The evolution of new combinations:

Drivers of British maritime engineering competitiveness during the nineteenth century

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I hereby declare that this thesis has not been submitted, either in the same or different form, to this or any other University for a degree.

Signature:

Dedicated to

Robin Craig

and

Chris Freeman

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A number of unexpected circumstances, sequences of events and coincidences of several sorts led me to the topic of steamships. I started with the barest knowledge of the outlines of the subject matter, marine technology and maritime history. I had never done historical research nor conducted archival work on any sustained basis. And I had previously done no work on the kind of statistics and econometrics I would need to carry the job through. This project, then, constituted a move away from my previous intellectual engagements in three unfamiliar directions. It is not surprising, therefore, that this has been a long-haul journey. The process was made more difficult by hard-pressing professional duties and a great deal of personal turbulence.

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Summary

This work is an attempt to explore early British steamship innovation during the 19th century from the point of view of innovation studies. The proposed analytical framework draws on neo-Schumpeterian and evolutionary economics for understanding the patterns and factors behind the phenomenon of technical change in the capital good under analysis. The thesis aims at filling a gap in the maritime economic and technological history literature, namely the issues connected to the process through which modern (mechanically-propelled, iron-hulled, screw-driven) ocean transportation emerged.

Two inter-related research questions are addressed: *how* and *why* did steamships evolve in the course of the 19th century? In other words, the present research focuses on describing the dynamics of technological evolution and on identifying the key drivers of those developments. While the thesis includes a review of the relevant literature (Part I), the main work consists of original empirical research (Parts II and III). The bulk of this work primarily rests on the compilation of two new main bodies of quantitative and qualitative evidence. First, a previously unpublished dataset on the population and characteristics of steamers is used to measure the rate and direction of technical change in steamers. Second, previously unpublished archival material is used to reconstruct the innovation processes of marine engineers and naval architects and the civil society arrangements around them.

The results suggest a number of stylised facts and institutional variables that have been subject to little discussion in the extant literature. On one hand, time-series and other statistical analyses suggest a technological "take-off" of steamship performance by the mid-19th century. This turning point, which was the outcome of a complex but rapid process of structural reconfiguration (the transition from wood-paddle to iron-screw as the new "dominant design"), occurred between the late 1830s and the late 1840s particularly among cargo traders and unsubsidised packets. On the other hand, documentary evidence shows that such technological breakthroughs were preceded and supported by a specific set of institutional innovations. These included the emergence of voluntary engineering associations, technical mass media and a not-for-profit ship classification society within the British national system of innovation.

The thesis argues that the process of revolutionary technological innovation leading to the economically efficient long-haul merchant steamer cannot be separated from the rise of a vibrant interactive environment promoting learning, knowledge integration and technological accumulation, which may be called a "technological public sphere".

Table of Contents

List of Tables

List of Boxes

List of Figures

Ship specifications, units of measure and glossary

Given its subject the thesis goes into a number of technical aspects pertaining to marine knowledge in general and 19th century British steamships in particular. Here some key technical information is described.

Hull

Gross registered tonnage (grt) – the total amount of internal volume of the ship measured in accordance to the law that is in force in a particular year; therefore, it is not a burden or weight measure; this volumetric measure includes the enclosed cubic space of the hull, superstructure and deckhouses; a ship may have altered its tonnage several times during its career for several reasons, including re-measurement and changes to the measurement law.

Length/Breath/Depth – these ship measurements are given in feet (or meters) and refer, respectively, to the distance from bow to stern, the width of vessel (excluding paddle boxes, unless otherwise stated), and the height from keel to deck at the hold.

Net tonnage – internal capacity of the ship available for cargo once space for machinery and crew accommodation is deducted; earning space could be available for cargo and/or passengers; assessment of port tariffs and canal transit dues was based ordinarily on this tonnage measurement.

Machinery

Boiler – a closed metal container partially filled with water, in which steam is generated from water by the application of heat; increases in the temperature of the steam increase the pressure, which is a force pushing outward on the surface of the boiler and is recorded in pounds per square inch; atmospheric pressure is that pressure normally existing in the air, surrounding and pressing upon objects (at sea level, atmospheric pressure is 14.7 pounds per square inch).

Horse power (hp) – the term comes from the early description of the output of a machine in terms of the pulling power of horse; James Watt established the correspondence between work and time by the formula 1 hp = 550 foot pounds per second.

Steam engine – machinery that produces mechanical motion from water and heat; an external combustion engine in which heat is developed separately by burning the fuel in a boiler.

Units of measure (British and universal)

1 foot (ft) = 30.48 centimetres
3.28 ft = 1 meter
1 mile = 1,609.34 meters
1 knot (based on the old Admiralty nautical mile) = 1,853.18 meters per hour
1 pound (lb) = 0.45 kilogram

Glossary

Blue Riband – unofficial award given to the passenger ship setting a new record for the fastest transatlantic crossing

Bulkhead – an internal wall in an iron ship's hull

Bunker – compartment where the coal is stored

Classification society – independent organisation inspecting vessels during construction and during their operation in order to ensure their assessment against known public quality standards

Compound steam engine – machinery in which steam goes through a two-stage cycle; steam is used twice, being first admitted to a higher-pressure cylinder and subsequently to a low-pressure cylinder

Composite ship – ship built with an iron structure (frame, beams, keel) but with wood planking as skin

Condenser – device that converts exhaust steam back into water, which is fed back to the tank

Deadwood – the solid timber fore and aft above the keel of a wooden ship

Double bottom – safety measure in a ship's structure; consists of an inner and outer bottom; also used for holding water ballast

Displacement – displacement tonnage refers to the weight or burden of a ship; it corresponds to the amount of water displaced by a ship once immersed; it is measured in units such as thousands of kilograms; the principle dating back to Archimedes' law; normally used for comparing naval vessels

Draught – depth of a vessel below the water line

Freeboard – the height between the deck and the water-line

Indicated horse power (ihp) – measure of the power (volume and pressure of steam) actually developed within a cylinder

Nominal horse power (nhp) – early method for approximating the value of a steam engine’s power based on the geometry of the engine; real power (ihp) was usually greater than this value, and the two measures diverged as engines improved

Packet – old designation of a sailing ship or steamer on a regular schedule between two pre-arranged ports

Piston – a component of the steam engine; sliding disc inside a cylinder on which the steam pressure acts; its back and forth (reciprocating) thrust is then transferred via a rod which converts the force into rotary motion; force is then transferred to the output shaft, thereby turning a paddle-wheel or a screw-propeller

Sagging and hogging – a hull in the high seas withstands contradictory strains; when two waves suspend a ship at her ends leaving the centre of the hull to fall it is called sagging; when the wave supports the ship in the middle section leaving the bow and stern unattended then it is hogging.

Stem – the foremost part of the bow of a vessel to which planking is fastened

1. Introduction

“My purpose is to tell of bodies which have been transformed into shapes of a different kind.”
John Maynard Keynes

“... even the past is forever uncertain ...”
David Mourão Ferreira

1.1 Introduction

Among the transport systems developed over the course of human history, ships have had an impact extending far and wide in terms of trade, migration, military conquest and cultural interchange. The enduring role of this technological artefact in socio-economic affairs was mostly carried out under sail, although oars were heavily depended upon at certain times. Wind power became even more important after the 15th century with the advent of deep-ocean travel. It was only during the 19th century that the picture changed. When the Napoleonic Wars ended in 1815, virtually all of the world’s long distance merchant cargo was transported in wooden sailing vessels; one century later, on the eve of the Great War, over 90% of all floating tonnage under the British flag was mechanically driven, screw propelled and made of metal. Britain, where the Industrial Revolution was born, took that revolution to sea. The shift was neither automatic nor smooth. We aim to analyse and understand this eventful transformation in the present thesis.

The subject of this work is the process through which steam-powered vessels became a viable and then a preferred alternative to sail. By drawing on a diverse array of sources, some previously untapped, we hope to be able to provide an account of the fundamental changes in this industrial technology and of the factors that appear to lie behind those changes. The focus of the research is the relationship between the dynamics of technical change and sources of innovation in the case of early British steam navigation. In this regard, this thesis is a contribution to innovation studies that uses historical material. The perspective proposed here is that British shipping was fundamentally transformed by a radical product innovation around 1850, i.e. the iron-screw design that definitively launched steam navigation for the purposes of competitive cargo carrying and later conquered all other market segments. This turning point in the history of the industry is found to be heavily dependent upon unprecedented institutional developments taking place within the British national system of innovation that stimulated knowledge sharing and integration among marine engineers, naval architects, and other expert constituencies.

This introductory chapter provides an overview of the thesis. Section 1.2 introduces the research project by briefly reviewing its backdrop. Section 1.3 highlights the agenda, the approach and the research focus. Section 1.4 presents the analytical framework. Section 1.5 discusses methodology and data. Section 1.6 outlines the key findings. Section 1.7 summarises the structure of the thesis.

The thesis then proceeds to lay out the theoretical and the historical scaffolding for the study (Part I). The core of this thesis deals with two tasks. First, we explore the population of steamers and their characteristics in order to obtain a detailed long-run representation of the rate and direction of technical change in this sector (Part II). Second, we inquire into the activities of the producers of new workable knowledge in order to uncover the practices and contexts that allowed them to break away from existing ship design and to sustain a cumulative path of technological improvement (Part III).

1.2 Background and research opportunities

Transportation in British industrialisation

Transport systems move goods, people and ideas. In addition, through their development over time, vehicles and their infrastructures transform the natural and human environment in particular ways. During the early days of industrialisation, Britain's economic growth and structural change was furthered by major advances in land and waterway transport (Landes 1999, p. 214). Better paved roads and the spread of canals, initially intended to connect mills and coal mines to towns and ports, opened up the internal market and encouraged regional division of labour. The role of transport would gain even more relevance in the 19th century – indeed, in no other period would it feature more prominently in British economic history. As a branch of economic activity, it not only responded to change; it also contributed irreversibly to furthering it in other sectors. Trains and steamers employed and distributed coal and iron, the staples of the newly revolutionised economy. In themselves railways and shipping became the largest, most capital consuming, geographically dispersed and organisationally sophisticated businesses of the era (Ville 2004, p. 295). They absorbed vast amounts of investment as well as demanding ever more sophisticated know-how from a growing multitude of engineers and managers. As Derry and Williams (1960, p. 364) point out: "Transport improvements occupy a key position in the history of the industrial revolution, operating both as a cause and as an effect of countless other changes."

Steam-powered transport was a major ingredient in British economic modernisation, playing a leading role in stimulating technological innovation and in shaping the regulatory arrangements of the 1800s. But in retrospect some technologies seem to have attracted more attention from scholars than others; and none "has fired the imagination as much as the railway" (Hobsbawm 1962, p. 60). In transport terms the Victorian period has undeniably been seen as the century of the railway and studied accordingly (Armstrong and Williams 2003, p. 181). The investment in railways was the largest ever undertaken in British history. Between 1830 and 1850 both iron and coal output trebled in Britain, a rise primarily attributable to the growth of the track network. While its backward linkages stimulated the iron and coal industries, railway services provided a major impetus to downstream growth and the qualitative transformation of the entire economic system (Freeman and Louçã 2001, pp. 189-90). The standard source of statistical reference of the end of the century, *The Dictionary of Statistics* compiled by Michael George Mulhall (1892), mentions "railways" on well over 100 pages whereas shipbuilding appears on only seven of its total of 620 pages. An inspection of the rather detailed index (10 pages) of a celebrated economic history book written from the perspective of technical change, *The Unbound Prometheus* by David Landes (1969), yields 19 entries for railways but none for steamships or shipbuilding. Yet is such a skewed allocation of intellectual attention warranted?

Steam navigation and technological development

It has been observed that the first complete description of a plan for locomotion using the force of steam occurred in the late 17th century and concerned water as the operational setting, not land (Eco and Zorzoli 1962, p. 204; Greenhill 1993b, p. 12). The idea only started to become practical more than one hundred years later. But in this slow, tentative way arose "the first key transport-related invention of the nineteenth century, the steamship." (Findlay and O'Rourke 2007, p. 380) The first steamer was put into economic use in Britain almost two decades before the opening of the first railway line designed for steam traction (the Stockton and Darlington railway) and the decisive Ravenhill trials of 1829. According to Feinstein (1976), railways represented only 13% of total British gross domestic fixed capital formation in 1882, steadily declining to 7%

in 1913. In contrast, ships kept being built in larger numbers and bigger average tonnages; in 1882 the shipping industry represented no less than 55% of the total contribution to the gross capital formation of the transport and communication sector (including railways, bridges, roads, and post offices). Coastal shipping handled a larger share of domestic output, measured in ton-miles, than railways throughout the entire 19th century (Armstrong 1987, p. 176). In 1850 two thirds of the total tonnage operating through British ports was coastal, but by the end of the century foreign maritime trade had surpassed it (Freeman 1991, p. 11). Openness to the world economy was unfolding as Britain became "the pivot of international trade" (Harley 2004, p. 191). The foreign trade to Gross Domestic Product ratio, i.e. the weight of visible goods shipped in and out of the economy, would grow and remain high until the Great War. According to Mathews *et al*. (1982, p. 442, own calculations) it represented 38.8% in 1855-1873, and 42.3% in 1874-1890, before falling slightly to 41.5% between 1891 and 1913. Openness was, moreover, related to British economic growth. Mathews *et al.* (1982, p. 321) state: "Foreign trade was the main proximate source of the growth of demand in 1856-73 and remained so, though somewhat diminished, in 1873-1913." Moreover, it was clear, at least to informed contemporary observers that steamers "contributed largely" to the trade expansion that ensued after 1850 by reducing the costs and uncertainties of overseas trade (e.g. Glover 1863, p. 7). In a word, modernisation of shipping was centrally involved in 19th century growth and globalisation. Therefore, it is somewhat surprising that this process is still not fully understood since, in retrospect, the Victorian age can be seen as the veritable "Golden Age" of British shipping and shipbuilding.

"Maritime history has, in some respects, been an ignored dimension of global history." So begins the introduction of a recent four-volume work of reference, *The Oxford Encyclopedia of Maritime History* (Hattendorf 2007, p. xvii). In turn, within maritime history, some topics have persistently remained in want of closer attention. Sixty years ago, Sydney Pollard remarked in the abstract of his unpublished doctoral thesis: "Modern shipbuilding has received surprisingly scant attention from economic historians." (Pollard 1950a, p. iii) Moss and Hume (1977, p. vii) agreed and in 1980 Basil Greenhill (1980a, p. 4) was still trying to rally research efforts to the issue of merchant shipping in order to fill "a large and vitally important gap in the economic history of Britain". A recent general survey of maritime economic and business historiography in Britain runs to just over thirty pages and eighty-two footnotes without explicitly referring to any work on the origins and effects of technical change in the shipbuilding industry (see Johnman and Murphy, 2007). Above all, in contemporary maritime history the rise of modern steamer itself still seems "largely written out of the script." (Smith *et al*. 2003a, p. 279) This neglect is particularly apparent in the period before 1850 (cf. Armstrong and Williams 2003, p. 181).[1] From the vantage point of innovation, it is worth noting that extant maritime historiography is precisely least abundant where it might have been expected to be most prolific: the industrial era.

1.3 Agenda and general framing questions

Central concerns of the research

The central issue of this thesis is how the ship as a capital good became part of the industrialisation process. "Merchant ships were and are machines for carrying cargo profitably." (Greenhill 1980b, p. 3) As the 19th century unfolded, the fundamentals of the ordinary merchant (and naval) vessel were radically altered. Even common sailing ships, although not becoming immediately extinct as cargo carriers, were very different

[1] The research leading to this thesis involved surveying a large array of scattered secondary sources in what appeared to be a rather non-cumulative field. The few of the classic contributions trying to make sense of the long run-development of the steamship, such as Gilfillan (1935b) and Spratt (1951), also referred to similar challenges in systematising existing material.

in 1900 from what they had been in 1800. In a sense, ships mirrored the changing world that they connected ever more efficiently. Britain in the late 18th century was embarking on an accelerating set of sustained, interrelated and reinforcing changes in metallurgy and mechanical engineering that would sweep across the full spectrum of economic activity and the various dimensions of social life, spreading thereafter to the rest of Europe and to North America. It is against this changing background, which we have been accustomed to call the Industrial Revolution (Hartwell, 1965; Buchanan 1991, p. xiii; Landes 1999, p. 187; Freeman and Louçã 2001, p. 140; Mokyr, 2010, p. 183), that we must understand the evolution of the merchant ship. This thesis addresses the issue of how the British shipbuilding industry reinvented itself by the mid-19th century.

In the post-Napoleonic period, Britain came under increasing competition from America, which was "already demonstrating its future capacities", in terms not only of agricultural expansion but also of its multiplying shipyards and its introduction of early forms of assembly-line production (Hobsbawm 1962, p. 211). American sailing ships were better designed, needed fewer hands to man them and, thanks to the abundant availability of inexpensive timber, were cheaper to build (Heaton 1960, p. 35; Mathias 1969, p. 286). By the 1840s the British shipbuilding industry had essentially lost its primacy to North American-built fleets (Freeman and Louçã 2001, p. 205). New technology appeared only to complicate matters further. Steam navigation had achieved its first technical successes in France in the late 1700s. But it would be on American rivers and lakes that the first commercial applications would occur. Britain was neither the pioneer in steamship invention nor the pioneer in its commercial introduction. By 1830, however, steamers were already operating intensively in Britain, mostly carrying high-value cargoes of small bulk over short distances. What happened represented an extraordinary reversal of fortunes:

> “British shipbuilding in that period [1860-1914] enjoyed a supremacy such as few industries are ever likely to rival. British yards produced between one and a half and four times as much tonnage as the rest of the world combined, and though some of their output went abroad, the tonnage and trade under the British flag exceeded that of all other countries put together. British superiority extended not only to quantity, but also to quality: throughout the period, Britain’s tonnage was more efficient than that of her competitors, and consisted of a larger proportion of steam ships, steel ships and long-distance vessels.” (Pollard 1952, p. 98)

Characterising and understanding this phenomenal renewal of the British shipbuilding industry, and the associated rise of the large seagoing steamer, is the key objective of the present research. As Lyon (1980, p. 8) put it: “Never before or since has any country held such a position of primacy in any one industry.” Shipbuilding seems to have been at its peak in terms of relative importance in the United Kingdom somewhere between 1870 and 1890 when the annual value of new tonnage exceeded 1.6% of the national income, up from 0.5% in the beginning of the century (Dean and Cole 1967, p. 235; see also Pollard 1957, 1989, and Pollard and Robertson, 1979). The industry was also on its way to becoming a major exporting industry: nearly 17% of the new annual tonnage was for foreign owners around 1880, a proportion that would rise to over a quarter in the first decade of the twentieth century (Dean and Cole 1967, p. 235; see also Mulhall 1892, p. 526); and it was even the case that shipyards were set up abroad, such as in Italy and Russia (McCord 1995, p. 249). As Mathias (1969, p. 286) noted: “This was one of the only sectors of the economy where Britain kept the world dominance after 1870 that she had enjoyed over a wide industrial field in 1850.” British steamship technology was the consistent international benchmark, and other shipbuilding nations did not to hesitate to follow suit, namely Germany, American and Japan (Ville 1991, pp. 76-9). But if Britain triumphed as the shipyard of the world, her ships also became “the carriers of the world”. It is hard to isolate the remarkable developments in this capital good from the dramatic expansion of what became an export-led economy (Hughes and

Reiter 1958, p. 381; Harley 1972, p. 1). The mechanised and metal constructed cargo carrier rose to become "one of the most conspicuous servants of empire." (Smith *et al*. 2003b, p. 447) What do we know about what lies behind these changes?

This inquiry follows available maritime historiography in that the reasons for the recovery of maritime pre-eminence have to be sought internally in Britain. During the 1850s, American merchant shipping was already losing its comparative advantage of cheap timber as the coastal forests vanished and labour, operating and overhead costs too were on the rise (Heaton 1960, p. 35). No longer exercising the same challenge as in the previous two decades, the Americans then plunged into the Civil War in 1861, and hence were unable to recover the lost ground (Mathias 1969, p. 286; see Sechrest 1998, p. 21). By the end of that war, American attention had definitely turned away from the Atlantic economy and towards the expanding West (Fayle 1934, p. 239). Confronted with a dwindling competitive danger, and with the threat of France and Germany as industrial and imperial powers still looming some way off, other fundamental causes of British shipbuilding competitiveness must surely have been at work.

The present research starts from the view that the field of innovation studies offers a suitable mode of understanding for the chosen historical subject. There is, indeed, no ambiguity in the literature that a significant technological transition to modern shipping happened around 1850 (e.g. Dudszus and Henriot 1986, p. 8; Lemmers and Ferreiro 2007, p. 649). Pollard and Robertson (1979, p. 230) put it clearly: "One of the most important influences on the industry was the changing nature of the end product, ships." As Hobsbawm (1975, p. 58) emphasises: "The triumph of the steamship was essentially that of the British mercantile marine, or rather of the British economy which stood behind it." Simon Ville (1993, p. vii) pushes the issue one step back: "The technological changes which transformed the industry in this period all originated, and were mostly exploited, in the United Kingdom."[2] The extant historical work suggests a view that a neo-Schumpeterian or evolutionary economist would expect to find, namely that one must understand the nature of the process of technical change in order to understand the long-term causes of this industry's success story. Contemporary observers had no doubt that this success was based on British private-led innovation. An early enthusiast of steam navigation said: "Government neither did anything to encourage and protect the infant power, nor has rewarded the individual who first showed the country its use and advantages." (Boyman 1840, p. 137) In an address to a meeting of the British Association in the North East in 1863, Charles Palmer, one of the greatest steamship builders of his day, pronounced this perspective:

> "The commercial men of this country have set the Admiralty a signal example of industry and enterprise. It is they who have made the experiments, and adopted the inventions that have established the maritime supremacy of this country; and it is owing to their energy that we find on every sea, in the shallow rivers of the east, and the deep broad waters of the west, English-built ships of commerce diffusing the benefits of free trade, and linking nations and tribes together in the bonds of amity and peace." (Palmer 1864, p. 287)

Scope of the enquiry

In the study of major economic innovations of the past, steamships are a "classic" research topic.[3] An inspection of the available literature shows, however, that important ground remains to be covered. First, most economic and business assessments of the

[2] Throughout a period of roughly one hundred years, the technological story was essentially an Anglo-centric one. British ingenuity and enterprise pioneered iron-building, the practical screw-propeller, the iron-screw combination, double-skinned hulls, composite construction, steel shipbuilding, economic marine steam engines, then compounding, then triple and quadruple expansion, and then the turbine (see Pollard 1989, p. 24; see also de Voogd 2007, p. 294). "Britons were responsible for the great majority of the multifarious innovations which underpinned the maturation of the steamer," says David Starkey (1993, p. 127), and "British shipbuilders adopted the new technology so comprehensively that over 80 per cent of the world's steam tonnage was launched from their yards by the early 1890s." Hence, given Britain's incomparable and uncontested hegemony in industrial age ships, it seems justified to tell this story mainly from a British viewpoint (cf. Lyon 1980, p. 8; see also Pollard, 1989, p. 24, and Griffiths 1993, p. 127).

[3] Paul David in a personal communication; when learning about this doctoral project. Balliol College, Oxford, June 1st, 2007.

steamship phenomenon begin only after 1850, but tend to focus most seriously from 1870 onwards (Armstrong and Williams 2007, p. 145). Such are the cases of Pollard and Robertson (1979), Harley (1972), Starkey and Jamieson (1998), and Schwerin's (2004) – notable exceptions in this regard are Clarke's (1997) work on North East coast shipbuilding and Arnold's (2000) work on Thames shipbuilding from the 1830s onwards. Second, economists have been typically drawn to the role of steamships in driving down ocean freight rates after the 1850s and not to the process of revolutionary change in the new industrial technology that might have laid behind the reductions in transportation costs. Belonging to this category are well known papers such as North (1958), Harley (1988), and Mohammed and Williamson (2004). Third, economic and business history has mostly focused on the industry, region or firm levels, emphasising in turn Britain's comparative static strengths in terms of cheap endowments of coal, iron and an able workforce, advantages of locations such as the Clyde and the North East, and the particular fates of private yards and their owners. Examples of these various strands of scholarly literature are Pollard and Robertson (1979), Ville (1993), and Arnold (2000).

The purpose of this thesis is to examine and explain the build-up of technological potential until the point at which the bottlenecks that previously constrained it were finally overcome, providing the basis for the rapid, cumulative and self-sustained growth already noted. This means that we have to study the "backstage" of the industry, as it were. We need to direct our attention to the events that took place before technology changed gear and allowed modern shipping to play such a leading role on the world economic stage. Hence, we will structure the subsequent analysis in the following way:

i) *Time frame* – We will focus on the least well studied period in the development of the modern ship. At one level, the time frame that is relevant for this study is broad and covers what many historians call the "long 19th century". For a closer scrutiny we select a shorter but eventful time period (1812-1860). It begins with the launch of the *Comet*, "the first successful demonstration of the commercial potential of steam power of vessels in Britain." (Slaven 1992, p. 1) It ends by 1860 when the *Great Eastern* had taken to sea, bringing together a collection of solutions that would inform ship design until the dawn of the 20th century (Lemmers and Ferreiro 2007, p. 654). In the space of two generations shipping was transformed.

ii) *Object of analysis* – We focus on ships themselves, "the tools with which merchants work" (Porter 1912, p. 509). In particular, we will be concerned with merchant ships, in other words, those that carried goods and people over water for profit.[4] We have chosen to focus on technical improvements in the design of the capital good, and not so much the process innovations that almost certainly accompanied it.[5] In our study we look at the product level and deal with that part of the shipping sector that conceived and designed the capital goods employed by downstream sectors. We also make only a secondary analysis of sailing ships (the type of vessels that were eventually displaced from the major trading routes) as well as of steamship developments in other countries.[6]

iii) *Analytical perspective* – We trace the learning processes leading to the major practical breakthroughs. The aim here is not so much to explain how the steam engine, the iron hull and the propeller mechanisms came into existence, but how the various combinations of these elements were experimented with (either embodied in ships facing the trials of real operational environments or discussed and evaluated in engineering circles) until a sound working configuration of those elements emerged. In our research we explore extensively the conditions prior to, and the factors surrounding, the technological "take-off" of the modern steamer.[7] Given the space constraints, we focus on the British case and on the intellectual infrastructure underpinning the innovative engineering in steamship shipbuilding.

Research questions

The research problem here has to do with appraising the emergence of what might be termed the "modern ship" (steam powered, metal-hulled, screw-driven) principally

[4] Merchant shipping is generally taken to include cargo, passenger, fishing, coastal, and ocean-going ships (Feinstein, 1978, p. 73), but here we also include tugs, a rather neglected category. We exclude naval (military) ships from our assessment and, given our stringent space constraints, refer only developments in Royal Navy policy when they intersect with the evolution of civil technology.

[5] This is still a relatively unexplored aspect of the transition to the modern ship (cf. de Voogd 2007, p. 273). This also implies that we have omitted shipyard labour relations from the study. The problem of labour relations, which early on involved the change in status and roles of shipwrights and later involved disputes among steamship building specialist trades and between workers and shipyard managers, has been addressed by Arnold (2000), Lorenz (1991a), and Pollard and Robertson (1979).

[6] For references on the development of 19th century sailing ships, see Brock and Greenhill (1973). For merchant steamship fleets in other countries see Greenhill (1993a). For a recent analysis of the international diffusion of steamship technology, see also Pulkki-Brännström and Stoneman (2010).

[7] Further research on the interplay of steamship technology with the alternative of sail, with the complementary infrastructure of railways, and with government policy (in the form of regulations and the doctrine of Royal Navy) had to be omitted from the final draft for reasons of space.

during the first half of the 19^{th} century. Our overarching question is “What was the process by which the iron-screw steamer emerged?” Our major concerns can be broken down into the following questions: How did steamships evolve? And why did they evolve?

Ours is an appreciative account of what might be termed the “industrial revolution in shipping” occurring during the 19^{th} century in Britain. Our discussion concentrates on the early phase of steamship development: the formative years leading to the modern ship paradigm analysed from the perspective of innovation studies (see Part I). The first question leads us to consider the main empirical patterns that surface in the technological features and performance characteristics of steam vessels as time went on. A set of quantitative exercises will allow us to determine the existence and the timing of a particular paradigm shift and if the rate and direction of technical change are indicative of the wood-paddle/iron-screw transition (Part II). The second question extends the investigation to the forces at work. That patents may have provided an incentive for steamship innovation is one hypothesis to explore while another hypothesis is that an inclusive organisational infrastructure supporting creativity and learning encouraged technical changes to emerge and accumulate (Part III).

1.4 Ships as evolving packages of community-generated innovations

Hence, in this thesis we ask *how* and *why* steamships evolved in Britain from 1812 till 1860. Our research is informed by the broad network of insights, generalisations and stylised facts that usually goes under the label of “innovation studies”. Over the past thirty years this perspective has been adopted by a growing number of researchers dealing with industrial innovation and the phenomenon of knowledge growth, especially following the influential works of Chris Freeman (1974), Nathan Rosenberg (1976, 1982), and Nelson and Winter (1982). This framework takes technological change to be the emerging outcome from tentative (rationally-bounded) and interacting (competing or collaborative) learning processes undertaken by a variety of actors such as individuals, business organisations, and a number of other institutions in real historical time. This explicit neo-Schumpeterian or evolutionary worldview provides the foundations on which we embed the three particular strands of literature from which this thesis will borrow a number of theoretical insights. The three elements that provide the operational focus for the examination of past events are the following:

i) *Technological evolution* – In innovation studies the evolutionary metaphor has been employed to generate powerful hypotheses with regard to the economics of technical change (see Metcalfe and Foster 2010, p. 66). As noted by Ziman (2000a), it is helpful to see "technological change as an evolutionary process". This broad statement recognisees that mechanisms of variation, selection and retention in human know-how are central to innovation. The emphasis on technology is in fact an emphasis on knowledge, which is defined as an accumulation of learning processes taking place within the broader context of national systems of innovation (von Tunzelmann 1995, p. 4). A core assumption of this school of thought is that the evolution of technology can be described with recourse to the language of "paradigms" and "trajectories".[8] An artefact embodying a radically new paradigm may at a certain point stabilise in a specific architecture of characteristics, or a "dominant design", and then keep being incrementally improved thereafter. The establishment of "dominant design" may, however, first take place in a particular segment of the population of artefacts and gradually spread so as to eventually change the outlook of the entire industry.

ii) *Complex projects* – In a steamship, as in any other complex artefact, its several parts and technologies mutually interact with each other. A steamer is an ensemble of disparate components in which congruence matters for it to function effectively as a whole and perform a useful function – transportation. The consideration of elements and linkages suggests the importance of knowledge integration between technologies (Prencipe *et al*., 2003). The steamship was a complex, multi-technology product system that was not mass produced. This defining characteristic of the artefact is related to a feature of its production – the ship business remained a construction activity even in industrial times (Hobsbawm 1975, p. 44; Pollard and Robertson 1979, p. 230). Learning took place ship-by-ship, with intense feedback loops and new information helping designers and builders in the process of dealing with technological uncertainty. Hence, ship design and construction can be seen as a project-based business (Davies and Hobday 2005).

[8] In this frame of analysis, a radically new technology represents a discontinuous breakthrough while progress along a particular path of technological and economic trade-offs represents a cumulative increase in the body of knowledge. The notion of a "technological paradigm" refers to a shared new set of recognised problems and to the methods for pursuing solutions that conventionally become accepted. "Technological trajectories" refer to the sequence of specific solutions that improve the technology's performance, as defined by the paradigm.

iii) *Community-based innovation* – John Scott Russell, the distinguished Victorian naval architect and shipbuilder, was keenly aware that "the creation of the steamship appears to have been an achievement too gigantic for any single man" (quoted in Griffiths 1997, p. 4). Shipbuilding was a trade that was also a place for the construction of social identity (recognisable communities with a positive sense of their status, their own jargon, modes of passing knowledge to each other, and so on; see, e.g., Unger 1978, and Davis 1991). There is little doubt that British technological leadership in industrial-age shipbuilding was the result of the efforts of independent engineers.[9] There is, however, not much in the literature that plots the interpersonal dynamics taking place among these often free-lance and largely self-taught consulting engineers.[10] The work of Constant (1980) and Vincenti (1990) showed how innovative engineers dealing with complex capital goods have been embedded in "technological communities", the prime site of knowledge generation, appraisal, and accumulation. That such communities of engineers (i.e. cooperative and inclusive institutions), and not market transactions (e.g. patenting behaviour), were the prime driving force of innovation is a key conjecture we aim to test in the present thesis.

1.5 Methodology

In historically-oriented research a tension often arises between the subject of interest and the theoretical tools required to analyse it. Since we cannot directly observe past behaviour, a compromise has to be struck between description and theorising (Floud and Johnson 2004, p. xviii). This means that one has to use constructs that, on the one hand, may shed some light on historical phenomena, but, on the other hand, may lead the researcher to concentrate on a restricted set of variables and possible explanations. The historian who uses explicit conceptual frameworks is also urged to avoid the traps of "presentism" (the anachronistic deployment of current-day concepts and modes of explanation to past phenomena; see, e.g., David and Thomas, 2003) and "whiggism" (portraying the past as part of the inevitable progress to new and better forms of institutional organisation and technology; see, e.g., Lamoreaux *et. al*., 2004). Models and theoretical insights should be carefully "adapted" to the particular object of analysis

[9] That private enterprise and, in particular, private individual professionals like consulting engineers were behind the key breakthroughs in 19th shipping technology is a consensual matter among historians of the field (see Smith 1938, p. 95; Ferreiro 2007, p. ix and p. 26; and Lemmers and Ferreiro 2007, p. 654).
[10] There are some helpful modern biographies such as those by Rolt (1965), Emmerson (1977), Buchanan (2002), and Chrimes (2004). Surprisingly, there seems to be much less on the rise of engineering as an institutionalised profession – the outstanding exception being Buchanan (1989).

or, if necessary, discarded as inappropriate for the historical task at hand (Floud and McCloskey 1981, p. xiii).

Above all, historical work is empirical in nature, implying it is more than just a retrospective application of today's concepts. With David and Thomas (2003, p. 9), we believe that historical inquiry can hardly be passive with respect to the analytical framework with which it starts out; its prime value resides "in taking past circumstances and problems first on their own terms, within their particular historical contexts." History needs, above all, to be advanced through more historical research. And, if in the course of historical work, new categories are found to be of explanatory value, they may be re-used and be subject to further scrutiny in subsequent research. As Kitson Clarck (1968, p.18) aptly pointed out, "(a)n historical work becomes as much an historical document as the primary sources on which it purports to be based", which, in turn must be submitted to the "standard questions which ought to be asked about all historical documents." The object of analysis and the instruments of analysis are, therefore, in mutual interaction. This makes history not a graveyard of old facts but, instead, a fertile land of evidence and argument – what Corfield (2007, p. xvii) has called the "unfolding past".

In our work we have tried to cope with the above methodological concerns by following an "appreciative theorising" (Nelson and Winter 1982, p. 9) or "reasoned history" (Freeman and Louçã 2001, p. 117) strategy of inquiry. By this, we mean that we have relied on our theoretical framework to illuminate the subject matter, but have also allowed the unfolding of (quantitative and qualitative) evidence to grow out of the preconceived categories, which we have subsequently revised to reconcile with the research data, and so on. In the present thesis we have focused our major efforts in working with primary sources of evidence (and in reading what other historians have written in order to critically appraise the data regarding their accuracy, reliability and significance). The research data used here are the following:

i) *Quantitative data* – Two basic sources of data are analysed. The first is a set of secondary datasets, ranging from the better known (e.g. Mitchell and Dean 1962, and Mitchell, 1988) to some rather unexplored raw statistics available in more specific literature such as data on the evolution of Channel steamers (Grasemann and McLachlan, 1939), ship-related British patents since 1618 (Woodcroft, 1848), or the founding dates of learned societies in Britain (Hume, 1853). The second set of quantitative empirical data, and the most important, is an unpublished database of the total population of steamships constructed in Britain from 1812 to 1859. The resource was amassed over several decades from an immense array of original records by the late Robin Craig, the Honorary President of the International Maritime Economic Historian Association at the time of his death (see Burton, 2007). His card index contains ship information regarding the year of construction, physical measurements, machinery, and a whole variety of assorted information. The data provide a unique insight into the characteristics of steamers being built on a yearly basis and cover the time around 1850 when a technological turning point seems to have taken place. The quantitative analysis of this information is carried out here for the first time.

ii) *Qualitative data* – Compared to other topics in economics, Baumol and Strom (2010, p. 527) argue, the study of innovative entrepreneurship must rely heavily on qualitative historical evidence. For our purposes, primary sources of the qualitative kind were found in a variety of locations. As Lemmers and Ferreiro (2007, p. 656) have remarked, post-1800 developments in ship design "must be reconstructed from technical textbooks and the numerous transactions, bulletins, and conference proceedings from professional societies worldwide." Our theoretical emphasis on technical change, on project-based learning and on communal innovation encouraged inquiry into forces that could bear witness to engineers' interactions and interrelations. Archival evidence and published contemporary accounts of engineers' events and engineering developments were found mostly (but not only) at the Institution of Civil Engineers, the *Mechanics' Magazine*, and Lloyd's Register. Minutes of meetings, personal journals, and transactions of learned societies were the main items inspected. It came as something of a revelation that so much remained to be discovered from digging through old documentary material and by triangulating disparate sources of evidence. This exploratory work is reported in the present thesis.

1.6 Outline of research results

Working with the quantitative and qualitative empirical information allowed us to re-evaluate the technological rise of the steamship and to shed new light on the origins of the collective creativity by which it was nurtured and sustained. We chronicle the initial erratic accumulation of innovations in specific technological aspects of the artefact and date the point after which further innovations appear to have become more incremental and cumulative. This technological shift capitalised on the broad “technological paradigm” of mechanisation, i.e. the employment of machines motivated by non-natural power (i.e. coal-consuming engines) and the use of new raw materials (e.g. iron instead of wood). In order for this paradigm to diffuse and take over from sailing ship technology, a set of complementary physical infrastructures had to be gradually put in place, such as a global network of coaling stations, the telegraph and the Suez Canal.

This revolution in ship technology took place before visible signs of progress were apparent in aggregate statistics, and well before the attainment of Britain’s international supremacy in the steamship industry. The establishment of the modern features of mechanised shipping accelerated from the late 1830s onwards and started to appear in several steamers engaged in different activities, but it was in the general cargo-carrying steamship trade that iron-screw elements first succeeded as a “package” in the mid-1840s. The attributes of service efficiency prized by the broad majority of merchants and ship-owners helped this new combination to take hold and progress, and are found to be behind the boom in construction of iron-screw traders. The process of gathering speed for the eventual “take-off” was already observable in several manifestations in the 1830s and 1840s such as the experimental *Archimedes* or the packet *Great Britain*, and first became dominant in the lesser known steam colliers *Q.E.D.* and *John Bowes*, which formed the basis from which steam tramps later evolved. By 1850 the major transitions from wood to iron and from paddle to screw had been achieved and were being implemented in new ships of increasing capacity. In other words, a clear “technological trajectory” in modern shipbuilding had been established. As iron hulls and screw propellers coalesced and more powerful marine engines were built to fit this combination of elements, the new product lay-out increasingly became the “dominant design” we recognise today in ships of every trade.

We started out from the broad assumption that direct interaction between engineers, and its influence on technology, could not be ignored. If the influence of engineers' learning on one another is important, it follows that we must seek to identify the structure of this interaction. We find reason to conjecture that, at least in the steamship case, learning was not merely "communitarian" or collective as postulated by our theoretical framework. Technological development and integration was promoted and shaped by concrete institutional mechanisms that contributed to coordinating and accumulating the evolving network of related insights on steamship design. Unblocking the reluctance of individual engineers to share privately acquired lessons from experience and experiments turns out to have been a crucial factor in fostering innovation in this sector. Intellectual property rights, perhaps surprisingly, had only a minor role to play in this process. Steam navigation is an important case in which to explore the advantages or limitations of patents as an inducement of invention and innovation.

In our view, the rise of the modern mechanised ship is tied to the emergence of a novel social apparatus. As steamship design was consolidated, so too were close (but not *closed*) social practices of knowledge interchange. The study of engineers' behaviour from previously underexploited primary sources shows how their interactions were increasingly mediated and leveraged by a maturing set of structures promoting the disclosure and discussion of technological successes and failures. Quasi-academic or collegial-like behaviour and open communication platforms resembling (indeed drawing on, as we latter found out) the historical norms of the scientific revolution, appear to have been at the centre of the inclusive learning processes from which the modern ship emerged.

More to the point: progress in steamship technology, an area of industrial know-how in which innovation depended heavily on coordinating different insights, was, we will suggest, supported by a new combination of community-based processes of learning. It was through institutions of knowledge-sharing and validation that steamship technology came to be stored and passed on (i.e. "selective retention"). We will try to show how the innovation process regarding iron-screw steam navigation became organised around three institutional developments: *i*) the establishment of societies of engineers devoted to the open discussion of technological knowledge, which was then printed as transactions and other publicly accessible documentation; *ii*) the growth and development of the technical press, which reported on and welcomed debate over the findings and failures of new technology; and *iii*) the advent of a classification society, in the form of a non-profit and geographically distributed technical standards organisation, that represented the common interests of shipping stakeholders, such as merchants, owners and insurers, and which provided independent assessments of innovations embodied in ships as well as disseminating the state of the art. These were independent developments (the major ones being the establishment of the Civils, the *Mechanics' Magazine* and Lloyd's Register in 1818, 1823 and 1834, respectively), but nevertheless overlapping ones (all bearing heavily on steam navigation, having complementary agendas, and involving cross-communication). We term this partially interrelated and interlocking ensemble of institutions emerging from within the British national system of innovation a "technological public sphere", a space that stimulated creative conversations and resolved disagreement about technological possibilities and changing constraints posed by the needs of steamers' final use. Together these and other institutions in their wake enabled and sustained a process of knowledge integration[11] and redistribution between different actors (marine engineers, naval architects,

[11] Our emphasis on knowledge integration certainly owes much to Douglass North, who has argued, and, indeed insisted, that this should become the major issue in the study of economic organisation in the 21st century (personal communication, San José, California, September 10, 2004).

shipbuilders, local Lloyd's surveyors). As we will show, these institutional developments can be related to the turning point observed in steamship design and the improvement of performance thereafter. In brief, this thesis attempts to establish that the "technological public sphere" was the central workroom of the modern ship revolution.

1.7 Structure of the thesis

Part I of this thesis reviews the relevant theoretical literature and summarises the background to steam navigation. Chapter 2 describes the analytical tools and major theoretical categories that guide the pursuit and interpretation of the data. Chapter 3 contains a literature review of the wide and rather fragmented previous work that needs to be surveyed in order to map the origins of steam navigation, the core technical aspects of steamship design, and the major categories of steamships.

Part II of the thesis examines secondary and original quantitative data to account for the transformation of steamship technology in Britain during the 19th century. It attempts to answer the question of "how steamships evolved" on the basis of two key datasets. On the basis of the available historiography and Brian Mitchell's data, Chapter 4 analyses the patterns of growth and the general diffusion of steam navigation in the British mercantile marine. It provides estimates of key dates (e.g. the existence of a major shift around 1850) and sets out the major stylised facts (e.g. the quickened pace of average ship size growth after that date). Chapter 5 draws extensively on the database originally compiled by Robin Craig, and attempts to identify and characterise in detail the main patterns of technical progress in steam-driven vessels in a varieties of trades. In particular, Chapter 5 focuses on differential evolution across various types of steamships to show that the iron-screw design was first consolidated in cargo steamers (built in a variety of ports in Britain) and then followed by (unsubsidised) steam packets.

Part III analyses the creative context framing the circumstances in which steamship development processes occurred. It deals with the question of “why steamships evolved” by looking at first-hand qualitative evidence on the behaviour of engineers. Chapter 6 appraises the effect of the patent system on steam navigation. Evidence from patent statistics and extensive records of pronouncements by engineers (e.g. public statements and debates, parliamentary committees and petitions, etc.) suggests that radical innovation happened in spite of, rather than because of, the patenting system. Chapter 7 brings together previously unpublished archival material with the aim of casting light on the collective practices and institutional mechanisms that supported innovative steamship engineering. The richness of these little used data (e.g. engineers' minutes of conversations, technical press articles, Lloyd's Register survey records), and their connections to the quantitative evidence (e.g. links between the emergence of the steam-iron-screw cargo steamer and the close monitoring by Lloyd's Register of this phenomenon), provide evidence that is central to the main argument of the present thesis.

Chapter 8 summarises the argument as well as the main findings from this study. A discussion of the limitations and implications of the thesis is provided, as well as an outline of the possibilities for future research.

Part I

Part I sets the stage for the remainder of the thesis. The next two chapters address current knowledge on innovation research that is of interest to our understanding of the evolution of ship technology, and review the process of technical change in steam navigation from the early steamboat plans to the large vessels that dominated the seas in the early 20th century.

Chapter 2 lays out the theoretical framework. It presents and discusses key theoretical concepts such as technological paradigms and trajectories, dominant designs, technological and service characteristics, core inputs, national systems of innovation, complex projects, and technological communities. It does so by presenting an extensive review of the relevant literature.

Chapter 3 provides an historical perspective on the development of the steamer. It starts by briefly reviewing the process of slow gestation of steam navigation. It mostly concentrates on the technical aspects associated with the emergence of the mature working steamer. The chapter appraises the actual major breakthroughs in steamship design by focusing on the concatenation of certain technological developments in specific ships brought together by particular individuals who were embedded in a communal learning process taking place in real time. It does this by tracing the evolution of the marine steam engine, the transition to screw propulsion, and the replacement of wood by iron in the modern steamer. The chapter ends by describing the different types of steamers that comprised British steam navigation in the 19th century.

2. Theoretical background: Understanding the forces shaping steamship innovation

2.1 Introduction

The subject of this thesis is the process through which steam navigation first appeared and then developed into an ocean-going industrial-age capital good. The rise of the "modern" ship took place in Britain in a period stretching from the 1810s to the 1850s. The present chapter provides the remainder of this work with the analytical elements necessary to make sense of innovation phenomena in the early steamship story. The following chapter (Chapter 3) attempts to synthesise the available technological and economic history of steamship building, a vast fieldwork that still lacks an integrated and up-to-date treatment at the hands of a full-time maritime historian.[1] The major thrust of this thesis, however, is the appraisal of observed patterns derived from new quantitative and qualitative datasets (a task carried out in Parts II and III, respectively). Our account is mostly an interpretative rather than a descriptive one. This chapter assembles the theoretical and conceptual tools for the exploration and explanation of 19th century ship innovation and diffusion.

Our reference point is the "neo-Schumpeterian" or "evolutionary" economics perspective. This research tradition has its roots in the original insights of Schumpeter

[1] From an economic history point of view Pollard and Robertson's book (1979) remains the source of reference, although it only covers the industry from 1870 to the Great War. The closest thing to coverage of the life-cycle of the steamship is the collective undertaking coordinated by Basil Greenhill (see Greenhill, 1993a), a book in which the many aspects of steam navigation deserve separate analysis rather than a comprehensive critical overview. At the time of writing, Larrie Ferreiro is engaged in a follow-up to his notable *Ships and Science*; his forthcoming book (*Bridging the Seas*, mimeo in 2011) covers progress in marine propulsion and naval architecture in the period 1800-2000.

on the endogenous nature of change under industrial capitalism, and it emphasises how innovation is central to any long-run understanding of the structure of the economic system (see Freeman 1974, 2008). As an economic theory, this approach stresses the evolutionary logic governing the technological and institutional changes that channel the broader process of economic transformation in real time (see Nelson and Winter, 1982). At the core of the theoretical framework, Dosi (1997, p. 1531) states, is a methodological prerequisite: "the explanation to why something exists intimately rests on how it became what it is." Hence, this empirically-minded perspective has been proposed as particularly apt for studying historical problems of technological change (see Murman 2003, p. 17; Nuvolari 2004a, p. 3). The steamer was a complex machine in which the constituent technologies did not advance in isolation, hence the need to understand it in historical time and to emphasise the actual sequence of changes.

Historians of marine engineering and naval architecture have for a long time evoked the notion of evolution to better understand how ship technology came into being.[2] So far, however, the notion of evolution has appeared only loosely articulated in maritime historiography, and we believe that an explicitly evolutionary approach can provide a more productive interpretation of this thread of the literature. The main thrust of the historical literature, as we shall see in Chapter 3, is that ships in general result from a cumulative process of novelty generation, in which a variety of players and stakeholders collectively take part. This leads us to employ the neo-Schumpeterian/evolutionary perspective as a framework for concepts highlighting three major themes. We concentrate on the following three variables shaping the specific innovation

[2] It is reassuring to note that the word "evolution", which is not to say continuity, has been used by many prominent students of ship technology, and steamships in particular. Even if it is but a small sample, it is worth mentioning in this respect a number of concrete instances in works by Bradley (1921), Lubbock (1922, p. 2), Dollar (1931, p. 36), Boumphrey (1933 p. 70), Gilfillan (1935b, p. vii), Hendry (1938, p. 18), Hornell (1946, p. xv), Course (1960, p. 18), Davis (1973, p. 6), Craig (1978, p. 18), Kemp (1978, p. 172), Graham (1980, p. 3), MacGowan (1980), Dudszus and Henriot (1986, p. 80), Greenhill (1988, p. 21), MacGregor (1988, p. 114), Johnstone (1989, p. 18 and p. 45), Lambert (1992a, p. 7), Griffiths (1997, p. 1), Milne (2006, p. 24), Ferreiro (2007, p. ix), Fenton (2008, p. 195), Clark (2007; 2010, p. 7), among others. One could hope here to reconcile these insights with the more formal innovation economics literature.

phenomenon under analysis: the underlying technology, the artefacts themselves, and the communities designing steamers. Hence, the first theme concerns the structure and dynamics of technological knowledge. The second considers the particular class of large project-based products. Finally, the third theme refers to communities of innovators as sources of learning. This collection of themes has been treated in various parts of the field usually referred to as innovation studies. These bodies of research have seldom been brought together but can potentially illuminate relevant features of steamship evolution that resonate with the maritime engineering literature.

This chapter is organised as follows. Section 2.2 focuses on the main concepts concerned with the nature and dynamics of technology. Section 2.3 deals with large artefacts from the angle of project-based construction. Section 2.4 reviews the issue of collaboration between innovators. The final section synthesises the key theoretical constructs and provides an overview of how these theoretical elements fit together.

2.2 Technology, systems and evolution

Key concepts for analysing innovation

This thesis suggests that the steamship story fits well in the main canvas of neo-Schumpeterian economics in which “competition from the new or improved product, process or organization is a more devastating form of competition than non-innovative competition” (Freeman 2007, p. 130). Early industrial shipbuilding appears to have conformed to this mode of competition, one in which price is not the only or even the decisive factor (see Ville 1993, p. 11). However, in what concerns our exercise in “reasoned history”, it is prudent to keep in mind Mokyr’s (1990b, p. 105) note of caution: “Unfortunately, we have no good taxonomical system in technological history. Judgement and common sense will have to remain our guide here.” We consider that

that the fundamental notions available in innovation studies provide powerful instruments for unpacking the steamship story, but especially once the historical material is well understood on its own terms.

Schumpeter (1934, 1943) placed innovation firmly at centre stage of his dynamic view of industrial capitalism. A major source of economic development, understood as a process of qualitative change unfolding in historical time, was innovation in the sense of “new combinations” of ideas and resources. Transformation in economic structures was brought about from within through the innovations introduced by entrepreneurial individuals (the emphasis of the younger Schumpeter, 1932) or large organisations (the older Schumpeter, 1943). This gave rise to what he termed “creative destruction”, the way through which capitalism evolved. The stress on innovation as an economic phenomenon led him to a sharp distinction between what innovation is and is not. Innovation (the first successful introduction of a new product or process into the marketplace) was preceded by invention (the initial availability of the original insight, sketch or prototype) and succeeded by diffusion (the replication and spread of the new device, technology or system). This dynamic process of development was seen by Schumpeter as an uneven but relentless one, occasionally shaken by major discontinuities in the operation of the economy. According to Schumpeter (1939), technological and institutional change cluster in time and play a large part in business cycles, marking distinct periods in economic history.

A large chunk of innovation studies literature developed in the Schumpeterian spirit, especially after the 1970s and 1980s (see Fagerberg *et al.*, 2004; Hanusch and Pyka, 2007; Hall and Rosenberg, 2010). One important generalisation, which we will adopt, is that the analysis of new technology may include both the artefacts themselves (what and how things are made) and the knowledge base (on what principles are things invented, designed and built) (see, e.g., Grübler 1998, p. 20; Saviotti, 1996). As Dosi and Nelson (2010, pp. 55-6) argue, describing and understating technology, i.e. any a conscious manipulation of natural effects to achieve human defined ends, invariably entails considering these distinct but complementary levels of analysis (the devices and products in themselves on the one hand, the knowledge and capabilities underpinning them on the other). In other words, technology can be both appreciated as an "idea" (say the steamship as a framework for an integrated set of specific technological solutions) and as a "thing" (the steamship as a concrete product with a set of characteristics that can be mapped and measured). The present study tries to integrate both dimensions.

Another important distinction, also based on Schumpeter's concepts, is between "radical" and "incremental" innovation. Radical innovations (like the introduction of an unprecedented type of machine) are very uncertain in outcome and relatively few in number, while the day-to-day incremental ones refer to relatively small improvements and minor adaptations but usually carry the largest economic benefits (Freeman and Soete 1997, p. 312; Dodgson *et al.* 2007, pp. 55-6). Joel Mokyr (1990a) has made a similar distinction between what he terms "macro-" and "micro-inventions": the former being discontinuous change (innovations that emerge without a clear precedent and open up a new realm of technological possibilities), the later referring to smaller adaptations (the offshoot innovations that evolve out of macro-inventions through tinkering and adaption to particular application settings).[3]

Besides refining and reinforcing many aspects of Schumpeter's vision, scholars in the innovation studies tradition have not shied away from questioning and extending it (see Freeman, 1974, 2008). One complication is related to useful but somewhat artificial theoretical distinctions between invention, innovation and diffusion. New products are

[3] Modern neo-Schumpeterian theory integrates both aspects of technical change, for instance, in arguing that long-run economic growth primarily depends on the industries where the combination of the two types of innovation occur most effectively in any given historical period (see Freeman and Louçã, 2001).

often introduced without being fully worked out and, as historical analysis shows, the most important innovations “go through drastic changes in their lifetimes” (Kline and Rosenberg 1986, p. 283). A long and costly process of development takes place as innovations diffuse, a process that in the end becomes vastly more economically significant than the initial introduction of the invention. Improvement reduces the relative costs and increases the range of applications of the initial innovation, widening its reach to the bulk of users in the most important potential markets (von Tunzelmann 2000, p. 127). One implication is that innovation is not to be understood as a single event but rather as a time-consuming process in which the relatively long lags between invention and innovation, and between innovation and diffusion, reflect the many requirements that have to be met for refining and fully exploiting new ideas (Bruland and Mowery, 2004; Fagerberg, 2004). The historical record shows, in particular, that the assimilation of new revolutionary technologies may take many decades and that a flow of secondary technological and institutional improvements accumulate over time to generate far-reaching impacts in the economy (Freeman and Soete 1997, p. 184 and p. 220). The importance of the users’ side in the learning process leading to such incremental improvements has, moreover, been much documented in empirical and historical studies of innovation (e.g. Rosenberg 1976, 1982; von Hippel, 1988). In this respect innovation is identified as a coupling and iterative process, i.e. one of matching technology and markets in which concepts and approaches that are technically feasible are continuously adapted to evolving commercial needs and tastes (Freeman and Soete 1997, pp. 200-3).

Complex artefacts

As Chris Freeman (1982, p. 175) noted, “many new products are essentially engineering ‘systems’”. These complex artefacts or systems assemble a number differentiated and interdependent components and technologies in order to fulfil a particular goal.

Innovations such as novel large and multi-technology products "represent the coming together of preceding technological components in a radically new design architecture, rather than springing fully conceived into the world." (von Tunzelmann 2003a, p. 169) Innovation studies and historical investigations of technology have addressed this class of innovative products, both in terms of types of technological change and in terms of the dynamics of change over time.

In the case of products of this kind, such as capital goods, a number of specific types of innovation may be distinguished. Following Henderson and Clark (1990; see also Dodgson *et al*. 2007, p. 56), a significant change in a part of a product is called a "modular innovation" if it does compromise the coherence of the overall product. A change in the way the (unchanged) components are combined represents a change in the product's internal structure or overall design, i.e. it is an "architectural innovation". Framed in this way a "radical innovation" represents a new architecture linking together core components that are themselves new or significantly overhauled, whereas an "incremental innovation" is a minor change in a component within the pre-existing design. A key implication that we learn from this work is that innovation at the level of the integrated system is rather infrequent and has larger long-run consequences than at the subsystem level.[4] A new complex combination of components and technologies demands more comprehensive knowledge (both technological and managerial) of how different component technologies interact and link together to produce a coherent effect. Recent literature on high-cost engineering-intensive complex products (e.g. Davies, 1996; Prencipe, 1997; Hobday, 1998; Prencipe *et al*., 2003; Acha *et al*., 2004) has emphasised that systems integration capabilities entail nurturing core design know-how and the ability to internalise the requirements of the most important usage contexts.

[4] Evidence shows that even seemingly self-contained improvements to individual technologies may have quite dramatic consequences in the operation of a given piece of equipment and that changes in the basic design principles may transform the entire industry (Tidd *et al*. 2001, p. 12 and p. 23).

When we consider engineering and technological systems, in particular large ones, over extended periods of time a number of features stand out. One feature is that because components evolve in different rates and directions it is difficult to predict where complementarities will arise (Powell and Giannella 2010, p. 578). In addition, Hughes (1983) and Vincenti (1990) show that complex artefacts tend to be stable over time as innovators hesitate to depart radically from the province of proven solutions.[5] Given non-linearities in component interdependencies, even slow or small alterations in design may lead to unexpectedly fast and far-reaching changes in the workings and services provided by the product as a whole. Hughes (1987) stresses the role of internal disequilibria leading to sequences of innovation: because the components of a system interact with one another, a change in the properties of one part will bring about "compensatory changes" in other components, in turn triggering changes in other parts of the system, and so on. Similarly, it may happen that limitations in a particular component will hold up the development of the system as a whole, such as a component that has fallen behind in terms of relative performance or that is unexpectedly out of phase with others, a phenomenon known as the occurrence of a "reverse salient" (Hughes 1983, p. 79).[6]

In the early days steamers tended to be seen simply as the sum of two different technologies: "the shipyard construction of hull and fittings and the engineering provision of engines, boilers and paddles." (Ville 1991, p. 74) As steamers grew in size and complexity, so too the highly non-linear or complex relationships between their parts demanded a deeper understanding, i.e. unilateral improvements in the performance of one technical aspect could compromise the ability of the system as a whole to

[5] These authors drew on their historical studies of electrical power and high-speed airplane respectively.
[6] The words of Murmann and Frenken (2006, p. 937) provide a good summary of this particular dynamic: "when a new solution is accepted, this defines further problems in other parts, which in turn may define new problems in other parts."

achieve useful results or even lead to an outright breakdown.[7] Such unpredictable imbalances are likely to be faced when increasing the size of an engineering system, which leads to changes in the external form and internal structure of the product as a whole. Sahal (1985, p. 63, emphasis in the original) has noted: "the origin of innovations lies in *learning* to overcome the constraints that arise from the process of *scaling* the technology under consideration."[8] Since in this process the parts of the product are themselves developing, but not necessarily at the same rate, it is worth observing that at a given time they may converge – to great effect. Engineering systems "that originate in an integration of two or more symbiotic technologies constitute the most important types of innovations." (Sahal 1985, p. 80) Indeed, as Slaven (1980, p. 113) noted: "The interplay between wood, sail, steam and iron is complex, but it is clear that the separate potentials of steam and iron were only fully realised when the two were linked." The consolidation of a new engineering system affects the dynamics of its development as the new architecture channels exploratory activities in particular path-dependent directions. Engineers struggling with such challenges collect feedback from the experience and experiments around the artefact of interest in what becomes both a "cumulative" and a "communal" learning process (Vincenti 2000, pp. 187-8). In the face of immense technical uncertainty, knowledge sharing becomes a cost-effective way to keep abreast of developments and potential synergies in the field (Powell and Giannella 2010, p. 578).

[7] As Schwerin (2004, p. 92) notes about steam shipbuilding at mid-century: "Minor differences in ship design have drastic effects on the vessel's performance, and most aspects of hull design, propulsion etc. (e.g. questions like 'How do changes in design affect speed and coal consumption?') were as yet totally unclear from a theoretical perspective. Any gain of information, from which source whatsoever, was thus highly welcomed."

[8] von Tunzelmann (1995, p.15) reinforces this observation when noting that the typical search solutions, or heuristics, involve the "continued scaling (up or down) of key performance characteristics."

The evolution of technological knowledge

In line with innovation studies we will define “technology” as a body of useful engineering knowledge (see, e.g., Freeman and Soete 1997, p. 24). Hence, technological change represents learning and the accumulation of knowledge that is “usually concerned with the reordering of the material world to make it more productive of goods and services” (Hughes 1984, p. 53). Learning, understood as the “search” for solutions to technological puzzles or problems, is a “localised” and “path-dependent” venture into the unknown corners of the “design space” in the sense that it develops in the proximity of existing combinations and specific designs (Antonelli, 2007; Stankiewicz, 2000). This learning process accumulates in individual interpretative structures (expertise) and in organisations’ repetitive procedures (routines), which remain largely tacit, agent-specific and not marketable (von Tunzelmann 1995, pp. 4-5). Direct imitation and practice are the most efficient mechanisms for the transfer of tacit knowledge (Dosi and Marengo 1999, p. 19). Otherwise technological knowledge may be packaged and transferred by becoming embodied in products (embodied technological innovation) or by being used to produce codified information (i.e. organised data articulated in formal language) in the shape of patents or publications (see, e.g., Foray, 2007). What is more, on the producer’s side making knowledge explicit is a costly activity that itself depends on tacit knowledge, while being able to absorb it also requires investment in tacit and indigenous knowledge on the user’s side (Cohen and Levinthal, 1990; Cowan *et al.*, 2000). Difficulties in developing such knowledge creation and decoding capabilities can indeed become a better guarantee of the appropriation of the fruits of intellectual labour and a higher barrier to imitation than patents, which typically do not stop entry but only make it more expensive, especially in fast-moving technologies and industries (Mansfield 1986, p. 314; see also Granstrand, 2004). Advances in new technologies, especially of the radical type, are inherently uncertain (in a Knightian sense), motivating actors to create special kinds of institutions to help them to deal with challenges "involving specific judgment in each individual instance." (Freeman and Soete 1997, p. 244) The many limitations in developing and accumulating productive knowledge (especially at the individual level given "bounded rationality", in the sense of Herbert Simon) help to explain why individuals group together in firms and in other inter-personal organisations (von Tunzelmann 1995, p. 5).

When there are many efforts going on to push technological options beyond what is already understood, broader patterns form. Central concepts in innovation studies were introduced to represent these dynamics (see Dosi, 1982).[9] A "technological paradigm" is a set of guiding principles shared among engineers and innovators that define the relevant puzzles to be tackled and the acceptable methods for pursuing solutions. A paradigm (say, mechanisation in manufacturing during the British Industrial Revolution) is therefore a general model or template informing the search for solutions to specific technological challenges within a particular historical context: it constitutes the first solution tried by engineers and innovators in order to break existing bottlenecks and to solve technological puzzles (say, applying an engine to do the job, or applying iron to tackle a problem, etc.). A technological paradigm is typically characterised by great internal consistency and extensive external application (von Tunzelmann 2000, p. 132).[10] Under this shared cognitive framework, the communities of engineers follow generally accepted rules of thumb ("heuristics") in order to arrive at solutions to technical problems (for instance, employing iron to strengthen a structure, or making a vessel proportionally longer to increase its cargo capacity). As the technology takes hold and develops to realise its potential, new advances tend to follow in the footsteps

[9] The approach draws on work on the history of science. The rise of a major new technology has parallels with what Thomas Kuhn's (1970) account of "revolutions" "and "normal" activity in science. For further comments, see von Tunzelmann (1995, pp. 14-5).

[10] The notions of a paradigm as a general mode of understanding the workings of technology and the notion of trajectories as consisting of particular avenues of exploration in an unfolding paradigm have been applied to specific historical cases such as British steam engineering (see von Tunzelmann 1995, pp. 14-6 and pp. 400-3, and Nuvolari and Verspagen, 2009).

of previous ones with demonstrated success. The string of innovations that further articulates the original breakthrough in a specific avenue of improvement is known as a "technological trajectory": the exemplar is improved through a series of localised changes to raise the performance in particular functional characteristics (e.g. speed, size; cf. Frenken, 2006).[11] A trajectory is both strongly cumulative and sensitive to the operational and economic pressures of the selection environment.

There are many historians emphasising discontinuous stages in the development of oceanic navigation (e.g. Kemp, 1978; Woodman, 1997). For instance, the 15th century was marked by "great revolutionary developments" (Greenhill 1980c, p. 3; see also Gardiner, 1992)[12], something only witnessed again in the 19th century (Davis 1962, p. 391; Stopford 2009, p. 45). The historiography of the ship, by emphasising the constant refining of general templates (e.g. Gilfillan 1935b), is consistent with notions of localised path-dependent learning and with evolutionary thinking in general (cf. Dosi and Nelson 2010, pp. 53-4). In the maritime sector, change was mostly, but not always,

[11] Broadly speaking, size was a key target in steamship technological change. Maritime speed did not go through spectacular improvements during the 19th century as size did. In particular, this was true for long-distance travel and in the years after the transition from the wood-paddle to the iron-screw steamer paradigm. Hobsbawm (1975, p. 53) notes that between 1851 and 1873 gains in the duration of transatlantic trips between Liverpool and New York were modest, remaining at 11 to 12.5 transit days for most of the period. It should be underlined that this was a premium trade in which the pressure for rapid passages was at its highest; liner speeds were not pursued in other trades such as tramping (Stopford 2009, p. 28). In the words of a contemporary, this urge to provide fast transport in the liner business, many times racing for the Blue Riband prize, was carried to the point of being economically "insane" (Lindsay 1876, p. 184). The jargon of the time referred to these crack steamers as "greyhounds of the ocean" (Conrad 1921, p. 220).

[12] In the early 1400s most European ships were single-masted, square-sailed and utterly dependent on favourable wind or on rowing power. Around the middle of the 15th century, sea-going vessels were decisively improved with the Portuguese caravel, which became the paradigm for deep-sea travel. This vessel proved to have a sturdy design, capable of voyages of exploration (beating rough unknown seas against the wind) and exploitation (capable of carrying large cargoes) (Love 2006, p. 7). As a system of methods for harnessing wind to make its way to distant places, this instrument of discovery and empire tilted the outcome of the struggle against heavy seas and unpredictable weather in favour of the Portuguese enterprise (Law 1987, p. 117). The caravel provided the basis on which further improvements could be built and, as the phase of exploration switched to a phase of imperial exploitation, the sailing ship grew in size and seaworthiness but changed little in design until the end of 18th century (Lemmers and Ferreiro 2007, p. 648). Over several centuries, changes to the classic sailing ship occurred largely in the details, such as the addition of the steering-wheel and fore-and-aft sails as well as a progressive increase in sail area (Boumphrey 1933, p. 50; Davis 1962, p. 391; Greenhill 1980c, p. 3; McGowan 1980, p. 5; Law 1987, p. 117). At the dawn of the 19th century, construction methods for ocean-going wind-powered ships had changed so little that Columbus and da Gama would most probably have recognised them (McGowan 1980, p. 5).

gradual (Stopford 2009, p. 45). Thus, there is scope for stasis as well as transition in this mode of reasoning about technologies and products (Saviotti 1996, pp. 1-3).[13] Once a new product framework emerges, it becomes progressively entrenched as minor improvements extend its functionalities. According to this perspective, moreover, new paradigms and heuristics cannot be initiated purely from customer demand, institutional procurement or changes in market circumstances. Pecuniary incentives and latent demand are too unfocused to bring about a new radical technology or to kick-start the avalanche of related minor innovations, which are in large part determined by the "internal compulsive sequences" that push inventive efforts in particular directions (see Rosenberg 1976, pp. 112-3).[14]

Design varieties and the selection of a dominant design

As already seen, the paradigm-based perspective of technical change has both a "cognitive" dimension (technology as a body of useful knowledge) and an "artifactual" dimension (the object itself) (cf. von Tunzelmann 1995, p. 14). The present study attempts to integrate these two levels of analysis by discussing the interaction between the intellectual work behind the steamship development and the actual characteristics of the concrete population of steamships that found employment in a variety of trades. From the viewpoint of this thesis, a key bridging concept is that of "dominant design" originally introduced by Utterback and Abernathy (1975) and Abernathy and Utterback (1978).

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[13] To use Hughes' (1984) terminology: as technological systems mature they acquire a particular "style" and thereafter gain "momentum". Or, as Sahal (1985) put it: technological patterns serve as "guideposts" to the subsequent path of development, or "technological avenues". This language points broadly to the concepts already summarised under the headings of "paradigms" and "trajectories".

[14] See Rosenberg (1976, pp. 108-25) for a classic discussion of the relative rigidity of technical choices in the face of price signals - the case in point being complex mechanical technologies. He recognises that economic incentives are, of course, pervasive but so diffuse that as an explanatory variable "they do not explain very much in term of the particular sequence and timing of innovative activity." (Rosenberg 1969, p. 110, emphasis in the original) Mokyr (1990a, p. 295) concurs, saying that micro, gradual, continuous inventions are governed by their own logic of advance and are not "predictable by economic forces."

The concept of a "dominant design", important here as the equivalent to a technological paradigm at the product level, refers to the emergence of a well-defined set of features and functions in the course of the product cycle (see von Tunzelmann 1995, p. 18, Utterback 1994, p. 49).[15] A dominant design is linked to the consolidation of a new core set of technological characteristics and lays out a clear vision of what the product is all about, that is, a dominant design is a "consensus good" (in the words of Geroski 2003, p. 111) or a "consensus configuration" (to adapt Geroski's terminology to Henderson and Clark's (1990) emphasis on the internal architecture of a complex multi-component product).[16] The occurrence of a lasting template of product characteristics carries momentous consequences for an industry. The work of Abernathy and Utterback (1975, 1978), Dosi (1982) and Henderson and Clark (1990) has shown that during the pre-paradigmatic period the general lay-out of a product remains undefined and a large number of players try out very different approaches when resolving the technological challenges. The early stages of development of a new product may require a long period of time (Utterback 1994, p. xxii). This exploratory phase is one in which product design is primitive, and great uncertainty exists concerning the fundamental technical notions behind the new technology (Klepper 1997, p. 148; Malerba 2007, pp. 356-7). In terms of industrial organisation, the market is a low-volume one, albeit with many new firms entering the business and with intense competition, as well as intensive collaboration, occurring between technological players (Dodgson 2007, p. 195). Once the new dominant design becomes accepted, the variety of structurally different technological solutions begins to diminish (Malerba 2007, p. 357). At this point a major technological

[15] The "dominant design" hypothesis does not seem to apply to all classes of products, such as non-assembled products (rayon, glass, metals, pharmaceutical molecules; see Utterback 1994, p. 48, Dosi and Labini 2007, p. 340) and extremely complex products (telecommunications equipment, nuclear power plants, flight simulators, etc.; see von Tunzelmann 1995, p. 19).

[16] Utterback (1996, p. xx) notes: "A dominant design usually takes the form of a new product synthesized from individual technological innovations introduced independently in prior product variants. A dominant design has the effect of enforcing or encouraging standardization so that production or other complementary economies can be sought. Then effective competition begins to take place on the basis of cost and scale as well as of product performance."

discontinuity triggers important changes in the evolution of the industry. In the event cost competition rises in importance (based on the exploitation of scale economies and process innovations) causing less-efficient producers and those unable to adapt to the new design to leave the market, a phenomenon known as “shake-out” (see Klepper, 1997; Klepper and Simons, 1997). In neo-Schumpeterian language, the transformation associated with the emergence of a dominant design is akin to the transition from the so-called Schumpeter Mark I, creative destruction, entrepreneur-based “technological regime” to the Schumpeter Mark II, creative accumulation, large incumbent-based “technological regime” (Dodgson 2007, p. 195). At the same time the market rapidly expands, bringing in an increasing array of different types of users into a mass market and calling for a new set of complementary infrastructures required to support the effective deployment of the innovation (Utterback 1994, p. 25 and p. 31; Grübler 1998, p. 22; Geroski 2003, pp. 16-7; Saviotti 2007, p. 828).

In line with the evolutionary framework of neo-Schumpeterian economics, it is now worth noting that technological change is taken here to be driven by the coupling of variation (i.e. the generation of novel economic conjectures) and selective retention (i.e. the success and spread of specific innovations in particular domains of application). The usefulness of the evolutionary analogy has been noted in the study of economics (Nelson and Winter, 1982), technological innovation (e.g. Ziman, 2000a, 2000b), and technology history (e.g., Mokyr, 2000). Dosi *et al*. (2005, p. 691) note in this respect that three methodological issues stand out: *a*) *the unit of selection*, which they consider to be the “paradigm” and the “dominant design” at the technology and product levels, respectively; *b*) *the nature of the process of selection*, which is a collective mechanism that mainly includes *ex-post* market pressures as well as *ex-ante* institutional factors shaping the process of technical change; and *c*) the *selection criteria*, where the authors suggest that economic criteria influence the selection over a population of artefacts both "directly", through prices and preferences, and "indirectly", through the producers' expectations in choosing a particular avenue of search and exploration.

It is worth noting, furthermore, that evolution in the technological realm presents some further complications. First of all, the process of technological development may not be characterised by a "pre-paradigmatic" phase as such (i.e. a given radically new product may start with a set of stable features from the outset), so in this case it would be more appropriate to talk about a "paradigm shift" rather than a "paradigm emergence". By implication, it should also be remarked that the occurrence of a dominant design does not have to punctuate a given industry or product category only once (Frenken 2006, p. 57). Moreover, a given paradigm may change while a given trajectory is continuously followed without interruption; for instance, the trajectory toward higher speeds in aircraft continued without interruption from the 1920s-1940s to the 1950s-1960s while the transition from piston propeller engines to jet engines took place (Frenken 2006, p. 52).[17] Furthermore, given that market selection is imperfect, there is no reason to expect a new design to automatically replace an old one (Dosi and Nelson 2010, p. 69). In analogy with the notion of "anomalies" (see Kuhn, 1970), the existing technology may experience several episodes of imperfect performance when stretched beyond its ideal range of operation before better suited alternatives are developed and taken up.[18]

It is seldom the case that a dominant design marks a clear, immediate break with the past and crowds-out all the remaining alternatives. Variety may persist in the population of objects (Dosi and Nelson 2010, p. 69). This coexistence of old technology with a radically new innovation may be interpreted as indicating different market niches or

[17] Arguably the same happened in ship technology around the same time with the transition from steam to internal combustion technologies; in spite of the conversion to a motor fleet (new, diesel-engine ships) during the first half of the 20th century the technological trajectory of ever increasing size kept being pushed as an engineering aim (Corbett and Winebrake 2008, pp. 9-10).

[18] An example of this concerns again the case of piston propeller engines in aircraft. These engines caused increasing vibration and became less efficient as the speed of propellers' tips approached the speed of sound (Frenken 2006, p. 53). This bottleneck hampered the development of aircrafts as a whole, triggering search efforts in radically new directions (like jet engines).

segments. This underscores the notion of qualitative change as change in the composition of the different categories of goods or technologies in a population (Saviotti 1996, 2007). The distinction between the technical and service characteristics proposed by Saviotti and Metcalfe (1984) is of relevance here: the first are variables that can be shaped directly by the engineers and producers (say, the length of the vessel), while the second variables refer to the performance of the object for the purposes valued by the users (say, the effective carrying capacity). Hence, different designs based on different trade-offs of technical characteristics may yield different services. These services, in turn, prove more or less "fit" in specific economic and operational niches, which are understood as distinct "selection environments" (Frenken and Nuvolari, 2004; see also Fontana *et al.*, 2009). In other words, a given design may start to occupy a specific niche before becoming a dominant or "monopoly design" (to use the term adopted by Geroski 2003, p.110).

Different service requirements are expected to give rise to differentiated learning trajectories over time, even if drawing on the same dominant design. This dynamic process of product differentiation is understood through the lens of a "population" method of analysis, that is, it is seen as taking place within the overall population of products and activities, and the emerging heterogeneity is referred to as "speciation" (Saviotti 1996, pp. 78-85; Metcalfe and Foster 2010, pp. 69-71). Murmann and Frenken (2006, p. 949; see also Saviotti 1996, p. 78, and Geroski 2003, p. 80) have argued that the paradigm is a kernel of constant characteristics in a product population. These authors argue that product design consists of a hierarchical architecture of attributes, i.e. an ordered combination of "fundamental"/"core" and "adaptive"/"peripheral" characteristics. Hence, the pattern of evolution is one of multiple designs developing along specific trajectories (non-fundamental characteristics being adapted to particular uses) within a fixed generic platform (a constant set of characteristics defining a paradigm or dominant design). In other words, a given basic structure or design is to be understood as allowing the construction of specific variants by adapting or adding certain secondary features which can more easily be manipulated in order to perform more efficiently in specific settings.

Technology at a macroeconomic level

At an aggregate level, technical change comes across as "sometimes explosive, sometimes very gradual" (Freeman and Louçã 2001, p. 139). Many historically-informed accounts suggest, moreover, that "major innovations", once they are established, set in motion a sequence of follow-up innovations which are complementary and distributed across the entire economic system (Rosenberg 1986, p. 111). Freeman and Pérez (1988) and Freeman and Louçã (2001), building on the notions of Dosi (1982), refer to "techno-economic paradigms" to describe the disruptive/smooth dynamic structure of change at the level of the economy as a whole. As a new constellation of radical innovations (that kick-start a number of individual technological paradigms) starts to overhaul the production system, new sectors and modes of conducting business begin to develop. The "techno-economic paradigm" notion predicts that the transformation of the economy's knowledge-base will be followed, with a certain lag, by a broad process of social and institutional adjustments. The rise of a new techno-economic paradigm punctuates the path of growth, leading to "long waves", i.e. fluctuations in economic variables measuring macroeconomic performance and industrial profitability. This school of thought characterises industrialisation as an evolutionary phenomenon (von Tunzelmann 2000, p. 125).

Neo-Schumpeterian authors argue that there are a few recurrent patterns for industrial revolutions, although of course there are many unique features too. How do they analyse the first one? British industrialisation exhibited a particular pattern of technological and institutional change, in what might be characterised as a "path-dependent" process (Allen 2009, p. 140). According to Freeeman and Louçã's (2001) account, the major innovations of the British Industrial Revolution (i.e. the radical innovations, the macro-inventions) in mechanical technology (in the earlier phase water-powered then steam-powered machinery) spread from their original sectors of application (the cotton industry and coal mining) to become pervasive throughout the manufacturing sector. While adopting this perspective, von Tunzelmann (1995, 2000) has emphasised that the new industrial technology became first associated with process innovations; only later on did distinctively novel products emerge.[19] After some time, economic growth was driven by industries of great market potential called "carrier branches" (first cotton spinning during the first half of the 19th century, then railways in the third quarter of the century).[20] These leading sectors used the new radical innovations and combined them with the available "core inputs" (coal and iron, i.e. the new inputs characterised by multiple applications and falling relative prices), becoming exemplars of the entire "era" (cotton spinning and iron goods during the period from 1780s to the 1840s, railways and engineering during the period from 1840s to the 1890s).[21] Industrial innovation was "systemic in nature" (Freeman and Soete 1997, p. 21). It required, in turn, a set of infrastructural and institutional complementary changes (e.g. in physical infrastructure, laws and regulations, labour organisation and training, management and capital ownership, etc.). Table 2.1 synthesises this tradition of analysis.

[19] Economic historians also differ somewhat in their chronological schemes, although a broad consensus exists around the First Industrial Revolution starting in Britain in the late 18th century, the second in Germany and the US in the late 19th century and the third in the late 20th century in the US (and East Asia). In the innovation studies literature, for reasons that would mean exploring a debate that would then divert us from the main topic, there are some differences in cut-off points and duration. Freeman and Louçã (2001) subscribe to the periodisation 1780s-1890s, 1890s-1970s, and 1970s onwards for the three successive cycles of long waves, respectively, whereas von Tunzelmann (2003), who focuses on the initial sub-phases of the industrial revolutions, demarcates 1750s-1815, 1870-1914, and 1973 onwards.

[20] von Tunzelmann (2003, p. 172) has remarked that production in a new technological revolution tends to precede a major growth in output, which can be seen as a long-term response to the rise of the new economic potential contained in the constellation of radical innovations.

[21] von Tunzelmann (2000, p. 28 and p. 133) has noted that "carrier industries" can be described as "user industries" which, in turn, stimulate the expansion of the up-stream industries.

Table 2.1 Summary of the neo-Schumpeterian view of the British Industrial Revolution

Phase of the British Industrial Revolution	**Approximate timing**	**Technology (innovation emphasis)**	**"Core inputs"**	**"Motive branches"**	**"Carrier branches"**	**Infrastructures**
Launch phase (or first "long wave")	1750s-1815	Machinery (primacy of process innovations)	Iron Coal	Metallurgy Coal mining	Cotton spinning Iron products	Canals Turnpike roads
Consolidation phase (or second "long wave")	1815-1895	Machinery (primacy of product innovations)	Iron Coal	Metallurgy Coal mining	Machine tools Engineering Railways Shipbuilding	Railroads Industrial ports Coaling stations

Source: adapted from Freeman and Louçã (2001, p. 140) and von Tunzelmann (1995, 2003)

The notion of a "techno-economic paradigm" has, moreover, a correspondence with the establishment of a new macro-level structure of governance, production, and social relations. To address the country-specific regularities that are organised around historically-rooted engines of technical change, the neo-Schumpeterian tradition has developed the concept of the "national system of innovation" (a "complementary, somewhat more cross-sectional" notion – cf. Dosi and Labini 2007, p. 340). Broadly speaking a national system of innovation represents the particular combination of modes of technological innovation and forms of socio-economic governance that characterises a country in a given historical period. Moving further away from Schumpeter, authors such as Freeman (1988) and Lundvall (1992) have argued that there are more factors affecting innovation performance at an aggregate level than just entrepreneurs or large R&D-intensive corporations: innovation is a structured and distributed process embedded in institutions supporting, constraining and shaping learning and the accumulation of knowledge (Dosi *et al*. 2005, p. 692). This view underscores the need to consider the multiple interactions (behaviours and activities) and interconnections (institutional arrangements facilitating knowledge spillovers) between many economic actors (von Tunzelmann 2000, p. 127; Carlsson 2007, p. 859). In referring to institutions, an author like Freeman (1987) emphasises existing private and public organisations and the role of policy, while for Lundvall (1992) the "institutional set-up" represents shared behavioural rules and user-producer relations (see, e.g., Carlsson 2007, pp. 864-5).[22]

What can the national innovation system framework tell us concerning the "classical/Victorian" period?[23] The systems framework generally brings to the fore a number of features: key actors and their activities; relationships and the nature of interactions; the functions of the innovation system and the overall direction in which it takes the broader economy (Edquist, 2004). Pointing out that historians such as von Tunzelmann (1995) and Mathias (1969) have long argued that no single factor can explain British industrialisation, Freeman and Soete (1997, p. 296) provide a first sketch of how a set of specific national institutional factors underpinned technological change in Britain from the late 18th century to the late 19th century (Table 2.2). In terms of institutional factors, the work of Freeman (2002) and Freeman and Soete (1997, p. 296 and p. 313) identifies a uniquely "congruent" combination of developments in the British economic space: a hospitable cultural and political environment for science, invention, and associations of individuals devoted to their promotion; an increasing acceptance of free-market ideals in policy circles and the dismantling of the old mercantilist restrictions on trade; new ways of managing economic ventures (first partnerships, then joint-stock companies); the rise of professional business services, namely financial and insurance industries; a skilled and productive labour force that benefited from good professional training through the apprenticeship system and from formal intermediate-level schooling. It is also worth noting that until the middle of the

[22] Other, derived notions of the innovation systems framework have been proposed at the level of sectors, regions and technological systems (see Dosi *et al*, 2005 and Carlsson, 2007). Given that there is a lack of historical material at the regional level for the shipbuilding industry in our period and because there are empirical difficulties in applying the sectoral or technological systems approach to the case of the iron-screw steamer product, we will stick to the national level and not employ these more recent levels of analysis.

[23] Here we use the term provided for this historical context by Dosi and Labini (2007, p. 339).

19th century the patent institution was a rather patchy system in which it was more difficult to obtain a protection on a new product rather than a new machine (von Tunzelmann 1995, p. 108), and in which there was a general reluctance among judges to enforce intellectual property rights and among the Royal Navy to pay for intellectual property (see Dutton, 1984; von Tunzelmann, 1985; see Chapter 6). Mokyr (1990, p. 252) and von Tunzelmann (1995, p. 418) have argued that an imperfect patent system was probably advantageous for an early industrial leader like Britain since it fostered fast imitation and rapid experimentation in the formative stages of mechanical technology.

Table 2.2 The British national system of innovation in the 18th and 19th centuries

Key characteristics of the first industrial economy
▪ Scientific inquiry had become an established activity, encouraged by government, esteemed by entrepreneurs and popularised by gentlemen's clubs ▪ Mechanics and engineers went through an apprentice system and on-the-job training and also benefited from formal instruction in the new industrial towns (by 1850 Britain had twice the productivity of the European average) ▪ Partnership as a viable way for inventors to raise capital and use entrepreneurs' connections to advance market positions (e.g. Askwright/Strutt, Watt/Boulton) ▪ Strong investment by wealthy individuals and an increasing proportion of the general public in transport projects (canals, roads, railways, steamships) ▪ Increasing role of the capital market and, after 1855, joint-stock companies in channelling investment to the manufacturing sector and the shipbuilding industry ▪ Economic policy guided by foreign commerce openness, imperial policy and growing industrial/export-oriented interests ▪ In terms of technology policy there was reluctant internal regulation (e.g. long drawn out legislation over boiler explosions, delayed patent law reform) and a weakening technological protectionism (i.e. barriers to the export of inventions and capital goods) ▪ Expanding internal market (consumers developing an increasing appetite for British-made middle-quality manufactured products and for imported exotic goods such as tea, sugar and tobacco) and expanding overseas trade (safeguarded by an active Royal Navy)

Source: adapted from Freeman and Soete (1997, p. 296 and p. 313) and Freeman (2002); consolidated with von Tunzelmann (1995), Pollard and Robertson (1979), Craig (2003, 2004) and Mokyr (2004)

In terms of interlinkages, the British system was characterised by collaboration between entrepreneurs and inventors, interactive learning between producers and users of new raw materials and new technologies, and a growing transportation network. Finally, the functions of the overall system resulted from the nature of the actors' activities and interactions: the direction of industrial change was increasingly geared towards overseas trade, in line with the ascendancy of the social classes with vested interests in the new activities of capitalist enterprise and international trade.

Summary of section 2.2

As a "new combination" of previously existing technologies (i.e. a physical object based on knowledge of steam engineering, construction materials, and propelling devices), the steamer represented a "radical" departure from the established sail-only approach to merchant navigation. The transformation of the ship was driven by "mechanisation", the new prevailing "standard solution" or "common sense" approach to technical problems in navigation (i.e. the overarching "technological paradigm" of the first Industrial Revolution). A myriad of micro changes in component technologies occurred after the steamer's introduction and co-existed with a prolonged process of diffusion spanning more than one hundred years (as we shall see in Chapter 3 and 4). But a big change in overall design occurred around the mid-century. This change had to do with a new "dominant design" that primarily rested on the "symbiotic" convergence of iron-building and screw-propulsion. This reconstruction of the steamship concept represented a major discontinuity in the life-cycle of the technology and is associated with a major re-organisation of the shipbuilding sector, that is, the transition from an exploratory or "Schumpeter Mark I" phase to an exploitation or "Schumpeter Mark II" phase (Chapter 3). From this point onwards the "technological trajectory" of ever greater average tonnage was a clear trend in the population of steamers until the Great War. The great market potential of the "modern ship" made shipbuilding a "carrier branch" of the British industrialisation process. It used intensively the "core inputs" of coal and iron and called for the deployment of major new public works, that is, complementary infrastructures such as modern port facilities and the Suez Canal (Chapter 4).

The steamship was a complex product innovation that was dependent on the successful coupling of technology potential and application domains (see Chapter 5). Thus the new-born artefact was still not “modern”, i.e. it had yet to evolve to the features (metal-hull, screw-propelled, large in size and efficient in operation) that would make it fit for a variety of trades. In the transition from the “primitive” wood-paddle to the “modern” iron-screw configuration, the ability to master the overall design of the steamer (knowing how to integrate different parts in a coherent solution) was fundamental for carrying out successful projects in the most competitive environments. It would therefore seem a reasonable expectation that, in the context of the British national system of innovation, exclusionary mechanisms, such as patenting, would be less important than the development of “communal” knowledge governance mechanisms for the rise of the steamship as a mature industrial capital good (see Chapter 6 and 7).

2.3 Complex projects

Steamship construction as a project-based activity

Steamers, as large multi-technology machines, were a particular class of undertaking. The great number of elements involved, from the type of engine to the kind of materials employed, allowed for a large combinatorial scope of solutions (i.e. a large “design space” – cf. Stankiewicz, 2000) given the particular know-how of those engaged in the design and construction as well as the client’s needs. Unlike other branches of heavy industry, shipbuilding remained primarily a “construction activity” (Pollard and Robertson 1979, p. 230). “Almost every ship was different” (Dougan 1968, p. 58; see also Sechrest 1998, p. 7). Steamers, as well as other ships of that (and, indeed, our) time, were essentially individual “projects”. Engineers of the day, not least some of the most prominent ones like I.K. Brunel and William Fairbairn, even used the term themselves in this sense in their working correspondence (e.g. Brunel 1870, p. 314) and memories (e.g. Pole 1870, p. 156). Every single ship was an innovation, in the sense of a exhibiting a new combination of attributes, although not necessarily a superior one in terms of overall performance. As in the case of other large and expensive structures like the erection of blast furnaces or the construction of pumping engines, each new steamer was a form of "experiment", i.e. an informal way of conducting research and development (R&D) (see Allen 2009, p. 168).[24] That is, design and production overlap.

A project is a set of related activities organised toward the production of a specific major output in a limited period of time. A project is an idiosyncratic, temporary, knowledge-intensive undertaking that is addressed within a fluid, collaborative logic of organising (Eksted, 2003; Whitley, 2005). Project-based processes tend to deal with discrete and customised products. In the limit, the job to be done is unique and incompletely specified before-hand. The combination of resources employed and the targeted product attributes tend to be idiosyncratic. A given project has no exact match in the past, nor will the lessons extracted fail to influence future projects directly or indirectly. Projects are transient modes of organisation operating in a particular corner of the volume-variety space. Table 2.3 shows how project-based activity fits into the broader context of production when analysed in the light of these two dimensions. Projects are geared toward low-volume/high-variety production. They can be contrasted, in particular, with the mass manufacturing of homogenous goods or with continuous flow production like utilities or the capital and energy-intensive methods of production usually associated with the "Second Industrial Revolution". Project assignments are unlike what is often dubbed "niche" production in current day terminology (small but serialised batches). In shipping there is the little scope for mass production (Pollard and

[24] In this respect, industrial history seems to have come full circle. In today's learning economy Davies and Hobday (2005, p. 77) argue that for a variety of industries, not just in heavy capital goods, "(p)rojects are becoming the basic unit for achieving a firm's strategic objectives for innovation and diversification".

Robertson 1979, p. 230).[25] Moreover, non-uniformity is a feature of production in projects, but not necessarily an objective in itself like in today's digitally-empowered mass-customised service operations.

Table 2.3 Positioning projects in the volume-variety space

	Low variety	**High variety**
Low volume	Niche products	Projects
High volume	Mass production	Internet-empowered businesses

Source: the author

The governance of projects

The literature on projects is short on historical stylised facts but can still be a useful reference point. First, the project emphasis in the field of innovation studies is relatively recent and therefore tends to focus mainly on contemporary examples. This work mostly discusses projects from a managerial perspective, often concerning R&D projects (e.g. Pinto and Slevin, 1989; Shenar, 1993; Asmden and Hikino, 1994; Shenar and Dvir, 1996). In this literature the conception of a project is very much an in-house organisational solution to develop new products that require cross-functional competences within the firm. Second, initial scholarly work also implicitly discussed projects as stand-alone, closed phenomena, as if they were implemented in a vacuum. This particular limitation has recently been somewhat mitigated. Projects may be depicted as singular in terms of goal and outcome (Whitley, 2005), but their interior processes are now seen to reflect the influence of context and history. Engwall (2003), for instance, has argued that projects inherit features from the structures and processes of the surrounding organisation. In other words, the institutional environment matters.

[25] There were some occasions in which vessels were built in small tailored batches, for example during the Crimean War (see Arnold, 2000). Later, and more prominently, during the World War Two the same happed with the "Liberty Ships" (see Lane, 1951). Interestingly, a recent study Thompson (2001) noted that in the case of Liberty ships product quality decreased with cumulative production.

The subset of literature that deals with the design and implementation of large engineering and technological systems is of particular relevance to us (see Prencipe *et al*., 2003, and Davies and Hobday, 2005). This line of work addresses undertakings that tend to be infrequent, large in value, long in duration, individually tailored and carried out through multiple collaborative arrangements. As Prencipe and Tell (2001, p. 1374) put it, large technological systems are “engineering-intensive”, “business-to-business” products that are built in a customised way. Technological systems are usually collaborative ventures extending well beyond the boundaries of individual organisations (Gann and Salter, 2000). Arms-length transactions are known to be inefficient in the task of exchanging, coordinating and integrating fields of knowledge changing at different rates and in different directions (Tidd *et al*., 2001; Dosi *et al*., 2005). In a transaction costs economics perspective, project-based forms of organising economic activity can be thought of as a relational phenomenon occupying the middle ground between market and hierarchy, Williamson’s (1985) two polar mechanisms of governance. Given bounded rationality and risks of opportunism, vast innovative multidisciplinary tasks become exceedingly complex and as well as costly coordination challenges. As a result, supervision and decision rights are observed to migrate to knowledge-workers and specialist partner organisations. Designers and managers in complex products are more likely to make the production decisions than manual labourers (von Tunzelmann 1995, p. 408). On the one hand, traditional bureaucratic structures organised along functional departments give way to more decentralised, “hybrid” schemes combining at once market-based incentives with resource-allocation authority (Davies and Hobday 2005, p. 9; Zenger 2002, p. 80). On the other hand, projects become a valuable flexible platform for amalgamating differentiated forms of expertise. Once the project is finished, the network may be disbanded, with participants moving elsewhere to mix with other experts around new business initiatives.

Project-by-project learning and the selective retention of the lessons learned

Steamers are seen as an integration of existing mechanical knowledge at any given point in time. A new ship (i.e. the result of a new project) is not isolated from past experiences and, likewise, is also likely to influence future experiments. Each new ship corresponds to a space-time juncture where the state of the art (experience) and innovation (experimentation) meet. A steamship represents an instantiation of evolving best-practice (a technological paradigm being explored along a specific trajectory), representing an attempt to advance the technological system. Each new ship launched is a link between the past and the future of the technological system. As Henry Petroski (1997, p. 143), the structural engineer, reminds us, "ship design or any other kind of design is a matter of looking forward and backward at the same time."

But each new ship, then and now, can take months or even years to materialise. Projects are time-bound but also time-consuming.[26] It follows that the notion of a "project" introduces a distinctive temporal aspect into our analysis. The real-time sequence of projects becomes a relevant issue, and this contingency underscores the importance of an historical approach in the study of this type of innovation. On the one hand, previous discoveries and incidents can stimulate an innovative project in a particular direction.[27] On the other hand, as a project unfolds over time, exogenous events or shocks arising from the external context may radically alter initial conceptions and trigger the designers or builders to solve the problems encountered in a new way.[28] That is to say,

[26] Between 1830 and 1870 the typical construction time for a ship was around six to nine months (Slaven 1980, p. 120).

