hes & De Graaf.

Schotte, Margaret E. 2019. *Sailing school: navigating science and skill, 1550-1800*, *Information cultures*. Baltimore: Johns Hopkins University Press.

Smith, Adam, Edwin Cannan, and Max Lerner. 1937 (1776). *An inquiry into the nature and causes of the wealth of nations*, ed. Edwin Canaan. New York: The Modern Library.

Solar, Peter M. 2013. "Opening to the East: shipping between Europe and Asia, 1770-1830." *The Journal of Economic History* 73, 3: 625-61.

Staples, Eric, and Lucy Blue. 2019. "Archaeological, historical, and ethnographic approaches to the study of sewn boats: past, present, and future." *International Journal of Nautical Archaeology* 48, 2: 269-85. doi: 10.1111/1095-9270.12361

Steensgaard, Niels. 1990. "The growth and composition of the long-distance trade of England and the Dutch Republic before 1750." In *The Rise of merchant empires: long-distance trade in the early modern world, 1350-1750*, ed. James D. Tracy and University of Minnesota. Center for Early Modern History, 102-52. Cambridge-New York: Cambridge University Press.

Stern, Walter M. 1960. *The porters of London*. London: Longmans.

Trigger, Bruce G. 1986. *Natives and newcomers: Canada's "Heroic age" reconsidered.* Kingston, ON-Manchester: McGill-Queen's University Press. Manchester University Press.

Unger, Richard W. 1980. *The ship in the medieval economy, 600-1600*. London-Montreal: Croom Helm. McGill-Queen's University Press.

Unger, Richard W. 1981. "Warships and cargo ships in medieval Europe." *Technology and Culture* 22, 2: 233-52.

Unger, Richard W. 1985. "Dutch design specialization and building methods in the seventeenth century." In *Postmedieval boat and ship archaeology*, ed. Carl Olof Cederlund, 153-64. Oxford: B. A. R.

Unger, Richard W. 1992. "The tonnage of Europe's merchant fleets 1300-1800." *The American Neptune* 52,4: 247-61.

Unger, Richard W. 2006a. "Warships, cargo ships and Adam Smith: trade and government in the eighteenth century." *The Mariner's Mirror* 92, 1: 41-59.

Unger, Richard W. 2006b. "Investment and Risk: Ships design and investment in port infrastructure, 1200-1800,." In *Ricchezza del mare. Ricchezza dal mare. Secc. XIII-XVIII-Atti delle "Settimane di Studi" 11-15 aprile 2005*, ed. Simonetta Cavaciocchi, 317-42. Firenze: Le Monnier.

Unger, Richard W. 2010. *Ships on maps: pictures of power in Renaissance Europe*. Houndsmills, Basingstoke, Hampshire ; New York: Palgrave Macmillan.

Unger, Richard W. 2011. "Ship design and energy use, 1350-1875." In *Shipping efficiency and economic growth 1350-1850*, ed. Richard W. Unger, 249-67. Leiden-Boston: Brill.

Unger, Richard W. 2013. "The technology and teaching of shipbuilding 1300-1800." In *Technology, skills and the pre-modern economy in the East and the West*, ed. Maarten Prak and Jan Luiten van Zanden, 161-204. Leiden: Brill.

Unger, Richard W. 2015. "Trade, taxation and government policy in the high middle ages." *Viator* 46, 3: 195-217.

Unger, Richard W. 2019. "Ship types in Atlantic navigation from the fourteenth to the seventeenth centuries,." In *Navegação no Atlântico/Atlantic navigation, XVIII Reunião Internacional de história da náutica/XVIII International Reunion for the history of nautical science*, ed. Francisco Contente Domingues and Susana Serpa Silva, 39-50. Ponta Delgada, Azores: CHAM.

Van Zanden, Jan Luiten, and Milja Van Tielhof. 2009. "Roots of growth and productivity change in Dutch shipping industry, 1500-1800." *Explorations in Economic History* 46, 4: 389-403.

Vliet, Jeroen van der. 2006. "Tussen wal en schip De Amsterdamse Lastage in de zestiende eeuw." *Tijdschrift voor zeegeschiedenis* 25: 23-32.

Vosmer, Tom. 2019. "Sewn Boats in Oman and the Indian Ocean." *Journal of Nautical Archaeology* 48, 2: 302-33. doi: 10.1111/1095-9270.12371

Waghenaer, Lucas Janszoon. 1965. *Thresoor der zeevaert, Leyden, 1592*. Amsterdam: Theatrum Orbis Terrarum.

Wegener Sleeswyk, André. 2003a. "Building costs and carrying capacity of European merchant ships, 1400-1800." *Tijdschrift voor zeegeschiedenis* 22, 2: 137-46.

Wegener Sleeswyk, André. 2003b. *De Gouden Eeuw van het fluitschip*. Franeker: Van Wijnen.