[27] Past experiments and experience concentrate attention and focus the efforts of designers and other actors. The state-of-the-art of technology is the springboard for the adaptation to the local situation (van de Ven *et al.* 1999, p. 29).

[28] As an innovative project develops from the initial conception to its final implementation, it remains open in terms of process and uncertain in terms of outcome. Whatever the serendipitous reasons, project changes are almost impossible to avoid (Dvir and Lechler 2004, p. 12).

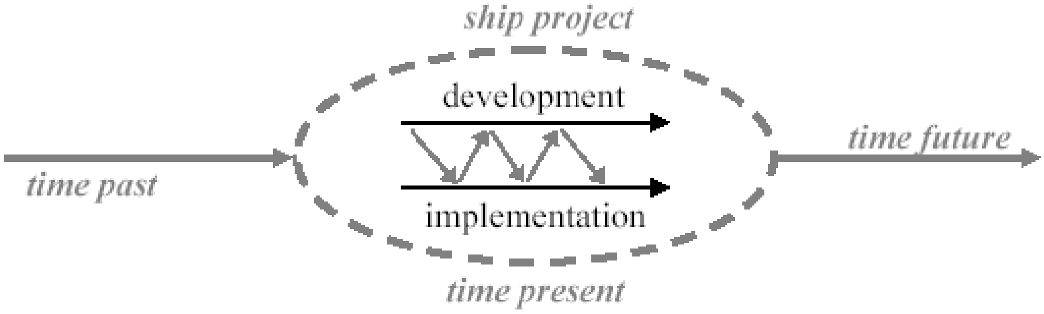
innovation and knowledge diffusion overlap. Because of simultaneous knowledge circulation and learning-by-doing (i.e. “off-line” and “on-line” learning – c.f. David 2004), an ongoing project is likely to be influenced by new findings elsewhere.

As depicted in Figure 2.1, we expect learning to have occurred not only between steamship projects, but also within projects themselves as they were carried out. This factor is important as we will be focusing most especially on the formative years of steamship development. This is in line with what van de Ven *et al*. (1999, p. 7 and p. 10) mean when they refer to an innovative project in terms of an “innovation journey”, i.e. projects are open in process, uncertain in outcome, and have their own individual stories. The usefulness of innovations can only be assessed *ex-post*, that is, the “summative evaluation” that occurs after the project is completed and actually deployed in its operational setting (van de Ven *et al*. 1999, p. 11). News on selection events (e.g. economic successes, technological setbacks, product accidents) carry the power of “demonstration effects”.[29] This information is of interest to experts and observers who are undertaking their own innovative projects. Given the difficulties of learning and the risks of miscalculation in large projects, actors use these “summative evaluations” and demonstrative “selection events” to guide their work. Thus, external events produce knowledge spillovers that, once made available are incorporated in the views and priorities of the actors, these having the cumulative effect of augmenting the recognition of a new technological path to a great extent. External events are especially influential when sufficient dissatisfaction with an existing technological approach leads certain ideas with the potential to overcome existing bottlenecks or to capitalise on an emerging opportunity to gain increasing currency. These features of *inter*- and *intra*-project learning constitute a necessary, but not a sufficient, condition for irreversibility and the

[29] Trajtenberg (2009, p. 386) defines “demonstration effect” as “a catch-all label for the well-documented fact that early adopters positively impact the decisions of later adopters, and hence their actions entail a spillover.”

non-ergodic dynamics (that is, a path-dependent process in the sense of David, 2001) of an engineering or technological system. When a given paradigm encounters severe anomalies and trajectories experience decreasing returns, news of (radical and exemplary) projects developed elsewhere may have the power to shift construction into a fundamentally new direction (based on a new "dominant design") that will be elaborated in follow-up projects. The building of daring ships was attentively watched and their business debut was intensively commented upon by those in the trade[30]; likewise incidents, crossings and other noted events were publicised and widely discussed in newspapers and other periodicals, thus geographically re-distributing the lessons learned (see, e.g., Maginnis 1892, p. 231 and p. 274).

Figure 2.1 Learning taking place from project to project and within projects



Source: the author

But how is the interpretation of past experience (the state of the art) and of "summative evaluations" carried out in practice? In considering such a question, Prencipe and Tell (2001) note this to be a difficult cognitive challenge for designers. Lessons must be drawn from a short number of idiosyncratic experiments in often distant selection environments.[31] Nelson (2005b, p. 207) notes that knowledge accumulation is hindered

[30] See Dollar (1931, p. 62) for an example of technical information concerning new innovative steamships spreading among shippers and shipbuilders at the middle of the 19th century.

[31] Petroski (2006, p. 6) highlights the problems of design testing with large structures: "In particular, the testing process, by which an unanticipated mode of failure is often first uncovered, must necessarily vary. Small things, which typically are mass produced in staggeringly large numbers, can be tested by sampling. However, very large structures, which are essentially custom or uniquely built, do not present the same opportunity."

by difficulties in collecting quick, sharp, reliable feedback on what is and is not effective. The effects of design innovation in large, expensive, and complex products are only experienced after they are built and put into operation, which creates incentives towards economising on misjudgements (Allen 2009, p. 168). Moreover, because projects are temporary "containers" of accumulated experience, knowledge developed in this context may be assumed to be highly perishable so that mistakes may be repeated if the experience is not re-used and furthered (Asmden and Hikino 1994, p. 114; Ekstedt 2003, p. 8). As a consequence, the ability to retain expertise is essential for the continuation of the business in the future. Given the contingent nature of projects, in terms of temporal finiteness and the group of participants involved, one prediction we may make is that the sharing of the lessons learned must have been crucial for these to be retained, remembered, and recombined.[32] Hence, the ability to access existing knowledge concerning the current and prior practice of others is one way to mitigate the costs and risks of experimentation. Knowledge sharing is crucial to minimise repeating old errors in new trials and to establish design innovation in complex projects as a highly cumulative enterprise. Our expectation is that in early 19th century innovative ship design, some sort of communal process of lesson retention must have existed.

Synthesis of Section 2.3

The idiosyncrasies of customer specifications, the particular solutions applied to design, and the assembly of components that underwent technical change mean that the construction of early steamers can be portrayed as projects. It is still the case today that every single ship's individuality is underscored by her own unique name. As maritime historians Dudszus and Henriot (1986, p. 8) put it: "There is hardly a single ship which

[32] Memory loss (or ineffective technology retention) was a comparatively greater problem in shipbuilding due to the volatile business cycle dynamics that characterise the sector. For instance, as Craig (2004, p. 8) reminds us, during crises years in shipbuilding, it was common that some steamers were built "on speculation", i.e. with no prospective purchaser in hand, "just to keep skilled workers employed."

is exactly identical in all characteristics to another." New projects deploy lessons learned from previous projects and capitalise on solutions tried elsewhere. Experience comes with each new experiment. New ships almost invariably represented a variation on the existing state of the art, i.e. more opportunities for innovation (or variety generation). That is, qualitative change in ship knowledge is assumed to be related to the growth of the population of ships built as individual projects.

Projects are considered an open organisational process that is influenced by networks including a wide number of different agents. The project is the context in which knowledge integration takes place. This *collage* of contributions happens through the intertwining of internal learning processes with technological trajectories emanating from outside. This is a useful framework to understand the exploratory years of steamship evolution since, during the formative phase of modern shipping technology, the most common arrangement was a web of trusted ties linking specialist firms (hull and engine builders) and consultant engineers (marine engineers and naval architects). Due to their large size, prominent visibility and the large number of people involved during the lengthy periods of construction, learning from others' experiments was pervasive in steamship building. Ships were built under the "open sky", clearly visible, so that designers and builders simply accepted that they could not hide their innovations and learned to live with the existence of local knowledge spillovers (Schwerin 2004, p. 90). Once built, any remaining secrets having to do with the ship's structural and performance details were further compromised by "their large size and travelling" and by the inter-project mobility of consultant engineers (Gilfillan 1935b, p. 76). This gave rise, not only to lots of exposure (outbound technical information), but also to many changes of plans in order to incorporate, within reason, the latest technical data (inbound technical information). For instance, intelligence on "summative evaluations" (appraisals of selection events) was of much importance to contemporaries dealing with technological and economic uncertainty. The contingent and cumulative aspects of steamship evolution are discussed in Chapter 3 (on the basis of the extant literature) and in Chapter 7 (on the basis of original archival research).

2.4 Technological communities

Age-old traditions of collective learning in shipbuilding

We have seen in Section 2.2 that large technological systems are too complex and potentially too varied to be explored at random: ship innovation is guided by a given technological paradigm and perfected through moving along particular trajectories of improvement. Section 2.3 suggests that individual ship projects embody the set of beliefs about the core features that are feasible and worth extending at any given point in the historical timeline. The question now becomes one of how exactly innovation-by-projects becomes cumulative. In particular, how do designers and engineers keep track of, make sense of and produce new syntheses out of the huge variety of empirical and theoretical lessons available? The present section contains the key ingredients for the discussion of the sources of steamship innovation available in Chapters 6 and 7. The issue of what collective learning mechanisms might have been at stake is the focus of the present section. A good starting point is to go back and assess what were the main knowledge governance structures before steamships emerged.

In the old days of wooden sailing ship construction, “ship designers” or master shipwrights lived, learned and plied their trade in the shipyard. In the absence of formal education, and just like in any other pre-modern industry, the “mysteries” of line drawing were kept tightly closed within families of artisans, primarily passed from father to son. Historical evidence shows, moreover, that collective structures offered a broader framework governing the transmission and circulation of ideas. Individual shipwrights belonged to guilds, which were among the earliest of the craft guilds and a relatively well paid one (Dougan 1975, p. 7; see also Lane 1934, 1973). Robert Davis (1991, pp. 3-5) shows how master craftsmen in the 13th and 14th century Venetian Arsenal combined the habits of individual independence with close-knit obligations like training apprentices and caring for elderly masters no longer in their prime.[33] Dutch shipbuilding in the 16th and 17th centuries overcame its inferior position by producing innovative types of vessels for its merchant marine.[34] The major technological breakthrough, the fast *fluitschip*, was the outcome of a form of collective experimentation by ship carpenters' guilds (Unger, 1978), where attendance at regular meetings was compulsory (Epstein and Park 2008, p. 18).

Moreover, and unlike other craft activities in which knowledge acquisition was solely through hands-on apprenticeship and face-to-face skill transmission, there was an early element of knowledge codification in shipbuilding. For example, in England the lines of a warship were set out on paper for the first time as early as 1586, containing enough details to enable a ship to be built, whereas the first textbook for English shipwrights was published in 1711 (Abbel 1948, p. 39 and p. 65) At that time, shipbuilding treatises were already established as the key methods for conveying time-tested design and construction rules within the small circles of naval administrators and master builders in almost every European maritime nation (Ferreiro 2007, p. 48).

In the 19th century, the challenges posed by new technologies of the industrial revolution were quite unlike those faced by ordinary shipyard workers for hundreds of

[33] "Arsenalotti" formed a special social category within the broader society and were self-conscious as a group. Their product, the galley, was the most visible output of what could be described as "the most anomalous state of Ancient Régime Europe": The Most Serene Republic of Venice (David 1991, p. 182). The city-state's navy dominated the Mediterranean during the 16th century, mainly through light-framed oared ships, capable of being built quickly and in large numbers. The Venetian Arsenal, the physical site where shipwrights worked, was arguably the first industrial cluster in early modern Europe.
[34] These vessels were inspired by the Iberian three-masted vessels, the dominant ocean ships of the period based on the pioneering Portuguese caravel, but adapted to the shallow Dutch coastal waters (de Vries and van der Woude 1997, p. 296).

years. At the same time, knowledge about steam power and iron structures was rare. Mechanical engineering and iron shipbuilding demanded more science-based knowledge and created a clear distinction between engineers and ordinary labour (Ville 1991, p. 80). The displacement of traditional shipwrights seems to have happened rather quickly. Between 1841 and 1851 the term "carpenter" appears to have been dropped from the list of occupations of the UK Census. Neal (1993, p. 131) suggests that the extinction of this label "may have reflected a recognition of the growing importance of iron." As Chapter 3 will show, iron shipbuilding was pioneered and mastered by a new generation of engineer builders and naval architects.[35] How did technical learning cope with the erosion of the old craft institutions and the unfolding of vast new technological possibilities? If imitation in shipbuilding was a common feature of the sector (see Chapter 3 and 6), and if imitation is costly due to bounded rationality and the difficulties in absorbing tacit knowledge, how was it carried out and even promoted (see Chapters 6 and 7)?

Professional communities in knowledge-intensive activities

In the period that concerns this thesis, the radical redesign of the steamship was carried out by individuals with scientific and technical backgrounds who were increasingly committed to free-lance inventive activities in the context of project-based businesses.[36] In this context, professional communities, as a social unit of analysis, may have had an

[35] This is in line with von Tunzelmann's (1995, p. 117) observation that "(s)ome of the most radical advances were first suggested by people from quite outside the industry concerned". That so many maritime historians and economic historians (e.g. Smith 1938, p. 95; Mitchell 1964, p. 112; Rowland 1970, p. 114; Slaven 1992, p. 3; Clarke 1997, p. 62; de Voogd 2007, p. 573) have noticed this for the early decades of steamship development is a strong indication of the occurrence of a major innovation is 19th British shipbuilding. The screw and iron steamship innovators came from the ranks of engineers, millwrights, mechanics, and others with no prior connection to shipbuilding. That these innovators did not come from the established wood-sail shipbuilders is evidence of a radical shift in the sector's knowledge base.

[36] Brunel, for instance, described himself as "consulting engineer" (from a letter dated 16 November 1854, with concerns the *Great Eastern* steamship; Brunel 1870, p. 314). The term appears free of the dishonourable and fanciful connotations of the older term "projector" or "schemer". It is employed with normative neutrality and in a seemingly very modern sense.

instrumental role in accelerating this design restructuring and the subsequent process of knowledge accumulation. More specifically, the radical innovations associated with shifts in a technological paradigm may be expected to be associated with the rise of new social structures supporting the transition to a new direction of learning. In Thomas Kuhn's original work (the original basis for "technological paradigm" concept in neo-Schumpeterian economics), there is a parallel between the structure of (scientific) revolutions and the emergence of new (scientific) communities. In the second edition of his book, and answering his critics, it is noteworthy that Kuhn adds a postscript that starts out by clarifying what he meant by "community".[37] In analogy with his definition, we may define a technological community as consisting of the practitioners of a technological speciality that mostly approach their subject matter from compatible viewpoints (Kuhn 1970, p. 178). Members of a community share a body of beliefs, i.e. a paradigm, and are bound together in their professional judgements by a full range of formal and informal communication processes (Kuhn 1970, pp. 178-99). In his articulation, a "scientific community" may exist even in a pre-paradigm phase. A paradigm shift and a transition to paradigm maturity both imply a reconstruction of group commitments and the crucial "exemplary" experiences (guiding solutions to further experiments) they share. Kuhn was writing at a time when the first empirical studies of the subject were being carried out, and he cites some of these under the label of "invisible colleges". We shall now describe this and other related concepts. As an early reviewer of this literature noted, although they referred to "pure knowledge", works such as Kuhn (1970), Price (1963) and Crane (1972) constitute valuable benchmarks "against which the more complicated processes of technological innovation may be compared." (Storer 1974, p. 139)

[37] He remarks: "If this book were being rewritten, it would therefore open with a discussion of the community structure of science" (Kuhn 1970, p. 176).

Varieties of communities

First used in the scientific revolution of the 17th and 18th centuries, the term "invisible college" was recast by Derek de Solla Price in his book *Little Science, Big Science* (1963). The term defines a cosmopolitan, relatively small and like-minded intellectual community. He referred to the informal networks of collaboration and communication that have always underpinned the scientific enterprise. Price (1965a, p. 515) concluded that scholars needed to draw upon the "totality of previous work" and, in order to stay at the research front, each researcher also needed "an alerting service that will keep him posted".[38] In other words, research depends both on consultation between peers and on access to the record of knowledge.[39] The modern scientific enterprise started from the onset as a collaborative venture undertaken by dispersed writers and readers of science in the context of the underdevelopment of formal academic institutions and print outlets.[40] It is important, however, to bear in mind that visible manifestations of this initially invisible collegial enterprise soon started to appear (see Box 2.1).

In the 1980s, the community framework received an additional stimulus, again from the field of social studies of science, with the book *The Manufacture of Knowledge* by Knorr-Cetina (1981). In this book, which Amin and Cohendet (2004, p. 75) credit with having introduced the term "epistemic community", the author closely monitored the day-to-day activities of a group of plant protein researchers. Set against the common

[38] The community transcended different languages and home countries and was structured around principles of cooperation, relying on the personal circulation of findings and reports to bridge distance and maintain the exchange of ideas (see Goodman 1991, p. 183).
[39] Incidentally, a twin term had also emerged in Ancién Regime Europe, the "Republic of Letters". The two labels refer, with changes of nuance, to collaborative ventures undertaken by dispersed writers and readers of science. Discoveries were initially communicated by such means among those who knew each other to be working on the same topics; this correspondence became the basis of contributions to journals, which began to spread in the second half of the 17th century (Ferreiro 2007, p. 54).
[40] The "invisible college" model was taken up from a sociological perspective by Diana Crane (1972). Her book was influenced by Kuhn and Price, but also by a growing literature on communication, social circles and innovation diffusion. Crane realised that high-producers or intellectual leaders were important in the social structure of scientific research in guiding the work of others and in recruiting fresh members. These central peer groups at the frontier of a given research segment are surrounded by successive rings of moderate, aspirant, transient and even defecting producers, all of them linked by academic connections.

representation of the small and dispersed specialist community delineated by a specific body of literature but with loose organisational integration mechanisms, she pointed to the laboratory group as the actual context of knowledge production. In a further articulation of this work, Knorr-Cetina (1982, pp. 122-3) proposed the name "transepistemic arenas of research" to emphasise that actual scientific work was continuously traversed by other calls having to do with non-research issues, like dealing with administrative staff, relationships with publishers, negotiations with grant agencies or signing of contracts with industry. The point is that knowledge production is also responsive to mundane calls and connections involving more pragmatic issues of resource allocation. Knorr-Cetina placed renewed emphasis on problem translations to non-specialist professionals and underlined the impregnation of everyday research activity by strategic goals. This discussion ties in with the contribution of Peter Haas (1992) a decade later, in which the concept of epistemic community is explicitly used and refined.[41] Under his definition, epistemic communities are groups or coalitions of recognised experts, who may come from a variety of professions but who share a set of normative values and pursue a common enterprise. Haas notes that in the face of scientific uncertainty, i.e. if confronted with conflicting data, these agenda-setting goals could still bind the community together. On the basis of evidence drawn from a number of cases, such as the depletion of the ozone layer or whale management, it was found that epistemic communities often framed the parameters of collective debate, "thereby influencing subsequent negotiations and bringing about their preferred outcomes to the exclusion of others" (Haas 1992, p. 5). In other words, the notion of an "epistemic community" points to aspects of political entrepreneurship that are involved in research-intensive activities and which shape the dynamics of policy-relevant knowledge production.

[41] The author roots the concept, which he noted was (and still is) defined in variety of ways, in the arena of "scientific community" studies and pointed out that it resembled the Kuhnian notion of a paradigm.

Box 2.1 The emergence of learned societies

With the Renaissance there were several attempts to establish learned societies in Italy between the 1560s and the 1660s. Each was later shut down for religious reasons. The Royal Society succeeded in being founded in London in 1660. Its stated goal was to promote investigation and experiments in natural philosophy. It operated under the protection of the Crown but received no financial backing from it.

The Royal Society was followed by the Académie des Sciences in Paris in 1666, and, until the French Revolution, by similar societies in Germany, Russia, Sweden, Denmark, the United States, Ireland, Portugal and Scotland. Such societies and academies reflected the fact that the accepted approach to any problem was increasingly seen as involving a strategy of enquiry, that is, observation, experiment and debate of ideas (Dickinson 1938, p. 3). These societies tended to have a "predominately fashionable dilettante membership of aristocrats and monied gentlemen with, but not always, an amateur's interest in the Sciences to the detriment of many scholars and the virtual exclusion of skilled craftsmen." (Clark 2007, pp. 11-2) There was, nevertheless, some real interaction going on in the societies and the outcome of their transactions was published in the form of papers and journals.

The subject of ships was an appreciable part of the agenda of these early learned societies. Most of this referred to naval architecture (see Ferreiro, 2007), but the topic of steam propulsion also surfaced from time to time (Clark 2007, p. 12).

At the time this body of work on epistemic communities was unfolding, another perspective was being developed drawing on the field of pedagogy and linguistics. The pioneering work of Lave and Wenger (1991) would make the largest impact on innovation studies and in debates concerning the production of useful knowledge.[42] According to Lave and Wenger, learning is socially mediated as it requires participation of the individual in a group of people engaged in the same activity. Drawing on ethnographic research, they show the community to be "an intrinsic condition for the existence of knowledge, not least because it provides the interpretative support necessary for making sense of its heritage." (Lave and Wenger 1991, p. 98)[43] Brown and Duguid (1991) redirected this emerging theory to the realm of the organisation of innovation and would be responsible for giving currency to "community of practice"

[42] In this approach, effective learning implies some form of belonging and participation, a notion encapsulated in terms such as "communities of practitioners" or "communities of knowledge". The contribution of Lave and Wenger is connected to a tradition of philosophy of practice, as articulated by Bourdieu (1977, p. 72), and its images of orchestras without conductors, that is, of structured contexts in which the ordered deployment of expertise takes place without obedience to any plan or hierarchy.

[43] The authors further argue that "*Knowing* is inherent in the growth and transformation of identities and it is located in relations among practitioners, their practice, the artefacts of that practice, and the social organization and political economy of communities of practice." (Lave and Wenger 1991, p. 122, emphasis in the original)

term. Learning comes to be seen as a distributed phenomenon happening continuously in contact with the environment, being about "interpretative sense-making, congruence finding and adaptation" (Brown and Duguid 1991, p. 53).[44] Learning thus conceived takes place in working communities which transcend organisational boundaries. Such communities have their own identity and shared knowledge repertoire, of which jargon is one indicator (Wenger 1998, p. 104). Interpretative communities are as much about absorbing know-how as they are about partnering and empathy (Duguid, 2008). All in all, the concept suggests that professional practice (shared experience with similar projects) shapes individuals' perspectives and values (Lam 2004, p. 125). Hence, the advance of knowledge goes hand-in-hand with knowledge sharing and accumulation activities, these in turn guide individual problem-solving and patterns of agent interaction.

The three knowledge governance structures – invisible colleges, epistemic communities and communities of practice – have much in common. One commonality is that the use of each of them is appropriated in many ways by many authors to address the phenomenon of communication among peers in knowledge-building activities.[45] The constructs also exhibit a rich array of differences so that, at the current point of conceptual development, it would be unfortunate to have to choose from among them. Each concept emphasises different aspects of collaboration and communication phenomena, which is a major focus of the present thesis. The diversity of the three definitions is tentatively captured in Table 2.4. The invisible college literature brings out the cross-spatial relationships among highly heterogeneous research-driven individuals (Price, 1963; Crane, 1972). The epistemic community point of view calls

[44] A point that would later be reinforced is that "knowing" is analytically separate from knowledge. What matters for innovation is not a stock of knowledge that is possessed, but rather knowledge that is practiced, located in material action (Cook and Brown, 1999; Amin and Cohendet 2004, p. 17; see also Amin and Roberts, 2008a).

[45] These concepts are sometimes rather under-defined and have not apparently been systematically compared and consolidated (for recent, but partial, attempts see Amin and Cohendet, 2004, and Amin and Roberts, 2008b).

attention to the pragmatic agenda of members of the reference group, who need resources and support to achieve their goals (Knorr-Cetina, 1981; Haas, 1992). Finally, the community of practice perspective suggests that knowing is an activity of particular groups in specific circumstances (Lave and Wenger, 1991; Brown and Duguid, 1991).

Table 2.4 Contrasting conceptions of knowledge-based communities

	Invisible colleges	***Epistemic communities***	***Communities of practice***
Main activity	Deliberate exploration	Deliberate exploitation	Exploration as a by product
Source of learning	"Off-line" development	Policy-oriented	"On-line" development
Retention of repertoires	High memory	Medium memory	Low memory
Internal structure	Informal and formal structure	Semi-formal structure	Informal structure

Source: the author of this thesis, on the basis of literature review

The fundamental commonality in these frameworks of interaction is that they involve collaborative learning, thus providing a richer techno-economic environment for innovative individuals and helping them to overcome the problems of uncertainty and bounded rationality (Dodgson 2007, p. 196). These three types of communal behaviour and institutions constitute examples of a supportive "soft infrastructure" for learning (cf. Cohendet and Amin 2006, p. 311). Indeed, collaboration and imitation practises that follow the principles of "open science" have been found to be key ingredients for knowledge sharing and accumulation in the realm of technology (see Foray and Hilaire Perez, 2006, for a discussion and a list of case histories). The glue is not just one of a compatible and shared ethos; such behaviour makes sense in the long-run as a knowledge-building strategy (Powell and Giannella 2010, p. 596; Foray and Hilaire Perez 2006, p. 249). When great technological opportunities lie before them, the private interests of participants are better safeguarded since they are less likely to be left behind.

The role of technological communities in complex knowledge-intensive projects

Communities typically are the answers to the difficulties of learning. We will refer to such communities as networks of practicing engineers, individuals brought together by a joint conceptual enterprise (say, the steamship), in which sharing and learning are mutually constitutive (the borrowing of new ideas and the growth of knowledge reinforce each other). Innovation studies have found many such collective entities to be a driver of technological learning. Stankiewicz (2000, p. 234) lists a few examples of evolutionary accounts of technological change where "technological communities" (his generic term) were found to exist. He specifically points to the work of the historians Walter Vincenti (1990, 2000) and Edward Constant (1980, 2000), both partly indebted to Kuhn, and both well known for studying the design of large structures, complex machines, and heavy engineering systems such as iron bridges, high-speed aircraft, axial-flow air compressors and industrial gas turbines. The need to learn provides motives for cooperation. Shared knowledge is commercially valuable but tacit, experience-specific, not easily replicable requiring values of trust and interpersonal reciprocity, and characterised by dense and continuing communication practices (Dodgson 2007, p. 198). Stankiewicz (2000, p. 246) notes that the increasing complexity and sophistication of technological challenges "demands corresponding development in the social infrastructures supporting them." In a word, innovation in social structures is closely correlated with technological evolution. This means that in our case study we expect technological learning to have had an institutional underpinning, especially in a context of project-based activities and complex engineering systems undergoing radical change.

In project-based activities the acquisition of experience is technically risky: understanding is acquired with an element of real-time experimentation in full-scale circumstances; “learning itself is improvised practice” (Lave and Wenger 1991, p. 93). Experience is economically costly: mistakes leading to breakdowns in the expensive capital goods can have dire terminal and even fatal consequences, especially on the high seas. Experience can also be highly equivocal and individual interpretation alone is hardly sufficient for effective learning. Something supra-individual must be at stake in order to harness the learning potential of an increasing population of ship projects. van de Ven *et al*. (1999, p. 14), for instance, refer to “collegial relationships among peers”, i.e. those knowledge-seeking individuals and experts committed to a project or a common innovation agenda. Prencipe and Tell (2001, p. 1376) found, from a number of case studies, that knowers avoid losing the collective accumulated experience through “the creation of a memory external to individuals”, that is, through collective activities that draw upon the tacit knowledge obtained in experiments and transform it into codified knowledge.

In complex systems of interconnected technologies, the end-result of localised innovation in given components of the artefact is highly uncertain due to the non-linear relationships between the various components. Upheaval in the configuration should not be expected frequently as the engineering system generally grows within the possibilities of the paradigm (the core elements of a product remaining relatively fixed for a prolonged time). This growth trajectory or momentum is facilitated and reinforced by the enlisting of increasing numbers of engineers and supporting institutions, among which are professional societies (Hughes 1983, p. 15) The transformation of the situated, individual experience into generic, common knowledge requires the integration of “communally shared previous solutions” (Constant 1994 p. 449). On the other hand, radical change is exceptional and infrequent by definition but, perhaps, unavoidable in the life history of complex artefacts. The scaling up of large assembled products cannot go on indefinitely without running into decreasing returns and hence requiring a major shift in design. According to Sahal (1985, quoted in Frenken 2006, p. 52), this is due to the “well-known observation that change in size of an object beyond a certain point requires changes in its form and structure as well.”[46] Design re-configurations above certain scale thresholds are uncertain and costly. Meeting the challenge of radical re-design places a great strain on the agents’ knowledge repertoires. In other words, incremental learning along a particular trajectory is a communication-laden activity, but revolutionary change seems to be even more so (Kuhn 1970, p.7).

Historically speaking, technical change has often been a collaborative enterprise, especially where capital goods were concerned (Rosenberg, 1976, 1982). This includes Britain during its pioneering industrialisation process (Allen 2009, p. 150). Allen (1983) and Nuvolari (2004a, 2004b) have respectively found such a cooperative approach to innovation in the iron industry of Cleveland during 1850-75 and in the mines of Cornwall over the period 1810-1850. They found that innovative producers freely released technical and economic information to competitors concerning design and performance details of the technologies they had just introduced (Allen 2009, p. 150; Nuvolari 2004b, p. 97). In their analysis of this behaviour, the process by which inventors learn openly from each other is labelled “collective invention”. In taking stock of this research, Powell and Giannella (2010, p. 578) have defined the notion in the following way: “Collective invention is technological advance driven by knowledge sharing among a community of inventors who are often employed by organizations with competing intellectual property interests.” This definition highlights the dual tension between community and sharing, on the one hand, *and* competition and patenting, on the other. On the one hand, as Dodgson (2007, p. 194), has pointed out, it is not uncommon that very dynamic and competitive industries (i.e. sectors undergoing rapid

[46] This was certainly felt in the construction of large steamships as the “sheer size of the ship also meant that relatively familiar components would be extraordinarily large, would involve unfamiliar stresses” (Arnold 2000, p. 55).

technical change) are more collaboration-intensive. On the other hand, knowledge sharing may have prevailed over direct appropriability through patents in certain institutional settings during the British industrial revolution, even though some inventors tried to protect their contributions (Nuvolari 2004b, p. 118; Allen 2009, p. 164).[47]

The nurturing of technological conversations and the rise of the modern steamer

How can these theories and stylised facts be applied to the steamship case study? The empirical findings discussed in Part III of this thesis provide a tentative answer. In Chapter 6 it is shown that patenting was not a predominant strategy among innovators. Innovative and influential marine engineers and naval architects often demonstrated an outright hostility toward patented inventions and most declined to protect patentable designs. On the contrary, engineers were aware of the benefits of knowledge spillovers. Chapter 7 reveals that there were a number of novel collaborative behaviours and institutional arrangements promoting knowledge sharing of the latest information concerning new steamer technology, analysing events involving innovative ship projects, and establishing a common understanding of what was considered "good practice" in construction. If the increasing numbers of steamships built provided a great deal of experimentation with individual ships (i.e. a mechanism of variation), this "soft infrastructure" transformed it into collective experience that could be freely drawn upon for further progress (i.e. selective retention).

[47] Nuvolari (2004b, p. 117) stresses that Allen's (1983) notion of collective invention is distinct from other processes of technology exchange. According to Nuvolari (2004, p. 117), collective invention describes sharing among producers of technology, not between users and producers (see Lundvall, 1992). The phenomenon also differs from von Hippel's (1988) "know-how trading" as this only refers to bilateral exchanges between engineers, while in collective invention all actors, even non-participant inventors and competing firms, have access to potentially proprietary information. For collective invention to take place, three conditions have to be met: *a*) a high-rate of investment, since new experiments effectively represent a form of R&D that reduces the need of resources explicitly devoted at innovation; *b*) technical change is mostly driven by incremental innovation, i.e. micro-inventions; and, *c*) new technology is not normally patented, and instead inventors engage in "voluntary knowledge spillovers" (Nuvolari 2004b, p. 97; see also Allen 2009, p. 150, Powell and Giannella 2010, p. 578).

Iron-screw steamer innovators hardly worked in isolation or responded solely to individual incentives. Technology practitioners engaged in steamship innovation were organised around a new set of inclusive (quasi-academic) engineering societies that were characterised by a specific combination of the modes of knowledge governance illustrated in Table 2.4 above. First, like “invisible colleges”, the community of engineers invested in strong memory (through the production of written records of their interactions and the accumulation of valuable knowledge in the institutions’ libraries) and organised themselves for the deliberate exploration of the new opportunities through “off-line” discussions (presenting papers to each other and debating them). Second, these marine engineers and naval architects constituted a kind of “epistemic community” in as much as they consciously created institutions to pursue their common interests in innovative iron-hulled screw-propelled steamship design, i.e. these individuals forged a collective identity and pursued a conscious technological agenda. Finally, their common ground was derived from being a “community of practice”, a group of individuals that acquired first-hand expertise from direct engagement with steamship design, building, and consultancy.

We examine three overlapping platforms of technological learning and knowledge sharing: engineering societies (in particular, the Institution of Civil Engineers), the technological press (more specifically, the *Mechanics’ Magazine*), and a non-governmental/not-for-profit organisation for ship classification (namely, Lloyd’s Register). This idiosyncratic combination of institutions, which constitute a relatively little studied part of the British system of innovation, preceded the transformation of shipbuilding into a modern high-tech industry. The evidence uncovered shows these developments to be causally implicated in the critical breakthroughs (specifically, they are associated with pioneering irons hip design and the refinement of screw-propulsion) and in the promotion of their integration in a new paradigmatic design (i.e. the modern ship). This evidence, that points to something akin a set of collegial-like structures emerging as a knowledge infrastructure in the most crucial years steamship industry, constitutes the bulk of the new qualitative empirical studied in this thesis. [48] Our argument will be that such structures were a peculiar feature of the British national system of innovation that had a crucial bearing on the shipbuilding industry in times of technological transition to the modern, iron-built, screw-driven mechanised vessel. In our case study we believe an open ongoing technological "conversation" influenced the process of problem-solving and the subsequent evolution of the shipbuilding industry.

2.5 Conclusions

One of the greatest developments in 19th century engineering was the modern ship, which brought together a number of innovations into a single machine. This chapter has discussed three main conceptual issues in the field of innovation studies literature that may guide our analysis of steamship innovation and the factors behind it. These theoretical premises guide the search for empirical data concerning the structural changes in British sea transport during the early Victorian times. This is a study of a particular historical innovation that explicitly deploys the neo-Schumpeterian or evolutionary angle of analysis. Notwithstanding, we are also sensitive to the concern that theory may pile up excessively at the expense of plain historical narrative (Buchanan, 1991). What we try to do here is an "historical reconnaissance mission", to

[48] As a source of innovation this institutional setting has indeed many similarities with the notion of "collective invention". Innovations were driven by the actual building of many new projects. Innovations were disclosed through informal channels (like visits to competitors' steamers) rather than passed on or closed down via patents. However, there are important differences. In the context of this thesis the prime importance of this ensemble of institutions was on the overhaul of the core elements of the steamer (i.e. iron and screw) and in the establishment of a new architecture linking those elements (i.e. the iron-screw configuration). In other words, they were involved in bringing about a radical innovation that redefined the merchant ship and established the paradigm of the modern ship. The foundation of formal sites of learning (engineering societies and scientific-like gentlemen clubs), formal publications (institutions' transactions, technical press), and the role of independent institutions fostering the public good (ship quality control) has a more prominent role in our account.

use Rosenberg's (1976, p. 108) felicitous phrase, using the mainstream tools of innovation studies.

This chapter began by stressing, in Section 2.2, the value of adopting a neo-Schumpeterian or evolutionary view of technological change. We presented categories of innovation and reviewed the notions of technological paradigm and affiliated concepts that have proved useful in field of the economics of innovation. The perspective that these concepts imply is one of relatively long periods of stability of incremental change within established templates that are punctuated by occasional radical changes (i.e. the emergence of a new dominant design). We paid particular attention to how this view is applied to the case of large, complex technological systems that are adapted to perform specific services in different economic environments. Consensus configurations concerning multi-attribute/multi-technology capital goods emerge through complicated historical processes. In the context of our thesis, the way steamships moved from a wooden-paddle to an iron-screw architecture between the 1830s and 1840s is the case in point. The insights of Section 2.2 will be useful to engage with the material ahead, namely the history of the steamship in Chapter 3, the secular trends characterising the growth of the British steamship merchant fleet in Chapter 4, and the in-depth analysis of the mid-century changes of steamship technology in Chapter 5.

Each ship is a project, as Section 2.3 argued, and hence an actualisation of an evolving concept of the steamship. Design evolves from steamer to steamer in historical time, even if sometimes only slightly. Projects are situated at the intersection between the state of the art (experience, memory) and innovation (experimentation, variation). Knowledge is recombined in rarely-to-be-repeated circumstances, thereby injecting an element of historicity into our analysis. Ship projects were very public affairs and hence the source of many spillovers. The time-bound nature of projects makes them insecure sites of cumulative learning in the formative years of a new technological approach to ship design. It is possible, however, that with the help of an appropriate social infrastructure, learning *within* projects can be transformed into learning *across* projects. Emphasising the institutional context of ship projects offers a way to relate technical change to the development of the broader social organisation in which learning takes place. The concepts surveyed in Section 2.3 will be especially useful to understand Chapters 3, 6, and 7.

Section 2.4 discussed how technological change can be related to changes in the social infrastructure underpinning it. Relationships and interactions between the producers of new knowledge allow the sharing of up-to-date experiments and the capitalisation on past experiences. Communal settings of knowledge exchange (referred to as “invisible colleges”, “epistemic communities”, and “communities of practice”) are usually involved in the process of transforming hard-won individual lessons into collective repertoires. Reviewing the several streams of scholarship on technological collaboration makes us more aware of the specific set of productive and institutional circumstances surrounding the rise of the modern steamer. The theoretical work described in Section 2.4 will be especially useful in the context of Chapter 7.

3. Historical background: Origins and evolution of the modern ship

3.1 Introduction

The application of steam as motive power to river and sea transport went through an extended gestation period. It took about two centuries to move from the first ideas, sketches and proposals of steam-propulsion to the first trials. Even then, trying out working configurations of motive power, paddle-wheels and hull design was a long drawn-out affair. After a number of experiments with prototypes, mostly in France in the late 1700s, the effective economic debut of the steamboat came with Fulton in 1807 in America. This year can be taken to denote the passage from “invention” to “innovation” or, in other words, this was the moment of the shift from the experimental phase to the commercial development phase in steam navigation. Thus, when the *Comet* is launched in Scotland in 1812 we have the first clear step in the international “diffusion” of steam-vessels beyond North America. Britain soon took the lead in terms of both technical change and new uses given to steamships. The steamer changed in shape and function as the small short-range estuarial steamboat of the early 1800s grew into the large multi-purpose open-seas vehicle that by the early 1900s had succeeded in displacing sail in virtually all maritime trades. During this time the steamer fundamentally changed. What were these differences? Why did they matter?

This chapter surveys the available historical literature on the evolution of steamship technology. The rather scattered nature of this literature has previously been something of a constraint to any attempt to consolidate aspects of steamship innovation into an overall view; one objective here is therefore to provide a more integrated account of past research. On the basis of the theoretical framework presented in Chapter 2, we interpret these secondary sources in the light of a central conceptual tool: the establishment of a “technological paradigm” in the process of “variety generation” and “selective retention” in steamship design. The re-examination of the history of steamers, their technologies and trades involves three tasks which are carried out in the following Sections: *a*) describing how the steamer was pushed to its limits within the classic wood-paddle layout; *b*) detailing the major improvements in the technological system that coalesced in the mid-19th century; and *c*) outlining how these emerging qualities expanded the range of economic applications of this capital good as time went by.

The examination of secondary sources reveals a long-run process of continuous and relentless improvement and refinement of steamers but also a significant breakthrough: the transformation of the steamer from a small, slow and often dangerous wooden-paddler of limited capabilities into a large, safe and efficient metal-made screw-driven vessel with a huge potential for serving both old and new markets. By the 1850s the key features of the modern mechanised merchant ship were established in a way that closely resembles the neo-Schumpeterian frame of analysis put forward in Chapter 2 (Section 2.2). The insights gathered from the available maritime and technology historiographic literature provide a foundation to Part II of this thesis: insights on technological trends and turning points will be measured and tested in Chapter 4 (which focuses on the growth trajectory in the population and average size of steamers) and Chapter 5 (where structural design of steamers is set against their commercial exploitation in an ever widening set of services). The present chapter also motivates Part III in the following way: it assembles the first indications that individual incentives to invention (further investigated in Chapter 6) may have been less decisive in driving innovation than mechanisms of knowledge circulation and sharing (as described in Chapter 7).

The chapter is organised as follows. Section 3.2 focuses on the early days of the steamboat and follows steamers' emancipation from their initial activities in short-distance services to their deployment in longer-distance trading. Section 3.3 takes an "internalistic" perspective by breaking down the steamer into its key constituent parts (the engine, the driving mechanism on the water, and the hull material). Section 3.4 explores a variety of steamer types according to their functions: ferries, tugs, packets and cargo steamers. Section 3.5 summarises the main conclusions to emerge from this chapter.

3.2 From fresh water to blue ocean

Early pioneers

The first specific proposal, as opposed to early vague suggestions, for the application of steam to locomotion was concerned with water transport (cf., Eco and Zorzoli 1962, p. 204).[1] Britain was not particularly distinguished by the contribution of its early inventors. There were claims by English "projectors" as early as 1618 but, as Woodcroft (1848, p. 11) noted, no single proposal proved to be particularly consequential. In contrast, the French were pushing the technological frontier (Derry and Williams 1960, p. 327). A key initial step was taken by Denis Papin (1647-1712?), a natural philosopher who moved in European scientific circles. He conducted experiments, reported to the Royal Society, and wrote several articles and pamphlets (McConnell, 2004b). In one of these papers he made the first distinctive proposal for steam to move a piston and turn revolving paddle-wheels fitted in a boat (Spratt 1958, p. 23). Thus, the year of this publication, 1690, marks the year in which a steamboat was "surely planned" although "never built" (Gilfillan 1935b, p. 74). As Spratt (1958, p. 24) declares, the "mental conception was there in all its mechanical detail" so that Papin has a claim to be

[1] The origins of the steamboat are indistinct and difficult to trace. It should be kept in mind how hard it is to reconstitute the history of these early attempts: "many were an idea, tried, failed or abandoned, others were built, tried, amended and altered, most of these changes related to the engine and propulsion method and to a lesser extent the hull." (Clark 2007, p. 9)

considered an early inventor of steam navigation. From this point forward, it “was well afloat that some novel contraption could and should be thought up, to supplement the immemorial sail and oar, especially on rivers.” (Gilfillan 1935b, p. 74)

The first actual attempt to move a boat by steam was made in France in 1775 – a moment that for Spratt (1958) establishes a transition from “inventive aspirations” to a period of “experimental steamboats”. This experiment was led by Jacques Constantin Périer (1742-1818), but it was a failure (Preble 1883, p. 10; Spratt 1958, p. 35). It was left to the Marquis Claude de Jouffroy d’Abbans (1751-1832) to conduct the first successful trial in steamboat propulsion in 1783. The first attempt to introduce a steamboat into operational service took place on the Delaware river, in the United States in 1790, with John Fitch (1743-1798). But this was a frustrating experiment; the boat lost money on every trip and the venture soon came to an end (Boumphrey 1933, p. 78; Thurston 1878, p. 240; for a detailed account see Sutcliffe, 2004). The most important early experiments in Britain were led by William Symington (1764-1831), who in 1801 was working on a steamboat called *Charllotte Dundas* on the Forth and Clyde Canal (Beare 2004, p. 586; Spratt 1958, p. 62). Another steamboat, confusingly also called *Charllotte Dundas*, was publicly demonstrated in 1803, showing it could tow barges against an unfavourable wind. The (second) *Charlotte Dundas* is generally considered to have been the “first practical steam boat” (Woodcroft 1848, p. 53; see also Thurston 1878, p. 247; Dollar 1931, p. 17). However, the steamboat lost the confidence of the Forth and Clyde Navigation Company, being deemed harmful to the integrity of the canal because of the waves it generated, and it was never deployed for routine work.[2] The next key achievement in steam navigation would yet again take place outside Britain.

[2] Back in America John Stevens (1749-1838) tried out the *Little Juliana* in 1804, which represented the first successful use of a screw-propeller (Clark 2007, p. 140).

Steam travel on water was a first great example of American technological ingenuity; it preceded the large scale adoption of steam on land by almost half a century (cf. Allen 2009, p. 180; Hunter 1949). Robert Fulton (1765-1815) achieved immediate economic success with the *Clermont*[3] on the Hudson river in August 1807 (Figure 3.1). This arguably constitutes the definitive transition of prototype steamboats into commercial steam navigation. The steamer was named after the residence of her other owner, the well-connected Chancellor Robert Livingstone, who had been granted the exclusive privilege (a "patent") of steam navigation in the state for a period of twenty years (Woodcroft 1848, p. 61; Dear and Kemp, 2007). Gilfillan (1935b, p. 93), however, surveys a number of commentators to argue that no parts of Fulton's vessel were novel in themselves. Fulton was particularly good at improving what others had attempted before (Cain 2010, p. 339).[4] But Fulton was even better at networking, "having the ability to contact and gain the help of people of wealth and influence, and *by choosing the Hudson River, and getting a patent on it*." (Gilfillan 1935b, p. 98, emphasis in the original)[5] Hence, Fulton was the first to "strike the happy combination of forces" that enabled him to demonstrate the profitability of the steamer (Morrison 1903, p. 3). In this sense he was an exemplar of the Schumpeterian entrepreneur (Lamoureaux 2008, p. 415). From 1815 to 1860 this innovation contributed to transform the western river system into a vibrant and integrated agricultural hinterland (Lilley 1976, p. 210; Cain 2010, p. 340).[6] This, however, was the greatest impact of the steamer in America during

[3] Although the vessel came to be known as the *Clermont*, it was originally called *North River Steam Boat* (Cain 2010, p. 339).

[4] Clearly the concept of a steamboat was not of his independent making (Timmons 2005, p. 12). As Clark (2010, p. 7) puts it: "The appellation of inventor is however inapplicable to any single individual in respect of steamboats, the concept of steam powered vessels evolved over many years, Symington and Fulton merely brought the idea to fruition."

[5] Not being a pioneering inventor, he succeeded by finding a partner who provided adequate financial support and the means to secure market control.

[6] As a young country lacking a developed road system, the steamboat redefined inland (up-river) navigation in North America (Harvey 2007, p. 1). Fulton's success generated interest in the US and Canada (Clark 2007, p. 153). This was in spite of many shortcomings of the early American river steamboats. These were risky and expensive investments; their boilers could often explode and their average working life was no more than five or six years (Cain 2010, p. 340).

the main period covered by this thesis (1810s-1860s). Sea services, even along the coast, remained largely underdeveloped for many decades (see Still *et al*., 1993).

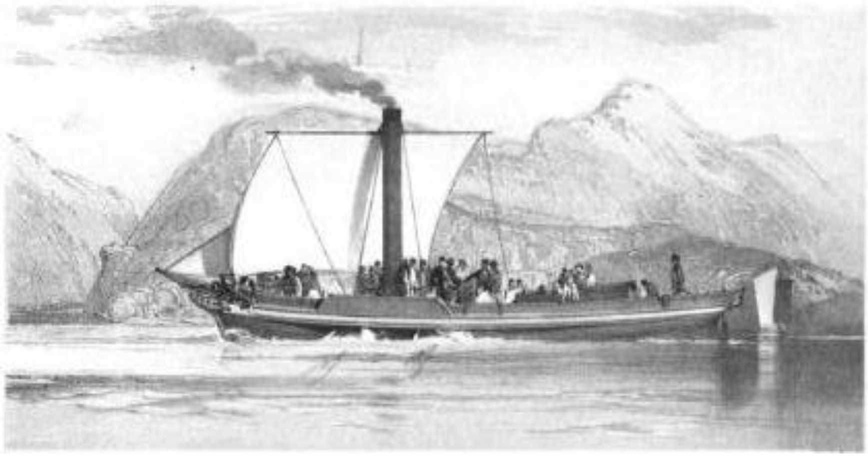
Figure 3.1 The *Clermont*, presumably in 1808 after having been rebuilt

Source: Woodcroft (1848, facing p. 60)

Early steamboats in Britain

The next steamboat to enter into commercial service elsewhere was launched in 1812; by then 50 steamboats were already running in America (Gilfillan 1935b, p. 100). Henry Bell's (1767-1830) *Comet* is generally acknowledged to be the first steamboat to operate in Europe for the remuneration of her owner. The hull was built by John Wood (1788-?) of Port Glasgow, at the centre of which was positioned the engine and boiler, on opposite sides of the boat. At that time Bell was a frequent visitor to the Camlachie foundry of David Napier (1790-1869), who became the builder of the boilers (Burton 1994, p. 67; Moss, 2004b). The engine, built by a Glasgow engineer named John Robertson, had a small "side-lever" as it was initially intended as the engine for a particular factory whose owners did not want the expensive supporting structure normally associated with the conventional Boulton & Watt (Moss and Hume 1977, p. 4 and p. 36). As can be seen in Figure 3.2, the boat's funnel also served to drape a sail. She plied the Clyde, much to the anger of flyboat and coach proprietors, but never really prospered commercially. Notwithstanding, pioneering British steamboat projects such as the *Comet* were important for the early accumulation of expertise: John Wood and David Napier would move on to become influential steamship players and the side-lever engine became the *de facto* standard in marine propulsion.[7]

Figure 3.2 Henry Bell's *Comet*, 1812



Source: Woodcroft (1848, facing p. 82)

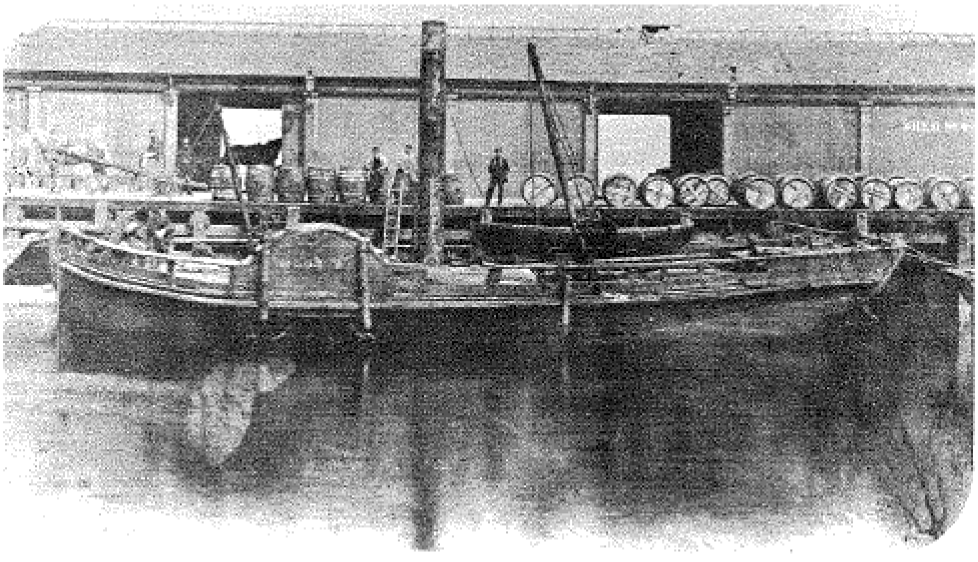
Economically speaking, and as Slaven (1992, p. 1) puts it, "the *Comet* in 1812 was the first successful demonstration of the commercial potential of steam power in vessels in Britain." The vessel was indeed able to answer callings and was gradually sent to make longer passages (Parker and Frank 1928, p. 79). Her example "soon excited competition" (Preble 1883, p. 85). The new vessels adhered to the *Comet's* design framework. For instance, the second steamer on the Clyde, and the *Comet*'s first competitor, was the *Elisabeth*. Launched in November 1812 she started to carry passengers in March 1813. She was built by a Glasgow engineer named Thomson, who had worked with Bell in 1811 in a series of experiments with a small boat carrying paddles moved by hand-labour (McQueen 1924, p. 15). James Cook built her engine, considered the first true marine engine, following the side-lever approach, and moved on to make another 12 engines of the kind (Moss and Hume 1977, p. 36). More

[7] In an account of steam navigation, John Scott Russell asserted: "We believe that from the year 1818 until about 1830 David Napier effected more for the improvement of steam navigation than any other man. (…) It is to Mr David Napier that Great Britain owes the establishment of deep-sea communication by steam vessels and of Post Office Steam Packets" (cited in Moss 2004d, p. 163).

steamers followed along this model and in a short time more steamers were active in Britain than in North America (Dollar 1931, p. 38; Clark 2007, p. 153).

By 1814 there were nine or ten steamboats built or being completed on the Clyde estuary (Harvey and Downs-Rose 1980, p. 146; Williamson 1904, p. 23). One of these would become one the most enduring steamboats ever launched (see Figure 3.3). Built in 1814 and grossing 83 tons, the *Industry* had the form of a small sail ship and was intended for carrying goods and passengers (Thomas 1983, p. 12; Corporation of Glasgow 1912, p. 29). She also increased her usefulness by towing barges, making her one of the earliest tugs. She had a strongly-built wooden hull, measuring 68.3 ft in length and 18.5 ft wide, which would keep her in service until 1862, when she went down after a collision; by then she was a well known vessel and the oldest working steamer afloat.[8]

Figure 3.3 The paddle steamer *Industry*, built for the passenger trade, operated as a cargo vessel and then as a tug, here depicted at the end of her days



Source: Hume and Moss (1975, p. 26)

[8] Remaining in business for almost sixty years, she went through various extensive repairs and overhauls (McQueen 1924, p. 19). As a testimony to her sturdiness, her remains were still visible in 1924 in Bowling Harbour (Hume and Moss 1975, p. 26).

From boats to ships - the first taste of salt water

Vessels like the *Industry* illustrated to contemporaries just how flexible and robust wooden-paddle steamers were in spite of being considerably expensive.[9] From the outset, the combination of a wooden hull, side paddle-wheels and side-lever engines represented the "technological paradigm" or generally accepted model solution to the design challenges encountered (cf. Chapter 2, Section 2.2). The Clyde's lead in steamboat building and steamboat operation was quickly followed on other rivers. In 1814 the first steamboat was completed on the Tyne, the *Tyne Steam Packet*, later renamed *Perseverance*, which began transporting passengers between Newcastle and South Shields (Dougan, 1968). By 1820 only the Wear had not built its own local version of the steamer (Slaven 1992, p.2). A number of these vessels were later sold and went on to pioneer steamboat services in many European countries, particularly in France, now a net importer of the technology (Armstrong and Williams 2010, p. 45).[10] In 1818 Lloyd's Register, the first modern classification society, had surveyed and declared fit its first steamer, the *Woodford* (Watson 2010, p. 124). As confidence grew, more vessels started to be employed on rivers, canals and lakes; and, given Britain's insular position, they were soon operating beyond them.[11] Steam was starting to be

[9] The relative costs of early steamers *vis-a-vis* sailing ships are difficult to estimate (Armstrong and Williams 2010, p. 54). Besides the extra cost of the machinery, hulls had to be made stronger to accommodate the weight of the engine and the room needed by the paddle mechanism. Building costs were further augmented in the case of steam packets due to the additional expense of fitting out the vessel for passenger service. Early steamers could be between three and four times as expensive as sailing packets of comparable sizes (Hughes and Ritter 1958, p. 370).

[10] An example was the *Margery*, a paddle steamer launched in June 1814 by William Denny & Bros and engined by James Cook of Tradeston, the renowned Glasgow engineer of the *Elisabeth* (Moss and Hume 1977, p. 88; Mackinn 1921, p. 95; Spratt 1958, pp. 92-4). A steamer with a round bluff bow typical of the time, she measured 73 ft in length, breadth of hull 12 ft, 19.5 ft over the paddle boxes, depth 5.5 ft, and was propelled by machinery of 10 nominal hp, the same power fitted to the *Industry*. She ran for a short time on the Clyde but she was sold and driven down by sail (with the funnel serving as mast) along the East Coast to London. The *Margery* became the "first steam packet on the Thames", entering service on January 23, 1815. Later in the same year, four other steamers were already operating on the Thames (Braynard 1963, p. 12). In March 1826 the *Margery* was sold to French owners, renamed *Élise* and refitted for the trade on the Seine, where she never enjoyed commercial success.

[11] A good example is the *Rob Roy*, the steamer that inaugurated open sea steam traffic communication between England and Ireland, namely between Broomielaw on the Clyde and Belfast (Duckworth and Langmuir 1939, p. 113). This ship was the first to break away from the safety of the smooth waters of

applied to transport along coastal waters and across channels and narrow seas (Heaton 1960, p. 35). It is around this time that the first steamers start making longer passages, sometimes because they were sold abroad.[12] During the 1820s, the obvious short-distance routes were becoming saturated in and around Britain (Brock and Greenhill 1973, p. 13). Steamers were not short of employment and business rapidly extended to cross-channel routes (for instance, a steam service was in operation between England and France as early as 1816, according to Kemp 1978, p. 149). Many steamboat-operating companies became active in this initial period, and the extension of steam navigation to open waters was encouraged by the dense social and economic links between the Northwest of Britain and Ireland.[13] In this period, terms like "steam boat" and "steam yacht" were common, but the term "steam packet" also started to gain currency (Armstrong and Williams 2010, p. 43). By 1827, that is, only 15 years after the *Comet*, there were no less than 225 steamers under British registration (Brock and Greenhill 1973, p. 9, citing Robin Craig, personal communication). In other words, the steamship industry was flourishing; more and more ships were being produced for an even greater variety of operational settings.

Early steamers, such as the *Industry* or the *Rob Roy*, followed conventional sailing ship lines (Abbel 1943, p. 110; Clark 2007, p. 153; see also Craig 1980a, p. 31). But this was soon found to be disadvantageous: steamers gradually evolved their own form (Deeson

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rivers and canals and, thus, in the words of her owner and engine builder, "established steam navigation in the open sea" (Napier 1839, p. 2). She was a boat built by William Denny of Dumbarton to the order and design of David Napier, who also cast her engine. The boat's hull exhibited a wedge-shaped bow and had machinery designed to overcome the relatively more challenging waters of the Channel crossing. She had a successful career starting on the Glasgow-Belfast route, but after two years she was transferred in 1823 to the English Channel to operate as a packet on the Dover-Calais service for the French government (Preble 1883, pp. 116-7; Armstrong and Williams 2010, p. 59).

[12] The very first steamer to be exported was a wooden paddler called *Conde de Palmella*. In 1820 she travelled from Liverpool to Lisbon to ferry on the Tagus (Greenhill 1993b, p. 15). That she completed such a voyage is evidence that steamers were withstanding longer journeys (Woodman 1997, p. 178). In 1825 she plied all days of the week except for Sundays (*Gazeta de Lisboa*, Vol. 30, 4 February 1825, p. 119).

[13] Among the earliest ones were the Glasgow Castles Packet Company in 1814, the Laird Line in 1814, and the Glasgow and Londonderry Steam Packet Company in 1815 (Rowland 1970, p. 59). By the early 1820s, Leith and Aberdeen as well Glasgow and Liverpool, were connected by steam, and from the latter port regular steamers also reached the Isle of Man, Belfast, Dublin and Whitehaven (Maber 1980, p. 5).

1976, p. 55). Work as early as 1818 by David Napier reportedly involved testing in specially built water tanks, and this has been credited with influencing the introduction of finer lines (Williamson 1904, p. 95; Dollar 1931, p. 40; Rowland 1970, p. 52). For instance, it was important for the efficiency of the paddle-wheels that the hull was less prone to heeling. Gradually the bow thinned down in steamboats, while the stern became less stumpy and the hull became less square amidships. In the *James Watt* of 1821, to take one concrete example, the builders abandoned the "cod's head" and "mackerel tail" design typically used in sailing ships to accommodate the force of masts and sails on the bow, and instead introduced a hull that was symmetric in the middle section of the ship (Moss and Hume 1977, p. 87). This was an important and well studied innovative steamer, as it was the largest steam vessel of this early period and one of the earliest steamers to figure in Lloyd's Register books, being classed as A1 in 1823 (Blake 1960, p. 37; Jones 2000, p. 20; Watson 2010, p. 124).[14] It is also worth noting this trend toward the production of larger steamships in larger numbers for a widening range of environments. The persistent line of improvement in a given performance attribute of a technological system – i.e. the increasing growth in size – can be theoretically recognised as a "technological trajectory". These improvements were cumulative, suggesting learning progressed step-by-step, or project-by-project in the terminology introduced in Chapter 2. This is in line with the interpretation suggested by Palmer (1978): the process of continuous feedback between new experimentation and growing experience constituted a key factor shaping early steamship evolution.

The steamship comes of age

Spratt (1951) presents a useful periodisation of the progress of steam over the Atlantic during these years. He divides this progress into three periods: "Spasmodic pioneers"

[14] She was 141 ft in length and had a total width of 47 ft over her paddle-boxes, she operated on the coast between London and Leith (Kemp 1978, p. 149). She was driven by a Boulton & Watt engine of 100 hp with two cylinders, and her hull was built by John and Charles Wood of Port Glasgow, the same experienced builder of the *Comet* and many other early steamers.

(1819-1837), the advent of “Sustained steam power” (1838-1839), and “Atlantic paddle ferry” (1840 onwards). The first period effectively begins with a false start: the crossing of the Atlantic in 1819 by the auxiliary steamer *Savannah* (Griffiths 1997, p. 8). However, she would just be a (very) partial (and solely mechanical) success as in her (only) ocean voyage under steam the engine operated on only seven occasions during a total of 41.5 hours (representing 12.9% of the time).[15] After the original run of the *Savannah*, there was to be no other American steamer on the Atlantic until the mid-1840s.[16] She was the second (auxiliary) steamer to be listed in Lloyd’s Register books (Watson 2010, p. 124). While the Americans were mainly meeting the demands of inland transportation, the British were increasingly building larger vessels for trading in any waters (Smith 1938, p. 17).[17] Whereas lucrative opportunities for steamers in inland waterways and on the coastal trade were being quickly exploited, experiments on longer service routes were still technically difficult and often uneconomic. In the two decades following the *Savannah*, only nine other steamers crossed the Atlantic, the majority of them British but not run for commercial purposes (Tyler 1939, p. 47; Spratt 1949, p. 69). These ships could hardly be thought of as steamers in the full sense of the word as

[15] Thus, the *Savannah* can be described as the first vessel *with* a steam engine on board to take an ocean voyage. But she only functioned as a steamer on the eastbound voyage, and very partially so, namely when in presence of audiences on the shore (Rozwadowski 2005, p. 10). The *Savannah* had been built as a sailing packet, not as a steamer. She had collapsible paddle-wheels and was fitted with an engine of 90 indicated hp that was supplied steam by low-pressure boilers (Spratt 1958, p. 107). Another peculiarity was that her smoke stack was bent, the intention being to direct the smoke away from the sails, but other steamers would not follow her in this detail (Braynard 1963, p. 40). With a considerable spread of sail her famous transatlantic trip took 27 days and 11 hours, carrying no passengers but stowing 75 tons coal, at a mean speed of 6 knots, having arrived with no coal to the coast of Ireland. Perhaps for good reason, because she was not a persuasive exemplar, she seems to be the only “steamer” ever classed by Lloyd’s Register for which such a designation was not recorded (Jones 2000, p. 21). The boilers had to be cleaned at least once a day to avoid the effects of salt-water concentration.

[16] The words of Hope (1990, p. 266) provide a good summary: “The Americans produced no further ocean-going steamships until well after the British had established themselves as leaders in this field.” Braynard (1963, p. 210) points to 1845 as the year when the next American built steamer crossed the Atlantic, the *Massachusetts*. Morrison (1903, p. 408) mentions the crossing of the *Washington* and the *Herman*, both constructed as heavy sailing vessels, which left for Europe on June 1st, 1847, and March 21st, 1848, respectively, under a US mail contract to carry letters, newspapers and pamphlets.

[17] A famous naval architect and a great contributor to contemporary engineering debates would remark: “America is distinguished by its improvement of inland steam navigation. The nature of the country determined the efforts of invention in that direction, as in our own country the position of our ocean island decided our attention to the navigation of the deep sea; and by the success of our efforts we are now distinguished above the rest of the world immeasurably.” (Scott Russell 1841, p. 243)

they "did not demonstrate the practicality of the navigation of the Atlantic by ships using steam as the main motive power" (Smith 1938, p. 38). They were, in fact, vessels built and designed as sailing ships but equipped with auxiliary steam engines.

By the late 1830s steamship operations had become common on the Baltic and the Mediterranean. Regular steamship service across the Atlantic (a new phase, according to Spratt's periodisation) came in 1838 when the British steamer *Sirius* made the first port-to-port voyage under continuous steam power. The voyage to America by the *Sirius* (see Figure 3.4 and Appendix 3.1) was followed hours later by her rival *Great Western*, the first steamer to be purposively conceived for the Atlantic trade and also Isambard Kingdom Brunel's (1806-1859) first steamer.[18] The "steam-packet" *Sirius*, although not built for the Atlantic crossing (before she plied between London and Cork), was nonetheless an innovative steamer[19] and much bigger than the previous vessels that had made the crossing with the assistance of steam (Lindsay 1876, p. 170).

[18] The *Sirius* was chartered by the newly formed British and American Steam Navigation Co. when it became obvious that its own *British Queen* would not finished in time to beat the *Great Western* (Preble 1883, p. 141; Paine 2007, p. 5). The *Sirius* had two masts and it is believed she was propelled by side-lever engines of 320 nominal hp. Under the command of Lieutenant R. Roberts, she left London for Cork harbour, where she stopped for coaling and departed on April 4th carrying 40 passengers and 35 crew (Spratt 1949, p. 41; Paine 2007, p. 5). The *Sirius* reached New York 18 days 10 hours later, on the 22 of April, having covered a total distance of 2897 miles at a mean speed of 6.7 knots (Sheppard 1837, p. 87). She consumed 431 of the 453 tons of coal with which she sailed (Paine 2007, p. 5). *Great Western*'s time was 15 days and 5 hours from Bristol at an average of 8.8 knots (Tyler 1939, p. 52; Kemp 1978, p. 151). Having departed four days later, the *Great Western* arrived with only about 12 hours difference, on the same day of April 23rd. She still had plenty of coal in her hold.

[19] She was the first steamer on the Atlantic to be fitted with Samuel Hall's patented surface condenser, which allowed the recycling of water and hence avoided stops for clearing salt concentration from the boilers (Spratt 1951, p.31). Samuel Hall (c. 1782-1863) suggested an improvement to the method of condensation in 1834 with a patent that disposed of the cold water jet used by Watt and introduced the surface condenser (McConnell, 2004a). His proposal combined a number of known devices, such as a circulating pump, evaporator, air pump and a steam saver that captured steam escaping from the safety valve and led it back to the condenser (Smith 1838, p. 153). The surface condenser, which was suitable for any engine type not just the side-lever, allowed steamers to use fresh instead of salt water and thus reduced scale formation and improved fuel efficiency (Griffiths 1997, pp. 13-4). Seawater, apart from salt and magnesium sulphate, also contains carbonate of lime and sulphate of lime, which form incrustations on the heating surfaces and need to be removed at considerable time and labour cost (Guthrie 1971, pp. 118-9). Hall's equipment was fitted to the *Prince Llewellyn* in 1834 and a few other steamers, including HMS *Megaera* and HMS *Penelope* and the early transatlantic steamers *Sirius* and *British Queen*. Surface condensers were rapidly abandoned, however. The effectiveness of the idea was held back due to difficulties in maintaining it in running order. The condenser tubes became blocked with the tallow used as a lubricant in those days (Smith 1938, p. 156). Only in the late 1850s were they revived, in particular by the firm Humphries, Tennant & Dykes of Deptford, engine builders who fitted surface condensers in the P&O steamer *Mootan* (Griffiths 1997, p. 35).

Even so, and to use Rowland's (1970, p. 76) analogy, this was a case of "David versus Goliath", the *Great Western* being almost three times larger. This double-success established steam as a credible competitor to sail for passengers and express goods. It was a "proof that, with a proper allowance of bunker space in their design, transoceanic passages were well within the capability of the new steamships." (Kemp 1978, p. 151) That after many years (it was now a full quarter of century since the launch of the *Comet*) two side-wheelers should suddenly dispute a close race over the Atlantic can hardly be seen as a coincidence: dependable steamship technology was maturing fast along the path defined by the wood-paddle combination.[20] There seems, however, to have been a proximate trigger: a combination of social events that structured the technological agenda and propelled steamships to the ocean (see Box 3.1).

Figure 3.4 The *Sirius*

Source: Merseyside Museum art collection, commemorative oil on canvas

Note: In the inscription can be read "Steam-vessel Sirius, Lieutenant Richd. Roberts; R.N. off New York. The first British Steam-Vessel that ever crossed the Atlantic: performed her Voyage from Cork in 18 days!!"

In the following year Spratt's third period began swiftly: three steamers plied the Atlantic in 1839, the *Great Western*, the *British Queen* and the *Liverpool*, a two-funnelled vessel (Bonsor 1955, p. 12). Lee (1930, p. 27) calculated times for voyages of sail and steam packets for 1839 and arrived at an average of 34.1 days westbound (22.1

[20] In ordinary historical accounts the "steamship age" is said to have started in 1838 with the inauguration of the Atlantic service (see, e.g., Kingender and Elton 1970, p. 107).

days eastbound) under sail and 17 days westbound (days 15.4 eastbound) for steamers; that represented a saving of 24.3 days in total or a decrease of 43.1% in the duration of the complete round trip. The development was widely reported to the broader public in newspapers.[21] But events were also channelled to specialised audiences. In 1840 shipping trade journals were giving detailed information regarding the crossing of the best sailing packets and the three Atlantic steamers in service, and they showed that new steam technology cut the duration of the voyage by about one half (Smith 1938, p. 47; see also Maginnis 1892, pp. 273-5). In this same year the "Atlantic paddle ferry" was cemented with the launch of the *Britannia*, the first vessel built for Samuel Cunard (1787-1865), the most famous name of the regular Atlantic liner business.

The new transatlantic steamers, with shorter and thicker funnels, were by now looking less like converted sailing ships and were taking on a shape of their own (Boumphrey 1933, p. 81; Tyler 1939, p. 367). Steamers for the North Atlantic would soon be seen carrying reduced rigging and stronger engines (Gilfillan 1935b, p. 118). However, there were "anomalies" as these ships were slow and difficult to operate[22]. They also lacked internal earning space due to their heavy timber scantlings, the large paddle machinery and the large engines needed to propel it. The consequence was that even in this privileged North Atlantic run all the non-subsidised British steam liner companies had faded out of business by 1847 (Bonsor 1955, p. 14). That is, the wood-paddle dominant design was resilient but, when experiments started on a larger scale new problems began to emerge. These technical and economic problems encountered by steamers can be thought of as "anomalies" (in a Kuhnian sense), or signs that the canonical set of

[21] Steamers were now very much in the spotlight. Rozwadowski (2005, p. 11) makes this clear: "Large crowds attended launchings of new steamships, whose arrivals and departures were newsworthy. Newspapers reported crossings by celebrities with enthusiasm."

[22] The sea-going wooden paddle-wheeler was coming head-to-head with its limitations. "In the great side-lever engines which were used in many British vessels massive weights moved up and down, stopping and reversing on every stroke and setting up stresses in the structure of the machinery and the hull which carried it." (Brock and Greenhill 1973, p. 16)

solutions (or current paradigm) was struggling with the new challenges. Large steamers of the classic wood-paddle layout, like the *Great Western*, had reached their maximum capabilities (Greenhill 1993b, p. 19). That is, without removing crucial bottlenecks, the steamship was condemned to niche economic activities.[23]

Box 3.1 Did an open intellectual debate launch the "Atlantic ferry"?

The 1838 race seems to have kick-started the Atlantic ferry. But what lay behind it? The answer echoes our argument in Chapter 7. The voyages of 1838 were undertaken in the midst of a "buzz of excitement" concerning the impending race (in the words of a contemporary reporter, quoted in Tyler 1939, p. 47) which provided ample material for illustrations and caricatures in the popular press (Kingender and Elton 1970, p. 162). Newspaper coverage was very much part of the process of focusing public and expert attention as well as resources on the challenge. But what was the media echoing?

Historiographical tradition has it that the voyage may have been triggered by a public controversy. In December 1835 the critic Dionysius Lardner (1793-1859), then a known science populariser and a leading member of the British Association for the Advancement of Science, had stated his views that making the voyage from New York to Liverpool was "perfectly chimerical, and they might as well talk of making a voyage from New York or Liverpool to the moon." (Sheppard 1937, p. 85) The theme would be raised again in Bristol in 1836 during the annual meeting of the British Association where no less than 1,350 participants attended, among them pioneering engineers like Brunel, Scott Russell, and Joshua Field (MacLeod and Collins 1981, p. 279).

Lardner's views attracted much comment and even some animosity (Griffiths 1985, p. 11). In particular, they drew "strong opposition from Isambard Kingdom Brunel and stirred the passions of those who had invested money or energy in the possibility of such travel." (Hays, 2004) *The Times* newspaper registered the Bristol debate including Brunel's harsh intervention. "Mr. Brunel", wrote the newspaper in August 27, 1836, "then pointed out some errors in the calculations made by Dr. Lardner which would be in favour of the undertaking". Brunel believed that the conventional pessimism was wrong and had been forming his conclusions on the basis of coal consumption data drawn from old vessels (see Lambert 1999a). Brunel's *Great Western* steamship project was also now becoming more than just a professional challenge. He would no longer take fees for this work; rather, he would bet his own money to test his ideas in "what was the most demanding engineering environment of the age" (Lambert 1999a, p. 10).

Summary of section 3.2

As the ship historians Dudszus and Henriot (1986, p. 14) have asserted: "Ships are the combined result of the labours of many individuals and groups of tradesman." That was

[23] Greenhill (1993a, p. 9) provides a good description of the general state of merchant steam navigation before it was revolutionised by a new set of technologies: "Steamers were still confined to packet routes, towing duties, short sea bulk carriers and subsidised deep sea routes".

certainly the case with navigation by steam. The process of transition from invention (in the form of plans and prototypes) to innovation (market introduction) proved painfully slow, taking the form "a gradual evolution, or accumulation of quite little steps" (Gilfillan 1935b, p. 103). It was not obvious at all how to propel a vessel with steam power, but in the first decade of the 19th century steam-propulsion was "convincingly demonstrated" (Lilley 1976, p. 210). Economic success was sudden and nowhere more remarkable than in Britain. The early steamers were very basic but already able to perform a wide range of duties in the 1810s and 1820s: from the outset this was based on a wooden side-wheeler vessel propelled by a side-lever engine, a dominant or paradigmatic steamer design that was continuously refined in its details and scaled-up in its size. The extraordinary expansion of the commercial exploitation of the new technology provided many chances for experimentation as well as the continuity needed to build up robust experience in steamship construction and navigation. There are still aspects to be uncovered (see Appendix 3.1), but in the 1830s widely publicised debates in intellectual circles and the press are regarded as having focused the steamship community's attention on establishing steam on the oceans (see Box 3.1). The race between the *Sirius* and the *Great Western* showed not only that steam navigation across the Atlantic was technically feasible and safe, but also that it could work to tight schedules, halving the time in comparison with sail-only crossings. The story captured the public's imagination, as well as engineers'. With such vessels, Britain gained a firm grip on what was to prove "the most lucrative passenger shipping route in the world" (Rowland 1970, p. 78). John Scott Russell (1808-1882), the naval architect and one of the active participants in those debates, could allow himself to write at this stage:

> "Our own island kingdom has been the scene of all the improvements made on steam navigation in Europe. We believe that there is not in the most improved European steamships of the present day a single item of construction which is not wholly British in its origin." (Scott Russell 1841, p. 243)

By this time, however, the wood-paddle design was probably being strained to its practical limits. Steam navigation was feasible ocean-going technology, albeit not technically efficient or economically profitable in this and other longer-haul trades (Dollar 1931, p. 35). The existing "dominant design" or "technological paradigm" was becoming an obstacle to further progress. The pursuit of sustained improvements in steamer size and economy was held up by a growing number of interrelated bottlenecks.

3.3 The key components of steam-driven ships

The steamer at a time of technology transitions

The path of the infant steamboat transforming into a mature steamship brought us to 1840, covering a period of a little over 25 years in the history of steam navigation. Great changes lay ahead in the next decade that would convert the wood-paddler into an iron-screw ship along a trajectory of ever larger size. The screw-propeller and the iron hull, as well as more powerful engines to drive them, were on the verge of unleashing a momentous mutation in the design and a surge in the performance of the steamship. This section breaks down the steamer into its core components (these three basis subsystems are the engine, propulsion, and hull – see Griffiths 1997, p. 4) and follows their lines of development before and after 1840. In this historical transition, a new cluster of related innovations (efficient engines, the propeller and iron hull) brought about the emergence of the modern ship.

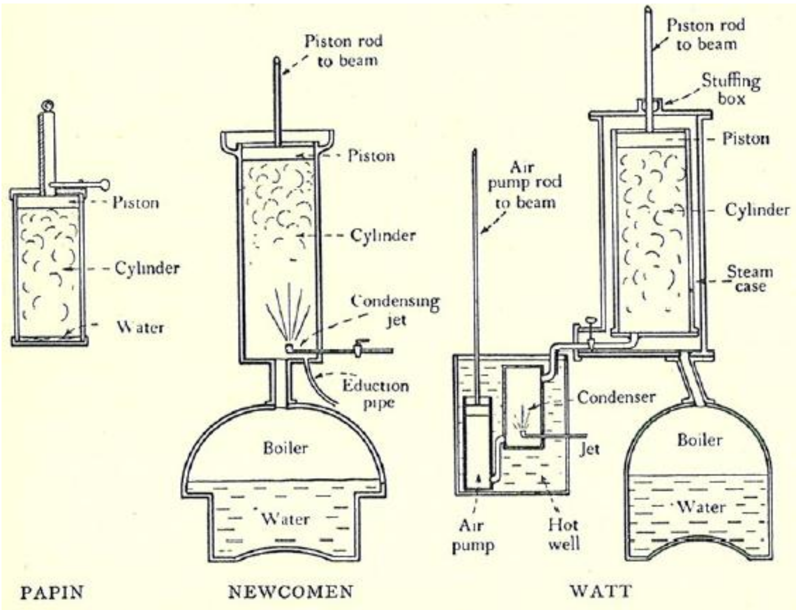
3.3.1 Marine engines

Origins of the marine engine

The roots of the steam engine are buried deep in the historical past. Often mentioned is Hero of Alexandria, who devised a toy steam-powered reaction turbine in 130 BC

(Guthrie 1971, p. 21). A specific proposal came much later with Papin, who invented the pressure pan and conceived an engine with a moving piston (see Dickinson 1938, pp. 8-9; Allen 2009, p. 158). His approach, embodied in a model built in 1890, was to boil the water in the cylinder, the piston descending slowly after steam condensed. The first practical results are usually credited to Thomas Savery (1650-1715), who in his 1698 patent sketched out what was then called a "fire engine". Then, in 1712, Thomas Newcomen (1663-1736) tried his pumping apparatus in a colliery. It produced a reciprocating or up-and-down movement. A boiler produced steam and released it to the chamber of a cylinder; this steam was then condensed by injecting cold water, bringing down a piston with the force of the atmosphere; a beam attached to a piston acted as a handle raising a bucket on the other end of the beam. The vacuum or atmospheric engine remained the dominant design for many years. Perhaps for the first time, this "fire-machine" was also described as a "steam engine" at time (Dickinson 1938, p. 37). By the 1770s the original Newcomen reciprocating version, which was fuel inefficient and irregular in its movement, was widely used in draining mines where coal was cheap and handy; a water-returning version was then also used for powering metal working machinery, especially iron blast furnaces (Frenken and Nuvolari 2004, p. 421, p. 439). Then James Watt (1736-1819), while working as an instrument-repairer at the University of Glasgow, brought forth the idea around 1765 of condensing the steam not in the cylinder itself but in a separate container. In his engine (patented in 1769 and extended to 1800 in 1775) the cylinder is enclosed to keep it hot and the piston is driven down pulling a rocking beam by the force of steam (not atmospheric pressure), the steam being exhausted to a separate condenser, thus having the effect of conserving heat in the cylinder and hence affording greater coal economy. On June 1, 1775, Watt entered into a partnership with Mathew Boulton, the Midlands industrialist, which would push him to work on the conversion of reciprocating into rotary motion, the applications of which were much wider. Boulton and Watt's solution to the problem, the direct-acting design where a vacuum was created on alternate sides of the piston enhancing the power and smoothness of the piston strokes, would be patented in 1782 and a first example was built in 1783 (Dickinson 1938, p. 83). Hence, by the beginning of the new century, an effective rotary beam engine was available, which could be of use in many areas, including navigation (Griffiths 1999a, p. 3). This evolution of the steam engine is portrayed in Figure 3.5.

Figure 3.5 Early steam engines: Papin (1690), Newcomen (1712) and Watt (1869)



Source: Dickinson (1938, p. 67)

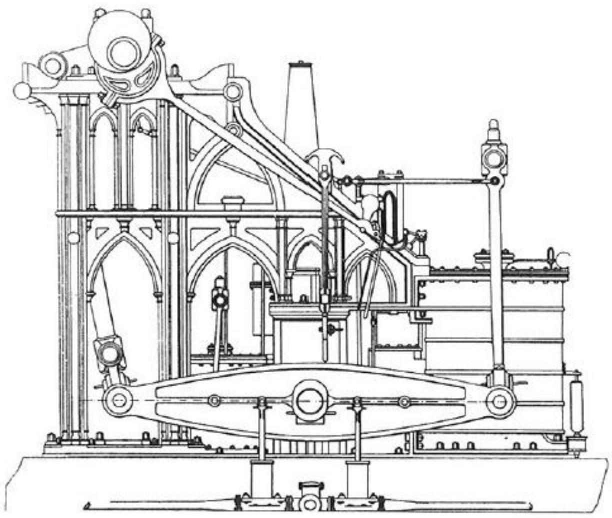
The application of steam to shipping followed the path of compactness and lightness, efficiency and portability (see, e.g., von Tunzelmann 1978, p. 22). In Britain the efforts initially centred on the Clyde and other rivers.[24] The machinery that was applied to Henry Bell's 1812 steamer was of a novel type and it was quick to spread. The side-

[24] Marine engineering sprung from the wider Glasgow tradition in engineering (see Moss and Hume, 1977). Skills had developed mostly in response to the calls of the cotton, flax and linen mills. Ever larger waterwheels, with more complex transmission mechanisms, and expertise for their construction and gearing, had been in increasing demand from the late 17th century. Many individuals contributed to marine engineering. David Napier, the boiler-marker for the *Comet*, started making his own marine engines in 1816 and, with his cousin Robert Napier, was behind the large-scale development of marine engineering on the Clyde. Of the 59 steamers active on the river in 1831-32 nearly half had engines built by the two Napiers. By 1900 Clyde marine engines comprised 35 per cent of the total hp built in Britain (Moss and Hume 1977, p. 41).

lever engine was an "architectural innovation" in itself, a re-arrangement of the elements of the existing beam design. As explained in Section 3.2, the modification consisted of replacing the heavy overhead beam, as was common in the tall Boulton & Watt engines, by levers laid down alongside the engine. Side-lever engines, as they would become known, started to appear immediately in pioneer ships like the *Industry*, the *Margery* and the *Thames*, all of them built as early as 1814. Although engines varied a great deal from builder to builder, this basic design became common for most paddle steamers for many years, not changing much except in size and power output (Griffiths 1999a, p. 11; see Box 3.2). By the 1850s the side-lever design was in general use across the whole spectrum of merchant vessels, from tugs to Atlantic liners (Guthrie 1971, p. 80).

Box 3.2 The "side-lever" marine engine

The side-lever arrangement is difficult to trace to any particular inventor but it was found appropriate for merchant paddle steamers for several reasons (Griffiths 1997, p. 7). First, its low centre of gravity made it suitable for ship propulsion by reducing the risks of capsizing (Buchanan, 2004b; Derry and Williams 1960, p. 327). Second, it allowed a long piston stroke that was ideal for driving paddle wheels that inevitably revolved at relatively low speeds (Smith 1938, p. 145). Third, its reliability, simplicity, and ease of operation meant the machinery could be operated by relatively unskilled and cheaper engineers, which made it also a favourite among shipowners (Griffths 1999a, p. 10; Greenhill and Giffard 1994, p. 57). This was a set of crucial characteristics during the formative years of steam navigation. By the early 1830s, "(c)losure had been achieved in the design and performance of the side-lever engine" (Macleod *et al*. 2000, p. 318). But the design was not without its drawbacks. Griffiths (1999a, p. 11) names two shortcomings: its heavy burden and the long engine room it required. It did not change much until the last large one was built for the last ocean-going paddler, the *Scotia* of 1862 (Griffiths 1991, p. 11).



Source of illustration: Griffiths (1997, p. 11)

Note: this engine was typical of Cunard vessels in the early 1840s

Developments in marine engineering

During the 1820s and 1830s Mersey and Thames builders adopted the side-lever design. In London Henry Maudslay (1771-1831) and his partners gained a reputation for building this type of engine for the Admiralty; they remained the central firm in setting the technological pace for many years in marine engineering as well as a site of on-the-job training for many influential engineers (Rowland 1870, p. 57). The Maudslays were joined by other mechanical engineers such as Penns and Seawards. John Penn (1805-1878), son of the engineer John Penn (1770-1843), established his works in Greenwich and in 1825 built his first engine, which was installed in the coastal paddle steamer *Ipswich*. In that year John Seaward (1786-1858) established the Canal Ironworks at Millwall and in 1826 was joined by his brother Samuel (1800-1842). The working places of these early pioneers also became a training ground for subsequent generations of innovators. In fact, apprenticeship remained the fundamental system in British shipbuilding throughout the 19th century (Pollard and Robertson 1979, p. 74). As a site for apprenticeship it is worth mentioning that the firms of David and Robert Napier, and Palmer also became very influential in forming very skilled engineers who would become influential in their own right.[25] This underscores Humphrey's (2003) point that apprenticeship was a crucial but neglected factor behind British industrialisation, namely in high-end craft-like activities.

Demand for steamers was up and small variations in design were ripe; and, since access to the latest attempted solutions was largely open, evolving best practice incorporated many developments from many sources (i.e. typically a search process under project-based conditions as described in Chapter 2, Section 2.3). It was common for builders to adopt the side-lever design and to develop modifications to suit the particular

[25] It also happened that members of the same family, like the Dennies and Napiers, were connected with several shipyards at the same time so that tacit knowledge and experience circulated profusely (Pollard and Robertson 1979, p. 74).

requirements of the project in hand. The two main shortcomings of the side-lever approach (the weight, which provoked undue hull stress; and the space it occupied, when space was at a premium in merchant ships) also set the stage for the proposal of other designs aimed at improving or superseding it. In the early 1830s David Napier introduced the "steeple engine", designed for ships with little space in the engine room. David Elder (1785-1866)[26] made several innovative arrangements for the air pump, condenser and slide-valve of the *Leven* in 1824, and introduced expansion valves for the first time in 1836 for the *Berenice* (Moss and Hume 1977, p. 36). His self-supporting engines were also not liable to damage if the hull got hurt. In 1837 Seaward installed an engine generating a new parallel-motion in the frigate HMS *Gorgon*, aimed at saving weight and space, a design variation that became known as the "gorgon engine". Under a contract for the Admiralty in 1844, Maudslays introduced the "siamese engine", with two cylinders placed in "fore" and "aft" positions, as another space-saving solution. Notwithstanding these developments, the side-lever approach remained alive until the 1860s and was still being implemented in a restyled form, known as the "grasshopper", into the 20th century (Griffiths 1997, pp. 10-20).

As Rolt (1970, p. 79) summarises it, two main alternative engines to the side-lever "were evolved". One was the "trunk engine", a paddle-wheel engine which saved on height by attaching the connecting rod to the piston, hence dispensing with the piston rod and crosshead by extending the skirt of the piston into the form of a hollow trunk working through a pole in the cylinder cover. The other alternative was the "oscillating" engine.[27] This arrangement resulted from mounting the cylinders in trunnions and connecting the piston rod directly to the crankshaft, without the intervention of a

[26] David Elder was marine engineering supervisor at Robert Napier's works. He was the father of the compound-engine innovator, John Elder (1824-1869).
[27] The idea behind this type of engine had been around at least since 1785 when one of Watt's assistants, William Murdoch, proposed it; patents on it had been granted in 1811 to a certain Mr. R. Witty and again, in 1821, to Aaron Manby (1776-1850), the entrepreneurial master of the Horseley Coal and Iron Company (Rowland 1970, p. 81; Canfield 2002, p. 431).

connecting rod. The engine was given new impetus in 1827 by Joseph Maudslay (1801-1861), who first fitted one in 1828 into a Thames pleasure steamer, the *Endeavour*. The engine was further improved at Penns' works in 1838, and later again in 1844 (Dickinson 1938, p. 111).[28] Penns' oscillating design was, for instance, adopted by John Scott Russell as the principle for the paddle-wheel machinery of the *Great Eastern*, Brunel's largest and last steamship. All in all, at any point in time many engineers were engaged in circumventing the problems posed by the latest proposal to improve steamship machinery. To use a characterisation employed by Sennet and Oram (1899, p. viii), authors of a 19th century textbook on marine engineering, the general practice among makers of machinery comes through as one in which "valuable features have been mutually borrowed". The practice of inviting competitors to attend test trials, of visiting other ships to draw conclusions for forthcomings ships, and other forms of direct cooperation was also not uncommon (Caldwell 1976, p. 153; Lambert 1992c, p. 48; Schwerin 2004, p. 92). This underscores a pattern of general behaviour that resonated with the technological community perspective highlighted in our theoretical framework (Chapter 2, Section 2.4): for marine engineers access to best practice allowed a free cross-fertilisation of solutions, which led to better-informed implementation of the solutions embodied in new projects.

With the increased usage of the screw propeller from the 1840s to the 1850s, new arrangements for power plants started to be experimented on. In this period of transition from wheels to screws, two main approaches were installed on numerous steamers: geared and direct-acting engines (Johnson 1906, p. 32). On account of the available boilers being built still at low pressures, geared engines of various designs were used

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[28] John Penn and his sixteen-year-old son of the same name had the opportunity to inspect a pioneering vessel in 1821, particularly her oscillating engines, when she was put together at Deptford (Lambert 2004, p. 550): this pioneering vessel was the *Aaron Manby*, of the builder and owner of the same name, which we will address again below in the context of iron shipbuilding. Within three years Penn had built his first marine engine and soon his services were procured by several leading Thames shipbuilders, in particular Ditchburn & Mare.

more frequently between 1840 and 1860 (Johnson 1906, p. 32; Watson 2010, p. 131). A form of geared engine that gained favour was first tried out, much to the initial resistance of the Admiralty, by the Blackwall shipbuilders Ditchburn & Mare in the screw-driven yacht *Fairy* (Griffiths 1997, p. 34). This was a two-cylinder oscillating engine connected to the screw-shaft by means of gearing. Another idea used by a number of builders, originally laid down by David Tod and John MacGregor, the Clydeside marine engineers who had been senior employees of David Napier, was the overhead beam screw engine that had been implemented successfully in the 1849 Inman Line's *City of Glasgow* packet steamer (Griffiths 1997, p. 34; Smith 1938, p. 104; Moss 2004d, p. 163). The work of this firm, especially due to its fashionable "horizontal trunk" type of engine, was very influential in spreading screw steamers during the 1850s (Moss and Hume 1977, p. 37).[29] These engines have been described as paddle-engines turned on their side, which made them rather large, prompting Scott & Sinclair of Greenock in 1853 to introduce changes to economise on space. The main problem of such engines being gearing[30], John Penn and Humphries[31], Tennant & Dykes of Deptford developed direct-acting horizontal engines, which they installed in naval and merchant steamers during the 1850s (Griffiths 1997, p. 37). An engine of this type was, for instance, fitted in P&O's *Himalaya* in 1853. In 1846 Caird & Co. of Greenock constructed a tall engine, which they installed in the coastal steamer *Northman*. It was an "inverted direct-acting engine", an especially compact engine in which the condenser was installed in-between the cylinders. This approach was improved by J. & G.

[29] Influential Clyde shipbuilders like William Denny (a distant cousin of Robert Napier) and the brothers James and George Thomson (who had worked under Robert Napier) would follow that model in the 1850s.

[30] A way to adapt paddle-wheel engines to screw-propellers had been through gearing so that the screw-shaft could revolve at higher speeds (Sennet and Oram 1899, p. 6). However, gearing gave rise to considerable difficulties in routine operation due to intense tear and wear of the apparatus and to the higher cost it represented given its heavy maintenance requirements (for general discussions on the mechanics of gearing, and constant trouble it led to, see Guthrie, 1971, and Griffiths, 1997).

[31] Francis Humphreys, who was appointed chief engineer at the Great Western Steam Ship Company, supported a trunk engine in his proposal as the prime mover of the *Great Britain*, the second of Brunel's great steamers, in the late 1830s while she was still envisioned to run on paddles.

Thomson in the early 1850s, and by 1856 their steamer *Laconia* exhibited a large version of such an engine. By the end of the decade these engine types (either horizontal-trunk engine or inverted direct-acting) had become well established and were to be commonly combined in screw steamers with Scotch boilers (see Maginnis 1892, p. 178). Following compounding, the inverted direct-acting type of engine gained favour, and a variation of it, the "vertical" variant (also known as the "steam hammer" engine) became almost universal for larger ships toward the end of the century (Guthrie 1971, pp. 106-7; Sennett and Oram 1899, p. 7 and p. 12).

Compounding, Scotch boilers and steam turbines

Experiments in compound marine engines were carried out from the 1820s[32] but the breakthrough for ocean-going steamers came in 1853 in a joint patent issued to Charles Randolph and John Elder.[33] Compounding was introduced in marine engineering through the machinery fitted in the *Brandon* , in 1854.[34] Her coal economy attracted a good deal of attention (Craig 1980a, p. 11).[35] Consumption was lowered first to 3.75 lbs, and then to something approaching 2.5 lbs of coal per indicated hp per hour, compared with the 4.5 lbs that was the current consumption with a regular engine (Smith 1938, p. 178; Moss, 2004c). Within about ten years, best practice was already

[32] Ideas on two-stage steam expansion had been introduced in 1781 by Jonathan Hornblower and yet again in 1824, when a patent on a type of compound engine was taken out, but it was never applied to marine propulsion with any success (Rowland 1970, p. 119). In the 1830s and 1840s, Arthur Wolf had fitted compound engines in very small steamboats (Rowland 1970, p. 119).

[33] They started a firm at Govan under the name Randolph, Elder & Company, afterwards known as John Elder & Company (and from 1885 onwards as Fairfield Shipbuilding and Engineering Co.). Like many others, John Elder was a second-generation engineer. He attended classes at Glasgow grammar school and, subsequently, at the University of Glasgow (Moss, 2004c). He became an apprentice in Napier's works, where his father also worked. His grasp of compound expansion was informed by a scientific point of view and did not owe much to the approaches taking place in stationary engines (cf. Nuvolari and Verspagen 2009, p. 24).

[34] Economy of fuel had to be traded against complexity of machinery (Grifiths 1997, p. 48). The introduction of compounding that was not an immediate success; its complicated machinery giving rise to breakdowns at the same time coal, its chief saving, was inexpensive (Pollard 1950. p. 310).

[35] The Pacific Steam Navigation Company, which mainly navigated along the west coast of South America where coal was expensive and difficult to obtain, was the first to adopt the new kind of engine in its new vessels, *Mooltan*, *Valparaiso* and *Inca,* built in 1856 (Rowland 1970, p. 120). It was so successful that within five years the company had ten ships with the new type of engine.

1.5 lbs in screw-driven ships and 2 lbs in paddle-wheeled ships (Moss and Hume 1977, p. 37). Acceptance of compounding was given a push with Alfred Holt's three steamers of 1865, the *Agamemnon*, the *Achilles* and the *Ajax*, built by Scotts of Greenock. These China trade steamers were a landmark in that they became the first economically successful ships using compounded expansion steam.[36] Although Cunard liners were being fit with compound engines as well before the decade was out, compounding was still comparatively little used well into the 1870s (Greenhill 1993b, p. 9; Griffiths 1997, p. 40). By the mid-1870s, however, Randolph & Elder's patent had expired and three Clyde firms started building compound engines, claiming good coal efficiency and space saving as a result (Moss and Hume 1977, p. 37).

High-pressure and compounding were defining design developments in the late 19th century steam engine making (Frenken and Nuvolari 2004, p. 438). These features only gained a foothold in marine engineering in the later 1860s, acquiring decisive momentum in the 1870s. Apparently that was not a long delay considering that diffusion on land was also slow; only by the 1850s were high-pressure rotary engines diffusing in Britain (von Tunzelmann 1978, p. 88). The lag in its spread to marine transport is not an often discussed issue in the standard references of marine engineering. Along with concerns for safety or scepticism among engineers as to the economies of compounding one major bottleneck that is referred by marine engine historians was related to boilers (see Smith 1938, pp. 174-88; Guthrie 1971, pp. 116-38; Grifiths 1997, pp. 40-57). Solutions adopted in land were not easy transposable to a marine environment where coal savings were extremely important but technical trade-offs were very acute. In Cornwall around 1850, for instance, high-pressure boilers were

[36] *Agamemnon*, with tandem compound engines, was so economical that it showed that steamers could now start to compete with sail in long-haul trades. Carrying 3,500 tons of cargo and only consuming 20 tons of coal a day, she could steam the 8,500 miles between Britain and the Mauritius without re-coaling (Corlett 1993, p. 103). Steaming in 64 days what the best sailing ships could only do in 90 uncertain days, the *Agamemnon* easily outsailed the crack clippers of the day (Greenhill 1993b, p. 9). Ironically, she and her sisters were built right alongside a yard building a composite tea clipper (Greenhill 1993b, p. 9).

built with thicker boiler plates (von Tunzelmann 1978, p. 88). Given the extra weight, however, in marine engineering such a solution created an extra problem in terms of fuel economy. Thus, as Craig (1980a, p. 11) and Slaven (1992, p. 6) caution, the development of compounding at sea was not an immediate or unqualified success, and its advance was contingent on boilers sustaining proper working pressure. Early marine boilers had been quite sufficient for river work and short-sea routes (Mitchell 1964, p. 111). Even so, boiler design had progressed reasonably well in terms of pressure (ten times the early pressures) and fuel economy by 1840 (Slaven 1992, p. 3).[37] The "Scotch boiler", a cylindrical fire-tube design that became the most common on ships, was to be an important step in ensuring boiler development (Slaven 1992, p. 3; see also Griffiths 1997, p. 66, who notes that this development cannot be attributed to any single inventor).

During the time boilers were being built with increasing strength, a number of innovations in machinery were being added.[38] Safe and reliable triple compounding was tested in the 1880s and came into general use afterwards (Moss and Hume, 1977, p. 39)[39]. The general abandonment of sails in large merchant ships came about this time when the combination of twin screws and the high-pressure triple-expansion engine became common (Brock and Greenhill 1973, p. 17; Moss and Hume 1977, p. 103; Graham 1980, p. 3). The quadruple-expansion type was later patented, again by Randolph & Elder, but the technology only took off in the 1890s with the Dennies

[37] Up until the 1850s boilers had not progressed at the same rhythm in America, they were relatively more inefficient and hazardous. In the period from steam navigation inauguration until mid-century nearly one third of western rivers steamboat accidents were related to explosions (Hunter 1949, p. 158 and p. 272).

[38] For instance, P&O had their 1863 Poplar-built *Carnatic* equipped with double expansion engines and an early form of super-heater by Humphries and partners, the engineers who about this time were also re-introducing the surface condenser (Greenhill 1993b, p. 9). Other significant modifications now spreading were the division of the pressure exiting from the high-pressure cylinder into two low-pressure ones of equal size and the also the tandem engine approach (Moss and Hume, 1977, p. 39).

[39] Although John Elder and Co. had fitted the *Propontis* in 1874 with the first successful triple-expansion engines, it was up to Alexander C. Kirk (1830-1892), the former designer of the engines of the *Propontis*, to introduce a modified design that proved reliable and successful (Moss and Hume, 1977, p. 39). Kirk had studied at Edinburgh University. He was one of many who started out as an apprentice under Robert Napier, then worked as a draughtsman for Maudslays and later on became a manager for John Elder & Co. at Fairfield (Rowland 1970, p. 152). After the triple-expansion demonstration, no more double-compound engines were fitted in large Atlantic steamers (Maginnis 1892, pp. 226-8).

(Moss and Hume 1977, p. 39). At the close of the century, the turbine appeared, but up to the Great War it did not have a significant impact in the British merchant fleet.[40]

3.3.2 From paddle to screw

Early experiments with practical screws

The general idea of using a submerged helix is of "indefinite antiquity" (MacGregor 1858, p. 337). The device, generally associated with Archimedes, had been known since the 3rd century BC and had been widely used as a sort of pump. For the purpose of ship propulsion, the screw had been proposed many times by several authors approaching it variously from "spiral oar" or from a "transverse paddle-wheel" perspective (Spratt, 1958). By the mid-19th century it was possible to write a volume just under of 300 pages on the history and technical details of the multiple variations on the principle (Bourne, 1852).[41] By this time it was also possible to go through the names of 470 individuals associated with its development (Smith 1938, p. 64). As an alternative to the paddle-wheel, however, "no permanent or practical progress had been made", and, up to 1836, "no vessel in existence was propelled by a screw" (Bourne 1852 p. 82). By then, however, experience with the paddle system had accumulated to reveal numerous problems: it was inefficient since floats were out of water most of the time; its performance diminished as the coal-consuming vessels became lighter during a voyage;

[40] As Pollard and Robertson (1979, p. 15) assert, "(t)he most original technical improvement following the development of the compound engine was the marine turbine of Sir Charles Parsons." Here steam is injected into a cylinder when a fan of blades is connected to a shaft, which rotates rapidly under the force of the steam against the blades. Parsons patented his turbine in 1884 and established his Parsons Marine Steam Turbine Co. in 1894. In 1897 he publicly and dashingly displayed his experimental launch *Turbinia*, steaming at 34.5 knots at the Naval Review at Spithead. By 1900 three other turbine engines were introduced commercially, the Curtis, the Laval and the Rhateau (Slaven 1992, p. 7). Due to their efficiency at higher speeds, up until 1914 turbines were mostly employed in naval vessels (the British destroyer *Viper* of 1900 was indeed the first non-experimental turbine ship) and passenger ships (*The King Edward*, a Denny-built passenger steamer, which became the first turbine-driven commercial ship in 1901). Hence, and until the end of the "long 19th century", the limited spread of the turbine only slightly changed the character of modern shipping.

[41] The book, *Treatise on the Screw Propeller*, was written by John Bourne, whose father in 1835 founded the Peninsular Steam Navigation Company (later better known as P&O).

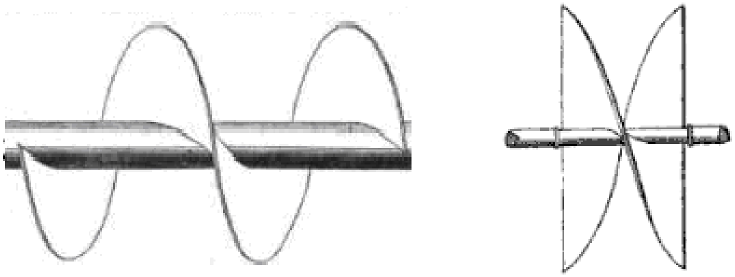
it provided uneven thrust in the high seas as the paddle-wheels submerged in the water with different degrees of depth; it was vulnerable to damage under heavy weather; it was not easily combined with high-powered engines; it offered no overwhelming advantage beyond shallow waters; for naval vessels the paddle-wheels were dangerously exposed to shot; and for storing and loading/unloading paying cargo the paddle-shaft amidships was not practical (see Thurston 1895, p. 298; Sennett and Oram 1899, p. 4; Brock and Greehill 1973, p. 16; Fenton 2008, p. 181).

The question on the eve of the inauguration the Atlantic steam service was increasingly one of how to correct the perceived defects in the conventional method of propulsion. At this time two notable (patented) propellers were sealed in England. A first patent was taken out on May 31, 1836, by Francis Petit Smith (1808-1874), an educated man then farming at Hendon, Middlesex.[42] His screw, with two complete turns (looking like a "worm", the word he used in his patent specification), was to be located aft in a cavity at the commonly designated "dead wood" of the ship. The motivation for this was to stop water coming in from the propeller's shaft. In a posterior trial, in February 1837, there was an inadvertent collision with a sunken object that took away half of the wooden screw after which the boat accelerated.[43] This prompted Smith to insert an addendum to his patent in 1839 to cover the shorter version of the screw (Figure 3.6). Meanwhile, on 13 January 1837, it was the turn of John Ericsson (1803-89), a one-time army captain and Swedish emigré who had moved to London to pursue a business life as a consulting engineer and inventor, to file a screw patent (see Appendix 3.2).

[42] Petit Smith's interest in the screw seems to have started as a boy building model boats and his hobby developed into a fixation, bearing fruit in an experiment in 1835, when a working model fitted with a screw acted upon by a spring crossed a pond on his farm (Brown, 2004a; Smith 1938, p. 69).

[43] This is a much recounted episode in the literature, one used to evoke the power of serendipity. Actually, according to Gilfillan (1935a, p. 60), "invention by accident is very rare or unknown in marine history." Unlike other technologies, "(m)arine equipment, contrasting with chemical, electrical and optical, usually needs to be so large and/or in dangerous situations, that it is not handled in the haphazard manner most productive for lucky incidents". Moreover, in the case of Smith, it is clear for Gilfillan that the happy accident was not entirely fortuitous; it happened of course to someone who was purposively experimenting and trying to improve the screw.

Figure 3.6 Smiths's 1836 (left) and 1839 (right) screw propeller



Source: details of the patent's illustrations, Bourne (1852, pp. 22-3)

Promoting the Screw Propeller (Company)

In 1839 Smith and his immediate associates launched the *Archimedes* (at first to be called the *Propeller*) at the not inconsiderable cost of £10,500 (Bourne 1852, p. 82).[44] This was a 237-ton vessel having two engines of 90 hp turning a screw of the new shorter type. She was taken to sea a year later, at the same time as the Ship Propeller Company was formed. This was incorporated as a joint stock company to purchase and exploit Smith's intellectual property (see Lambert, 1993). The main goal of the venture was to persuade the Admiralty to buy the technology, but, as no concrete contract was forthcoming, the owners of the *Archimedes* became eager to interest as many shipowners and shipbuilders as possible (Rowland 1970, p. 96). Immediately after the trials, a tour was planned for 1840 to show-case the new method of propulsion.

The *Archimedes* embarked on what became a high-impact experimental and promotional trip, visiting the principal British ports.[45] She also travelled out to Porto (in the quickest passage on record at the time, according to Bourne 1852, p. 86), Antwerp and Amsterdam. The vessel attracted the attention of the press and gave plenty of opportunity to engineers, shipbuilders and shipowners to become acquainted with the

[44] There had been a nod from the Royal Navy to demonstrate the propeller idea. It should be noted that Smith now counted on the support of Sir John Rennie (1794-1874), who had succeed his father John Rennie (1761-1821) in his post as engineer to the Admiralty. Smith and his associates followed this suggestion. The hull was built by Henry Wimshurst and the machinery by John's eldest brother, George. These three were now increasingly the major backers of Smith (Lambert 1993, p. 138).

[45] Preble (1883, p. 191) states she travelled 722 miles at an average speed of 8.5 miles an hour.

new system. It was during one of these visits that I.K. Brunel, who was engaged in the construction of his second steamer *Great Britain*, became interested in the screw. Brunel hired the experimental vessel and embarked on the "first 'scientific' attempt to generate useful data from a screw ship." (Lambert 1999b, p. 33) Before the *Archimedes* returned to London, eight different propeller designs were tested, the main ones being Smith's and Bennet Woodcroft's (Corlett 1990, p. 208). Brunel became convinced of the superiority of the screw and, more generally, that it would replace the paddle altogether. The public display of technology and unimpeded access to it were clearly important in the selection of the screw for the influential *Great Britain*.[46]

Other similar episodes involving the *Archimedes* are much less cited but scarcely less significant. On her tour round Britain to publicise the screw in 1840, she sailed up the Tyne. She created a large impression in the North East and it was reported that local builders developed an interest in the screw (Dougan 1968, p. 55).[47] In the event John Coutts, who was to prove himself as a remarkably innovative steamship builder, would reach the same conclusion as Brunel and succeed in launching his smaller screw steamer in 1844, that is, before the *Great Britain*. The ship was called the *Q.E.D.* In yet another encounter, in Dover, on May 2 1840, the *Archimedes* met the H.M.S. *Widgeon*, which was a navy paddle-steamer (Smith 1938, p. 71). When tested alongside the paddler she gained the approval of the naval officers for her swiftness and manoeuvrability, but it was also pointed out that the rotating shaft caused rapid wear, vibration and noise. Such limitations showed that extensive development work was needed in order to make the system suitable for naval or passenger steamers.

[46] The numerous authors that have examined adoption of the screw in the *Great Britain* found no trace of property right fees being paid to Smith (see, e.g., Rowland, 1971). The screw design that was finally adopted did not resemble too closely any of the patented screws that had been experimented with, the directors of Brunel's venture undoubtedly being delighted to save on any extra costs.

[47] In 1840 the *Archimedes* entered the Tyne for the first time: "She attracted much attention and it was not long before Tyneside shipbuilders wanted to copy her." (Dougan 1968, p. 55)

Managing the screw transition

As the 1840s begun the number of screw steamers was on the rise in both the merchant marine and the Royal Navy, although this was largely bypassing the Ship Propeller Company which never recovered the invested money.[48] After building the *Archimedes*, Wimhurst, acting alone, built the *Novelty*[49], a larger vessel using the screw as an auxiliary, not as the primary, mover (Lambert 1993, p. 141).[50] Other ships were built shortly after the *Novelty*: the *Great Northern* at Londonderry in 1842[51], the *Margaret* and *Senator* at Hull, and the *Princess Royal*, a pleasure craft built on the Tyne and launched in 1841 (Smith 1938, p. 72). Preble (1883, p. 195) also mentions another screw ship, the *Bedlington*, a pioneering 270 tons 60 hp double-screw steamer built in South Shields, and an old river steamer, the *Swiftsure*, was also fitted with one. The Royal Navy was also trying the propeller. The HMS *Dwarf*, originally the *Mermaid*, of 164 tons was purchased by the Navy in June 1843 and became its first screw steamer (Smith 1938, p. 72). This was followed by another non-fighting ship; the *Bee*, of 42 tons, built at Chatham. Following a tender by the Navy in 1841, the *Rattler* (originally the *Ardent*) would be first screw propelled steamship purposefully built for the Navy and the world's first screw warship (Lambert 1999b, p. 53). Brunel, who had no conflicts of interest since he had no stake in any screw patents, was entrusted with the

[48] After her promotional voyage the *Archimedes* had suffered problems and had to go into repairs, a further financial burden when no royalties from the patent were being realised. The Ship Propeller Company eventually tried to sell the ship to the Admiralty for £3,500, a small part of her initial cost. Not being in a hurry, the Admiralty had little use for the small steamer and had itself placed a tender for an experimental screw warship, the *Rattler*. The *Archimedes* became idle for a long time at the East India Dock, and was advertised for sale. She would eventually be stripped of her engines and finally find some employment (see Lambert 1993, p. 141; Klovland, 2009). No records of her exist after 1856.

[49] She originally used a locomotive boiler, although this was replaced given its limitations in high seas. In 1841 she completed a voyage from Liverpool to Constantinople with 420 tons of cargo, making her, according to Smith (1938, p. 72), a precursor to the merchant screw steamer.

[50] The builder also tried insistently to sell it to the Admiralty in 1842, 1843 and 1844, but to no avail (Lambert 1993, p. 141).

[51] Incidentally, the *Great Northern* was the first steamer to have her engine and boilers placed in the aft part of the ship (Corlett 1990, p. 58). This was probably testimony that new ways of placing the power plant were starting to be explored as dispensing with side-wheels no longer obliged the machinery to be nested amidships.

technical coordination of the *Rattler* project.[52] The *Rattler* would be launched in the spring of 1843 and would endure an extensive period of trials. The patented propeller was indeed the "prestige invention" of the 1840s (Hewish 1980, p. 11). The Royal Navy had no lack of individuals volunteering their ideas. During this time the *Rattler* was fitted with several screws for experimentation, but at the inventors' own expense, and they were then returned to them after they were no longer needed.[53]

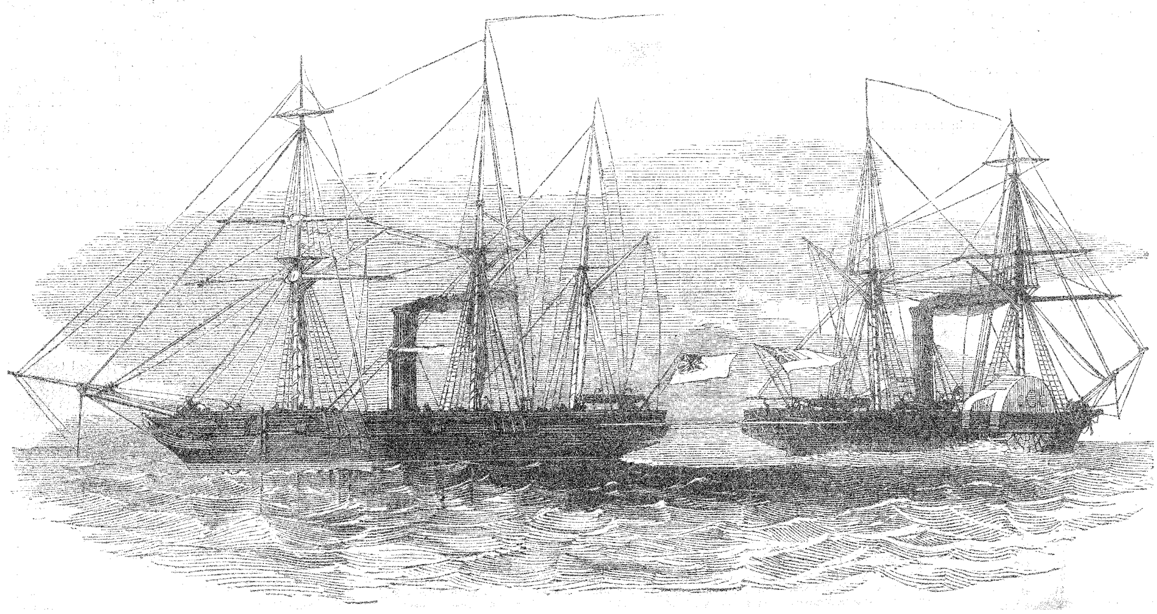
The Navy's approach also carried significant consequences for the publicity of the technology. On 30th March 1845, starting a series of famous trials to directly compare the merits of the screw against those of the paddle, the *Rattler* was tested against the HMS *Alecto*, a sloop side-wheeler (see, e.g., Thomas 1983, p. 15). The trials were brought to a close in a most conspicuous, and amply reported, tug-of-war on April 3 (see Figure 3.7). The vessels were fastened stern-to-stern and poised to exert their full power in opposite directions. The *Alecto* started first, but on the *Rattler* starting off she dragged the *Alecto* backwards at 2.5 miles per hour (Smith 1938, p. 73). Some authors have claimed that the *Rattler-Alecto* contest "was the turning point for screw propulsion" (e.g. Thomas 1983, p. 15). As Lyon (1980, p. 18) summarises it, though, "(t)his was as much a public relations exercise as a scientific trial, for by this time the Royal Navy had already ordered several screw frigates." A compromise interpretation is that trials just added more data to the Admiralty, by then already increasingly aware of the possibilities for screw-propelled warships against a still sceptical public opinion

[52] This was uncomfortable for Smith, who still thought of himself as enjoying some reputation with the Admiralty as he was asked to advise on the purchase of the *Dwarf* (Lambert 1993, p. 142). In another blow that happened in 1842, the Navy refused to commit to any one particular type of screw.

[53] Woodcroft (1848, p. 114), offering his own vivid example, recounts some of the astute money-saving schemes put in practice by the Admiralty Board that resulted in no profits for inventors in return for a wealth of experimental data. Lambert (1993, 1999b) has argued at length that on this and other occasions the Navy demonstrated a skill for exploiting the commercial sector's ambitions while managing a technological transition with uncertain but conceivably radical implications for the future of its entire fleet.

(Lambert 1992b, p. 30, and 1999c, p. 106).[54] Being confronted with Smith's extension of his patent in 1850, the Admiralty decided to cut any links with screw inventors once and for all: it offered £20.000 for the whole of patent rights that had been clinging to the screw system. The offering sought rights to all of the relevant patents and it was settled among the rights-holders that the proceeds were to be distributed equally among Smith, Woodcroft, and Lowe (see Lambert 1992b and 1993; also see Chapter 6, Section 6.9).

Figure 3.7 The tug-of-war trial between the *Alecto* paddle-steamer and screw-propelled *Rattler* in 1845



Source: *The Illustrated London News*, author's collection

Developing the screw-propeller solution

The issue of the shape and location of the propeller blades was just part of the issue; there were more complicated problems given the interdependencies of the screw system with the engine and the hull. Overcoming these difficulties would be reflected in the enhanced practical effectiveness of the approach (Sennet and Oram 1899, p. 6). The

[54] At this juncture, the Admiralty had not yet settled on any definitive propeller design, and even more expensive and time-consuming trials were still being carried out after it. The *Archimedes* and the *Rattler* had been used to test various types of screws, and the *Dwarf* had in a single year, 1845, been fitted with no less than 24 different screws (Smith 1938, p. 76). During 1847-8 the Admiralty used the *Minx* to test at least six other screws of varying surface and pitch and during 1849 used the *Archer* to experiment with yet more screws of differing diameters (Seaton 1909, pp. 209-12).

screw posed challenges to the engines that had never been experienced before. In particular, as Guthrie (1971, p. 94) points out, "gear drive was used in the early screw steamers for precisely the opposite reasons as for the early paddle steamers."[55] While gearing arrangements were known, initially the state of engineering knowledge could only offer noisy, failure-prone, and expensive solutions.[56] As engineers started to explore ways to dispense with gearing, there were other problems emerging elsewhere since the operation of the screw subjected the wooden hulls to substantial mechanical vibratory force. The problem was acute with the rotating shaft being below the water line. Leakage had to be prevented while absorbing the thrust of the propeller to the hull. This was eventually overcome by lining the stern bearings with *lignum vitae*, the hard and self-lubricating wood of the West Indian guaiacum tree (Deeson 1976, p. 84; Kemp 1977, p. 159).[57]

The replacement of paddle-wheels with screw-propellers began in earnest in the years 1845-1850 (Sennet and Oram 1899, p. 6) and increasingly gained momentum thereafter (Johnson 1906, p. 28). Paddle-wheelers' economic handicaps (or "anomalies") were revealed by the day as these for-profit steamers were being pushed farther afield: their variable immersion meant that the paddles only achieved optimal immersion for a short while; their limited use for carrying bulk cargoes like cereals, ores and stone; larger vessels had difficulties in manoeuvring in closed waters, hence losing precious time in harbour operations, etc. (Greenhill 1993b, pp. 16-7). In the early 1850s, popular interest in the contest between screw and paddle was so acute that the screw even featured in

[55] In the latter, engines had to be geared down to move paddles that worked only slowly. In the former, stepping up was necessary to allow the powerful but slow-running engines of the day to deliver enough speed to the propeller shaft in order to rotate a screw slicing the water.
[56] For instance, the engine of the *Archimedes* had a speed of 26 revolutions per minute but, through gearing, drove the propeller shaft at 140 revolutions per minute (Smith 1938, p. 70). Such gearing accounted for most of the cost of building the craft (Lambert, 1993).
[57] This solution was experimentally tested in 1854 by Penn and Smith and would remain in use for the next four decades. This complementary discovery, which contributed to the retention of the propeller technology, was moreover publicised in the *Proceedings of the Institution of Mechanical Engineers*. The initial installations of this approach were so successful that in two years more than two hundred vessels had their existing brass bushes replaced (Rowland 1970, p. 101).

advertisements of packet companies and in announcing coming departures of steamers (Maginnis 1892, p. 237). The screw eventually outcompeted paddles except in the case of navigation in shallow waters and in the towing business, where the transition took rather longer (see Emmerson 1981, p. 19; and Sennet and Oram 1899, p. 314). Vessels using screws were also not significantly affected by heeling, a problem especially encountered in cross-channel and ocean voyages. Heeling, by making the vessel exert more thrust on one paddle while the other could even rotate freely in the air in rough seas, exerted immense strain on the paddle shaft and often resulted in its collapse at the worst possible time. The perceptions of the relative advantages of the screw system, which had started to become publicly discussed in the press, grew as problems were gradually overcome (leakage prevention, thrust bearings, quicker engines). And so, over time, more and more screw propellers were fitted as substitutes for paddle-wheels. But, ultimately, the true importance of the screw-propeller lay in other "symbiotic" changes it called for (cf. Thurston 1895, pp. 300-2). As Sennet and Oram (1899, p. 4) asserted:

> "The adoption of the screw propeller in lieu of the paddle-wheel was the most important step in the progress of marine engineering, for this rendered many subsequent advances possible."

3.3.3 Iron shipbuilding

Inroads into iron shipbuilding

The first iron boat, although with a stem and sternpost made of wood, is believed to have been the canal barge *Trial*, 70 ft long, built in 1787 (Walker 1999, p. 53). She was built at Wiley, Shropshire, by John Wilkinson, the greatest ironmaster of the time and a specialised supplier to Boulton & Watt (Dickinson 1938, p. 83; Sherer 1965, pp. 176-8). Sir Samuel Bentham displayed a copper boat on the Thames in 1794 (Arnold 2000, p. 10). Other craft built of wrought-iron plates followed (Smith 1938, pp. 97-8). In 1815 a small sailing pleasure craft launched by Thomas Jevons was navigating the Mersey; this was the first recorded use of iron in a boat entering seawater (Rowland 1971, p. 23). Launched in 1818, and in operation in 1819, the *Vulcan* became the first practical passenger horse-drawn barge in service with iron plates riveted to the hull perpendicularly; she was built near Glasgow by Thomas Wilson and began working in the Forth and Clyde canal (Dollar 1931, p. 29; Walker 1999, p. 54). Her working life would offer testimony to the durability of iron since in 1875 this barge was still carrying minerals on the canal (*Lloyd's List* 1984, p. 218).

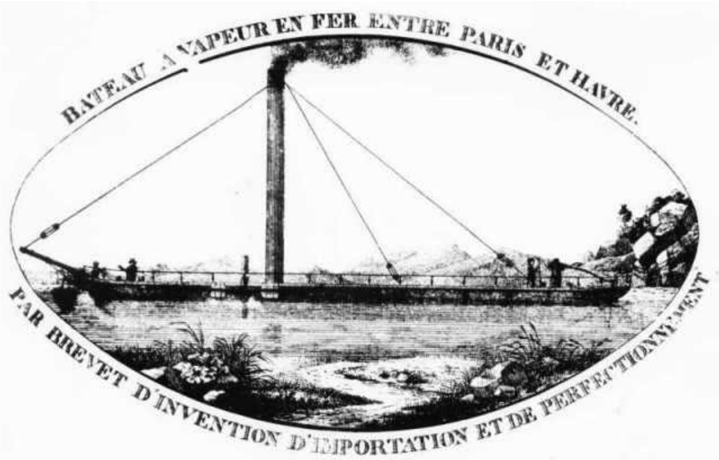
The *Aaron Manby*, a small but notable vessel that went to sea in 1822, became the first iron steamer ever built (we will return to this ship in Chapter 7, Section 7.2). She was a real "product innovation" as she was made of iron and had the first power unit ever installed based on the oscillating principle (see Box 3.3), but she also represented a "process innovation" as she was assembled from parts made elsewhere (see Appendix 3.3). As she travelled to Paris the *Aaron Manby* became the first steamer to connect London to Paris directly, the first iron steamer to go to sea and the first iron steamer to be exported. The next iron steamer, the *Marquis of Wellesley*, also came in plates from Horseley Iron Works (Fincham 1851, p. 385). She was assembled at Liverpool in 1825 for John Grantham senior (the father of the celebrated ironship builder and author of the same name, who in 1842 would also write one of the first books concerning iron in shipbuilding). Thirty years later, the ship could still be found afloat and working (Corlett 1990, p. 24). Next came David Napier in Glasgow with the *Aglia*, a 40 tonner. Meanwhile, other builders and engineers followed suit.

As the 1830s commenced, we see three features of the emerging iron shipbuilding industry. First, iron ships were being built in greater numbers and greater sizes. Second, we see London, but also Liverpool, setting the pace for iron shipbuilding excellence.[58]

[58] The Thames, in particular, started to attract iron steamer innovators. In 1834-35 William Fairbairn would also establish himself in Millwall, where until 1848 he would build upwards of one hundred iron

Box 3.3 The *Aaron Manby*, the first iron steamer

The vessel was first tested on the river Thames on May 9, 1822 (Canfield 2002, p. 432). She made a successful English Channel crossing, arriving in Paris on June 11 that same year (Greenhill 1993b, p. 27; Dumpleton 1973, p. 19). This was the first time the distance between London and Paris was bridged by steam and also the first time a metal-hulled steamship ventured to sea. According to Joshua Field, Manby had been working on several iron-made canal barges since 1815 (Canfield 2002, p. 431). With quarter-inch lapped and riveted iron plates, she can be considered the first true iron-hulled ship (Dumpleton 1973, p. 18; Kemp 1978, p. 152). Her parts were made at the Horseley works, near Tipton, Staffordshire, with the assistance of Manby's eldest son, Charles (Canfield 2002, p. 432). She was also powered by the first oscillating engine ever built (Rowland 1970, p. 81). Meant to operate as a pleasure boat on the Seine, she was of about 160 tons and could average 8-9 knots thanks to her 80 hp engine. The vessel was dispatched to Le Havre under the command of Captain Charles Napier, later Admiral, who would become an influential advocate of the "steam and iron navy" (Rowland 1971, p. 24). In the voyage the role of chief engineer was carried out by Charles Manby (Corlett 1990, p. 24; Canfield 2002, p. 432). Another iron steamer was built in pieces at Manby's foundry and engineering works during the winter of 1822-23, the *Commerce de Paris* (Canfield 2002, p. 432). Experience with iron was scant and opposition was considerable, but the *Aaron Manby* remained three decades in service, being broken-up in 1855 when iron ships were already well established.



The *Aaron Manby*

Source of illustration: Greenhill (1993b), reprint from the Science Museum

Note: According to Greenhill (1993b) this is the only contemporary picture of the steamer

Third, these iron ship builders were not previously linked with the shipbuilding trade (see Smith 1938, p. 95; Rowland 1970, p. 114). A few examples condense these three observations. In the early 1830s Maudslays of Lambeth and Lairds of Birkenhead started out in the iron steamer business by producing premium and specialist ships. Maudslays brought iron shipbuilding to the Thames but were better known as marine engine builders (Arnold 2000, p. 11). John Laird (1805-1874) took over his father's boiler-making works on Merseyside in the late 1820s; by the late 1830s he had

steamers (Fairbairn 1860, p. 244). At that point Fairbairn's shipyard passed into the hands of John Scott Russell, who had come down from Greenock in 1844. David Napier came down in 1836 to take over the shipyard next to Fairbairn, The Isle of Dogs (Moss 2004, p. 163). By 1850 it would be the turn of Macgregor Laird (1808-1861), John Laird's brother, to arrive in London.

produced the *Garry Owen* of 263 tons and 80 hp, that thanks to her innovative transverse bulkheads survived a serious stranding and would still go on to reach the coast of Africa, the *Robert F. Stockton*, which was Ericsson's screw-steamer, and Laird's most influential steamer, the *Rainbow* of 1838, at 4,000 tons the largest iron ship to date and the first ocean-going iron vessel (Johnson 1906, p. 40; Smith 1938, pp. 99-100; Corlett 1990, p. 25; Laughton, 2004).[59]

Iron as a shipbuilding material also posed unprecedented scientific challenges. And these had to be approached with an open research-like mentality. Let us mention two paramount examples. When in 1830 William Fairbairn (1789-1874) performed his experiments with light iron boats worked by steam on the Forth and Clyde Canal, its directors wasted no time in encouraging him to publicise the results (see Pole 1877, pp. 137-41). This was Fairbairn's *Remarks on Canal Navigation, Illustrative of the Advantages of the Use of Steam as a Moving Power on Canals,* which came out in 1831 with descriptions of experiments and proposed improvements. About this time, Fairbairn launched the sea-going paddler *Lord Dundas*, only to discover, with alarm, a great discrepancy between the course projected and her actual steering on her maiden trip. This prompted him to ascertain the cause of the mistake (magnetic deviation of the compass due to the effect of iron), to correctly determine the exact size of the effect, and to devise the first corrective measures. John Scott Russell, another iron ship innovator, conducted a series of experiments in the mid-1830s on the "solitary wave" or "wave of translation", a phenomenon that arises in restricted waterways (see Brown 2004b, p. 312). Scott Russell developed a combination of solutions (concave or hollow bow,

[59] During the 1830s Laird's shipyard built some other pioneering iron steamers. In 1831 he launched the *Alburkah* of 70 tons and 15 hp, a ship that would accompany his brother, Macgregor Laird, on his incursions into the river Niger and, in the process, enter maritime history as "the first vessel constructed entirely of iron to complete an ocean voyage" (Flint 2004, p. 232). In 1834 he constructed the *John Randolph* for a G.B. Lamar of Savannah; this was a prefabricated boat and "the first iron ship to be built for an American owner" (Laughton 2004, p. 231). Another achievement was the *Nemesis*, a ship armed with pivoting guns for the Honourable East India Company and the first steamer to have rounded the Cape of Good Hope (Preble 1883, p. 191). She was used successfully in the Opium War with China (1841-1842) and became a celebrated vessel henceforth.

closely arranged bulkheads, and longitudinal stiffeners) that constituted a new method of construction and, in the process, became "the first to exploit the real strength of iron as a structural material for ships" (Lambert 2008, p. 2). Russell was quick to disseminate his findings with a paper read before the newly formed British Association in 1835, and, in 1837, also in the context of this loose institution of scientist gentlemen, a "Committee on Waves" was constituted to further pursue this issue. Furthermore, and as early as 1842, John Grantham came forward with a book on *Iron as a Material for Shipbuilding*, which expounded the advantages of the new material and the lessons learned with iron steamers. This kind of community-like behaviour (a high commitment to public debate and publishing) is interesting to note in connection to Chapter 2 (Section 2.4), and will be further investigated in Chapter 7 (see especially Section 7.2).

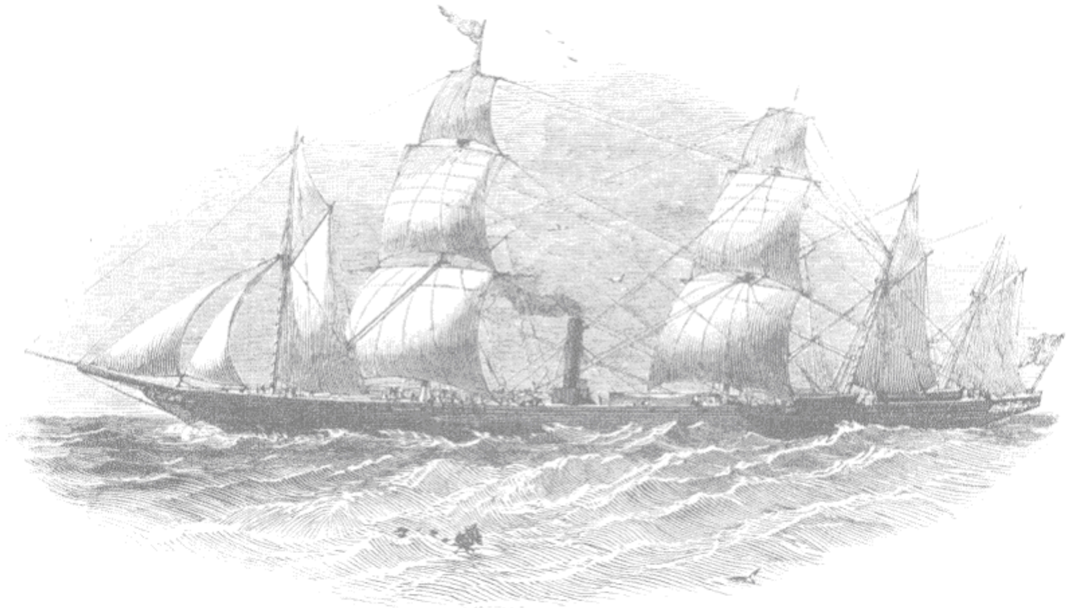
The institutional recognition of iron vessels was also advancing (Smith 1938, p. 97). In 1838 the records show that the first iron ship was examined by Lloyd's Register, the ship classification society. It was the *Sirius*. Classed A1, she received the highest certification of construction quality (Jones 2000, p. 22; Watson 2010, p. 110; see Box 3.1). The second such vessel to be examined was the *Ironside*, also in 1838, which was not classified but referred to as "Built of Iron". It is of note that the *Ironside* and the *Rainbow* were employed by Sir George Airy (1801-1892), Professor at Cambridge and head of the Royal Observatory at Greenwich, to devise ways to counteract the disturbance of iron plates on the ship's compass. His results were published in the *Transactions of the Royal Society* in 1839, showing that the deflection could be effectively neutralised. By the time the *Great Britain* was floated in 1844, the problems with the compass had been largely overcome (Rowland 1971, p. 55).[60] This same year happened to be the first in which a reference to iron shipbuilding appeared in Lloyd's Register Rules of good ship construction (Watson 2010, p. 109).

[60] The system of correction proved successful and was soon adopted, remaining in use for decades (Chapman, 2004). In fact the essence of the approach was still in use until satellite systems finally made it redundant over a century later (Corlett 1990, p. 37; Walker 1999, p. 59).

The first iron-screw "Mammoth", the paradigmatic exemplar of the modern steamer

The number of steamers grew in the 1830s, but their individual size remained relatively small. At this stage paddles ruled steamship architecture, while iron steamers were still used solely for short-haul work. The *Great Britain*, the Great Western Steamship Company's second ship, would change all this (see Figure 3.8). This vessel was originally referred to as *Mammoth,* an apt epithet for something more than twice as large as anything afloat in the world (Ball and Wright 1981, p. 5) and well over three times any iron vessel launched until then (Smith 1938, p. 101), and it was to set new standards in a variety of dimensions. She would bring together a constellation of technologies and characteristics in a way that would become a "paradigm" or an exemplar for the steamship community.

Figure 3.8 The *Great Britain,* newly rigged



Source: *The Illustrated London News,* reproduced in Ball and Wright (1981, p. 29)

The moment *Great Western*'s commercial success was apparent, the company's directors started considering a follow-up ship along the wood-paddle configuration (see Ball and Wright 1981, p. 5; Rowland 1971, p. 22; Corlett 1990, p. 14). This intention developed further during 1838 due to the mounting pressure from other steamship pioneers on the Atlantic (Griffiths 1999b, p. 63; Spratt 1951, p. 36). Cunard's operations, supported by his new exclusive mail subsidy for the North Atlantic run, would only made matters worse. The Great Western Steamship Company began to realise that only very large vessels could operate successfully without the benefit of government sponsorship (Rowland 1970, pp. 56-7). During the coming years, the vessel's name would not be the only thing to change (as Chapter 2, Section 2.3, made us expect). These were years of restless competition and continuous innovation creating high commercial and technological uncertainty. The ship's plans would go through six different versions before being finally launched in 1844 (Corlett, 1990). The concept behind the new ship also grew in size at each redrafting. But the project was an intellectual journey that evolved qualitatively as available information and experience in the surrounding steam-shipping world expanded. Two encounters, in particular, would shift the path of the project in the direction of the iron-screw design. In the event, several of these modifications became the pattern for future modern shipbuilding (Kemp 1978, p. 156). I.K. Brunel, who masterminded the project, would prove an able synthesiser of established lessons and ongoing learning processes.

In October 1838, during a fortuitous visit of John Laird's *Rainbow*, the first signs emerged that iron was being seriously considered (Griffiths 1999b, p. 63). According to historians, the *Rainbow* was the reason why iron would be adopted for the *Great Britain* (Corlett 1990, p. 25; Kemp 1978, p. 153). Brunel's partners, Guppy, Claxton and Patterson, went on the *Rainbow* for a number of trips and could see Airy's experimental correction system in operation (Griffiths 1999b, p. 63). Brunel went as far as to instruct Captain Claxton and the shipbuilder Patterson to obtain first-hand information on her performance by taking a passage to Antwerp and back (Rowland 1971, pp. 22-3). The personal investigation of this and other iron ships led them to conclude that iron "would afford greater strength, greater buoyancy and more capacity and less expense than wood" (quoted in Corlett 1990, p. 26). It was also concluded that oxidation could be guarded against more cheaply than the care that would have to be taken in maintaining timber (Corlett 1990, p. 26). In addition, Brunel would make use of Scott Russell's work on the "Committee on Waves" to work out detailed calculations on the connection between hull size and engine power (Lambert 2008, p. 4). The *Great Britain* would have the hull divided into six compartments by transverse watertight bulkheads, a construction approach pioneered in Laird's *Garry Owen*. This was an early use, and the first on a grand scale, of a structural feature that would be made compulsory by an Act of Parliament in 1846 for iron steamers of above 100 tons.

And what about propulsion? Patterson had laid down the keel at Bristol on July 19, 1939. The paddle-system now being considered for the new ship was enormous and was putting great strains on existing iron-styling expertise.[61] Brunel, at the same time the iron-paddle ship layout was taking shape, was already growing dissatisfied with the paddle system (Rowland 1971, p. 30). Indeed, he had spent the final months of 1839 and the early 1840 studying more efficient designs for paddle-wheels, and had already arranged for one his partners to collect data on rolling and pitching in the *Great Western* (see Lambert 1999b, p. 33). When Smith's *Archimedes* visited Bristol in late May 1840 (Corlett 1990, pp. 48-9), the time was ripe to draw the full implication (see Parker and Frank 1928, p. 14 and p. 127). This event was the first step in the process of abandoning the paddle-wheels. Brunel had one his associates to go on board the *Archimedes* for an excursion, during which they encountered heavy weather; this showed how the

[61] Brunel's new project reflected external learning as much as it promoted it. Before the change of plans, the enormous scale of the projected machinery was creating challenges beyond the capacity of the available machine tools. At Brunel's suggestion, James Nasmyth, an engineer apprenticed to Maudslays, was contacted in June 1839 with regards to forging the paddle shaft for the largest ship being built at the time, no one else being willing to make it (the often retold episode was originally described in Brunel's biography; see Brunel 1870, p. 252, fn. 1). This request for a new iron piece would lead to Nasmyth's seminal work, the steam hammer. Nasmyth informed Brunel, who approved the new forge hammer, and gave the shipbuilders permission to adopt it on the condition that his own firm would become the supplier (Petroski 1997, p. 39). On the abandonment of the paddle scheme, a need no longer existed for the tool. This invention, however, "was to form one of the foundations of Victorian heavy industry" (Corlett 1990, p. 17). The machine became indispensable for the expansion of railroads, as well as for the forging of large anchors for steamers of ever growing size, not only in Britain but also abroad, for example, in France and America (Petroski 1997, pp. 34-46). In 1851 it was proudly displayed at the Great Exhibition.

propeller was practicable even under such circumstances (Corlett 1990, p. 49). On June 18th Brunel stopped the ongoing work with a view to considering the new mode of propulsion for the new ship. Brunel would supervise the examination of the system and produce a report. On the following October 10th, Brunel laid before the board of directors an extensive analysis on the subject; interestingly, copies of this long and comprehensive document were also widely circulated and shared outside his company (Griffiths 1999b, p. 75). At a special meeting the following December 1840, the paddle-wheels were officially discarded in favour of screw propulsion. The *Great Britain* was to be the first screw-driven steamer purposefully built for the Atlantic.

The *Great Britain* can be said to be "the first vessel to embody all the elements of the modern ship" (Ball and Wright 1981, p. 5). The way how the necessary knowledge integration for this innovation was achieved provides a vivid illustration of the community-like mode of innovation (see Chapter 2, Section 2.4). As Walker (1999, p. 56) put it: "Most would know of each other's work, and without doubt there was considerable cross-fertilisation of ideas between engineers and builders of the time." Also, her size and the very public nature of her construction process and her adventures along the way (including a particularly important "summative evaluation" at Dundrum Bay) are in line with our theoretical expectations: non-representative projects mattered for reinforcing specific learning paths (i.e. Chapter 2, Section 2.3). Her story was a key source of lessons to the experts and the public in general (see Box 3.4).

In the particular case of the *Great Britain*, not only was she of large size and employed mechanical power, screw propulsion and metal construction, she also exhibited a number of other less conspicuous but nevertheless influential characteristics.[62]

[62] The bottom part of the ship was laid up with ten deep lengthwise beams, above which there was an iron deck, which effectively formed a "double bottom", a safety feature that would then spread to other ships (Abbel 1948, p. 115); the new "balanced rudder" adapted to suit screw propulsion made steering much easier in the water by making the iron rod (called the rudder stock) in such a way that the rudder area was evenly divided by the connection – this type of rudder come to be generally adopted some 20 years later and is exactly like a modern one; her fine hull lines, particularly the hollow (concave) entrance and long run aft were not dissimilar to those of the fast sailing vessels of the 1850s and 1860s (Corlett 1990, p. 40);

Box 3.4 The *Great Britain* project on public display, a source of "crucial impetus"

On July 19, 1843, almost exactly four years after the building started, Prince Albert shattered the bottle of champagne that baptised the ship as the *Great Britain*. She stayed in Bristol until January 1845, being fitted out and waiting for the locks of the harbour to be widened because of her size, yet despite this she got stuck on December 10, 1944. She measured 322 ft in overall length and her propulsion unit was the world's most powerful (discharging a nominal 1800 hp) as well as being most unusual (it was based on Mark Brunel's 1822 "triangle engine" design). She achieved an average speed of more than 11 knots, with a maximum of 12.5 knots, over a 95-mile run on her first trials in January 1845 (Ball and Wright 1981, pp. 12-7; Greenhill and Giffard 1994, p. 135). Experienced engineers and enterprising inventors such as George Rennie, Samuda, Petit Smith and Woodcroft as well as 140 other people were guests on board during trials held on January 8 (Rowland 1971, p. 61).

She departed for London on the 23rd of that month and moored on the Thames in the mid-afternoon of the 26th. Thousands gathered to see her and many groups were taken aboard (Rowland 1970, p. 85). She would stay for five months for final refurbishment of her interior. On the 23 April, 1845, she was visited by Queen Victoria and her consort. On 12 June she departed for Liverpool and was again opened to the public for visits; 2,500 visitors came everyday. She sailed for New York on July 26, 1845, with 45 passengers (out of a possible maximum total of 253 in two classes) and 360 tons of cargo (Corlett 1990, pp. 98-9).

On September 22, 1846, a significant event would occur. An accident took place that would be a "summative evaluation" for the iron-screw community but one which would prove too much for the straitened Great Western Steamship Company. She left Liverpool for her fifth voyage to New York on the morning of that day, carrying 180 passengers and 130 crew, but she became stranded that evening in Dundrum Bay, on the Northern Ireland coast (Ball and Wright 1981, p. 31). No lives were lost but for nearly a year the ship remained aground. In December Brunel went there to assess the situation, and was appalled by what he saw: the ship was "lying like a useless saucepan kicking about on the most exposed shore you can imagine" (Ball and Wright 1981, p. 32). After enduring winter storms, she was finally salvaged on August 28, 1847, without suffering any substantial damage or change of form, a strong testimony to the value of an iron structure for ships – a selection event or a "natural test", as it were, of the strength and safety of iron ships. For example, James Laing (1823-1901), by then already an innovative builder of wooden ships, would come to witness the stranded *Great Britain* and become conscious of iron as the material of the future - his first iron ship, also the first built on the Wear, was *The Amity* in 1853 (c.f. Richie, 2004). Corlett (1990, p. 194) says of the Dundrum Bay 1846-1847 episode that it was a key lesson for "shipbuilding and shipping fraternities" that iron and screw were practical and reliable approaches for large ships. The ship survival would prove influential, i.e. a "demonstration effect", as Chapter 7 will argue. Hence, Greenhill (1993b, p. 25) asserts, the *Great Britain* gave a "crucial impetus both to iron construction and to the adoption of screw propulsion".

In the eyes of contemporaries who authored pieces with pretentions to become textbooks on steamship design she was a case study (e.g. Curr 1847, p. 148) and a "magnificent specimen of iron-shipbuilding" (Fincham 1851, p. 387). For observers like William Shaw Lindsay (1816-1877), the shipowner and one-time MP for Tynemouth and North

finally, her six-mast schooner arrangement was a world's first and proved very economic in handling, anticipating by several decades American and German sailing ships with this rigging at the turn of the century (Brock and Greenhill 1973, p. 75; Hope 1990, p. 277); all the masts, with exception of the main one, could be lowered to the deck when not in use (cf. Gilfillan 1935b, p.165).

Shields, the importance of this vessel was clear enough. Judging from his experience in shipping and with the benefit of hindsight, Lindsay, the author of the encyclopaedic *History of Merchant Shipping*, perhaps the closest thing to a "definitive" history of merchant shipping written in the 19th century, considered the *Great Britain* the model of, in his words, the "perfect ship" (see Marsden and Smith 2005, p. 91). As a contemporary newspaper put it, here was "the most splendid experiment in shipbuilding ever submitted to the British public" (quoted in Baker 196, p. 45).

The selection of iron and the realisation of new advantages

In 1850 about one-tenth of all ships were iron-built, but just ten years later that proportion had risen to one third (Smith 1938, p. 105). Of the newly-built vessels of the early 1860s half was of iron (Maywald 1956, p. 45; Underhill 1963, p. 11; Slaven 1980, p. 113; MacGregor 1984a, p. 16).[63] Almost all of iron vessels were steamers, the type of vessel where advantages of the new material were most evident (de Voogd 2007, p. 573). From the 1830s to the 1850s, this process mainly took place in ships designed for short-distance routes, while between 1850 and 1860 the change was mostly taking effect among the population of longer-route steamers. Experience grew "quantitatively" with the growing number of iron ships built but also "qualitatively" as design had to cope with the requirements of a widening array of trades. Throughout these years the relative advantages of iron would have become apparent to an increasing number of engineers, naval architects, shipbuilders and shipowners.[64] Not only was knowledge circulated in

[63] In contrast iron took much longer to make headway in the United States. The first iron ships began being built in the 1830s (Pollard and Robertson 1979, p. 40). Iron shipbuilding started in some volume only after 1870 and by 1904 there was still 58 per cent of American tonnage built of wood, compared to about 99 per cent under the British flag (cf. Johnson 1906, p. 41). See also Sechrest (1998, pp. 18-20).

[64] Iron was, nevertheless, not problem-free. Its drawbacks, however, were not seen as insurmountable. One was oxidation of the hull, which was made worse by erosion due to the mechanical action of the water. Nonetheless, it was soon found that painting provided a satisfactory answer to the difficulty (Corlett 1990, pp. 36-7). The other problems were largely unexpected, but not seen as unsolvable: the interference with the magnetic compass, the quick fouling of the bottom by algae and marine growths, and the sweating of inadequately ventilated iron hulls which tainted valuable cargos such as tea. As referred above, approaches to correct the deflection of the compass were rapidly devised. By the 1870s a

the form of documents on iron ship building (penned by Fairbairn, Scott Russell, Brunel, Grantham, and others) but information also spread on a number of demonstrative projects and "natural experiments" (i.e. highly-visible and reported accidental selection events providing "summative evaluations" for engineers and naval architects).[65] As a reflection of the spurt of iron ship building, Lloyd's Register issued its first specific rules for iron vessels in 1855, by then a main area of interest for the classification society (Jones 2000, p. 22; Watson 2010, p. 110).[66] The use of iron was still evolving but a number of operational advantages were already recognised (such as fewer repair requirements, larger internal space, and improved safety)[67] when compared

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fair measure of success had been achieved in terms of anti-fouling paints and naval architects had learned to make proper arrangements for the efficient ventilation of the cargo space (Corlett 1990, p. 37; Walker 1999, p. 59; Craig 1980a, p. 9).

[65] Certain new projects were very influential events for the steamship building community. This was not confined to the case of the *Great Britain*, the largest steamer of her time and the most influential exemplar of the iron-screw steamer (Fenton 2008, p. 181), there were many others (see Rowland 1970, p. 91). The arrival of the *John Garrow* on the Tyne is credited to have prompted T.D. Marshall of South Shields to produce the first North Eastern iron ship, the *Star* in 1839 (Dougan 1968, p. 28; Clarke 1997, p. 58). John Laird's *Nemesis* went onto rocks in 1840 and survived, proving the superiority of iron construction (Warren 1998, p. 31); the same happened with the *Garry Owen*, but during that storm several wooden ships were lost, a comparative performance that served as a strong argument in favour of iron (Dollar 1931, p. 58). The *Rainbow* was employed by the General Steam Navigation Company to carry goods and passengers between London, Ramsgate and Antwerp. Besides being seaworthy and easy to handle, it was immediately apparent that this vessel could store nearly twice as much cargo in her holds as a wooden ship of the same size (Kemp 1878, p. 153). From the point of view of structural engineering an instructive episode involved another iron steamer, the *Prince of Wales*. In the spring of 1845 she was in the process of being launched at Blackwall when the launching gear broke, leaving the hull unsupported over a length of 110 feet. This caused some bewilderment since she was still undecked amidships, i.e. she was still waiting the machinery and boilers to be fitted (Rolt 1970, p. 84). Another lesson, this time having to do with safety concerns, was supplied by the auxiliary screw ocean-going steamer *Sarah Sands*, built in 1846 following John Grantham's design (see Bonsor 1955, p. 50; Craig 1978, p. 24). One day in 1857 she was 400 miles off Mauritius when she caught fire, yet she remained seaworthy. The fact that she was made of iron and divided by bulkheads averted the spread of the fire and no lives were lost (Smith 1938, p. 103). Following the destruction of the wooden-hulled *Amazon* on January 4th 1852, burnt out by fire at the onset of her maiden voyage carrying mail to the West Indies, the Admiralty lifted its objections to iron hulls for mail packets (Maber 1980, p. 7).

[66] This can be though as an indicator of the attention given to higher standards, the number of iron ships having greatly increased as well as the demand from shipowners and underwriters for their quality assessment and official recognition (Clark 1912, p. 291).

[67] Iron lowered running costs generally and promised particular gains in specific trades. Iron vessels were not liable to hogging and sagging (Derry and Williams 1960, p. 371; Pollard and Robertson 1979, p. 13) and the perpetual small leaks of wooden vessels (Kemp 1978, p. 153; Greenhill 1980a, p. 18) or to rot (Beeler 2000, p. 18). Timber was also of uneven quality, while iron production was more controllable (Pollard and Robertson 1979, p. 13). Although sceptics argued that in the event of an accident timber would be a more suitable material to repair (*Encyclopaedia Britannica*, "History of Transportation", p. 654), it was also found that iron ships were more easily and cheaply repairable than timber ships and hence could have longer working lives (Smith 1938, p. 97). Another argument in favour of iron, as noted by Brunel in the *Great Britain* project, was that it brought freedom from the unhealthy and unpleasant vapours of bilge water (Corlett 1990, p. 26); this, of course, helped cargoes to arrive at their destinations

with timber as a shipbuilding material. However, the most powerful reasons for adopting iron, to which we now turn, were related to structural engineering and economy.

An important feature of iron ships was that they led to the selective retention of new hull shapes and proportions. In other words, ships could now be made larger and, in particular, longer. New materials and framing methods were being actively sought as a means to go beyond the practical limits of traditional timber construction (Souza 1998, p. 106). "To the engineer at least," Slaven (1980, p. 11) pointed out, "iron was the answer to size and strength."[68] New ships were soon to show a marked increase in size (Dollar 1931, p. 54). But greater tonnage was not obtained by pushing equally all major dimensions: iron made it easier to produce proportionally longer ships, a "heuristic" that never failed to be pursued by engineers designing larger vessels ever since (Walker 1999, p. 57; Sahal 1985, p. 62; see Chapter 2, Section 2.2). Before, a wooden hull presented increasing difficulties at a length of 300 ft or at a tonnage of 5,000 tons beyond which it would lose rigidity, especially if further strained by a fast-turning shaft for screw-propulsion (Slaven 1980, p. 112; Hope 1990, p. 297; Souza 1998, p. 106; Watson 2010, p. 124). Now length could be further extended to the point that by 1844 Napier believed that a length of 6 beams was adequate for ocean steamers (Pollard and Robertson 1979, p. 132; Macgregor 1988, p. 131).[69] Walker (1999, p. 57) provides a good synthesis of the benefits of a long and narrow hull: "increased speed for the same power output, greater cargo-capacity rising by the cube of the length, better sea-keeping

in better condition (Smith 1938, pp. 96-7). Moreover, iron structures were not so easily damaged in accidents and, by allowing for the introduction of watertight sections and double-skinned hulls, iron greatly diminished the consequences of stranding and collisions (Dollar 1931, p. 64).

[68] Another alternative, introduced in 1852, was the composite approach. But it had a relatively short life; it also was applied especially to the tea clipper sailing ship market segment. It came to represent a sort of interim stage (Underhill 1963, p. 11), a sort of "temporary compromise" (Derry and Williams 1960, p. 368). Clippers of iron frame and wooden planking could then be built very narrow and long indeed, with a length to beam ratio of up to 8:1 (Dudszus and Henriot 1986, p. 73). Composite construction was used in tropical waters where fouling was intense but copper sheathing could not be combined with iron as it set up a galvanic reaction. See also MacGregor (1993) and Allington and Greenhill (1997).

[69] See also Dollar (1931, p. 64) for a contemporary witness perspective on iron allowing for the minimisation of resistance and improved sea performance of new hulls.

in the long swells of the oceans and, subject to good design, better handling qualities in rough conditions".[70] At the same time that engines grew more powerful and screw-propellers became more compelling, so too did iron became more attractive since it could stand the weight of larger engines and could absorb the vibration of the rapidly rotating shaft. Thus, new (iron) steamers began increasing in cargo capacity and it was not long before they achieved "dimensions which any contemporary shipwright would have regarded with absolute incredulity" (Rolt 1957, p. 236) (see Box 3.5).

Later, in the 1870s and 1880s the introduction of steel brought further gains along the same trajectory: steel meant thinner plates without reduction in hull strength, saving between 15% and 25% in hull weight (Kemp 1978, p. 172; Pollard and Robertson 1979, p. 14) and about 23% increase in internal cargo space proportional to external dimensions (Maywald 1956, p. 47). This implied less coal consumption, an extra knot or two in speed with the same power unit, as well as more earning capacity per registered tonnage (i.e. greater "effective carrying capacity", see Chapter 4, Section 4.4). Steel as a new construction material enhanced the ability to further increase ship size and derive economies of scale without implying an overhaul in structural design, i.e. it was a readily adopted "modular innovation" (a radical component alteration without major architectural consequences, see Chapter 2, Section 2.2). From this point onwards, iron could only be found in tugs and trawlers (Thomas 1993, p. 22). That steel did not present major structural changes in the general outlook of steamship is underscored by how fast it replaced iron, "within a time even shorter than that needed by iron for its victory over wood." (Maywald 1956, p. 47)[71]

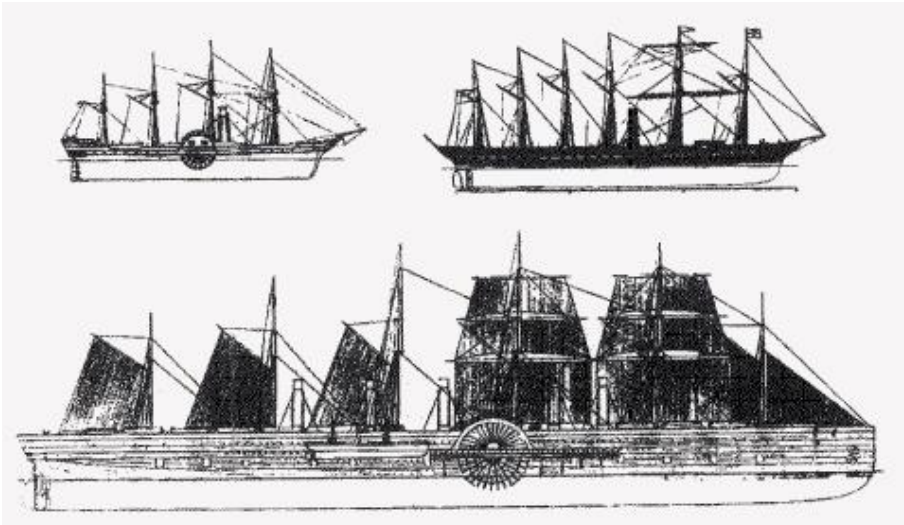
[70] An additional advantage, in the early days, was that longer ships could fit the pre-existing docks and harbours, which could not accommodate as easily wider and deeper ships (Craig 1978, p. 35).

[71] The coming of steel will not be investigated further in this thesis. For reasons of space it will suffice to note that once the Dennies of Dumbarton put out the first steel merchant ship in 1878, the *Rotomahana*, the extinction of the iron hull was remarkably swift. Corlett (1990, p. 201) asserts that the iron ship virtually disappeared in new British tonnage shortly after steel's introduction. By 1886 steel tonnage afloat exceeded iron, which from 1862 had prevailed over wood and composite onwards, and in a short while steel comprised more than two thirds of new tonnage (Johnson 1906, p. 41; Maywald 1956, p. 49). In the three decades before 1914 British shipbuilding absorbed almost 30% of national steel output

Box 3.5 Brunel's third and final transatlantic steamship, the iron "Leviathan"

In the early 1850s Brunel, now with two successful ocean-going ships to his credit, was Britain's most influential steamship designer (Kemp 1978, p. 168). It has been argued that the rise in the size of British ships is, at least in part, related to his thinking (Corlett 1990, p. 11). Even so, there were new and bold plans in his mind for a great ship, the largest of them all, the *Great Eastern*, "the most gigantic experiment of the age."* Here then, on a massively untried scale, were all the elements of the modern ship integrated into one hull: "metal construction, steam-driven screw propeller, and large size deliberately aimed at good economics." (Corlett 1990, p. 11) Launched in 1858 the newest of Brunel's ships would be, with little doubt, the greatest milestone in the history of ship technology in the 19th century. Some of the best intellectual work of the mid-Victorian age would be drawn into this "magnum opus" in some way or another: among those involved were John Scott Russell, William Froude, Airy, Robert Stephenson, William Fairbairn, and Joshua Field of Maudslays. If the "*The Great Britain* was at the very edge of technological knowledge, the *Great Eastern* was well beyond it." (Corlett 1993, p. 97)

Brunel's three ocean-going steamers



Source of illustration: Caldwell (1976, p. 137)
Note: An indication of the increasing size of and complexity of Brunel's undertakings can be inferred from this figure. The *Great Western*, the *Great Britain* and the *Great Eastern* ships, launched in 1837, 1843, and 1858, had a length of 236, 322, and 692 feet respectively

* From an address of the President of Institution of Civil Engineers, quoted in the obituary of Brunel in *Yearbook of Facts* (1859, p. 283).

Iron offered new opportunities in terms of structural design because it allowed new shapes and sizes and because it had synergies with the screw.[72] Above all iron made sense in terms of economics. Early on, John Grantham (1842) was arguing that iron became cheaper than timber for vessels above 300 tons (Rowland 1971, p. 25). By the

(Pollard and Robertson 1979, p. 6). Looking back, a learned shipowner remarked: "Wood yielded to iron slowly; steel displaced iron in a surprising short time." (Dollar 1931, p. 59)

[72] This was equally true for naval design: "The iron hulled warship had opened up an almost limitless horizon for larger, more powerful and better designed ships." (Lambert 1992c, p. 58) See also Brown (1990). On how iron had been creeping into wooden sail see Sutton (2000, p. 45) and McCarthy (2005).

mid-1840s a large wooden hull was 40 percent more expensive than an iron hull of the same size (Corlett 1990, p. 11; see also Slaven 1980, p. 117) As Brunel had explained to the Great Western Company directors already in 1836, frictional resistance on the water increases much more slowly than size, hence the economic advantages of larger vessels (Corlett 1990, p. 13). These advantages were increased by yet another key factor in the economics of shipping, the greater earning capacity of iron ships for the same overall dimensions (Greenhill 1993b, p. 25). By doing away with the heavy beams to sustain the hull from within, there was more accommodation inside and especially more room for taking on bulky loads. As Fred Walker (1999, pp. 56-7) explains, comparing "two identical ships, one iron and the other timber, it is possible to have an increase in cargo space of the region of 20 per cent."[73] Iron hulls made with thinner plating and supports could be made about 40% lighter in the mid-1840s, and thus considerably faster and more fuel efficient. Because steamships still "absorbed great quantities of coal in relation to the distance steamed" (Brock and Greenhill 1973, p. 13), the smaller weight and larger internal space were crucially economical over longer routes (Corlett 1990, p. 11). Hence, "changes in materials had important effects in carrying capacity per ton, and were thus of considerable economic importance." (Maywald 1956, p. 46)

Material costs eventually contributed to tip the balance in favour of iron. The advantage of cheap timber was vanishing at the same rate of the coastal forests disappeared; labour, operating and overhead costs were also rising (Heaton, 1960 p. 35; Hope 1990, p. 273). Throughout the 1840s and 1850s the cost of iron, the "core input" of the age, decreased faster than that of wood, and by 1860 there were problems with timber supply (Pollard and Robertson 1979, pp. 13-4). Meanwhile, the iron industry was on the path of a sustained expansion, one that would occur between 1815 and 1875 (Riden 1980, p. 65). Of course, iron production became closely tied to the fortunes of railway activity so

[73] See also Maywald (1956, p. 47), Pollard and Robertson (1979, p. 14), and Macgregor (1988, p. 131).

that when in the early 1840s, in between two railway manias, as iron output decreased, prices decreased even faster (Lloyd-Jones and Lewis 1998, p. 53).[74] Prices of pig iron fell from 1836 to a low in 1851, but then iron exports jumped vigorously and iron production recovered very fast so that the 1850s became years of rising prices (Riden 1980, p. 65 and p. 78). At the same time improving technology of some of the new rolling mills was allowing larger plates to be made more easily and with better quality, thus reducing bolting and welding needs (Deeson 1976, p. 78). Hence, by the mid-1840s iron plates were coming in prices and sizes acceptable for building steamers for oceanic purposes (Brock and Greenhill 1973, p. 16; Greenhill 1980, p. 18; Greenhill 1993b, p. 22). By the 1850s iron tonnage was already less expensive to build than wood (Mitchell 1964, p. 115 and p. 166; Slaven 1980, p. 117) and the relative price of the input kept falling down (Pollard and Robertson 1979, p. 14). Iron was cheapest in comparison to wood on Northern rivers (Arnold 2000, p. 48). Hence, shipbuilders on Clydeside and the North East coast, closer to more abundant iron and coal sources, increasingly became better placed to take the initiative in the industry on the basis of comparative advantage (Moss and Hume 1977, p. 87; Walker 1999, p. 61; Schwerin 2004, p. 87).[75]

Summary of section 3.3

Ships are big aggregations of knowledge; they are large machines that incorporate thousands of smaller inventions accumulated throughout scores of years. In this section we abstracted from this complexity and identified three key components of steamships: the power unit, the type of propulsion on the water and the hull material.

[74] According to Riden (1980, p. 82), domestic railway consumption of iron peaked at 20.8% in 1840, falling to 8.2% during 1840-45; but as a new mania started (the years of 1846-50; see Hobsbawm1867, p. 110; Ville 2004, p. 305) the proportion rose to 18.7%.

[75] A number of northern rivers' players increasingly vied to build competitive iron steamers. Clyde marine engine builders, like Robert Napier (first iron steamer in 1843, the *Vanguard*) or Tod & MacGregor (builders of the profitable iron-screw packet *City of Glasgow* in 1849), more experienced with working with wrought iron, and T.D. Marshall of the North East, who started out as a smith, became important references in the iron-screw steamer business as London and Liverpool started to lose their relative position in the industry by the mid-1850s (see Craig, 1980a; Clarke, 1997; Fenton, 2008).

The "side-lever engine", with minor variations since the *Comet*, was the standard layout until the 1840s, when new varieties of marine engine started to appear. Largely borrowing from each other and the firms in which they were apprenticed, steamship innovators were able to learn from many variations of best practice and free to adjust their ideas to the ever larger ships increasingly built on the iron-screw foundation. At the turn of the 1840s the screw-propeller was a growing focus of attention. The open display of ships showcasing the technology (e.g. the *Archimedes*) and public demonstrations of its merits (e.g. the *Alecto-Rattler* trials) were key factors in the spread of this approach as an alternative to the paddle system. Iron as a construction material was adopted in connection to steam navigation with early vessels like the *Aaron Manby* in the 1820s but only very gradually so. Pioneering practitioners like Fairbairn, Scott Russell and Grantham published the results of their experiments, their research and their shipbuilding experience; in so doing, they promoted an open and academic-like pattern of behaviour – i.e. the freedom to implement, study, modify and share technology (see Chapter 2, Section 2.4). As the absolute and relative price of iron plates went down at the turn to 1840s, experimentation became cheaper and steamers like those built by John Laird (e.g. the *Rainbow*) or Brunel's great ships (i.e. the *Great Britain*) provided models (exemplars of a new paradigm) of the benefits that could be achieved through iron. Iron was the container in which the full potential of new marine engineering developments and screw-propellers could be harnessed (see Chapter 2, Section 2.3).

Unlike many technologies there was not a fluid pre-paradigmatic phase in which many different designs competed: the wood, side-wheel, side-lever combination had been the "dominant design" from the outset. The wholesale adoption of the iron-screw design was not so much the emergence of a "technological paradigm" on a landscape in state of flux; rather it was a paradigm shift representing a fresh promise to break away from the limitations of the existing paradigm to a steeper trajectory of sustained improvements in terms of ship size and coal efficiency. This happened because "symbiotic technologies" converged in a radically new product "architecture" that became capable of extending the economic services into new and existing "selection environments" (Chapter 2, Section 2.2). During the 1840s new technologies coalesced into a pioneering and influential project, which constituted the first exemplar of modern ship design:

> "constructed of metal, thus attaining rigidity, lightness and water-tightness in one step; mechanically driven, thus attaining independence of favourable winds for making a passage; screwpropelled, thus attaining propulsion whose efficiency was not affected by draught and which left the hull clear of encumbrances; of modern proportions and good hull form. Appropriately, the name of that first modern ship was *Great Britain*" (Corlett 1990, p. 11)

3.4 Varieties of steamers

The changing heterogeneity of steamers

So far we have learned that progress in steam navigation followed a basic template for its few first decades (Section 3.2). Drawing together a rather fragmented body of literature, we also gather that by 1840 steamship development was held in check by a number of limitations. But it is also at that point in time that we see the first demonstrative experiments successfully interlinking new developments in propulsion and construction, with marine engines being continuously improved (Section 3.3). The iron-screw combination became the foundation of the modern ship, the basic layout of a new powerful and enduring technological paradigm in merchant shipping. The new solution vastly expanded the productive potential of the steamer: ships were soon to become larger and more capacious but also increasingly capable of operating in new environments and trades. By mid-century the iron-screw ship was well on its way.

In this section we will see that innovation took place in the context of different application sectors in which user groups emphasised particular functional requirements in an artefact so as to extract different services from it. In other words, the history of steam navigation is seen as the outcome of technological evolution in different selection environments. Thus, the remainder of this chapter will deal explicitly with the growing heterogeneity of the population of steamers.

The variety of steam vessels can be categorised and subdivided in a number of different ways.[76] In this thesis we will focus on two criteria, namely the technological and service characteristics. On the one hand, as engineering systems, and as discussed in Sections 2.2 and 3.3, steamers differed according to "core" attributes in engine features, propulsion transmission to the water, and structural material. On the other hand, as capital goods, steam vessels could carry out a range of productive tasks in transport services. Having already discussed the key (and changing) technical aspects of steamers, we will now focus on their intended uses. That is, we will talk of "trades" or "ship types" as a way to understand the diversity of the population of early steamers, while recognising that many details of the ships' careers are inevitably lost by such a simplification (see Appendix 3.4). This is done on the basis of the available literature which, with a few notable and useful exceptions, is both scarce and permeated by enthusiastic and ad-hoc treatments of steamers for the first half of the 19th century. Bearing these methodological qualifications in mind, we specify trades according to the commercial exploitation of the new technology. The present work identifies four main economic functions performed by the merchant steamer during the initial five decades of her development: ferries (carrying people and low-bulk goods in rivers, lakes or across channels), tugs (towing other vessels), packets (passengers and high-value cargoes) and general cargo steamers (low-value bulk freight).[77]

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[76] There are many methods to differentiate between vessels: buoyancy (rafts, boats/ships, submarines), duty (merchant or naval), number of masts, size, etc. (see Dudszus and Henriot 1986, p. 9 and pp. 15-6). Steamers, of course, could also be distinguished according to the context of their operations: local, regional, national, and international range of work (see Armstrong and Williams 2010, pp. 43-4). Many other methods of partitioning could be thought of, however.

[77] Our typology is in line with Greenhill (1993a, p. 9) who also identified four key trades in this period: "packet routes, towing duties, short sea bulk carriers and subsidised deep sea routes." It is also in line with de Voogd (2007, p. 574). We will refer to the short-sea work (very little of which subsidised) as being performed by "ferries".

Ferries

Following the *Comet*, other inland services were started on the Clyde and elsewhere. The usage of steam was especially attractive as vessels could go upstream, drive with greater precision along waterways without being battered by wind to the sides, and carry people and goods with increased speed, regularity and predictability. These services supplemented, but increasingly supplanted, travel by coach and fly-boats, and, of course, pre-dated railways (Maber 1980, p. 5; Body 1971, pp. 43-4). Early steam navigation was rudimentary and inefficient. It was first seen on the secluded waters of canals, rivers and lakes, where waters were calm, coal was accessible and breakdowns not necessarily disastrous (Woodman 1997, p. 175). It is also worth noting, with Harvey and Down-Rose (1980, p. 143), that the initial spectacular success of the steamer was really the success of the passenger ferry, i.e. the commercial breakthrough, in Britain as well as America, was not cargo-carrying but the people transportation business.[78]

From this point onwards steamboats, then mostly Clyde-built, started to appear on other rivers (see Williamson, 1904; Burt, 1937, 1949; McQueen, 1924; Dumpleton, 1973). The *Marjory* , the first steamer on the Thames[79], was brought down from Dumbarton where had been built by the Dennies; it was not long before the Thames became as busy with steamers as the Clyde (Body 1971, p. 46). It should be remarked that in the process of travelling to their new owners such steamers had to round the coastline, hence showing the viability of linking major port-towns.[80] By the early 1820s coastal routes were being plied by a growing number of steam navigation companies and links to Ireland and France had been inaugurated. In other words, the available technology was

[78] Incidentally, the same would happen in railways. Freeman and Louçã (2001, p. 194) note: “The advantages for passenger traffic were even greater, and the big surprise of the 1830s and 1840s was that passenger traffic initially grew faster than freight.”

[79] Her departure was announced for the 23rd January 1815: “Passengers and their luggage will be conveyed to and fro with more certain speed and safety, than by any other conveyance by land or water, and on reasonable fares. Passengers are requested to be punctual to the time specified.” (notice quoted by Burt 1949, p. 9)

[80] Farr (1956) is able to list 23 new passenger steamship companies in the 1820s and 1830s opening for business in the Bristol region alone, and plying a variety of routes in the Bristol Channel and between ports such as Bristol, Cork, and Waterford.

robust enough to be stretched out of its initial locus of application; it was also quite flexible since it could deal with a number of different environments.

For us, then, the term *ferries* will mostly refer to vessels of limited roles, involved in estuary or coastal work dealing with passengers and parcels. As coal bunkers took up much of a ship's cargo space, these vessels tended not to carry bulky freight (Hengst and Verkleij 2007, p. 394). Typically small and shallow-draught, these flexible ships could nonetheless be employed in rougher waters and even other related services such as towing and coastal cargo. Especially during the early days it is also difficult to distinguish them from packets either from a technical or a service point of view. That is, they could potentially be employed in the other three categories.

Ferries and cross-channel steamers were not in a hurry to adopt screw-propulsion and retained the wood-paddle design for much of the second half of the 19th century. There was not a lot of time to be saved in short passages and they did not have to venture into deep waters where large waves would make the action of paddle-wheels difficult. Paddles were popular with the public, worked well on shallow waters and had the advantage of rapid acceleration and stopping (Waine 1999, p. 12). Hume and Moss (1975, p. 16) indicate that only in the 1890s did paddle steamers start to be replaced in the various services around the British Isles. Shallow-draft and short-range ferries and excursion steamers kept being built well into the 20th century (Brock and Greenhill 1973, p. 16; Maber 1980, p. 12).[81] Indeed, such steamers doubled in job in the late 19th and early 20th centuries, their duties being "part-business, part recreational travel" with the increasing popularity of mass tourism on the rise in the late Victorian and Edwardian eras (Armstrong 1998, p. 40).

[81] Griffiths (1993, p. 117) states that the last paddler for river and short-sea routes was built in 1948. Dumpleton (1973, p. 187) claims the last big paddler built in Europe was the *Maid of the Loch* in 1953.

Tugs

"Steam power revolutionised the handling of ships in harbour" (*Lloyd's List* 1984, p. 66). Towing appears to have been an obvious line of work for mechanically-powered craft, even before steam navigation was technically feasible or even commercially proven.[82] Towing was one of the earliest applications of steam to navigation. The word "tug" appears to gain currency as early as 1817 (Clarke 1997, p. 88). In spite of being one of most discrete embodiments of steam navigation technology, towing represented a service innovation made possible by the new method of propulsion and one with great impact because it "permitted other major items of capital equipment to be used more productively" (von Tunzelmann 1995, p. 113).[83]

On the Tyne a towing service started in 1814 and its most important occupation was to be with wind-bound sail colliers (Ville 1986, p. 365). Towing started on the Thames in 1816, and by 1821 it had spread to Hull and Sunderland, and then to Liverpool in 1826 (Dougan 1968, p. 28). By the 1830s, the business was sufficiently extensive to warrant its own treatment in *Lloyd's List*. Several events coincided to cause a major development in the tug-building industry in the early 1850s: the gold rush to Australia in 1848, the 1849 California gold rush, and the outbreak of the Crimean war in 1854 (Dumpleton 1973, p. 155; Kemp 1978, p. 201; Thomas 1983, p. 21). Both events led to a frenzy of shipping activity and, as time was of the essence, to an increased demand for more powerful tugs. Enterprising owners made good profits and invested in more and better tugs (Bowen 1938, p. 29). Tug size and power had caught up with that of other ships when the post-Crimean war boom ended in 1856 (Bowen 1938, p. 30).

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[82] One is reminded of Jonathan Hulls who sealed a patent in 1736. This was the first unambiguous visual description of a steamboat (for towing tasks) in a patent claim (Spratt 1858, p. 33).

[83] There is very little literature covering tugs, their evolution and impact in economic history. Thomas (1997) wrote a remarkable and pioneering book on British steam tugs, perhaps the first real attempt to remedy the situation. Unfortunately, it mostly covers craft built from 1850 onwards.

Towing was an important service in helping deep draught vessels to manoeuvre in shallow and confined waters, and became more so as the numbers and average tonnage of ships increased throughout the century. Greatly important for port productivity, towage work also contributed appreciably to increasing the productivity of other ships when lack of wind, a head wind, an adverse tide or constricted waters prevented ships, especially sailing ships, from entering the port. But towage could also save ships in trouble from sinking and get them into harbour in time for repair, hence contributing to rescue mariners as well as extending the working life of tonnage afloat. Tugs were very versatile assets, an important characteristic especially in the early days when specialist steamers were not available. Tugs often carried passengers in their free time, i.e. dual use as tug and passenger ship was quite common (Body 1971, p. 147). A further example of versatility was apparent from tugboat *Goliath*, as she was chartered in 1850 to lay the first telegraph cable across the English Channel (Thomas 1997, p. 18). Thus, tugs filled several gaps in the supply and demand for transport services.

Branching out as a distinct part of shipping in their own right, towboats started to gain their own familiar profile. Tugs emerged more and more as heavily built vessels, with machinery taking up most space below deck, kept low if there would be bridges, having a broad beam to harness powerful paddle-wheels, working in congested harbours and thus usually small in size and not needing a high freeboard (Thomas 1983, pp. 9-10). Screw tugs came into use by the 1870s (Dumpleton 1973, p. 156). Nonetheless the paddle-wheel arrangement kept going well into the 1880s, with most of the tugs having two engines allowing for independent control of the wheels and increased manoeuvrability (Body 1971, p. 147; Thomas 1983, p. 21). This feature meant that tugs retained paddles for many years, especially when working in Navy docks (Dumpleton 1973, p. 160). Wood also remained as the principal material of construction up to the end of the 19th century, for instance into the 1890s on the Tyne, since it absorbed the bumping and other stresses while the small gains in cargo space made iron less relevant (Clarke 1997, p. 90). Iron tugs became a more familiar sight from the 1850s; but these were larger tugs chiefly employed in handling the biggest ocean-going ships, which kept growing in size (Body 1971, p. 146).

Packets

"The liner system evolved when there were dependable cargoes being carried on predictable routes between previously announced ports." (*Lloyd's List* 1984, p. 169)[84] It is not clear, of course, when it split from the simple ferry business. Less than ten years after the *Comet*, steamers were ready to work on fixed itineraries, tight time-tables and longer routes, whether full or empty. As early as 1821 the British Post Office began putting steamers on the same run as sailing-packets, conveying mail to Ireland and France (Tyler 1939, p. 18). Steamers were getting larger, less unreliable, and less uncomfortable. It was in this context that in 1824 the General Steam Navigation Company, the most noteworthy of the cross-Channel steamer companies, appeared; the following year it inaugurated a service to Lisbon (see Palmer, 1982). The technology available in the 1820s was thus sufficient to establish the steam packet working on short sea routes as well as on international waters (Armstrong and Williams 2007, p. 154)

Not all steam packets would benefit from state subsidies but the carriage of mail between specific stations would create a new level predictability of demand and provide the conditions for investment in more powerful, longer-haul vessels from the 1830s onwards, that is, when steam navigation was still a relatively young and fluid industry. Contracts for this sort of service started in 1833 when the General Steam Navigation

[84] Until 1816 the only existing regular ocean-going service was state-run. After the American Independence and Napoleonic wars, the first private company, and also the most famous, was founded in 1816 to operate on a regular schedule between New York and Liverpool – The Black Ball line. "Full or empty, in fair weather or foul," vessels departed from New York to Liverpool on the first day of every month (Hope 1990, p. 265). The service was innovative (the "liner" concept had been introduced) and it was dominated by Americans (Rozwadowski 2005, p. 10).

Company was granted a yearly subsidy of £17,000 in return for the weekly conveyance of mail between London, Rotterdam, Hamburg, and, later, to Gibraltar and Corfu (Tyler 1939, p. 74). As the Admiralty took over the packet service in 1836, a new era of steam navigation service would commence. A number of companies secured contracts in the following years: Cunard (began its operations in the North Atlantic in 1840), P&O (Mediterranean in 1837, India in 1840, Australia in 1842, China and Hong Kong in 1845), Royal Mail Steam Packet Company (Caribbean and South America in 1839, Australia in 1858), Pacific Steam Navigation Company (west coast of South America, 1840) and the Union Line (South Africa, 1857) (e.g. Moyse-Bartlett 1937, pp. 234-5).[85]

A new international network of fast postal communication was being built; the Empire was being linked up. But more distant voyages required more coal occupying more bunker space, and therefore more efficient steam technology and better economic returns were necessary. Given the state of the art, this could only done at the expense of "generous subsidies in the guise of mail contracts." (Maber 1980, p. 12) As Hope (1990, p. 272) makes clear, state financial support was not negligible, representing about 20% of running costs, and in the case of P&O it amounted to 40%. But these new opportunities came with stringent conditions, namely powerful engines, penalties for not keeping to the schedule, strong hulls capable of carrying heavy guns, and built-in adaptability to switch to troop-ships if needed. These companies developed a policy of purchasing the best steamers capable of providing punctual and reliable service in order to bid for and maintain government subventions under stringent contract terms, which until 1852 required mails to be carried in wooden vessels (Johnson 1906, p. 41). These had to be machines built for speed and comfortable service.[86] In the process, in what

[85] Steam packet (or liner) fleets of the second half of the century were even better known, and there is abundant, albeit rather romantic, literature covering it (e.g. Maginnis, 1892; Parker and Frank, 1928; Lee, 1930; Boumphrey, 1933; Tyler, 1939; Thornton, 1959). Bonsor (1955) could be included here but it is a high-quality reference source of detailed and documented information on the Atlantic liner trade, containing a wealth of particulars on companies and their steamers for over a century.

[86] Speed was an expensive service attribute. Coal consumption, experience would teach, increased as the cube of speed (Harley 1971, p. 217; Pollard and Robertson 1979, p. 16).

would otherwise have been an uneconomic field at this time, steamer technology was given a major impetus by exerting a stimulating effect upon marine engineering and naval architecture (Johnson 1906, p. 97; Hope 1990, p. 267; Pollard and Robertson 1979, p. 222).[87]

At this point one is reminded that those few unsubsidised steamers trying to compete in the Atlantic trade had to be even more cutting-edge vessels, and, indeed, vessels of great consequence: the *Great Britain* and the *City of Glasgow*, the first large iron-screw steamers (see Maber 1980, p. 15). Tod & Macgregor's iron-screw *City of Glasgow* of 1849 became the first really profitable screw steamer in the Atlantic (Bonsor 1955, p. 62; Brock and Greenhill 1973, p. 16). That is, the packet business called for ship projects that pushed the technological frontier ever forward (see Appendix 3.5). The efficiency of the "high-tech" combination attracted other non-subsidised shipowners. Technological competition was heightening and such developments led to policy changes even in companies operating under mail contracts. Cunard, for instance, soon abandoned wood on his fleet (the last wooden-paddler being the *Arabia* of 1851), and later the paddle (the last iron-paddle cunarder built for the Atlantic being the *Scotia* of 1862) (Bonsor 1955, pp. 15-7).[88] In the following decades passenger liners, mostly Clyde-built, kept being built larger, faster, and more luxurious. But they also increasingly absorbed the huge emigration flow to America (see Pollard and Robertson 1979, p. 13; Kemp 1978, p. 172). The square rig started to disappear in the 1860s, compound engines were being fitted in the 1870s, steel and triple-expansion came in the 1880s, then, at the turn of the century, quadruple-expansion engines and turbines geared to four propellers appeared (see Kemp 1978, pp. 171-3 and pp. 215-6).

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[87] In the words of a contemporary observer: "Though the ocean passenger service is of less importance than the freight traffic in the economy of society, the service of carrying passengers and the mails has had a greater influence than the freight business has exerted upon marine engineering and upon the introduction of technical improvements in ships." (Johnson 1906, p. 87)

[88] The mail packet market segment was indeed not the fastest in incorporating new radical technologies. Moyse-Bartlett (1937, p. 256) states that the first time a screw-propeller featured in one of this subsidised ships was in the *Esk* of 1849, a Royal Mail Steam Packet steamer. Apparently unsubsidised companies relying on more "standard" (not premium) packets had to rely in more economically efficient technology to make their ends meet.

General cargo steamers

Along with the emergence of the sea-going packet, another category would arise. The development of ordinary steam freighters "has been almost completely neglected by maritime, economic and industrial historians", notes Greenhill (1980a, p. 3), in spite of playing "a large part in establishing Britain's economic and political ascendancy." Indeed, increasingly utilisation of and improvements in cargo steamers constituted a key factor explaining why from 1820-24 to 1845-49 the volume of seaborne commerce entering Britain expanded by 195% while British tonnage increased only by 40% (Starkey 1993, p. 131). Cargo steamers became even more important when overseas trade more than doubled between 1850 and 1870, with British coal exports increasing almost four times between 1850 and 1870, from 3.2 million tons to 12.2 million tons (Clarke 1997, p. 93). The intensity of overseas activity is well reflected in figures showing that by 1914 tramp steamers had outstripped any other type of ship in terms of nominal tonnage volume: tramps amounted to 60 per cent of all British tonnage and two-thirds of British ocean-going vessels (Hope 1990, p. 338). The few but authoritative studies of the carrying trade have concentrated on the last third of the century when cargo steamers were already active on almost every ocean (see Harley, 1972; Craig, 1980a). By contrast, scholarly coverage is comparatively scarce up until the 1860s.

What were these cargo trades? Craig (1980a, p. 45) divides the practical cargo-carrying steamship into three main activities, although "with a great deal of interchange between them". First, there was tonnage almost exclusively devoted to coal, mostly from the North East of England to London. It should be said, however, that colliers never fully and constantly specialised in coal; they engaged in other trades as well (Ville 1986, p. 360).[89] Second, there were the cargo liners offering merchants more or less regular

[89] Fenton (2008, p. 177) names a few of earliest iron-screw steamers built for the coal trade but which came to be employed in other trades: the *Conside* (1847) which was immediately deployed on the Leith-Hamburg cargo route and the Clyde-built *Collier* (1849) also deployed in general merchandise liner trades.

schedules and accepting heterogeneous cargoes. A “liner trader” often had cabins for a limited number of passengers (Thomas 1993, p. 9). The third category of trader, hardly distinguishable from the coal and general cargo liners, was later known as the “tramp”, i.e. the “all-purpose” bulk cargo vessel (Dougan 1968, p. 51). Steam tramps were mostly a phenomenon of the latter part of the century and would prove to be the workhorse of the British merchant fleet (Harley 1971, p. 222). As Hendry (1938, p. 34) put it: “With the coming of the screw propeller the ocean tramp was born. Soon they were at sea in the hundreds.”[90] Tramps worked with no fixed time-schedules, carried virtually any kind of bulk, low-value staples “from anywhere to anywhere” depending on the best terms for freight available (Waine 1976, preface, unpaginated).

Work on the origins of general cargo steamer has revealed that these discreet vessels constituted ground-breaking projects in the history of merchant shipping. Robin Craig (1980a, p. 5), the staunch critic of the widespread tendency to concentrate on the “largest” and “fastest” ships, notes of a remarkable ship he was rescuing from oblivion:

> “... in 1842, the iron twin screw steamer *Bedlington*, 277 tons gross, was built by that highly innovative shipbuilder, Thomas Dunn Marshall of South Shields, intended to convey coal from Blyth to South Shields. She embodied several new features, including a double bottom for the carriage of water ballast, and revolutionary methods of loading and discharge … anticipating by several generations the rail ferry and the roll-on-roll-off ship.”

The *Bedlington* was a twin-screw collier; her three lines of rails were meant to load 40 coal wagons (Clarke 1997, p. 62; Fenton 2008, p. 176). She was an innovative ship and Lloyd’s Register surveyors would have inspected her (cf. MacRae and Waine 1990, p. 12). Another iron-screw collier that he goes on to describe was the aptly named *Q.E.D.* of 1844 (Craig 1980a, p. 5). Built by John Coutts at Walker-on-Tyne and engineered by Messrs. Hawthorn, she was fitted with four bulkheads and again a double bottom for carrying water as ballast. Bulk carriers in the coal trade probably occupied the lowest

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These early colliers spent over 40% of their working time employed outside the coastal coal business (cf. Fenton 2008, p. 195).

[90] For the same appreciation see also Course (1960, p. 22), Thomas (1993, p. 24), Waine (1999, p. 9).

rank in the scale of prestige among ship trades, with the luxury packet at the other extreme. Both these two vessels, however, were quietly doing their work before the *Great Britain*'s first voyage to America. Yet another example was the *John Bowes*, a robust and efficient iron-screw collier launched on the Tyne in 1852 by Charles Palmer under a blaze of publicity and press coverage; the vessel's cost was ten times that of an average-sized sailing collier, in addition to the higher running costs for fuel, but in her first five days she performed an amount of work equivalent to an entire month of cargo transported by two sailing colliers (Dougan 1968, p. 42).[91] Compared with the pure sail wooden collier, the steam-screw-iron combination lowered the cost of capital investment relative to cargo carried, these economies of scale were achieved via a higher throughput thanks to higher average speed and better regularity.[92]

The screw cleared the hull of the clutter and weight of the paddle gear, hence gaining new stowage space, reducing weight, making the handling of bulk goods easier and accelerating turn-around time (Fenton 2008, p. 181); and the screw needed an iron hull to withstand its twisting stresses (Waine 1999, p. 12, p. 16). That is, even early colliers and other humble cargo steamers could be seen as the forerunners of structural design developments that would later produce momentous impacts in terms of economic globalisation. They established that steamers "could successfully carry the low-value, bulk-cargoes which represented the major part of the world's trade, and by 1850 were still conveyed entirely by sailing vessel." (Fenton 2008, p. 197) A key instance that provided a clear demonstration of iron-screw colliers' multi-functionality was their hiring during the Crimean War, which could be regarded as an unambiguous "summative evaluation" of the potential of this design for efficient far-away cargo

[91] Fenton (2008, p. 188), based on estimates of coal carrying to London gas companies, states that an iron-screw steam collier could do the work of five or six sailing colliers: a steam collier could carry the double of coal of a sailing ship and complete 30 voyages per year against the ten done by the sailing collier.
[92] The advantages of steam have to be compared with the lower cost of build of sailing ships. By the early 1890s the cost per ton of a steamer was on average £25, that is, more than three times as expensive than as a sailing ship (£8), but it could do around four times as much work per unit of time on average due its higher speed and regularity (Mulhall 1892, p. 524 and p. 526).

carrying.[93] The development of the general cargo steamer took place well in time to be used during the rapid growth of foreign trade in the 1850s and 1860s (Freeman and Louçã 2001, p. 207). As Craig (1978, p. 23) puts it: "The mid-1850s saw the emergence of a growing fleet of screw colliers which steadily widened their sphere of operations of both geographically and in the diversity of freights." Vessels like the *John Bowes* became the template ("dominant design") for the mechanised collier niche as well as for the tramp, i.e. the modern general cargo trader that would eventually supplant the sailing ship in virtually all trades by the early 20th century (see Palmer, 1863; Dougan 1968, p. 5; Craig, 1980a; Fenton 2008, p. 195 and p. 197).[94] Hence, the tramp steamer concept would appear mostly a by-product of the North East coal interests as well as product of the age of steam, iron and screw (Hendry 1938, pp. 11-2).

The design of the economical general cargo-ship posed the most challenging design problems, as John Scott Russell would admit in the mid-1800s (Craig 1980a, p. 7).[95] Cargo carriers required maximum revenue-earning volume (that is, cargo capacity), low coal-consumption (implying a use of wind whenever possible, and the installation of relatively small engines, saving on bunker space), and simplicity of operation (to economise on stokers and seamen). As in other trades, larger vessels were more economical than smaller ones, both in terms of capital costs per ton (volume increasing as the cube of iron sheets used for building the hull) and in terms of running costs (for increased ship size factors like labour became a decreasing fraction of the total costs of operation) (Pollard and Robertson 1979, p. 16). However, unlike the premium ships

[93] The War Office hired steam colliers them to conveying supplies during the Crimean operations (Fenton 2008, p. 189). According to the pioneering iron-screw collier builder Charles Palmer (1963, p. 83) the ships did a good job: "The Government admitted, on that occasion, that screw colliers had proved to be more useful and economical than any other class of vessels they had employed." Shortly after, that there were several "small tramps knocking about the Mediterranean and the Black Sea and, as usual in wars, they did well." (Hendry 1938, p. 58)

[94] Coal remained the largest commodity transported in coastal trade in Britain. It is a testimony to shipbuilders' innovativeness that the collier improved its competitiveness against other modes of transport, particularly railways: it carried 38% arriving in London in the 1870s and 1880s and over 53% between 1898 and 1913 (Armstrong 1998, p. 39).

[95] Scott Russell, probably the leading naval architect of his day, knew what he was talking about: he built several of the earliest iron-screw colliers at his Millwall shipyard (Fenton 2008, p. 179 and p. 188).

engaged in the passenger liner trade, not every single technical advance represented a service improvement for cargo steamers. This meant that some characteristics of steamers were typically the target of selection rather than others. A first example is the speed issue. The vast bulk of cargo steamers had slower service speeds in the interests of economy in fuel consumption.[96] Hence, steam traders were "built for moderate speed" while vessel size kept increasing (Stopford 2009, p. 31). This leads us to a further example, the length-to-breadth ratio. Increasing relative length was important but did not have a straightforward link to economic efficiency if over-pushed: length was the most expensive dimension in naval architecture and the extra speed it facilitated was not in fact a prime consideration for the tramp steamer (Craig 1980a, pp. 34-5). Another issue was the economic efficiency aspect. Given the cost structure of cargo transport firms,[97] innovations that would impact on the cost of running the machinery and keep the hull in a good state were very important for undercutting rivals and surviving the downturns of what was a very volatile market (Craig 1980a, p. 40). While initially the distinction between tramps and liners was mostly one of the vessels' usages not the vessels themselves (Pollard and Robertson 1979, p. 18), differential incentives led to a divergence between the fast transatlantic vessels of the passenger/emigrant trade and the cargo steamer (Craig 1980a, p. 33). This bifurcation was reinforced later on by the opening of the Suez Canal (Thearle 1907, p. 92). This means that, even if cargo traders and packet were to gain the most from an iron-screw combination, since this design allowed virtually unconstrained improvements along the increasing size "trajectory", there was still room for different approaches to "peripheral" characteristics as a response to distinct economic selection pressures (cf. Chapter 2, Section 2.2).[98]

[96] The vast majority of cargo ships were not built with superior speed in mind, "(t)hus the tramp of 1939 typically was only a knot or two faster than the tramp of 1870." (Craig 1980, p. 34).

[97] Fixed costs were small compared with those of the mail/passenger liner companies which had to manage the complex operations of a timetabled service and to maintain several offices in the various ports of call and bunkering stations. Variable, or voyage, costs were the dominant cost component in the cargo carrying business.

[98] Two observations complement this interpretation. After the mid-1850s the smaller average size of wood steamers indicates that they were mostly used for river and port duties (Hughes and Ritter 1958, p. 373). By the late 1860s, it should be noted, no record of a single deep-sea paddle tramp is to be found (Course 1960, p. 24); the same is true for ocean-going liners (Dollar 1931, p.66).

Design developments that secured maximum economic advantage emerged and spread widely and quickly due to the nature of the industry. Much of the responsibility for steamship design had always rested upstream, with the shipbuilder, while in most cases ships were built and fitted according to the rules and scales laid down by Lloyd's Register and the Board of Trade (Craig 1980a, p. 31; Craig 2004, p. 4; Woodman 1997, p. 230). The cargo-carrying sector was composed of hundreds of cargo-oriented operators owned by small concerns, many of which were "single-ship companies" owning a single cargo carrier (Woodman 1997, p. 230; Pollard and Robertson 1979, p. 104; this reflected the fact that vessels could be registered and held in shares of 64^{ths}, see Craig 2004, p. 10). The large number of cargo-ship firms, and the international nature and efficiency of the freight market (the Baltic Exchange being the paramount example) assured that competition was strong and close to being perfect in this particular sector (Harley 1971, p. 225; Craig 1980a, p. 39). In addition to fierce competition and capital fragmentation, the fact that many shipowners were completely unfamiliar with the technology and the trade (i.e. many individuals dubbed by newspapers as "inland investors") meant they would do no more than sketch out the broad outlines of ship requirements (Craig 2004, p. 4 and p. 10).

Summary of section 3.4

As we have seen, there was no such thing as *the* steamship. Steamboats were initially indistinguishable in their technical idiosyncrasies and multi-purpose in function. Only gradually did they split into distinct ship types: categories of ships combining technical characteristics that were better adapted to the services expected in different trades. Hence, although much important information can be gleaned from aggregate statistics (see Chapter 4, Section 4.4), it would be misleading to portray the progress of the steamship as a universal straight line toward larger, better, faster artefacts. Given the inherent limitations of the available secondary literature, our goals are modest: to remove any simplistic assumptions concerning the existence of a “representative steamer” and to give some economic history detail to the spectrum of the vessels to be considered (in Chapter 5). But one implication is clear: it is appropriate from the outset to highlight aspects pertaining to product heterogeneity in transportation services.[99]

The secondary literature indicates that the iron-screw design did not achieve domination immediately and universally; rather, the old wood-paddle paradigm was retained for many years in the ferry and tug trades, while packets made a somewhat slow transition to the new. What seems to be the case is that the clear and instantaneous impact of the new paradigm was not so much one of replacing the established wood-paddle paradigm as to push steam navigation to a new domain of application: the iron-screw combination rapidly became a “dominant design” in a particular product class that virtually did not exist before the realm of steam navigation – the mechanised freighter (as shall be seen in more detail in Chapter 5, Section 5.5). The rise of this class of modern steamer was particularly well timed given the demand for this type of shipping activities after 1850. The origin of such modern yet unglamorous ship types remains a rather neglected aspect of maritime history in spite of their contributions to international trade, British industrial development and global economic efficiency until the Great War.

3.5 Conclusions

This chapter reviewed the major trends in the long-term evolution of steam navigation technology. Firstly, we have traced the development of the steamer until the late 1830s (Section 3.2). Early steamers represented a comparatively rapid success in Britain, one that surpassed the pioneer countries – France and the US. The steamer grew in size and

[99] From an evolutionary economics point of view these patterns were to be expected. There was a growing specialisation and differentiation of steamers according to the operational setting into which they were deployed. In other words, there was a crucial interplay between technological innovation and the selection environment as predicted by a population-based understanding of evolutionary change (Saviotti, 1996). See Metcalfe and Foster (2010) for a recent restatement of this “population perspective” as a core tenet in variation-selection-retention theories of techno-economic change.

scope of operations but its basic layout remained unchanged. However, technical and economic weaknesses (or Kuhnian "anomalies") showed themselves when the steamer was placed in an ocean setting. Even stretched to her full capabilities, the wooden paddler was no competition for the sailing ship in deep waters and long-haul routes.

Secondly, we have investigated the internal technological dynamics of the steamship by identifying transitions in its key components (Section 3.3). We have related the evolution and the complex interplay of marine engineering, the screw-propeller innovation and the transition to iron as the hull material. The iron-screw combination assisted by new advances in the power unit achieved a new kind of technological congruence (e.g. screws called for iron hulls, screws needed faster engines). During the 1840s this new paradigmatic configuration of elements re-defined the steamer and opened up possibilities in the trades and environments still not occupied by industrial-age navigation, namely overseas commerce.

Thirdly, we have examined steamers in a variety of selection environments (Section 3.4). In the 1810s and 1820s wooden paddlers swarmed in and around the British Isles, performing mostly ferry and towing functions. By 1840 steamships were safely (but inefficiently) making the Atlantic run as well as regularly delivering mail packages and passengers to other far away stations along government-sponsored routes. At this juncture, ferries, tugs and packets were founded on the wood-paddle principle. Subsequently, the iron-screw paradigm seems to have become established first and most clearly as the "dominant design" in a new category of steamers: general cargo steamers. Before this, freight transport had been a type of trade poorly served by the existing steamship technology. What also seems clear is that the direction of innovation was closely related to the progressive differentiation of ship types. In particular, the overriding effort seems to have been aimed at growth in size (a common "technological trajectory" for traders and packets) in order to reap economies of scale.

One aim of this chapter has been to provide an overview of the development of steam navigation. The extant literature is rather fragmented so we have tried to unify it through the lens of the theoretical framework set out in Chapter 2. Our survey revealed the value of appraising this subject from an evolutionary perspective. Concepts such as "technological paradigm" and "dominant design" seem to provide a useful way to understand the basic structure of steamship evolution. The notion of "projects" highlights how the many historical ships provided influential learning opportunities along the developmental path of steam navigation (e.g. the *Archimedes*, the *Rainbow*, the *Great Britain*, the *John Bowes*, etc.). The practice of informal and formal borrowing of knowledge – that is, face-to-face and publication-mediated interchange within "technological communities" – seems also to have been a pervasive feature of the early steamship sector's mode of innovation.

Issues that are sketchily dealt with in the available literature represent an opportunity for new research. One set of issues is related to the ships themselves and will be examined in Part II of this thesis. There seems to have been a trend towards greater vessel size as time went on; analysing changes in this trajectory may provide a dating of the fundamental changes in the technology (see Chapter 4). There seems to be plenty to learn in this respect by taking the level of analysis deeper in terms of the ships' characteristics and ship types, especially the rising class of iron-screw traders in the 1840s and 1850s (see Chapter 5). Another set of issues that will be dealt with in Part III. Individual incentives related to patents on new technology seem to have played a marginal role in the stimulation of novelty in the field of steam navigation; indeed, patents may even have been more of a hurdle (as we see shall see more clearly in Chapter 6). In contrast, from the existing accounts we have evidence of inclusive patterns of knowledge sharing and re-combination. We therefore believe that it is desirable to gather more comprehensive empirical evidence on the dynamics of the interactions between innovators in the processes of "variety generation" and "selective retention" involved in the development of this new technology (see Chapter 7).

Appendix 3.1 – Who, indeed, built the *Sirius*?

Although overshadowed by the more extensive literature on her rival (Brunel's *Great Western*), the *Sirius* displayed a number of pioneering characteristics. More interestingly, there are still intriguing lacunae concerning some of her aspects, issues that have not apparently been addressed in the existing literature. One particular issue remains unresolved and is of historical interest: the entity of her builders turns out to be particularly confused. This has, curiously enough, passed unacknowledged in the available secondary sources. There are conflicting references in the literature. Authorities like Greenhill (1993b) and Slaven (1993) contradict each other, while Smith (1938) and Watson (2010) contradict themselves and Jackson (2002, p. 274) says the builder is unknown.

The literature is inclined towards Menzies being her builder. Griffiths (1985, p. 100) points to Messrs Robert Menzies and Son of Leith, Scotland, as do Maginnis (1892, p. 18), the Corporation of Glasgow (1912, p. 49), Mackinnon (1921, p. 95), Parker and Frank (1928, p. 270), Lee (1930, p. 18), Sheppard (1937, p. 86), Spratt (1951, p. 30), Greenhill (1993b, p. 20), and Paine (2007, p. 5). Griffiths indicates as his source Parliamentary Papers (1846, Vol. 464, p. 46) whereas Sheppard cites the certificate of registry of Dublin, but neither refers to the engine builder. Spratt and Paine say the hull was wooden. Mackinnon (1921), Lee (1930) and Greenhill (1993b) say she was built by Menzies of Whiteinch and engined by Wingate & Company of Whiteinch. Lindsay (1876, p. 171), who does not name the hull builder, claims the engine was by Thomas Wingate of Glasgow.

Slaven (1993, p. 158), on the other hand, states that the *Sirius* was built of iron by William Fairbairn, one of greatest pioneers of iron shipbuilding, and alludes to Lloyd's Register as the source. Lloyd's Register corporate histories (Blake 1960, p. 40; Jones 2000, p. 22) support this version. Arnold (2000, p. 25), who made a close inspection of steamship building on the Thames, does not find reason to disagree. Martin (1876, p. 351), a 19th century author of a history of Lloyd's of London, also says the ship was built on the Thames. In Lloyd's Register records, the *Sirius* appears classed with the A1 symbol (i.e. best quality construction made under supervision) in 1838 with no term of years given because of its experimental nature. In the fall 2008 of Barbara Jones, Lloyd's Register's chief historian, found the *Sirius'* first entry report at the company's archives. Dated October 26th, 1837, it declares the "Steam Vessel Sirius" to have been built by Fairbairn at London Millwall. In 1839, as part of his testimony to the Parliament, Charles Graham, Secretary to Lloyd's Register, restated that the *Sirius* was built of iron in London in 1837 (*BPP* 1839, p. 136).

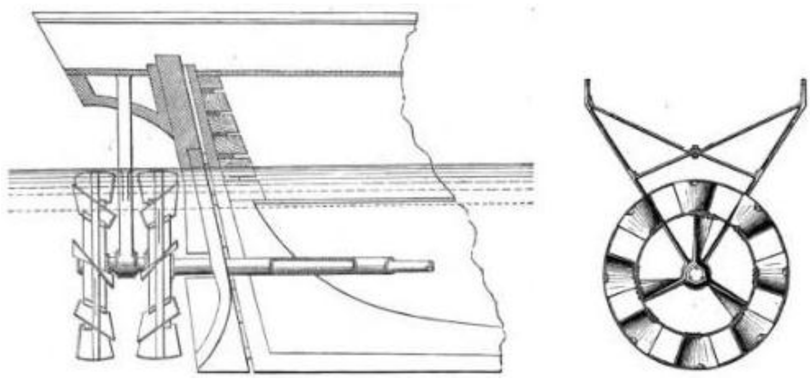
Incidentally, it should be said it was following the recommendation by MacGregor Laird's, who with his brother John Laird of Birkenhead was one of the pioneers in the construction of metal ships, that the *Sirius* was chosen for the transatlantic race (Lindsay 1976, p. 171; see also Palmer 1982, p. 16, in which Laird is also reported to have suggested other early iron steamers to join the fleets of steam packet companies). MacGregor Laird was instrumental in founding the British and American Steam Navigation Company, which chartered this vessel from the St. George Company, and later became its secretary (Lee 1930, p. 17; Smith 1938, p. 38; Bonsor 1955, p. 5; Flint 2004, p. 233).

In an inconsistent middle ground stands Edgar Smith, the author of the first and esteemed history of marine engineering. Apparently oblivious to the incongruity, probably to do with disagreements in his sources, he states that the *Sirius* was built both by Menzies (Smith 1938, p. 40) and by Fairbairn (Smith 1938, p. 97). Smith (1938) is not alone in being confused about the builders of the *Sirius*. Kennedy (1933, p. 71), a former captain and at the time of writing honorary librarian of the Ship Model Society, in his catalogue of steamers built in the UK was led to believe that two vessels named *Sirius* were built in the same year – a wooden one in Leith and the other in London built of iron. Recently, Watson (2010, p. 29 and p. 125) says the vessel was built by Menzies (who had a shipyard in Leith) in Millwall (that is, the site of Fairbairn's shipyard), a factual contradiction.

The gaps, ambiguities and conflicts of attribution concerning the construction of the *Sirius* are, indeed, puzzling and worth pursuing further in the future.

Appendix 3.2 – F.P. Smith’s rival, John Ericsson as a screw-ship innovator

Ericsson’s original proposal was for two screw-propellers coupled together and moving in opposite directions (see Woodcroft 1848, pp. 91-4; Preble 1883, p. 153; Smith 1938, p. 68; Tyler 1939, p. 117). In 1837 year he launched an experimental steamboat, the *Francis B. Ogden* (the sponsor’s name), which was able to tow a Navy barge with a crew of naval observers. In spite of all his efforts in raising awareness, and the actual technical success in this and other demonstrations, his advances were never welcomed by the Admiralty.



Ericsson’s screw propeller

Source of illustration: Bourne (1852, pp. 22-3)

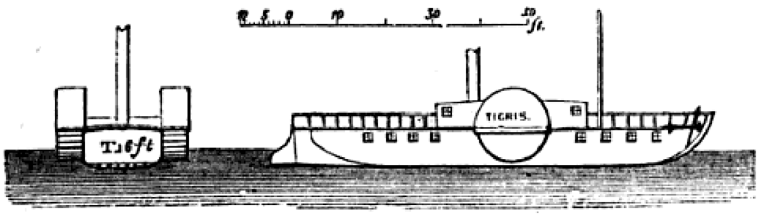
His system was fitted into the *Novelty* (a canal boat of the same name as the failed locomotive Ericsson tried in the Rainhill trials of 1829; see Rolt 1970, p. 89) which was set to ply the canals between Manchester and London. This first example of a commercial (canal) screw-propeller vessel did not work for long as her owners went bankrupt (Bourne 1852, p. 88). Then, Ericsson received an order to fit propellers for a ship built to the order of an American navy Captain, Robert F. Stockton. The *Robert F. Stockton* was built out of iron by John Laird and launched on the Mersey in July 1838. She left for the US under sail alone in April that year. In 1839, the ship’s name now changed to *New Jersey*, she could be found plying the Delaware, even in conditions of ice, when paddlers were of little use. This would be the first screw steamer at work in America, and probably the first in commercial use in the world, and her (amply reported) demonstration of the practical value of the screw would constitute another signal motivating the development of screw propulsion. Preble (1883, p. 152) cites the vessel’s particulars as described in the London’s *Mechanics’ Magazine* of June 1837 and notes that the experiment earned favourable accounts in other publications such as the *Journal of Arts and Sciences*, the *Civil Engineer’s and Architect’s Journal*, the *Times*, and others.

Ericsson subsequently left for America in 1839, never to return to Britain or his native country. In spite of all the coverage, his work would never directly affect the course of British marine technology. In the US, on the other hand, Ericsson would become very influential. In the America, after some manoeuvring on the part of Captain Stockton, he became the master-designer and construction supervisor of USS *Princeton*. Launched in 1843 this steamer became the first screw warship of the US Navy. Many years later, Ericsson became involved in the USS *Monitor*, the first ironclad warship commissioned by the US Navy during the American Civil War. In 1862 this vessel would engage the CSS *Virginia* in what became the first ironclad battle. Toward the end of his life Ericsson worked with torpedo boats and submarine technology.

Appendix 3.3 – Ships in sections, a process innovation in (iron) steamship building

It is often forgotten that building transportation artefacts out of pre-fabricated parts is hardly an invention of the 20th century, let alone of Henry Ford or the planners of the Liberty Ships. The earliest steamers made of metal and built for practical work had, in fact, such construction characteristics. The new material, which allowed for this novel convenience of construction, separated in time and place the assembly of the ship from the manufacturing of the parts. The *Aaron Manby*, the first iron steamer, was built at Horseley Iron Works and her iron plates sent to London where they were put together before the eyes of attentive observers.

There were other cases. In the early 1830s Maudslay, Sons and Field, who were familiar with the *Aaron Manby*, built several ships for the East India Company on the same principle. The result was the construction of four iron paddle steamers for work on the river Ganges: the *Lord William Bentinck* (launched on August 28, 1832), *Thames, Megna* and *Jumma*. They were sent unassembled from London to be put together in India. About the same time William Laird & Sons of Birkenhead built the *Tigris* and *Euphrates* in sections: these two ships of exploration were sent out to the Middle East in parts and assembled there (Greenhill 1993b, p. 25). These two steamers were designed for the low waters of the rivers of the same name.



THE 'TIGRIS' STEAMER.

The *Tigris*

Source of illustration: Chesney (1868, p. 185)

Note: Colonel Francis Rawdon Chesney (1789-1872) was the commander of the expedition in 1835-1836

The *Ma Robert*, a paddle-wheeler, was the first steel steamer. She was built in 1858 in Laird Brothers' shipyard and taken to Africa in pre-fabricated parts. She was to be used by the famous missionary-explorer Dr. Livingstone (the steamer was named after his wife) on the Zambesi river expedition. The vessel proved a total failure, however, with her engines not coping with the river's 9 knots current. The hull could not stand the chemical composition of the river's water, which made it rust very rapidly (see Baker 1965, p. 57; *Lloyd's List* 1984, p. 220; and Paine 2000, pp. 92-3).

Appendix 3.4 – Partitioning the population of early steamers, methodological issues

Accounting for diversity in terms of economic functions implies a number of choices and methodological challenges. Our choice of principal trades is at the same time general and specific enough so as to avoid as many borderline cases and exceptions as possible. Even so, there are four kinds of difficulties involved:

(i) Ships were always idiosyncratic. In part, this was related to the need to tailor them to specific commercial duties and operational conditions (i.e. they were "project" undertakings), meaning that distinguishing between them involves some degree of conjecture and abstraction;

(ii) Single-trade ships were the exception. Steamers were flexible and easily multi-purpose machines that allowed their owners to reap substantial economies of scope: many ships mixed cargoes (transporting people and post like those working on fixed lines and schedules such as the celebrated Cunarders or P&O vessels), others carried goods as well as towed barges or other vessels (like the *Industry*, the *Samson*, the *James Watt* and many other lesser known early steamers), others still were designed for certain kinds of business and were later employed in others (like the *Sirius*, redeployed from the short Irish-sea route to become an Atlantic ferry; similarly, others yet changed trade several times, often due to the business cycle dynamics, and went through various alterations during their lifetime to better fit their new operational challenges);

(iii) As the market for steamships expanded, a finer and more precise division of labour emerged. As demand-side pressure for greater efficiency and more sophisticated shipping services grew, so different kinds of ships appeared. This highlights how dynamics matter in the interrelationship between technological and service characteristics (particular configurations of technical characteristics should not be assumed to be remain rigidly constant, but rather increasingly responsive to the requirements of specific trades in order to realise economies of scale);

(iv) The secondary literature is highly uneven in coverage and quality. The bias in coverage favours the premium steamships of the transatlantic run. However, the backbone of British shipping was in the river, coastal and near-continent trades, with plenty of other vessels being employed in less romantic activities such as towing and livestock carriage. As underscored in this chapter, it would be wrong to dismiss the vessels involved in these more mundane traffics, and a considerable effort was put into finding information on ferries (many times mostly descriptive, more or less uncritical books and failing to point the primary sources), tugs (there is little literature covering such craft) and freighters (for which we are in debt to Robin Craig, 1980a, 2003, whose work constitutes the most multifaceted and detailed body of work available on the long-run evolution of this type of steamers).

Appendix 3.5 – Steam packets as technological "greyhounds"

Packets were atypical ships: they were "elite" ships (sometimes called "greyhounds" and "express steamers", cf. Conrad 1921, p. 220, Pollard and Robertson 1979, p. 19). These ships had high up-front costs and high running costs. The price-tag of a steam packet of the early 1840s was about four times a sailing packet's, but they did at least twice the amount of work (Heaton 1960, p. 36). Their running costs were only covered by contracted carriage of high-value, low-volume cargo transported on liner terms, that is, with the expectation of repetition, assisted whenever possible by convenient coaling stations, infrastructures that themselves required considerable amounts of capital investment (Craig 1980, p. 7).

The commissioning of such ships and the formation of the complex companies that managed them were not without broader consequences, two of which can be highlighted here. First, a downstream effect could be noted. Given that accidents such as fire and boiler explosions did occur in steamers and caused scepticism among prospective users, the acceptance of the steamer for the transport of mails amounted to an official seal of approval regarding its safety and reliability for the needs of passengers and cargo shippers (Griffiths 1985, p. 7). Second, one can refer to an upstream effect on marine engine makers and shipbuilders as companies kept placing continuous orders that pressed for ever larger ships and ever more powerful engines from the best builders in Britain.

By encouraging the industrial system to produce quality steamships the Royal Navy mail contracts amounted to a technology policy. So much was acknowledged by contemporaries (e.g. Pliny 1859, p. 6; Johnson 1906, p.87 and p. 294). As the former noted, for example, the objective of the mail subsidy policy was:

> "to foster maritime enterprise, and to encourage the production of a class of vessels which would promote the convenience and wealth of the country in time of peace and assist in defending its shores against hostile aggression. The reasons for desiring such communication are partly commercial, and partly political."

The available historiography is also remarkably consistent in this respect (see, e.g., Pollard and Robertson 1979, p. 222; Hope 1990, p. 297). On the one hand, Hope (1990, p. 271) notes that "it was mail contracts awarded by the British government which launched steamship companies across the Atlantic and beyond." As Freeman and Louçã (2001, p. 207) emphasise: "The government's support for the establishment of four subsequently famous shipping companies in 1839 and 1840 proved a highly successful policy, one which reinforced the rapid growth of trade in the 1850s and 1860s." On the other hand, and as Hope (1990, p. 297) remarks, by 1853 the subsidised owners ran 91 of the largest steamships, and there is little no doubt that the "contracts helped the ocean steamer to make progress". Andrew Lambert (1996, p. 154) takes up the issue in a plain-spoken way: "After 1837 British mail contracts subsidized the development of large ocean-going steamships." (Lambert 1996, pp. 154-5) Hope (1990, p. 270) concurs when he says that during the 1840s this policy "gave British ocean steam shipping a start that it did not lose for 100 years, a new impetus at a time when there was not much to be said for British merchant shipping or for those who served it." Freda Harcourt

(1988, p. 1) reinforces this appreciation when she describes how Britain shook off the bad performance that had plagued its shipping sector since 1815:

> "In the 1830s government adopted the policy of developing ocean steam navigation by way of mail contracts. Government support was essential because the primitive state of the art of early steam navigation made operating costs high. Subsidies at this juncture therefore enabled British shipyards and shipping companies to establish a lead which was not surpassed for a century."

State intervention was influential for the marine sector as a whole (i.e. shipbuilders and ship companies). Contracts forced a kind of technology race to acquire and retain them. An expression of this was the Blue Riband, the informal award attributed to the fastest of the express passenger liners on the Atlantic from the 1840s onwards (see, e.g., Allington and Greenhill, 1997). For companies shut out of the contract system, the uneven playing field led to two strategic developments: the investment in risky new technology embodied in very large vessels (like Brunel's and Tod & MacGregor's iron-screw experiments of the 1840s and 1850s which did not have to be designed with government restrictions and military considerations in mind) and the entry into the emigrant trade (taking over from the American clipper sailing ships in the early 1850s), a business of spectacular growth that pushed liners to become larger and larger (Kemp 1978, p. 172).

In short, the exogenous impetus provided by the subsidies had both direct and indirect consequences. It also came at a most crucial moment in the evolution of steam navigation. The path of development, i.e. the "technological trajectory", was one that involved negotiating the complementarities and trade-offs between speed and capacity.

Part II

Part I of the thesis argued that the notions of "technological paradigm", "technological trajectory", and "dominant design" are central for analysing the origins and development of the mechanised ship. With this perspective in mind, Part II focuses on *how* changes actually took place as revealed by the performance and characteristics of steamship technology in Britain during the 19th century. Hence, Part II seeks to rediscover the fundamental stylised facts by employing a number of metrics and analytical techniques. In so doing, the following chapters confirm the pertinence of analysing steamers from an evolutionary perspective.

Chapter 4 situates and assesses the long-run performance improvements of steamships in the broader frame of the changing British economy during the 19th century. This chapter draws new conclusions from known datasets on the aggregate British-built steamship population. An important corrective and much needed refinement to these aggregate patterns is presented in the subsequent chapter.

Chapter 5 investigates a new dataset on the characteristics of early steamships built in Britain between the launch of the *Comet* in the early 1810s and that of the *Great Eastern* in the late 1850s. It focuses on the evolution of new combinations of solutions incorporated in a diverse set of steamship types and looks at the trajectories emerging over time. It also pays attention to the rate and direction of technical change across the different types of steamers existing in the British mercantile fleet with a special emphasis on general cargo traders and standard steam packets.

4. Growth and diffusion of steamers: A long view of mechanisation at sea

4.1 Introduction

This chapter sets out to describe the broader context and long-term dynamics of British merchant steamships. We approach this objective by first addressing the broader context at the macro- and the meso-levels. That is, we survey the British economy's development and the evolution of the industry's organisation on the basis of extant economic history literature. After laying down this context, we analyse the available aggregate statistics in order to trace the major features of the population of ships being built in Britain from the beginning of the 19th century until the early 20th century.

The macro historical setting in which shipbuilding was situated is reviewed in Section 4.2. Steam navigation was developing in a growing industrial economy increasingly dependent on overseas trade as a source of raw materials and as an outlet for its manufactured products. Long-term trends that we could refer as industrialisation and internationalisation affected the supply-side and demand-side conditions framing the sector. Such developments contributed to changing the requirements landscape for which ships were built. But the external environment influenced this capital goods sector in more than one way. Additionally a number of discrete events phenomena like wars, mega-infrastructure deployment, and fluctuations of the business cycle took place at a time when the industry was going through a critical transition process.

Section 4.3 presents a survey of the literature covering changes taking place within the industrial sector of shipbuilding. A major re-organisation of the industry occurred as the expansion of aggregate output progressed. There were important shifts at mid-century concerning the location of the industry, the size of shipbuilding firms, and the relationships of these to suppliers and customers. If there was structural change in the broader economy, there was also structural change in the ship construction business.

Section 4.4 studies the development patterns of shipbuilding output. For that we rely on figures generally available to historians and economists obtained from two sources: Mitchell and Deane's *Abstract of British Historical Statistics* and Mitchell's *British Historical Statistics 1750-1975*. These datasets distinguish between sail and steam, thus providing opportunities, which remain somewhat under-exploited in existing research, for appreciating the rise of modern ship technology in Britain. Mitchell and Dean (1962) report data on newly registered ships, which we use in Sub-section 4.4.1, and Mitchell (1988) reports data for the stock of ships registered in any given year, which we use for the remainder of Section 4.4. Besides a description of the major patterns found, we conduct a series of structural break tests on the data and carry out a formal technology diffusion analysis so as to produce an empirically supported periodisation of the progress of steam navigation and a timeline of the principal technological transformations of the technology. The stylised facts thus put together allow us to reach preliminary conclusions with respect to a number of issues that have lacked clear quantitative backing in the literature, for instance the timing of technological "take-off" of steamers, the significance of the so-called "sailing ship effect" (for the study of which we draw out lesser known complementary data), and the impact of the opening of the Suez Canal on the supposed struggle between sail and steam.

4.2 The wider economy and British sea transport

Transport in an era of industrial capitalism and structural change

The development of the modern ship took place in the wake of the British Industrial Revolution, a phase in which "mechanisation" represented the "paradigmatic" solution first sought by innovators and entrepreneurs for any challenge posed by problems of economic activity (von Tunzelmann 2000, p. 132). In the late 1700s and the early 1800s, Britain was the setting for a series of accelerating and interrelated changes in machine engineering, iron founding, coal mining and concomitant broader sectoral and social transformations that are collectively labelled industrialisation. This process was bound to influence ship design, and, in turn, would also be leveraged by it (Lyon 1980, p. 5).

In spite of its obvious significance, the relationship between transport and the economy remains relatively poorly understood (cf. Ville, 2004). In particular, accounting for the impact of improved transport services on the economy or, conversely, how transport productivity increased in reaction to the demands of economic and population growth has proved a difficult task. There can be little doubt that transport drove as well as responded to change. Craig (1980a, p. 18) makes the point clear: "New technology was demanded and supplied, and the process in turn required new products, new methods of production, and particularly important in our context, new raw materials and new sources of supply." The transportation sector became progressively intertwined with the leading modern industries as both procurer and supplier, notably of the "core inputs" coal and iron. But, as Ville (2004, p. 326) also remarks, transport's influence was also due to its "pioneering role in meeting the challenges of large scale enterprise". The large size and geographical spread of operations, the ability to adjust indivisible (large and highly capital-intensive) resources to a highly volatile demand led to new methods of management, such as improved accounting techniques in shipping and internal labour markets in railways (Ville 2004, pp. 317-8). As a result, these emerged as exemplary modern industries in themselves, i.e. the "carrier branches" that demonstrated the potential of the new "techno-economic paradigm" to the wider globalising economy.

Like other infrastructures the transport system generated pervasive external effects. These effects were often more substantial than the direct contribution of the sector in terms of value added and employment, given the general contribution to economic efficiency by promoting market integration and by fostering greater informational transparency (Ville 2004, p. 296). Improved technology impacted on a variety of levels depending on the types of services of the different modes of transportation: roads and inland waterways broke local monopolies at the local and regional level, railways and coastal shipping opened up the national internal market, while ocean shipping led the way to the consolidation of the empire (Ville 2004, p. 327 and p. 331). The transport sector in general contributed directly to the broader British economic system by making room for the exploitation of economies of scale.

As the 19th century progressed a new phase of multilateral globalisation unfolded, propelled primarily by lowered transportation costs, and reinforced by population transfer and by British naval power which aided liberal economic policy (Harley 2004, p. 176). Globalisation in the 19th century was first and foremost driven by technology, a "new and unprecedented phenomenon." (Findlay and O'Rourke 2007, p. 379) Expanded international trade unambiguously enhanced the success of the British industrial economy as a whole in the new widening global arena (Harley 2004, p. 186). So much was clear to some of the best shipbuilding innovators of the time, like Charles Palmer (1864, p. 287), the North East iron-screw collier builder: "The true source of our national greatness is to be sought in this wonderful development of our merchant navy."

Shipping in an era of deepening international trade and global interconnection

From our perspective it is significant to note the effect of steam and iron navigation at all levels, that is the intra-national, the national and the international levels. This latter aspect, for an island nation with an extensive empire, should not be under-emphasised. The growth of the British industrial economy increasingly came to depend upon overseas imports of raw materials and, by the middle of century, foodstuffs and other staples for its growing population (Hughes and Reiter 1958, p. 376). As Broadberry *et* *al*. (2010, p. 180) vividly illustrate, the new modern transport systems of steam navigation (and railways) began from the 1820s and 1830s to widen the British internal market in terms of the distribution of perishables like flour and beer, while by 1870 the ports were awash with previously exotic imported non-perishable commodities such as tobacco, tea, sugar and cocoa. The economic environment was favourable to the new steamship technologies. And never did British exports grow so rapidly as in the period 1850-1857 (cf. Hobsbawm 1975, p. 30; see Crouzet 1980, p. 81). Historical events also clustered around this time to exert a major boost on shipping and innovative shipbuilding: the gold rush to Australia in 1848, the 1849 California gold rush, the outbreak of the Crimean war in 1854, and the American Civil War (see, e.g., Palmer 1993, p 58; Arnold 2000, pp. 50-1). This impetus was followed by a sustained growth of world trade. Overseas trade in and out of the UK more than doubled between 1850 and 1870; coal exports overseas increased almost four times between 1850 (3.2 million tons) and 1870 (12.2 million tons) (Clarke 1997 p. 93). World trade increased by a factor of five between 1860 and the Great War (Starkey 1993, p. 134). The high degree of trade openness that prevailed in Britain in the second half of the century provided a large demand-pull effect that accelerated the rate of growth of the British steam fleet (Hughes and Reiter 1958, p. 381). As we shall see, these were well timed economic developments in the chronology of technical change in sea transport.

North (1958, 1968) is the classic reference in which detailed gains in shipping productivity have been identified. North showed a precipitous fall in freight rates from 1816 to 1865 for a number of commodities on the North Atlantic, such as timber and grain. Harley (1988), based on alternative data, shows that more substantial efficiency gains took place after 1869. Hausman (1993) finds further evidence of continued decline in freight rates and shipping costs in the English coastal coal trade throughout the 19th century. Mohammed and Williamson (2004, p. 178) complement previous research showing freight rates on ore, a heavier cargo, carried from the Western

Mediterranean also fell as fast as the rates for transatlantic grain cargoes. However, not only did real ocean freight costs fall sharply (by nearly 35% between 1870 and 1910), economic efficiency was further enhanced by time savings in journeys across the Atlantic and to the Far East (Clark and Feenstra 2003, p. 295). In their review of these studies, Findlay and O'Rourke (2007, p. 382) conclude by noting this "unprecedented, dramatic, and worldwide decline in intercontinental transport costs – especially when decline in overland rates are taken into account." Fouquet (2008, p. 173) provides an overarching figure: by the end of the 19th century the cost of sea carriage services per weight-distance declined to between 20% and 30% of what it was at the beginning of the century. In the context of an expanding economy, the demand for ocean transport increased dramatically and declining freight rates show it responded accordingly. Sea transport was not a bottleneck to the sustaining of British industrialisation.

What were the sources of such large productivity gains? We can follow Ville (2004, pp. 301-4) and breakdown the sources into the following streams. First, the momentous decline in freight rates has been attributed to technological change in vessels themselves (Davis 1972, p. v), notably the introduction of steam propulsion and improved hulls (Harley, 1988; Mohammed and Williamson, 2004).[1] It is, therefore, surprising that there is little research on the nature and dynamics of maritime technical change. Knick Harley (1971, p. 215) pointed out that, at the time of his writing, there had been "little recent research on the improvements in late nineteenth-century shipping." Today, the situation concerning the earlier part of century could still be described in much the same terms, i.e. few works are available referring to productivity growth in shipping in the first half of the century. However, the few available studies do point in the same direction. David Starkey (1993, p. 131) finds that from 1820-24 to 1845-49 the volume of seaborne commerce entering Britain expanded by 195%, while in terms of tonnage the British

[1] For instance, according to Clark and Feenstra (2003, p. 294) the five-fold reduction in the amount of coal needed to generate 1 hp-hour from 4 kg in 1830 to 0.8 kg in 1881 represented nothing less than a "revolution".

merchant fleet only increased by 40%. He attributes the main sources for this to the increasing utilisation of steamers and a series of improvements in sailing vessels.

Second, technological change and the diffusion of better vessels were hardly an isolated process. As Freeman and Louçã (2001, p. 142, p. 206) have suggested, innovation is a systemic phenomenon that necessarily rests on the consolidation of a broader underlying infrastructure. The efficiency of merchant tonnage depended not only on the ship technology carrying the freight but also on industrial developments ashore, namely the establishment of supporting systems of prime importance for steamship operations: namely, but not exclusively, coaling stations and deep ports.[2] To start with, by the mid-1850s many British ports were already prepared for quick loading and discharge of steam cargo ships (Craig 1878, p. 18). So far as coaling stations are concerned, by the late 1850s a world-wide network of bunkering stations was improving generally, which meant steamers could devote more and more space to cargo (Kirkaldy 1914, pp. 454-5; Lilley 1976, p. 211; Souza 1998, p. 106; Allen 2009, p. 178).[3] Although infrequently acknowledged, the Royal Navy had a role in establishing a global chain of coaling stations, namely after the launch of the steam ironclad *Warrior* in 1860. Naval bases, although their role was primarily strategic, were a military investment that frequently served as coaling stations on routes to important destinations like the Far East (for instance Gibraltar, Malta and Aden), thus serving as "spring boards for trade, not conquest." (Preston and Major 1967, p. 4; see Figure 4.1)[4] Britain was after all, not only

[2] It is also worth remarking on two other ancillary types of infrastructure, both biased towards commercial steamers: the telegraph and the Suez Canal. Trans-ocean telegraph cables came increasingly to produce major changes in trading patterns and frequency. Cargoes could be negotiated more efficiently by brokers and local agents, helping to reduce turnaround times. This mattered mostly to steam traders as these had higher up-front and running costs than sailing ships (Thomas 1993, p. 11; see also Craig 1985, p. 241). The Suez Canal opening in 1869, which provided a shorter route to the Far East, has also been credited with reinforcing the growth of merchant steam fleets (see, e.g., Fletcher, 1958; Harley, 1971; Slaven, 1980; see also Sub-section 4.4.3).

[3] This development benefited longer-haul iron-screw steamers: "These technical developments could only be utilised effectively when a reasonable pattern of bunkering facilities had been established on the principal trade routes on which steamers could hope to compete with sail." (Brock and Greenhill 1973, p. 16)

[4] Throughout Victorian times and Edwardian times there was a sort of "co-evolution" between trade and empire in which the ordinary trading steamers played a pivotal role: "The spread of coaling stations over the world (...) was a result as well as a cause of the growth of steamship traffic, since the building up of stocks at suitable points was mainly the work of tramp-steamers." (Derry and Williams 1960, p. 373)

the world's sole industrial country, it was also the world's largest imperial power: it capitalised on "dual-use" assets. This aspect resonates with Hobsbawm's (1967, p. 26) words on the Royal Navy, "that most commercially-based and trade-minded weapon".

Figure 4.1 Royal Navy bases in use during the 19th century

Source: Preston and Major (1967, p. 5)

As far as port infrastructure is concerned during the 19th century British ports responded spectacularly to an unprecedented growth in the volume and variety of cargos brought in new and larger ships. This implied improved port facilities. Gordon Jackson (1988a, p. 223) forcefully argued this matter: "It was steam power that brought the first great qualitative changes to ports; the demand for space and facilities was no longer for 'more of the same'." Between 1830 and 1870, in particular, this implied the construction of what he termed "bigger 'second generation' locks and docks designed specifically for steamships." (Jackson 1988a, p. 224; see also Craig, 1980b) The new tonnage arriving was highly demanding of capital investment, engineering works, and new forms of work organisation. Development in ship technology put a huge pressure on ports:

deeper and larger quays were needed to harbour longer and wider vessels; bunkering stations were needed to serve steamers; new warehousing was needed to deal with the rapidly accumulating cargo; new equipment was needed to guarantee rapid loading and discharging with greater time precision of faster vessels; connections to railways were also in demand, and so on (Shepherd and Walton, 1972; Craig 1980b, p. 153 and p. 158; Greenhill 1980c, p. 14; Ville 2004, p. 302). Not only steamers crowded the harbours: sailing ships were also increasing in size, tirelessly being towed by steam tugs, and demanding quicker turn-around times so that they could be off again working for their owners. Not only did tugs increasingly find employment during this stage, but also, and for obvious reasons, so did another type of ancillary craft – steam dredgers.

Third, there were organisational innovations in the normal conduct of business. Managing the construction of very expensive capital-goods led to improved record-keeping processes (Moss 1992, p. 25;), better information and literature on shipping movements or stowage plans (Craig, 1982), and increasing specialisation in ancillary shipping support operations such as marine insurance and brokerage (Ville 2004, p. 304). And, fourth, there were pioneering forms of raising capital, setting a precedent for their generalisation in the twentieth century (see Craig 1978, 2004).

All these changes acted upon a shipping services sector that could be described as a competitive market (Harley 1971, p. 225, and 1972, p. 4; Craig 1980a, p. 39), which helps to explain the ability of the numerous operators in the estuary and coastal trades to respond effectively to increases in demand (Ville 2004, p. 311). Concerning deeper water and longer-distance trade, the progressive dismantling of the East India monopoly and the dismantling of the mercantilist restrictions (the Corn Laws and the Navigation Acts) from the 1820s to the 1850s signalled a long-term commitment to "free-trade" ideology at the level of the legislature (Harley, 2004). Economic liberalism and the supposedly self-regulating free-market in fact required the sophisticated operation of, to borrow a term from Eric Hobsbawm (1968, p. 15), "semi-automatic switchboards" in the freight and marine insurance markets like the Baltic Exchange and the set of institutions stemming from Lloyd's coffee house (Lloyd's Register, *Lloyd's List*, Lloyd's of London). Where competition was distorted (as in the case of the subsidised mail packet lines; see Chapter 3, Section 3.4 and Appendix 3.5), government contracts pushed inherently towards continuous investment in improved assets for the delivery of service, sometimes possibly to the point of over-capitalisation (Ville, 2004). As a consequence, the benefits of innovation were passed on to the rest of the economy in the form of cheaper and better transportation services, since private competition caused prices to fall and subsidised procurement encouraged quality to rise.

An era of laissez-faire and maritime re-regulation

In the first part of the 19th century, ideas about unrestrained commercial intercourse swept through political Britain and by the mid-century a new order was essentially established. This was "a period of militant economic liberalism" (Hobsbawm 1968, p. 17). It involved the mobilisation of a consensus against special interests and the "means of what is called protection" (Porter 1912, p. 501). It implied the removal of trade restrictions in the context of a major reshuffle of power in favour of the urban bourgeoisie and of industrialists, and away from aristocratic land ownership and from established East and West Indian merchants. The paramount instance of this process was of course the abolition in 1846 of the Corn Laws.[5] It must be noted, however, that the abandonment of mercantilism did not represent the end of government intervention. Especially in the maritime sector, the dismantling of old legal frameworks did not mean an end of regulation itself; rather it signified the entrance onto the stage of a new generation of industrial age policies (see Box 4.1).

[5] Other instances of the process of reform were the repeal of laws forbidding the emigration of skilled workers and artisans in 1825 and the unlicensed export of machinery in 1843 (Supple 1976, p. 320).

Box 4.1 The regulation of new technology and the limits of *laisser-faire* in the new industrial society

"The first challenge to this philosophy of leaving things to market forces came from the steamship, albeit not for positive reasons." (Armstrong and Williams 2007, p. 159). The technology of steam navigation, although in its infancy, was the locus of the first major industrial accidents.

As early as 1817, a mere five years after the introduction of the *Comet*, a Select Committee of the House of Commons sat to discuss the best ways to deal with the matter of boiler explosions. The Committee, however, hesitated to recommend government action because of its laissez-faire predisposition and its declared aversion "to propose any legislative measure, which the science and ingenuity of our artists might even appear to be fettered or discouraged." (*BPP* 1817, p. 3) Even so, its investigations led to the recommendation that, in the case of passenger vessels, vessels should be registered near to their ports of trade, that boilers should be of wrought iron or copper, that every boiler should be equipped with two safety valves, and that inspections should be conducted to ensure the safety of the passengers was guaranteed. Later, in 1831, another Select Committee conducted an enquiry into the same matters but still no concrete outcomes came out of it. But the problem simply would not go away and in 1846 a Committee on "Calamities by Steam Navigation" would finally introduce legislative measures, namely that safety valves would be compulsory. In America the persistent re-occurrence of disasters led to the establishment of steamboat inspections in 1852 (Hunter 1949, p. 271).

The shipping sector was subject to an old patchwork of statutes, ranging from registration, harbour conditions, manning, safety and trading rights (Ville 2004, p. 308). In the early years of the 19th century, this complex mantle of sometimes conflicting rules and inoperative duties, started to dissolve. Nowhere was this more visible than with respect to the exclusive rights benefiting the Honourable East India Company (HEIC). As early as 1813 the HEIC was deprived of the monopoly on the direct trade with India it had acquired in 1600, when it was founded as The Company of Merchants of London Trading into the East Indies. Notwithstanding, the HEIC still conserved some exclusive rights, namely, tea trade with India and the whole of the trade with China. With the *laissez-faire* ideology in the British Parliament well under way, however, the time came for the renewal of its charter. This was in 1833 and the HEIC was finally stripped of its remaining trading monopolies. China trade was now open. When the HEIC was broken up in 1874, it was but an empty shell.

Another instance of the crumbling of the old mercantilist frame was the termination of the set of laws regulating overseas trade between the metropolis and the colonies, i.e. the Navigation Acts, which had prevailed since 1651 (see MacGregor 1984a, p. 14, and Sawers 2003, p. 67).[6] The repeal of the protectionist Navigation Act in 1849, coming into effect on January 1, 1850, would seem to coincide with the mid-century metamorphosis in the merchant steam-powered ship. In other words, in the case of shipping it would appear that deregulation played some role in the major advances that would shape the rest of the century. However, the picture is mixed. It should be remembered that protectionism had been progressively watered down for a long time.

In essence the Navigation Laws required that any freight being imported into British ports had to be carried in ships that were British-built, British-owned and British-manned (Porter 1912, pp. 505-7). In 1815, following the war in the US which had started in 1812 partly connected to the issue of free trade, a treaty was celebrated granting the mutual abandonment of discriminatory duties in the ports of both countries. In 1822 the law was further relaxed by a revision that widened the scope of products and ports of origin that were no longer under the restriction of the classic statutes of the Act. From 1824 more exceptions were granted to countries ready to reciprocate. By the early 1830s the volume of British trade still governed by the Acts was decreasing rapidly (Hope 1990, p. 282; Woodman 1997, p. 190). Following the repeal of the Corn Laws in June 1846, and with the Navigation Laws temporary suspended because of the great Irish Famine of 1845-1851, a committee was appointed in February 1847 to re-examine the Act (Moyse-Bartlett 1937, p. 227). In its wake a Bill repealing the Laws was passed in the House of Commons and signed by the Queen. The manning

[6] Free trade ideas owe much to Adam Smith seminal book of 1775, who obliterated the economic theories that underlay mercantilism. So it is ironic to note that he was not an opponent of state intervention in matters maritime (Earle, 1986). In the *Wealth of Nations* he supported the protection to shipping by the 18th century Navigation Acts (see Smith's chapter 2, where Smith called it the "wisest of all commercial regulations of England.", cited in Earle 1986, p. 224). His support was justified on the basis that maritime technology was a necessary economic infrastructure: it was a "dual-use" technology, supporting British shipbuilding and naval power (Mowery and Nelson 1999, p. 13).

disposition would linger until 1853 and in 1854 coastal trade too was liberated. It was the end of a measure that for scores of years enjoyed wide recognition and to which much of Britain's commercial success was often attributed (Porter 1912, p. 505)[7].

As one type of state instrument declined, however, other forms of influence were on the rise. As Pollard and Robertson (1978, p. 201) remarked: "the state never abandoned its right to mediate and arbitrate in situations in which it was felt that the interests of the public could not be left to the mercy of individual initiative." Paradoxically, state encouragement, guidance and regulation were permanent and, if anything, on the increase; the subsidies paid to liner companies to compensate them for mail carriage being one paramount example. Steady reform pressure on the industry's regulatory architecture would continue until the Great War (Greenhill 1980a, p. 24). One crucial instance was the new Merchant Shipping Act of 1854. The Act was an immense edifice of legislation, with no less than 548 clauses (Hope 1990, p. 288). It was first and foremost an act of consolidation as it put together and gave a coherent rationale to a myriad of maritime-related dispositions. It regulated the terms of entry and assessment of masters and mates into the profession, along with ranges and conditions of pay, and thus paved the way to the professionalization of mariners. It also empowered the Board of Trade to take overall superintendence of general matters pertaining to the mercantile marine, among other dispositions (Johnson 1906, p. 9). If the government was trying not to get involved, it was not succeeding. Market forces, for instance, did little for the rights of passengers and sailors. Just the following year after the Merchant Shipping Act, a Passenger Act was passed. Much to the protest of many British shipowners – foreign ships were exempt – it ensured minimum safety standards for emigrants in British ships (Pollard and Robertson 1979, p. 11). Given that the emigrant trade was on

[7] In this regard Jackson (1988b, p. 260) provides a useful reminder: "Contrary to popular misunderstanding of the Navigation Laws, foreign ships had never been excluded from trading with Britain, and British merchants had for centuries been happy to leave some – less remunerative – trades in the capable hands of owners in developed countries, while they got on with the business of pursuing trade with underdeveloped regions unlikely to produce their own oceanic shipping."

the path for long-run growth well into the following century, this was by no means a small business. As the century went on, passenger ships were increasingly protected by safety regulation. The same reformist zeal was not, however, directed at cargo vessels, where safety regulations were virtually non-existent (Bagwell 1988, pp. 73-4). As early as 1836 there had been a parliamentary enquiry into the causes of shipwrecks, and another was set up in 1843 (Hope 1990, pp. 280-1). The situation would change decades later with the widespread public agitation, promoted by Samuel Plimsoll, the businessman and MP who had written *Our Seamen* in 1874 (see, e.g., Jones, 2007).

A final aspect we must consider has to do with tonnage law reforms. Tonnage, representing the amount of freight the ship could carry, served as the baseline for port dues, thereby affecting the incentives guiding hull design. After the Tonnage Act of 1773 which specified measurement, and the Act of 1786 which enforced registration, there were two other changes in measuring tonnage that are of concern, coming into effect in 1836 and 1855 respectively. The Tonnage Law that came into force in January 1836 stipulated a calculation of tonnage taking into account depth for the first time. Until then, what prevailed were the practices known as "Old Measurement", a rather arbitrary old formula for tonnage reckoning solely on the basis of length and breadth. Simple formulae were used to facilitate the measurements made by people of limited formal education and varying backgrounds. A collateral consequence was that shipbuilders moulded vessels in response to the economic incentives perceived by shipowners. In this case there was considerable advantage in terms of volume that could be obtained by investing in deep holds.[8] The ship design that emerged from this regulatory frame lacked stability and it required a powerful rigging to move and a skilled crew to handle it (Greenhill 1980a, p. 12). The 1836 method was introduced to rationalise the situation but the revision brought unintentional consequences: it led to

[8] MacGregor (1984a, p. 14) uses this case to provide a reminder that "it was the profit motive that governed the shipping industry, as indeed any branch of business, a fact which is often overlooked in sailing ship histories". See also Slaven (1980, p. 109) and Greenhill (1980, pp. 10-2).

new experimentation in design, effects that lingered on (Greenhill 1980a, pp. 11-2; Slaven 1992, p. 2).[9] The specific ways in which the new measurement approach could be circumvented induced hull shape alterations for the purpose of evading port taxes.[10] As we shall see below these institutional changes may be related to significant developments in sailing ship design and size. Years later, the Merchant Shipping Act, passed in 1854, brought about a complete revision of these tonnage measurement rules. It included a rigorous tonnage measurement system, elaborated following proposals of the naval architect George Moorsom, by which gross tonnage was defined as the cubic capacity of the total permanently enclosed space in the ship calculated on the basis of one gross ton being equal to 100 cubic feet (Moorsom 1860, p. 133; Johnson 1906, p. 9; Bonsor 1955, p. xvi). At the time the perspective of expert shipbuilders and naval architects was that the 1854 system inserted no palpable biases in merchant ship construction; in the words of a Lloyd's Register surveyor, builders and architects could now bring about ships "long or short, broad or narrow, as best suits their purpose." (in Moorsom 1860, p. 142; see the discussion section involving players such as Scott Russell, T.J. Ditchburn, J.R. Napier, and W.C. Miller). The new system, known as the Moorsom system, became the foundation of measurement rules and provided the template for systems adopted by almost all the other maritime countries in the world (MacGregor 1988, p. 151). The extant literature offers no evidence in conflict with this view (e.g. Pollard and Robertson, 1979; Hope, 1990; Slaven, 1992; Greenhill, 1993a).

Summary of section 4.2

Transportation featured heavily in a society undergoing epochal change, namely rapid industrialisation and globalisation. The ship-operating industry, in particular, faced huge increases in demand during the course of the 19th century as expanding trade

[9] From 1836 through to 1854 the ordinary merchant ships became "larger, shallower, and sharper in hull form than her predecessors." (Greenhill 1980a, p. 20)
[10] For a contemporary discussion of the consequences of the 1836 measuring method on ship design, see Moorsom (1860, discussion section).

accompanied the rapid industrialisation of the British economy. Yet, it never seemed to have suffered from supply-side bottlenecks as far as new technology was concerned. Shipbuilding not only stepped up to absorb the mounting pressure, but also responded with substantial productivity improvements. The sector's transformation was related to the spread of the new "techno-economic paradigm" (see Chapter 2, Section 2.2), i.e. the assimilation of the revolutionary "core inputs" of the industrial age into the maritime transportation system, which became one of the key long-run growth British industries (i.e. an iron and coal-intensive "carrier branch" or "user industry").

This adjustment was in the first place related to qualitative changes in the industry's output. But the changes were also "systemic", and encompassed a great many adaptations in other sectors and infra-structures. The peculiar political and military institutions of the British "national system of innovation" (in particular, the covert technology policy implicit in government mail subsidies and the investment subsidy implicit in the imperial management policy carried out by the Royal Navy) were part of the supporting background (see also Chapter 2, Section 2.2, and Chapter 3, Section 3.4). Reinforced by the rapid growth of overseas trade from the 1850s and 1860s these policies proved effective in creating the right conditions for longer-haul steamers, packets and traders, the highly successful new types of modern ship. Furthermore, institutional adaptation was rampant throughout the 19th century. The regulatory apparatus was not an unfavourable factor and played an influential role. The first part of the century was, broadly speaking, one of de-regulation whereas the second could be understood as one of re-regulation. Tonnage legislation, in particular, was part of these changes and had a direct bearing on the economic "selective environment" faced by ships. By 1836 the old restrictive measurement rules had been discontinued, a reform credited with provoking influential novelties in ship design, whereas the Moorsom rules of 1854 do not seem to have exerted substantial biases.

4.3 Industrial organisation in shipbuilding

Industrial structure

Vessels were historically built in small yards located on the forested coasts of Europe and North America, and Britain was no different in this respect (Pollard and Robertson 1979, p. 9). British shipbuilding was favoured by a number of factors, among them geographical (an insular position, sheltered ports, large navigable rivers, the availability of cheap and high-quality raw materials – first timber and in later years coal and iron ore), economic (a large share of world trade, a relative abundance of capital), and human factors (engineering skills, a large seafaring population). Between the mid-1500s and the late 1600s, shipping had risen from its previous insignificance to become the fastest-growing business in England (Davis 1972, p. 388). In the early 1700s London was the largest shipping centre in the country: it built one third of all British tonnage and owned a sixth of all ships (Dougan 1968, p. 22). By the end of the 18th century, however, London's relative importance had declined, while still preserving its national significance as the main British shipbuilding centre. In the first quarter of the 19th century London's output, just one activity among an unfolding range of many others, accounted for just under 10% of total tonnage (Palmer 1993, p. 46). Shipbuilding was now more evenly spread across ports such as Liverpool, Bristol, Newcastle, and Sunderland, with a long tail comprising virtually all other ports on the coastline, mostly producing for local buyers, although not all of them active on a permanent basis.

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The many small-scale players operated in a fragmentary and highly competitive shipbuilding business and charged prices in close relation to production costs (Ville 1989, p. 67). Such producers were, moreover, financially weak often short-lived establishments, entering and leaving the industry with the severe business cycles that characterised the sector (Pollard and Robertson 1979, p. 71 and p. 266; Ville 1989, p. 72; Slaven 1992, p. 1)[11]. The marked boom/slump dynamics that afflicted the sector cannot be overlooked. "As a producer of 'lumpy' non-divisible capital goods," Ville (1989, p.

[11] The fact that many enterprises were short-lived and informal in nature complicates the estimation of the exact number of shipbuilders at any point in time (Ville 1989, pp. 72-3).

67) remarks, “the shipbuilding industry was particularly susceptible to economic fluctuations through the working of the accelerator effect.” In a trade afflicted by severe crises, yards were more permanent than firms (Pollard and Robertson 1979, p. 73).[12]

Shipbuilding carried on being a craft (project-based) activity in which every vessel called for a great deal of skill. Men were akin to artisans and were supposed to bring their own tools to work on assembling timber and other materials that were brought in, and they were paid according to the work done, with gradations for their position, i.e. according to “job and task”, not on the basis of a wage rate system (Pollard 1950, p. 73; Arnold 2000, pp. 18-9). The shipwright would function as a middleman or broker, the “leading hand” that was supposed to control the discipline and quality of the work of a gang of men, much like it had always been under the guilds.[13] The coming of steam did not alter these arrangements very perceptibly until the 1850s (Slaven 1980, p. 122). There were at least two reasons for this: first, shipbuilding remained essentially an activity that built up products from parts like engines and boilers, often sourced outside and assembled on site; second, wood was still an important shipbuilding material, which kept old know-how in demand (Arnold 2000, pp. 18-9). As von Tunzelmann (2004, p. 327) remarked more generally, Britain consistently performed well in activities in which rigid organisational hierarchies were unsuited and initiative welcomed.

The mid-century, however, is a period when a major industrial reorganisation took effect (Slaven 1980, p. 107). Scale became more of a factor with the rise of iron shipbuilding (Harley 1972, p. 22). The move toward a less diffuse industrial structure coincided with a relocation of the industry (Schwerin, 2004). Although first flourishing

[12] The Blackwall yard in London, otherwise known as the East India Dock, was an extreme example. Starting in 1615, it survived ten ownership changes between 1770 and 1843, being the cradle of the so-called Blackwall frigates, several opium clippers and many iron steamers (*Lloyd’s List* 1984, p. 206). For abundant examples of shipyards engaged in steamship building on the Thames, see Arnold (2000).

[13] Customers, moreover, paid in installments, helping to fund the purchase of labour and parts as work progressed on the stocks, a form of contract that would continue to the early 20th century (Pollard and Robertson 1979, p. 105).

in London (the centre of innovation in the 1830s and 1840s), iron shipbuilding would mostly develop on the Clyde and in the North East (the growth areas from the 1850s).

Regional distribution

In the first half of the 19th century the industry continued to be geographically scattered. The industry moved away from its original relatively geographical diversified profile to become more concentrated in a small number of districts located on Northern rivers in the second half, with Belfast also becoming prominent in the early 20th century (see, e.g., Arnold 2000, p. 6, and Ville 1989, pp. 66-7). In the 1870s, with the industry launching nearly four times the output of 1815, the Clyde, Tyne, Wear and Tees accounted for nearly all the non-naval ordinary tonnage launched in Britain (Pollard and Robertson 1979, p. 49; Slaven 1992, p. 4). Northern districts produced every kind of tonnage but the North West was the most diversified (tending more towards high-class vessels such as liners and cargo-liners), whereas the North East was mostly concerned with cargo shipping (colliers, tramps, and specialised cargo carriers) (Slaven 1992, p. 8; Pollard and Robertson 1979, pp. 49-69). By the late 19th and early 20th century the North West and the North East dominated shipbuilding, each district accounting for 40 to 45 establishments (Lorenz 1991b, p. 919). Both regions also built for the naval market, with the Thames accounting for the (declining) remainder (see Arnold, 2000).

The inter-regional relocation in construction has been seen as closely associated with "the availability of cheap and docile labor, ready supplies of raw materials and other inputs, and easy access to markets." (Pollard and Robertson 1979, p. 51) The first systematic study on the regional dimension of the phenomenon likewise concurred with Pollard and Robertson in attributing relevance to this set of factors, emphasising the role of skilled labour of local heavy industries as a key source of external economies in these areas (Ville 1993, p. xii). Before, the cost of labour was comparatively small, possibly between one-quarter and one-third of the total cost of a vessel (Pollard and Robertson

1979, p. 52), but now this was an industry becoming more capital-intensive. While not disputing Pollard's (1950, p. 81) earlier argument that geographical relocation could not be explained by the wage differential between London and the rest of the country, since this was a matter of fact in the first as well as the second half of the century, Palmer (1993) nevertheless adds that the evolution of shipbuilding technology made other factor costs much more important after 1850. The closeness of deposits of coal and iron were contributing factors to the observed industrial relocation (Pollard and Roberson 1979, p. 69; Arnold 2000, p. 37; see also Slaven, 1975). Likewise the availability of land, the depth of the rivers, and large port facilities were fundamental pre-conditions for building longer and larger ships needing heavier machinery (e.g. cranes, riveting tools, and so on) in order to handle them (Pollard and Roberson 1979, p. 57 and pp. 116-7).[14]

Vertical relations

Before the modern steamer configuration crystallised, most hull and marine engine builders were independent (but, in a few instances, constructed the ship as whole). Then some semi-permanent links were formed among engineering and hull building firms, an interdependence that was accentuated with the introduction of iron (Slaven 1980, p. 123). Some firms, however, beginning with Robert Napier in the 1840s, built and engined ships all by themselves (Pollard and Robertson 1979, p. 89). But only by 1870 was vertical integration of hull and machinery becoming a feature of the industry (Slaven 1980, p. 123). Increasingly establishments tended to be more self-sufficient and organisationally more complex than before (see, e.g., McCord 1995, p. 248).[15] The

[14] Discrete historical events, too, played a role. Arnold (2000, p. 153) suggests two such factors setting in motion irreversible change. On the one hand, the conflict in the Crimea, while producing a shipping boom and boosting shipbuilding, brought rapid cost-inflation to the Thames that proved devastating once hostilities ended. On the other hand, blunders in the building of ever larger iron ships could have consequences in terms of economic ruin on a vast new scale. To take two examples: the *Great Eastern*, which led Scott Russell to bankruptcy while possibly killing Brunel, and the failure to launch the HMS *Northumberland* in March 1866, were decisive events, precipitating Millwall Ironworks into collapse.

[15] The new yards employed 400 to 500 workers, while previous ones typically employed only about 20 or 30 workers, and all adopted a organisational structure based on departmental specialisation, including engineworks, boilershop, shipyard, drawing office, and so on (Slaven 1992, p. 4).

increase in ship complexity and size greatly reinforced the trend toward concentration in Britain (Pollard and Robertson 1979, p. 86).

The industry remained dominated by competing family businesses until 1914, but often with the involvement of members of the same family in different yards at the same time (Pollard and Robertson 1979, p. 73). Shipbuilders sometimes had a stake in the ships they built by holding shares of 64ths, the prevailing ownership structure (Craig 1978, 2004). Sometimes they would hold a downstream stake because of the financial prospects and other times because no buyers could be found, the shipbuilder having to run the ships himself. In the liner business, closer and continuing ties, both formal and informal, between builders and liners deepened from the 1870s. These links attenuated the severity of the trade cycle in shipyards, which were now very capital-intensive, and guaranteed repeat orders, which allowed for further specialisation and savings of overhead capital.[16] By the end of the century, shipbuilders also developed a degree of relations with suppliers, as ships become more complex and they needed to embody a growing number of necessary components (Pollard and Robertson 1979, p. 232).

Industrial competitiveness

By the time of the American Civil War, Britain was already the uncontested leader in shipbuilding and it continued to be so until the Great War of 1914-1918. A striking performance indicator is the number of males engaged in shipbuilding: in 1871 there were 61,800 men in the industry (0.5% of the total labour force according to the census), whereas in 1911 there were 155,400 (1.0% of the labour force), an increase of 151.5% when the total number of males in Britain rose by 26.1% (Starkey 1998, p. 9). Table 4.1 illustrates Britain's world position. Amidst the relative decay of late Victorian times, this was an industry still going strong. As Sidney Pollard (1957, p. 426)

[16] The paramount case of such close financial ties with shipping lines were the Dennies, the builders where the first specific investments were made for introducing steel shipbuilding (Robertson 1974a, p. 41).

forcefully argues, such figures offer a pale indication of Britain's actual competitive supremacy. Not only was British-built tonnage of higher quality than the rest of the world, many of the ships built outside Britain were produced with the help of state subsidies or under protective legislation. For instance, it is apparent that Britain fared less well in the naval vessel segment, fully under steam by this time, as this was a price-insensitive market where governments did the buying. Overall ship exports grew even faster than tonnage built. During the period 1869-1883, 12% of British output was sold to foreign owners, and 24% in 1900-1913 (Pollard and Robertson 1979, p. 37).[17] There is no doubt that during this time British ships became the cheapest, the safest and the most technologically advanced in the world (cf. Pollard 1989, p. 24). The outcome was clear by the end of the 19th century:

> "Some of the merchant steamboat companies are equal in importance to the navies of some European Powers. (...) The vessels, moreover, of the first-class companies are unsurpassed." (Mulhall 1892, p. 525)

Table 4.1 Shipbuilding in the leading countries, average annual launchings of merchant vessels 1892-1914 in '000 gross tons

	1892-96	*1901-05*	*1910-14*	*Warships, 1892-1914*
United Kingdom	1021	1394	1660	112
Germany	87	215	328	49
USA	85	347	253	39
France	26	123	105	39
Holland	10	52	97	13
Japan	3	33	57	-
Norway	17	44	45	13
Italy	9	50	32	-
Russia	-	-	-	29
World (including others)	1299	2354	2739	340
UK as % of World	78,6%	59,2%	60,6%	32,9%

Source: Lloyd's Register returns, in Pollard (1957)
Note: 1914 data for some "other" world countries are incomplete

One should not take these data, however, to imply that the predominance of British-built ships on the world's seas was a constant feature of the whole 19th century, since that

[17] During this time ship exports were larger than the total United States and Germany new tonnage combined, the nearest industrial competitors (Pollard 1989, p. 23). But exports underestimate the full extent of the internationalisation of the British sector. Some companies from the northern rivers set up spin-off shipyards abroad, such as in Italy and Russia in the late 19th century (McCord 1995, p. 249).

would be a gross *ex post* reconstruction. "The myth of the permanent superiority of the British marine cannot be sustained" if we are to pay attention to the historical record in the first half of the 1800s (Jackson 1988b, p. 260). After American independence, the American fleet had grown in number and with the Napoleonic wars, having evolved faster vessels stimulated by the economic incentive to beat the British blockade of France, it had also improved in quality (Clark 1910, p. 8 and p. 58). The American Civil War, however, removed for the time being what had been Britain's most dangerous rival. The same cannot be said of the Canadian shipping industry. From the 1850s Canadian sailing ships, owned and operated by Canadian shippers, were at the core of the international long-haul, deep-sea bulk trade, a position that only weakened in the 1880s when the capitulation to steam finally occurred (Ommer, 1984). By that time, however, the most admired sailing ships were no longer North American but British again. From the mid-1850s, British-owned firms operating Aberdeen and Clyde-built ships of composite construction dominated the premium China trade. These were succeeded by large fully rigged iron clippers in the 1870s and 1880s operating on the Australia Wool run. And these, in turn, were supplanted in size and efficiency by four-masted steel barques. Some of these ships, the last windjammers, were still trading vigorously at the turn of the century and making record-breaking voyages (Hume and Moss 1975, p. 17).

Summary of section 4.3

There was a structural change in the shipbuilding industry that peaked around mid-century which bears a close resemblance to the passage from an entrepreneurial-based technological regime ("Schumpeter Mark I"), in which product innovation tends to be more prominent, to a routine-based technological regime ("Schumpeter Mark II"), where incremental change based on resource endowments (of labour, iron, coal, etc.) becomes the basis of competitiveness. The landscape changed from one characterised by a myriad of small-scale shipyards scattered around a wide geographical area into fewer large-scale, capital-intensive and vertically-integrated shipbuilding firms concentrated in Northern centres. This migration of the industry reflected the endowment of factors now mostly employed in the new ships. By this time it is apparent that process innovation was rising in importance *vis-à-vis* product innovation, another sign of a major shift in the industry life cycle (as pointed out in Chapter 2, Section 2.2).

Shipbuilding remained a project-based activity, where mass production routines mattered less, which perhaps explain why Britain fared continuously well in this sector. However, changes in the nature and size of ships were in large part responsible for changes in the industrial organisation and improvements in international competitiveness. There was nothing preordained in the international leadership of the shipbuilding industry. Ultimately Britain restored its competitive position thanks to a "paradigm" shift in ship technology (namely with ocean-going modern steamers), making it one of the most successful British industries up to the Great War while other industries were suffering from world competition (Pollard 1989, p. 23; Freeman and Louçã 2001, pp. 205-6). This performance of British shipbuilding is underscored by the astonishing continued development of the oldest of the technologies, the pure sailing ship, which had a much celebrated "apotheosis during her decline and just before her extermination" (Gilfillan 1935b, p. 156). But this was the kind of tonnage that was finally set aside and replaced by modern mechanised ships. One hundred years after the *Comet*, British steam tramps were the carriers of the world. It is to the task of assessing trends and turning-points in the evolution of ship technology that we turn now.

4.4 The growth and diffusion of mechanised ships: a quantitative assessment

The data

The analysis of the growing importance of steamers to the British merchant fleet offers what would seem a textbook example of the introduction of a new technology in an age-old industry. In this section the growth and the diffusion of the steamer is investigated over historical time both on its own and in contrast with the evolution of the wind-driven ship. The present section presents information based on numbers and net tonnage of steam ships and sailing ships newly-built and in operation in the UK for British individuals and companies between 1814, shortly after the introduction of steam navigation, and 1914, the year that marks the end of the "long 19th century".

The ship time-series data are given in Mitchell's (1980, 1988), which extended his earlier work with Phyllis Deane. We first use the data of Mitchell and Deane (1962, pp. 214-22) for new ships built and first registered in Britain (which provides a flow variable) and then proceed to use Mitchell's (1988, pp. 529-37) data for ships currently registered (a stock variable). The two datasets point to a number of convergent observations but, given its less volatile nature, we mostly employ data on registered ships (Mitchell, 1988). One author (Arnold 2000, p. 4), acknowledging the importance of these figures, states that they "are used as the starting point for almost all analyses of the industry". Unfortunately no examples are given of what such analyses were. What appears to be the case is that this is a surprisingly little utilised resource. Ommer (1984, p. 27), MacGregor (1984a, p. 7), Ville (2004, p. 303), and Fouquet (2008, p. 173) constitute rare exceptions, but their purposes have been merely descriptive.

Mitchell's data, although valuable, suffer from several limitations. The dataset does not refer to hull material (wood, composite, iron, steel) for all the period. The dataset does not contain information on the propulsion method (paddle-wheels, screw-propellers) and the prime movers (simple engines, compound, etc.). Another issue is that Mitchell's data do not allow for a regional disaggregation. This limitation forces us, for instance, to abstract from the spread among particular British ports and to focus on the overall patterns of technical change and diffusion. The series were collated from a variety of official and industry sources and are continuous for a substantial number of years.[18]

[18] Two breaks exist that are related to modifications in the method utilised in tonnage measurement: 1836 and 1855, the years in which measurement revisions were implemented. Tonnage law reform was geared at tax collection, which would imply a step-wise increase in reported tonnage. Commenting on the

4.4.1 First-registered ships

Aggregate numbers and tonnage

Figures in this sub-section are obtained from Mitchell and Deane (1962) with respect to newly registered ships added to the British merchant fleet, which may be taken as a proxy of newly-built ships. The figures show the volatile outlook of the dataset. So much should be expected of a capital goods industry. However, the fact remains that shipbuilding is a particular case of "a capital goods industry suffering exceptionally wide fluctuations" (Pollard 1989, p. 24).[19] The data provide evidence of "the unstable and difficult business environment in which the shipbuilder had to live." (Mitchell 1964, p. 178) The marked trade cycle that characterised the industry output reflects, moreover, the direct dependence of shipbuilding on commerce (Hume and Moss 1975, p. 23). Figures 4.2 and 4.3 show this unstable output dynamics for the aggregate number of ships and total net tonnage[20] (i.e. sailing ships plus steamships), respectively, for the whole period.[21] It can be seen that more ships were built later in the period than in the beginning. However, the data on total tonnage is more expressive, showing also higher volatility around a clearly rising trend especially after mid-century.

The point-to-point growth rate between 1814 and 1914 was 43.1% and 874.1% in total vessel units and total tonnage, respectively. That corresponded to annual growth rates of 0.4% and 2.3%. Hence, the increase in total numbers of newly registered vessels was comparatively modest: from a 706 to 1010 vessels between 1814 and 1914 – it did not even double. In marked contrast, aggregate tons added doubled every 32 years.

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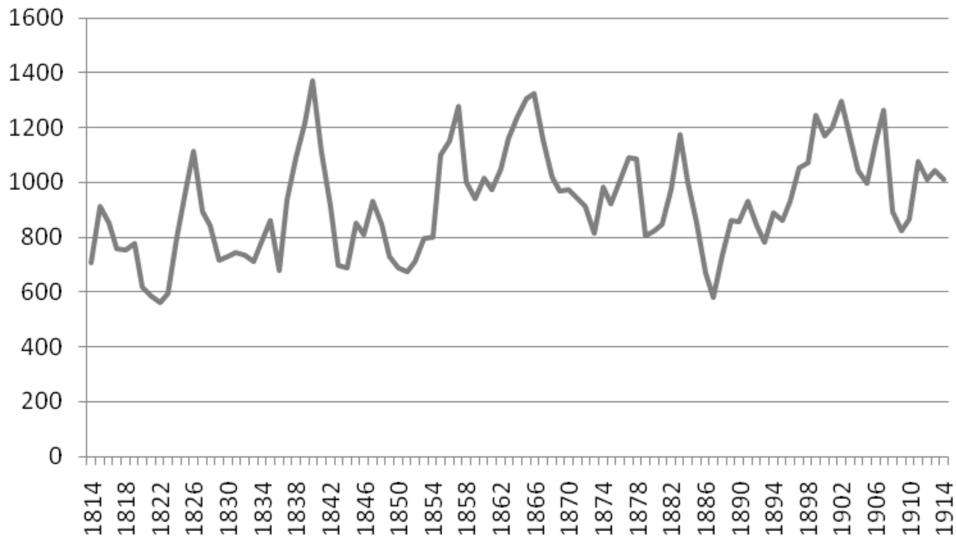
magnitude of this upward effect on the statistics, Mitchell (1988, pp. 530-1) notes that it may have been slightly larger in the second revision than in the first, but in both instances "the only certain thing is that the change was not large."

[19] The cyclical fluctuations of the British economy were accompanied by wider fluctuations in the shipbuilding output. Shipbuilding activity tended to have a lag (i.e. a delayed response) to changes in the demand for cargo to be transported (Craig 1968, pp. 386-7).

[20] Both measures "gross tonnage" and "net tonnage" refer to volume, generally the under-deck space. The difference between "gross tonnage" and "net tonnage" typically only exists in steamers and is accounted for by the engine room and the coal bunkers, i.e. non-earning space. Net tonnage is room that can be used to store cargo and accommodate passengers.

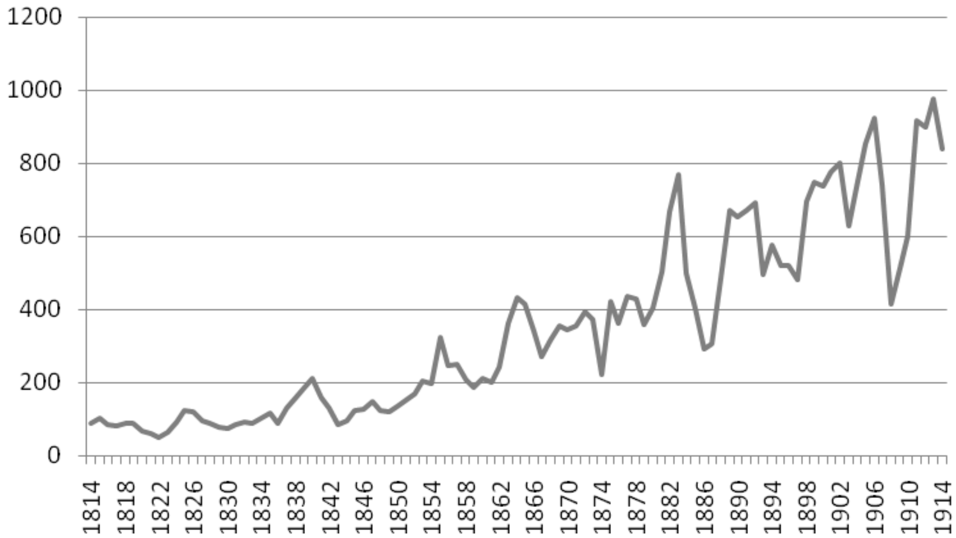
[21] For the years until 1824 the statistics are with respect to the 30th of September, and to 31st December from there onwards. From 1826 onwards the Isle of Man and Channel islands are included. Starting in 1848 only of vessels 100 gross tons and upwards are taken into account.

Figure 4.2 Total number of newly registered vessels in the UK, 1814-1914



Source: Elaborations by the author on the data available in Mitchell (1988, pp. 529-37)

Figure 4.3 Total tonnage of newly registered vessels, 1814-1914



Source: Elaborations on Mitchell (1988)

Numbers and tonnage, first registered sail and steam British merchant vessels

In Figure 4.4 we can see that more and more new steamers kept being added to the British fleet throughout the period. The commercial introduction of the first steam vessel deployed in the British Isles, the *Comet*, was in 1812. The first registered steam vessels appear from 1814 onwards. The following years are characterised by spectacular growth. The pattern for sail shows wide fluctuations of new ships around the level of 800 units per year until the late 1860s and a declining trend thereafter. The number of new steamers surpassed the number of new sailing vessels in 1872 for the first time. The year 1902 was the last in which the number of new sailing vessels was above that for new steam vessels. In terms of fluctuations it would would appear that fluctutations of new sailing ships and new steamships went hand in hand until the late 1860s (e.g. numbers of both types of vessels decreased together somewhat in the early 1840s, and both went up in the early 1850s and again in the early 1860s); however, that relation seems to break down afterwards.[22]

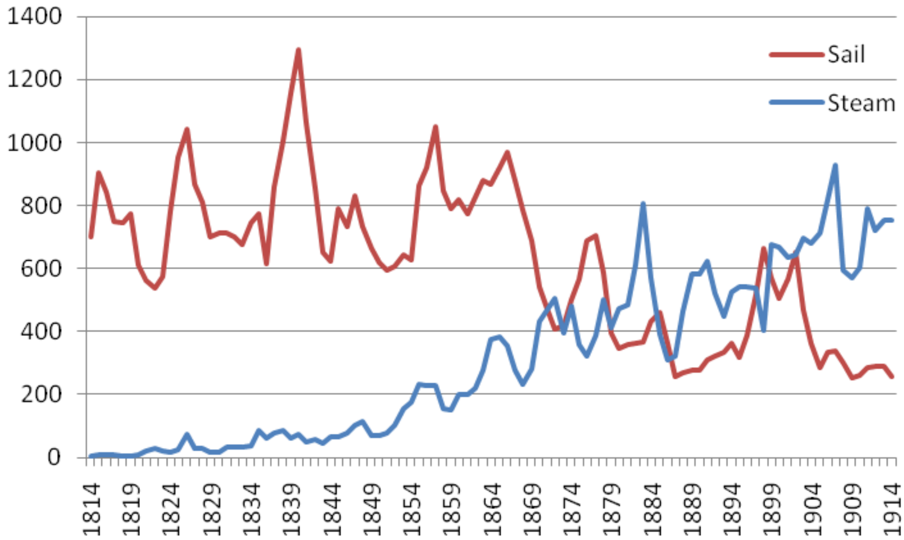
In terms of new tonnage under sail and under steam Figure 4.5 shows that the steam fleet nominal carrying capacity first surpassed new tonnage under sail in 1870. That was two years before the same reversal noted above concerning numbers of vessels, suggesting steamers tended to be larger than sailing ships. The year 1885 was the last year more tonnage under sail than under steam was added to the British merchant fleet. From the late 1890s newly added sail tonnage was marginal while steam tonnage dominated. These raw data, however, seem to greatly underestimate the growing importance of steam tonnage (see Box 4.2).[23] If we take into account steam's higher productivity in where new vessels are concerned, we can infer that from 1853 onwards the aggregate additions to the steam fleet did more effective work than the new sailing fleet being added (as Hughes and Reiter, 1958, previsouly observed using the same relation of one steamer being equivalent to four sailing vessels). Calculating now the total carrying power of the British merchant fleet (i.e. the tonnage of sailing ships plus the effective tonage of steamships), we may gain a glimpse of the real transportation

[22] The relation broke down both ways, so to speak. Steam could now increasingly be seen to displace sail in new acquisitions, but downturns lowered freight rates and still tended to favour sailing ships owing to their lower running costs. In this connection, David MacGregor (1984a, p. 14) noted that boom times favoured speed, bad times favoured capacity. For instance, in Figure 4.4 we can see that during the 1875-1879 depression many owners went back to order, purchase, and register sailing vessels. During this depression steamers had ventured as far as Asia and Australia but sail was still very competitive in this long routes. What increasingly became the case, though, was that ship-owners in times of depression became not so much anxious to revert to sail but keen to get rid of their uneconomic steamers and to replace them with compound-engine steamships (Hume and Moss 1975, p. 24). In other words, preferences were reinforced not towards (cheaper) sailing vessels but towards better (quality) steamships.

[23] After 1869 there were a few episodes that generated demand hikes for sailing ships. For instance, peaks can be noticed in the early 1880s and the late 1890s. These are explained by shocks unrelated to the pure dynamics of the trade cycle. As Pollard (1950 p. 305) noted, steamer prices rose markedly due to the Boer Wars (the first, in 1880-81, and the second in 1899-1902). In contrast we can see that the Crimean War of 1854-1856 led to a bubble in shipbuilding that affected both sail and steam in broadly the same way.

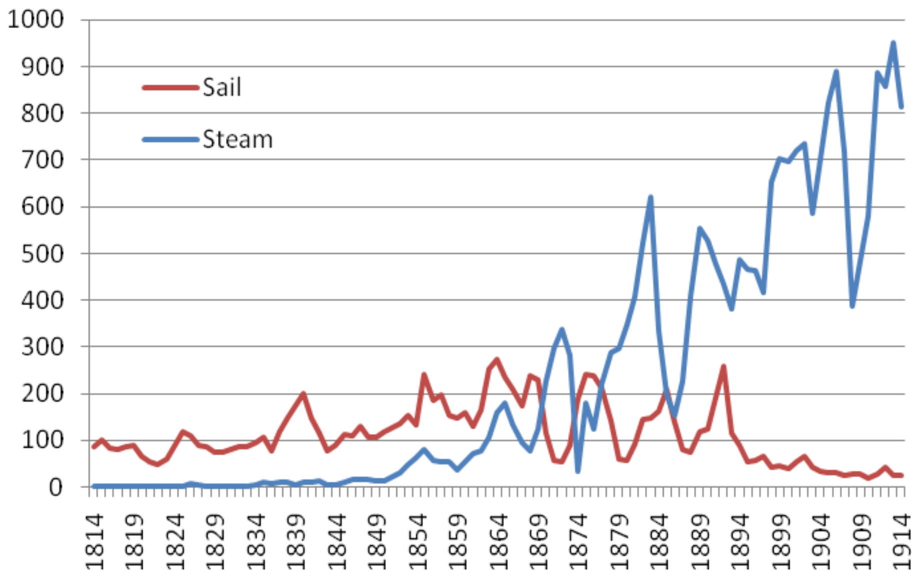
potential that was being deployed in the economy: in thirty years between 1820 and 1850, the total carrying power of the British fleet increased by a factor of two, while in the following thirty years (1880) it increased by a factor of no less than eight. In other words, Figure 4.3 greatly underestimates the explosion in total servives made available each year after the mid-century, something that was driven by steam and which more than compensated the gradual disappearance of sail.

Figure 4.4 Numbers of newly registered vessels, sail and steam, 1814-1914



Source: Elaborations on Mitchell (1988)

Figure 4.5 Tonnage of newly registered vessels, 1814-1914



Source: Elaborations on Mitchell (1988)

Box 4.2 From nominal steam tonnage to "effective" steam tonnage

Productivity differences between sailing ships and steamships could be staggering. Steamers were faster and more regular than sailing ships. They could also take the direct route while ships under sail were dependent on favourable winds.

Some writers have used the term "effective tonnage" (e.g. Ville 1991, p. 83), "cargo-carrying capacity" (Hughes and Reiter 1958, pp. 370-1) or "carrying power" (Mulhall 1892, p. 514) to denote the greater transportation services output delivered by steam. That is, there is a difference between the nominal tonnage of steamers and their real carrying capacity. Craig (1978, p. 20) and Ville (2004, p. 303), for instance, assume that *one* steam ton was equivalent to *four* sail tons from the 1820s to the first decade of 1900 (see also Slaven 1980, p. 116; Greenhill 1993a, p. 9). Craig (1978, p. 20) dates that equivalence figure from the mid-1840s at least. This same estimate was made by several contemporary observers, statisticians and experts (e.g. Glover 1863, p. 26; Mulhall 1892, p. 524; Johnson 1906, p. 23). Of course, no indisputable correction factor is asserted in the literature as efficiency varied greatly according to the historical period and type of trade.

On visual inspection we can also observe then that the tonnages of the different types of merchant vessels fluctuate in opposite senses for the first time after the opening up of the Suez Canal in 1869. That year is important because it signals a change in the cyclical pattern of sail and steam tonnages: until then fluctuations largely went together but they became contrary afterwards. A simple statistical analysis shows that in the period before 1869 (i.e. the fifty years of 1820-1869) there was a strong positive correlation between the two tonnage series (the Pearson correlation coeficient was +0.84, statistically significant at the conventional level of 1%, using a two-tailed test); from then onwards (the forty-five years of 1870-1914) the correlation was strong and significant but negative (-0.63, at the same significance level).[24] In other other words, this analysis points to a likely shift in the roles of sail and steam around that date. The evidence appears to suggest that sail and steam were initially complementary technologies, and became only substitute technologies around the time that coincided with the opening of the Suez Canal. This analysis was inspired by MacGregor (1984a, p. 7) who, based on his background knowledge and a simple visual inspection of the data, suggested this same conclusion which is now found to be statistically supported.

[24] The correlation for numbers of new steamers produces similar results: +0.27 (significant at the 5% level) for 1820-1869 and -0.35 (again at the 5% level) for 1870-1914. There is also a similar correlation for average ship sizes that echoes the observation that shipping booms were associated with the construction of larger ships (see Lewes, 1968, and Craig's 1978, p. 35).

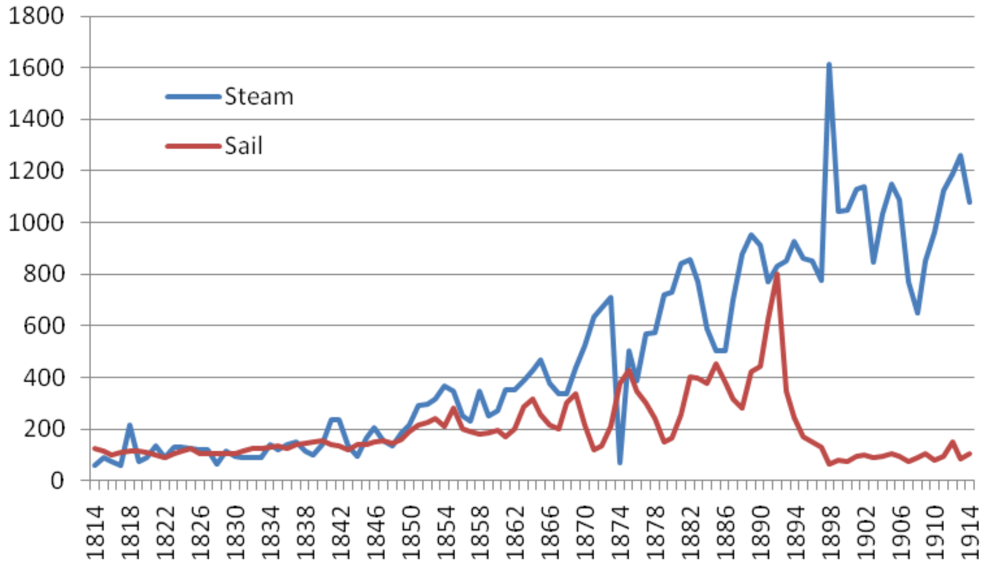
Average sizes of new vessels added to the registered population of merchant ships

A key technical attribute we can measure is average net tonnage. A ship's tonnage is a fundamental characteristic of a merchantman; it tells something about her capacity to carry goods and people. In this chapter we will use aggregate averages of the net tonnage data on sail and steam vessels as a key analytical variable. The reasons for this choice are instrumental and substantial. These have to do with the availability of historical data and our precise goals in accounting for the driving forces behind the empirical patterns. The variable also has limitations that should be acknowledged and understood. The rationale for using average ship size is explained in Appendix 4.1.

Figure 4.6 depicts the average size of sail and steam vessels. We can see that up until 1850 or so nominal carrying capacities were quite similar. It should be noted, nonetheless, that steamers were mostly occupied in marginal or highly-specific trades such as towing and river ferrying. If anything there was an increasing trend from early on: in the 1830s steamers scored a higher average than sailing ships during three of the ten years, but in the 1840s new steamers were larger in seven of the ten years and during the 1850s not for a single year were new steamers smaller than sail-only vessels.

The sail-steam divergence becomes clear in the second half of the century. True, the average size of sailing ships around the shipping boom of 1888-1893 reached four times that of 1850. Indeed, historians have remarked that the economic environment and the new metal hulls favoured sailing ships of maximum capacity in the period 1870s-1890s (MacGregor 1984, p. 16; Greenhill 1993a, p. 9). For instance, in the 1890s "Clyde four-posters" were noted for their economy as bulk carriers for the Australian grain, Chilean nitrates and other trades (Hume and Moss 1875, p. 18). After 1869 the average size of sailing ships tends to fluctuate inversely to that of steamers. After 1893 British shipyards were finished with large squared-riggers. Only small coastal sailing vessels kept being built (Greenhill, 1941; for an exception see Jakson 2002, p. 39).

Figure 4.6 Average tonnage of newly registered vessels, 1814-1914



Source: Elaborations on Mitchell (1988)

The trajectory of steamships echoes the words of a British shipowner of the day: "every ship we built was larger than her predecessor." (Dollar 1931, p. 138) We interpret this basic trend or stylised fact as a "technological trajectory", the "average net tonnage" being the *y*-axis considered as the formal quantification of the concept (as noted above in Chapters 2 and 3, see also Appendix 4.1). Thus, the average steamer of the 1850s was nearly two times larger than the steamer of the 1810s, whereas the steamer of the 1900s was more than three times larger than the steamer 1850s. The relative size of steamers also exploded in the second leg of the 19th century as Table 4.2 shows.

Table 4.2 Steamer size in proportion to sailing ship size, 1820s-1910s

1820s	1.1	1870s	2.8
1830s	0.9	1880s	2.3
1840s	1.2	1890s	6.6
1850s	1.4	1900s	10.6
1860s	1.6	1910s	11.4

Source: Elaborations on Mitchell (1988)
Note: Figures relate to mean steamship size over mean sailing ship size per decade

4.4.2 Registered ships in the British merchant fleet

Numbers and total tonnage of steamers

The most important additions to the stock of British shipping were overwhelmingly British-built ships for domestic registration and operation (Craig 1971, p. 49). The following figures refers to vessels (and their net tonnage) present at any time under British registration. The data are less volatile than for newly-registered ships, which allows for other types statistical analysis. Figures 4.7 and 4.8 represent the total number and tonnage of steamers in operation: both steadily rose until the Great War of 1914.

Figure 4.7 Aggregate number of steam vessels registered in UK, 1814-1914

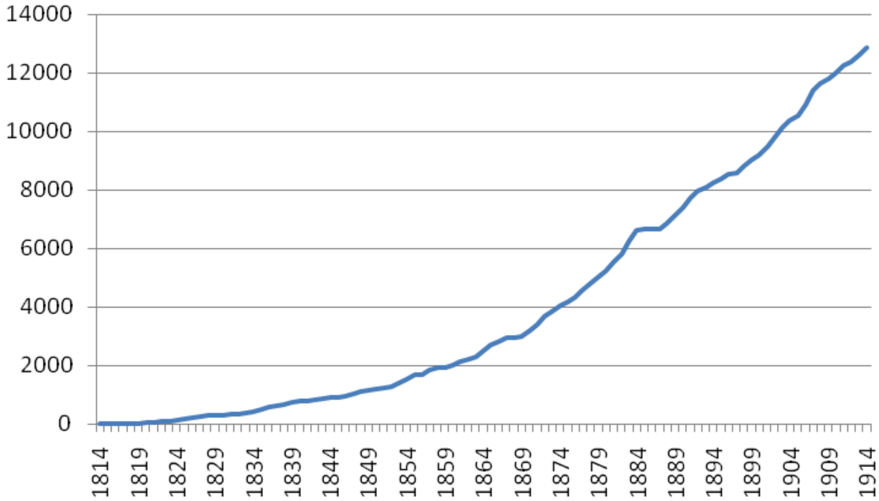
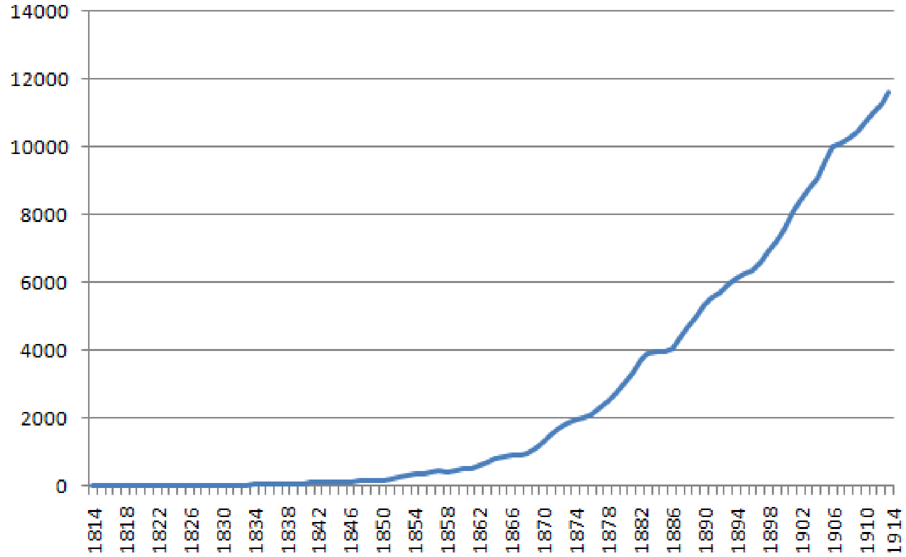


Figure 4.8 Aggregate net tonnage registered, British steamers, 1815-1914



Source: Elaborations on Mitchell (1988)
Note: First data point available for tonnage is the year 1815; ‘000s tons

The years following the introduction of the *Comet* are characterised by spectacular average annual growth rates. In the early years the total number of steamers grew faster than total tonnage, indicating the growth in the numbers of smaller size vessels and the initial application of steamers by small concerns in short-range trades. During these years, geographically speaking, whereas London, Liverpool, Glasgow and Hull dominated as the main ports when steamers were operating, there was a wide geographical dispersal among three dozen or so minor ports (Armstrong and Williams 2010, p. 45). Between 1815 and 1830 the yearly average compound growth rate was 25.4% in terms of registered units, and 23.7% in terms of tonnage. This pattern was exceptional. As Table 4.3 indicates, tonnage growth was above that of the population growth for the rest of the period under analysis. The differential between the growth in tonnage and numbers of steamers peaked in the 1850s, that is, tonnage during this decade increased at the fastest rate of the entire century relative to steamer numbers.

Table 4.3 Annual growth rate in the total number and total tonnage of steamships

	1820s	*1830s*	*1840s*	*1850s*	*1860s*	*1870s*	*1880s*	*1890s*	*1900s*
Number of steamers	28%	9%	4%	5%	4%	5%	3%	2%	3%
Net tons	25%	10%	6%	10%	8%	8%	6%	3%	4%

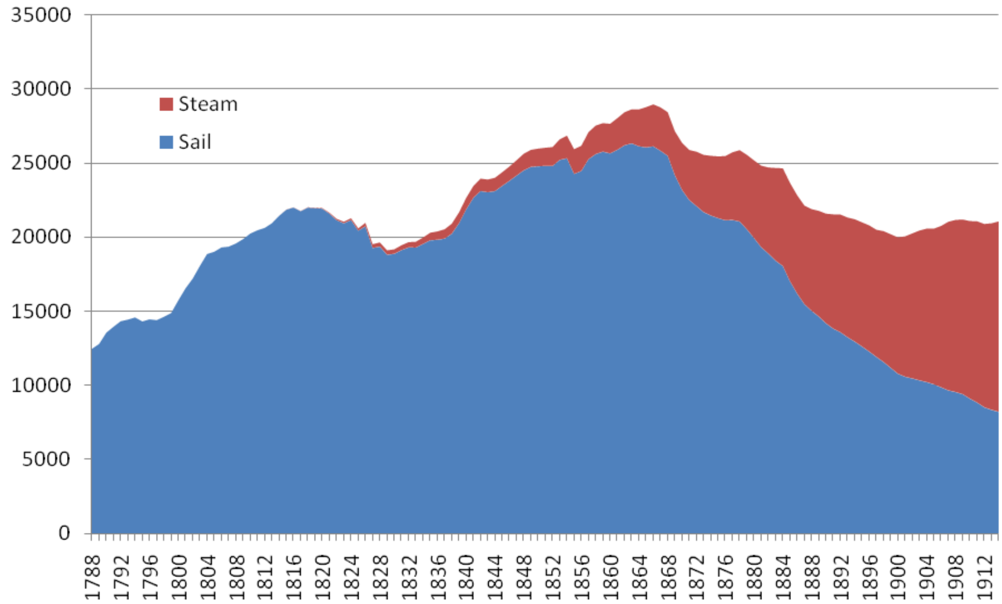
Source: Elaborations on Mitchell (1988)
Note: Yearly average compound growth rate per decade (1820-9, and so on)

Sailing vessels and steam vessels

In 1912, one century after the operational debut of steam navigation, a stock of over 12,000 steam vessels were in operation. This number was substantively larger than the number of sailing vessels active in that year (8,510), although this figure for sail is by no means a small one. Notwithstanding, the relative importance of steamers in the British merchant fleet was much higher in terms of tonnage than in terms of numbers: the shares of steam being 93.6% and 61.1%, respectively, at the very end of our period, i.e. 1914. The role of commercial sail was much diminished but, as maritime historians like Graham (1956), Greenhill (1980) and MacGregor (1984a) have stressed, its presence was not at all negligible well into the 20th century.

Although the rise of steam was characterised by a steady and robust upward trend from the outset, it occurred over a long period. The breakthroughs in the steamship technology and design, which are supposed to have occurred during the 1840s and 1850s, took place without rendering the sailing ship immediately obsolete. Only by 1904 were steamers as common as sailing ships under the British flag. The numbers of sailing ships went through several cycles of growth and contraction after 1788 (the earliest available data point for sail) and peaked in 1863. The number of sailing ships dwindled fast and inexorably beyond the early 1870s. Only after that can one observe a negative relation between the two types of vessel on the seas: sailing ships were disappearing while steamers were increasing (Figure 4.9). It is also interesting to note that in a vibrant period of trade the total population of ships did not expand until the Great War: the higher productivity of steamers absorbed the expansion of business while compensating for the destruction of sail capacity (see Sub-section 4.4.1 above).

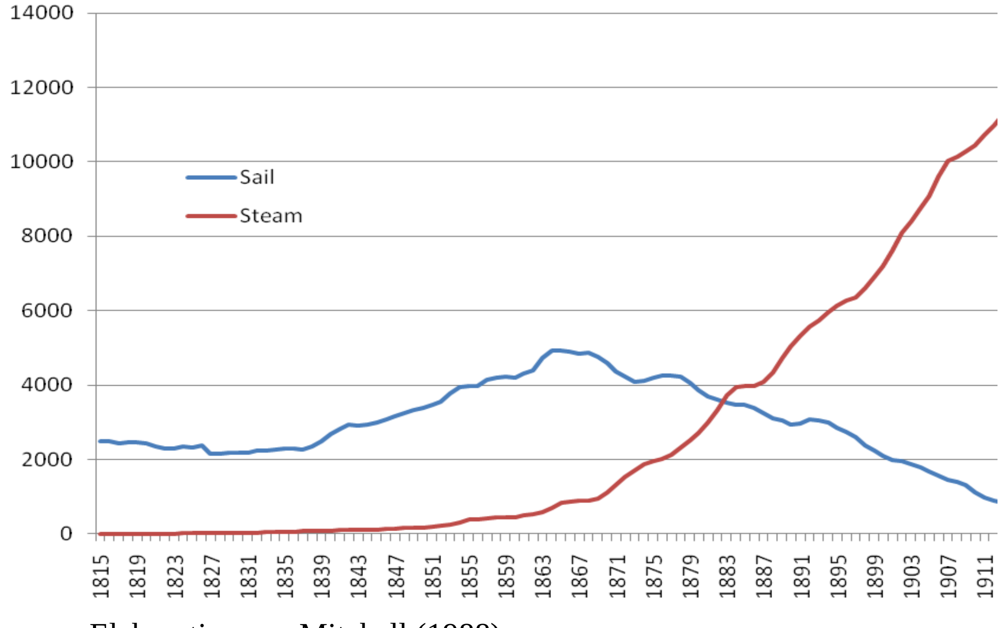
Figure 4.9 British-built ships, total numbers registered, sail and steam, 1788-1914



Source: Elaborations on Mitchell (1988)

Sure enough, the picture becomes more dramatic if we address total tonnage as the key variable. The total tonnage of sailing ships peaked in absolute terms in 1865 and decline then ensued. As may be gathered from Figure 4.10, 1882 was the last year sailing tonnage represented more than half of total net nominal tonnage. Thus, in terms of nominal tonnage, it took a full seven decades for steam to catch up with sail. Ocean-going sail would not resist much more. The years of 1888-1893 would see the last gasp of sailing ships. It is worth noting as well that by now sailing vessels were very different machines: they were much more productive than before and much cheaper in comparison to steamers. In 1882 the cost of a steamer was £15 per ton while a sailing ship was £11, i.e. more than 25% cheaper (Maywald 1956, p. 65). Sailing ship quality kept abreast with the times: while in 1882 more than 80% of newly registered sail tonnage was iron-built, during the period 1888-1893 steel made up 86.4% of sail tonnage launched (Mitchell and Deane 1962, p. 223). In other words, sail disappears from the British merchant fleet when sailing ships were modern, not outdated.

Figure 4.10 British-built ships, net tonnage, sail and steam, 1815-1914



Source: Elaborations on Mitchell (1988)

All this emphasises how steam shipping took a very long time to rise to prominence in terms of the tonnage stock in use, in spite of being sometimes characterised as a revolutionary means of water transportation. Moreover, perhaps surprisingly if the discussion is framed in terms of alternative technologies, for a considerable time the number and total capacity of both sail and steam shipping grew together. Indeed, from

1830 to 1864 British steam and sail rose together both in terms of numbers of ships and in terms of total tonnage. As Slaven (1992, p. 1) put it, the industry "moved on two fronts" for almost sixty years. The rapid expansion of the total market no doubt eased the entry problem for steam (Hughes and Reiter 1958, p. 375). Figures 4.11 and 4.12 focus on the period in which sail and steam jointly became more important.

Figure 4.11 Sail and steam, growth in terms of numbers of ships, 1830-65

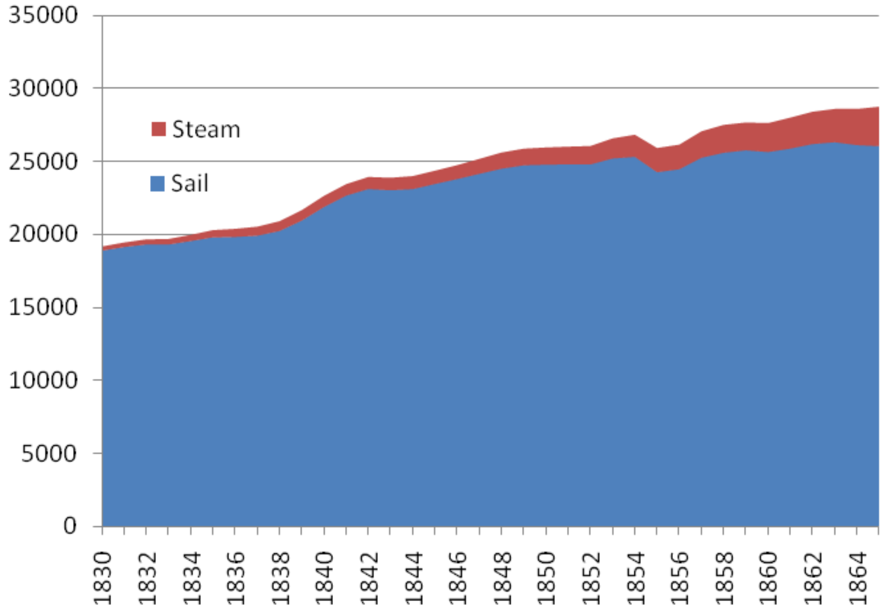
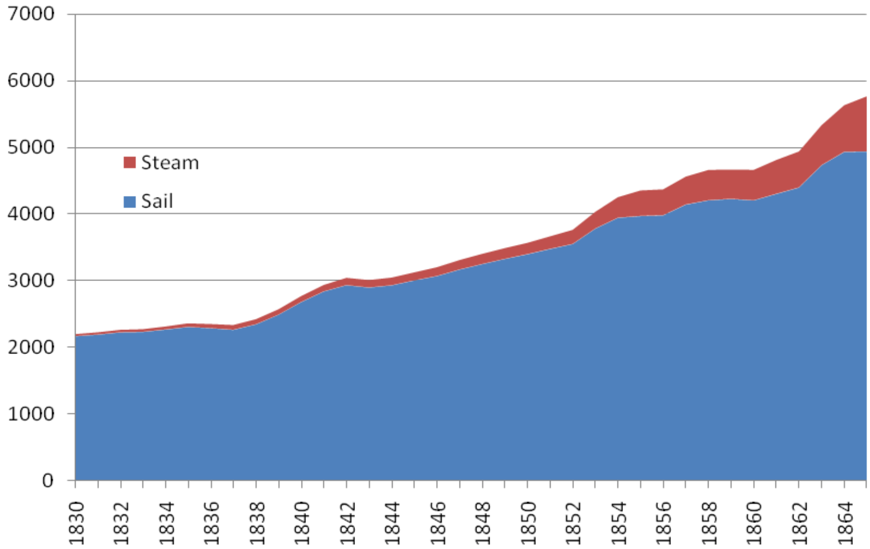


Figure 4.12 Sail and steam, total tonnage, 1830-65



Source: Elaborations on Mitchell (1988)

These were years of great expansion for the shipbuilding industry as a whole. Dyos and Aldcroft (1969, p. 232) describe growth in shipping from the 1840s "as an automatic response to the rapid expansion in international trade which occurred during the period in question."[25] With the 1840s came fully-fledged free-trade prompting unrestricted mobility of goods, especially, the imports of commodities (particularly raw cotton) and the exports of coal and manufactures (Harley 1994, pp. 300-1). Trade continued to grow, but the relationship between steam and sail was changing, the emphasis being more on substitution by the end of the 1860s (this is again in line with Sub-section 4.4.1). A contemporary observer writing a popular technology book in the 1860s viewed steamers "as the successors of, and supplements to, the old sailing-vessels" (Dodd 1868, p. 3), indicating that steamships were co-existing and increasingly surpassing sailing ships in an increasing array of trades.

4.4.3 Diffusion of steam in the registered population of ships

Steamship diffusion over time

Figures 4.13 and 4.14 show the usual sigmoid curve typical of technological diffusion for the period 1815-1914. In comparing the two figures, it is interesting to note again that the importance of steamers was much more overwhelming when measured in terms of tons than in terms of numbers of ships. In terms of sheer numbers, only in 1904 are there more steamers registered than sailing ships. This grossly underestimates the importance of steam, but, as noted above, even nominal tonnage still underestimates the effective tonnage of steam. Correcting for steam's real carrying capacity would present a steeper sigmoid: instead of steam representing 50% of the total stock of nominal tonnage in 1883, steam actually achieved parity with sail in terms of total carrying capacity around 1871. As in this thesis we are mostly concerned with the supply side (technology enabling the production of new vessels), not with the demand side (the services extracted by users), we will keep focusing on nominal tonnage.

[25] Indeed, Slaven (1980, p. 107) indicates that during 1830-1875 employment in UK shipbuilding trebled.

Figure 4.13 Steamers in total registered population of ships, 1815-1914

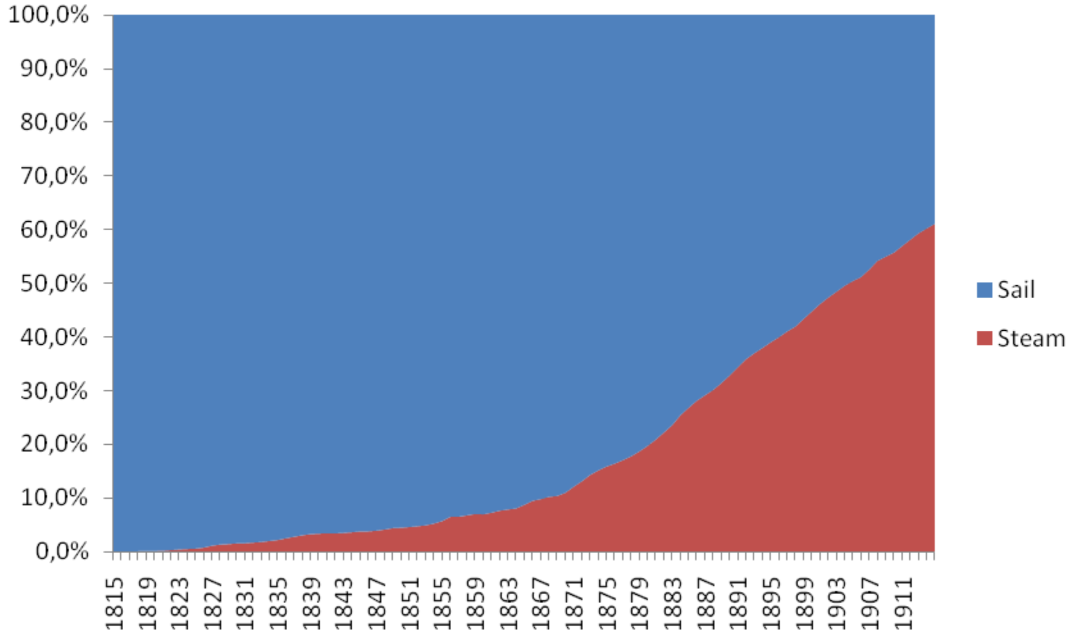
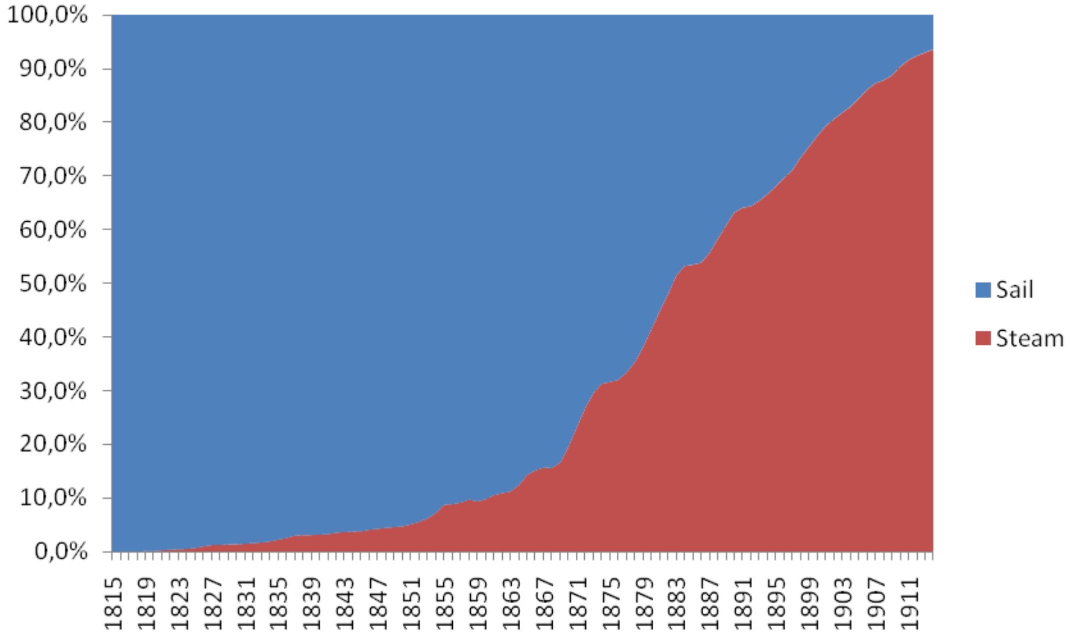


Figure 4.14 Steamers in total registered tonnage, 1815-1914



Source: Elaborations on Mitchell (1988)

Modelling steamship diffusion

Given the observed pattern, several theoretical S-shaped curves could possibly be adjusted to the figures. The features of several of those curves are well known and of interest in the context of the economics of technological diffusion. The literature on this is voluminous, however, and cannot possibly be covered here. There are some recent and comprehensive surveys that give an account of the foundations of this subfield, including Sarkar (1998), Geroski (2000), and Hall (2004).

Let us focus on tonnage because it is the prime technical characteristic at hand that directly mattered to ship operators.[26] The logistic curve is a summarising device and provides results that can be interpreted with a minimum of ambiguity (for a similar point, see Grilliches 1957, p. 503). It is in this spirit that it is chosen for our present purposes since we are not aware that it has previously been used for these data. The standard logistic growth curve is defined as

$$p(t) = \frac{k}{1 + e^{-(\beta_0 + \beta_1 t)}}$$

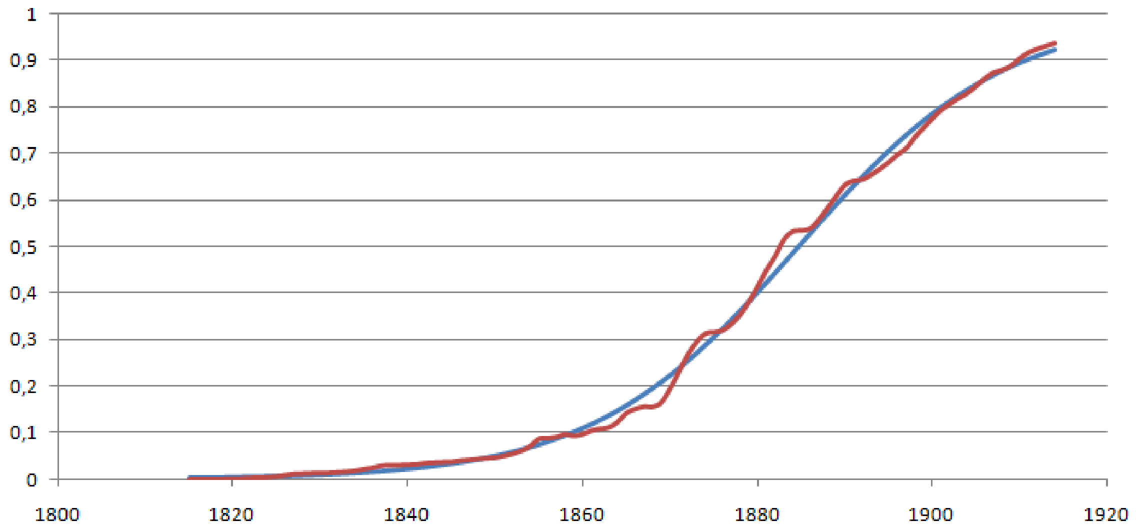
where p is the proportional penetration of steam in the total population of registered British ships. We have three parameters that we can interpret, with Grilliches (1980), in the following way: k is the ceiling value or upper limit (the maximum feasible penetration level, which for convenience could be thought of as unity), t stands for time, β_0 is the constant that positions the curve on the time scale (the date of the first commercial availability of the challenging technology) and β_1 is the coefficient giving the rate of growth (of diffusion). Appendix 4.2 gives further details concerning the definition of the curve and ways to expand it. In Figure 4.15 a simple, deterministic logistic model is adjusted to the observations (the blue line refers to the fitted values). Estimation followed a numerical iterative procedure for optimising the parameter values.

One interesting result is that the estimated inflection point is the year 1885 (this is not easy to glean from visual inspection; see Appendix 4.3, Table A, Model A for the formal statistical evidence). That is, from this point onwards the p (weight of steamers out of the total population) grows at an ever slowing speed. It is as if the major market

[26] To reiterate what has been said in Chapter 2, Section 2.2, and Chapter 3, Section 3.4: speed, on the contrary, remained of little significance to shippers in the bulk trades (see, e.g., Harley 1971, p. 217). For the premium trades, greater speed was important, although not the only significant characteristic.

segments had all been exploited, after which point only less profitable niches remained to be taken away from sail. If this interpretation is plausible, the corollary is that it took many decades for sail to lose the important battles, as it were. From this point onwards, only smaller, increasingly marginal markets were left to be taken away from sail.

Figure 4.15 Logistic curve fitting total steam tonnage diffusion, 1815-1914



Source: Elaborations on Mitchell (1988)
Notes: Proportion of steamers on total floating tonnage (steamer and sailing ships, total tonnage); red colour = observations, blue colour = fitted values

The impact of the Suez Canal

By the year 1885, it should be noted, the opening up of the Suez Canal had already taken place. Did this event have consequences in the shift of sail to steam? In order to test the significance of the effect and to measure the extent of the impact, if any, we present two additional models (B and C) in addition to the base-line model (A):

A. Base-line model of logistic regression estimation;
B. Model singles out the year of the Suez Canal opening (taking it as a dummy variable);
C. This model is actually two models, the first is fitted to the data-point until 1869 (i.e. the purpose is capturing the pre-Suez data generating process) and the other is estimated only for the remaining years (i.e. capturing the post-Suez data structure.

Table 4.4 summarises the results. We use the yearly change of the steam/sail ratio as an indicator of steam tonnage diffusion. Model B detects a large jump occurring as a consequence of the Suez Canal opening. Model C assumes that there could be two models defining the series: one behaving as if there had not been the inauguration of the Suez Canal and the other explaining the series only taking into account the observations affected by the opening of the Canal. As reported in Appendix 4.3, model C is found to be significantly superior to models A and B.

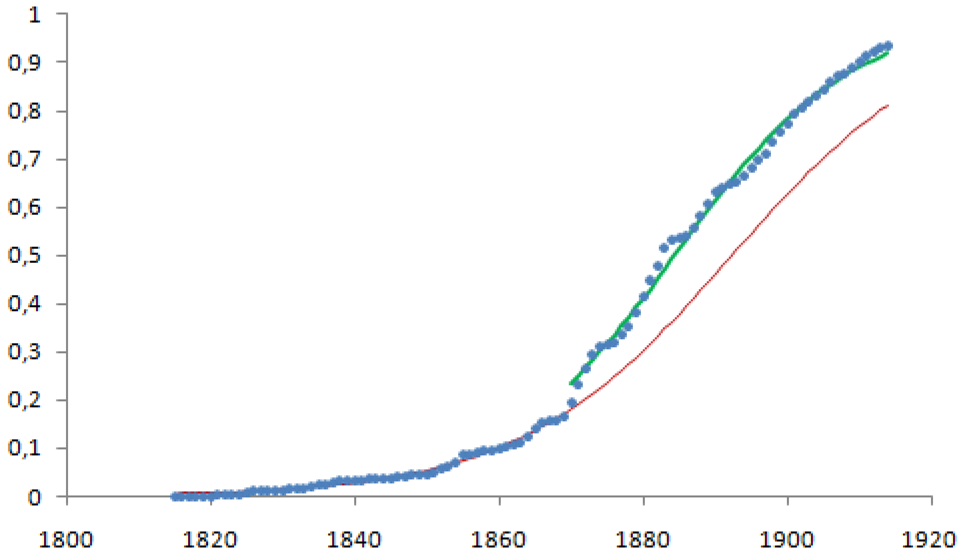
Table 4.4 Three ways to model diffusion of steam tonnage, 1815-1914

	A. Single logistic curve estimation without Suez	*B. Single logistic estimation with Suez*	*C. Two logistic curves, fitted before and after Suez*
Growth of steam/sail ratio	Steam/Sail ratio increased 8.5% per year	Steam/Sail ratio increased 8.5% per year, except for the year the Suez was opened: for that single year the steam/sail ratio jumped 36%	In a world in which the Suez would not have been opened the Steam/Sail ratio would have increased 6.9% per year; in a world with the opening of the Suez canal the yearly increase of the Steam/Sail ratio was 8.5%.

Source: Elaborations on Mitchell (1988)

Figure 4.16 illustrates the result of estimating model C. Data-points are in blue and they are clearly better approximated by the green line: this line fits the model only taking into account post-1869 data. It is remarkable that it indicates that the change in the Steam/Sail ratio is 8.5%, virtually the same as estimated from model A. The red line emerges from estimating the parameters for the pre-1869 years and projecting them forward in time. According to this (red) fitted line the inflection point would have come about only by 1892, while in a Suez-affected world the inflection point was earlier, i.e. 1884 (again a close result to Model A, which pointed to the year 1885). In other words, this exercise can be used to support claims that the Suez Canal infrastructure accelerated the process of overall steamship diffusion (by nearly ten years, as measured by the weight of total net tonnage of steamers in the total British registered tonnage).

Figure 4.16 Modelling the impact of Suez



Source: Elaborations on Mitchell (1988)

Did the Suez Canal (really) have an infrastructural effect?

The Suez Canal reduced by 41% the distance between London and Bombay, and by 32% that between London and Shanghai (Clark and Feenstra 2003, p. 295). Estimating the qualitative impact of the opening of this great canal has been, however, a more elusive task. “It is not easy to estimate the effect of the Suez Canal on the decline of the sail trading vessel” (Kemp 1978, p. 203), yet this is a factor often associated with the acceleration of the spread of steamers and the disappearance of sail (e.g. Hendry 1938, p. 49; Derry and Williams 1960, p. 373; Rowland 1970, p. 118; Deeson 1976, p. 95; Stopford 2009, p. 25). However, there are other views: “the cutting of the Suez Canal did *not* mark a turning-point in the life of sail” (Graham 1956, p. 75, italics in the original); or “this contention [that the Suez opening was a turning point] is not supported by facts.” (Greenhill 1980c, p. 33) Thomson (1993, p. 11) also seems sceptical that the Suez Canal was a definitive event by itself and points to telegraph and bunkering stations as complementary infrastructural factors. Other authors, for instance Harley (1971, pp. 223-4) and Slaven (1980, p. 116), maintain that this moment marks a discontinuity in the process of steamship diffusion. The influence of the Suez Canal has been an object of debate concerning the development of late 19th century shipping but explicit attempts offering quantitative support for one argument or the other have so far been rather scant. Our approach has apparently not been tried before and turns out to lend weight to the latter view. There are a number of facts giving support to our results.

The Canal was of little use to sailing ships (Rowland 1970, p. 118). A first barrier "was the prohibitive cost of being towed the hundred miles through the canal" (Fletcher 1958, p. 558; see also Rowland 1970, p. 118). The other problem was that "the Red Sea is not navigable by sail" (Kirkaldy 1914, p. 318; see also Rowland 1970, p. 118)[27]. The first sailing ship passing through the Canal was the French barque *Noel*: she was wrecked on the very evening she pulled out of the Canal, a mere 86 miles south of the Suez (Fletcher 1958, p. 58). Thus, of the total number of ships using the Canal during the first five years, less than five per cent were sailing ships (Fletcher 1958, p. 58). The number of passages through the Canal rose from 486 in 1870 to 2,026 in 1880, 3,389 in 1890, 3,441 in 1900, and 4,553 in 1910 (Porter 1912, p. 541). The mean net tonnage per vessel, an indication of the development of steamship carrying capabilities, also increased steadily: 898 net tons in 1870, and then 1,509 nt (in 1880), 2,033 nt (in 1890), 2,830 nt (in 1900), and 3,658 nt (in 1910). It is clear why steamers immediately took over the new route. When the Suez Canal was opened to traffic, on 17 November 1869, it slashed thousands of miles from the route between Europe and the Far East overnight (Woodman 1997, pp. 173-4). The route was more than 4,000 nautical miles shorter and meant that steamers undercut clippers (and could do more regular sailings) in less than half the time via the Cape (Kirkaldy 1914, p. 330; Kemp 1978, p. 203; Stopford 2009, p. 26). Suez, and the possibility of now coaling in Singapore, combined to yield a gain of a month or more over clippers engaged in the long route round the Cape of Good Hope (Lubbock 1945, p. 48). Indeed, the Suez route to India and the Far East offered

[27] Hendry (1938, p. 51), someone who was still referring to trading square-riggers at the time of his writing, supplies a vivid description of why sailing ships could not have used the Canal: "Outward bound they were liable to meet strong southerly winds at the southern end; and beating among the reefs, mainly uncharted, and through narrow straits would have been almost impossible, except for man-o'-wars with large crews. Homeward bound they were likely to meet strong northerly winds at the northern end, with the certainty of long delays in the bottleneck of the Gulf of Suez."

plenty ports of call, bunkering-stations at shorter intervals and better weather conditions than the alternative Cape route (Sargent 1918, p. 29; Hendry 1938, p. 51; Stopford 2009, p. 26).[28] MacGregor (1988, p. 211) claims furthermore that the opening of the Suez Canal provided the final inducement for the provision of coaling stations.

True, sail had already peaked (in 1865, as seen above), but steam tonnage only accounted for 16.6% of total tonnage when long voyages to the Far East were shortened. In Kemp's (1978, p. 203) words: "Up to 1870 the clipper was a certain money-spinner." After the opening of the Suez Canal, however, the end of the tea route via the Cape was abrupt. The advantages provided to steamers by the Suez route proved beyond the capabilities of even the fastest composite clippers, those "large racing machines" (MacGregor 1984a, p. 219). Two of the most famous clippers built for this trade actually did not have much time to pursue their vocation. The *Thermopylae* and the *Cutty Sark*, built respectively in 1868 and 1869, were among the last of the tea clippers. After a few years they were redeployed, starting with the Australian wool run. Even the best sailing ships were now being pushed to less remunerative trades. The tide was turning, as it were.[29]

We are thus inclined to side with Harley (1971) and Slaven (1980), and to agree with Fletcher (1958, p. 572), who has observed: the "Suez forced a speed-up in steamship construction and the mass introduction of the compound engine, thereby reducing fuel consumption by nearly half and making it possible for steamships to challenge sailing ships as cargo carriers in the East and on almost any other of the world's major shipping

[28] It might be recalled that in Jules Verne's Around the World in Eighty Days the imperturbable Phileas Fogg was able in 1872 to steam through the Suez Canal in only seven days, a crucial saving given his race against time (see Hobsbawm 1975, p. 52).

[29] Moreover, as MacGregor (1984a, p. 17) observed: "Prior to 1869 it will be noticed that the rise and fall in the building of sailing ships was complemented by the building of steamers; but after 1869 the position was reversed, and the tonnage of sail increased in years when that for steam declined." The periods in which this reversed relationship was especially perceptible were the depression years of 1873-79, 1882-86 and 1890-96: during times of slow business, sailing ships could wait less expensively for cargo and, hence, were preferred by ship-owners. As Hume and Moss (1975, p. 17) have pointed out, in times of depression even the most advanced iron shipyards of the Clyde, such as Dennies and Elders, would churn out sailing ships.

routes." Stopford (2009, p. 25) notes "The opening of the Suez Canal in 1869 was well timed to generate a surge of investment in innovation". Owners of steamers engaged in an accelerated renewal of their fleets, adopting steamers with the latest technologies, in order to take immediate and full advantage of the Eastern trades.[30] This reorganisation of trade movements was powerful enough, moreover, to finally stimulate the deployment of a world-wide network of bunkering stations, the infrastructural bottleneck that previously favoured sail in the long distance-trades (Lilley 1976, p. 211; MacGregor 1988, p. 211). As Fletcher (1958, p. 572) concludes: "by throwing open the whole of the vast, lucrative trading area to exploitation by efficient steamships, Suez hastened the replacement of sail by steam, not only in the Eastern trade alone, but indirectly in all other trades as well." Sargent (1918, p. 53), who had witnessed the consequences, agreed: "The transference to steam was inevitable, but the process was somewhat hurried by the special needs of the new route." Our analysis offers perhaps a first formal test of this insight within a known and well-accepted statistical framework.

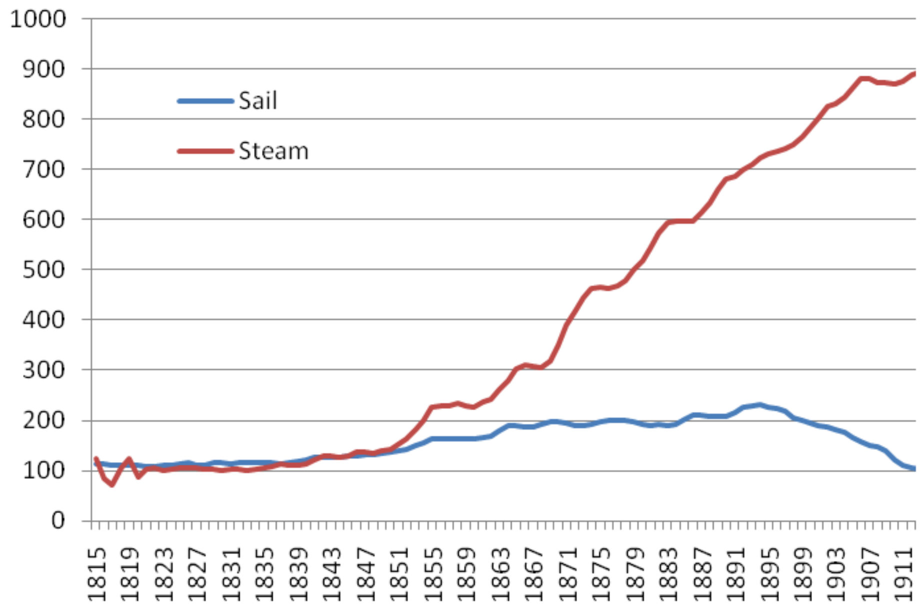
4.4.4 Size trajectories of steam and sail

Divergent performance paths between sail and steam

The performance of steamers in terms of average tonnage eventually dwarfed that of sailing ships, as Figure 4.17 makes clear. During the 1830s and 1840s, however, the average registered tonnage in the two types was roughly equivalent: 115.5 tons per sailing ship, and 105.4 tons per steamship. In the 1870s the average steamer's tonnage was more than double that of sail: 444.4 and 192.2 tons respectively. The steamer had made the transition from transporting only premium and urgent freight (restricted by its size and fuel-efficiency limitations, possessing only better speed and time-keeping than sailing ships) to carrying just about any kind of cargo over trans-oceanic distances. The 1850s mark an increasing divergence in tonnage capacity; until then, the two alternatives were similar in terms of size.

[30] So much was apparent to a contemporary observer like Kirkaldy (1914, p. 318). For experts in the maritime business it was also clear that there was a link between the exploitation of the Suez Canal and the acceleration of the ascendency of steam in the British marine (see, e.g., Sargent 1918, p. 29 and p. 53).

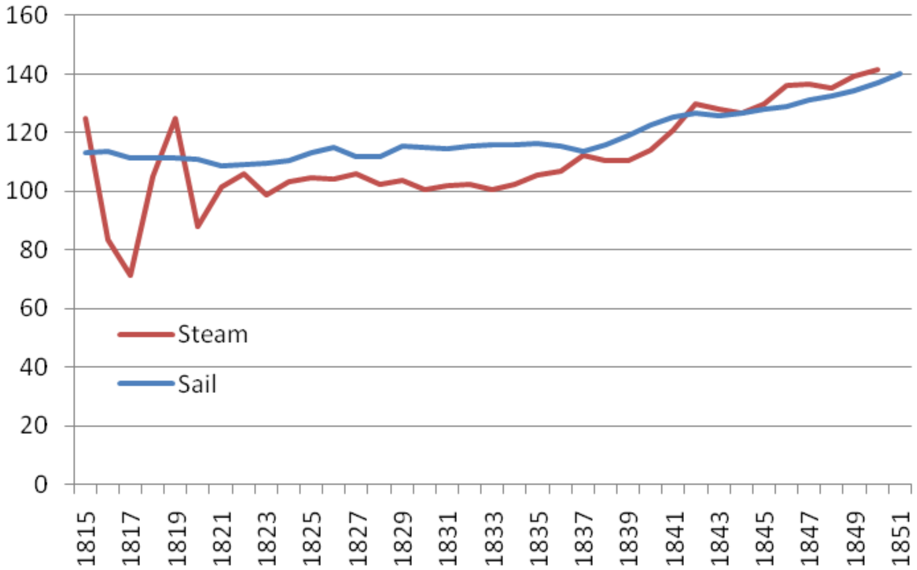
Figure 4.17 Ship performance as measured by average tonnage, sail and steam



Source: Elaborations on Mitchell (1988)

By the 1850s onwards, it is clear that average ship size increased markedly from decade to decade. It should be noted that not only steamers (the "new" technology) but also sailing ships (the "old") grew larger. This common trend held until the irreversible demise of sail in the 1890s. Figure 4.18 takes a closer look at the period before the bifurcation. Between 1820 and 1850, the performance of sail and steam is quite similar. In the early 1830s steam shows the first signs of catching-up with sail and, already by 1840, both were already on an upward trend.

Figure 4.18 A closer look at performance as measured by average tonnage, 1815-51



Source: Elaborations on Mitchell (1988)

When did sail and steam vessels become different (in their average size)?

Progress in steamship size was not a smooth-running trend. Figure 4.17 above would appear to suggest the existence of a sharp upturn occurring in steam at mid-century that was not matched by sail. In order to date the beginnings of the divergence, we carry out a set of formal tests. First, because the two series are comparable, in that they both refer to net tonnage, we will reduce the two to just one series of the difference between them. In other words, we start by focusing on the differential performance (average tonnage) of sail and steam ships on a yearly basis. Second, we will analyse the series with the help of a model that assumes the existence of a structural break in a given trend and tries to find the date that optimises the probability of its existence.

Procedures for testing for the presence of a break in a trend function at an unknown date have been a focus of recent research in econometrics and time-series analysis. This increased attention has followed in particular the contribution of Perron (1989). We will adopt this approach, which allows for the possibility of a unique change in the deterministic component of a time series. The date of the break is denoted by T_B with $1 < T_B < T$, where T is the sample size. The break is assumed to occur instantly.

$$y_t = \mu + \beta t + \theta DU_t + \gamma DT_t + u_t,$$

where, *DU* and *DT* are dummies for a break in the intercept and the slope:

$$DU_t = \begin{cases} 0 & \text{if} \quad t \le T_B, \\ 1 & \text{if} \quad t \ge T_B + 1, \end{cases}$$

$$DT_t = \begin{cases} 0 & \text{if} \quad t \le T_B, \\ t - T_B & \text{if} \quad t \ge T_B + 1. \end{cases}$$

Thus, the model allows for both a shift in the intercept and slope. If the dummy parameters are significant, a break exists (in the intercept or slope, or both) and can be dated. The error u_t is assumed to be an ARMA (auto-regressive, moving average) process. Under the alternative hypothesis, u_t is stationary, so that y_t is stationary around a broken trend. Under the null hypothesis of a unit root, u_t has a unit autoregressive root, so that y_t is I(1) and Δy_t is a stationary process given by

$$\Delta y_t = \beta + \theta D_t + \gamma DU_t + v_t,$$
$$\Delta y_t = \beta + \gamma DU_t + v_t,$$

where,

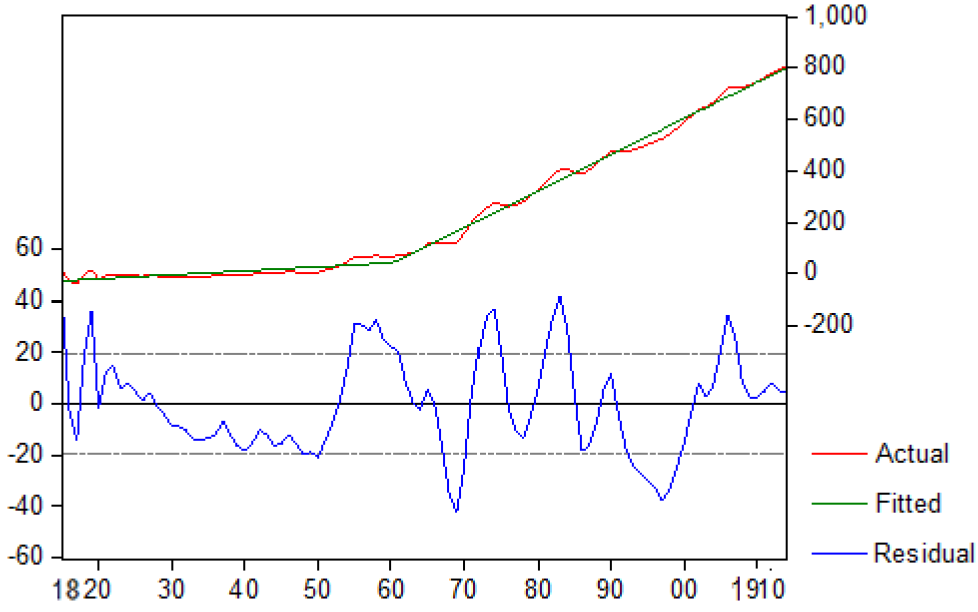
$$D_t = \begin{cases} 0 & \text{if} \quad t \neq T_B + 1, \\ 1 & \text{if} \quad t = T_B + 1, \end{cases}$$

and the error term v_t is a stationary ARMA process.

When the break date T_B is not known, Vogelsang and Perron (1998), following the initial proposal by Perron (1989), suggest choosing the break date that maximizes or minimizes a statistic that tests the significance of one or more of the break parameters (θ, γ). This methodology allows us to estimate an unknown trend-break, admitting a unit root and controlling for its potentially confounding effect.

Figure 4.19 shows the result of plotting a variable Y defined as the difference between yearly average steamship tonnage and the yearly average sailing ship tonnage.

Figure 4.19 Sail and steam, average nominal tonnage compared, 1815-1914



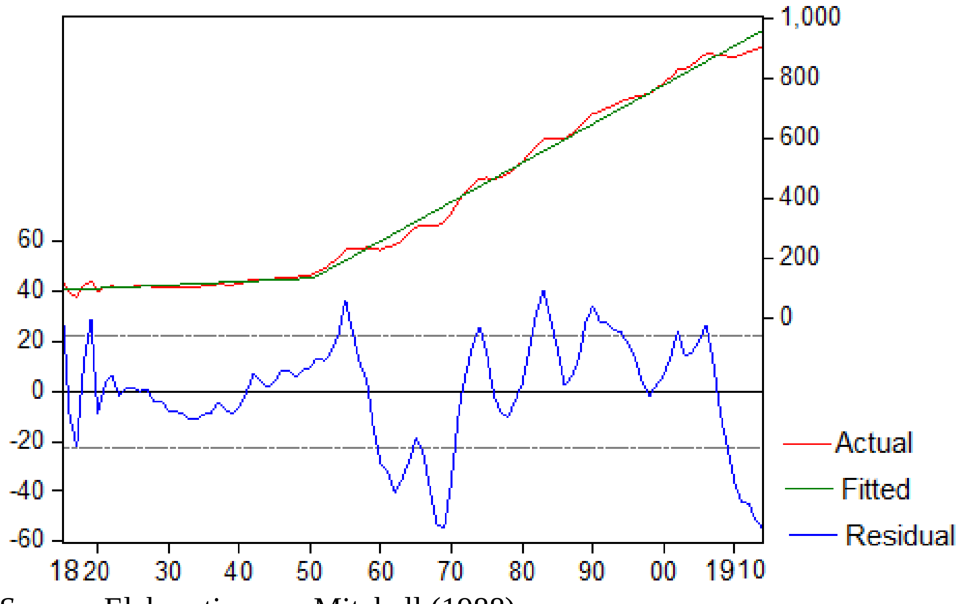
Source: Elaborations on Mitchell (1988)
Note: Dependent variable = average steam tonnage – average sail tonnage

For this time series the optimal trend-break occurs in 1861; there is a statistically significant shift in the slope and no unit root is found (for the estimation output see Appendix 4.4). Hence, this model suggests 1861 as the definitive point of bifurcation in the performance of the two types of vessel. That is, beyond 1860 sail and steam vessels were fundamentally different machines in terms of size.

The technological take-off of steamship trajectory toward higher capacity

But when, specifically, did the technological "take-off" of steamships occur? Applying the same econometric analysis to the variable defined as average steam tonnage generates Figure 4.20 (for the estimation output see Appendix 4.5).

Figure 4.20 Dating the take-off of steamship performance, 1815-1914



Source: Elaborations on Mitchell (1988)
Note: Y = average steam tonnage

The conclusion is that the take-off of steamship technology (as measured by the product's performance in terms of average net tonnage) occurred in 1851. Until that date average steam tonnage growth was slow and erratic, reflecting the long gestation of the technology. But from then on, steamer capacity increased consistently on an upward trajectory. Moreover, increase in steamship size was sustained throughout the period, i.e. the series has a unit root, and shocks to the technological system are permanently incorporated into the trend, which is a desirable property to be inferred in the case of technological phenomena. These are significant findings. It should be noted that the structural break in the series occurs before the Crimean War and also before the 1854 revision of the tonnage measurement methodology. It also took place long after the 1836 tonnage law reform. What was the nature of this change in the rate and direction of the "technological trajectory" of steamers? What lay behind it and what made it linger until the Great War? Could these changes be related to a radical change in the underlying "technological paradigm"? What were the sources of innovation that unleashed this transformation? These fundamental questions will be addressed in Chapter 5 and the remainder of this thesis.

What about ship quality and economies of scale?

Further checks of these structural change findings may be obtained from different angles of analysis and other sources. So far we have said nothing about quality. Quality considerations have largely lingered in the background of this analysis for expediency purposes. However, to omit a discussion of quality would leave the analysis incomplete in several respects. First, as noted above, we have to acknowledge that one net ton of sail was not equivalent to one ton of steam for purposes of commercial transportation: that is, combining sail and steam, steamers were faster and more predictable in their service (Appendix 4.1). We also saw that, having got rid of bulky paddle-boxes and being more efficient on water: an iron-screw steamer like the *Rainbow* had in the early 1840s twice as much cargo space as the typical vessel, and this was not counting the advantages of self-propulsion (Chapter 3, Section 3.3).

Second, both steam ships and sailing ships dramatically improved over time. Both steamers and sailing ships were not the same at the beginning and at the end of the period. So, for instance, a steamer of the 1830s was very different from one of the 1870s of comparable size in terms of efficiency since the typical steamer of the 1870s was iron-screw and much more durable and fuel-efficient than the typical steamer (a wooden paddler) of the 1830s. Likewise, a tall ship sailing vessel of the 1890s would have been much cheaper to maintain thanks to her steel hull and small crew (helped out by donkey engines) than a mid-century sailing ship, whose flexible hull would be continuously working on the water (and leaking) and needing a large number of able men to operate her complicated rigging.

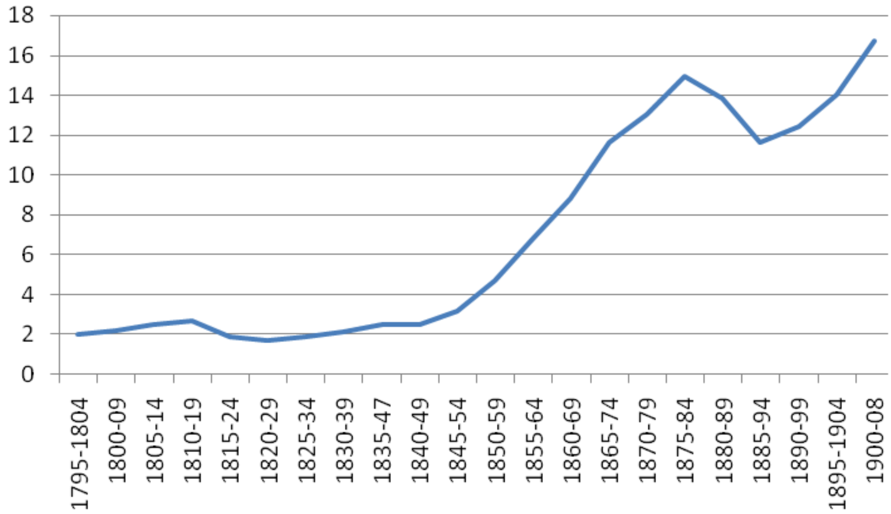
It is difficult to find a synthetic indicator for quality but to introduce this perspective markedly reinforces the conclusions so far, rather than weakens them. One can find an indication of ship quality in the estimates of new ship's construction costs by Dean and Cole (1967, p. 234). They found, as shown in Figure 4.21, that the construction cost of new ships built in UK rose sharply at mid-century. This shows that, generally speaking, something must have happened that justified this hike. Interestingly, Slaven (1980, pp. 117-8) finds no general increase in *average* prices in pounds per gross ton of either sail or steam tons. Iron-built ships were also comparatively cheaper than wooden or composite ones of the same tonnage between 1850 and 1875 of the same tonnage. Taken together, these observations point to the following: as the cost per ton diminished, a rise in the cost of ships must be explained largely by a dramatic rise in ship size. In such a quantitative growth in ship size a qualitative transformation in the technological nature of ships was surely involved (see Chapter 2, Section 2.2).

An increase in average ship size was going on after the 1850s. The ultimate goal served by this technological trajectory was "economy and safety" in the freight service and "speed and safety" in the packet business (Johnson 1906, p. 87).[31] How can we see the economic reflection of the increase in size? As we have discussed (Appendix 4.1),

[31] This, of course, seems not to have been the case with naval ships. Philip Pugh (1986), in his comprehensive book on naval costs from the early 19th century to the late 20th century, argues that the industrial revolution at sea made a large impact in military shipbuilding costs. In naval ships technological change set a trend toward "bigger, more powerful and more expensive ships" which, as Lyon (1980, p. 22; see also Lambert, 1992c) has pointed out, was already visible by the 1850s.

larger ships were cheaper to build and operate per ton and, being steadier and faster on the water, they allowed more voyages per unit of time (higher throughput). Moreover, as ships grew in size, manning levels tended to grow less than proportionally.

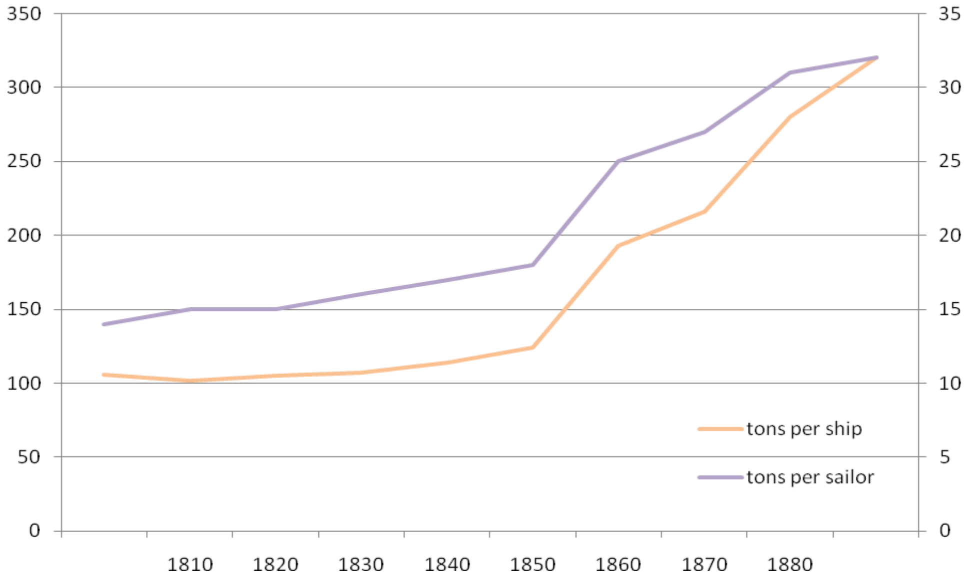
Figure 4.21 Value of tonnage built and registered in the UK



Source: Dean and Cole (1967, p. 234)
Note: Annual value of new ship tonnage in millions of pounds, estimation of the average construction cost of new steam and sail tonnage built during each decade

Tons per ship and sailors per ton constitute two variables indicative of "economies of scale". Figure 4.22 shows data published by Mulhall (1892), who does not distinguish between sail and steam vessels and who aggregates metropolitan and colonial shipping. Another problem is that, as with many of other of Mulhall's other data, the sources are not known or given. von Tunzelmann (1978, p. 29) calls them "guesstimates", but points out that sometimes they are the only ones available. Whatever the quality of the figures in terms of *level*, they seem to point to an already familiar pattern in terms of *dynamics*: something happened in terms of economies of size that became very clear during the 1850s. A trajectory towards greater size (and economies of scale) seems to take-off at mid century, and kept being stretched thereafter. The pressure exerted by this trend of course led port authorities to enlarge and deepen their facilities (and use steam dredgers for that job) in order for those economies to be realised (Craig 1980a, p. 45). To find out what lies behind this pattern we need better evidence obtainable from more specific and accurate data (see Chapter 5).

Figure 4.22 Tons per ship and per man, British and colonial shipping 1810-1888



Source: Mulhall (1892, p. 524)
Note: Tons per ship on the left-hand side *y*-axis; tons per sailor on the right

4.4.5 The "sailing ship effect"

What was the "sailing ship effect"?

This subsection attempts to offer a partial measurement of the famous so-called "sailing ship effect". According to available scholarship (Freeman and Soete 1997, p. 105; Grübler 1998, p. 204; Mom 2004, p. 308), the phenomenon appears to have first been labelled by a New Zealand scientist in a short article more than four decades ago (Ward, 1967). Something akin to the "sailing ship effect" can, perhaps, be inferred from Gilfillan (1935b, pp. 156-75) when he refers to "the brilliant sunset of the sailing ship" in the face of increasingly efficiently engined steamers. The "stylised fact" of a latter day revival of an aging technology was made popular in the innovation studies community by Nathan Rosenberg (1976). Freeman and Soete (1997, p. 355) describe the "sailing ship effect" as a series of improvements in the older technology which prolong its life and retard the diffusion of the new technology. Grübler (1998, p. 204) also refers to the slow displacement of the incumbent technology: "the major technical improvements in clippers when challenged by competition from steam ships." (Box 4.3)

Box 4.3 The "sailing-ship effect"

The term seems to have been introduced by Ward (1967). The general observation is that even old technologies are dynamic and can still evolve when new technologies arrive. Rosenberg (1972, p. 28), who popularised the notion, put it in the following way: "The sailing ship of the 1880s was far superior to its predecessor of 1850 or so, and it seems plausible to attribute this improvement to the strong competition of steam." The story ran a course of its own and has been repeated many times as the so-called "sailing ship effect". So, Hall (2004, p. 462) refers to the "frequently given example" of "the rapid productivity increase in sailing ships during the nineteenth century". "This usually happens", asserts Geroski (2003, p. 45), "when they are challenged by a new, potentially displacing technology whose competitive challenge galvanizes those scientists and engineers who are committed to the old technology."

Now, it may well be that, in general, old technologies may experience a "'last gasp' improvement" (Hall 2004, p. 462), or that established products "fight back" (Geroski 2003, p. 178), or that incumbents demonstrate "vigorous imaginative responses" in the face of new challenges (Rosenberg 1972, p. 26). The conjecture is plausible. But we must be concerned with the empirical validity of this claim in the very field from which it was extracted. As it happens, this simple formulation turns out to be rather problematic (see Howells, 2002).

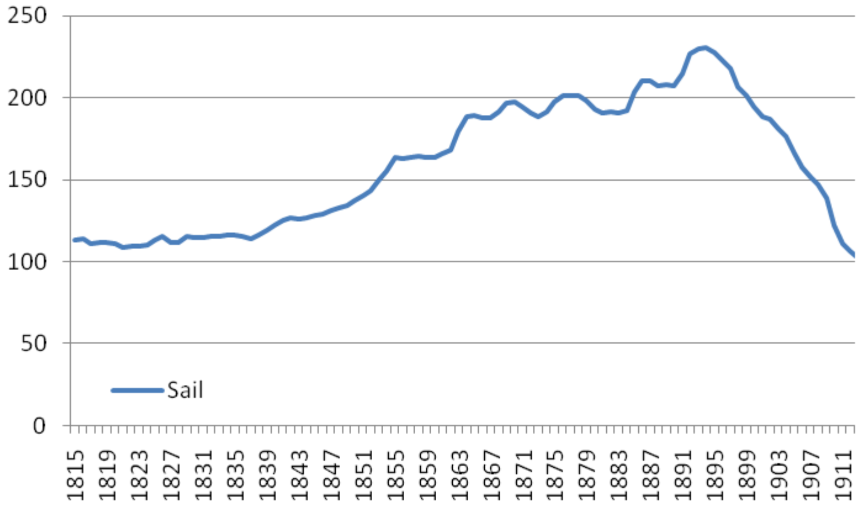
What was the magnitude of the "sailing ship effect"?

It is apparent from Figure 4.23 that something did indeed happen to the average size of the sailing ship in the period under analysis. It is thus possible to attempt to assess the magnitude of the "sailing ship effect" and to place it on a time-scale: from 1837 until 1894 the average tonnage goes up from 114 to 231 tons. That is, in 57 years the average tonnage in the register was multiplied by a factor of 2 from a state of the art that took millennia to arrive at. Indeed, and as Graham (1956, p. 75) put it, "the great days of sail lie not before but after the middle of the century".

The evolution of the average size of sailing ships represented in Figure 4.23 exhibits the abrupt downward turn starting in the mid-1890s. At the dawn of the twentieth century, most sailing ships under British flag were, on average, smaller craft confined to lesser activities such as coastal commerce between ports of local importance. So, the chart also yields a perspective of the shift from sail to steam through changes in the sailing fleet, pushing it to ever more marginal trades.

As the large sailing vessel entered the 1900s, she "was consigned to increasingly peripheral transport of bulky, low-cost, homogenous freights such as coal, fertilisers, feed-stuffs and china clay – these were typical consignments that sustained the declining and ageing fleet that constituted the last survivors of a glorious era.” (Craig 1980a, p. 45) Small sailing ships outlived the large bulk traders by many years, remaining economically viable long after deep-sea sail passed into irrevocable decline.[32]

Figure 4.23 Developments in the average size of sailing ships, 1815-1914



Source: Elaborations on Mitchell (1988)

Dating the “take-off” of sailing ship technology

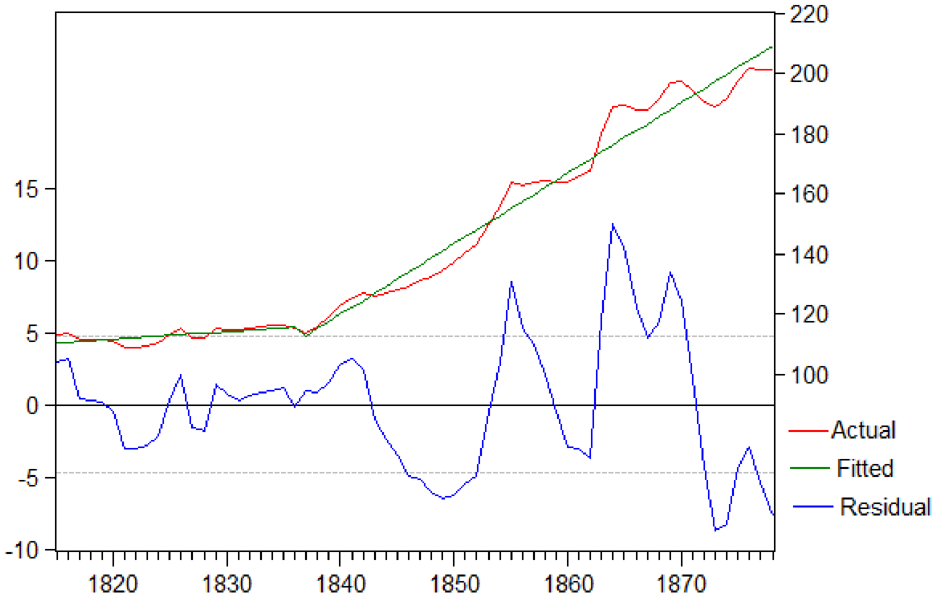
Figure 4.24 presents the results of a trend-break analysis into the performance of sailing ships built and registered from 1815 until the period they actually started to shrink in size. We use the same method as above to allow us to indentify a turning point at an unknown time (Appendix 4.6). What we find, however, is somewhat surprising. For this truncated sample size, the date that emerges is 1837. From this year onwards, the trend function suffers a significant alteration both in the intercept and the slope, and a unit root cannot be rejected at the conventional significant levels. Thus, this finding presents something of a puzzle. The take-off of the sailing ship occurs *before*, not after, the mechanised ship had become a real threat from the mid-1850s to the early 1860s. What is more, the sailing ship take-off happened much before the age of the tea clipper, i.e.

[32] Owing to their capability to sail from small ports and harbours inaccessible to deep-draught steamers – where it was not efficient to operate steam vessels – and to their low running costs, vessels like schooners, sloops and ketches remained active on the British coasts for some years to come (Greenhill 1941, p. 245).

the late 1860s (c.f. MacGregor 1984a, p. 16). This observation is given additional force by a closer inspection of Sunderland data, the port which came to dominate the English wooden sailing shipbuilding industry by mid-century: the average size of Sunderland's sailing vessels grew 73% (from 253 to 450 tons) between 1834 and 1853, faster than the British average (Ville 1989, p. 71). Thus, the conventional notion of the "sailing ship effect" as a *response* to the challenge of the steamship seems rather hard to maintain.

Experimentation in British sail had, indeed, become pronounced in the 1830s (see, e.g., Brown, 1990). Sharp decreases in passage times of cargo merchantmen, a variable not readily captured with Mitchell's data, were reported following the removal of HEIC's monopoly in the early part of the decade (Woodman 1997, p. 191). Two major examples of British innovation under sail stand out, marking the disappearance of the old East Indiamen. In the second half of 1830s, the "Blackwall Hull" and the sharp "Aberdeen Bow" first made their appearance. While very few builders made design and construction breakthroughs, they were followed by many others, copying the improvements that relied on widely shared skills (Slaven 1992, p. 2).

Figure 4.24 Sailing ships at a turning point, average size, 1815-78



Source: Elaborations on Mitchell (1988)
Note: Y = average sail tonnage

The first Blackwall Frigate was the *Seringapatam* built in 1837 by Messrs. Money Wingram and George Greene, otherwise known for their steamship work. She immediately set a new record of 85 days when she sailed from London to Bombay (Kemp 1978, p. 200). The new vessels had greater length, a cleaner run and less freeboard (Clowes 1936, p. 30). Their finer entrance and under-water lines made them faster than their predecessors. This new type did not remain still; it kept the same designation but evolved. MacGregor (1984a, p. 53) notes on the basis of the builder's plans how several of them were, to use his term, "semi-experimental". Underhill (1963, p. 121), who compiled a table with a number of known Blackwallers, shows that these vessels averaged about four beams per length in the 1840s, five beams in the 1850s and six beams in the 1860s. Likewise average tonnage increased from around 900 tons in the late 1830s, to 1000 in the 1840s, 1100 in the 1850s and 1300 in the 1860s. Less demanding in terms of manning than the most fashionable clippers, Blackwallers constituted for decades the standard cargo vessel at the core of the British merchant sailing fleet, enjoying a busy career in the emigrant trade, until the last was produced, in 1875, by descendents of Greene.

The so-called "Aberdeen bow" or "clipper bow" was introduced in the *Scottish Maid* of 1839 by Alexander Hall & Co. of Aberdeen. While it has been suggested that this vessel had been built to compete with paddle-steamers between Aberdeen and London (i.e. Boyd Cable 1943), the most detailed accounts actually link its emergence to the 1836 tonnage law (Clark 1910, p. 58; Lyman, 1944; MacGregor, 1988). The sons of the elder Hall, James and William, faced the newly revised tonnage law in which depth was taxed, inducing a shallower form and a longer hull. However, length was measured at half the depth, presenting an opportunity to reduce measured tonnage while simultaneously enlarging capacity by raking both ends (MacGregor 1988, p. 100). It is believed that tank experiments were conducted to study how the modified bow could cleave the water with a minimum of effort (Boyd Cable 1943, p. 76; Macgregor 1988, p.

105). Hence, the design "must have been evolved partly with the idea of reducing the taxable figure of register tonnage and partly to improve her sailing qualities." (MacGregor 1988, p. 99) On the one hand, and according to Lloyd's Register Joint Principal Surveyor, J.H. Ritchie, the hull shape of the ships called at the time Aberdeen Clippers was able to extend tonnage by as much as 100 tons (in Moorsom 1860, p. 142, discussion section). On the other hand, Hall's bow, for which no patent was filled, "would become generally accepted as producing a graceful appearance with improved sailing qualities" (MacGregor 1988, p. 115). In 1844 the first clipper appears classified by Lloyd's Register. Clippers with the new racked bow began being built in Aberdeen to the orders of London and Liverpool, and by 1848 the same principle was being generally followed in the Clyde (MacGregor 1988, pp. 115-6).

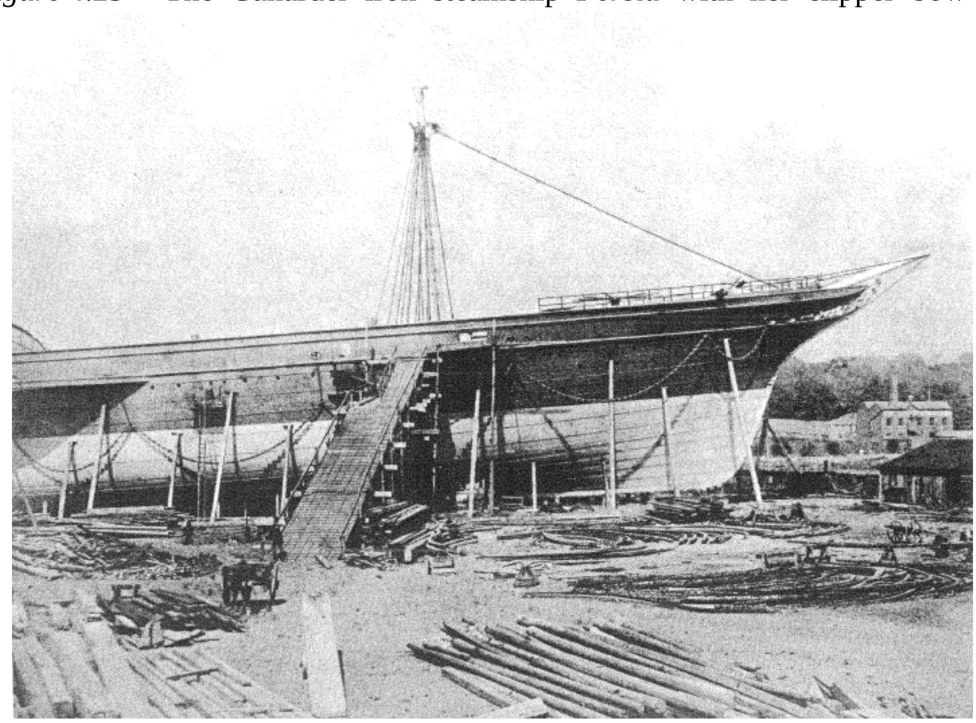
A "reverse" sailing ship effect?

Even more surprising, given the extent that the "sailing ship effect" has been canonized in the innovation literature, may be the observation that the influence of the Aberdeen bow did not stay confined to sailing ships. Provocative evidence suggests it was the steamships that greatly benefited from the search for efficient designs under sail. The *Iris*, a ship built in 1842 by Alexander Hall's for trade in the Baltic, has been identified as the first steamer to receive the "improved bow" (Boyd Cable 1943, p. 79; MacGregor 1988, p. 107). According to MacGregor (1988, p. 120), the new clipper design was spreading fast among top builders and through different shipbuilding areas from the mid-1840s onwards. In London, Thomas Ditchburn was also displaying a preference for very hollow shapes by the mid-1840s and on the Clyde the new style gained much favour among steamers in the second half on the 1840s.[33] Ewan Corlett (1990, p. 40) asserts that a notable and influential steamer also deferred to this design: "The *Great Britain* was the first large ship to be built with what came to be known as 'Clipper

[33] Most of the steamers produced by the Dennies up to the mid-fifties had also adopted the Aberdeen bow.

Lines', in other words with a fine hollow entrance and a fine run aft." Another pre-eminent case was the *Persia* by Robert Napier in 1855 (see Figure 4.25)[34]. She was a paddle-steamer built for Cunard and notable for several reasons. Built expressly to break the Atlantic speed record (Maber 1980, p. 10), she became the first iron trans-Atlantic mail steamer, the fastest of her day and the largest afloat when she was launched (Kemp 1978, p. 166; Hume and Moss, 1975, p. 11). A less known aspect of her biography is recounted by Hume and Moss (1975, figure 3): "Her clipper bow saved her from sinking when she hit an iceberg on her maiden voyage." Therefore, not only does the "sailing ship effect" only very deficiently capture the dynamics at play, but we can perhaps even talk of a "reverse sailing ship effect". Steamers are in fact found to have "learned" from the older sailing ship technology.[35] Appendix 4.7 provides a partial account of the extent to which this happened.

Figure 4.25 The Cunarder iron steamship *Persia* with her clipper bow at Robert



Source: Hume and Moss (1975, Figure 3)

[34] The new system of tonnage measurement stopped favouring an extreme raking stem. The Merchant Shipping Act, enacted in 1855, "abruptly terminated the basis for the bow." (MacGregor 1988, p. 114)

[35] Given the complex dynamics in what appeared at first sight a simple substitution process between pre-defined alternatives, it seems safer to appreciate the flow of influence that occurs in both directions and which goes through several stages in historical time. To use Mom's (2004, p. 308) words: "When alternative technologies compete for dominance, feedback mechanisms occur, a kind of interartifactual transfer of technology and knowledge."

As a last additional point it should be noted that the most famous of the composite tea clippers, the *Cutty Sark*, was not commissioned to beat any steamship competitor nor indeed to take over from an American clipper, but to “lower the colours” of another British-built clipper, the record-breaking *Thermopylae* (Lubbock 1914, p. 288; Steele 1939, p. 279). It is appropriate to underline that the context was the “Great Ship Races”, as the newspapers of the day called them (Lubbock 1945, pp. 20-2), disputing the delivery of the first load of “new teas” (Shewan 1927, p. 127). Steamers had nothing to do with this business. Ironically, and probably due to the cost of the high standards exacted on her, the *Cutty Sark* builders went bankrupt before she was finished; it was left to the Denny Brothers, the most famous steamship builders of the day, to finish her.

4.5 Conclusions

This chapter addressed three tasks: the description of the shipping macro-environment, of the industry level, and of the product-level (the ships composing the merchant fleet). Section 4.2 outlined the broader historical context in which British shipbuilding was moving during the 19th century: it found that the institutional and economic environments stimulated innovative shipping. Section 4.3 drew lessons from secondary literature concerning the organisation of the sector: we found that a major re-configuration of the industry took place at around mid-century. Section 4.4 provided a first-hand analysis of the growth and spread of steamships *vis-a-vis* the sailing ship fleet.

The quantitative material surveyed in Section 4.4 points, in particular, to a number of findings. The 19th century was not one in which the aggregate number of working ships changed very much, in spite of a marked business cycle pattern. The major features were: first, the sustained raise in aggregate tonnage; second, the relatively late decline of sail; third, the discontinuous and remarkable increase in size of mechanised vessels. In particular we found evidence of a take-off of steamship performance occurring at mid-century which was preceded (not followed, it should be stressed) by a take-off of sailing ship performance. This finding was reinforced by auxiliary analysis based on other variables (i.e. vessel costs and tons per sailor). Steamers were by 1860 already distancing themselves from sailing ships in terms of size. Steamships incorporated a good deal of innovations first developed for sail. It took much time, however, for steam to displace sail as the main trading vessel and, it seems, the opening of the Suez Canal had a significant (and accelerating) role in this process of diffusion.

As Harley (1971, p. 215) noted, technological change should be seen as a process and not as an event. The notions of innovation and diffusion are often too artificially separated. In the process of diffusion, the original technology of steam navigation became modified to the point of non-recognition. There is no diffusion without adaptation, i.e. the ship (both wind-driven and steam-powered) was an artefact rich in developments throughout the full length of its life cycle. However, at some point between 1840 and 1860, each branch of the mercantile navy evolved independently, the configuration of characteristics becoming fixed and ever more distinguishable with improvements accumulating over time. At around this time, steamers were catapulted onto a new path of sustained growth of performance (a new "technological trajectory" measured by internal earning space, or net tonnage). To appropriate Hobsbawm's (1967, p. 45) prose, the increase in performance of steamships, which had so far resembled "the movement of a respectable river", was marked by "the exhilarating leap of a waterfall".

The interpretation we place on the material reviewed in this chapter is that some sort of radical technological change in the internal nature of steamship technology took place that greatly enhanced steamship performance from 1850-51 onwards. The hypothesis itself suggests that a "paradigm change" (a shift in the "dominant design" prevailing in steam navigation) was behind the positive up-ward bend in the "technological trajectory" of steamships. Chapter 5, to which we now turn, introduces new empirical material to understand the precise nature of the mid-century change, while Chapters 6 and 7 inquire into the sources of that technological change.

Appendix 4.1 – Ship size, economies of scale and technological trajectories

Aggregate average tonnage and the study of ship innovation

Ship size is an interesting and available metric and this thesis is not the first one to deal with this advantages and limitations.

First, it is convenient to keep this indicator given the absence of any other for long term analysis. To be sure, as highlighted in Chapters 2 and 3, other vessel characteristics were also important. These include coal efficiency in the case of steamers and manning in the case of sailing ships, but unfortunately such fine-grained aspects are not covered by the existing aggregate statistics. Speed was also a relevant functional attribute, but was mostly relevant for the passenger trade and also for conveying mails, expensive parcels and perishable cargoes. Available evidence on hull costs, hull materials, and machinery costs is also limited in coverage (it is only available from the middle of the 19th century onwards, and not always consistently; see Maywald, 1956; Mitchell and Deane 1962, pp. 223-4).

Second, average tonnage serves here as proxy of technological change. Hull size is a fundamental techno-economic characteristic of the artefact under study. Larger vessels allowed for *economies of scale* (i.e. larger vessels are found to be more economic in costs per ton), a fundamental benefit in a very cost-conscious business. The ability to build larger vessels also affected the range of usable services they could perform (i.e. ability and to carry more payload, to carry more kinds of commodities, better seaworthiness in all kinds of water, expanded room for coal and, hence, greater capacity to travel greater distances without refuelling), hence contributing to flexibility of the entire merchant fleet and the options of the individual ship-owners. To realise the efficiencies associated with increasing physical ship size intangible resources like architectural expertise and construction know-how had to be developed. This was so because new challenges in terms of size led to non-linearities in design and to continuous alterations in the profile and trimming of ships, i.e. to continuous learning through project based-experimentation. Thus, tentative inferences can be drawn concerning innovation from the basic rate and direction of hull size over time. In line with Chapters 2 and 3 we refer to these basic patterns as “technological trajectories” and specify “average net tonnage” as the *y*-axis for measurement.

Third, this chapter reconstructs a summary metric of ship size from Mitchell’s (1980, 1988) original data. The information contained in ship size is preliminary evidence for the purposes of this thesis. But the introduction of this variable is not without qualifications. A major drawback is that it is a central tendency statistic of a population characterised by great heterogeneity. What is more, changes in the average can mask composition effects, that is, it may appear that the whole of the fleet in increasing in average size just because a particular class of larger vessels is increasing its importance in the total population. Of course, at times the average size was pushed up by the expansion and development of particular categories of large vessels (say large steel barques of the 1880s and 1890s, or the huge Atlantic turbine-driven liners of the 1900s and 1910s). On the basis of the sources surveyed we would argue that a tendency *across* different ship types to follow a relatively common pattern of increasing size. The growing size of sailing ship was a persistent trend in ocean-going navigation (see Chapter 2, Section 2.2; see also Chapter 5, Section 5.2). Where steam navigation is concerned even tugs, generally outside of the database since they were too small, displayed some signs of an increase in size in order to keep up with the increasing size of other ships they had to tow (see Chapter 3, Section 3.4). More broadly, there was a significant inter-sectoral change in the steamship population. But as Chapter 5 argues on the basis of new evidence, this re-composition of steamer varieties largely took place around 1850; after that, innovation mainly involved incremental sophistication of ship types adapting to expanding and changing demand on the basis of the new unifying "iron-screw" paradigm.

On average ship size (vs. speed) as an analytical variable

Increasing ship size and complexity has been a conspicuous aspect of ship technology development for a long time. Ever since the Discoveries of the 15th century the paradigm of the three-masted ship kept being pushed in terms of size (Boumphrey 1933, p. 50; McGowan 1980, p. 5). With regard with size, Davies (1972, p. 44) noted that by the 16th century already the trend towards lengthening was becoming common among English ships. The size of ships was only held back by market possibilities and the risks of under-utilisation. As van Zanden and van Tielhof (1999) have argued in connection with development of the Dutch *fluit*, improving know-how allowed for larger and more economical ships but productivity depended on a set of other factors exogenous to the vessel itself such as port depth and cargo handling technology. In England by the end of the 18th century many plans were afoot as make hull structures stronger in order to carry larger cargoes and larger sails. Innovations in construction introduced in naval and merchant vessels were guided toward improving structural quality and reducing the usage of wood (MacGregor 1988, pp. 15-21). The trend in sailing ships toward larger size was already noted in the first decades of the 19th century thanks to improvements such as the diagonal system and iron fittings (see, e.g., Brown, 1990, p. 31; and Sutton, 2000, p. 45; and see Grantham, 1842, p. 42 for a contemporary appraisal). This trend toward larger (and also faster) sailing ships was continued by the Blackwall frigates, tea clippers, windjammers and the large schooners of the second half of the century (see, e.g., Underhill, 1963; Kemp, 1978; Greenhill, 1980a; MacGregor, 1993; Woodman, 1997).

What about mechanised, steam-driven ships? "The inexorable growth in size of steamers was the chief and best known feature" of industrial-age shipping (Jackson 1988b, p. 265). There was the highly cyclical yearly pattern characterising but the average ship size did increase from decade to decade (Pollard and Robertson 1879, p. 230). Again, there seemed not to be technical obstacles to size, only economic limits. As a ship-owner observed: "It is well and proper for ships to keep pace with the growth of freight (…)" (Dollar 1931, p. 101). But fortunately the trend was one of long-run trade expansion. According to Craig (1980a, pp. 31-4) the growth of ocean commerce led to the growth of the "average size" of the iron-screw carrier, especially from the 1860s onwards which lead to continuous incremental alterations to ensure efficiency while optimising tax-paying registered tonnage. Addressing the same issue Mohammed and Williamson (2004, p. 197) note that growing ship size was a key factor allowing the British merchant fleet to absorb the growing trade volume of the second part of the 1800s. One visible consequence of "increasing vessel size" was the greatest investment of all British history in port facilities as larger ships required deeper and larger berths, an aspect “broadly familiar to anyone with an interest in British port history.” (Palmer 2003, p. 29; see also Kirkaldy 1914, p. 484, and Pollard and Robertson 1979, p. 57; see especially Jackson 1988a, p. 218). The push toward greater size had to adapt to port capacity and to give due consideration to the greater difficulty to manoeuvre a large ship in closed waters, the longer time needed to unload larger vessels, and the higher port dues charged to larger ships (see, e.g., Heaver and Studer, 1972; Thomas 1993, p. 10).

Thus, several historians have used the notions of “average ship size” and “average cargo capacity” in their analyses of technical progress at sea. To name a few others that cover our time period: Hughes and Reiter (1958, p. 366), Underhill (1963, pp. 121-3), Slaven (1980, p. 120), Macgregor, David (1984a, p. 19), Ville (1986, p. 360; 1993, p. 7), MacRae and Waine (1990, p. 27), Thomas (1993, p. 14), Arnold (2000, p. 35). What is more, even contemporaries employed it in technical reports (see Armstrong *et al*. 1964, p. 8).

And what about speed? For 19th century sailing ships speed was a requirement only in a minority of trades. It was limited to premium freights such as tea from China and oranges from the Azores (Greenhill (1980a, p. 20). What about steamers? “If size was a source of economy, speed was a source of cost, because of the more than proportional increase in horsepower and provision for bunkering were necessary for each addition knot attained.” (Pollard and Robertson 1879, p. 16) So much was clear to contemporary shipowners (Lindsay 1878, p. 212). Except in the case of short-sea packets and ocean liners that needed to secure government contracts, most steam traders were designed for moderate speed (see Kemp 1978, p. 172; Stopford 2009, p 31).

But average speeds kept on increasing, there being a positive relation between size and speed. One factor was sheer size; as one contemporary expert asserted: “Again, advantages are gained by the employment of larger and still larger ships, as only a large steamer can give both speed and great carrying-capacity combined with economy in working” (Sargent 1918, p. 30; see also Lindsay 1878, pp. 491-2, and Greenhill 1980a, p. 20). A second issue was metal hulls. With thinner skins, without a reduction in hull strength, weight was saved, less coal was consumed, and extra knots of speed could be gained out of the same power unit (Kemp 1978, p. 172). A third factor was the application of the screw, which made the vessel smoother on the water and more fuel efficient. In this way more stability was achieved and less coal was needed in bunkers so that speeds increased (Corporation of Glasgow 1912, p. 13).

Scale economies and guideposts of technical progress

The average size of the hull is a technical characteristic related to the prime function of a merchant vessel: the transportation of paying cargoes. Of course, larger hulls meant a larger earning capacity for the ship-owner. Hence, for most trades larger ships have been known to operate at a smaller cost per ton than smaller ones. This phenomenon is known as “economies of size” or “economies of scale” and has been recognised a defining feature of shipping for the 18th (Davies 1972, p. 73; Love 2006, pp. 105-6), 19th (Clowes 1936, p. 121; Brock and Greenhill 1971, p. 9; Pollard and Robertson 1979, p. 2), and 20th centuries (d’Oliveira, 1959; Jansson and Shneerson, 1982; Cullinane and Khanna, 2000; Corbett and Winebake, 2008). This was a general trend (or “trajectory”, in the language of Chapter 2) from the old wooden sailing ship, to the iron-screw steamer, and later to the container ship. But effective carrying capacity was also a function of shape and the key "heuristic" employed by naval architects was increasing the length-to-beam ratio. Long and narrow hulls made the vessel roomier but not necessarily slower (see Chapter 3, Section 3.3).

During our time-frame, moreover, size was more than an engineering aim in itself. It was good economics both in terms of ship construction and ship operation. On the one hand, the costs of building a large hull were less per ton than the cost of building a smaller ship, "so increases in average vessel size would have worked to lower average cost per ton produced." (Pollard and Robertson 1979, p 30) One the other hand, innovations that facilitated greater stowage allowed entrepreneurs to take advantage of potential running cost savings per ton mile of cargo carried (Thomas 1993, p. 10; Milne 2006, p. 25). A fundamental source of operational efficiency, as explained by Greenhill (1980, p. 36), was in manning: crews did not increase proportionally with the carrying capacity of big vessels. That is, all else being equal, a path of technological learning made sense if it supplied engineering answers to the general economic pressure in terms of greater size.

Regarding the specific innovations that concern this thesis, and as argued in Chapter 3, the iron-screw combination lowered cost to capital investment relative to cargo carried while allowing for higher speed and improved regularity, which ensured higher throughput. Many authors have claimed that the rise of the size of British ships can be, at least partially, related to the thinking of I.K. Brunel (Corlett 1990, p. 11). In launching the *Great Western* in 1838, Brunel proved that to double the size of a hull would not imply twice the power to push it in the water nor twice the amount of coal (Dumpleton 1973, p. 33). But the real landmark came in 1843 with the launch of the *Great Britain*. This was the first ship deliberately built big enough to take full advantage of economies of scale (Corlett 1990, p. 11; Greenhill 1993b, p. 21). This was done by integrating for the first time the synergies of mechanical power, iron hulls and screw-propulsion in a coherent whole. It showed the way to future developments.

Appendix 4.2 – The logistic function

The functional form of the logistic growth curve is:

$$p(t) = \frac{1}{1+e^{-\eta}}$$

with

$$p = \frac{steam\ tonnage}{steam\ tonnage + sail\ tonnage}$$
$$k = 1$$
$$\eta = \beta_0 + \beta_1 t$$

Let the function be rearranged as

$$p = \frac{1}{1+e^{(-\eta)}} \ (=)\ \frac{1}{p} = 1+e^{-\eta} \ (=)\ e^{-\eta} = \frac{1}{p} - 1 \ (=)\ \eta = -\ln\left(\frac{1}{p}-1\right) \ (=)\ \eta = \ln\left(\frac{1}{p}-1\right)^{-1} \ (=)$$
$$\eta = \ln\left(\frac{1-p}{p}\right)^{-1} \ (=)\ \eta = \ln\left(\frac{p}{1-p}\right)$$

which shows that the ratio between steam and sail tonnage is linear in the parameters. That is:

$$\ln\frac{p}{1-p} = \ln\frac{steam}{1-steam} = \ln\frac{steam}{sail} = \eta = \beta_0 + \beta_1 t$$

A useful reformulation of the parameters is the following. Let

$$\beta_0 = \left(\frac{-d}{c}\right) \quad \text{And} \quad \beta_1 = \left(\frac{1}{c}\right)$$

then

$$\eta =_0 + \beta_1 t = \left(\frac{-d}{c}\right) + \left(\frac{1}{c}\right) t = \frac{t-d}{c}$$

Thus the logistic can be understood as

$$p = a + \frac{b-a}{1+e^{-(\beta_0+\beta_1)}} = a + \frac{b-a}{1+e^{\left(-\frac{t-d}{c}\right)}}$$

where

a : left-hand side asymptote (which can be defined as zero, for convenience)
b : right-hand side asymptote (*k* or unity)
c : scale parameter (with no substantive interpretation)
d : inflection point (which cuts the curve in half, since it is a symmetrical curve)
t : time (in years)

We should note that a dummy variable is easily inserted. Let a parameter be included to detect the possible effect of the Suez Canal, which was opened in 1860 (we shall count the year 1870 as the first year in which the new infrastructure was in full operation).

$$p == a + \frac{b-a}{1+e^{-(\beta_0+\beta_1+\beta_2)}}$$

Appendix 4.3 – Modelling the diffusion of steam-driven tonnage

We identify three approaches to model the diffusion of steam tonnage for the years 1815-1914 using the logistic function. Estimation results are as follows:

Table A

	A. Single logistic curve estimation without Suez	*B. Single logistic estimation with Suez*	*C. Two logistic curves, fitted before and after Suez*
a	0	0	0
b	1	1	1
c	11.78	12.28	$c_{pre\text{-}1869}$ = 14,80 $c_{post\text{-}1869}$ = 12,21
d	70.7 (i.e. the 70.7th observation corresponds to the 1885, rounding the closest unit)	73.2 (year 1885)	$d_{pre\text{-}1869}$ = 77.8 (year 1892) $D_{post\text{-}1869}$ = 69.4 (year 1884)
Yearly growth of the steam/sail ration	8.5%	8.5% for the whole period 36% for the first full post-Suez year (i.e. for 1870 only)	6.9% if no Suez (1815-69) 8.5% with Suez (1869-1914)
Sum of Squared Errors*	SSE_A = 3.3030	SSE_B = 14.4477	SSE_C = $SSE_{pre\text{-}1869}$ + $SSE_{post\text{-}1869}$ (=) SSE_C = 0.9805

Source: Elaborations on Mitchell (1988)

Note 1: the “Steam/Sail ratio” can also be thought as an “odds”, while the yearly growth (or change) of the “Steam/Sail ratio” can be though as the “odds ratio”

Note 2: “Yearly growth of the steam/sail ration” = e^{β_1}, with = 1/c

Note 3: SSE* for the models corresponds to the SSE using the time series of the empirical observations $y = \ln \frac{Steam}{Sail}$ and the predicted values η. Thus $y = \eta + \varepsilon_t$, with ε being an error term with the distribution $\varepsilon_t \sim (0, \sigma)$. The reason for the computation of the SEE* is to obtain Sums of Squared Errors from linear models which can then be compared using the *F*-test (a test of the Lagrange-multiplier family which is valid under the condition of linearity).

Note 4: SSE* are computed for the years 1830-1914, observations before 1830 being discarded for these purposes because they do not conform to the logistic model. It should be noted, as did Grilliches (1957, p. 504), that this can be done safely because extreme-end observations are liable to large percentage errors but have little weight. Indeed, the results of comparing the SSE* for the models are not affected by this truncation.

Comparing models:

- The models are compared by using the standard *F*-test

$$F = \frac{\left(SSE_{restricted} - SSE_{unrestricted}\right)\ /q}{SSE_{unrestricted}\ /\ (n-k-1)}$$

With

q : number of restrictions
n : number of observations
k : number of parameters of unrestricted model

- Model A vs. Model B: Comparing model A and B is trivial because B has one more parameter and has a larger SSE*. It should have a smaller SSE, because with one more parameter it should fit the data better. The reverse happens. Thus, model B is inferior to Model A.

- Model A *vs*. Model C:

Model A: $y = \beta_0 + \beta_1 t + \varepsilon_t$

Model C:
(restricted model)=

$$\begin{cases} y_{pre-1869} = \beta_0 + \beta_1 t + \varepsilon_t & for\ \ t \le 1869 \\ y_{post-1869} = \beta'_0 + \beta_1 t + \varepsilon_t & for\ \ t > 1869 \end{cases}$$

The number of restrictions (q) in Model is 2 (i.e. $\beta_0 = \beta'_0$; $\beta_1 = \beta'_1$),
The number of observations (n) is 84 (the period is 1830-1914),
The number of parameters (k) is restricted model is 4 (i.e. $\beta_0, \beta', \beta_1, \beta'_1$),

F (statistic = 94.7427; q = 2; n-k=80): p.value < 0.000 (i.e. below 1%)

Hence, Model C is significantly superior to Model A.

Appendix 4.4 – Results of trend-break tests and unit root tests for the difference of average net tonnage between steamers and sailing ships, 1815-1914

This appendix reports the results of the analysis using the asymptotic critical values available in Perron (1989). The analysis was conducted using Eviews software for the following data:

Dependent variable: Y = average steam tonnage – average sail tonnage
Sample years: 1815-1914

Table A reports test to a single unknown break in the determinist linear trend (T). The break could happen in the intercept (in which case DU dummy would not be rejected) or in the slope (DT would not be rejected) of the trend. Results show that a break in the slope of the trend cannot be rejected ($p<0.000$). It happened in 1861. It should be noted that R^2 values, although reported, are not typically given much weight in time series analysis since they tend to be inflated.

Table A

Dependent Variable: Y
Method: Least Squares
Sample: 1815 1914
Included observations: 100

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-30.56348	5.845930	-5.228164	0.0000
_T	1.549140	0.216590	7.152400	0.0000
_DU	-3.961168	7.809428	-0.507229	0.6132
_DT	12.61959	0.275510	45.80451	0.0000

R-squared	0.994845	Mean dependent var	232.9300
Adjusted R-squared	0.994683	S.D. dependent var	267.4663
S.E. of regression	19.50214	Akaike info criterion	8.818104
Sum squared resid	36512.01	Schwarz criterion	8.922310
Log likelihood	-436.9052	Hannan-Quinn criter.	8.860278
F-statistic	6175.083	Durbin-Watson stat	0.373963
Prob(F-statistic)	0.000000		

Table B presents results of tests to the present of a unit root. In this case the usual critical values are not valid and the “t-statistics” have to be compared against the tables available in Perron (1989). The break takes place at the 44th observation ($T_B/T = 0.44$ or 44%). The “t-statistic” (-0.4154) is thus above the critical value (-4.34). The null hypothesis, that there is a unit root, is rejected.

Table B

Dependent Variable: _DY
Method: Least Squares
Sample: 1824 1914
Included observations: 91

Variable	Coefficient	Std. Error	t-Statistic	Prob.
_Y(-1)	-0.226507	0.054517	-4.154764	0.0001
_DTB	-19.27304	2.758799	-6.986025	0.0000
_DY(-1)	0.556677	0.096548	5.765776	0.0000
_DTB(-1)	13.09093	3.297019	3.970535	0.0002

R-squared	0.570770	Mean dependent var	0.028277
Adjusted R-squared	0.553369	S.D. dependent var	4.056325
S.E. of regression	2.710861	Akaike info criterion	4.882330
Sum squared resid	543.8088	Schwarz criterion	5.003187
Log likelihood	-186.4109	Hannan-Quinn criter.	4.930711
Durbin-Watson stat	1.714932		

Appendix 4.5 – Results of trend-break tests and unit root tests for the average tonnage of steamers, 1815-1914

Results reported for:

Dependent variable: Y = average steam tonnage

Sample years: 1815-1914

Table A shows that there is evidence of a break in the slope of the trend (DT) in the year 1851 ($p<0.000$), while a break in the intercept is not statistically significant.

Table A

Dependent Variable: Y
Method: Least Squares
Sample: 1815 1914
Included observations: 100

	Coefficient	Std. Error	t-Statistic	Prob.
C	90.31233	8.230641	10.97270	0.0000
_T	1.155234	0.387924	2.977989	0.0037
_DU	-6.172967	9.986775	-0.618114	0.5380
_DT	11.80041	0.421016	28.02843	0.0000

R-squared	0.993061	Mean dependent var	390.1495
Adjusted R-squared	0.992845	S.D. dependent var	285.8430
S.E. of regression	24.17923	Akaike info criterion	9.248043
Sum squared resid	56124.99	Schwarz criterion	9.352250
Log likelihood	-458.4022	Hannan-Quinn criter.	9.290218
F-statistic	4579.945	Durbin-Watson stat	0.770480
Prob(F-statistic)	0.000000		

The estimated trend break occurs at the relative location 37% (T_B/T), for this location in the sample the critical value is -4.22 while the "t-statistic" observed is -4.18. The implication is that a unit root cannot be rejected, that is, "random shocks" in performance (which we interpret as technical innovations) have a permanent effect.

Table B

Dependent Variable: _DY
Method: Least Squares
Sample: 1824 1914
Included observations: 91

	Coefficient	Std. Error	t-Statistic	Prob.
_Y(-1)	-0.351796	0.084126	-4.181753	0.0001
_DTB	7.476960	18.94409	0.394686	0.6940

R-squared	0.163992	Mean dependent var	-0.545029
Adjusted R-squared	0.154598	S.D. dependent var	20.58470
S.E. of regression	18.92675	Akaike info criterion	8.740763
Sum squared resid	31881.76	Schwarz criterion	8.795947
Log likelihood	-395.7047	Hannan-Quinn criter.	8.763026
Durbin-Watson stat	2.127837		

Appendix 4.6 – Results of trend-break tests and unit root tests for the average tonnage of sailing ships, 1815-1878

Results reported for:

Dependent variable: Y = average sail tonnage

Sample years: 1815-1878

Table A shows that there is evidence of a break in the intercept and the slope of the trend in the year 1851 (DU p<0.035, DT p<0.000, respectively).

Table A

Dependent Variable: Y
Method: Least Squares
Date: 07/30/09 Time: 16:34
Sample: 1815 1878
Included observations: 64

	Coefficient	Std. Error	t-Statistic	Prob.
C	110.0543	2.073317	53.08129	0.0000
_T	0.254004	0.157860	1.609048	0.1129
_DU	-5.252486	2.434924	-2.157146	0.0350
_DT	2.094218	0.168807	12.40600	0.0000

R-squared	0.980681	Mean dependent var	144.4106
Adjusted R-squared	0.979715	S.D. dependent var	32.98232
S.E. of regression	4.697485	Akaike info criterion	5.992393
Sum squared resid	1323.982	Schwarz criterion	6.127323
Log likelihood	-187.7566	Hannan-Quinn criter.	6.045549
F-statistic	1015.264	Durbin-Watson stat	0.343063
Prob(F-statistic)	0.000000		

The estimated break date is 1837, this is the 23rd year in the 64 years of the sample (T_B/T = 36%). The critical value is -4.22 while the reported "t-statistic" is -3.66. The null hypothesis (i.e. there is a unit root) is not rejected.

Table B

Dependent Variable: _DY
Method: Least Squares
Date: 07/30/09 Time: 16:34
Sample: 1824 1878
Included observations: 55

	Coefficient	Std. Error	t-Statistic	Prob.
_Y(-1)	-0.260898	0.071252	-3.661634	0.0006
_DTB	1.851319	2.376703	0.778944	0.4396
_DY(-1)	0.557441	0.120105	4.641288	0.0000
_DTB(-1)	-0.498374	2.375318	-0.209814	0.8346

R-squared	0.347499	Mean dependent var	-0.088579
Adjusted R-squared	0.309117	S.D. dependent var	2.853141
S.E. of regression	2.371513	Akaike info criterion	4.634880
Sum squared resid	286.8277	Schwarz criterion	4.780868
Log likelihood	-123.4592	Hannan-Quinn criter.	4.691335
Durbin-Watson stat	1.763233		

Appendix 4.7 – The penetration of the "clipper bow" on Channel steamers

In a little known book on English Channel passenger packets (Grasemann and McLachlan, 1939), it is possible to find what can be seen as quantitative evidence of the spread of the clipper bow. This constitutes a singular effort by individuals connected to the trade to unearth otherwise inaccessible sources, having scrutinised contemporary descriptions and systematised all their information from various documentary records.

Thanks to the original chronological data in Grasemann and McLachlan (1939, pp. 148-89) it is possible to make our own elaborations. Their data report the year of build for the packets engaged in regular cross-channel service, not the year vessels entered service. The first steamer on record to enter the Channel for work and to have been assigned a clipper bow was the *Dispatch* of 1847, built by Ditchburn and Mare. Other vessels appearing with the design came from other known builders such as Robert Napier, Caird of Greenock, and the Samuda Brothers. It can be noted from Table A that clipper bows peaked in 1850s, being apparent in 8 out of 31 vessels. In other words, during the 1850s a full quarter of all the new-build English Channel steamers exhibited the clipper bow, a feature mostly associated with the deep-sea large square-riggers of the same period. Until 1860 the feature was only observed in iron paddle steamers and the *Alliance*, built in 1855 by Ditchburn and Mare, presumed to be wooden-built.

Table A Technical characteristics of English Channel packet vessels, 1810-1879

	Structural types of vessel					Types of entrance	
	Sailling vessels	Wooden paddle steamers	Iron paddle steamers	Screw steamers	Total	Clipper bow	Straight stem
1810-9	23	4			27		
1820-9	4	33			37		
1830-9		14			14		
1840-9		30	3		33	1	
1850-9		14	14	3	31	8	
1860-9			28	3	31	7	5
1870-9			12	7	19	4	4

Source: Elaborations on Grasemann and McLachlan (1939, pp. 148-89)

The clipper bow design endured for almost 20 years after the revision of the tonnage laws that partly gave rise to it, which may be evidence of the bow's intrinsic qualities. The last steamer exhibiting a visible clipper bow was built by John Cockerill in Antwerp in 1873, the *Parlement Belge*. Straight stems, *Great Eastern* style, never enjoyed the same degree of popularity. The first Channel steamer to exhibit such a profile was the *Alexandra*, built in 1862 by Caird.

Incidentally, it is worth appreciating the duration of "older technology" on the Channel trade. Sail was quickly ousted: three sail vessels were built in 1820, then commercial steam is introduced in 1821 with eight paddlers. The last sailing vessel for Channel service was built in 1825. The last wooden (paddle) steamer was built in 1857, *The Prince Frederick William*, and the last (iron) paddle steamer to enter service was built in 1899, the *Victoria*. Steel arrived in 1878 with the *Brighton*, and almost immediately all the following steamers (paddle and screw-driven) were constructed of this metal. The same is true for the turbine engine, which made its entrance with the *Queen* in 1902: after her, and until the Great War, almost all the steamers are reported as being turbine-driven, twin or triple-screw.

5. How did steamships evolve? Quantitative evidence of technological change

5.1 Introduction

The present chapter attempts to cast new light on the technical characteristics of early steamers. Available empirical material on the output of the British steamship industry is either too aggregated or too fragmentary. Detailed evidence on the ships themselves may allow a more informed look into qualitative change during the critical years of steam navigation development. The present chapter uses new data on the number and building dates of wood and iron, paddle-wheel and screw-propelled steamers, and on the type of business services they performed. Revealing the shifting nature of this capital good is fundamental for appreciating the rate and direction of technical change and, importantly, for guiding any inquiry concerning its drivers. The work draws on a unique information pool which, until now, had not been systematically explored and analysed from a quantitative point of view. We refer to the late Robin Craig's "Card Index" of all non-naval steamships built in Britain between 1812 and 1859. This Index was the focus of Robin Craig's research on steamship history for at least forty years, and comprises one of the most original contributions to maritime economic and technological history. While alive, Robin tutored the present writer on how to use his Card system, which, on his passing, was bequeathed to the University of Hull. It is, to our knowledge, the most comprehensive and detailed listing of early British steamers in existence. Robin Craig and the author of the present thesis reached an agreement to digitise his original Index and to jointly own the digital steamship database (see Appendix 5.1). During the process of digitisation of the database, new data were added by both of us. It is this digital resource, henceforth termed the Craig-Mendonça database, that provides an opportunity to say something new about this old, almost forgotten, part of Britain's innovative industrial past. Robin Craig carried out the bulk of the work but this needs to be continued. This is the best way to celebrate Robin's unique contribution.

In what follows, we examine the development of the steamship by deploying a set of tools to measure its technological dynamics over time. We start, in Section 5.2, by considering the origins, reliability and potential limitations of the dataset, and the sample we extract from it. Section 5.3 provides an overview of the steamship population from a perspective that emphasises the types of steamers being built for different market settings (or selective environments) and their technical characteristics. Section 5.4 emphasises the heterogeneity of the transportation services and highlights the different combinations of characteristics that were attempted in steamship construction, namely in hull materials (wood, iron) and propulsion method (paddles, screw). Section 5.5 deepens the analysis by focusing on cargo traders and steam packets, the types of ships that account for most of the observed technological transformation in the population. Section 5.6 summarises the main findings to emerge from this analysis.

5.2 The data

The origin of the database

There have been a number of attempts to develop steamship data. In a pioneering article, published shortly before Mitchell and Deane (1962), Hughes and Reiter (1958) used official returns printed in the 1861 session of Parliament of merchant steamers permanently registered. Particulars such as date of build, dimensions, tonnage, horse power, hull material and propulsion system were given for 1,945 vessels from 1814 through to 1860. There were missing observations for certain characteristics of ships, which the authors tried to estimate from the profile of similar ships. The data were analysed from 1823 and ships smaller than 15 tons were not covered, as well as many steamers built for export. For a critique of the data source used by the authors see Craig (1966a, 1966b).

The limitations of official returns data led Robin Craig to develop his own listing of ships. He was not alone in his efforts to reconstruct the record of early British-built steamers, but he was probably unsurpassed in the scale and scope of his project. Grahame E. Farr (1950), who mentions Craig in the acknowledgements of his book, published particulars for Bristol vessels over 150 tons for the period 1800-38 by using registry archives and by adopting a "system of gleaning scraps of information" from a variety of other sources. Another of Craig's close acquaintances, David Lyon, did similar work on complementary objects of analysis.[1] Using a list of ships built between 1825 and 1860 also compiled by Lyon, and data on aggregate tonnage obtained by Palmer (1993), Arnold (2000) was able to consolidate and extend the available data on naval and mercantile iron steamers built on the River Thames for 1832-1915. For the US, work on this area has proceeded along similar lines. Around the year 1920 an employee of the Bureau of Navigation compiled a list of US-built merchant vessels which, although plagued with omissions, Thomson (2005) has been able to use in his work on the industrial dynamics of American shipbuilding. Heyl (1956) is another work of compilation of the early American commercial system, one that to our knowledge is yet to be thoroughly exploited in a systematic empirical analysis of ship characteristics.

Features of the database

Thus, the best data-series generally available are often either macroscopic but continuous or microscopic but incomplete. As a result, researchers often try to pool several sources in order to reduce the gaps to a minimum. This is what Robin Craig did for working steamers built in the British Isles. Craig had concrete experience from early on in this work as he and Rupert Jarvis had published in 1967 a book on the merchant vessels listed in the register-book of the port of Liverpool (Craig and Jarvis, 1967). Craig's card list may be thought of as an expansion of this venture. Robin Craig's

[1] For instance, Lyon (2004), while working at the National Maritime Museum, compiled a list of all the sail and steam ships of the British Navy for the years between 1815 and 1889.

original Card Index was collated from direct consultation of British ports of registry archives, British Parliamentary Papers, the Public Record Office, builders' and shipowners records, Lloyd's Register, newspaper stories and advertisements, master mariners' and ship engineers' notebooks, and many secondary sources (Farr, 1950, being one of the favourites). Many of these sources are referenced on the cards. Each of Craig's cards contained space for more than 50 different quantitative and qualitative entries ranging from bureaucratic details (official registry number[2], port of registry, etc.), identification details (name, name changes, year of build, shipbuilder, etc.), structural particulars (wood/iron, paddle/screw, length/breadth/depth, gross and net tonnage, etc.), power unit (engine builder, cost, horse power, boilers, etc.), economic purpose (ferry, packet, cargo, tug, other), career (notable passages, remarkable events, owners, etc.), and an array of miscellaneous information (e.g. lengthening and reconstruction, double bottoms and water ballast tanks, ship activities and noted features, etc.).

Given the number of possible entries on a card, complete specification of all the characteristics is unavailable even for the most well known steamers, and this database is best seen as work in progress, to be further enriched and elaborated upon.[3]

The sample

Given the huge size of the database, and in line with other historical studies of economic innovation (e.g. von Tunzelmann, 1970, and Nuvolari and Verspagen, 2009, for Cornish steam pumping engines), a slice of it was extracted for closer inspection. Steamer cards were digitised for vessels having their names starting with the letters A to

[2] This is a particularly important and useful identification code as an official number was allocated to a British ship when first registered and this did not change over her lifetime under the British flag, i.e. it remained the same even if her owner, name or trade changed.
[3] This was what the present author did in a few cases, for instance by inputing data found in secondary sources such as Parker and Bowen (1928) or in Greenhill (1993), while digitising the original Card Index. Even so, the more information that is obtained, the more likely are discrepancies to be found, as details vary depending on the source and the year of the report (for a discussion of this kind of problem see Thomas 1983, p. 5).

M, that is, half of the alphabet (see Table 5.1). For our present purposes this sample provides a useful picture of the key development patterns of the whole population. The total number of steamers is in the vicinity of 4,500 vessels. This means that the present sample is large relative to the size of the total universe of British steamers built in the period. Moreover, in comparative terms, our sample size is bigger than the 1,945 steamers used by Hughes and Reiter (1958). This, and the alphabetic sorting, should remove most bias and, it would seem to us, ensure the representativeness of the observations.

Table 5.1 Structure of the sample, vessels sorted by initial letter of name, 1812-1859

	Ferries	***Packets***	***Traders***	***Tugs***	***Other***[4]	***Total***
A	47	40	58	57	35	237
B	41	29	42	64	30	206
C	58	77	69	68	39	311
D	31	33	27	51	27	169
E	58	28	50	51	41	228
F	36	11	35	30	20	132
G	27	16	34	32	28	137
H	28	11	29	40	13	121
I	16	15	20	15	14	80
J	12	6	15	31	26	90
K	8	9	4	3	10	34
L	48	28	42	50	44	212
M	58	30	41	43	37	209
Total	468	333	466	535	364	2166

Notes: Letters in the lines represent the first letter of the name of a vessel, while columns give the economic function of a vessel. For instance, the *Active* was an 1817-built ferryboat that paddled in the Clyde and is one of the 47 steamers counted among those in left-hand column of the table while, to take another example, the *Merry Andrew* was an 1857-built tug that was registered for work in London.

[4] There were 364 “other” vessels in the sample: 230 (10.6% of the overall sample) of them correspond to vessels for which the activity remains undetermined; 51 had peculiar occupations (dredging, fishing, whaling, yachting); the remaining vessels shifted functions appreciably in their working life (ferries to tugs, packets to yachts, etc.).

We concentrate on those ships for which commercial specialisation is known, that is, on those described as ferry, packet, trader (i.e. cargo vessels) and tug types. From an evolutionary economics point of view, the following patterns should be expected: *i*) not all the ships built were at the technological frontier, *ii*) not all the ship-owners needed vessels for the same exact purposes, and *iii*) the older design solutions of wood and paddles were not forgotten or rendered obsolete overnight. In other words, the database was built along principles that allow its exploration from a "population perspective" (see Saviotti, 1996). In brief, there was no such thing as *the* steamship. Thus the present chapter brings forward aspects pertaining to product heterogeneity in transportation services so as to assess the extent to which branching processes in design took place.

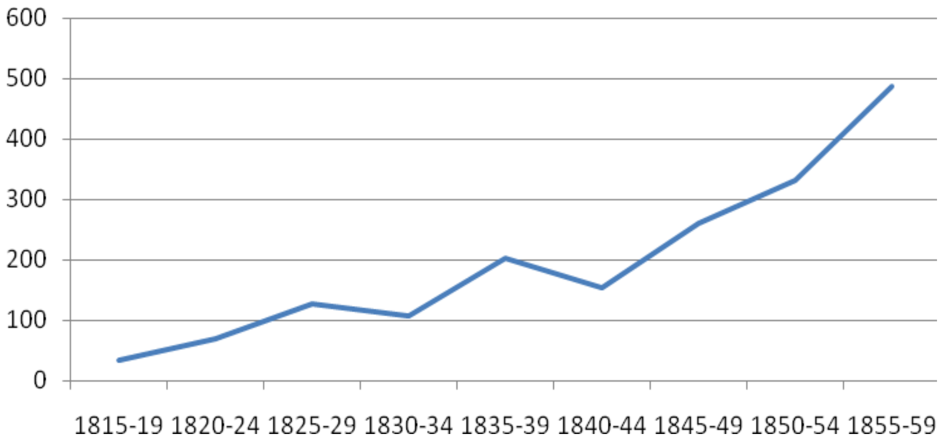
From the outset it is worth bearing in mind what Craig (1980a, p. 5) himself thought of the difficult task of classifying ships: "It is almost impossible to describe representative types of vessel engaged in the coastwise and short-sea liner trades as the vessels were notably heterogeneous in design and construction." Also, individual steam vessel usages overlapped (the *Industry* of 1814 is one example; see Chapter 3, Sections 3.2 and 3.3). Many other boats were built for one trade, say short sea trips, but ended up in more demanding routes (a case in point being the *Sirius*, which started her career as a coastal steamer and became the pioneer of the Atlantic ferry; Chapter 3, Section 3.3). Single-trade ships were the exceptions, especially early on. At the same time, of course, there was hardly anything standardised in steamers. Nonetheless, as cargoes increased in variety, as more destinations were reached, as ports needed to ensure faster loading and unloading, and as more sophisticated shipping services were increasingly expected, so too were different kinds of ship taking form (Chapter 3, Section 3.4). In sum, product segmentation should not be over-emphasised (see Chapter 3, Appendix 3.4), and hence we arrive at four categories of vessels: river ferries, tugboats, packets and general cargo steamers. This categorisation is an important; distinctions, however, should be thought of as a useful differentiation between ideal-types rather than as a clear-cut typology.

5.3 Basic features of early newly built steamers

5.3.1 The growth and diversification of working British-built steamers, 1812-59

The growth of newly-built steamers is a major feature in the data. Figure 5.1 shows the aggregate number of steam vessels built during five-year intervals in our sample and which worked either in the ferry, packet, cargo or towing businesses. The number of steamers built rose steadily (the yearly series would depict more pronounced fluctuations typical of investment-good industries).

Figure 5.1 Number of steamers built, reported at five-year intervals during 1815-59

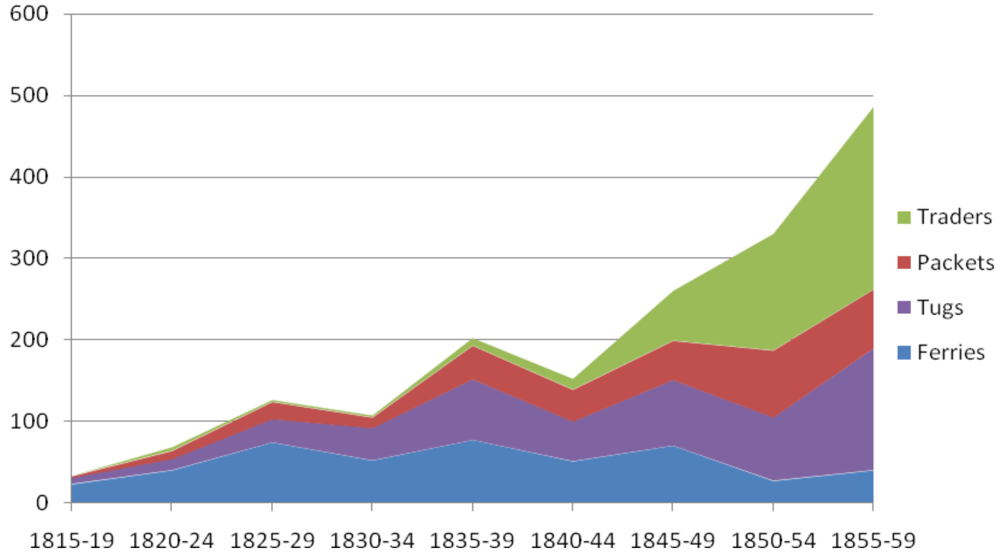


Source: Craig-Mendonça steamship database
Note: only vessels for which the economic function is unambiguous are included here

Economic functions of newly built steamer population

What lay beneath this growth in terms of types of ships? Drilling down through the aggregate data allows us to start acquiring finer-grained quantitative information that so far is unavailable in the extant literature. Figure 5.2 shows the types of working vessels contributing to the previously shown overall trend. Initially, most steamers were short-distance, estuarial passenger steamers (ferries), but increasingly steam navigation is seen to venture into other jobs and waters.

Figure 5.2 Number of steamers built by type, reported at five-year intervals



Source: Craig-Mendonça steamship database

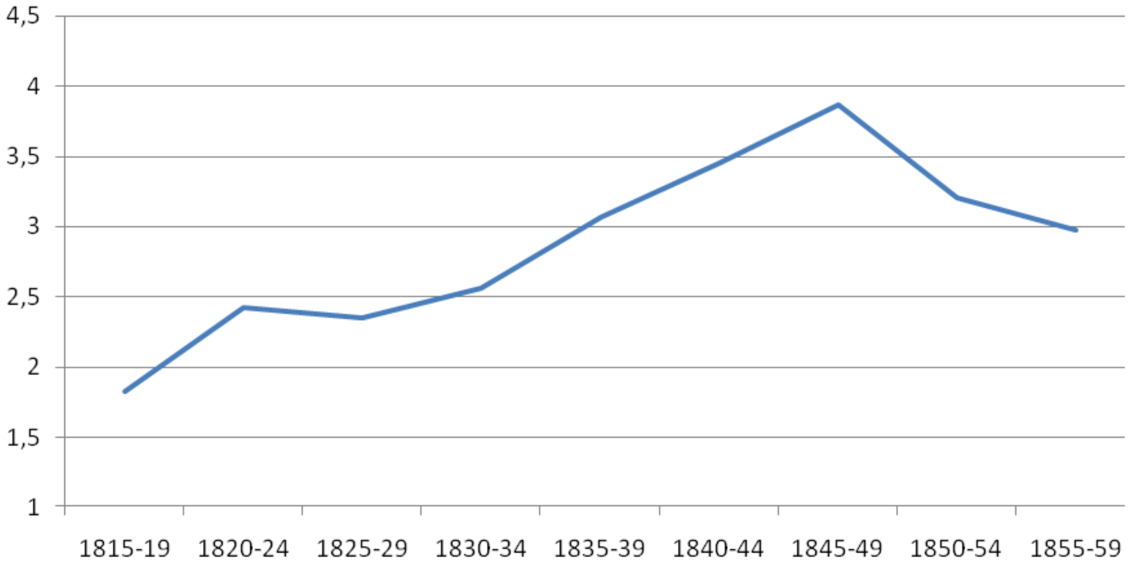
Business diversification of newly-built steamers

In order to show that steamers became present in a wider array of application sectors, we apply a diversification index. The Hirschman-Herfindahl index (HHI) is a familiar measure of concentration, one that in the present case is obtained by calculating the sum of the squares of the shares of all the steamer types in the total number of steamers built. Since the HHI is a measure of concentration, it is convenient to invert the index, i.e.

$$1/HHI = 1/\sum_{i}^{n} x_i^2$$

in which x_i is the share of a given ship type as a proportion of total steamers built. A higher 1/HHI indicates that steamers are spreading across a broader set of fields, ie., it reveals that the range of viable applications of steam navigation is increasing. A lower 1/HHI shows a concentration of the steamship activity in fewer areas of economic activity. The 1/HHI has a lower bound of 1 and a maximum of 4. Results, reported in Figure 5.3, show that for most of the time in the early adoption of steamers their growth in numbers coincided with an extension of business diversification. This relationship breaks down in the years approaching 1850, however, when the index shows a downward trend.

Figure 5.3 Diversification of economic applications of steam navigation



Source: Craig-Mendonça steamship database
Note: The *y*-axis reports the 1/HHI scale (higher values representing increased diversity)

These are important observations that require further examination in the remainder of the present chapter. It could be, nonetheless, that sectoral diversity decreased more mildly in the 1850s than it seems perhaps due to the uncomputed data relating to those vessels that served in more than one activity during their careers. Early ferries had, indeed, busy and eventful commercial lives which sometimes tested their capabilities to the full (see Chapter 3, Section 3.2). It should be noted, however, than the number of vessels shifting functions diminished over the decades (28 in the 1820s moved between occupations, 26 in the 1830s, 11 in the 1840s and 10 in the 1850s). That is, differentiation in design does seem to have taken place quite early on in the course of steamship evolution, with a split already becoming quite visible in the 1830s. This process, sometimes called "speciation" (see Chapter 2, Section 2.2), stemmed from increasing adaptation to varying operational environments and forms of economic specialisation. In our case we see that more and more purpose-built steamers came to occupy the marine areas for which they were specifically designed. This provides a sidelight to an unfolding pattern of activity for steam navigation, developing from nearby exchanges (ferries) and auxiliary roles (tugs) to longer courses of action serviced by increasingly differentiated types or "species" of ships (packets, traders).

5.3.2 Numbers of different steamship types

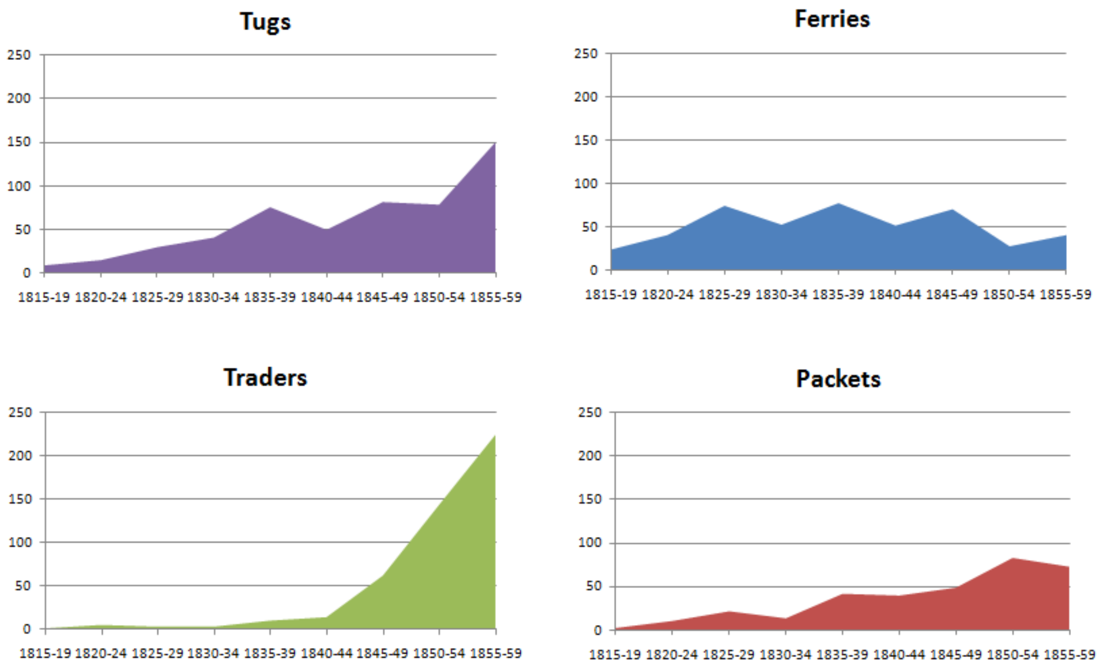
Overall dynamics of ship types

Many of the early steam vessels were closely associated with transportation in calm and secluded waters. These were the origins of commercially-oriented steam navigation, but what about the subsequent years? In accordance with the sources surveyed in Chapter 3, Section 3.4, we know a few stylised facts. Ferrying was a first application of steam navigation, an estuary and nearby port work dealing with passengers and parcels. Longer distance steamers known as packets then came along, often subsidised to carry mails, and became more numerous with time. Steam tugs, the only efficient way to tow, became increasingly common in every port where they towed every kind of vessel and barge. Traders carrying cargo are not usually reported in the literature as a common type of steamer, but reports on their activity appear to be common from the 1850s.

Unpacking the aggregate time series of steamships indeed reveals noticeable dynamics for different types of vessels. Figure 5.4 unveils the starkly different dynamics in the various subpopulations. Ferries remained a relatively stable sub-population throughout the period, although they shows signs of the business cycle (with the 1840s recession seeming to have taken a severe toll, for instance). Packets experienced a general growth trend. These expensive premium capital goods were relatively immune to the 1840s business cycle but suffered, it would appear, from the general excess tonnage after the Crimean war. The most vibrant trends come from those relatively unsung ships, the humble towing boats and cargo traders. As reflected in our sample, tug-building was increasing, with 40% of all the 458 tugs built in the period 1815-59 being added during the 1840s alone.[5] The most striking performance was that of traders, a category which exploded onto the steamship scene in the mid-1840s and dominated shipbuilding in the 1850s. Such dramatic growth has not apparently been documented in previous literature.

[5] That tugs were important in many ways, including in sheer numbers, was a point surfacing in many conversations with Robin Craig.

Figure 5.4 Number of different types of steamers built between 1815 and 1859



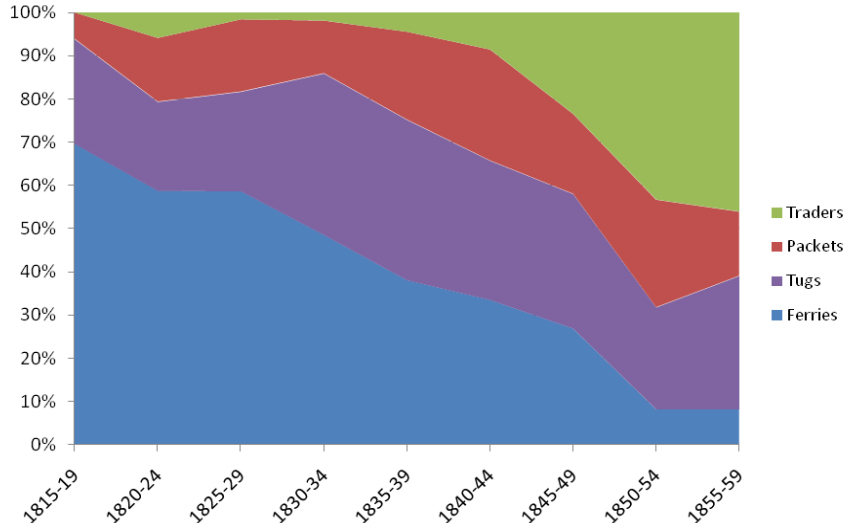
Source: Craig-Mendonça steamship database

Relative importance of different ship types in the total population of steamers

Figure 5.5 allows us to see the proportions of the different types in our population of early steamers as time went on. Ferries were the most common type of steamer produced until the early 1840s: ferries represented 70% of new steamers in the 1810s, 59% throughout the 1820s, 49% during 1830-34. By 1840-44 ferries were still holding the leading position with a share of 34% of all steamers built, but during 1845-49 tugs took the lead: they were the type built in largest numbers in this five-year sub-period. That is, the start of the 1840s, with the debut of the Atlantic steamer trade, marks the "end of the beginning" for steam navigation: new distances and economic uses for the steamer were becoming feasible (something that confirms, but adds substance to, what we already had seen in Chapter 3, Section 3.2 and 3.4).

It is also interesting to observe that for the entire period under analysis, i.e. 1815-59, tugs were the most common type for which economic functions are unambiguously recorded (see Table 5.1 above). It should also be remarked that the share for packets never rose above 26%, and that their peak share was reached during the early 1840s. The 1850s were dominated by what would seem to be a fresh class of steamers: traders. Coming from a marginal position (4% in 1835-39 and 9% in 1840-45) cargo steamers jumped to 23% in 1845-50 and became the most numerous type of steam vessel built from then onwards (43% in 1850-54 and 46% in 1855-59).

Figure 5.5 Numbers of newly-built steamers, relative shares according to function



Source: Craig-Mendonça steamship database

In other words, the start of the 1850s, with the rise of the steam trader, marks the “beginning of the end” of the steamship transition towards an industrial age: the steamer fit for economical deep-sea duties was becoming the backbone of the steamship population (see Chapter 3, Section 3.4). But what may explain the remarkable developments of the 1840s and 1850s? What was the technological profile of the longer-haul ships, like traders and packets? Such issues occupy the remainder of this chapter.

5.3.3 Vessel capacity and power unit

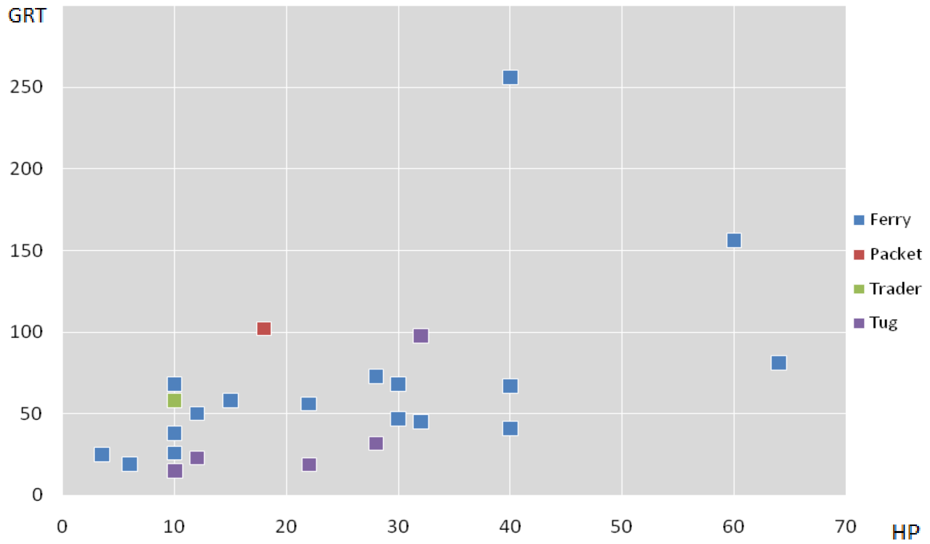
As Pollard and Robertson (1979, p. 13) argued: “The two most important changes in shipping in the nineteenth century were the increases in vessel size and power.” These two operational attributes are linked through the material used in the hull and the method used to transmit motion to the water. As Arnold (2000, p. 11) notes: “Few technologies advance in isolation and the development of iron as a major constructional material for ships was linked to and partially depended upon progress in two related technologies: the use of steam as a source of power (…), and the slightly later development of the screw as a form of propulsion." As larger ships became possible, it should also be remembered that marine engines steadily developed, decade after decade, even before the first attempts at developing compound engines in the 1850s. To give an example, by 1850 marine engine improvements had allowed gearing to be eliminated (Slaven 1980, p. 111). This opened the way for engines to develop higher revolutions, which in turn allowed for direct connection to the screw, which subsequently encouraged the adoption of iron as the hull material (see Chapter 3, Section 3.3).

As "size was a source of economy" but "speed was a source of cost" (Pollard and Robertson 1979, p. 16; see also Appendix 4.1), we will focus on the relationship between nominal horse power or *HP* (not average speed, a "noisy" indicator very sensitive to the circumstances surrounding its measurement) and gross tonnage or *GRT* (taken as a proxy for size). These are functional performance variables rather than technical characteristics of ships. This sub-section analysis the relationship between HP and GRT by type of steamer during our time window (for an explicit exploration of the temporal dynamics of the two variables using time series analysis see Appendix 5.2).

Gross tonnage and horse power for different types of working steamers

Figure 5.6 depicts all the steamers built in the 1810s. As can be seen, most vessels were ferries, there were a few tugs, and there was one ship classified as a packet (the *Caledonia* in 1816) as well was one trader-like vessel (the all-service *Industry* in 1814). The relationship between HP and GRT emerges as a positive one. The expansion of steamship know-how can be thought of as a movement away from the origin; the higher the performance of the ship, the further the technological frontier has been pushed. The space charted by steamers can be thought of as a performance space.

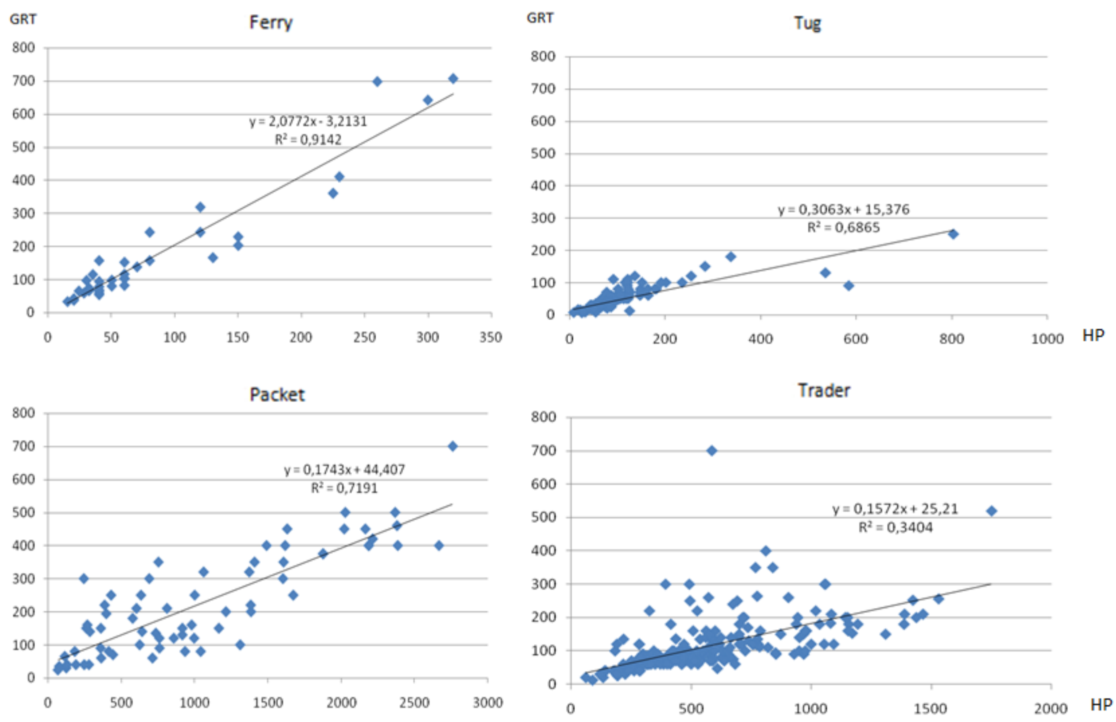
Figure 5.6 Steamers of the first decade, gross tons and horse power, 1812-1819



Source: Craig-Mendonça steamship database
Note: "HP" refers to nominal horse power, while "GRT" (gross tonnage) refers here to the old measurement tonnage; all figures are rounded to the nearest unit

The positive association between HP and GRT remained a distinctive feature of the overall steamer population. Figure 5.7 plots the different types of individual ships built during the 1850s on HP-GRT charts. As can be noted from the values on the *x* and *y*-axes, we are now much farther away from the origin, representing an expansion of the performance possibilities of steamers and an outward movement of the technological frontier. As far as the relation between the two variables is concerned, we can see that this is stronger for ferry types, and then for packet, tug and trader types in descending order. The tug data show a few very powerful tugs for their size, while heteroskedasticity (i.e. the increasing dispersion of observations around the trend-line) appears severe in traders due to their large size relative to their power units (suggesting they were auxiliary steamers, probably colliers). Plotting the vessels using net tonnage does not change the overall patterns (there is a strong correlation between gross and net tonnages), although generally the data-points get more scattered around regression lines.

Figure 5.7 HP-GRT relationship for different types of working steamer, 1850s



Source: Craig-Mendonça steamship database

Notes: The scale of the y-axis is normalised for all charts but not the x-axis, which refers to nominal HP; the *Great Eastern* (considered an outlier) is not included in the packet chart

Figure 5.8 concentrates the information above into a single plot (while omitting the *Great Eastern*). It shows how different types of vessel occupied different areas in the characteristic space while conforming to the empirical regularity observed above, i.e. the positive association between the size of the vessel and the power delivered by the marine engine. Packets achieve higher performance along both the HP and GRT variables (perhaps to the point of being uneconomical; see Chapter 3, Section 3.4), while tugs remained low down on both attributes. Traders appear to be more dispersed than ferries, which were built and engined with a tighter relationship between the two variables. Figure 5.9 presents the same data cloud but adds an idiosyncratic vessel. The inclusion of the *Great Eastern* of 1858, which is the data-point in the top-right corner, distorts the data cloud immensely.[6] Assuming a linear relationship for the HP-GRT relationship, the Brunel/Scott Russell achievement also pointed the way to the trajectory

[6] Incidentally, this chart presents a novel way of representing the degree of achievement that this leviathan represented in her time.

of growth for this particular marine service segment. It took other vessels of the kind, commonly called liners by then, almost 50 years to catch up with her performance. The chart gives hitherto unavailable visual support to claims that the *Great Eastern* was well beyond the technological frontier when she was built (see Chapter 3, Box 3.5).

Figure 5.8 Steamers of the 1850s, excluding the *Great Eastern*

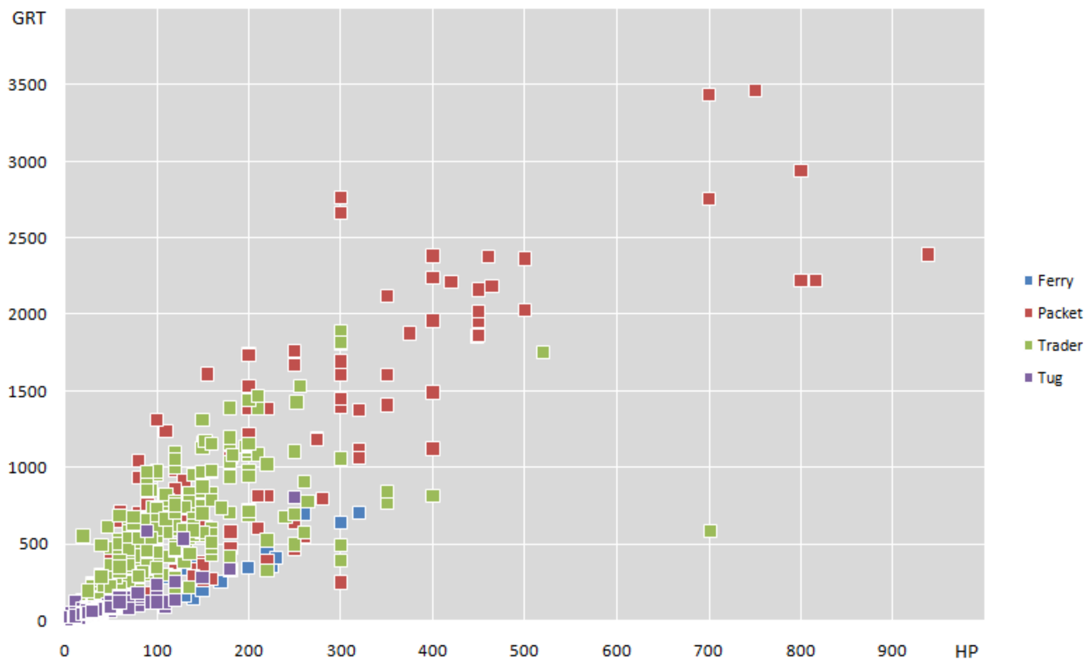
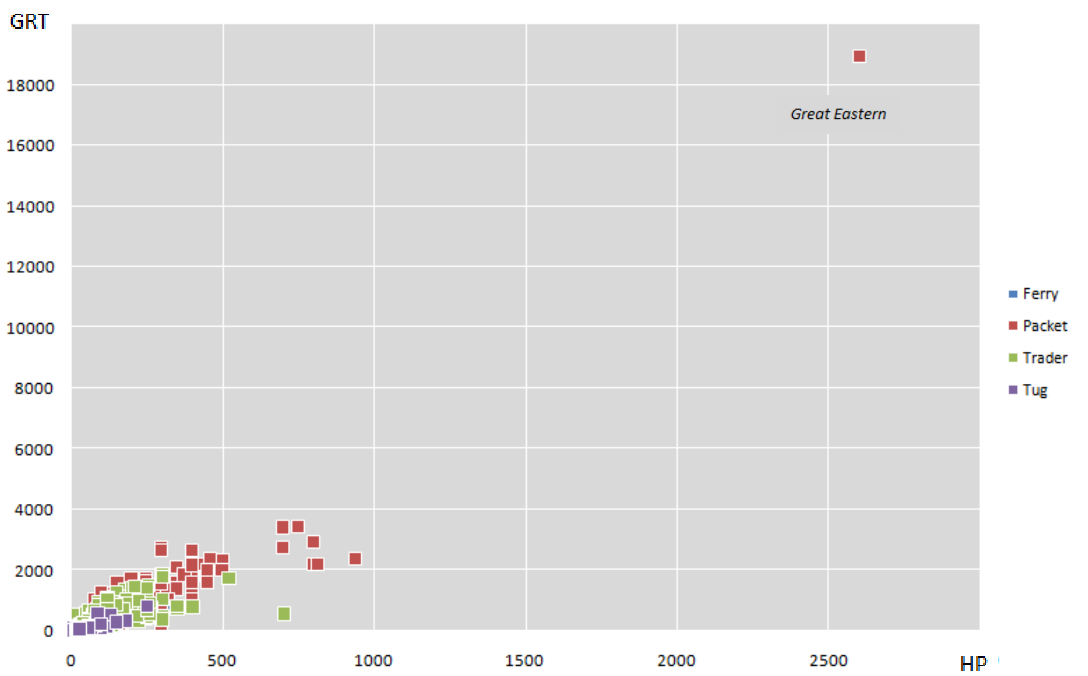


Figure 5.9 Steamers of the 1850s, featuring the *Great Eastern*



Source: Craig-Mendonça steamship database

Summary of Section 5.3

We have observed how early steamers grew in numbers and became increasingly useful in a variety of employments. We also found a strong relation between vessel size and engine power. The performance space (measured in terms of average ship size and the engine power needed to move it) was stretched outwards as time moved on for all types of steamer, representing pervasive innovation and an advance of the technological frontier. By 1850 larger and more powerful steamers were a familiar sight in and around Britain being increasingly entrusted with premium and bulk cargos to and from ever more distant shores. The trend toward greater business diversification was interrupted around 1850, a date Chapter 4, Section 4.4, had already signalled to be a turning point. What lies behind this event? And how different were the technologies supporting the various ship segments? Answers to these questions may simultaneously validate Robin Craig's classification of ships and resonate with both the paradigm-view and the population-variety approaches introduced in Chapter 2 and already applied in Chapters 3 and 4.

5.4 Varieties of design and varieties of trades

5.4.1 The technological nature of the different steamship types

We have learned from the previous sections that the composition of the steamship population changed (namely in the 1840s and 1850s) and we have now started to take a closer look at what sectors were behind that change. However, before going deeper into the issue of inter-sectoral change, let us give some attention to intra-sectoral change. How, in particular, did the different types of steamers evolve? How did different steamers hold their own in the ebb and flow of technical change?

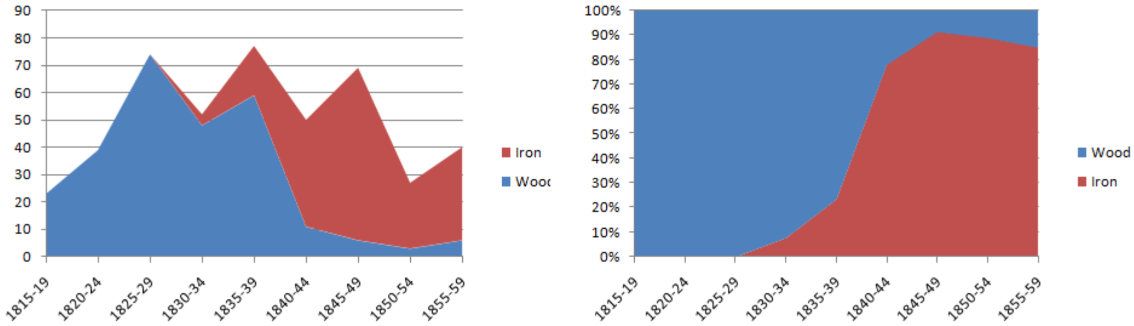
The growth and change of steam vessel varieties

For an analysis of the steamer's design or technological configuration, we will focus on two key technological characteristics, hull material and propulsion mechanism. As noted in Chapter 3 (Section 3.3), these are major components of the steamship. In this and other analyses, we will resort to yearly data, not shown here, to pinpoint the years of transition with more precision than can be gleaned from the five-year aggregate data. The following analysis will make more apparent the growth of steam vessel size across the several economic functions considered (for that it draws support from the economic histories of the vessels surveyed in Chapter 3, Section 3.4). It will also provide evidence that this common growth trend in average size has links with the structural change affecting the design of steamers, namely, the adoption of the iron-screw combination.

Ferries

Figure 5.10 breaks down ferries into timber and metal-built ships. It shows that the absolute number of wooden ferries declined irrevocably from 1840 onwards, while iron-built ones almost fully compensated for this decline. The last year the number of wooden ferries was higher than that of iron ferries had, in fact, been 1837. Hence, we can observe an S-curve, reflecting the early spread of iron steamers within the ferry niche.

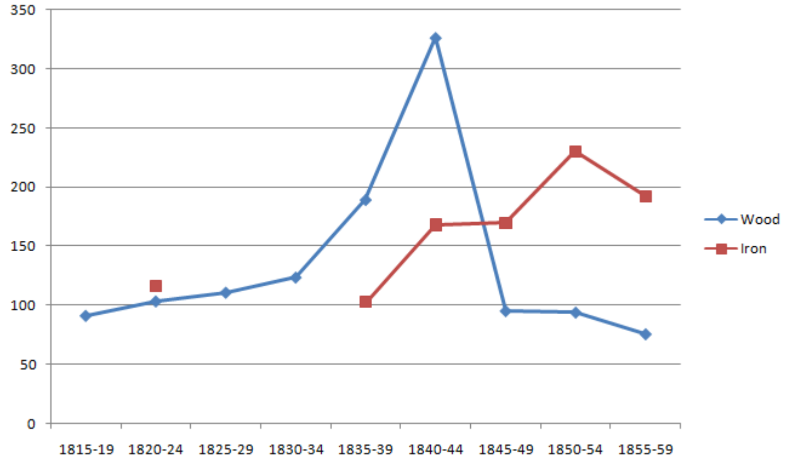
Figure 5.10 Wood and iron ferries, absolute numbers and relative weight



Source: Craig-Mendonça steamship database

The size of wooden vessels decreased as iron took over as the preferred ferry building material. Figure 5.11 shows just how iron ferries came to dominate the niche in the 1840s. In this decade, some 80% of the total tonnage was iron-built, with 1842 being the last year in which wooden tonnage exceeded iron tonnage. In other words, in the transition of hull materials those built of iron soon became the largest in the ferry sub-population. By the late 1850s wood was a residual material in this class of vessels.

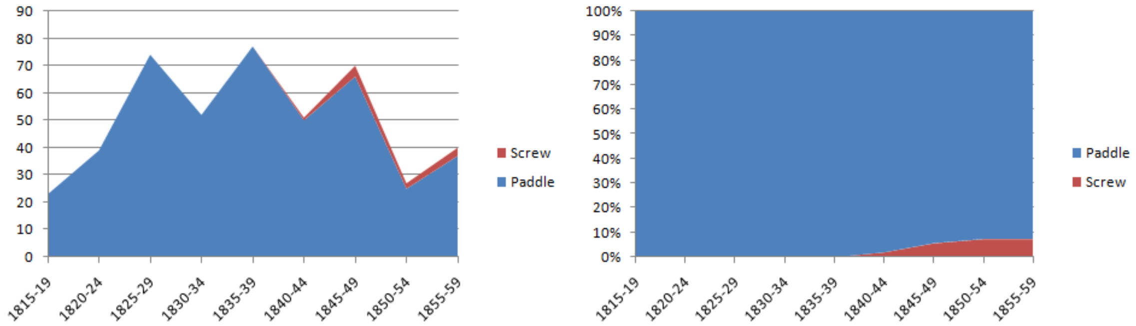
Figure 5.11 Average gross tonnage, newly-built wooden and iron ferry steamers



Source: Craig-Mendonça steamship database
Notes: isolated observation in the early 1820s is the *Aaron Manby*; tonnage measurement rules for all steamers change in 1834

Figure 5.12 reveals that the screw solution made little headway among ferry boats. Consequently, by the 1850s the most popular combination in the ferry business was the iron-built paddler. This observation is supported by the secondary literature surveyed in Chapter 3 (Section 3.4). The clumsy paddle was not a significant problem in the ferry business niche, a selection environment in which coal stations were always close and one in which cargo (i.e. people and light parcels) paid good prices for travelling.

Figure 5.12 Paddle and screw ferries, absolute numbers and relative weight



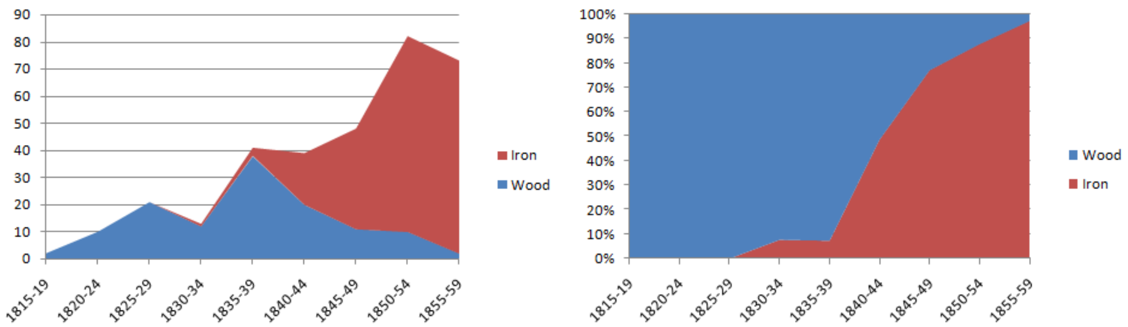
Source: Craig-Mendonça steamship database

Packets

As the steam ferry service succeeded spectacularly in rivers and ports, so confidence grew and steamers began being taken farther afield. The ships delivering mixed consignments of passengers and packets (of, say, mail, newspapers and magazines) on advertised dates and regular frequencies, at fixed rates, to known destinations were referred to as *packets* (*Lloyd's List* 1984, p. 169). Given their ability to work on schedule, steamers prospered on this point-to-point trade. More distant voyages required more coal occupying more bunker space and thus more efficient steam machinery and better economic returns were necessary. As Craig (1980a, p. 7) stresses, however, this trade was only made possible by contracted carriage of high-value, low-volume cargo. Liner companies, mostly big and specialised companies that eventually would become organised under joint-stock ownership, were formed to operate mail and passenger services. As seen in Chapter 3 (Section 3.4), such ventures were concerned with building up high-quality fleets that would allow them to bid for and maintain government subventions under the normally stringent contractual terms.

Packet steamers began the transition to iron hulls in the early 1840s, 1842 being the last year in which wood numbers were greater than those for iron. Hence, packets may be though as early adopters of iron as a shipbuilding material, something that calls for closer inspection (see Section 5.5). As can be seen in Figure 5.13, by the end of the period the transition was virtually complete. Only two wooden (screw) packets were built in 1859 out of a total of 72.

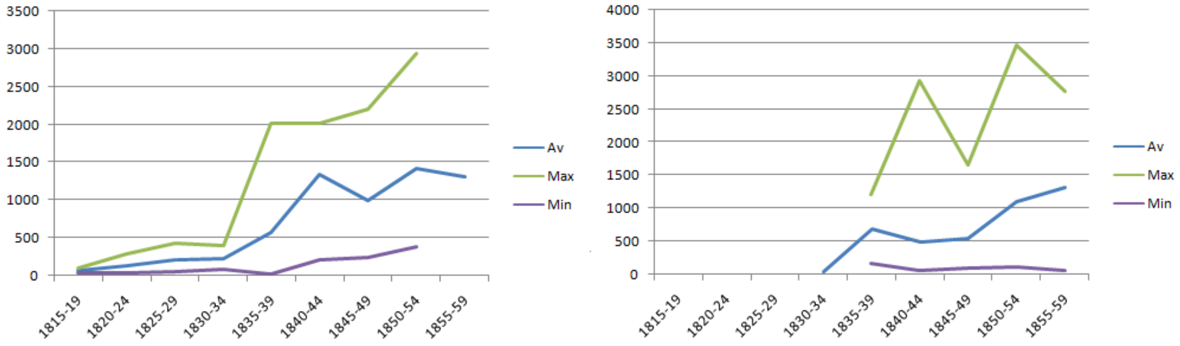
Figure 5.13 Wood and iron packets, absolute numbers and relative weight



Source: Craig-Mendonça steamship database

Curiously, the rise in size of iron packets was accompanied by a (less pronounced, but still positive) increase in the size of wooden packets (Figure 5.14). This coexistence of similar-sized packets during the 1850s can, perhaps, be traced to the slow changing preferences of the authorities regulating the packet business. In addition, given the peculiarity of mail contracts, the subsidised companies could survive with less than ideal levels of ship performance. By the 1850s, however, the performance of wood for employment in large commercial steamers had probably approached its limits.

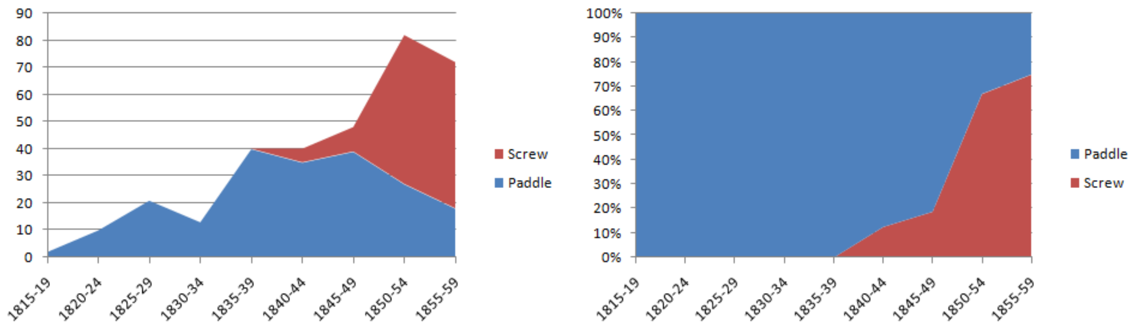
Figure 5.14 Tonnage of wooden (left) and iron (right) packets



Source: Craig-Mendonça steamship database
Note: for both kinds of steamers the lines represent the average tonnage, the tonnages of the largest and smallest packets built in the year interval; the last period for iron packets excludes the *Great Eastern*

Over two thirds of all packets built in the 1850s were screw-driven, their number having shot up early in the decade. Figure 5.15 shows the pattern for the numbers built. In terms of total tonnage, in the years 1855-9 some 70% of all packet tonnage was iron-screw, rising to 90% if we include the gigantic *Great Eastern*. Nonetheless, we see that the adoption of the screw was not as swift as the adoption of iron; a substantive number of iron-paddle steamers kept being built throughout the 1850s.

Figure 5.15 Paddle and screw packets, absolute numbers and relative weight



Source: Craig-Mendonça steamship database

Traders

Traders are another category of steamers that came to evolve alongside ferries, tugs and packets. We refer here to sea-going general cargo steamers, or *traders* for short. This development has been one of the most neglected topics in industrial history in spite of the large part it played in cementing Britain's economic and imperial supremacy (Greenhill 1980a, p. 3). As Craig (1980a) reminds us, some of these vessels, although mostly not designed by the great engineering names of the time, would nonetheless constitute ground-breaking projects in the history of merchant shipping. One example was the *Q.E.D.* launched on the 15th of July 1844, the first iron-screw steamer on the Tyne (Clarke 1997, p. vi; MacRae and Waine 1990, p. 9). This was, to use Dougan's (1968, p. 39) words, "an extraordinarily far-sighted pioneer". Another example was the *John Bowes* of 1852, the efficient Tyne-built coastal iron-screw collier that would be an archetype for the tramp later in the century. Unlike the packet business, the cargo-carrying sector was composed of hundreds of cargo-oriented operators owned by small concerns, many of which were "single-ship companies" owning a single cargo carrier (Woodman 1997, p. 230; Pollard and Robertson 1979, p. 104; see Chapter 3, Section 3.4).

Cargo steamers, the workhorse of the sea-going mercantile marine transporting staples of every description, can now be shown to offer by far the most dramatic example of the wholesale adoption of the combination of technologies that we have dubbed the "modern steamer". The mechanised trader appears essentially as a new "species" in the context of steam shipping and "takes-off" as early as 1846 with the iron-screw layout fully deployed. Figure 5.16 shows the growth in the number (and relative weights) of wood and iron traders, and is closely mimicked by Figure 5.17 which shows the growth of paddle and screw traders. Cargo steamers come to the fore as wholly modern package. The iron-screw configuration clearly became the "dominant design" in this steamer sub-population as it exploded in numbers. This was a striking and significant development, a dramatic instance of a quick and twin technological transition associated with the emergence of a differentiated new product category. This is a most important finding given the crucial role of the steamer as an overseas trading platform and a key contributor to the strong balance of trade performance in the second half of the century (Hughes and Reiter 1958, p. 374).

Figure 5.16 Wood and iron traders, absolute numbers and relative weight

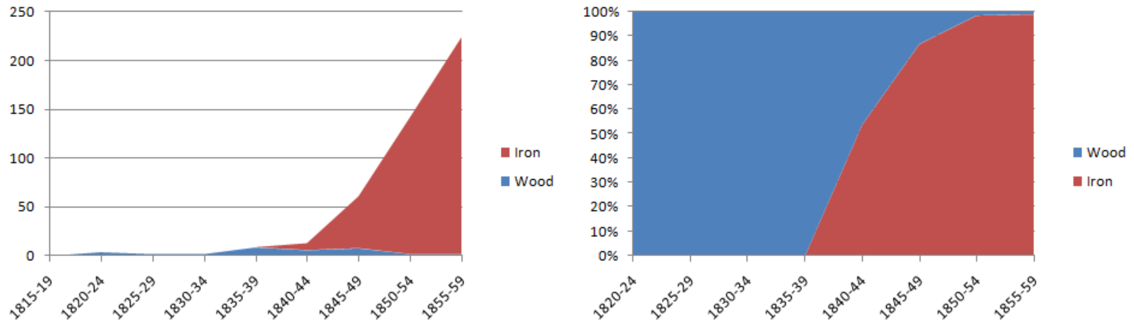
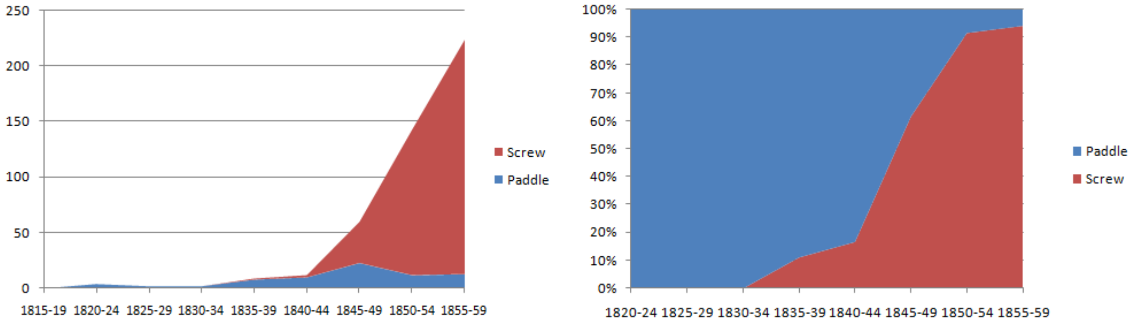


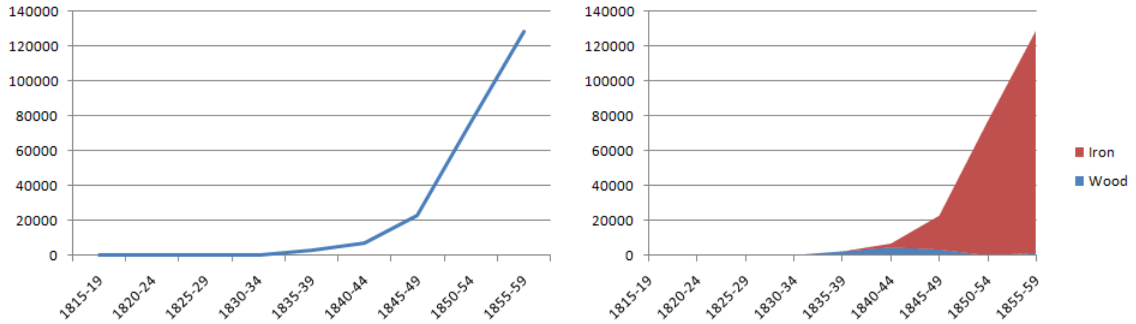
Figure 5.17 Paddle and screw traders, absolute numbers and relative weight



Source: Craig-Mendonça steamship database

Figure 5.18 shows the (gross nominal) transportation capacity that was created by the sudden boom in the construction of cargo steamers modelled on the new (modern) basic design. Gross tonnage figures are only a pale approximation of the real services provided by this new generation of vessels, since their effective transportation capacity was much increased by the extra speed and greater wind/tide independence when compared with a sailing ship of equivalent size (as discussed in Chapter 4, Section 4.4). As Hughes and Reiter (1958, p. 366) argue, the productivity of such steamers was probably higher than that of any other variety of steamer. Indeed, as we have just seen, they employed early and unambiguously the combination of modern technologies that later would succeed in every other market niche. This class of steamers engaged in the toughest "selection environment", both economically (high levels of competition, no state support) and operationally (longer open-sea travel duties), is evidence of the economic efficiency and technological effectiveness attributed to the iron-screw solution (i.e. evidence of selective retention of the new design).

Figure 5.18 Total gross nominal tonnage of cargo trading steamers, aggregate (left) and broken down by iron and screw vessels (right)



Source: Craig-Mendonça steamship database

Thus, as Craig (1980a, p. 5) concluded: "The decade of the 1840's was remarkable for experiment and innovation, during which the practical cargo-carrying steamship progressed by a tortuous process of trial and error." Here Robin Craig was referring to the combined application iron and screw in the carriage of coal along the coast from the Tyne to the Thames. He highlights early innovative vessels such as the *Bedlington* of 1842, the *Experiment* of 1845, the *Conside* of 1847, and the *Collier* of 1848. Thanks to his database we now know that behind these vessels there were many other cargo steamers being built to profit from the new-found advantages over wood, sails and paddles. Thanks to his data we can now appreciate that the iron-screw transition was also extraordinarily rapid and tremendously successful.

Tugs

Towing appears to have been an obvious line of work for mechanical-powered craft. In spite of being one of most discrete embodiments of steam navigation technology, it was one of high impact. As a product innovation performing a radically improved towing service, it apparently did not need to change much to keep its relevance. Figures 5.19 and 5.20 make it clear that the old wood-paddle combination continued in intensive use in the towing business for a long time, even through other types of working steamers went through sudden and thorough transitions. We should therefore qualify Hughes and Reiter's (1958, p. 373) statement that the wood steamer was increasingly used only for "river transport": it was also used in ancillary port work. It is furthermore notable that tug building remained unaffected by the post-1855 recession in shipbuilding.

Figure 5.19 Wood and iron tugs, absolute numbers and relative weight

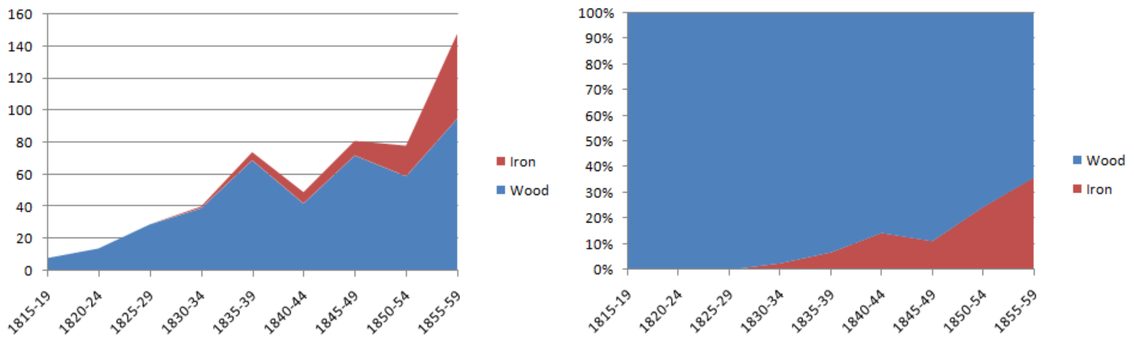
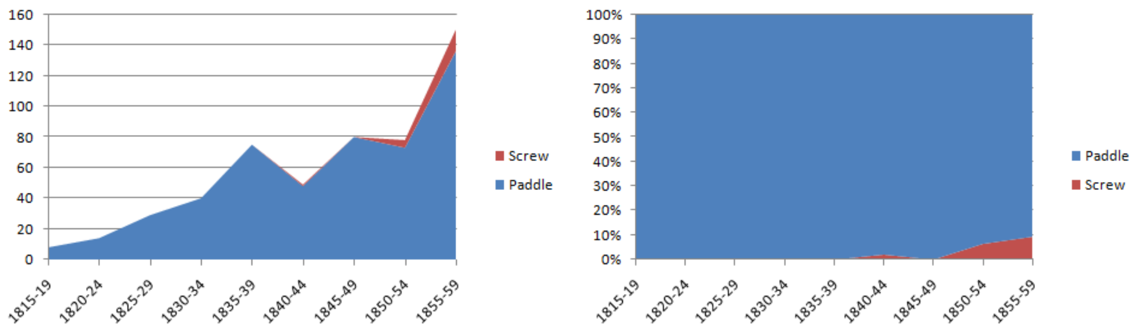


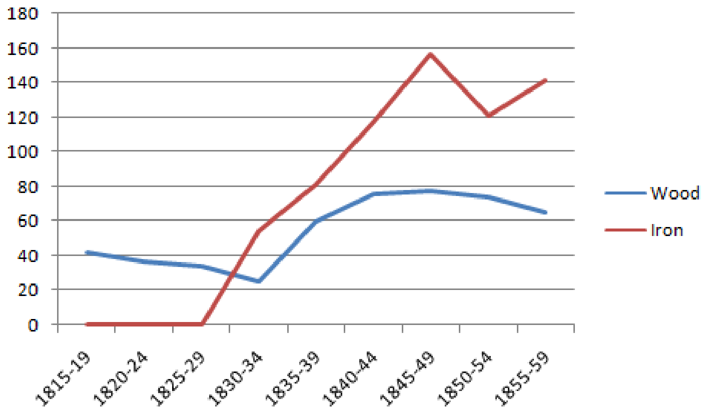
Figure 5.20 Paddle and screw tugs, absolute numbers and relative weight



Source: Craig-Mendonça steamship database

In the tug niche, as depicted in Figure 5.21, wood and iron-built tugs both grew in size (especially iron tugs, mostly because they were part of the "modernisation trend", i.e. the employment of iron as a structural material in hull construction) from the turn of the 1830s onwards, stabilising during the 1850s.

Figure 5.21 Average gross tonnage of wood and iron tugs



Source: Craig-Mendonça steamship database

5.4.2 The evolution of variety in the transition to the modern technological configuration in steam navigation

The findings so far indicate a number of technological developments that seem to have experienced temporal patterns worthy of further exploration.

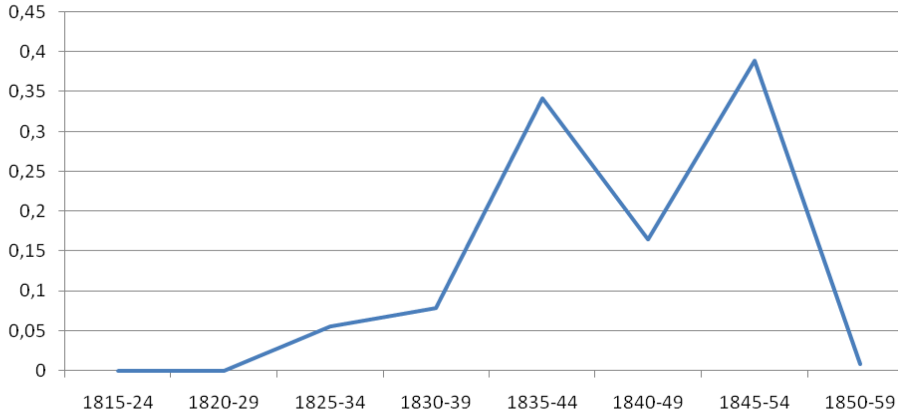
Instability

In order to locate this turbulence more clearly in the historical sequence of events, we have calculated an Instability index (*II*) which, following Cabral (1994), is given by

$$II = \frac{1}{2}\sum_{i}^{n}\left|S_{i2} - S_{i1}\right|$$

in which S_{i1} is the share of a particular technological combination *i* (say wood-paddle) in the total number of steamers built in year 1, while S_{i2} is the same for year 2. The number *n* is the number of possible technological combinations, which in this case is 4 (wood-paddle, wood-iron, iron-paddle, iron-screw). The *II* index assesses the degree of share changes between these various combinations. *II* is a pure number ranging between 0 and 1, with 1 being the maximum level of instability. Figure 5.22 presents the time pattern of the technological turbulence. It emerges that the major perturbation of the established steamer design takes place between 1835 and 1854. In other words, these twenty years can be thought of as representing transformative years for the steamship.

Figure 5.22 Instability of the technological configuration of the steamer, 1815-59



Source: Craig-Mendonça steamship database

We use part of the data employed to obtain Table 5.2. The figures represent the share of a particular technological configuration in the total number of steamers built in the early 1840s and in the early 1850s. This tabulation depicts the phenomenon of structural change, and displays the general movement toward iron-screw as a "consensus configuration" of wide appeal during this critical period of technological transformation.

Table 5.2 The general transition from wood-paddle to iron-screw, 1840s-1850s

1840-44	*paddle*	*screw*	*1850-54*	*paddle*	*screw*
wood	52%	1%	wood	21%	2%
iron	42%	5%	iron	21%	57%

Source: Craig-Mendonça steamship database
Note: Figures may not add up to 100% due to rounding

The contrast over time is not only substantive, it is also statistically significant. Comparing the structure of steamships between 1840s and 1850s lends itself to a Chi-square test, a conventional non-parametric test that is used to compare the distribution of steamers by category (*s* classes of design) for the two periods (*r*). The null hypothesis, that the structure of the distribution of steamers was the same, is rejected. The result is highly significant and is presented in Table 5.3. This confirms the general observation by Hughes and Reiter (1958, pp. 360-1) "that the iron-screw steamer was predominant in new British steamship construction from at least 1851 onwards". This "predominance", as it is now becoming clear, was highly uneven across ship types.

Table 5.3 Structural change in the composition of steamships, 1840s-1850s

Number of steamers	**1840s**	**1850s**
Wood-Paddle	171	170
Wood-Screw	5	11
Iron-Paddle	178	171
Iron-Screw	54	463

$$T = \sum_{i=1}^{r} \sum_{j=1}^{s} \frac{(O_{ij} - E_{ij})^2}{E_{ij}} \bigcap \chi^2_{((r-1)\times(s-1))}$$

$$T = 214.24 \qquad \chi^2_{(2\times3)}, p < 0.000$$

Source: Craig-Mendonça steamship database

Entropy statistics

We now need a better grasp of what this seeming technological transition signified for the population of steamers as represented in our sample. For that purpose, we will employ entropy measures. This is a quantitative approach that indicates the structure of variable distributions at given moments in time and which, in the context of the economics of innovation, has been used to analyse the evolutionary nature of the process of technical change (see Frenken, 2007). In particular, this method of analysis has been applied to a number of complex products as a way to study their variety and speciation over time, including steam engines, motorcycles, aircraft, helicopters, and microcomputers (e.g. Frenken *et al*., 1999; Frenken and Nuvolari, 2004).

Entropy statistics have emerged as a central technique in examining the phenomenon of qualitative change, defined both as the change in the weights of the constituent components of a phenomenon and the change taking place within the components themselves (Saviotti, 2007). A relevant feature of the entropy measure is that it can be decomposed at several levels, a property the Hirschman-Herfindahl index does not have. Thus, in our case, we may measure entropy at the most disaggregated level p_i (wood-paddle ferries, wood-screw ferries, ..., etc. etc., ... iron-paddle tugs, iron-screw tugs), but also examine technology shares P_g (wood-paddle, wood-screw, iron-paddle, iron-screw) and the sector level S_g (ferries, packets, traders, tugs). The overall entropy is computed from the equation:

$$E = \sum_{i=1}^{n} p_i \ln(1/p_i)$$

Entropy increases if the number of individual categories *n* increases and when the shares p_i (the share of the technological design, or category, *i* in the total of the population) become more even. The entropy E_0 computed at a less disaggregated level, called "between-group" entropy is obtained with the formula:

$$E_0 = \sum_{g=1}^{G} P_g \ln(1/P_g)$$

where *g* represents the different technological configurations, *g* =1, ..., G, and *Pg* is an aggregation of p_i:

$$P_g = \sum_{i \in Sg} p_i$$

The entropy *E*' is given by the weighted average of the within-group entropy values:

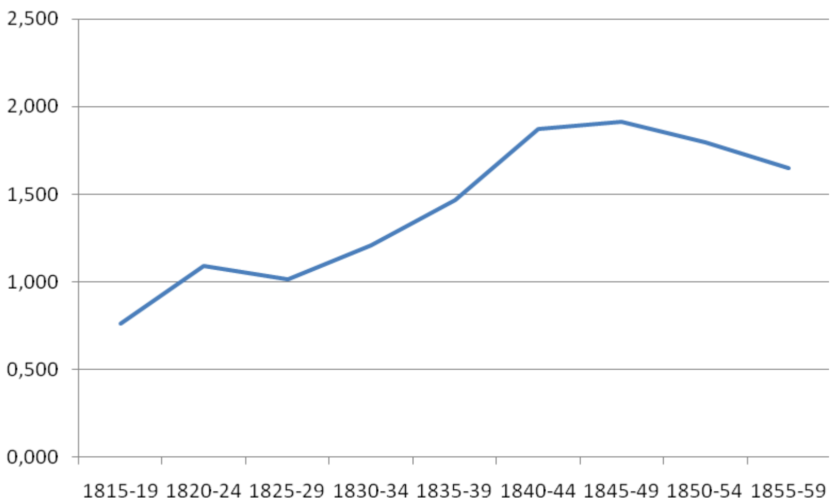
$$E' = \sum_{g=1}^{G} P_g E_g$$

with the within-group entropy (E_g), which measures the extent of variety in the sectors of application of steam navigation, defined as:

$$E_g = \sum_{g=1}^{G} p_i / P_i \ln\left(\frac{p_i}{p_i / P_g}\right)$$

The results are as follows. Overall entropy changed as displayed in Figure 5.23, i.e. it grew steadily until stabilising in the 1840s, and then declined. What contributed to this?

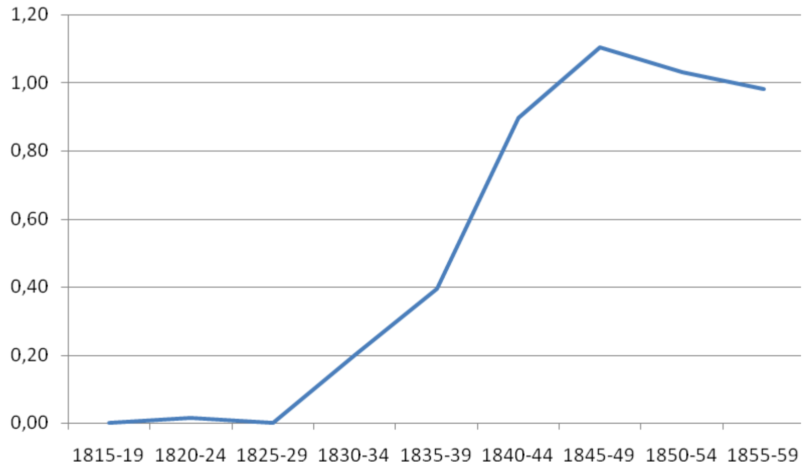
Figure 5.23 Overall entropy (*E*), measuring variety in the total population



Source: Craig-Mendonça steamship database

The “between-group” entropy (E_0) followed the path shown in Figure 5.24: after a steep increase from the mid 1820s onwards, it peaked and then turned downwards in the 1850s. This measure examines the evolution of the shares of different technological configurations in the steamer population. It indicates that in the 1850s the array of technological alternatives showed signs of becoming narrower. In other words, lay-out variety decreases and a “dominant design” seems to set in during the later time period.

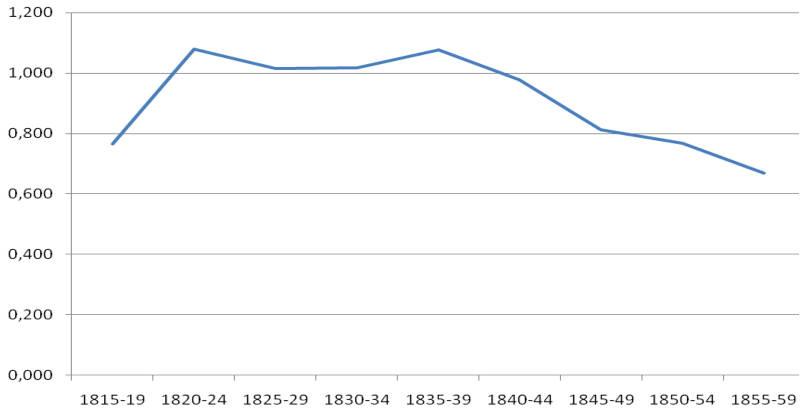
Figure 5.24 “Between-group” entropy, E_0



Source: Craig-Mendonça steamship database

Finally, as we see in Figure 5.25, after a stage of stability during the 1820s and 1830s, the “within-group” entropy (E') went down steadily. This means that from 1840 different sectors of application had been selecting their own varieties (technological configurations). That is, there was a pattern by which steamers working in given contexts of operation became more and more differentiated. In other words, over time given areas of steamship application, on average, became dominated by specific structural designs or configurations of attributes.

Figure 5.25 "Within-group" entropy, E'

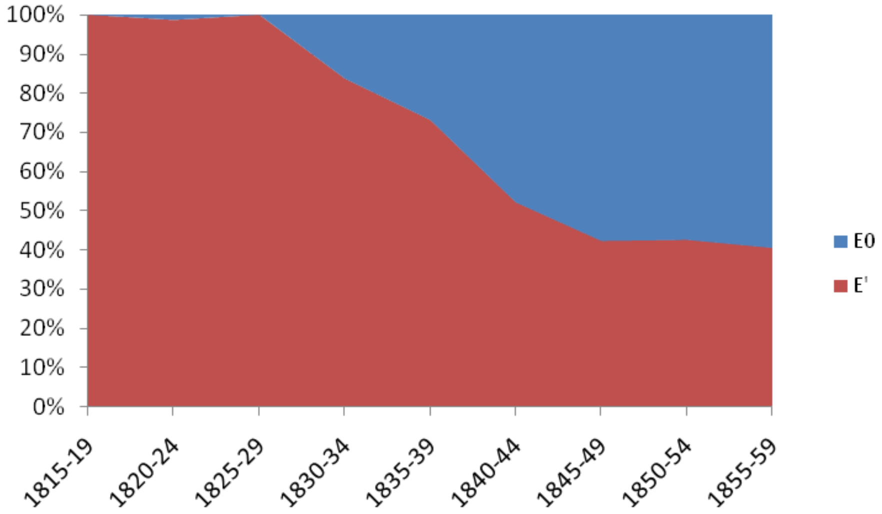


Source: Craig-Mendonça steamship database

That for the 1850s both the E' and E_0 are found to decline means that different product segments were finally converging on the same design. That is, after a long period of coexisting configurations, a single design finally started to be adopted across marine sectors. The result was less entropy (variety) at the technological configuration level at the sectoral level during the 1850s.

Figure 5.26 integrates the "between-groups" and "within-groups" perspectives into a stand-alone figure. The chart simply shows how overall variety (E) was decomposed into intra-sectoral variety (E_0) and inter-sectoral variety (E') over time. Our interpretation of the evidence is that there was always a degree of inter-sectoral variety (i.e. the co-existence of steamers of different sectors/types: ferries, packets, traders, tugs), hence E' dominated for most of the time. The revealing feature is brought in by E_0, i.e. the design change. At the beginning, this number was virtually zero, indicating the same configuration of steamer (wood-paddle) was built in all sectors. The E_0 starts to rise from the 1830s, and this component of overall variety becomes the more important towards the end. The co-existence of "between-groups" and "within-groups" entropy points to a degree of specialisation of design in given sectors.

Figure 5.26 The structure of variety in steam navigation, 1815-59



Source: Craig-Mendonça steamship database

Specialisation

One way to obtain a concise picture of the relative strength of particular technological combinations (hull material - propulsion method) in different sectors of application is by using a specialisation index analogous to the Revealed Technology Advantage (RTA). Introduced by Soete (1980), the RTA is defined as a company's or country's share in each of the patent fields divided by the share of total patenting in the same field. It indicates the relative patenting activity (*P*) of an actor *(j)* in a specific patent class (*i*), normalised to the total patenting of the relevant population in that field. For our purposes, we will define technology specialisation (TS) as involving the shares of technology *j* (P_j) in steamship type or application sector *i* as follows,

$$\mathrm{TS}_{ij} = \left. \frac{P_{ij}}{\sum_j P_{ij}} \middle/ \frac{\sum_i P_{ij}}{\sum_i \sum_j P_{ij}} \right.$$

As the RTA (our TS) is a non-symmetrical index, a transformation has been proposed to scale the index between -1 and +1. Following van Essen and Verspagen (1999, p. 77), the re-centring procedure is simply computed as

$$TS^*_{ij} = \frac{TS-1}{TS+1}$$

according to which a positive value indicates a particular technological configuration to be relatively specialized in a particular sector of marine business. Table 5.4 gives the value of the technological specialisation indexes for the 1850s. The table shows how sectors (in the columns) are dominated by different technological designs (in the rows) for the years 1850-59. It should be noted that the data include a miscellaneous sector of application composed of steam vessels performing a number of ("Other") heterogeneous activities. This is done for reasons of comprehensiveness and sensitivity analysis.

Table 5.4 Specialisation of technological combinations in marine sectors, 1850s

	Ferries	***Packets***	***Traders***	***Tugs***	***Other (dredgers, whalers, yachts)***
Wood-Paddle	-0,21	-0,73	-0,95	**0,54**	-0,36
Wood-Screw	-1,00	**0,27**	-0,65	-0,50	**0,86**
Iron-Paddle	0,58	**0,11**	-0,54	**0,07**	-0,13
Iron-Screw	-0,77	**0,08**	**0,25**	-0,77	-0,18

Source: Craig-Mendonça steamship database

We see that, among the well defined market segments during the 1850s, the packet sector was witnessing a considerable degree of design competition while the trader business was dominated by a single hull-propulsion configuration. Comparatively speaking, the wood-paddle combination was still resisting in the tug niche. The stability of this solution co-existed with the lack of noticeable changes in tug machinery from the 1820s to the 1860s (Armstrong *et al.* 1864, p. 296). The wood-screw found a relatively comfortable habitat in the (subsidised) packet segment and in residual areas (such as whaling). Wooden hulls, Greenhill (1980c, p. 18) reminds us, were difficult to combine with powerful engines (and expensive to maintain), especially if turning propellers:

> "the vibration of a primitive steam engine and the stresses and strains by the torque imposed by the transmission of any reasonable amount of power through the long shaft and the consequence was that the working life of a screw-driven wooden-hull was liable to be expensive, short and troublesome."

The iron-paddle architecture was the most versatile, showing relative success in the ferry, packet and tug businesses. The iron-screw combination had a relative advantage in the longer-distance, salt-water sectors and it overwhelmingly dominated the group of trading steamers. Once more, we see that we cannot understand the basic platform on which British overseas trade rested in the second half of the 19^{th} century without the twin transitions to iron and to screw that constituted the basic attributes of the freight specialist of these years and its successor, the tramp. For years to come, paddlers continued to be built for ferry duty and coastal excursions (Maber 1980, p. 12). But around 1850 the iron-screw arrangement would increasingly penetrate more kinds of trades and waters. From this point onwards, the iron-screw combination emerged as the template, or "paradigm", within which problem-solving in shipbuilding activities progressively advanced. As Craig (1980a, p. 5) put it:

> "Once the screw propeller and iron hull conjoined to manifest their superiority over wooden hulls and paddles, a new impetus was generated by entrepreneurs, shipbuilders and marine engineers who vied with one another to devise novel and enterprising solutions to the intractable problems posed by substituting steam for the large fleet of sailing colliers deployed on the coast between the Tyne and the Thames."

Differential efficiencies: wood vs. iron, paddle vs. screw

This section seeks to determine the sources of relative advantage between the "core" design characteristics we have been discussing so far (building material and power transmission). For this analysis we use packet statistics, those relatively large and sea-going vessels for which size and capacity especially mattered. There are reasons for this. Ferries tended to remain relatively small passage ships, while size was not a consideration for tugs. A reason for choosing packets over traders for the current analytical purpose is that the iron-screw design was so dominant in the latter sector that they drove out the competing designs with which we wish to make comparisons.

Two indicators of configuration efficiency are tested: the Net-to-Gross tonnage (N/G) ratio and the Length-Breath (L-B) ratio. The closer to 1 the N/G ratio the larger the amount of free cargo or earning space and, thus, the more efficient the steamer variant. The higher than 1 the L-B ratio, the more hydrodynamic and frictionless a given unit of transport capacity would be. Tables 5.5 and 5.6 make systematic comparisons for 1850s steam packets. These comparisons are admittedly simplistic and ignore any interaction effects occurring between the design dimensions, i.e. iron hulls are simply compared with wooden ones (the confounding influence of the propulsion is not taken into account in this comparison) and *mutatis mutandis*. The last column reports *t-Student tests* applied, whenever possible (i.e. for large enough observations), to the differences between the averages of the appropriate indicators computed for different configurations of the core design. This analysis is justified because until now we have mostly looked at technical attributes that are directly produced by designers and builders. Looking into measures of the vessel efficiency on the water (translated into less coal consumption) is a way of not losing sight of the distinction between technical characteristics and service characteristics. As Saviotti (1996, p. 74) reminds us, the demand for capital goods is less influenced by the former than it is by the latter.

Table 5.5 Net-Gross tonnage ratio, comparisons between 1850-1854 and 1855-1859

			Count	*Mean*	*St.Dev.*	T-test
Early 1850s	Hull	Iron	72	0.6384	0.1043	Not valid
		Wood	10	0.6303	0.1236	
Late 1850s	Hull	Iron	71	0.6555	01292	Not valid
		Wood	2	0.88,15	0.893	
Early 1850s	Propulsion	Paddle	27	0.6392	0.794	0.918
		Screw	55	0.6366	0.1176	
Late 1850s	Propulsion	Paddle	18	0.5932	0.1012	0.011*
		Screw	54	0.6843	0.1362	

Source: Craig-Mendonça steamship database
Note: (*) significant at the 5% level, (**) significant at the 1% level

From Table 5.5 we find only one statistically significant result. By the late 1850s screw-driven vessels appear to be clearly superior to paddle-wheelers in terms of cargo space optimisation as measured by the N/G ratio. It is notable, because Hughes and Reiter (1858, p. 373) had also observed this, that the wooden vessels (which happen to be screw-driven) compare favourably to iron vessels in the late 1850s. However, the paucity of wooden vessels for ocean steam transport could, perhaps in itself, be taken as evidence that the disadvantages of the material were evident to builders and operators. Overall, these results may be taken as a tentatively supporting something that is found in the secondary literature, i.e. that both iron ships and screw-driven vessels provided greater internal room given the same external proportions (Chapter 3, Sections 3.3 and 3.4). Larger "capacity for stowage" was, indeed, seen by contemporary experts as one of the "advantages of iron vessels" (see, e.g., Fincham 1851, p. 388 and p. 390).

Table 5.6 shows that, taking only the simple statistics at face value, since the observations are too few for a formal test, iron steamers were longer than wooden ones. This, however, conforms to the accounts gleaned from the secondary literature (Chapter 3, Sections 3.3 and 3.4). In terms of propulsion, paddlers happened to be significantly longer than screw-driven ones in the early 1850s (here an interaction effect is probably present, as most paddle packets were iron-built). This may have been the case because such large and long steamers were "greyhound" mail-packets, having been built on the basis of "artificial" (subsidised) market conditions. It is notable, however, that this difference (which was highly significant earlier) disappears toward the end of the decade. That is, the new screw-driven packets begin to be very similar to the more established longest paddle-wheel packets.

Table 5.6 Length-Breath tonnage ratio, comparisons between 1850-1854 and 1855-1859

			Count	*Mean*	*St.Dev.*	T-test
Early 1850s	Hull	Iron	72	7.388	1.220	Not valid
		Wood	10	6.876	0.815	
Late 1850s	Hull	Iron	71	8.656	7.790	Not valid
		Wood	2	5.799	0.683	
Early 1850s	Propulsion	Paddle	27	7.866	0.961	0.003**
		Screw	55	7.060	1.203	
Late 1850s	Propulsion	Paddle	18	8.714	0.779	0.933
		Screw	54	8.534	9.001	

Source: Craig-Mendonça steamship database
Note: (*) significant at the 5% level, (**) significant at the 1% level

Hence, combining the results, we can say that screw-propulsion vessels improved their relative hull efficiency as the decade went on. Vessels incorporating this solution became more efficient than paddle-wheelers in terms of the N-G ratio, and ceased to have an L-B disadvantage. These two attributes meant long and lean shapes that ensured more efficient and capacious merchant vessels, therefore contributing to the survival of unsubsidised packet companies and the commercial viability of the steam carriage of the great majority of cargoes. That very few, and progressively fewer, wood and paddle steamers are observed in the sample can be taken as indirect evidence that their relative weaknesses for the functional requirements of the packet business were already too many and difficult to overcome in the face of the iron and screw alternative.

Summary of Section 5.4

To sum up, certain patterns have become clear. All types of steamer are found to grow in size as time moves on, something that is especially clear when the transition to iron hulls happens. This finding is important in order to support the findings of Chapter 4, Section 4.4, that the tendency for growth in individual vessel size in the general population of steamers cannot be explained only by a sudden shift in the types of ships dominating the population (i.e. there is no evidence of a "composition effect" being the explanation since the growth in average tonnage was a broadly shared phenomenon). As John Fincham (1851, p. 326), the Master Shipwright at the Royal Naval Dockyard in Portsmouth, noted in his book on naval architecture, it would seem that the growth in size of steamships of every type as a response to growing demand was apparent to contemporary observers: "the gradual and continuous enlargement of steam-vessels, to meet the growing wants of the trade for which they were provided."

It is also appropriate to say that technical change in the steamship population was a complicated process of qualitative change. Steamship evolution was no simple story of technological replacement of the older wood-paddle combination by the new, "modern" combination of iron-screw. Different variations of technological designs co-existed over time (as expected in Chapter 2, Section 2.2). What is more, these different combinations of technical solutions were "selected" and "retained" in different sectors of steam navigation. This is an unsurprising finding from a neo-Schumpeterian perspective, but one that has now begun to be uncovered in steam navigation, thanks to the Craig data.

A major finding is that no other type of steamer embraced the iron-screw combination as rapidly and thoroughly as traders. The coalition of iron hulls and screw propulsion was swift and virtually simultaneous and it rapidly became the *de facto* standard or unmistakable "dominant design" in this business. Sail traders existed for centuries but steam-propulsion did not begin by penetrating that old and most important activity until late; it was up to the new iron-screw architecture to bring steam navigation to cargo carrying. Cargo steamers surged in numbers as soon as the new combination became available, and from then onwards the numbers of sea-going steamers in the population increased as a share of the total population. This also means that there was a great deal of qualitative change in the population supporting the general trend towards greater average tonnage between the 1840s and the 1850s. Steam traders exploded into action already modern. This is a result that adds to the extant innovation studies (and also maritime economic history) literature and gives substance to the turning-point findings in Chapter 4 (Section 4.4).

With the help of a number of analytical tools (Specialisation analysis, Instability analysis, Entropy statistics) we find evidence of a technological upheaval with its epicentre in the 1840s. By the 1850s a momentous transition had occurred: the new iron-screw solution emerged as the most frequent configuration at the level of the population, and, first and foremost, the undisputed design in cargo-trading steamers. The new design had attributes that were fundamental for the services performed by unsubsidised, competitive transport ventures. The modern design was first selected and retained in the toughest of the economic selection environments because, the evidence suggests, it allowed for hull shapes with superior stowage and hydrodynamic efficiencies. As the engineers Rankine and Rankine (1862, p. 79) noted at the time:

> "(…) high speeds have not been obtained by the improvements made on the engines alone. They have been obtained by giving more power to vessels, which at the same time have been much improved from being built with finer lines – thereby forming less resistance in passing through the water."

5.5 In depth analysis: Packets and traders

Ship types dominating the technological transition

New steamships between the 1810s and the 1850s can be characterised by a set of stylised facts established by the work carried out so far in this chapter. This section deepens the investigation of the connection between the transition to the modern iron-screw configuration and the rapid changes taking place in cargo and packet ship types.

Table 5.7 shows the numbers of iron-screw steamships being built from the early 1840s through to the late 1850s. The first iron-screw cargo traders were built in 1842 (the *Bedlington* in South Shields and the *Clara* at the Liverpool) and the first steam packets in 1843 (the *Great Britain* at Bristol, the *Mannheim* at Blackwall, and the *Margaret* at Hull). In our sample of 517 newly-built iron-screw ships during these years 72.5% (i.e. 375 ships) were cargo steamers and 22.2% (115 ships) were steam packets. In other words, the transition to the iron-screw design was largely dominated by a single category of steamships, traders, with packets coming in a secondary, albeit not marginal, position. We now focus on these two ship types, starting with packets.

Table 5.7 The distribution of new iron-screw steamers across functions over time

	1840-44	1845-49	1850-54	1855-59
Ferries		4	2	3
Packets	5	8	50	52
Traders	2	34	129	210
Tugs	1		5	12
Total	**8**	**46**	**186**	**277**

Source: Craig-Mendonça steamship database

Packets and the character of the transition to the iron-screw design

One way to start a deeper examination of design changes is to focus on steam packets. As a form of sensitivity analysis, we will re-examine the packet classification itself since there was some diversity in terms of activities within it.

Most packets were built either in London or in Glasgow. Moreover, as discussed in Chapter 3 (especially in Section 3.4) this group of ships contained sub-types, and we can sub-divide it into at least two classes of packets. On the one hand, we can consider the sub-type of near-sea steamers, i.e. those engaged in business around the British Isles and regular passages to the continent. On the other hand, we can consider those packets running on more elite trades, i.e. the crack steamers involved in the Atlantic ferry (the "greyhounds") and the heavily subsidised mail liners in the longer routes to the Mediterranean, the West Coast of Africa, and beyond.

Table 5.8 gives a picture of what may be gained by refining our original packet category. We separate packet steamers into "standard" packets (the first sub-type) and "elite" packets (the second sub-type). We did that by comparing our list of packets with the names of the "greyhound" Atlantic and mail-carrying steamers operated by companies identified in the specialised historical literature (especially Moyse-Bartlett, 1937; Tyler, 1939; Bonsor, 1955; Thornton, 1959) (see also Chapter 3, Section 3.4).

Table 5.8 Numbers of newly-built sub-types of packet steamers across design over time

"Standard" packets	**1815-19**	**1820-24**	**1825-29**	**1830-34**	**1835-39**	**1840-44**	**1845-49**	**1850-54**	**1855-59**
W-P	2	10	21	12	31	7	8	3	
W-S							1	5	2
I-P				1	3	13	20	13	16
I-S						4	8	48	36
Total	**2**	**10**	**21**	**13**	**35**	**24**	**37**	**69**	**54**

"Elite" packets	**1815-19**	**1820-24**	**1825-29**	**1830-34**	**1835-39**	**1840-44**	**1845-49**	**1850-54**	**1855-59**
W-P					6	13	2	2	
W-S									
I-P						1	9	9	2
I-S						1		2	16
Total					**6**	**15**	**11**	**13**	**19**

Source: Craig-Mendonça steamship database
Notes: W-P = wood-paddle, W-S = Wood-screw, I-P = iron-screw, I-S = iron-screw; the different designs may not add-up to the total due to lack of data on particulars or difficulties in design classification (for instance, a standard composite packet of 1831 having a wood-iron hull counts for the total although not being classified here according to her design; the screw-paddle *Great Eastern* is another example)

The unsubsidised near-sea packets constitute the bulk of the category, and until the late 1830s they made up the whole of it in our sample. Overall 328 packets of any kind were built during the full extent of our period; only 19.5% of them were of the "elite" sub-type. That proportion was 15.9% in the 1840s and 26.4% in the 1850s. In other words, the packet category was mostly made-up of more "pedestrian" packets. Crack steamers were a minority sub-type.

What about the rate of adoption of the emerging iron-screw architecture by both sub-types? Overall, 115 iron-screw packets were built, of which only 19 (i.e. 16.5%) were “elite” sub-types. That is, “elite” steamers were relatively under-represented in this technology configuration. They were also late: there was a step-jump in iron-screw “standard” packets in the early 1850s, while the same only happened later in the decade for “elite” steamers. This transition is also accompanied by a change in the geographical origin of iron-screw packets, both “standard” and “elite” ones: if in the mid-1840s London (followed by Liverpool) was the main centre, in the mid-1850s shipyards in the Clyde-side shipyards became predominant.

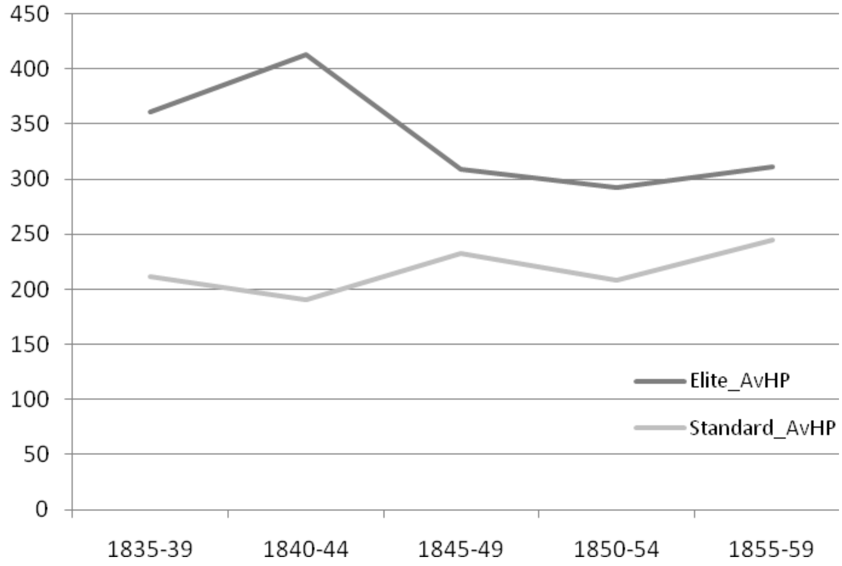
Thus, the most humble sub-type of packet steamer was the most reliant on radical innovation for commercial success: with the turn to the 1850s the iron-screw configuration became the dominant design for this kind of sub-type. While we already knew from the literature surveyed in Chapter 3 (namely Bonsor, 1955, and Kemp, 1978) that by the 1850s the only packets competing with subsidised mail steamers were iron-screw vessels, we now have further evidence showing that the iron-screw combination was an efficient solution fitting even for shorter route trades. A plausible explanation for the early conversion of the “standard” packet fleet to iron-screw may have to do with the fierce competitive environment in which these companies operated (Dumpleton, 1973). A factor that may have also played a part was the pressure put on shipbuilders by the higher standards of the steamer-operating railway companies; the interest of these companies in acquiring their own steamers was rising precisely around 1845 (they owned the vessels through subsidiary companies; see Body 1971, p. 95). One explanation for the delayed adoption by “elite” packet companies can be related to their lesser incentives for fuel-efficiency. Moreover, only by the 1850s did construction regulations ease while at the same the contract packet business did not suffer much from the recession in shipping following the Crimean war boom (see Thornton, 1959).

Hence, the iron-screw was certainly giving rise to operational and economic advantages that unsubsidised packet companies could not ignore. This interpretation is reinforced by the rise in size and power that followed the transition to the iron-screw configuration, something already suggested in Chapter 4. The iron-screw combination allowed "standard" packets to catch-up in terms of size and power with "elite" steamers. As Figures 5.27 and 5.28 show, by the late 1840s the gap between "standard" and "elite" sub-types was being reduced. This convergence is especially visible in terms of capacity, the frontier of which was defined by the "elite" type of ships. The convergence was especially fast as the "standard" packets aggressively adopted the iron-screw design. The transition to the iron-screw configuration seems to have improved the relative performance of those steamers facing the most competitive environments. Thus, it may well be that from the late 1830s mail contracts helped the British long-haul steamer to make progress, and indeed there is abundant evidence for this (see Pollard and Robertson 1979, p. 222; Craig 1981, p. 375; Hope 1990, p. 297). However, in just a few years the iron-screw innovation gave a major impetus in furthering the development of the important "standard" parcel and passenger steamer which provided very diverse and sought-after services around and nearby Britain.

Figure 5.27 Average gross tonnage of packet sub-types over time

Source: Craig-Mendonça steamship database
Note: The *Great Eastern* is taken as an outlier and not included in the computations

Figure 5.28 Average horse power of packet sub-types over time



Source: Craig-Mendonça steamship database
Note: The *Great Eastern* is taken as an outlier and not included in the computations

Traders and the geographical source of the iron-screw design

General cargo traders, which operated in a harshly competitive and volatile business, explode into existence by thoroughly embracing the iron-screw combination in the mid-1840s. This is the type of work where modern ship technology really started to gain traction. But where did these vessels come from? And what were the specific shipping activities they were engaged in? This sub-section furthers our analysis of the database by investigating the geographical pattern of technological advance and relating it to the economic history context (thus feeding into the survey done in Chapter 3, Section 3.4).

Table 5.9 shows the distribution of trader designs as built in a number of British regions. We identify the most important ports where shipyards were located and assign newly-built ships to the port where the hull was constructed and the vessel launched. From the tabulation it becomes clear that steam-driven cargo vessels were built in an intermittent and spasmodic way during the 1820s and 1830s. These few vessels were wooden paddlers and came mostly from the northern rivers.

Table 5.9 Where cargo traders were built, 1820s and 1830s

		North East	Clydeside	Thames	Bristol area	Mersey	Irish ports	Other	*Total*
1820s	W-P	1	4		1				**6**
	W-S								**0**
	I-P								**0**
	I-S								**0**
	Total	**1**	**4**	**0**	**1**	**0**	**0**	**0**	**6**
1830s	W-P	4	3	1	1				**9**
	W-S							1	**1**
	I-P								**0**
	I-S								**0**
	Total	**4**	**3**	**1**	**1**	**0**	**0**	**1**	**10**

Source: Craig-Mendonça steamship database
Notes: W-P = wood-paddle, W-S = wood-screw, I-P = iron-screw, I-S = iron-screw

It was during the 1840s that traders started to appear in greater numbers, especially after 1846, the year when the number of new iron-screw vessels exceeds ten. Table 5.10 offers a compelling picture of this dynamic. If by the early 1840s all the main British steamship building ports were producing cargo traders of several designs, by the end of the decade there was only one design that was produced in all ports: the modern iron-screw design. By then this was the most common layout in this type of ship. About two-thirds of these traders came from three separate regions: the Clyde, the North East, and London. To put it in other words, the "big bang" of the new iron-screw steam carrier was geographically distributed. No single port, let alone a region, can unequivocally be associated with the emergence of the iron-screw trader: it seems to have been a simultaneous collective British achievement and the monopoly of no single region. This is an important finding as it may indicate the existence of a broad pattern of knowledge spillovers concerning the breakthrough of the iron-screw design (the mechanisms underpinning this observation are explored in Part III).

Table 5.10 Where cargo traders were built, 1840s

		North East	Clydeside	Thames	Bristol area	Mersey	Irish ports	Other	*Total*
1840-1844	W-P	1					1	4	**6**
	W-S								**0**
	I-P	1	1	1		1	1		**5**
	I-S	1			1				**2**
	Total	**3**	**1**	**1**	**1**	**1**	**2**	**4**	**13**
	100%	*23%*	*8%*	*8%*	*8%*	*8%*	*15%*	*31%*	*100%*
1845-1849	W-P	1	1	1	1				**4**
	W-S	2		2					**4**
	I-P	2	6	2	3	6			**19**
	I-S	7	11	6	3	4	3		**34**
	Total	**12**	**18**	**11**	**7**	**10**	**3**	**0**	**61**
	100%	*20%*	*30%*	*18%*	*11%*	*16%*	*5%*	*0*	*100%*

Source: Craig-Mendonça steamship database

The sources of iron-screw traders continued to be scattered across space throughout the 1850s (Table 5.11). It should be noted that the Clyde lead in terms of additions to the stock in the early 1850s and that it continued to grow vigorously until the end of our period (an increase of output from 58 to 77 vessels). The North Eastern rivers (Tyne, Tees, Wear and other rivers) started out at the same level as the Thames in the early 1850s, but, as the Thames subsided, the North East region rose to overall prominence by the final years of the decade, i.e. well after the new vessel type was firmly established.

Thus, it could be said that the Clyde pioneered construction of modern traders in sizeable numbers (it still produced more iron-screw steamers than any other place in Britain in 1857). But the North East helped to boost total production more than any other region in the second half of the 1850s (from 1854 onwards we witness a double digit yearly output in the region). Taken together the two regions become more important over time, that is, concentration increased: they accounted for 49.2% in 1845-49, 61.5% in 1850-54, and no less than 80.4% in 1855-59. The Thames still churned high-quality cargo traders (for instance, in our sample we can find several cargo steamers built in Millwall by John Scott Russell between 1852 and 1855), but the quantity had dropped appreciably by the middle of the decade (as documented in in Pollard 1950a, 1950b, 1952, and Arnold, 2000).[7]

Table 5.11 Where cargo traders were built, 1850s

		North East	Clydeside	Thames	Bristol area	Mersey	Irish ports	Other	*Total*
1850-1854	W-P	1							**1**
	W-S	1						1	**2**
	I-P	1	7	2	1				**11**
	I-S	27	58	18	1	22	3		**129**
	Total	**30**	**65**	**20**	**2**	**22**	**3**	**1**	**143**
	100%	*21%*	*45%*	*14%*	*1%*	*15%*	*2%*	*1%*	*100%*
1855-1859	W-P								**0**
	W-S								**0**
	I-P	2	8	3			1		**14**
	I-S	93	77	14	8	3	11	4	**210**
	Total	**95**	**85**	**17**	**8**	**3**	**12**	**4**	**224**
	100%	42%	38%	8%	4%	1%	5%	2%	*100%*

Source: Craig-Mendonça steamship database
Notes: percentages may not round to 100% due to decimals

The geographical outline of the developing iron-screw shipbuilding sector has connections to the intensification of certain trades that succeeded each other in the 1840s and 1850s, namely cattle, copper and iron ore, and the coal trade. During these critical years, as Craig (1978, p. 19) indicates, these factors had a measure of influence "on the future direction of development on oceanic steam transport." The importance of the continental cattle trade came after the 1844 ban on imported cattle duties, and this was followed by the carriage of the copper and iron ores at the turn of the 1850s. These businesses were an important part of the intra-European trade network, which represented two thirds of all European trade on average throughout the 19th century and made plenty of room for the operation of early steamers (Bairoch 1989, p. 4). These

[7] During these years Scott Russell built seven iron-screw cargo steamers: *Lady Berriedale* in 1852, *Caroline* and *Falcon* in 1853, *Bordeaux*, *Gothenburg* and *Julia* in 1854, the *Loire* and *New Pelton* in 1855 (see Fenton 2008, pp. 198-200). No Thames shipyard churned out as many iron-screw colliers. During this decade he built many other ships, including ("standard" and "elite") packets and naval vessels, screw and paddle-wheeled, to domestic and foreign orders (Emmerson 1977, p. 76; Watson 2010, p. 347).

trades encouraged the building of superb general iron-screw cargo vessels from a number of the finest shipbuilders of the day, such as Ditchburn & Mare on the Thames and Tod & MacGregor on the Clyde. During this time even the Swansea district became a centre of construction for iron-screw cargo ships, the copper ore trade being behind the building of iron-screw bulk carriers like the *Augusta*, the *Fire Fly,* and the aptly-named *Cobre* of 1849. [8]

These vessels were pioneering bulk freighters in Britain (see Craig 1979, p. 75, and 1980b, p. 164). But these trades behind them never expanded sufficiently to sustain the continuous investment in new (iron-screw) ships and determine the evolution of the steam freighter. This role was played by the coal trade, which was characterised by its stability and growth. The sustained production of iron-screw colliers would reflect the effective local demand for these vessels (Craig 1980b, p. 164). Bringing coal from the North East was the most important bulk trade of the age and provided plenty of scope for experimentation and for the accumulation of shipbuilding capabilities. As Craig (1981, p. 346) and Milne (2008, p. 4) emphasised, North East historiography is rather thin at the mid-19th century, especially in connection with iron-screw steamship building. A number of features are nonetheless known. This coastal coal trade was “peculiarly susceptible to early penetration by steam vessels”, Greenhill (1980a, p. 16) asserts, “and the classic north east collier brig was to vanish well before the end of the century.” The investment in the new modern cargo vessel was made by those interested in the coal industry itself (Fenton 2008, p. 176, p. 197). It was in this context that the *John Bowes* was built in the North East in 1852; the vessel successfully exploited the iron-screw design that was already being tried out in a number of other ports (see

[8] Some of these Swansea-built steamers embodied a number of innovations. The *Fire Fly*, for instance, had watertight bulkheads and was fitted with a surface condenser (Craig 1979, p. 75). She became the first steamer to navigate the Strait of Magellan.

Dougan 1968, p. 5; McCord 1995, p. 250).[9] By 1860 the coal trade, including exports, was growing rapidly (Craig 1978, p. 26), making iron-screw shipbuilding the most important industry in the region (Clarke 1997, p. 69). As Milne (2006, p. 23) put it: "As well as being the fundamental cargo linking the North East with the European coasting trade, coal drove a revolution in the construction and operation of ships themselves." From the beginning colliers were flexible machines, and even early colliers spent a considerable amount of time operating outside their coastal coal trade (Fenton 2008, p. 195). The North Eastern iron-screw vessels were reliable and easy to operate, cheap to purchase and economic to run (Craig 1981, p. 359). By the early 1900s more than half the world's new shipping output was British, and over half of this came from the North East, where standard tramps and specialist cargo liners continued to be built in great volumes (Pollard and Robertson 1979, p. 62; McCord 1995, p. 246).

But these developments only started to emerge just prior to the mid-1850s (Clarke 1997, p. 89). There was considerable screw collier building going on in many British ports in the decade before. For instance, a remarkable vessel was the auxiliary Liverpool-built collier *Sarah Sands* of 1846 (see Craig 1978, p. 24; see also Chapter 3, Section 3.3, and Chapter 7). Another example was the Glasgow-built *Collier*, a robust ship capable of deep-sea voyages and one that was still afloat in 1914 (Craig 1980, p. 5; Fenton 2008, p. 177). In the year that saw the launch of the *John Bowes* two other iron-screw colliers were launched on the Mersey (the *Haggerston* and the *Hunwick*) while the *Lady Berriedale*, John Scott Russell's first collier, was being built on the Thames (Fenton 2008, p. 198). That is to say, the coal trade was a key application (but by no means the only one) of the new (dominant) design since the emergence of steam colliers arose due to the regularity requisites of London's demand, but coal carrying cannot be taken as having led all by itself to the invention of the iron-screw design.

[9] This vessel seems to mark the passage from the "entrepreneurial" regime in which the product configuration was tentatively explored in steamship building to a routine-based regime in which process and cost advantages mattered relatively more (see Chapter 2, Section 2.2, and Chapter 4, Section 4.3).

All in all, iron-screw shipbuilding capabilities were widely distributed by the mid-century (an empirical result which complements the regional literature on steamship building – Chapter 4, Section 4.3). The new British design was now well-known and ready to exploit the great opportunities that lay ahead, namely a more than doubling of overseas trade and an almost quadrupling of coal exports between 1850 and 1870 (Clarke 1997, p. 93). The technological breakthrough preceded the “regional shake-out”; steam colliers, which would become the “trademark” of the North East, were an early landmark of the new species of steamer but hardly an isolated case. It does appear that distributed innovation was a major feature in the early life of cargo steamers, static regional comparative advantages becoming prominent only later.[10]

Summary of Section 5.5

This section provided a number of perspectives that consolidated and detailed our previous findings. Iron-screw innovation was a relatively dispersed phenomenon of the mid-1840s, but it grew quickly to become the “dominant design” in cargo traders and non-subsidised packet steamers by the mid-1850s. On the one hand, the iron-screw configuration met the needs for efficient short-sea travel of parcels and people. This high-value trade was a core component of the intense development that intra-European trade was going through in the period. The data allowed us to see that “standard” packets were soon challenging in terms of capacity and power the “elite” packets that benefited from state subventions; this performance was related to the early adoption of the iron-screw design in the “standard” packets. On the other hand, the iron-screw configuration allowed the definitive “take-off” of the modern steamship in the form of the general cargo vessel. The iron-screw trader met the demands for the efficient carriage of general cargo and bulk commodities, such as coal, timber, grain, cattle,

[10] Additionally, this is an important observation since it gives more substance to a point already raised in Chapter 4, Section 4.3: only after the iron-screw introduction (the explorative entrepreneurial phase known as Schumpeter Mark I) did factor prices and regional resource endowments (coal, iron, cheap skilled labour force) seem to drive industrial organisation into an exploitation and routine mode of operation for the remainder of the century (i.e. Schumpeter Mark II).

copper and iron ore. The development of the iron-screw trader was not a monopoly of the North East coast during the formative years of the mechanised carrier.

The iron-screw design represented an appropriate (working and efficient) response these market forces. The North East iron-screw collier was a landmark in this process, but its importance in the early days should not be overplayed. That the formidable technical problems leading to the general cargo steamer were solved with economic success between the mid-1840s and the mid-1850s in such geographically distant places such as Millwall, Swansea, Liverpool and Glasgow is an important finding. It is significant because it downplays the individual merits of specific ports and invites a more comprehensive appraisal of the forces revolutionising and then raising the standards across the regional centres. These empirical patterns serve to introduce a hypothesis concerning the factors leading to steamship innovation in the first half of the 19th century. The hypothesis is that some sort of collective mechanism, rather than simple individual incentives and engineering competition, played a role in integrating and re-distributing the knowledge that brought about the modern ship.

5.6 Conclusions

The nature of the steamship underwent significant changes over the course of time. To understand what occurred during the first five decades of steamship evolution, we have studied the technological variety and the functional performance exhibited by the heterogeneous population of steamers built in Britain. As explained in section 5.2, this chapter analysed for the first time a new database to explore those patterns. This dataset, originally put together by Robin Craig, the eminent maritime historian, is a tremendous resource that remains to be fully studied and developed over years to come. It represents a valuable addition to the tools of marine historians, as well as innovation economists and economic historians. Our findings in this chapter conform very closely to the literature surveyed in Chapter 3 and the aggregate trends identified in Chapter 4.

Steamers could be said to belong to different types corresponding to distinct economic functions: namely ferries, tugs, packets and cargo traders. Section 5.3 showed how steam navigation was applied to an increasing number of domains and activities throughout the period. Different types of vessels were found to change their internal structure, and the contrasting configurations persisting in different sectors suggest that the different variants of steamer adapted their characteristics to fit the users' environment. Steamers generally tended to grow in size as a result of the use of iron as a shipbuilding material. A given ship also tended to become more spacious (larger, roomier) and hydrodynamic (longer, faster) as iron and screw were combined. We also examined how the size and power characteristics of steamers were related to each other. A strong relation was found between horse power and gross tonnage independently of steamer type. The cross-interaction of these variables, creating pressures for further advance as time went by, remains an elusive issue and warrants additional data processing and methodological work in the future (Appendix 5.2).

Section 5.4 investigated in detail how different types of steamer changed in quantity and quality over time. Between 1835 and 1854, however, broad technological changes swept through the population. This was shown by using a range of data analysis techniques. A key result is the relatively sudden drop in the variety of the product population can be taken as a key indication of a turning point. For most of the time, change was slow and incremental but a new basic design was introduced, namely the self-reinforcing and efficient iron-screw layout. This development transformed the old steamer into another technological system in a relatively short period. Remarkably, as soon as the new design took over the trader type, there was an explosion in the number of this type of vessels. In other words, the stabilisation of the modern steamer configuration coincided first of all with a sharp upturn in the construction of cargo steamers, the newest and fastest growing branch of shipbuilding at mid-century. The growth of this sea-going transport capital good (the sea-going steam trader), and the connection between its rise and the radical technological change underlying it, is a fundamental finding in light of the importance of overseas trade and investment for the British economy in the latter half of the 19th century.

Section 5.5 conducted additional analysis in order to further test and refine the results. It was found that the new radical iron-screw design first became established as the dominant design among "standard", competitive, non-state supported packets which further underlines the economic rationale behind its adoption. In terms of cargo-traders it was found that the emergence of the new iron-screw configuration was a rather geographically distributed phenomenon. The rise of the cargo steamer was not exclusive to the North East region. The North East emerged as the undisputed regional centre for steam colliers, but largely from the mid-1850s onwards – a development that would be a precursor to the emergence of the ordinary tramp ship, the backbone of the British merchant marine up until the Great War. The first inroads into steam cargo carrying, however, were made in a number of trades (cattle, copper ore, iron ore, etc., as well as coal transport) in a number of regions (including the Thames, the Clyde, and others).

Technological knowledge is embodied in the characteristics of the product. The product mutated over time. In connection to the first of the research questions motivating this thesis, the present chapter explained the process through which this happened. It thus sets the scene for addressing the second research question, i.e. explaining the major forces stimulating the development of such underpinning technological knowledge. From 1850 onwards, ship designers' creativity would be expressed in the language of steam, propeller and iron. Hence, the issues become: how did engineers and naval architects continually learn to surpass their previous best practices? How were these achievements collected, combined, and then communicated in a way that accounts for the multi-regional origin of iron-steam traders in Britain?

Appendix 5.1 – Copy of steamship database agreement

Steamship Database

STEAMSHIP DATABASE AGREEMENT

Robin (Robert) Craig
The Anchorage, Bay Hill
St. Margerets Bay
Dover, Kent
CT15 6DU
UK
Fix

Agrees to lend to

Sandro Mendonca
Pr. Novas Nacoes
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1170-277
Lisbon
Portugal
Email (PT): sfm@iscte.pt
Email (UK): s.m.mendonca@sussex.ac.uk
Mobile (PT): 00 351 96 487 30 53
Mobile (UK): 00 44 7791 879 080

A Card Index and other data on steamships 1813-1859 on the following conditions:

(i) The Card Index remains the property of Robert Craig and will be fully acknowledged in any published work;
(ii) The Card Index must be returned after processing on 6 months, renewable for periods of 3 months by agreement;
(iii) Sandro Mendonca guarantees safety of Card Index and will ensure that all the material without exeption is returned

safely, without alteration;
(iv) Any work intended to be writen and/or published resulting from this arrangement shall be communicated to Robin Craig;
(v) The resulting digital steamship database shall be jointly owened between us.

Dated 15th of May 2005
St Margerets Bay, CT15 6DU,UK

Signed

Robin (Robert) Craig

Sandro Mendonca

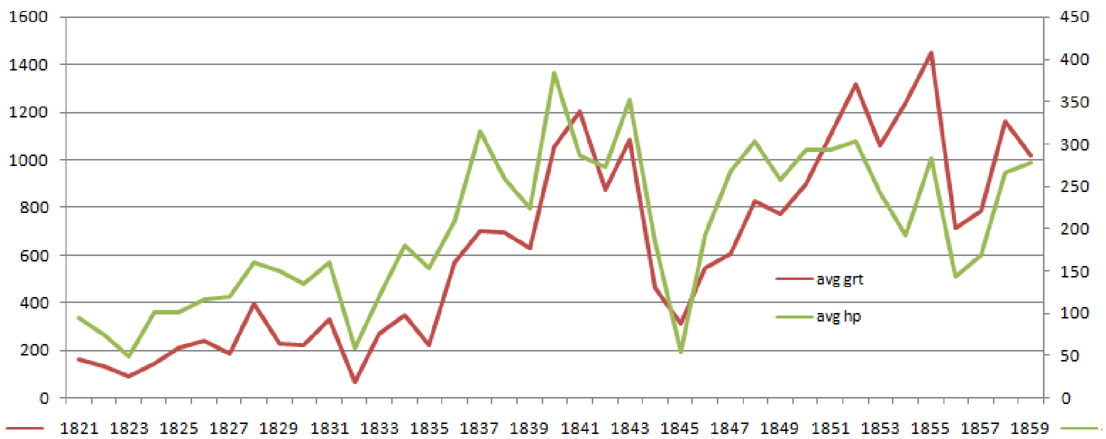
Appendix 5.2 – Dynamic interactions between gross tonnage and horse power

The notion that progress in GRT would induce a response in HP, or vice-versa, provides the motivation for a plausible hypothesis to be tested. In this scenario, improvements in the ability to build larger hulls would provide a stimulus for more powerful engines to drive the increased capacity and, in turn, higher HP would invite renewed naval architecture efforts to develop ways to make the most of the new marine engine knowledge (and vice versa). A problem with this hypothesis is devising a methodology to test it.

One way to think about the temporal relationship between HP and GRT is to imagine an average steamer that would represent, for every year, the archetype of the state of the art of marine engineering and naval architecture. The internal structure of this imaginary steamer would change, reflecting the advances in best practice and the inner logic of localised search in response to the pressures and inducements that the two aforementioned dimensions of performance would exert on each other. This, of course, is a highly abstract view of the advance of the technological frontier and, strictly speaking, one that reduces the population approach that we have favoured to its most simplistic version.

Let us take the mean of built steamers as a benchmark and take once more the packet sub-population of steamers as an exploration ground for further analysis. Figure A plots the time series of HP and GRT for the average steamer for the continuous series running from 1821 to 1859. The number of steamers built annually varies substantially (as does the variance of their characteristics – this information is completely lost in the chart).

Figure A Packets, yearly average tonnage and horse power, 1821-59

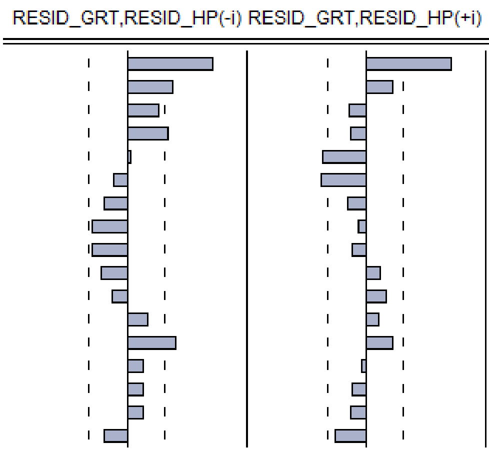


Source: Craig-Mendonça steamship database

Note: The left-hand axis represents the scale for average yearly gross tonnage (avg grt) and the right-hand axis corresponds to the values for average yearly horse power (avg hp)

In a time series analysis framework, the concept of correlation captures the sign and degree of contemporary association of one variable with the other. Conversely, the notion of cross-correlation captures the sign and closeness of association of a given variable in one year, say HP in year *t* (HP_t) with the other variable in the past (say GRT in the previous year, i.e. GRT_{t-1}) and in the future (say GRT one period ahead, i.e. GRT_{t+1}). For the correlations to be valid both series have to be stationary. Once the trend is removed for both time series, the cross-correlogram appears as depicted in Figure B. The variables are highly contemporaneously correlated and the correlations appear significant until lag 5 (lag 12 also appears significant but may be spurious). Lags present a fluctuating structure hinting that a cyclical temporal structure (perhaps the business cycle?) is affecting the variables.

Figure B Cross-correlogram of (de-trended or stationary series for) HP_t and GRT_t



i	lag	lead
0	0.7391	0.7391
1	0.3977	0.2424
2	0.2716	-0.1350
3	0.3589	-0.1278
4	0.0338	-0.3634
5	-0.1169	-0.3827
6	-0.1917	-0.1554
7	-0.2980	-0.0598
8	-0.3041	-0.1191
9	-0.2211	0.1303
10	-0.1232	0.1831
11	0.1788	0.1167
12	0.4260	0.2326
13	0.1379	-0.0334
14	0.1449	-0.1195
15	0.1343	-0.1294
16	-0.1885	-0.2615

Source: Craig-Mendonça steamship database

A further step can be taken by reasoning in terms of "Granger causality", that is to say, one variable *x* "Granger causes" *y* when its past values help in predicting the value of *y* in the next period. In our present context, causality can, of course, work both ways. In this frame of analysis, ship performance levels and changes in the state of the art are taken as time-ordered sequences of random variables. Sequences of random variables are called stochastic processes. The challenge is to find a probabilistic model that appropriately identifies and correctly estimate the basic regularities of technological change as represented by the data. Let us assume that the true model describing the two series is:

$$HP_t = \beta_{10} + \beta_{11} GRT_{t-1} + ... + \beta_{1n} GRT_{t-n} + \varepsilon_t^{HP}$$

$$GRT_t = \beta_{20} + \beta_{21} HP_{t-1} + ... + \beta_{2n} HP_{t-n} + \varepsilon_t^{GRT}$$

with ε_t^{HP} and ε_t^{GRT} as the independent and identically distributed (i.i.d.) error terms, which are assumed to be uncorrelated with each other. Under the null hypothesis that there is no "Granger causation", that is

$$H_0 : \beta_{10} = \beta_{20} = \beta_{11} = \beta_{21} = ... = 0$$

Running the appropriate test for n=5 lags, as suggested by Figure B, it turns out that no causality is detected in either direction (Table A). In other words, although the Figures A and B seem to suggest a pattern of cross-influence in the same period, it is not possible to reject the null hypothesis of no "Granger causality".

Table A “Granger causality” test

Null Hypothesis:	Obs	F-Statistic	Probability
RESID_HP does not Granger Cause RESID_HP	34	0.49920	0.77360
RESID_GRT does not Granger Cause RESID_HP		1.14223	0.36682

Source: Craig-Mendonça steamship database

The lack of statistical success in detecting the influence of past technological events with regard to one variable on the other may be due to several reasons. First, there may be no causality defined in this way. Second, the causality may exist but it is not being captured, i.e. it is being incorrectly modelled, the data may be too noisy, the time series may be too short, etc.

We are, therefore, reporting a negative result. We have tried to come up with good approximations of the yearly rate of progress in the performance and attempted to model the dynamics of the advance of the technological frontier along the horse power and gross tonnage dimensions, but with limited success. This should motivate further work in the future.

Part III

Part I highlighted the theoretical background and the technological context of the dissertation. Part II explored less familiar territory by examining changes in steamship design and performance on the basis of a thorough econometric and time-series treatment of both available and previously unpublished empirical material. Part III tries to complete the picture by focusing on why those transformations took place. It does that by isolating a set of specific institutional factors framing steamship evolution. The discussion is based on the integration of a mass of dispersed qualitative data on early steamship development that, so far, have remained relatively unexplored in the work of previous maritime economic historians.

Chapter 6 examines a particular dimension of the institutional framework, namely the patent system, and the ways in which it affected steamship-related inventions. The bulk of this analysis rests on documentation left behind by innovators themselves and on a listing of English patents compiled by Bennet Woodcroft, a contemporary intellectual property lawyer and a steam navigation pioneer in his own right. The lack of a clear positive connection between patenting and previously identified technological breakthroughs leads us to look elsewhere for explanatory factors influencing inventive behaviour.

Chapter 7 explores a set of neglected formative influences behind the rise of mature mechanised shipping. The chapter points to the importance of expert communities as collective learning entities. This chapter finds that the rise of engineering societies, of technical journalism, and of a not-for-profit quality control system converged between 1818 and 1834 to become an effective learning mechanism that had a bearing on specific crucial junctures of early steamship innovation. The effects of this “technological public sphere” were visible in the iron-screw steamer by 1850. We conclude that the role of civil society institutions built to foster engineering communication and shared learning needs to be taken into account in any attempt to explain the evolution of steam navigation.

6. Individual incentives to invention: The role of patents

6.1 Introduction

Intellectual property is a very old institution. As it spread in Europe from the 15th century onwards, the first proposals for mechanically propelled vessels started to emerge. The question that arises is how, and to what extent, intellectual property rights influenced (i.e. induced, hampered or biased) technical change in steam navigation. This chapter extends the concern with the influence of policy and regulation on the technological development of steam navigation by focusing on the incentive system providing rewards to invention.

The present chapter assesses the views and uses of the patent system in Britain by contemporary inventors and experts in ship technology. We try to complement extant maritime literature concerning the role of patents in two main ways. First, drawing from qualitative primary sources, we identify and relate a number of views on patents held by contemporary informed observers and active participants in developing the technologies behind steam navigation. Second, we explore records of actual patenting to build a quantitatively informed understanding of the patenting phenomenon in steamship technology. A number of questions can be asked on the basis of this material:

- *On the character of patents and the profile of patentees*: Were there many marine inventions for which patents were sought? To what extent were significant improvements (radical innovations) and minor changes (incremental innovations) patented? Were patents channelled towards specific sub-fields of marine technology (say, propulsion)? Were there many non-improvements for which patents were sought, that is to say, were there many trivial patents? Who were the patentees, i.e. were they centrally involved in the design and production of steamships or were they individuals largely unconnected to the industry trying to reap benefits through means other than the actual application of their ideas to working artefacts?

- *On the motivations to patent*: Were improvements contingent upon the granting of the patent, i.e. would they have not taken place were it not for patents? Or would these changes have happened anyway without the protection of exclusive rights? Were there other inducements, besides the economic incentives, adequate and sufficient to stimulate innovation? Did innovation come about through the piling up of small additions by many individuals and would it be difficult to ascribe a specific contribution to any of them? Were patents taken out not for exploiting the invention itself, but rather for building up a litigation position or to take advantage of the real users?
- *On the consequences of patenting*: Did exclusive rights inhibit the free exploration of the technological space? Did patent proliferation around a large complex machine like a steamship create problems for the combination of different elements arising from different sources? Did patents create obstacles for a cumulative process of technical change? Were patents decisive for attaining industrial leadership and international competitiveness in this field?

It should be noted that the topic of this chapter is situated at the intersection of what remain two relatively neglected areas of scholarly research: the role of the patent system in British economic history, and the early technological development of the steamship in maritime historiography. On the one hand, comprehensive reviews of the role of intangible forms of business property in our period of interest are scarce. The book of Harold Dutton (1984) remains about the only attempt to thoroughly review the role of patents in the first half of the 19th century, while Christine MacLeod (1988) traces the long process by which a recognisable patent system emerged from the time of the Stuarts to 1800. On the other hand, there is a relative lack of explicit scholarly attention to property rights in the story of the steam-powered vessel. The extant maritime and naval literatures mostly offer brief and indirect accounts of such episodes, treating the issue of claims to intellectual property as a sideline to other subjects such as the early contributions to steam boats by pioneers on both sides of the Atlantic (e.g. Gilfillan 1935a, 1935b). The notable exception to these somewhat cursory treatments has been the analysis of the procurement policies of paddle-wheels and screw-propellers by the Royal Navy (MacLeod *et al*., 2000; Lambert 1993, 1999b).

Section 6.2 places the subject of this chapter in the broader context of the role of patents in economic history. Section 6.3 briefly reviews the emergence of patents as an economic institution in Europe, and Britain in particular. Section 6.4 refers to salient steamboat patents in the early phase of steamboat development. Sections 6.5 to 6.8, review a number of public events in which the views and attitudes of marine engineers and naval architects were expressed. Section 6.9 focuses on the uncertainty and ambiguity caused by patent litigation in steam propulsion and how the Royal Navy contributed to dispelling these difficulties. Section 6.10 assesses patenting behaviour in steam navigation by drawing quantitative evidence from an index compiled by Bennet Woodcroft (1848), which thus far has apparently remained unanalysed in economic maritime history even though it appears to represent the earliest known uses of patents as an indicator of technological events and developments. Section 6.11 concludes with a summary of the main findings to emerge from this chapter.

6.2 Intellectual property rights as an economic institution

Our study touches upon a broader debate in current scholarship. The traditional economic argument, as classically articulated by Douglass North (1981), is that private property institutions were well established in Britain and that this facilitated the Industrial Revolution, while the rest of Europe was still cluttered by customary but unclear feudal obligations and dominated by arbitrary and often despotic orderings of rights. A further step is often made that the same argument can be extended with no great analytical difficulty to intellectual property rights. The conventional view, inherited from North and others, is then that intellectual property systems had an important and positive impact on the course of economic development of the western world (see Khan, 2008). Appealing to North's work on institutions, Baumol and Strom (2010, p. 535) have recently declared:

> “The patent system is evidently an institution that effectively promoted innovative entrepreneurship not only via the reward of a temporary legal monopoly, but also by making it possible to transform access to such intellectual property into a salable commodity. Patents offer the entrepreneur an additional means to acquire wealth for herself and her associate inventor while simultaneously ensuring widespread use of her invention”.

At first glance Mokyr (2004, p. 27) seems to concur: “Secure property rights were essential for continuing investment in the capital goods that embodied the new technology.” And were patents important for major technological turning points? Baumol and Strom (2010, pp. 534-6) are quick to offer a view: the fact that the patent institution made its appearance before the Industrial Revolution suggests that it had a major role in igniting that very explosion of creativity. This leads, then, to a more specific re-statement of the previous question. Did the establishment of patent rights pave the way for Britain’s sweeping “wave of gadgets” (to use the famous phrase of T.D. Ashton 1948, p. 58) and their subsequent development? The answer must surely matter, as Baumol and Strom (2010, p. 527) themselves argue that “history may well provide the most fertile field for the germination and gathering of ideas for policy.”

Economic historians of technical change, however, were never as convinced that patents were a key explanatory variable in the Industrial Revolution. David Landes (1969, p. 64), for instance, expressed his scepticism over “the incentive effect of patent legislation” because such protection was not new, it was costly and difficult to obtain, and it was not effective in deterring competitors, especially when compared with the alternative of secrecy. MacCleod (1988, pp. 144-57) provides, moreover, a persuasive account that largely complicates the positivist narrative of the upsurge in patents in terms of a rise in inventive activity or better incentivised technical talent. Doubts by economic historians concerning the advantage of patents over other property rights, as Bessen and Meurer (2008a, pp. 9-10) recently note, seem to have grown considerably over time. Thus, Joel Mokyr (2008a, p. 3) has now been moved to ask of the standard view: “What could be wrong with this picture? The answer is basically ‘almost everything.’” As von Tunzelmann (1995, p. 418) noted: “Even early leader countries like Britain in the Industrial Revolution probably benefited from having imperfect patent systems.” The hypothesis is that intellectual property may constitute an exception (and, if it is so, a very major one) to the consensus among economists on the centrality of private property institutions for growth and development. The comparatively unfamiliar marine aspect of the Industrial Revolution offers an opportunity to further explore this debate.

6.3 The patent system in England up to the late 19th century

The use of patent-like rights has been regarded as being among the pioneering policy tools aimed at inducing innovation (Granstrand 2004, p. 266). In England a procedure for granting patents was enacted as early as 1536, in the Clerck’s Act (Dutton 1984, p. 29). The system was oriented toward the acquisition of superior foreign technology and the “introduction of entire industries or manufacturing techniques from abroad” (MacLeod 1988, pp. 12-3). In 1624 the “Statute of Monopolies” was enacted and became a landmark in the early evolution and spread of the patent system. After a public outcry on the King’s abuses of his discretionary powers, this Statute was introduced to curb “royal grants to rent-seeking companions” (Baumol and Strom 2010, p. 534). Patents survived as an exception to an otherwise rather drastic removal of the previous restrictive regime of monopoly privileges.

The patent system evolved and increasingly became the particular subject matter of new manufactures. It was defined as an award granted “to the true and first Inventor” alone. It was up to the crown clerks to issue the patent. A patent expired after 14 years, the time it then took to enrol two generations of apprentices (Kaufer 2002, p. 7). It was only during the reign of Queen Anne (1702-1714) that it became required that a written description of the invention had to be submitted. Further changes came in 1778, when a new form of disclosure (i.e. specifications, involving a full and detailed description of the invention) became compulsory (Harris 2004, p. 232; Sherman and Bently, 1999; Kelsall, 1984). The specification as a form of disclosure amounted to a recognition of a fundamental *quid pro quo*, “a change from a contract between the patentee and the Crown to a ‘social contract’ between the patentee and society” (Dutton 1984, p. 75).

Unlike the French system, which had instituted pre-grant examination procedures by the Académie as early as 1699, throughout this time the English patent system was one of simple registration (MacLeod 1988, p. 41). This meant that sealing a patent was tantamount to a “purchase”, a term used by contemporaries themselves (Woodcroft 1848, p. 102; see also Dutton 1984, p. 110). As many authors have remarked, the cost was anything but trivial. Before 1852, the filing fee was £100 for England and Wales alone, while extending it to the rest of the UK would cause the expenses to mount to £350, not counting travel, gratuities, and other opportunity costs implied in approximately two months of effort. The process of obtaining a patent was legendarily cumbersome and the rights were relatively insecure (Janis 2002, p. 906). Faced with situations of illicit use without payments, patentees faced a court that was largely hostile towards patents. This attitude was changing rapidly from the 1830s and calls for reform began increasingly to be heard (Dutton 1984, p. 79). The system was not reformed until 1852 with the Patent Law Amendment Act, which broadly coincides with our half-century turning-point findings. The new law unified the system for the United Kingdom (separate systems existed for Scotland and Ireland), simplified the application process, lowered the initial cost and introduced renewal fees to keep patents in force. Even so, patents bore little resemblance to the conventional present-day approach. In 1883 the procedures were once more simplified and the fees fell again, but only from 1902 onwards were applications examined for novelty (Khan 2005, p. 38).

6.4 Early steamboat patents

There are numerous patents punctuating the long and slow process of arriving at a working steamboat. On 21 January 1618, David Ramsey, "page of the king's bed-chamber" (Murray *et al*. 1863, p. 113) and another member of the court, obtained the first English patent in which the idea of steam for propulsion is implicit – for a method "to make boats, ships and barges goe against wind and tyde". After this we find several instances of patents that were impractical and failed to describe the contrivances proposed. Jonathan Hulls, who obtained a patent in 1736 and published a pamphlet the following year, was the first to articulate detailed plans describing a steamboat. In 1788 the Scotsman Miller, with James Taylor and William Symington, built a double-hulled steamboat that operated with some success but which was not followed up. James Watt's threats of litigation may have contributed in no small degree to the discontinuation.[1] In 1802, coinciding with the expiration of Watt's basic patent, Symington was able to demonstrate the first steamboat capable of doing useful work: the *Charlotte Dundas*.

The desire to take economic advantage of a monopoly right and to hinder challengers played an important role in the introduction of steam navigation in America by Robert Fulton. Not having been the inventor of the steamboat, and arriving in the United States with a Boulton & Watt engine, a technology for which exports were usually blocked, he hesitated but eventually filed patents claiming original contributions to the principles of steam navigation (Cain 2010, p. 339). Fulton succeeded in operating the *Clermont* under a 20-year exclusive privilege of steam navigation in the state of New York that had been granted to his partner, Robert Livingston (laws in this years in several states allowed this kind of monopolies – see Thurston 1891, p. 149). But the partnership's exclusive

[1] See Williamson (1856, p. 219), one of Watt's early biographers, who quotes a letter by Watt to Miller dated April 24, 1790, denouncing "attempts to evade our exclusive privilege"; see also Rowland (1970, p. 34), Deeson (1976, p. 22), and Harvey and Down-Rose (1980, p. 7).

grants were also seriously disputed and they became embroiled in law-suits.[2] Their petitions for exclusive rights on other rivers were rejected or ignored (Hunter 1949, p. 10). By 1824 the river steamer monopolies were declared unconstitutional (Cain 2010, p. 339).

No-one before Fulton made any money with patents. Fulton himself died and left "his family in embarrassed circumstances." (Woodcroft 1848, p. 62) Moreover, not only did patents bring no significant financial reward to the aspirations of early steamboats inventors, they also increasingly seemed to be associated with litigation. A telling case of a patent spat among pioneers involves Symington, who himself is thought to have been an early victim of patent bullying by Watt. On the offensive after the successful demonstration of the steam passage boat in Scotland, Symington sued Henry Bell in December 1814 for infringing his patent of 1801, a broad patent covering "machinery put in rotative motion by a steam engine and which may be used to navigate boats." (Harvey and Downs-Rose 1980, p. 147) Bell counter-attacked, claiming libel and disputing the novelty and utility of Symington's patent. He later withdrew the action. Symington was also forced to defend himself from Taylor's relations, his former associate with Miller, who claimed his 1801 patent in fact covered inventions conceived by him[3]. Towards the end of his life he became entangled in controversies over his credits as the rightful inventor of steam navigation and disputes over patent rights, which added to his financial distress and apparently his drinking problems (Beare, 2004)[4].

So, what is one to make of the influence of patents in the invention phase of the steamboat, i.e. the period up to Fulton's commercial breakthrough? On the one hand, it appears that patents were more a source of expense than revenue for tentative inventors.

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[2] See Woodcroft (1848, p. 62), Morrison (1903, pp. 3-4), Dickinson (1913, pp. 240-59), and Hunter (1949, p. 10).

[3] Woodcroft (1848, pp. 57-8); see also Marsden and Smith (2005, p. 92), who refer to Lindsay (1874, p. 40).

[4] Early, apologetical, biographers, claiming to have access to sources in the possession of his family, emphasise how Symington in the last years of his life became a "broken spirit", totally dependent on his relatives for his substance and still engaged in clearing his name and establishing his claims to priority (see Bowie 1833, pp. 23-6; Boyman 1840, p. 108; Rankine and Rankine 1962, pp. 7-8; according to Clark 2010, p. 7, Bowie and the Rankines were descendents of Symington and should be read with reservation).

On the other hand, patents were hardly enforceable and litigation proved to be a source of distraction and further cost. Furthermore, it is possible that litigation may even have delayed the commercial introduction of steam navigation for several years (perhaps even twenty years) in the case of Britain. Hence, the key inventors in the "pre-innovation" phase never prospered for one reason or the other. Moreover, it is also be difficult to assign too much of a role to patents in this period since comparisons with modern-day patents would risk anachronism. In Britain at the dawn of the 19th century patents "were still regarded as monopolies that restricted community rights and they were to be narrowly construed and carefully monitored." (Engerman and Sokoloff 2008, p. 395) And as Gilfillan (1935a, pp. 92-3, italics in the original) remarks for the American case:

> "What are always called the 'patents' … could not have been granted under modern law, and were not patents in the modern sense, but *concessions* for the navigation of certain best waters by steam."

What, one ought now to ask, was the character of marine-related patents of the innovation phase, that is, during the period of commercial exploitation of steam navigation? And what had informed opinion to say about it? To tackle this question, we will shift perspective from the early 1800s to the mid-1800s, the period when the modern approach to mechanised sea transport became established.[5]

6.5 "Absurd", but patented

On March 3rd 1860, Nathaniel Barnaby (1829-1915)[6] produced a pioneering discussion of the "influence of patentees and pamphleteers have already had on naval architecture". He was addressing a distinguished and influential audience of marine engineers, naval

[5] The North American case is beyond the scope of this thesis. It has been documented that steamboats evolved quickly and were pervasively adopted in the US after Fulton's debut in 1807 on the Hudson (Hunter, 1949). This success appears to have owed little to patents since steamboat machinery was developed by men that "had little awareness of or use for the patent system." (Hunter 1949, p. 175)

[6] Barnaby was an eminent Victorian naval architect. Apprenticed as a shipwright when he was fourteen, Barnaby had a long career in the Royal Navy. He assisted in the designs of the last wooden sailing line-of-battle ships in the 1850s, the *Warrior*, the world's first iron-clad screw battleship launched in 1860, and the *Dreadnought*, the first a new class of all-big-gun 20th century battleships. He was a founder of the INA and a regular participant in the debates. An innovative and respected designer, Barnaby rose to the top of his profession first by becoming chief naval architect in 1872 and then director of naval construction in 1875 (Watts, 2004).

architects, Lloyd's Register officials, and Royal Navy officers at the opening session of the new Institution of Naval Architects (INA). Barnaby's topic was "mechanical invention in its relation to the improvement of naval architecture" and he reviewed 600 years of technical change and, having scrutinised all "letters-patent" relating to ships and ship-building between the early 1600s and the early 1800s, he could "find no improvement worth recording except in the manufacture of sheathing, and the construction of pumps. Indeed, between the years 1618 and 1800 more than one-third of the patents claim improvements on the ships' pumps." (Barnaby 1860, p. 153)

He then turned his attention to more recent times and the changes that came about in ships after the introduction of steam. "While the present period is remarkable for the changes which are taking place in the character, dimensions, and modes of construction of our ships," Barnaby said, "it is no less remarkable for the number of amateur inventors who desire to effect still greater changes." (Barnaby 1960, p. 155) Judging from his years of close contact with inventors submitting plans to the Royal Navy he synthesised his views while confessing himself "sorry to say that the majority of patents relating to our profession are of the same character" (Barnaby 1860, p. 156), using the adjective "absurd" to characterise them (Barnaby 1860, p. 157). He went on to list a number of examples, such as plans for hydrostatic ships, vessels propelled by levers working floats producing waves, and vessels centred on vibrating chairs. Barnaby notes, moreover, that these had been "granted under the old law when patenting was a costly proceeding." (Barnaby 1860, p. 157) The reform of 1852 effectively lowered the fees and, according to him, "still more absurd" patents were subsequently taken out.[7] None of Barnaby's views, it should be noted, was challenged in the period of debate that followed his intervention, which was transcribed in the *Transactions* of the INA.

[7] A recent study (Nicholas, 2010) examined the change in patent applications before and after a substantial reduction in the cost of obtaining a patent, the 1883 British Patent Act. Fees fell 84%. It was found that a great increase in patenting across the technical categories followed the reform, but that the drop in patenting cost did not increase innovation (the quality of the patents actually dropped).

Among the authorities who contributed to the first volume of the transactions were Sir George Airy, William Fairbairn, Joseph Maudslay, Scott Russell, John Grantham, George Moorsom, and the Vice-Admiral of the Royal Navy fleet.

These views were certainly not uncommon in the steamship community during the 1840s and 1850s. Elsewhere William Fairbairn (*BPP* 1851, p. 174), the iron-steamer innovator, referred to a multiplicity of "ridiculous and absurd inventions". John Ericsson, both a steamship pioneer and a screw-propeller patentee, came to regret that so many people spent their time and money over "mechanical absurdities" and "worthless schemes" (Church 1906, p. 240). Robert Napier went so far as to assure his prospective client, Samuel Cunard, in 1839: "Every solid and known improvement that I am made acquainted with shall be adopted by me, but no patent plans." (Napier 1904, pp. 136-7) Tyler (1939, p. 82), for instance, takes these words as evidence of Napier's suspicion regarding patented inventions for untried marine improvements.

In sum, what we can gather from these testimonies is that the overwhelming majority of patented marine technology was apparently of little value, and that this was likely to be a widespread belief in marine engineering circles. Thus, the character of most steam navigation patents was judged to range from the "ridiculous" to the "absurd". But could we respectfully follow Barnaby and inquire the background of these "suggestors"?

6.6 The "amateurs" who "run wild" over "monstrously ingenious" and "useless inventions"

Barnaby duly states that the majority of the marine patents do not come from the profession. Out of the patentees of the 292 patents "for matters relating to shipbuilding", he identified that under the old patent law, i.e. between 1618 and 1852, there were only 20 from shipwrights or naval architects (Barnaby 1860, p. 156). Besides "eighty who are styled gentlemen", Barnaby found a "strange medley of colonels and lieutenant-colonels, graduates of universities, barristers, coal-merchants, wool-dealers, agricultural machinists, upholsterers, goldsmiths, dyers, coach-makers, toy-makers, fruiterers, tallow-chandlers, and brewers." (Barnaby 1860, p. 156)

In the analysis of the social backgrounds of these pioneers, we are, furthermore, helped by another contemporary testimony. It was authored by John Macgregor, presumably the statistician who was Joint Secretary of the Board of Trade in the 1840s (Porter 1912, p. v) and the co-founder of INA. In another public meeting, on 14 April 1858 at the Society of Arts, he presented a remarkable paper in a session chaired by John Scott Russell. MacGregor (1858, p. 335) referred to the whole of English patents between 1618 and June 1857 on paddle wheels and screw-propellers. He used as a source the new "Abridgments of the Specifications", an index that Bennet Woodcroft in his capacity of assistant to the commissioner of patents had just succeeded in making publicly available. MacGregor found 802 patents on marine propulsion, 305 of which came under the new law of 1852 (of these 110 were abandoned after six months). Among the patentees, he found 38 belonging to occupational groups having something to do with things maritime (14 naval officers, 11 shipbuilders, 8 shipowners and 5 mariners). He listed the remainder of the patentees: 278 engineers and machinists, 251 gentlemen, 160 with undeclared occupations, 25 assorted professions, 8 peers, and 2 women. With regard to patents with multiple inventors, that is, with two or more patentees, he found 66 patents.

What followed was a lively discussion, with the Chairman leading the way.[8] "Of the hundreds of inventions", remarked Scott Russell in addressing the members of the audience, "were they not amazed to see how few were at this day in practice; and were they not struck with the fact that nearly all the inventions they now heard of no more seemed monstrously ingenious." John Grantham, the builder of the pioneering iron

[8] The discussion is on pages 340-2, and all the passages quoted here are taken from the transcription.

steamer *Sarah Sands*, also entered the debate and offered his own experience as evidence. Many persons called on him for advice concerning inventions. Individuals "who look upon themselves as inventors" approached "with some adaptation as they call it, of the laws of nature applied to mechanics" and seemed to have a tendency "to run wild over those matters."

So, what was the profile of the patentees or "suggestors"? Gilfillan (1935b, pp. 83-4), who was perhaps the first to examine the interventions of Barnaby and MacGregor reported in this chapter, sums it all up by noting the "many foolish patents" coming from "a motley array of landsmen of all ranks."

6.7 On the utility of patents from the point of view of steamship engineers and builders

From the two previously mentioned gatherings in 1858 and 1860, one gains the impression that the overwhelming majority of patents in the marine field were seen as irrelevant and detached from practical concerns. This was taken for granted by qualified experts who, moreover, were not shy in saying so in front of their peers and having their words recorded in print. If the technology protected by patents was unhelpful in this field, how did this community see patents as a general institution?

Some leading innovators in steam navigation, who relied on the products of their intellect to make a living, held strong views on this topic. I.K. Brunel, we learn, was one. An occasion that gives us an insight into his thoughts on the matter came on a Wednesday evening, March 26th 1856. Brunel had been asked to chair a session of the Society of Arts. The circumstance was the presentation of a paper on soap manufacturing by a certain Mr. William Hawes (1856), the brother of a friend. Brunel's views, exposed in an open intellectual context, were recorded in the debate's transcript.[9]

[9] All the quotations are extracted from the debate that followed the reading of the paper.

In the discussion of the paper, several members of the audience digressed into the subject of patents. Brunel was presumably getting somewhat impatient. As the chairman rose to wind up the session, he could not help but make room for his own intervention. In a time when many were alive to the issue of patent reform, he “sided with a small minority on this question.” His position was clear: “He did not agree at all with the advantages of patents.” Granted, as with any other thing, inventive activity should be remunerated, especially, he thought, if the inventor was a worker or someone solely dependent on abilities within him, but,

> “...having had considerable experience with patentees, manufacturers and workmen, he was of the opinion that any practical benefits derived from the patent laws did not compensate for the injury inflicted. He believed, on the contrary, that both the inventors and the public greatly suffered from the attempt to protect innovation.”

Having devoted his career to engineering, he was undoubtedly the most experienced engineer in the room. It is worth quoting Brunel at length:

> “He had had great experience on this subject, being compelled daily to examine inventions of various kinds, and having himself constantly to invent in the occupations in which he was engaged. Having, then, all his life been connected with inventors and workmen, he had witnessed the injury, the waste of mind, the excitement of false hopes, the vast waste of money, caused by the patent laws, in fact, all the evils that generally resulted from the attempt to protect that which did not naturally admit of protection.”

Brunel never took out a patent. He went on to explain why:

> “He was disposed to encourage every step towards facilitating the obtaining patents [sic]; he hoped they would be made dirt cheap, as he thought that that would be the most effective way of destroying them altogether. Therefore, whenever he had been consulted on the subject of Patent laws, he had always advocated the rendering of patents as open and free and cheap as possible; in the first place, because he saw no reason to attach a price to them, and, next, because they would sooner arrive where the principle would be fully tested. We were nearly arrived at that state of things where engineers were brought to a dead stand in their attempt to introduce improvements, from the excess of protection. He found he could hardly introduce the slightest improvement in his own machinery without being stopped by a patent. He could mention a striking instance, in which, a few months ago, wishing to introduce an improvement that he thought would have been valuable to the public on a large work in which he was engaged, he had no sooner entered upon it, with a willingness to incur considerable

> expense in the preliminary requirement, and in the trial of it, than he was stopped by a patentee; but he was fortunate enough to find that another patentee existed for the same thing, and a week after a third appeared. There was thus, fortunately, a probability that, by the destruction of all value in any patents, he might be able to conclude the improvements he was desirous of introducing."

He does not say what was the enterprise he was engaged in, but it is probable that it was the *Great Eastern*. Thus, Brunel refers quite explicitly to patents as an obstacle in the way of practical engineering, not as an incentive to innovation.[10] William Fairbairn (*BPP* 1851, p. 173) concurred and worried that patents often constituted an "inducement to litigate", especially in connection to the introduction of really important technologies: in the case of the immense numbers patents covering meaningless inventions, they meant "ruinous losses for patentees"; in the case of useful inventions, patents ended up being inoperative as profits were "lost by lawsuits" and, in the event, the "body of true inventors" come out as "generally losers, instead of gainers."[11]

Brunel's partner in the *Great Eastern* venture appeared in print in pretty much the same vein. Scott Russell saw the proliferation of patents as partially driven by the fear of pre-emption. Shortly after the 1852 patent reform, Scott Russell publicly stated:

> "In regard to Patent laws he must plead guilty to being the owner of two or three patents; but he fully agreed, that it would be an advantage to the ingenuity of this and every country, if all property in patents were annihilated; and he believed that such a consummation was rapidly approaching. The position of inventors at present compelled them to patent their plans, not so much to prevent others using them, as to secure themselves the right to do so; for if they neglected to take out a patent for an invention perhaps the next day some one else would, and they might be prevented from using their own discovery. Patents were multiplying so rapidly, that they would shortly be of no service. Their great number would prevent them being of any use as advertisements, and the same cause would destroy the *prestige* at present attached to them." (April 22, 1853, in *Journal of the Society of Arts*, Vol. 1, No. 26, p. 271, emphasis in the original)

[10] Here Brunel was echoing what he had said years before at a session of the Institution of Civil Engineers. In a little known passage during the discussion of a paper, and drawing again on his experience, he said: "It was notorious, that engineers frequently found their practice restricted, by the claims of some theoretical patentee, whose obsolete invention never would have been heard of, but for the adaptation, in practice, of some, perhaps the only useful, portion of an invention, originally applied to some widely-different purpose." (transcript in the *Institution's Minutes of Proceedings*, Vol. XI, 1852, p. 287)

[11] See also Fairbairn (*BPP* 1851, p. 173 and p. 178).

Scott Russell was not alone.[12] The steamship machinery engineers Maudslay and Field were known to be quite hostile toward patents but they too took out some, as did John Penn and others (*BPP* 1851, p. 36). Why did some of the leading steamship innovators take out patents? One possible explanation is supplied by MacLeod (1988, p. 145): there were, of course, dangers of being blocked if one dared to ignore the patent system. Fairbairn seems to offer an explanation for this seemingly contradictory behaviour. He, in fact, did not describe his motivation to produce innovations in mechanical engineering in terms of a desire for the "exclusive possession of them". He stated instead that his key motives to invent were the "estimation of our fellow-men", the "inward satisfaction of obtaining a result", and the stimulus of doing something "advantageous to the public" (*BPP* 1851, p. 172). Fairbain stressed that two main forces were in operation in the process of introducing advances in technology: "one is, that you will ultimately benefit by the invention: another is, that you will rise in the opinion of society as an inventor". (*BPP* 1851, p. 172) As patentee himself, Fairbairn goes on to provide a subtle rationale for his attitude toward patents:

> "I am of opinion that the patent laws are of no great value, because I have five or six patents myself, and it is not any great advantage which I receive from the patent, as a patent; but it gives me precedence over all other parties who are not inventors of the same article, whereby, as a matter of trade, customers would come to me, in the first instance, for the machine I have invented, rather than go to the copyist." (*BPP* 1851, p. 172)

And he added:

> "I stand out as the author of that machine, even without a patent; and the impression upon the public mind is that, as an inventor, I know more about that machine, and can work out the details and make it better than any one else." (*BPP* 1851, p. 172)[13]

[12] Other engineers who had a prominent role in advancing steam navigation also pledged their aversion to patents, but apparently not to owning them (a pointed observation made by Dutton 1984, p. 29).

[13] These views are in line with another observation by MacLeod (1988, p. 155): "The value of a patent lay in kudos and, potentially, in the collection of royalties (...)." In other words, there was a perceived competitive edge in fame and reputation.

Hence, it seems that at least a considerable part of patentees were moved by "false hopes" of realising material benefits, and that their ventures mostly ended in financial losses, but not before becoming obstacles to those engaged in the actual design and building of working artefacts. This was certainly Brunel's view. Thus, litigation may have been a goal in itself for several patentees in marine technologies as in other fields. Among able engineers, patents emerged both as a defence against such threats but also as a publicity tool. Information and reputation were important in the market for talent and technology. In this context, patents became a communication device (i.e. a signal of capability and a public claim to priority) that could have a role, not for appropriating the returns of existing ideas but in securing future business.[14] We may glean from Fairbairn that a patent's best use is not so much as a patent as such but rather as a trademark. This is precisely the instrumental value that Scott Russell attached to patents and the one he expected to be eroded by the new 1852 patent law. Now, if skills and marketing were probably the must-used means to appropriate the fruits of knowledge and innovation, what was the steam navigation community's attitude towards the reform of formal intellectual property rights?

6.8 The climate of opinion just before the 1852 reform

The patent system in Britain had been under recurrent criticism from many directions for many years. There were numerous inventors, entrepreneurs and other interested parties for whom its high cost and complex granting process were the main problems. For others, of a free trade persuasion, the monopolies and privileges conferred by patents constituted obstacles standing in the way of further technological developments. Increased agitation concerning the overhaul of the prevailing law and practices culminated with the Crystal Palace Exhibition and led to the appointment of a

[14] This interpretation is broadly consistent with that of Kingston (2010, p. 49), in which the returns to innovation were mostly appropriated through tacit knowledge incorporated in technological capabilities rather than through a legal system providing "full" property rights in 19th century Britain.

parliamentary Select Committee in 1851. The outcome of this inquiry was the Patent Law Amendment Act of 1852. In the Hearings that followed thirty-three individuals gave evidence between 15 April and 15 June 1851. The whole report comprised 419 pages. Among the witnesses a number of professions and occupations can be identified: engineers (8), businessmen (6), barristers and solicitors (4), patent agents (4), representatives of inventors' associations (2), professors (2), and former or current civil servants and officials (4). A foreign perspective was also brought in, thanks to three witnesses coming from France, Prussia, and Switzerland. The individuals summoned to these Hearings were asked a total of 2881 questions.

The House of Lords Committee wanted views concerning an array of aspects. Paramount among these were the arguments for having patent laws, whether they provided the correct inducements for inventors and for investment, how the British system compared to others (in particular, the American one), and what could be done to reform it. The great majority of the witnesses complained about the dysfunctional patent system and called for its modernisation. But opinions varied considerably about the perceived problems having to do with the operation of the system and the nature of reform. Unsurprisingly, patent lawyers were among the least unsatisfied with the *status quo*. And among those presenting themselves as representing the voice of inventors, the dominant argument was for cheaper, faster and less bureaucratic processes of patent granting. The other represented vocations, however, offer a mixed picture and showed there was much more variance of opinion. These ranged from the radical extremes of suppression of fees to patents granted automatically to the abolishment of the patent laws altogether, with a number of other pragmatic arrangements in between.

As MacLeod (2007, p. 250) remarks, eight[15] out of the 33 witnesses advocated abolition altogether; among these were prominent public figures like I.K. Brunel and William Cubitt[16], President of the Institution of Civil Engineers, both leading engineers and organisers of the Great Exhibition. Among the witnesses were some influential names in the history of steamship development. While not opposing a shake-up of the system, someone like William Fairbairn was rather dismissive of the role of patents in promoting invention.[17] There was also the case of Bennet Woodcroft, a fervent patent law moderniser (not an abolitionist) but one who stressed a particular angle. It is worth noting that while Woodcroft did not oppose the existence of the patent system, he agreed it represented one of the greatest obstacles to the process of invention: “that you are always afraid of touching upon something which has already been invented” (*BPP* 1851, p. 229). He insisted on a reformed patent system geared toward the increase of information on the state of the art in order to avoid litigation and unproductive duplication of inventive efforts.[18] Details on previous or existing patents were still not published or indexed and, hence, were almost unsearchable. The appeal for greater transparency and information diffusion clearly had wide resonance, being also endorsed in the testimonies of Fairbairn and Cubitt.

[15] MacLeod (2007, p. 250) undoubtedly includes here John Lewis Ricardo, the nephew of the classical political economist David Ricardo, Chairman of the Electric Telegraph Company, and an MP who had had a voice in the process leading to the repeal of the Navigation Acts. Ricardo was not listed as a witness but his answers were recorded in the first appendix to the report of the hearings.

[16] Asked whether patents were not just compensation for the great expense someone like James Watt incurred to develop his steam engine, Cubitt’s single sentence answer was telling by its dryness: “It cost him a great deal to defend his inventions in the courts of law, as I have heard him say.” (*BPP* 1851, p. 215) At a more macro level Cubitt’s position reiterated the theme of free-trade at a time when Britain had no equal in international competition. He believed that there was no need for patents if their objective was to promote the country’s industrial prominence.

[17] William Fairbairn, when questioned about whether he himself would invent less in the absence of patents, answered by saying he did not know, but said he “did not attach much value to the patent laws” (*BPP* 1851, p. 172 and p. 180).

[18] In his testimony, Bennet Woodcroft said he had first come to realize the problems of the situation when, after having paid for his first patent of 1826. He came across “a considerable number of patents that had been previously granted for the same invention.” (*BPP* 1851, p. 224) A few years later, Thomas Webster, a prominent lawyer who had been the first witness to supply evidence to the 1851 Select Committee, observed that a “community of information” was still very much absent in regard to what was being protected, thus harming the efforts to separate proper from trifling patents (Palombi 2009, p. 22).

Does steam navigation technology explicitly surface in the hearings? The answer is yes, and always in connection to pathologies of the patent system. The Select Committee wanted also to hear cases showing the existence of problems with the existing situation. It is to be noted that the first case of litigation to be offered by a witness, as an example of a problem in the system, was one that opposed the innovative steamship builder Seaward against a lesser known inventor, resulting in an impeached patent for steam-driven paddle-wheels (*BPP* 1851, p. 7). Furthermore, the screw-propeller is mentioned several times during the hearings: as an example of an invention with many inventors (*BPP* 1851, pp. 15-6); as the widest known case in terms of waste of individuals' resources with patenting (*BPP* 1851, p. 216); and as an example of the way that the Admiralty did not want to pay for patent rights (*BPP* 1851, p. 352). In a word, schemes for steam-propulsion appear in the hearings and seem to stand out as known examples of some of the worst evils the critics ascribed to the patent system.

Brunel was again particularly forceful in backing his views with concrete cases taken from his first-hand experience. He though that overall patents were "productive of almost unmixed evil with respect to every party concerned with them"; they did not benefit the inventor, the prospective client or the public (*BPP* 1851, p. 246). As for the inventors themselves, "the class of men at present called schemers", he believed them to be "a pest to society" (*BPP* 1851, p. 248). Overall, he found that "they rarely have ideas themselves, but they include so many other ideas in their patents, that you cannot move without dealing with them for the use of their patents." (*BPP* 1852, p. 251) He called these "rambling patents", patents that cover at the same time a variety of similar things. This was the situation of Britain at the time as he saw it, but his distaste for patents had an old origin and it illuminates another of his arguments. One particular case he mentioned during his examination was later emphasised and amplified by his first biographer, his son Isambard Brunel (1870, p. 490). It happened early on in his career when I.K. Brunel was working under his father, Mark Brunel, who took out patents for many of his inventions. It was concerned with the carbonic-gas engine, but for the sake of securing a patent its development was carried out in secret. For I.K. Brunel, this prevented them from receiving the advice that would have saved them all the time and money that they sank into an enterprise that eventually proved to be an utter failure.[19]

Brunel was not alone. The chairman of the Committee, Lord Granville, largely adopted the position personified by the great engineer. Against the bulk of the views encapsulated in the final report, Granville would declare: "the whole system is unadvisable to the public, disadvantageous to inventors, and wrong in principle." (cited in MacLeod 2007, p. 250) This strong anti-patent perspective, in its rejection of a specific type of protectionism and restriction, resonated with what could be described as a general mood favouring "free trade" (Palombi 2009, pp. 16-7; Kingston 2010, p.50). *The Economist*, with its "uniquely distilled versions of *laissez-faire*", was a most ardent player during the abolitionist movement that existed in the 1850s and 1860s (Dutton 1984, p. 29). In 1851, the following could be read in its pages:

> "[The patent system] inflames cupidity, excites fraud, stimulates men to run after schemes … begets disputes and quarrels betwixt inventors, provokes endless lawsuits [and] makes men ruin themselves for the sake of getting the privilege of a patent, which merely fosters a delusion of greediness." (cited in Dutton 1984, p. 25)

In spite of this, in 1852, Parliament would indeed remove most of the perceived difficulties to increased patenting. The up-front cost of obtaining a patent dropped to one quarter and the number of patents jumped from several hundred to several thousand per year (Khan, 2008). A side-effect was that the previously main form of dissent (appeals for reform arguing the case for cheaper patents) would switch to a stronger rejection of the patent system in the 1850s and 1860s based on other kinds of arguments

[19] The mature Brunel usually counted on access to a variety of external sources to arrive at his own conclusions. For instance, he carefully examined Robert Napier's *Persia* and carried on with new ideas for the *Great Eastern* (Caldwell 1976, p. 153; see also Chapters 3, Section 3.3, and 7, Section 7.2).

(Kingston 2010, p. 50). In another wide-ranging parliamentary inquiry, conducted between 1862 and 1864 to assess the reforms introduced by the 1852 legislation, a general tone of criticism prevailed (see Palombi 2009, pp. 16-26). The final report referred to problems linked to excess litigation of speculative intent (and its consequent costs) and the proliferation of patents (many of which were useless and trivial in nature), reaching such an extent that patent monopolies were seen as obstructing "instead of aiding, the progress and improvement of arts and manufactures" (*BPP* 1865, p. v). As a consequence of continuous dissatisfaction, the abolition movement would be kept going until the 1880s (MacLeod 2007, p. 250). The controversy was not exclusive to Britain, and raged throughout Europe (see Machlup and Penrose, 1950). However, with the onslaught of the so-called "Great Depression" beginning in 1873, and the heightened international rivalry and protectionism that followed, the abolition movement dwindled (Dutton 1984, p. 29; Coulter 1991, pp. 160-1 and p. 199).

The steam navigation community remained largely outside these debates after the 1852 reform, probably because players were busy innovating anyway and the industry as whole did not need any artificial inducements to remain competitive. A further piece of evidence of the apparent lack of interest on patents by those engineers actually involved in steamship building can be obtained from a petition to Parliament calling for extended time for sealing patents and/or filling specifications under the new patent law: of the 63 petitioners between August 1853 and May 1855, not a single one declared himself to be involved in marine engineering, naval architecture or shipbuilding, while 16 of them were patent agents (*BPP*, 1854-55).

Hence, we can perhaps conclude with some degree of safety that marine engineers and naval architects did not think much of patented inventions, nor did they believe that patents were either necessary or even a beneficial inducement to invention in their field of expertise. Patentees tended to be represented as "parasites" of true innovation taking place in the context of ongoing real-world projects and works. In such a situation, many individuals reportedly arriving at several variations of the same basic idea so that it would be difficult to ascribe a single authorship for a given robust answer to a particular technical challenge. Moreover, true innovators counted on each others' free advice.

6.9 Marine technology litigation and the role of the Royal Navy

Both contemporary participants (e.g. Boyman 1840, p. 137; Palmer 1864, p. 287) and subsequent historians (e.g. Hobsbawm 1975, p. 58; Smith 1938, p. 95; and Ferreiro 2007, p. 26 and p. 305) have acknowledged that the Royal Navy did not play a leading role in the transition of sail to steam. Notwithstanding, and given the huge size and influence of this institution (it traditionally absorbed the largest share of government spending), the Navy's relation with the private sector remains an interesting aspect of the story (MacCleod *et al*. 2000, p. 308). The Navy, indeed, played an important part in smoothing the transition from the wood-paddle to the modern iron-screw configuration. The main support of the Navy for technical change was arguably in clearing the ground from patent litigation involving the screw-propeller.

The 1840s had been a decade of grievance and dispute among screw-propeller patentees, as alluded to during the 1851 patent hearings (see Chapter 3, Section 3.3). The Screw Propeller Company, the organisational vehicle created by Petit Smith to promote his intellectual property with the Navy, was unable to conduct any proper business. As its financial position deteriorated, the Company was reduced to litigate against other inventors and entrepreneurs. For instance, a lawsuit was directed against Woodcroft, who had applied for an extension after his 1832 increasing pitch patent, a patent which expired in 1846 without making any profit (Woodcroft 1848, p. 114). The court frustrated this opposition and Woodcroft was allowed to continue with his patent. In December 1844, James Lowe (1796-1866) went to court, this time, against John Penn for infringing a curved blade design he had protected in March 1838 (Boase, 2004a). The verdict was in his favour but Lowe, too, never received any significant remuneration for his patented inventions; on the contrary, the pursuit of his schemes eventually exhausted his fortune. When Smith succeeded in extending his patent in 1850, the Navy decided it was time to end the inconveniences and ambiguities once and for all.

Not interested in becoming caught up in a web of litigation, the Admiralty moved toward the wholesale acquisition of the property on screw technology. In 1852 the Board of the Admiralty secured £20,000 from Parliament and offered it as a final settlement and reward on account of all patents and claims to royalties on the screw propeller used in the Navy's ships. This lump-sum payment represented a mere 40% of all the losses incurred by the Ship Propeller Company alone, so it was scant consolation, but in fear of recovering no money at all, this action forced the interested patentees to act together (Lambert 1993, p. 145). Henry Currie, an MP between 1847 and 1852 and one of the original investors in the Company, applied for the money while representing the screw propeller promoters as their lawyer. In the end, the grant (termed "remunerative compensation") was divided equally between Smith, Woodcroft and Lowe.[20] No complaints regarding the misapplication of the sum by members of the community of marine engineers and naval architects have been noted by the extant literature.[21]

How should we assess the influence of the Navy at this critical juncture in the transition to the modern steamer? Generally speaking it shared with other players of this period "a marked resistance to the idea of paying for the use of intellectual property." (Lambert

[20] The Ship Propeller Company, which had been organised around Smith's patent, ultimately failed to take over the British (naval) market. As for Smith himself, he returned to farming, falling into straitened circumstances in 1860 but fortunate to secure an appointment at the Patent Office museum (now the Science Museum), thanks to the person he had tried to sue, Bennet Woodcroft (cf. Tyler 1939, p. 121).

[21] Grievances were nonetheless voiced by others. One example (not referred to in the literature as far as our review allowed us to detect and further attempts made to find secondary sources documenting it) was a claim to be included in the grant by a Royal Navy captain called E.J. Carpenter, the inventor of a "propelling apparatus" patented in 1840, who wrote a letter to an M.P. giving testimony of the "private injury" he felt (c.f. Carpenter, 1855).

1993, p. 145) It effectively closed the patent issue, which might have otherwise delayed the widespread diffusion of the screw propulsion approach over future years. Neither the Royal Navy nor the shipbuilding industry would thereafter be tangled up in patent disputes on propellers restricting their adoption choices.[22] The fact that the screw had structural interactions with other steamship technologies (i.e. its introduction had "architectural" implications since its efficiency could only be exploited in combination with iron hulls and fast engines) means it could have represented a bottleneck and an impediment in the transition to the modern steamship design. True, the Navy did not seek to develop and was not anxious to introduce radically new technologies in the field of steam propulsion (Lambert, 1993; MacLeod *et al*., 2000). Its role in the rise of the modern steamer was, indeed, not so much a direct as an indirect one. But it was a rather instrumental and crucial one: avoiding gridlock and enforcing "open innovation" [23]. The Royal Navy, that most peculiar institution of the "British innovation system", had a uniquely influential role in making the screw propeller an unobstructed option at a time when it was becoming an increasingly compelling solution for designers and shipbuilders.

6.10 Examining patenting statistics in steam navigation technologies

Patents as the oldest of the new indicators of innovation and technical change

Bennet Woodcroft (1803-1879) is a remarkable figure in what is a rather peculiar cast of characters in the history of steamship innovation. He stands out both as a player in his own right (a screw-propeller inventor, and an active participant in the patent debate) and

[22] After this episode the Navy continued to be critical of the patent system and followed a policy aimed at minimizing expenses and dependency on patented inventions. For instance, in the 1860s the Admiralty complained that in any attempt to combine iron and wood in its ships the Navy would be "stopped at every turn" by the holder of a composite construction patent (Palomi 2009, pp. 23-4). In any case composite construction would turn to be a just a transitory solution, confined to small vessels after 1870 (Hope 1990, p. 310).

[23] Heller (2008) uses the term "gridlock economy" to describe a situation in which too much intellectual property and fragmented ownership stop innovation and increase transaction costs to the point of market failure. The term "open innovation" was introduced by Chesborough (2003) to broadly denote situations in which innovation is not exclusively dependent on the direct appropriation of revenues through patents.

as one of the first chroniclers of this particular branch of industrial technology.[24] Woodcroft was actually the person most frequently referred to in the testimonies of all the other 1851 Committee witnesses, this being in connection to having spent several years compiling the only reliable and complete list of patents in existence (*BPP* 1851, p. 95, p. 187, p. 204 and p. 315). As it happened Woodcroft became the leading figure of the reformed Patent Office after the law of 1852. He is well known among technology and economic historians for having published in 1854 a compilation in three volumes of all patents granted in England from 1617 onwards (Kingston 2010, p. 44; for a recent re-examination of the potential of Woodcroft's work see Nuvolari and Tartari, 2011).

What is less known, however, is that in 1848 Woodcroft published one of the first histories of an emergent technical field of the day, *A Sketch of the Origin of Steam Navigation*. In his *Sketch*, Woodcroft traced the development of the application of steam engines to water transport and gave particular attention to the mechanical devices that communicate motion to the water, the paddle and the screw. Here Woodcroft first demonstrated in public his skills as a compiler of historical technical information that were to make him eminent over the next decade. The appendix of his pioneering book contains a list of inventions and patents – "Nearly all of which are for Propelling Vessels, and other Documents relating to Propelling". The list starts in January 1618 and ends on July 11th, 1847, with 558 entries running through 17 pages. By tracing the development of steam navigation using many sources, but mostly with the help of patents as a major yardstick, this work may be regarded as a pioneering methodological contribution to the research field known today as innovation studies (see Box 6.1).

[24] Woodcroft inherited a large family fortune derived from silk manufacturing and trading, which was subsequently dissipated in railway speculation (McConnell, 2004c). While at Manchester, he sought to educate himself in engineering, and up to 1840 produced several patented inventions in the field of textile machinery. He then worked as a consulting engineer and became a patent agent. He started to move in several intellectual circles, eventually including the Society of Arts, and by the mid-1840s he had developed friendships with several leading engineers, among them Fairbairn, Whitworth, and Nasmyth (McConnell, 2004c; Pole 1870, p. 156). By 1847 he was in London serving as professor of machinery at University College, London. During this period Woodcroft amassed a great deal of knowledge regarding the patent system and was called as a witness to the 1851 patent law hearings.

Box 6.1 The first recorded use of patents as indicators of technological events and developments

In face of this evidence one could perhaps claim that Woodcroft (1848) and the subsequent papers by MacGregor (1856) and Barnaby (1860) are probably the first known contributions to systematically employ patents as an indicator of invention and innovation.

It is surprising that this pioneering work is not signalled by the literature on technology indicators. As Benoît Godin (2005, p. 123) has noted, patents were apparently the first indicator to receive attention for the purpose of science and technology measurement: analytical work using patent statistics appeared in academic economic journals in 1930s and 1940s.

It thus seems proper to push back the date of the earliest use of patents as a source of technical information to the 1840s and 1850s and link it to efforts to understand the evolution of steam navigation.

This recognition even made it to the official record of the time. A patent agent acting as a witness in patent law hearings (*BPP* 1851, p. 157) revealed how a subtle understanding of patents as technological indicators was already available by then:

> "Do you consider the number of inventions and the number of patents to be all synonymous terms?
>
> I do not; but still the number of patents is the only criterion we can have of the amount of available invention.
>
> (...)
>
> With regard to the statistics which you have now given, do they furnish any evidence as to the proportionate amount of invention in each country?
>
> Yes."

The remainder of this chapter draws upon Woodcroft's chronological enumeration of schemes and inventions as the raw material for understanding the usage of patents in the realm of steam navigation technology.[25] The perils of using patents as an indicator of technical change in the 20th and 21st century are well known and too numerous to be formally reviewed here (see Grilliches, 1990; Patel and Pavitt, 1995; Smith, 2004; Grupp, 2007; Nagoaka *et al*., 2010). Patents are, at best, a very imperfect indicator of technological breakthroughs and cannot be taken at face value for the measurement of innovative dynamics. Patent data may, indeed, lead to unsound inferences, especially

[25] Woodcroft's (1848) record certainly has some shortcomings. Some patents are missing, for instance, Manby's for an oscillating marine engine in 1821 and a marine boiler patented by Henry Maudslay in 1824. Hence, a thorough analysis should instead use Woodcroft's later corrected and amended general indexes. The *Sketch* list, however, undoubtedly covers the vast majority of patents taken out in England during the period and serves as a benchmark of what technologies were known by the best informed of experts and interested parties in this field at the time.

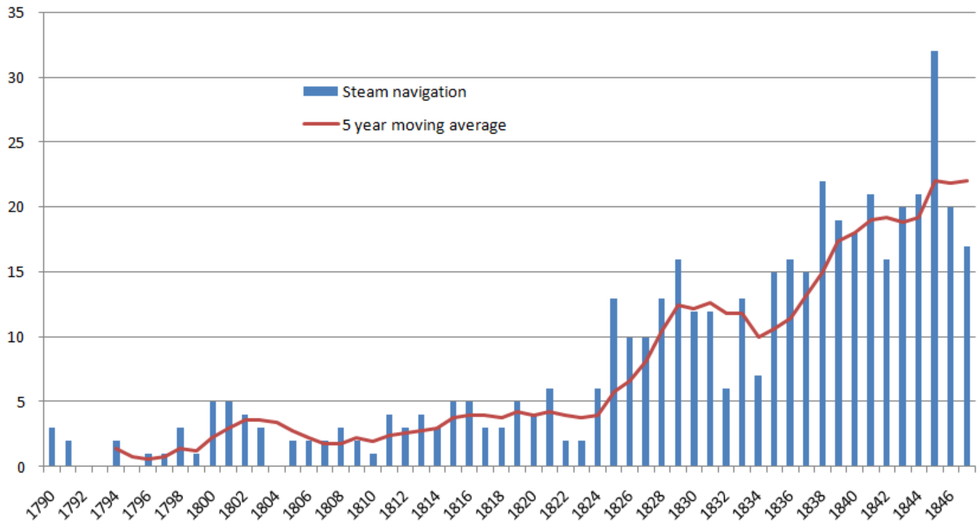
when it comes to historical analysis (cf. Pollard 1989, p. 135). von Tunzelmann (1985, p. 308) has summarised the promises and pitfalls of the use of patents in the period we are concerned with: “they evidently underestimate quantity (large numbers of inventions for one reason or another going unpatented) and are uneven in quality (giving the same weight to the heroic and the trivial).” There are substantial differences between patenting levels among different technologies because not all are suited to patenting in the same way, i.e. given the same level of invention there are different propensities to patent depending on how technologies lend themselves to formal protection (Scherer, 1983).

As a unique source, however, patent data “should not be abandoned because they are imperfect.” (Dutton 1984, p. 7) For the purposes of historical research, in particular, this sort of relatively systematic data may reflect salient features of the invention process and the industrialisation phenomenon (Inkster, 2003). Inferences, of course, can only be made carefully. But “with appropriate historical sensitivity,” adds MacLeod (1988, p. 2), “they can illuminate a range of economic and social developments.” Although a somewhat “noisy” indicator for covering the Industrial Revolution, there is no other quantitative source for gauging innovative activity as comprehensively as patents, especially where capital goods are concerned (Bruland and Mowery 2004, p. 352).

Steam navigation patents in a time of radical change

Patents are clearly linked to the history to steam navigation, though in ways we need to carefully understand. Up until 1800, only 65 steamer-related patents were taken out in the English patent system. We will start our analysis in the last decade of the 18th century as mechanised water transportation starts to witness its first experimental trials. Figure 6.1 plots the total number of patents sealed up to the middle of the 19th century. There appears to be a relative rise from the mid-1820s, although with yearly fluctuations becoming more pronounced.

Figure 6.1 Annual totals of sealed steam navigation patents, 1790-1848



Source: elaborations on Woodcroft (1848, pp. 122-39)

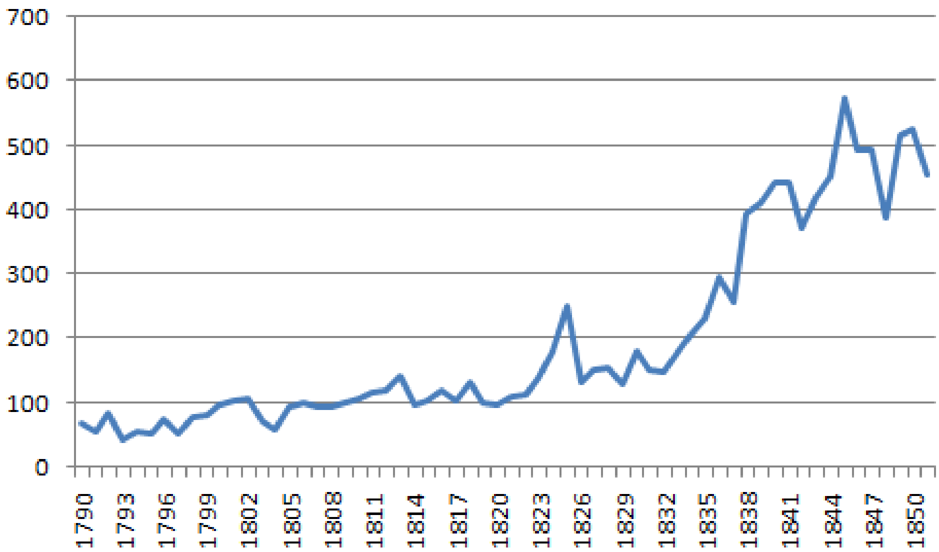
The graph prompts a number of comments. The year 1804 is the last for which there were no patents granted. Patenting in steam navigation technologies balloons in the mid-1820s, and picks up again on an upward trend in the mid-1830s. The average number of patents per decade steadily increases from 3.6 in the 1810s, to 4.6, 5.5 and 6.9 for the (incomplete) 1840s. The 1840s recorded the highest level of patents and this was probably due to the fact that the screw-propeller was the "prestige invention" of the decade (Hewish 1980, p. 11). Woodcroft himself felt sufficiently encouraged to have obtained a patent in 1844 and to have sought an extension of the term of his 1832 patent in 1846 (which was granted for a further six years). There are possible reasons, however, why the remarkable year of 1846 represented the peak of activity: the Royal Navy had been offering its steam warship *Rattler* as a platform for screw trials in the preceding years and inventors may have expected a new series of trials – which did not come (see Lambert, 1999b). If one removes that single year as an outlier, the number of patents did not grow after 1838, the yearly patenting total fluctuating around 21. Indeed, our estimate for the entire year 1848 is 14 patents in total, down from 17 in 1847.[26] By

[26] More patents in general were granted in the first half of the year compared to the second. In steam navigation 56.6% of the patents since 1840 were sealed until the end of the month of June, with only one year having been otherwise (in 1842 six patents were obtained in the first semester and ten in the second).

then, it was common knowledge that the *Archimedes* had been lying idle for a long time in the East India Dock, advertised for sale, the whole venture having represented a loss of £5,000 to its promoters (Woodcroft 1848, p. 104). One reading is that the entire decade was even less robust in terms of marine patenting than it might appear if we compare it the broader patenting trends in England. Moreover, in a climate of great technological effervescence between the launch of the *Great Western* and the *Great Britain*, with ocean-going and iron-screw experiments taking place in steam navigation, marine patents covering the modern steamer showed no particular response.

The pattern for steam navigation patenting is nonetheless one of overall growth for the whole period, and in this it seems to follow that of the overall total of English patents. Figure 6.2 shows the total patent enrolments for the same period (Khan, 2008). The large increase in aggregate patenting in England quite clearly occurred after 1835.

Figure 6.2 Total English patents, 1790-1852

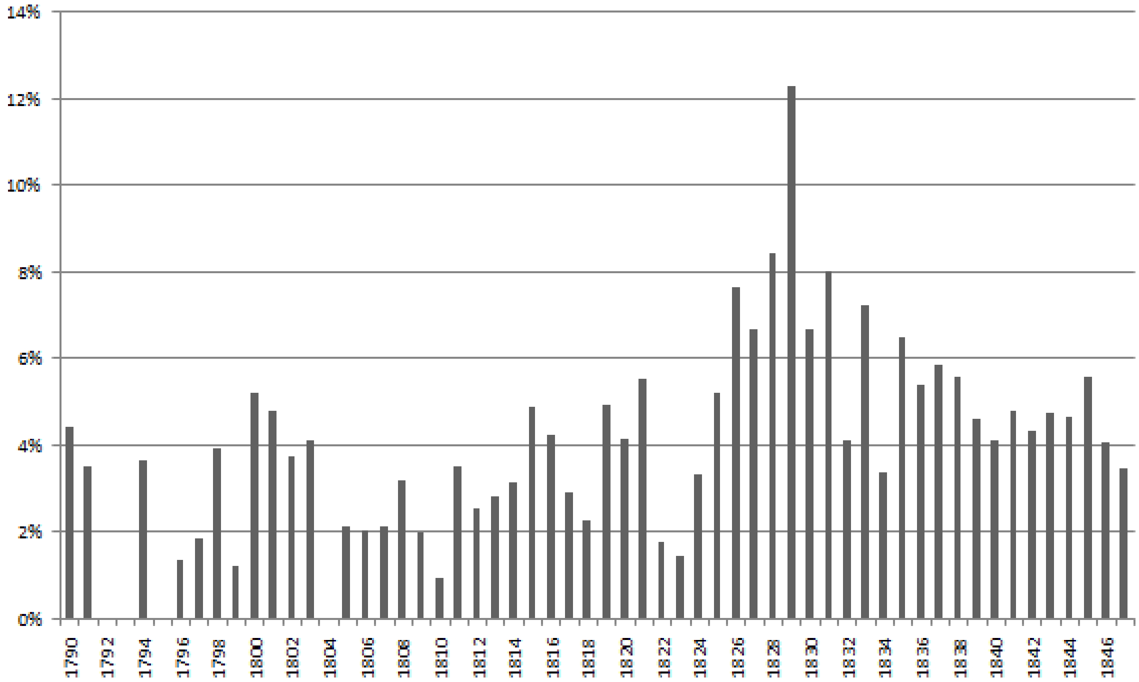


Source: elaborations on Khan (2008)

In this context the picture becomes more clear if we plot the relative weight of steam navigation in the total patenting for the comparable years (Figure 6.3).

Assuming 1848 would be a typical year the majority of the patents had already been assigned (probably not more than eight and not more than six would be forthcoming until the end of the year).

Figure 6.3 Steam navigation patents as a proportion of total patents, 1790-1848



Source: elaborations on Woodcroft (1848, pp. 122-39) and Khan (2008)
Note: the peak in the late 1820s is caused by the coincidence of an up-tick in marine patents and a weak evolution in general patenting in England

We find that after 1830 the share of patents in steam navigation cease to show any growth; in fact, its share steadily declines until the end of the series. This is important. The 1840s were the so-called "hungry forties" and, since the patent indicator is well known to be sensitive to the business cycle (see Grilliches, 1990), one might have expected patenting to have been relatively stronger in the marine sector. This is because the 1840s were not exactly slow for steam shipping. Short sea traffic as well as inland traffic was growing robustly for steamers, and mail-subsidised longer distant trade, including over the Atlantic, was just starting. There were swings in steamship construction but the general trend was upwards, accelerating markedly in the second half of the decade (Slaven 1980, p. 114; Hughes and Reiter 1958, p. 363). As Chapters 4 and 5 showed, the number of working steamers, as well as the total tonnage, had been steadily growing year after year since the debut of steam navigation. Demand for steam navigation technology, it follows, was also on the rise. Likewise steamship performance, as measured by the very rough proxy of average steamship size, was showing its first signs of progress since the early 1830s (as discussed in Chapters 3, 4, and 5). This was, of course, before its decisive and definitive take-off, which we have dated as having occurred around 1850, that is, before the patent law reform. The 1830s and 1840s were intensive with regard to experimentation, learning and accelerating technical change. In particular, the major technological transitions in steamship technology that pushed steam navigation from inland and short-distance services to transoceanic longer-haul routes took place during this time. This feverish agitation does not seem to surface in the patent data.

By the early 1850s, apparently coinciding with the Patent Amendment Act but not triggered by it, the modern steamer had all the characteristics in place that would allow spectacularly cumulative growth and improvement: efficient and reliable engines, screw-propellers and iron hulls. If patents had been an overwhelmingly important part of this process, either by providing incentives to invention or other less orthodox motives (such as defensive or publicity motivations), would not this be evident in the statistics?

If anything, the data show that the importance of patents in steam navigation decreases relative to overall patenting levels. Hence, steam navigation patents do not soar in the years leading up to the introduction of the major innovations in steam navigation and it does not appear that skilled players were exploring the new set of unfolding opportunities by capitalising on their ideas through patents. Instead, it appears that the ratio of patenting to invention actually decreased as the rate of invention increased. Moreover, the structure of the steamship was changing and the emphasis of problem-solving became more focused on the links between technologies than on the individual technologies themselves. It may have been the fact that the creative work of adapting different technologies to each other (say, screw shafts and iron plates) was less amenable to patenting than improvement on the components themselves. Design knowledge on how to produce working associations between technologies is a central capability in systems integration that, in this historical period at least, appears to be more effectively managed through "communal" learning mechanisms (this is in line with the historical literature on the evolution of complex engineering – see Chapter 2, Section 2.2 and 2.3, and in particular Vincenti, 2000). The hypothesis, which is explored in Chapter 7, is that the bulk of creative work required a system of knowledge governance other than a strictly individually-based mode of exclusive appropriation.

The origins of steam navigation patenting

Table 6.1 shows the absolute numbers of patentees classified by profession and social background. Unavoidable ambiguities of classification are involved in such a task (see Mokyr 2010, p. 199). One should note that we are bound by the description patentees themselves gave of their own occupation or status, and one should also be reminded that "it is rarely possible to know whether the named patentee was the *bona fide* inventor or merely the capital backer or purchaser of the invention" (MacLeod 1988, p. 116). That the largest proportion of British patentees usually gave no occupation or described themselves as "gentleman" or "esquire", as MacLeod *et al*. (2000, p. 327) point out, tells us nothing apart from a pretence to status, although sometimes revealing someone with engineering knowledge. These are assigned to the category "Other", which includes all sorts of individuals, from merchants to surgeons, from attorneys to farmers and silversmiths, and those not assigned any occupation. Naval officers, along with other military officers, are grouped under the category "Naval". All individuals connected to maritime trades, such as shipwrights, sail makers, rope makers, ship carvers and master mariners, (and the only ship owner found for the entire time period, Robert Smart from Bristol, with a patent in 1844) are included in the category "Shipwrights". Technical professions such as civil engineers, mechanists, and millwrights have been allocated to the "Engineers" class.

Table 6.1 Patentees by occupation, 1790-1848

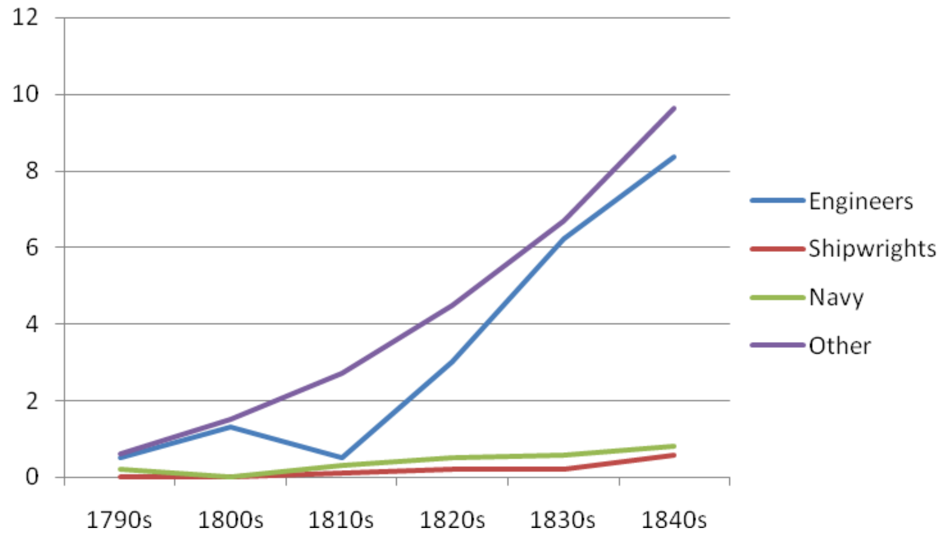
	Engineers	*Shipwrights*	*Naval*	*Other*	*Total*
1790s	5	0	2	6	13
1800s	13	0	0	15	28
1810s	5	1	3	27	36
1820s	30	2	5	45	82
1830s	62	2	6	67	137
1840s	71	5	7	82	165

Source: elaborations on Woodcroft (1848, pp. 122-39)

Inventors not connected to the shipbuilding trade or its techniques ("Others") are found to be larger than any other category in the six decades depicted here. This is the group of "outsiders" associated with the "schemers" patenting on speculation to whom Barnaby and Brunel referred to so negatively. They grew in absolute numbers, as can be seen from Figure 6.4 (decade averages are used to smooth the effect of having an incomplete final decade). The proportion of "Other" patentees did, however, consistently decline from the 1820s (75%), through the 1830s (55%) to the 1840s (49%). Navy-related and other officers constituted a residual category that grew somewhat over the period; these are perhaps individuals seeking promotion as a reward for their inventive skills (MacLeod *et al*. 2000, p. 327). A category that, interestingly enough, is remarkable for its almost complete absence is that of "Shipwrights". What could be thought of as the ultimate type of "insiders" (even relaxing the category to include users, that is, mariners and shipowners) turns out to be the smallest group of patentees. Shipbuilding was, it should be noted, a radically new technology that was branching out of the old methods of construction. Finally, we come to those individuals claiming to be in the engineering professions. Their absolute numbers grew rapidly after the decade in which steam navigation was first proven (the 1810s). Although not climbing to the dominant position engineering became expressive in the occupation distribution: 13.9% in the 1810s, 36.6% in 1820s, 45.3% in the 1830s, and 43.0% in the 1840s. This trend appears to have preceded a similar tendency among overall British patentees from the mid-1850s, a pattern that suggests inventive activity was relying more on industrial skills (Inkster

2004, pp. 194-5). In the crucial decade of the 1840s, however, the rate of growth in patenting by "Engineers" decelerated somewhat compared with that of "Others".

Figure 6.4 Number of patents by type of patentee occupation, decade averages



Source: elaborations on Woodcroft (1848, pp. 122-39)

We now turn to the issue of patentee productivity, i.e. those with more than one patent sealed over the period and cases where there is more than one name assigned to a given patent. First, we find that 130 of all 467 patents sealed, or 27.8%, originated with "repeat patentees". In other words, we find 58 inventors who on average each took out 2.7 patents over the entire period. Second, of the total of 130 patents by "multiple patentees", 59 patents were taken out in the 1840s. These 59 patents were taken out by 37 multiple patentees; the majority of the patentees belonged to the "Others" category (19 patentees, or 51.4%), but there were also 14 engineers (or 37.8%), the remainder of the multiple patentees of the 1840s comprising two Navy commanders, one lieutenant and one master mariner.[27] When more than two names are listed in a single patent, it is very difficult to know "which (if any) of them was the inventor." (MacLeod 1988, p.

[27] By far the most prolific inventor was Elijah Galloway, a self-described engineer (but perhaps better described as a prototype "quasi-professional inventor" for this arena), who took out seven patents between 1829 and 1845. His first patent, for a (feathered) paddle-wheel, was considered the only one of significant importance; it never proved remunerative to its purchasers, who tried to offer it to the Royal Navy (Woodcroft 1848, p. 105; MacLeod *et al*. 2000, p. 325).

116) Only 36 of the 467 patents from the period are of this type, being granted during the 1820s, 1830s and 1840s at a roughly constant rate.

Finally, a note should be made of the fact that, among the most prolific patentees there happen to be certain engineers known for their lasting contribution to the field of steam navigation. We refer, first, to Maudslays and Field, who taken together, obtained four patents (in 1841, 1843, 1845, and 1846), and, second, to Seawards with six patents in total (1825, 1828, 1831, 1840, 1845, 1846). These engineers were contractors to the Navy and were also prominent members of the Institution of Civil Engineers. Incidentally, the most important patent agent in Britain in the first part of the 19th century was also a member of the Institution, Moses Poole (Skempton *et al*. 2002, p. 530). Poole, who was a lawyer not an engineer, became a member of the Institution in 1827 and remained so until 1849. In 1829 he gave evidence to the Select Committee on the costs and delays of the existing patent system. We know nothing about his motivations for entering engineering circles but it would not be surprising, given Poole's prestige and presumably his powers of persuasion, that easy access to potential clients of such a technical caliber would have been one. This connection would have raised the propensity to patent among the members of the Institution. That Moses Poole himself obtained a patent in steam navigation (in 1831) suggests that business opportunities were in his mind, at least in this particular field of marine technology.

Summary of Section 6.10

In summary, patents (and patent statistics) were put to productive use by contemporary observers to draw inferences about the nature of inventions and the profile of inventors. This seems to represent a pioneering use of patents (as an indicator of new technology) that has so far passed unacknowledged in the specialized literature.

When put into perspective, the level of patenting in steamship-related technologies seems rather unimpressive during the years when the major innovations in propulsion and materials were being introduced. During the 1830s and 1840s, a period in which the iron-screw combination emerged, steam navigation patenting is decreasing in relation to overall patenting in England. The assembled evidence suggests that the great majority of innovations in this sector were not patented. It may also be the case that these improvements were difficult to patent because the scope of the solutions was just too large (encompassing the whole structural design of the ship under which different individual technologies were made to fit together) or too small (a myriad of minor adjustments based on evolving ideas to warrant a patent). Where patented ideas are concerned, these were mostly held by individuals unconnected to the steamship building business, although a few engineers became rather more active in patenting over time.

6.11 Conclusion

How important were patents in the formative development of steam navigation in Britain? This chapter has considered the patent system in its own right and examined the views and the behaviour of those centrally involved in the development of steam navigation in the first half of the 19^{th} century. It was found that patents have been the subject of comparatively little research in the field of maritime economic and technological history. Previously underutilised qualitative and quantitative evidence has thus provided ample material for our analysis. Patenting was not something ignored by marine engineers and naval architects. Indeed, the very existence of a wealth of primary material owes much to the level of self-awareness about patents that this community was showing by the first half of the 19^{th} century.

Section 6.2 reviewed the set-up of the English patent system. Section 6.3 examined several cases of patenting in the early phase of steamboat development and observed that patents were apparently more a source of expense and litigation disputes than anything else. Sections 6.4 to 6.8 showed that practicing marine engineers and naval architects connected to steam navigation offered rather bleak views on the value of patents in promoting usable invention and welfare for the public in general. We do not see steamship-related engineers pressing the case for reform and being active in the movement that led to the 1852 revision of the patent law (the exception is Woodcroft, who saw in reform a chance to unlock past technical information so as to put a stop to the misallocation of inventive capabilities). Section 6.9 showed how the Royal Navy contributed to the emergence of the screw-propeller as the mainstream propulsion technology of the future by putting an end to the ambiguities and uncertainties posed by the recurrent patent disputes of the 1840s. Section 6.10 analysed patents taken out in steam navigation and found that they offer an unreliable measure of the momentous changes occurring in this capital goods sector during the 1830s and 1840s. Practicing engineers and architects would appear to have largely rejected intellectual property as an appropriation strategy during the very years they were in the process of revolutionising ship technology. Appendix 6.1 syntheses these findings by addressing the questions set out at the beginning of this chapter.

From this analysis we may conclude that the modern steamship emerged before the reformed patent law was enacted in 1852, and its development does not seem to have relied noticeably on the protection afforded by the old law either. Obtaining patents and licensing inventions apparently never generated economic profits in British steam navigation. Practicing pioneers engaged in steamship technology generally treated the old patent law with disdain and did not see any great positive benefit from the new patent law. Patenting in steam navigation technologies does not exhibit an upsurge in advance of the transition to the modern mechanised ship. Most patenting, at least until 1848, was done by individuals who were little connected with the technical professions, shipbuilding or shipping business. Immaterial and intrinsic rewards, fame and reputation are mentioned by accomplished innovators as more important motivations for their high-quality and breakthrough work. This may have even more the case from the 1830s to the 1840s when a new dominant design or consensus configuration was emerging and finding working combinations between new individual technologies became the engineering emphasis. As far as one can judge from the written record, patents probably operated mostly as a hindrance to the most proficient as well as to the bulk of active professionals, and as an obstacle to the adoption of innovations by the Royal Navy and the mercantile marine.

Consequently, it would seem more accurate to claim that steam navigation progressed not *because of* patents but rather in *spite of* patents. Gilfillan (1935a, p. 93) was almost certainly correct when he wrote: “the patent system hardly seems justified by the history of the ship”. What this conclusion might mean for historical innovation studies and current-day innovation policy is perhaps best expressed by Baumol and Strom (2010, p. 528):

> “In short, here, as in few other parts of economics, we are driven to history for insights, despite all of the complexities of the phenomena it reports. It is true that historical analysis draws its inferences from messy examples that bear no resemblance to controlled experiments. Particularly apropos [sic] is the old Yiddish proverb, “*For example* is not a proof.” Yet, as a means to consider the validity of hypotheses, it is not as powerless as this adage might seem to imply. A series of examples may not prove convincingly that an inference is true, but we must also recognize the validity of the converse: an example (or, rather a counter example) can indeed be a disproof.”

Something beyond the individual incentives and exclusionary mechanisms afforded by patents was apparently at play. Chapter 7 attempts to understand what this might have been.

Appendix 6.1 – Patents and steam navigation: A summary of questions and tentative answers

- *On the character of patents and the profile of patentees*:

  Were there many inventions for which patents were sought?

  - Patenting in this field grew from the mid-1820s, but then tended to stagnate between 1838 and 1848 (Figure 6.1). However, steam navigation patents represented a declining share of total English patents from the early 1830s onwards (Figure 6.3). That technical change revolutionising steamships exploded during these years appears to suggest that many developments could seemingly have been patented. What seems to have been the case instead is that not many inventions and combinations of inventions were patented (Section 6.10).

  To what extent were significant improvements (radical innovations) and minor changes (incremental innovations) patented?

  - Some successful shipbuilders, like Robert Napier, claimed to avoid using any patented technologies in their ships (Section 6.5), while the Royal Navy refused to pay for any (Sections 6.8 and 6.9). One significant technology was heavily patented by many inventors (the screw) and became a well-known example of financial losses (Sections 6.8 and 6.9). Many low-quality inventions were routinely patented, and even more so after the 1852 law that lowered the cost of patenting (Section 6.5). Most importantly for the period when iron and screw-propulsion were coalescing in a new product architecture, the new innovative combinations of individual technologies may have had a low propensity or suitability to be patented (Section 6.10).

  Were patents channelled towards specific sub-fields of marine technology?

  - Many patents were linked to the area of power transmission to the water, in particular, to paddle-wheels in the 1830s and screw-propellers in the 1840s. In both cases a great proportion of them were taken out with the intention of being sold to the Royal Navy, something that the Admiralty rebuffed in both cases and spectacularly so with regard to the screw (Sections 6.9 and 6.10).

  Were there many non-improvements for which patents were sought, that is to say, were there many trivial patents?

  - Many "worthless schemes", to use John Ericsson's words, were apparently patented (Sections 6.5 and 6.6).

  Who were the patentees, i.e. were they involved in the design and production of steamships or were they individuals unconnected to the industry trying to reap benefits through other means than the actual application of their ideas to working technology?

- Many early patentees were seemingly little more than “cranks” (Sections 6.5 and 6.6). As time went by, patentees who tried to benefit by strategically blocking practitioners with threatening lawsuits become more noteworthy (Sections 6.7 and 6.8). Individuals unconnected to shipbuilding and steamship technologies were always the larger group of patentees (Section 6.10).

▪ *On the motivations to patent*:

Were improvements contingent upon the granting of a patent, i.e. would they not have taken place if it was not for patents?

- Accounts of inventors realising pecuniary rewards through patents are scarce, while many suffered heavy financial losses (Sections 6.4 and 6.7). Technological contributions to steam navigation kept being achieved in spite of this. Sharing, rather secrecy, seemed to be the most preferred alternative behaviour to patenting.

Or would these changes have taken place anyway without the inducement of the protection of patenting?

- This seems to have been the case for a number of pioneering marine engineers and naval architects (Sections 6.7 and 6.8).

Were there other inducements, besides economic incentives, that were sufficient to induce innovations?

- The desire to avoid being pre-empted and the pursuit of fame as way to secure future business seem to have been significant factors in a number of cases (Sections 6.7 and 6.8).

Did innovation come about by the piling up of small additions by many individuals and is it difficult to ascribe a specific contribution to any of them?

- Both in the cases of the overall ship design and of specific components like screw-propellers that seems to have been so (Sections 6.7, 6.8 and 6.9).

Were patents taken out not for protecting the invention itself, but rather for the purpose of building up litigation or to take advantage of the real users?

- Practitioners were convinced that excessive and strategic litigation occurred in the field of steam navigation technology (Sections 6.7 and 6.8).

▪ *On the consequences of patenting*:

Did the exclusive rights associated with patenting inhibit the free exploration of the design space?

- Prominent individual steamship innovators and the Royal Navy considered that patenting was indeed wasteful and obstructive (Sections 6.7 and 6.8).

Did patent proliferation around a large complex system like a steamship create problems for the combination of different elements arising from different sources?

- In the case of the screw-propeller (a critical new technology that had structural interdependencies with other technologies, namely the hull construction) the problem was averted by the Royal Navy forcefully bringing litigation to an end (Section 6.9).

Did patents create obstacles for the development of a cumulative process of technical change?

- Many engineers were of this opinion, and none more so than Brunel, perhaps the most influential of the age, who was known to be willing draw upon the best ideas around him and to build on them (Sections 6.7 and 6.8)

Were patents decisive for attaining industrial leadership and international competitiveness in this field?

- Patents do not seem to have played a decisive role in providing the incentive that motivated the key innovators to bring about a product that was a world first: the large ocean-going, iron-hulled, screw-driven steamer. These innovators must surely have been motivated through other means (Section 6.11).

7. Why did steamships evolve? Qualitative evidence and the rise of the "technological public sphere"

7.1 Introduction

Technical breakthroughs in steamship technology were not the product of isolated individuals. The work of improvement needed to be continuous and collective in order to be cumulative. How knowledge developed and diffused during the formative years of the steamship is the focus of the present chapter. It draws heavily on direct work with primary sources and explores connections that, so far, have apparently not been documented in the extant literature. The key finding is the essentially collaborative attitude and dense patterns of interaction prevailing among engineers. But this collective behaviour was not conducted spontaneously. A number of institutional innovations took place that coincided with the rapid maturation of reliable and efficient steamship technology. Some sort of collective learning mechanism would appear to offer the best competing hypothesis with the individual incentives described in Chapter 6. Describing what institutions emerged and explaining how they worked to produce decisive effects is the key task of this chapter and the final one of this thesis.

Section 7.2 probes the way in which the engineering communities were organised in Britain until 1860, when the modern ship had already appeared and was on its path of steady long-run growth. Section 7.3 focuses on the role played by the technical press during the critical years of the Industrial Revolution at sea. Section 7.4 addresses the nature and work of Lloyd's Register, a marine non-profit organisation specialising in cargo vessel classification. Section 7.5 pulls the various analyses together and appraises the findings. Section 7.6 summarises the conclusions to be drawn from the chapter.

7.2 Technological learning societies

Learning societies as part of the British national system of innovation

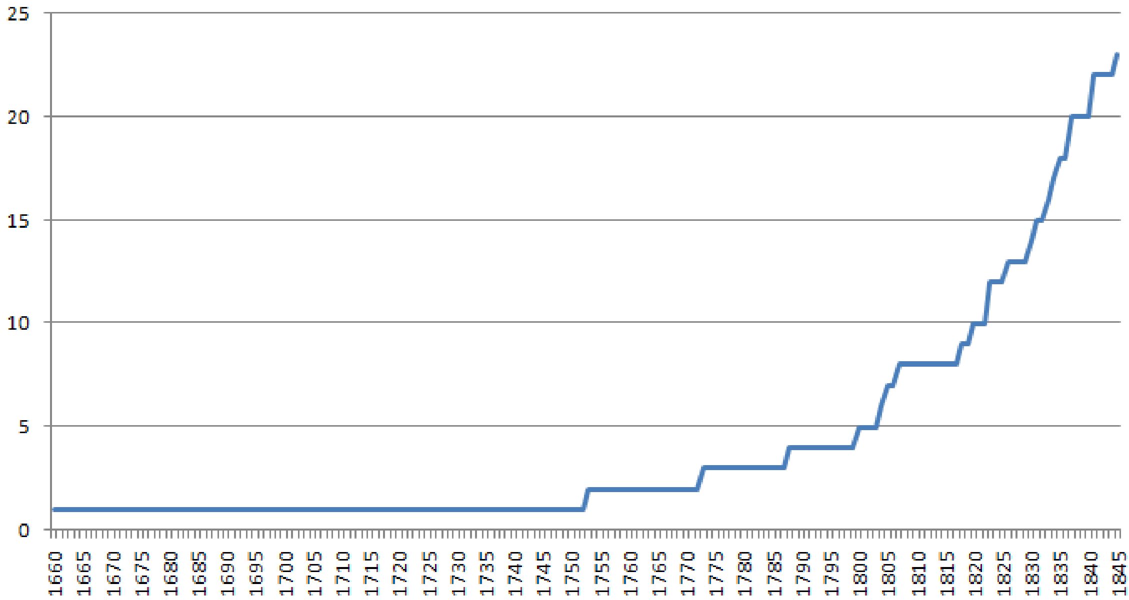
The present Section describes the evolution of the professional organisation of engineers from the particular perspective of steamship developments. It starts by laying out the intellectual context of the age and identifies certain institutional precedents of engineering bodies. It then focuses on one particular institution, informally known as the Civils, and details its connections to steamship innovation. Finally, it shows how the institutional environment supporting marine technical change became richer as time unfolded. It shows that by 1860 the fundamental institutions for encouraging the long-run growth of the sector were already in existence.

An age of civil engagement and intellectual association

There are early instances of ship research being fostered in Britain by associations of private citizens gathered together around common intellectual pursuits. But these were part of a broader movement of knowledge engagement and intellectual debate. Clubs of gentlemen philosophers, known as "learned societies", started out in the late 17th century (see Chapter 2, Box 2.1). In line with Mokyr's (2009) observation, we find that by the mid-1700s this form of intellectual association was becoming increasingly popular.

An interesting source for appreciating this manifestation of an emerging civil society can be gleaned from a book by the Reverend A. Hume (1853). Hume's work supplies a list of the founding dates of those institutions in existence in the late 1840s. Using this data, we can obtain a temporal profile of the phenomenon of associations devoted to the pursuit of knowledge. Figure 7.1 plots the accumulated number of societies that can be assigned to science and technology topics on the basis of Hume's description of their focus. The figure does not include provincial institutions. We note that the monopoly of the Royal Society, the first of such institutions in 1660, is only broken in 1753 with the arrival of the Society of Arts. This type of learned societies then starts to grow in number at a fairly modest rate, only to soar at the end of the Napoleonic war, as Hume (1853, p. 18) himself noted.

Figure 7.1 Number of continuously active British "learned societies" devoted to science and technology subjects, 1660-1845



Source: elaborations on Hume (1853)

Between 1815 and 1845 no less than 65% of the voluntary organisations founded in Britain aimed at the study and promotion of science and technology, two landmarks being the Institution of Civil Engineers of 1818 and the British Association of 1831. These learned societies became quite popular. During the 19th century their great jump in numbers happened between 1830 and 1850 (Mulhall 1892, p. 520). By 1880 those devoted to science and technology numbered 118 in Britain, with an aggregate membership of more than 44,000 (Mulhall 1892, p. 520). Describing this landscape as a "luxuriant proliferation of societies, associations, clubs, institutes and institutions", Sidney Pollard (1990, p. 189) distinguished five types with a substantial degree of overlap with one another: *i*) those focused around some general cultural interest, *ii*) special subject societies, *iii*) associations formed out of the hobbies of scientists and technologists, *iv*) groups focusing on professional certification, such as medical advisers or ship-masters, and *v*) proper scientific societies committed to advancing the knowledge frontier and to publishing reports of such achievements. This last type of society is of direct interest to our inquiry. A common goal of these associations was personal networking and the lubrication of community bonds among their members.

Early learned societies addressing marine problems

The emergence in Britain of a "knowledge civil society", as a particular expression of the Enlightenment, would develop a strong link to ship design. Curiously, this historical fact has so far not apparently been linked with the specialised historiography covering the origins and early development of the steamship.[1] Two examples of this connection nevertheless stand out: the Society of Arts and the Society for the Improvement of Naval Architecture. These two cases provide instances illustrating the way in which rational mechanics was key to unlocking the principles of hydrodynamics and to exercising control over them in 18th century Britain (see Box 7.1).

The emergence of an organised engineering community

The years leading up to the end of the 18th century were a time of accelerating industrialisation, a process that brought with it the ascendency of a new set of professions. In the interval of a generation, men such as Watt, Trevithick, Newcomen, and Maudslay raised their standing from that of "mechanics" of some ability to that of engineers central in the "hothouse atmosphere that was developing in Britain" (Corlett 1990, p. 10). Gentlemen philosophers were morphing into "gentlemen engineers", as Buchanan (1983) called them, and a new professional consciousness was emerging. A trend was forming toward the development of engineering societies organised for the discussion of technical problems arising from specific business challenges.

[1] This connection has not been explicitly acknowledged in a number of major references in maritime history, such as Corlett (1990), Greenhill (1993), and Griffiths *et al*. (1999).

Box 7.1 The Society of Arts and the Society for the Improvement of Naval Architecture

The "learned society" phenomenon has a bearing on the development of steam navigation that should be noted since it features strongly in the early history of its progress.

Nurtured in meetings at London's coffee houses, the beginnings of the Society of Arts are tied to issues of naval architecture. The Society was founded in 1753 to consider the communication of improvements in mechanics, chemistry, agriculture, manufacturing and trade. From 1758 to 1763, the Society of Arts commissioned a series of small-scale but ingenious experiments into the speed and stability of vessels (see Harley, 1991). A mechanism conceived by John Smeaton (1724-1792), the pioneering British engineer, to measure the friction and efficiency of his water wheels was employed to compare the performance of model warships (Schaffer 2004, pp. 72-3). In these trials, stopwatches were used and both smooth-water and rough-water conditions were tested. No practical effect of these experiments on naval design or mercantile ship construction has been ascertained.

More influential, although it lasted less than a decade, was the Society for the Improvement of Naval Architecture. Its foundation marked the beginning of independent investigations by private individuals on technological issues of public interest and, as Ferreiro (2007, pp. 61-2) forcefully remarked, it was "the harbinger of specialised engineering societies that would come to dominate the landscape in the 1800s." Founded in 1791 amidst fears of rampant republicanism and French ships' superiority, the society was set up with the aim of promoting experimental research and preserving exemplary ship models (Schaffer 2004, p. 88). Between 1793 and 1798 over 1,500 model runs in the East India Dock were conducted and carefully recorded by Mark Beaufoy (1764-1827), who elaborated on the methodology of Smeaton. Beaufoy's trials showed that curved hulls were more stable and that hulls could be made much longer than they were wide. Reports of his experiments were published in 1794 and his massive data collection was finally fully tabulated and published in 1834 by his son (Schaffer, 2004; Wright, 1989). The existence of a direct link between this sponsored work and the coming of steam navigation is a fact worth stressing: Beaufoy's work was given a first practical use in Fulton's 1809 estimations of the size of engines for his steamboats (Wright 1989, p. 322; Ferreiro 2007, p. 183); I.K. Brunel used his resistance calculations in 1840 while conceiving the *Great Britain* (Brunel 1870, pp. 546-7; Ferreiro 2007, p. 183); and J.S. Russell again used Beaufoy's work in the design of the *Great Eastern* (Wright 1989, p. 322; Ferreiro 2007, p. 183).

In his work on the emergence of engineering in Britain, Buchanan (1989, p. 11) describes how a group of practical men started to style themselves as "civil engineers" around the middle of the 18th century. The qualifier "civil" was primarily intended to distinguish them from military engineers. A sign of this transition was the creation of the Society of Civil Engineers (later called the "Smeatonians"), which helped to shape the character and internal processes of subsequent engineering associations. Smeaton took the initiative to launch the Society in 1771 (Buchanan 1989, p. 38 and pp. 54-5).

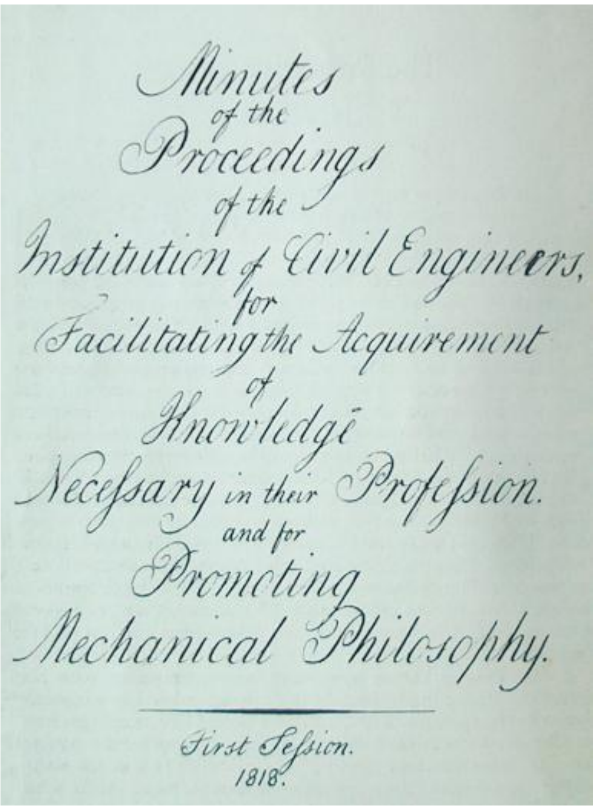
A man prominent in the first period of canal construction, John Smeaton appears to have developed quite early on a concept of the consulting engineer as a mediator between the client and the contractor, and hence someone for whom networking and communication skills were of much use. He was also respected in scientific circles, being elected a fellow of the Royal Society in 1753. According to Buchanan (1989, p. 41), this familiarity with the workings of the Royal Society was directly imprinted on the organisation of the Society of Civil Engineers. This is an important connection since here the "learned society" element can be seen to be passed on to subsequent bodies of professional engineers. The Royal Society was known for excluding artisans and skilled craftsmen (Clark 2007, p. 12). Yet its style of organising rational and informed debate penetrated engineering circles, the link being Smeaton. The practice of presenting papers was there from the beginning of the "Smeatonians", and this approach was continued by the organisation that replaced it in the early 19th century, namely the "Civils".

As the canal mania collapsed at the onset of the Napoleonic Wars, the Society was progressively to enter a dormant state. The baton was subsequently picked up by a new generation of engineers who rallied around Thomas Telford (1757-1834), the last of the great canal engineers. The event that Buchanan (1989, p. 61) calls a "intuitional innovation" was the foundation of the Institution of Civil Engineers in 1818, henceforth referred to as the ICE or the Civils, and this effectively represented the establishment of a stable organizational base for an increasingly self-conscious group of consultant engineers. The institution was founded by eight young engineers, a new breed of professionals experienced with steam power and machinery. Among them it is noteworthy to find William Thomas Maudslay and Joshua Field, the partners who would soon specialise in and set the standard for marine engineering.

The principles of the institution were laid down in the very first meeting. "Mutual instruction" was the goal. At this meeting it was stressed "the inestimable importance of some means of continued intercourse of persons studying this profession that they may have some general means of availing themselves of the observations of each other."

(*Minute Book* 1818, p. 6, see Figure 7.2) In other words, the Civils were fashioned as an "association for the diffusion and advancement of useful knowledge" (*Minute Book* 1818, p. 6). A resolution was passed outlining the method of communication in the society. It provided for the posing of questions of technical importance to which solutions would be discussed and written down in the minutes. The discussion of the merits of inventions, discoveries and publications was also expected to occur. The resolution stated, moreover, that

> "it shall be expected of every member that he at all times communicated any matter which may be of utility, either by giving direct information or by pointing out where such information is to be found." (*Minute Book* 1818, p. 10)


Minutes
of the
Proceedings
of the
Institution of Civil Engineers,
for
Facilitating the Acquirement
of
Knowledge
Neceſsary in their Profeſsion.
and for
Promoting
Mechanical Philosophy.

First Seſsion.
1818.

Figure 7.2
Cover page of the first book of minutes of the Civils, 1818

Credit: The Institution of Civil Engineers, photo by the author

A change of gear came in 1820 when Telford agreed to become President. Telford, an influential expert in Parliament, would be an active and diligent head officer attending meetings regularly, encouraging membership, inviting contributions, equipping the library of the institution with his own collection, and turning the stated principles of the Civils into a respected tradition. The year 1828 marked by the incorporation through the

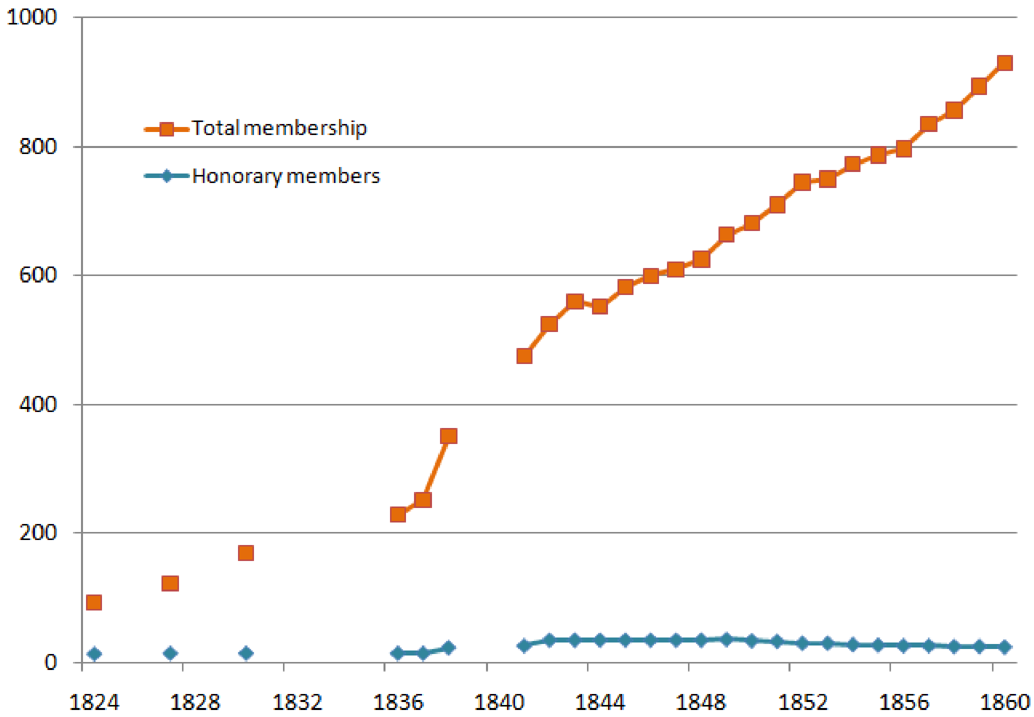
Royal Charter, a development that gave the institution public renown, a legal existence, and flagged its permanence. The following year, the Henry Maudslay and the young I.K. Brunel joined. In 1833 the session opened in more spacious premises. Here there was a library to accommodate the books, drawings, models, and other items – i.e. providing a physical space to store the organisation's "collective memory" (Watson 1988, p. 20). Telford died in 1834, leaving a mature social infrastructure to support the rapid growth and transformation of the industrial landscape.

The Civils as a technological community

Total membership grew at a healthy pace (Figure 7.3). About 44 members joined between 1818 and the end of 1820, a number that rose to 51 by the end of 1821. Membership subsequently increased rapidly, especially in the 1830s and 1840s, and by the early 1860s total membership had reached 1000, passing the 2000 mark in the early 1870s. In 1824, along with 13 Honorary members there were 80 ordinary ones, among which 38 were regular members while 42 were "corresponding members" not located in London or nearby.[2] Among corresponding members, there would have been a few overseas members, but the major observation is that from early on the Civils had a diversified geographical composition. Corresponding members received a notice before each meeting, stating what the subject under discussion would be, so that these members could then send in comments to be read at the meeting. Thus, the Civils were a dispersed community and shared an academic curiosity that gave it the semblance of an "invisible college" (see Chapter 2, Section 2.4). The Civils linkage was certainly of value for marine engineers and architects, many of whom were trained in the best London workshops and who constituted "a diaspora of trained engineers and mechanics who took their skills to provincial shipyards which were to benefit from the diffusion of their expertise." (Craig 1981, p. 346)

[2] Data for "corresponding members" exist only from 1824 to 1837, the proportion of these climbing from 54% to 66% of total membership in between these dates.

Figure 7.3 Membership of the Institution of Civil Engineers, 1824-1860



Source: ICE (undated), "Membership of the Institution of Civil Engineers from the Earliest Record, i.e., 1824", mimeo

The British engineering community evolved a pluralistic but cohesive professional structure, where all sorts of technological news and improvements were discussed. Efforts were pooled toward purposive joint-learning on practical matters, i.e. towards the deliberative collective exploitation of its members' economically useful knowledge. In brief, its strategic agenda gave it the characteristic of an "epistemic community" (Chapter 2, Section 2.4). It is also worth noting that members shared an identity; they were individuals engaged in engineering-like activities, who derived their start-up knowledge mostly by directing or assisting others' technology-based ventures. That is, they were a "community of practice" (Chapter 2, Section 2.4). Their formal association was a form of by-product that allowed them to stretch and complement their know-how. The Civils effectively worked toward the re-distribution of insights gained by its members through personal consultancy-based (or "contractor" work) experience in a variety of engineering projects. Now engineers could learn not only through their own observation and practice; they could also learn from the observations and practices of (sometimes distant) others. This development made up for some of the inadequacies of technical education at a time when the knowledge base was being radically shaken up by the fast pace of change of the industrial era. As we shall argue, the Civils, the first modern technical "learning society" and one that counted prominent steamship innovators among its founders, was a very British institutional innovation that proved particularly well-timed to support an ongoing revolution in merchant ship design.

Britain was apparently the first country in which engineers organised as a profession (Matsumoto 2006, p. 14). The Civils became the earliest of the engineering societies and the model for the later foundation of similar national, regional and international organisations (Buchanan 1989, p. 64). The American and French societies, the next two similar organisations, were founded somewhat later and in very different national systems of innovation. The British engineer was raised in a master/pupil relationship, went on to serve in projects under the patronage of a more experienced engineer, and later spent years practicing as a consulting engineer. In a few activities, and specifically in shipbuilding, builders and works' managers were well aware of the increasing importance of technological improvement and that foreign architects and workmen were often better educated (Robertson 1974b, p. 223). In this environment, active engineers came to rely on mediating institutions (the Civils and later others) to network and keep abreast of the latest developments in their trade. In France, where engineers had much more technical training, access to the profession was obtained via the formal Écoles system, from which the engineers' association known as the Société Centrale des Ingéneurs Civils developed in 1848. The French technological community was never broad-based, and remained primarily fragmented between the alumni of different schools and hierarchies of specialisation (Kranakis 1997, pp. 231-3). Unlike in France, informal skills were prized in America: in the context of a feverish economic and demographic expansion, practical experience was considered an advantage in gaining admission to the profession. The American Society of Civil Engineers was founded in 1852 with a view to being a comprehensive institution from the outset in terms of engineering trades and geographical areas (Wiseley and Fairweather 2002, pp. 6-7; see also Layton, 1971). Its main criterion for membership was prior leadership responsibilities in designing and directing engineering work. However, the Society would subsequently acquire a sort of elite status in the context of a growing number of specialised professional bodies in the second half of the century. Hence, the organised British community of technologists was more geographically integrated and had fewer barriers to entry than in the French case. Compared with the American community, the British one was more inclusive and less defined by the specificity of local challenges.

Early reflections and conversations on steam navigation at the Civils

An important early link between the Civils and the development of the steamship is Thomas Tredgold (1788-1829). Tredgold was a self-taught engineer. Elected as a member of the ICE in March 1821, he became an Honorary Member in 1824.[3] He took an active part in the life of the institution and was a prolific writer and commentator. Tredgold presented six papers between 1824 and 1828, and was also a contributor to many outlets and journals, including the *Mechanics' Magazine* (Booth 2002, p. 717). Some of his books, such as treatises on cast iron and on structural engineering, became standard textbooks in these fields (Carlyle, 2004). Although he is now best known for his definition of engineering[4], his intellectual work made him "the most influential author of his generation and possibly of the nineteenth century" (Booth 2002, p. 716).

It is notable that Tredgold, an influential engineer and well respected ICE member who moved in the very heart of the institution, developed an understanding of the technical nature and potential application of steam navigation. He was acquainted with steam vessels as he had on occasion travelled in steamers with the purpose of testing the power of engines. Tredgold (1825, p. 3) wrote in a technical piece: "surely no other art

[3] In 1828 he was approached regarding the position of Secretary; while accepting it, he never took up the post as he passed away soon afterwards.
[4] A shortened version of his definition of the engineering profession entered the ICE Charter in 1828 "Civil engineering is the art of directing the great sources of power in nature for the convenience of man." (*ICE Council Minutes*, Vol. 3, p. 20, 5 January 1828)

ever advanced with such gigantic strides in the public service." He expected the "gradual extension of the voyages of steam-vessels; and if not great improvements in them, at least systematical construction, combining the advantages which time generally adds to the perfection of a complex machine." He supported steam-driven navigation at the micro and the macro-levels, as it afforded "competent returns to the capitalist" and promoted "commercial intercourse and general welfare to the British empire" (Tredgold 1825, p. 4). Interestingly he advocated the establishment of a body of examiners to establish whether the vessels were "in a right condition for the service", thus anticipating by ten years the reconstitution of Lloyd's Register, which would play a paramount role in the modernisation of shipping (see Section 7.4). Tredgold went so far as to suggest that "a regular report of the state of all vessels examined should be forwarded to the office of a principal superintendent or director in the metropolis, as a check on the conduct of the reporting inspectors"; this task would also need "a code of instructions". In another book, on *The Steam Engine,* published in 1827, Tredgold dedicated one full chapter to steam navigation in which, amongst other things, he discussed the efficient shape of ships, their structural strength, and the relative merits of the "spiral propeller or water screw" versus those of "paddle wheels".

Evidence shows that Tredgold's interest in steam navigation was broadly shared. For the first twenty years, communications taking place within the Civils can be approached via a series of four large binders entitled *Minutes of Conversations*. These volumes provide a list of handwritten notes taken of the communications and discussions at the meetings. This has been so far a rather underappreciated source, which was quick to yield results for the purpose of the current thesis.

The earliest paper connected with marine issues was number 10 in the paper list. It was read in 1826 "On the stability of vessels" and resistance on canals by a Mr. Carlsund, a corresponding member from Sweden. There is what seems to be a detailed record of papers and debates until 1834, after which the minutes became vaguer. It is nevertheless possible to assert that up until that year in no less than 33 out of 169 sessions were marine-related topics debated. Steam navigation was just one issue among a myriad of others, including masonry, the properties of coal, measurement instruments, diving bells, bridges and street pavements, but it nonetheless accounted for nearly a fifth of all meetings, not an insignificant proportion.

Within steam navigation, the topics ranged widely, from paddlewheels to the speed of canal boats, through tug steamers and bottom sheathing. It is important to observe that between 1828 and 1832, i.e. between sessions 41 and 126, all the key dimensions that together would comprise the modern ship were studied and discussed: safe long-haul engines (marine boilers), iron as a material for vessel construction (in comparison with wood), and the Archimedean screw (curiously not for propulsion but as a spiral pump, but immediately followed in the same session by a discussion on steamboats). The Civils were very much alive to, and seeking lessons about, steamship-related technologies. Such paper reading sessions no doubt were often followed by social events during which gossip was traded, opinions shared and social ties lubricated.[5]

The first volume of the *Transactions* came out in 1836 in a volume of 325 pages, and brought together a number of memoirs that had been read in the preceding years. Two other volumes appeared in 1838 and 1842, but the series was discontinued, probably owing to its considerable cost. There were two papers published in this set on steam navigation that are instructive for the purposes of our research. The first paper, presented originally in 1833 by Joseph Farey, was an analytical attempt to predict the speed of steam vessels before they were built. The rules of thumb obtained from empirical experience with new vessels were inappropriate, he asserted, as steamers were

[5] Such occasions were used to organise dinners and to visit sites or works of common interest. A rare example where such practices were documented appeared later in the century as reported in an article entitled “Scientific and Useful. The first century of the marine engine” published a newspaper called *The Mataura Ensign* (Vol. 11, Issue 831, 7 December 1888, p. 8).

becoming too different from traditional vessels. Interestingly, in a note added when it was finally published in 1836, his text hints at a sign of cumulativeness in the study of naval architecture. Farey (1836, p. 111) inserted a comment indicating that in the meantime Beaufoy's tables had been posthumously published and they constituted a "fund of valuable information on this subject", adding that "a copy is preserved in the library of the Institution." Thus, the Civils had an exemplar Beaufoy's report of 1834, which could be accessed and was now being drawn upon. It is not impossible that this was the copy that Brunel used as the benchmark for his own calculations on the *Great Britain*.

The second paper was by Samuel Seaward (1842), the London wooden-paddler builder and developer of the Gorgon engines. He emphasised that steam, in spite of its advantages of "celerity and certainty", still had limited applications. Seaward estimated that voyages were confined to distances compatible with three weeks of continuous steaming, that is, excluding the South America and India trades. Citing a pamphlet he had written back in 1829, Seaward advocated a compromise combination of screw and sail until the weight and efficiency of the engines had been substantially improved.[6] He argued on the basis of specific cases (projects) he was aware of, discussing ships like the *Liverpool*, the *Gem*, *Vernon*, the *India* and the *Earl of Hardwicke*.[7]

In other words, as Tredgold's case also shows, there was no lack of good working knowledge of steamship technology in the 1820s. There was, additionally, an awareness of trends in design as well as of the limitations of the state of the art. Steamship technology made up a considerable part of the Civils' agenda. By the 1830s papers and debates show that the critical aspects of the "dominant design" of the future were being explored. The discussion of naval architecture and of particular vessels embodying the most recent innovations were, moreover, showing the first signs of cumulative advance.

[6] Craig (1980a, p. 9), perhaps the maritime scholar who made most use of learned society papers in the age of steam, cites Seaward's point of view as an influential one for several following decades.
[7] Most subsequent papers would follow this descriptive style, preferring examples and experimental data to mathematical analysis.

The Civils and the iron steamer – a key connection

Until 1839 the post of Secretary was simply an honorary office. In that year the Council decided that the business of the institution had developed to such an extent that it required a full-time position. The chosen individual was Charles Manby, whose surname should by now sound familiar (see Chapter 3, Section 3.3). His first responsibilities were to edit and ensure the continuous publication of the materials produced at the Civils, which became a hallmark of the society. He became known as a stern curator of the workings of the institution. Charles, the son of Aaron Manby, retired in 1856 but remained Honorary Secretary until his death in 1884. On the retirement of Charles Manby a committee was formed to honour him. In his note of thanks Manby started by saying that his relation to the Civils was much older than his appointment as Secretary. He had met the elder Rennie and Telford at the India Docks in London, and then been introduced to Maudslay, Field, and others. He was allowed to attend the meetings of the then infant institution. Then Manby makes a revelation:

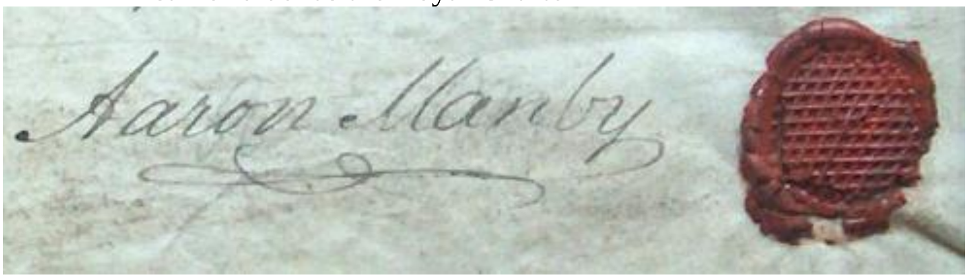
> "...and when his father entrusted to him the construction of the first pair of Marine Engines with Oscillating Cylinders, and the building of the 'Aaron Manby', the first iron steam-ship that ever made a sea voyage, it was to the Institution he resorted for advice in difficulties, and he was happy to record the expression of his gratitude for the aid so kindly and unreservedly afforded to him." (*Minutes of Proceedings*, Vol. XVI, 1856-57, p. 482).

The birth of the iron steamer, completed in late 1821, and the nascent learned society of a profession that had just acquired its authoritative president in March of 1820 are thus intimately connected.[8] This connection has not apparently been emphasised in the available literature. The importance of this link is compounded by another, rather unexpected, finding. The original Royal Charter of ICE is kept today in a folder with another document. On inspection, this document turned out to be the patent for the *Aaron Manby*'s engine (see Figure 7.4). The existence of these two rather disparate

[8] The *Aaron Manby* was not exactly an isolated case for Charles Manby. He also went on to build the machinery for the *Carolina* (1823), a paddle auxiliary vessel for the French navy and the first French steamer to cross the Atlantic (Spratt 1958, p. 116).

items in the same folder had apparently not been previously noted by ICE archivists and librarians. The co-location of these two relics is a surprising finding that is interpreted here as indicative of the closeness of the connection between the early career of the Civils and of the modern steamer. This amounts to “hard evidence” linking the ICE and the sea-going iron steamer from the outset.

Figure 7.4 Signature of Aaron Manby on the marine engine patent kept at ICE in the same folder as the Royal Charter



Credit: The Institution of Civil Engineers, photo by the author

The case can, therefore, be made that the Civils produced relevant effects almost immediately upon its foundation in the form of an impact on the origins of modern shipbuilding. It did so by becoming the site for mutual assistance that was envisioned in its constitution. In the face of complex and uncertain technical challenges, this approach mattered as it facilitated knowledge-sharing and promoted the integration of best practices coming from different specialities and provenances. Thus, the Civils were directly involved in the emergence of the sea-going iron steamer; to our knowledge, this has so far passed relatively unremarked in previous research.

Debating paradigmatic exemplars of the modern steamer

In 1837 a publication came out, the *Minutes of Proceedings,* giving an account of the internal business of the Institution. A combined version of the *Minutes* and the *Transactions* appeared in 1841. Buchanan (1989, p. 70) credits the crystallisation of the publication outline as Charles Manby’s achievement. The *Minutes* reveal a vibrant period in which the new transportation and communication technologies of railways and steamship were very much in the foreground at the Civils.

A few examples serve to convey the tenor of the ongoing conversation. In June 1839, George Rennie, who had an interest in the venture, advanced details of the *Archimedes* experimental screw steamer (*Minutes of Proceedings*, 1839, pp. 70-2). An abridged version of Seaward's paper appeared in 1841, which he supplements with an account of a case study of auxiliary steamers. In that year, the Civils used the *Minutes* to advertise a call for communications on "The comparative advantages Iron and Wood, or of both materials combined, as employed in the construction of Steam Vessels", "The sizes of Steam Vessels of all classes, whether River or Sea-going, in comparison with their Engine Power: giving the principal dimensions of the engines, and vessels, draught of water, tonnage, speed, consumption of fuel, &c.", and "The various mechanism for propelling Vessels, in actual or past use." (*Minutes of Proceedings*, Vol. IV, 1841, p. 175) In other words, the institution was setting forth the agenda of the modern steamer.

In March 4, 1845, there was a clear answer to the above call. Thomas Guppy, Brunel's associate and member of the Civils, delivered a "Description of the 'Great Britain' steam ship; with an Account of its Trial Voyages" with Sir John Rennie in the Chair (*Minutes of Proceedings*, Vol. IV, 1841, pp. 151-85). The paper supplied a wealth of data. All the main pre-existing technological trends converged in this ship, and she was thoroughly dissected in the presentation and in the subsequent discussion. This was a momentous occasion, as this ship embodied powerful engines, a metal hull and screw propulsion in one large ocean-going package. The full account of the session occupied 34 pages, 14 for the paper and 20 for the discussion, in a total of 357 pages of content of the minutes.[9] That is, nearly ten percent of the total content was devoted to the description of just one single ship. The audience was a distinguished selection of epoch-making characters, who sustained a lively debate: Captain Charles Napier (the captain of the *Aaron Manby* in her pioneering cross-channel voyage), F.P. Smith (the pioneer behind the *Archimedes*), Robert Stephenson, Scott Russell, Field and Miller, among

[9] Excluding the presidential address, index, notices and the like.

others. Brunel, however, was absent. This debate was summarised and amplified in an article in *The Times* newspaper of 6 March 1845. Thus, here we see "off-line" learning (i.e. topical technical conversations) involving "on-line" learners (engineers taught through learning-by-doing), in which the object of analysis was the key exemplar of the future "technological paradigm" of efficient ocean-going mechanised navigation.

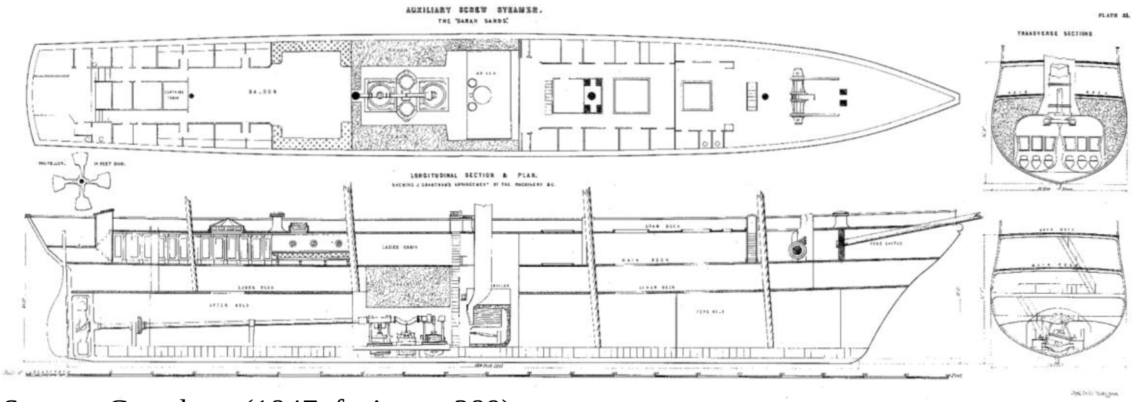
During these early Victorian decades, from 1840 to 1860, there were many other steam navigation topics discussed. Less famous, smaller scale, iron-screw (auxiliary) steamers were also discussed in these years. Some of these are the same traders described in Chapters 4 and 5. For instance, like Scott Russell, the eminent iron ship expert, John Grantham built iron-screw cargo vessels: some of his steamers, like the *Liverpool Screw*, the *Vanguard* and the *Sarah Sands*, featured prominently between 1844 and 1847.[10] It was to Grantham, incidentally, to whom Brunel turned for assistance when he decided to build his first iron ship.[11] Details and images of iron-screw steamer specimens were published (see Figure 7.5). Other topics included steam colliers[12], tugs, iron barques, exploration steamers, sheathing, measurement of a steamer's tonnage, etc. All these constitute instances of "the fairly relaxed manner in which engineers and shipbuilders of the earlier years of the nineteenth century were willing to share their knowledge and experience, often by publishing in the journals of the learning societies or the Proceedings of the Institution of Civil Engineers" (Walker 1999, p. 56).

[10] The *Sarah Sands*, in particular, was a steamer of some note. Built at Liverpool in 1846, in 1849 she became the first iron-screw vessel to reach the Pacific via South America and the first steamer to cross the Pacific Ocean, hence deserving the title of "one of the first deep-sea tramp steamers" (Craig 1978, p. 24). As noted in Chapter 3 (Section 3.3), she also gained distinction by surviving a fire onboard in 1857, and by being one of the earliest screw-driven cargo steamers (Chapter 3, Section 3.4, and Chapter 5, Section 5.5). It is significant that this well-designed steamer attracted attention from the beginning of her career.

[11] Letter by Brunel dated November 17, 1838: "Will you have the goodness to let me know who makes the best and largest plates adapted for boat building and who makes the angle irons?" (quoted in Corlett 1990, p. 26)

[12] It worth mentioning a paper "On the Comparative Cost of Transit by Steam and Sailing Colliers, and on the Different Modes of Ballasting" presented in February 1855 (*Minutes of Proceedings*, Vol. XIV, pp. 318-48). This paper provided an exhaustive account of the comparative costs of coal transport from the North East to London, and supplied details about several ballast systems.

Figure 7.5 John Grantham's auxiliary iron-screw steamer *Sarah Sands*



Source: Grantham (1847, facing p. 289)

To sum up, particular steamships were assessed at the Civils from many angles, including their technical ingenuity, architectural soundness, and economic suitability. This was especially true of innovative steam packets (such as the *Great Britain*) but also of that new breed of unassuming iron-screw colliers (like the *Sarah Sands*). In other words, the key exemplars of ships that supplied the template for modern shipping were analysed and debated in an open critical way in the 1840s. These reflections and discussions were recorded and published, becoming available to the general public in a variety of ways. It is clear, as Buchanan (1989, p. 73) points out, that "papers presented and discussed, week by week, comprised the core-function of the Institution, and there can be no doubt that they maintained a steady production of high-quality technical information on matters of great current interest to the professional engineers of the day." All this, given space constraints, is but a brief indication of the depth of the recorded technological conversation.[13] Of course, it should be also kept in mind that much of the knowledge sharing, such as that involving members like Brunel and Grantham, took place outside the four corners of the institution and thus went undocumented[14]. Other

[13] One drawback of these primary sources, as Layton (1971, p. 257) found in his own study of American engineers, is that professional associations tend to "keep their own inner workings secret." One can, however, have a feel for the values that sustained the institution during these formative years. For instance, via private letters: in one, to Charles Manby, the reformist Civils' Secretary, Brunel praised the "the free and liberal communication now existing in the profession" (quoted in Buchanan 1976 p. 19). On another occasion, and again to Manby, Brunel wrote about the continuous importance of "encouraging and promoting improvement." (quoted in Buchanan 1976 p. 20)

[14] John Hawshaw 1862's inaugural presidential address gives an impression of the extent to which free and unimpaired informal communication was valued. Hawshaw urged the institution's members to firmly

forms of the voluntary disclosure of technical information also left some traces, like the sending out of detailed ships' plans by members, for example by John Scott Russell.[15] It may also be conceded that if fame and prestige among peers was a key motive for innovating (as William Fairbairn admitted in the 1851 patent hearings), these circles provided an echo chamber for establishing the reputation of engineers and their projects. What is clear is that this pattern of sharing was a valuable resource in the instruction of individual engineers, who were thus better equipped to deal with their innovative projects. Such inclusive creative interactions almost certainly stimulated invention and diffusion in a way that bypassed the patent system (see Chapter 6).

Specialised institutions and the sustaining of the trajectory of the modern steamer

The dissemination of science and technology data and information was empowered by a growing number of other complementary structures, which we should, at least succinctly, describe in the remainder of this section. We are referring to the appearance in succession of the British Association (BA) in the early 1830s, of the Institution of Mechanical Engineers in the late 1840s and, towards the late 1850s, of the Institution of Engineers and Shipbuilders of Scotland and the Institution of Naval Architects (INA).

The British Association for the Advancement of Science was founded in 1831 with the purpose of giving a strong "impulse and more systematic direction to scientific inquiry, to obtain a greater degree of national attention to the objects of science, and a removal of those disadvantages which impede its progress" (BA, *Report of the First and Second*

adhere to the ethos of cooperation, the true "tools of the trade" of engineers (quoted in MacLeod 2007, p. 269). Given the context this may be read as a critique of the patenting trend, which after 1852 was in certain circles perceived to create a risk to the information-sharing culture.

[15] Many other forms of information sharing took place outside formal institutions. At the National Maritime Museum we found that a huge lithograph of the *Great Eastern* has been given by Scott Russell to the Denny brothers. Why such expensive specimens and offered to what (at least in theory) should be a competitor shipyard has been little questioned or even acknowledged in the literature. Proficient steamship builders such as the Dennies were experienced enough to learn something from the plans without having all the details spelled out to them. It is unknown at this point how general this practice was (although the existence of similar lithographs suggests this was not an isolated case – see Corlett 1993, p. 97, and Griffiths 1993, p. 163) or what it meant. This is an interesting question for further research.

Meetings, 1835, p. 22). It commissioned studies and assessments of specific fields of "useful" research. A few of these were directed to naval architecture, like those in which Scott Russell became involved. In the years 1838 and 1863, boundary dates from the vantage point of our study, the BA happened to repeat its meetings at Newcastle. On both occasions, separated by 25 years, attendees heard papers on the ship trade: first by Philip Laing on "Improvements on Shipbuilding" (a paper unfortunately now lost, cf. Dougan 1968, p. 19); and the second on iron steam colliers by Charles Palmer, the builder of the *John Bowes* (see Craig 1980a, pp. 6-7). The progress of steam navigation must have been obvious to the 2,400 and 3,335 participants, respectively, at these two events (MacLeod and Collins 1981, pp. 279-80). Throughout this time, and beyond, the BA worked as an annual sounding board for the many ongoing technological conversations, which were never perhaps as loud as during the summer of 1836 at the meeting in Bristol, when the debate over the possibility of the Atlantic ferry raged (discussed in Chapter 3, Section 3.2; see also Box 3.1).

Meanwhile, the first specialist engineering institution appeared in 1847 – The Institution of Mechanical Engineers, also known as IMechE or the Mechanicals. George Stephenson, the pioneering locomotive builder, was elected "by acclamation" as the first president, only to die in the following year (Parsons 1947, p. 12); he was then succeeded by his son Robert, who also continued to be part of the Civils. There was a respectable contingent of the steamship community involved. Early officials included prominent members who were also members of the ICE, for instance Scott Russell, Joshua Field, and Joseph Miller.[16] Marine engineers like Henry Maudslay (son of the elder Henry Maudslay), William Denny, David Elder, and James Caird of Greenock, among others, also became members, and William Fairbairn (1854-5), John Penn (1858-9, 1867-9), and Robert Napier (1863-5) served as presidents. The Mechanicals continued the Civils' practice of presenting papers and discussing the results of

[16] Joseph Miller (1797-1860), of Miller and Barnes, and later Miller and Ravenhill, had built the engines of the first P&O mail steamer, *Iberia*.

experiments and experiences, but now with a peculiar focus on problems of steam propulsion on land and on the sea (Rolt 1967, p. 5). The Mechanicals advertised their interest in hearing about the particulars of engines, boilers, paddle-wheels, and other features observed in "British war steamers, in British merchant steamers, and in Foreign ditto, ..., &c" (*Proceedings of IMeche*, 1850, Vol. I, p. 43).[17] One paper on an important issue that engaged the attention of marine engineers was delivered by John Penn (*Proceedings of IMeche*, 1856, Vol. VII, pp. 24-34). This described his and Smith's work, drawing on several friction experiments carried out in a tank at Greenwich in 1854 on the water-lubricated lignum vitae propeller shaft bearing. A meeting held in 1858, and attended by Henry Maudslay and William Froude, confirmed the approach as a "complete success" (*Proceedings of IMeche*, 1858, Vol. IX, pp. 81-91). The Mechanicals themselves became a success story (Buchanan 1989, p. 83).

In 1860 the Scottish Shipbuilders' Association (SSA) was formed, and it published bound volumes of its business for the years 1860-3 and 1863-5. In 1865 it was amalgamated with Institution of Engineers in Scotland which had been founded in 1857, assuming the title of the Institution of Engineers and Shipbuilders of Scotland (IESS) in 1875. This institutional development reflected a shift in the centre of gravity of steamship building from the Thames to the Clyde (Schwerin 2004, pp. 91-2).[18] The discussion of papers was often very intense and, for the first time, we can witness specific issues relating to sailing ships being discussed.[19] James Hall, whose name is associated with the Aberdeen bow, assumed the presidency of the SSA in 1862. His speech is a neat summary of how, at this time, it was taken for granted that an open forum of professionals was instrumental in generating a variety of technical ideas (i.e. variation), in selecting through tough discussion which of them were robust enough for

[17] Evidence that the new institution was happy to receive papers on marine technology was an early paper on "The best High Pressure Marine Boiler" (*Council Minutes of IMechE* 1847, pp. 2-3).
[18] Similarly, the North-East Coast Institution of Engineers and Shipbuilders would be founded in 1884 (see Matsumoto 2006, Table 2).
[19] No doubt there is here a collection of interesting material that can, perhaps, be linked to the continuous technical change in sailing ship performance that we discuss briefly in Chapter 4. This, however, extends beyond the scope of present study.

trial (i.e. selection), and in constructing a cumulative collective memory retaining the innovations that really worked (i.e. retention). It is worth quoting at length:

> "We ought ever to bear in mind that we are not the same to-day as we were yesterday, and, therefore, the amount of knowledge which served our fathers will not suffice for us, neither will our knowledge suffice for those who come after us; hence the utility of such associations as these, by drawing together men whose minds are engaged in similar pursuits, and by registering our ideas in the records of the Association, not only mark the progress of our profession at the time, but in a truly liberal spirit of communicating our ideas to each other on whatever any of us may think of importance, or worth being taken notice of." (Hall 1862, p. 7)

And:

> "Here associates may write down their ideas, which immediately become opinions, and being subject to discussion, the chaff will be separated from the wheat, and the valuable parts laid up in the storehouse of the Association's *Proceedings*." (Hall 1862, p. 8)

Finally, on January 16th, 1860, there was a major event in London: the Institution of Naval Architects (INA) was established. The members invited an influential figure to become President: Sir John Somerset Pakington, who as First Lord of the Admiralty had ordered the *Warrior* to be built. It is telling that the new President, in his inaugural speech alluded to the Civils as a model institution. E.J. Reed, a young man of technical ability and at the time Editor of the *Mechanics' Magazine*, became Secretary (Barnaby 1960, p. 8). Many known figures were prominent members from the outset: among them were Joseph Maudslay, Grantham, Fairbairn, Airy, Moorson, Penn, Samuda, Fincham, Barnaby, John MacGregor, John Laird, the Denny brothers, and others. John Scott Russell, a member of the Civils and the Mechanicals, has been credited as the key instigator of the formation of this new institution (Lambert 2008, p. 18; Brown 2004, p. 312). It is significant that INA was the springboard for "what was probably the most important joint action ever taken by the profession, the establishment of the Royal School of Naval Architecture and Marine Engineering," founded at South Kensington in 1864 (Pollard and Robertson 1979, p. 146). As a sign of further division of labour along this path of institutional refinement, the Institute of Marine Engineers would be founded in 1889. As Gilfillan (1935a, p. 82) observed, it was nevertheless with the INA that naval architecture became a scientific profession in Britain during the period 1860-80.

Hence, in the second half of the century there was a permanent social infrastructure in place assuring the constant free exchange of technical information that served effectively as a quasi-R&D system as the industry evolved (Matsumoto 2006, p. 2).

Summary of Section 7.2

Early 19th century British engineers issued and used critical technical information on innovative projects through community-based mechanisms. The British community of engineers and mechanics was the first to become voluntarily wired-up in formal sites for mutual learning. The evidence suggests there was a continuing link between the Royal Society and the Civils through Smeaton, a thread that capitalised on his emphasis on an academic spirit of open communication and close cooperation. Starting with the Civils, other similar institutions can be said to have played a particular role in the British innovation system. These institutions were geared to produce constructive debates (fostering new combinations of ideas, i.e. fuelling “variation”), to discuss new empirical observations and theoretical results (i.e. helping in the “selection” of innovation and engineering solutions), and to keep records of intellectual and practical results (i.e. building a collective memory and increasing the “retention” of past advances).

For innovators living through the transformational years of steam navigation, an important part of their interaction was mediated by a key institution, the Civils. From early on, there were connections between the Civils and steam navigation, since its early leaders (Maudslay, Field, Tredgold) were active practitioners and consultants in the field. The community of engineers moving within the framework of the Civils was instrumental in assisting the work leading to the *Aaron Manby*, the first iron steamer, and in discussing the particulars of the revolutionary *Great Britain* (as well as other pioneering iron-screw vessels, such as steam colliers), which embodied the paradigm of the modern merchant ship. The iron-screw ship was a central part of the Civils agenda, and the most influential steamship builders and designers, such as Brunel or Scott

Russell, had an active role in developing it. Through the ICE their concerns and insights fused and became more readily available to others. Since the ICE was a geographically dispersed organisation in terms of the origin of its members, the experiments and the experience of the Civils echoed in various corners of Britain and even abroad.

7.3 The rise of the technical press

Innovation-oriented media in the 19th century Britain

The role of the media in the innovation process has so far been a rather neglected topic in the field of science policy and innovation economics. The media is a peculiar piece of the dynamic puzzle of technical change as it instantly reports on all actors, their relationships, their achievements and blunders. More than just offering more efficient means of conveying news and stories, periodicals contributed to the reshuffling of technical information. Magazines and newspapers made possible the comparison of multiple, previously scattered insights, allowing readers to identify gaps, pinpoint discrepancies, identify opportunities and formulate new associations. In other words, the printed press became a tool not only for managing collective memory but also for making sense of overall current best practice; it was an instrument of the ongoing technological conversation. Because not even a small literature could be found surveying the intersection of these two phenomena (i.e. technical media and steamship development), we hope that the shortcomings of our exploration may be tolerable.

Science and technology media as a catalyst of change

In this section, we investigate the relationship, if any, between the rise of the engineering press and the rise of the modern, mechanised ship. Even though the media is a rather unacknowledged factor in the explanation of economic and industrial change (see, e.g., Nordfords, 2003; Norfolds, Ventresca, *et al*., 2006; Kauhanen and Noppari, 2007), it would be strange if the technical press, a novelty of this period, had not been an integral part of the communication shift that occurred in the production, validation and transmission of engineering knowledge. Fascinated by the idea of progress, there was growing intellectual appetite among the Victorians for news on science and technology. For instance, a popular publication like *The Yearbook of Facts in Science and Arts* (1838-80) reported on technological stories and in the first issue of the *Illustrated London News*, which appeared on May 12, 1842, one can see pictures of the war in Afghanistan, a dress ball the Buckingham Palace, a train crash in France, and a steamboat explosion in Canada.[20] Technology increasingly made news. A deeper question is if the news made technology.

With the end of the Napoleonic Wars and a growing share of total output and employment corresponding to non-agricultural activities, Britain was a place increasingly aware of, and concerned with, technological development. This fertile period witnessed the establishment of a publication called *Mechanic's Magazine* in 1823. This has been credited as *the* pioneering publication in "engineering journalism, which for so long played an indispensible part in the diffusion of technical knowledge" (Parsons 1947, p. 9). As further evidence of its standing among the community of steamship-related technologists it is worth mentioning a volume published by the Patent Office (1862, pp. 609-15). It referred to the *Mechanic's Magazine* in a list of "works relating to ship-building, etc.", where it appears as the only wide readership outlet on the matter and figures on a par with classic books and treatises, such as *Papers on Naval Architecture* of 1826 by William Morgan and Augustin Creuze, Beaufoy's accounts of *Nautical Hydraulic Experiments* in 1836, Scott Russell's 1843 reports on his wave-line theory, and Fincham's (1851) textbook.

The frontispiece of the magazine is the figure of Mercury, the god of trade, walking amidst the inevitable Greek columns bearing ten names associated with science and

[20] To be sure these topics were becoming fashionable throughout Europe. One example is the *Museu Portuense*, a Portuguese journal founded in 1838, which published early on a survey on the developments of steam navigation complete with statistics and illustrations (No. 10, 15 December 1838, pp. 149-52).

technology, one of them being Fulton. In contrast with these classical elements and under a motto paraphrasing into English Francis Bacon's adage "scientia potentia est", there is an illustration reflecting a choice concerning two symbols of industrial ingenuity: a steam pump engine and, especially relevant to our focus in this thesis, a steamship on the sea (Figure 7.6). One year after its appearance, commenting on the magazine's "cordial reception", the editor commented on its "nearly unrivalled circulation" and defined the purpose of the outlet as follows: "the chief object of our work [is] to encourage the communications of intelligent practical men" and the "edification of our readers at large" (*Mech. Mach.* 1824, Vol. II, pp. iii-iv). For the period between 1823 and 1859, the year in which it was re-launched, the magazine provides an uninterrupted record covering an epochal period in the history of modern shipping. During the transformational years of steam navigation, this technology and engineering newspaper had no rival. This is, therefore, a potential contributing agent of change as well as a unique source for understanding events and developments of the age.[21]

Figure 7.6

The *Mechanics' Magazine*, frontispiece of the first volume, 1823

All the inventions fit to print

One can start by observing that the magazine's subtitle changed over time. From its beginning in 1823, the magazine's name was appended by the words "Museum,

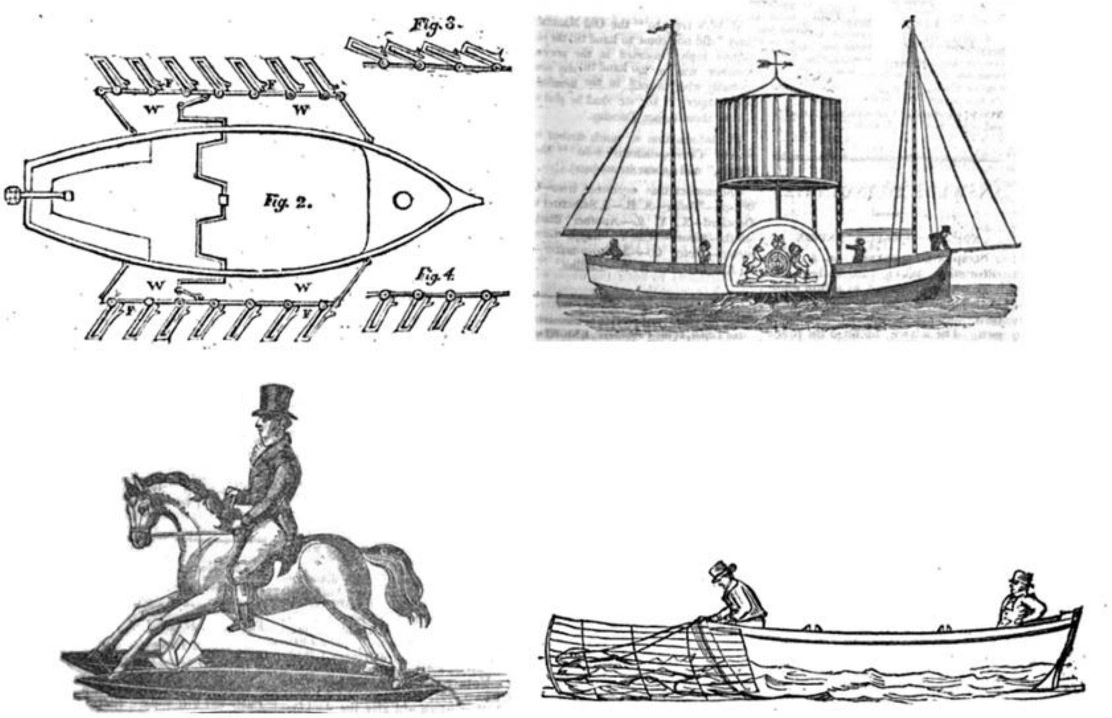
[21] This magazine became something of a standard reference for contemporaries. Its status is reflected in the fact that it is mentioned as such in textbooks and scientific popularisation books of the time. For instance, John Curr (1847), who wrote a volume on marine engineering (including the relative merits of paddles and screws, and the case of the *Great Britain*) talks about this outlet as a way to "ascertain the present actual and scientific knowledge of English engineers on the subject." See also Fishbourne (1856, p. xi).

Register, Journal and Gazette". This was dropped in the early 1850s and for the better part of the 1850s it stayed like that. At the start of a second series of the magazine in 1859, it gained a new subtitle, now reading "Journal of Engineering, Agricultural Machinery, Manufactures, and Shipbuilding". As the engineering profession grew into maturity, the contents and style of the magazine changed in parallel.

The magazine ranged over a miscellaneous array of subjects. It contained historical notes, mathematical demonstrations, book reviews, reports about the introduction of machines in Britain and overseas, suggestions of ways to tackle technical puzzles, notices of patents and of patent litigation, and so on. From its early days, plans for wacky inventions were quite common; this included a penchant for perpetual motion machines complete with detailed explanations and illustrative drawings. The first magazine front page covering steam navigation, under the title "First steamboat", appeared on the seventh issue and consisted of a commentary on Jonathan Hull's 1736 patent, with an engraving (*Mech. Mag*. 1823, Vol. I, No. 7, October, pp. 96-7). Many pieces followed. That is, ship technology, in particular steam navigation, clearly emerged early on as a not insignificant topic in the portfolio of themes.

From the very start, the magazine appealed to "[c]ommunications from intelligent Mechanics, and from all others who may take an interest in the diffusion of useful information on any of the subjects embraced by this work". It should be realised that readers themselves produced a great proportion of all the contents. Figure 7.7 shows some particularly fanciful schemes for ship propulsion that were submitted in the 1820s. By the 1830s, however, proposals were becoming more credible and the work of known marine engineers and naval architects was also being referred to and reported. The magazine was increasingly covering parliamentary hearings (like those on accidents in steam navigation during the 1830s or the report on coal in the 1840s) as well as reproducing the proceedings of the Civils and the BA.

Figure 7.7 Implausible solutions to the problem of boat propulsion in the 1820s



Source: *Mechanic's Magazine*
Note: Clockwise, "Boat with wings" (*Mech. Mag.* 1825, Vol. III, No. 81, March 12, p. 385), "Vessel to sail against the wind" (*Mech. Mag*. 1825, Vol. IV, No. 90, May 14, p. 81), "Employment of seals to draw boats" (*Mech. Mag.* 1827, Vol. VIII, No. 96, November 17, p. 275) , "Description of a water-horse" (*Mech. Mag*. 1825, Vol. IV, No. 96, June 25, p. 96)

What did the magazine cover in terms of ship technology?

The *Mechanics' Magazine* was remarkably early in publishing material on the breakthroughs that later on would be incorporated into what is referred to in this thesis, for purposes of simplicity, as the "modern ship". This point deserves emphasis as there was a radical uncertainty back then as to what were the most suitable technologies, and the best working manner to combine them, for steam navigation.

In our reading the notion of the screw-propeller first surfaced as early as 1824 (in issue No. 31). One tiny notice, published in 1829 (No. 321), made a very early reference to iron as a working material for vessels. Iron as a shipbuilding material featured again in July 1831 (No. 413) and again in the same year (No. 427). These observations give a concrete meaning to the expression that a given "idea was in the air". And the fact that the magazine also published the details of several early successful iron steamers, like Fairbairn's or Laird's (Nos. 413 and 427 in 1831, No. 503 in 1832, No. 554 in 1834) also gives flesh to a concept sometimes used in innovation studies, i.e. the "demonstration effect" (see Chapter 2, Section 2.3).

A platform for waging debates, dissecting trials and following up experiments

Ocean steaming received plenty of publicity in the *Mechanics' Magazine*. A debate before a Select Committee held in 1834 on the best means to reach India by steam found space in the publication's pages, as well as the Committee's final report of 1838. Another public discussion that occupied a large number of pages between 1837 and 1838 was the feasibility of steam navigation across the Atlantic, a debate that started with Lardner's negative opinion, and ended with the successful crossing of the *Sirius* and the *Great Western* (see Chapter 3, Section 3.2 and Box 3.1).

Overlapping with the Atlantic-ferry debate, details of various methods of steam propulsion started to make their way into print. The *Mechanics Magazine*'s first salvo was an article of June 1837 entitled "Captain Ericsson's new propeller", describing the propelling apparatus fitted to the *Francis B. Ogden*. Ericsson's *Robert F. Stockton* also managed to attract a few news pieces in 1839, but attention was by then moving away to other players. The propeller-related news-item that would unleash more articles for a number of years to come appeared in October 1838: the *Archimedes*. F.P. Smith's demonstration vessel became a frequent object of reporting (including its promotional voyages round Britain and to Porto). In the year 1839 alone both paddle-wheels and screw-propellers (Lowe's, Smith's and a Navy Captain's) feature three times as cover-illustrations. In July 1840 the matter was being vigorously debated in the pages of the magazine as one of "paddle-wheel versus the screw." Christopher Claxton, Brunel's associate, discussed and compared trials (No. 895 in 1840). The *Rattler*'s experiments with particular screws were reported from 1843 onwards, and the discussion reached its climax with the *Rattler's* much aired tug-of-war with the paddle-steamer *Alecto*. The extant literature generally describes this contest as a famous event in the history of steamship technology, but one is reminded that it was *famous* precisely because it was *made* famous by this magazine and other media outlets (e.g. the *Illustrated London News*).

In September 1842 the *Great Britain* made the cover of the magazine and filled no less than 14 continuous pages, an absolute record for any steam navigation subject and undoubtedly one of the longest articles ever published in the *Mechanics Magazine*. The ship was thoroughly dissected: a longitudinal section of the hull was printed, several vertical and longitudinal sections of the engines were displayed, dimensions and characteristics of the machinery were spelled out, the propeller was shown, costs were given, as well as many other details. In December 1843 she was referred to as "A Leviathan Project", terminology that could be used in a newspaper of today. This vessel was to supply a steady stream of news for years to come as her completion was followed and her troubled career was reported. An important event that was covered in detail featured the Dundrum Bay stranding. Significantly, this accidental "summative evaluation" of the first true exemplar of the modern ship made up a particularly long article in 1847. This kind of topical news continued through the 1840s and into the 1850s.

Technologists making the news

As we have noted, the magazine was never monopolized by cranks and it is reassuring to note that this outlet was sufficiently important from the point of view of the creators of the new steamship industry that not a few of them wrote contributions themselves. Marine engineers, shipbuilders, naval architects, steamship promoters and inventors were among them, namely Samuel Seaward, John Penn, Christopher Claxton, F.P. Smith and James Lowe. Many of these individuals were, of course, habitual members and guests at the Civils. In other words, a number of influential contributors to steamship technology were also producing texts for broad audiences and contributing to the public discussion of steamship technology. This might indicate that public opinion on technological affairs somehow mattered to these shipbuilders and technologists.

It should be remarked that one individual not among those already mentioned above, boasted especially detailed and self-assured knowledge about ship technology. One George Bayley not only made high-quality contributions, providing deep accounts of ships and producing sustained arguments on steam navigation, he was also unsurpassed in terms of quantity. His name does not feature, however, in the *Oxford Dictionary of National Biography*. For more than ten years, Bayley was a regular commentator and unmatched in his remarkably detailed knowledge and prescient opinion. It was only by triangulating across different sources that it was possible to establish that this was the man who became Lloyd 's Register (LR) first ever Principal Surveyor. That the LR, an otherwise rather discreet institution, played a part, through him (but not only through him), in the technological discussion on steam navigation at its most defining time is an observation apparently missing from the literature until now.

The first article signed by George Bayley appeared in 1832, that is, just before he joined LR. It discussed the crucial matter of "Iron steam boats" (*Mech. Mag*. 1832, Vol. XVII, No. 469, August 4, p. 302). Bayley started by observing that an iron steamer built by Maudslays would shortly be appearing and trusted the editor "to furnish your readers with full particulars respecting her." He went on to say that he held the view, "for a long time", that iron could be advantageously employed in the construction of steamers. Iron would be especially interesting for canals or exploratory expeditions as boats "would draw but little water and contain a much larger quantity of fuel than boats of the ordinary construction." Bayley ended with a request for information concerning an iron steamer called *Aaron Manby*: the builder, dimensions, purpose, and if she was still in existence. The Editor answered below by giving particulars of Maudslays' steamer (the

Lord William Bentinck, intended as a tug on the Ganges), expressed doubts concerning the advantages of iron, and responded with little information about the *Aron Manby*, except to say that she was still "plying on the Seine, where its name has been naturally enough corrupted into the 'Iron Manby'". This interchange calls for several comments. We see someone who apparently is creating a culture of free broadcasting of information concerning innovative (iron-built) steamship projects. We also see an expert on merchant ships appealing to others for data he does not have. And, it should be emphasised, it underlines the importance of data on past (even old) "high-tech" projects that could yield lessons concerning what was still a largely unproven approach.

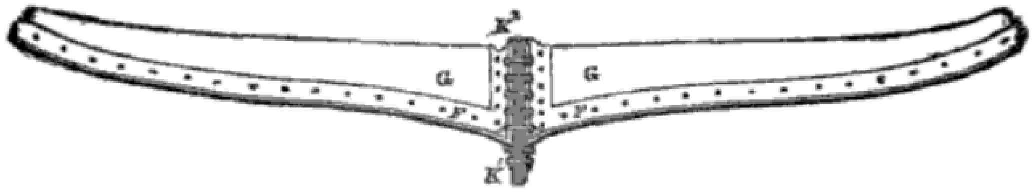
Later in the same year of 1832, engaging the Editor on the suitability of the new shipbuilding material, Bayley could be found forcefully making the case for iron. In August 1837, already Principal Surveyor at LR but not presenting himself as such, he was arguing strongly in favour of steam navigation to America. He cited the great improvements in marine steam engines and insisted that it was essential to give "a fair trial to any project" (*Mech. Mag*. 1837, Vol. XXVII, No. 730, August 5, p. 302). In September, Bayley was writing again on the feasibility of long-distance steaming and makes known the fact that he had a chance to investigate the *Great Western*, which had arrived on the Thames to receive her Maudslays' engines. The following year, he was using the magazine to attack what he saw as an erroneous idea, the use of fir for planking sea-going steamships. This is significant as it reveals the deliberate choice in choosing this as the channel for disseminating expert knowledge. It should also be added that on August 1840 Bayley commended the "highly satisfactory" performance of the *Archimedes* in her experimental voyage. This is critically important as records of pronouncements on the screw-propeller by LR officers are extremely rare.

The first reference to LR in the *Mechanics' Magazine* appears in 1834, when the society was being established. And it is a self-described inventor who complained about LR unwillingness to approve his plans; these claims were effectively destroyed by another reader (signing himself "An old correspondent") who dismissed the inventor as obviously ignorant of the shipbuilding trade and said LR's refusal to approve an untried improvement brought only credit to the society. By 1839 the magazine was printing the Select Committee reports on steamship boiler explosions, in which readers could observe positive references to the role of LR. A survey on steam navigation, appearing one year later, was also positive toward LR.

Interestingly, a reproach to LR's conduct was published on September 1843. An unsigned piece (presumably written by the magazine's staff) condemned LR for not classifying iron steamers. This piece in fact exposed a contradiction: Mr. Bayley had always said in the magazine's pages that iron was advantageous in many respects but still no allowance was in reality being made for the ships built of that material. It cited other newspaper sources where suspicions were raised concerning the motive for the discrepancy. Coincidentally or not, a few months later, in January 1844, the magazine lauded LR for recognizing iron shipbuilding and reprinted a communiqué of LR which had appeared in several newspapers: iron ships built of good materials with good workmanship were to be classed A1, provided such ships were subject to an annual survey. Hence, it may well be the case that the magazine had a role in this development.

In 1848, and for the first time, a Surveyor (Robert Fowles, then surveyor at the port of Newcastle) wrote a contribution identifying himself as working for LR. Significantly the piece was on iron vessels. It advocated a revisiting of LR *Rules* for the construction of the bottom of vessels made of iron. And he submitted a plan "for consideration" having to do with the form of the keel (k) and keelson (k^2). Figure 7.8 was supplied as an illustration. This is a straightforward attempt to broadcast a form of best shipbuilding practice adapted to the properties of a new material in the face of uncertainty that still held LR back from drawing up a new complete set of *Rules* concerning iron ships.

Figure 7.8 “Improved method of constructing iron vessels” submitted to the readers of the Mechanics’ Magazine by an indentified LR Surveyor



Source: *Mech. Mag*. 1848, Vol. XLVIII, No. 1298, June 24, p. 608

Summary of Section 7.3

The *Mechanic’s Magazine* introduced a novel element in the British national system of innovation. Here was a specialised media outlet that reported critically, accurately and timely on technological events, ideas and debates. Steam navigation was a topic covered from the beginning in the magazine. The fundamental breakthroughs of modern shipping (namely iron hulls and screw propulsion) and the major challenges and achievements involving steamships (the story of early iron ships like the *Aaron Manby*, the possibilities of north-Atlantic steam ferrying, the proceedings of Select Committees on steamship accidents, the voyages of the *Archimedes*, the method of construction of the *Great Britain* and her stranding in Dundrum Bay, several trials involving screw-propellers versus paddle-wheels, etc.) were intensively documented and discussed between the late 1830s and the late 1840s. Leading ship and marine engine builders, such as Seaward, Penn, and Rennie wrote in the magazine and seemed to reproduce there the spirit of open and focused technological conversation they engaged in at the Civils. The otherwise discrete LR’s Surveyors did so too (mostly on iron shipbuilding, screw-propulsion, and long-haul steaming), something the extant literature seemingly makes no mention of.

Hence, the evidence suggests that the *Mechanics’ Magazine* provided a forum where conversations on high-tech topics involving steam navigation took place. One implication is that this platform should be recognised as having played a role in redistributing and consolidating knowledge in high-tech challenges. This media outlet was used by steamship engineers and surveyors to facilitate the process of sorting out credible engineering solutions, taking stock of past achievements, steer technological development away from dead ends, and to broaden the intellectual raw material for new productive combinations; in short, guaranteeing information disclosure, speeding up the learning process and spontaneously coordinating it on several fronts.

7.4 Lloyd's Register: Classification society

LR as a not-for-profit, standard-setting institution in the 19th British shipping industry

Lloyd's Register (LR) was, and is, a peculiar institution with no straightforward equivalent in other industries, especially during the 19th century. LR was consolidated in the mid-1830s. Its purpose was to act as an independent party in the shipping industry producing sound information on which other players could base their decisions. For shipowners, charterers and underwriters, interpreting ship-related information implied weighing numerous factors; this was an essentially technical task that amounted to evaluating the structural quality and seaworthiness conditions of any given vessel. It was a crucial activity that relied at once on familiarity with the technology and on a reputation for honest evaluation (Kingston 2007, p. 386). LR was, and still is, a non-profit professional organisation. LR was the only British institution of its kind in these years, so the Society was a *de facto* monopoly in the services it was delivering; but one that did not behave as such. Since LR was charging as little as one shelling per ton in the 1850s and providing free advice to builders of ships under survey on a continuous basis, "(t)here can be no doubt the shipbuilders got good value for money, given the then *primitive* state of what would now be technical support staff." (Clarke 1997, p. 52, emphasis in the original) It is our contention that the LR's role in the rise of the trading iron-screw steamship has been rather underestimated and underreported in the literature. LR emerged as the trusted curator of sound standards acting in the best interest of the industry as a whole at a most critical point of its evolution.

There have been a number of corporate histories produced or ordered by the corporation over time (another was published as this thesis was being completed on the occasion of its 260th anniversary, i.e. Watson, 2010). Moreover, there is a overwhelming consensus among a number of eminent maritime scholars who have made reference to LR that its role did help to improve the quality of construction and maintenance of ships (e.g. Greenhill and Giffard, 1970; Craig, 1980a; Macgregor, 1988; Corlett, 1990). The existing literature acknowledges that LR crystallised in its classification rules the evolving consensus on designs and materials suitable for building and operating sound vessels (cf. Pollard and Robertson 1979, p. 12). Whilst useful, these treatments provide no more than a passing reference to what connection there may have been with other subjects such as the emergence of the iron-screw design. The lack of systematic research on the part played by this central institution during the steam revolution in the maritime sector is another puzzle that this thesis has stumbled across. That there is a wealth of virtually untapped archival material only compounds the puzzle further.

The business of assurance, not insurance

Late 17th century London was the breeding ground of numerous coffee houses, which were frequented by businessmen of all interests. Shipping circles gravitated around Edward Lloyd's (c. 1648-1713) establishment, conveniently situated between the City and the docks. Lloyd's main customers cut across the merchant, shipowner and insurer communities, "who met regularly to transact business and exchange information." (Jones 2000, p. 2) The proprietor made sure his premises remained the favoured one for the marine business by investing in authoritative shipping intelligence. By 1692 he was producing a weekly news sheet and later in the decade printing a bulletin, *Lloyd's News* (Palmer, 2004). That is, Lloyd's managed an open ("public") house, and produced a "public good" (i.e. reference information). In 1760 the customers of the successors of Lloyd' Coffee House founded "The Register Society", which would later become

Lloyd's Register. Charterers and underwriters needed a reasonable idea of a vessel's build quality and sailing fitness. A guarantee as to the faithfulness and accuracy of that information was of the essence. It was in the interest of all concerned that ships were surveyed and their general condition classified, and to keep that information on record. Along the way, underwriters had established another organisation solely for the pursuit of insurance activities; this was to be Lloyd's of London. The two activities, insurance and assurance, branched out and the importance of independent and expert classification grew. Hence, the tradition of ship classification emerged in Britain in 1760, ahead of the other early classification societies like Bureau Veritas (Antwerp in 1828, moved to Paris in 1832), Registro Italiano Navale (1860), and the American Bureau of Shipping (1861).

The classification activity was reconstituted as Lloyd's Register of British and Foreign Shipping in October 1834. In that year it published its first Rules for the survey and classification of vessels, and started to publish a list where ships were assigned different classifications (the Society's *Register Book*). Prior to this, two registers were in existence. It was common parlance among merchants, shipowners and underwriters that, on the whole, the outcome of the work of the competing assessment systems was the building of inferior ships. So much was expressed in the final report of the Select Committee on Shipwrecks in 1836: "That the defective construction of ships appears to have been greatly encouraged by the system of classification, which from the year 1798 up to the year 1834 was followed at Lloyd's (...)" (*BPP* 1836, p. v). The new classification rules that LR came to supervise contributed to removing prejudices and increasing the focus on technical quality for rating ships (Ville 1989, p. 84).

LR's first permanent Committee was composed of eight representatives of merchants, shipowners and underwriters, together with the chairmen of Lloyd's corporation and the General Shipowners Society. In 1836 Thomas Chapman, FRS (1798-1885), a respected merchant and philanthropist, was elected Chairman. He was joined in 1837 by Charles

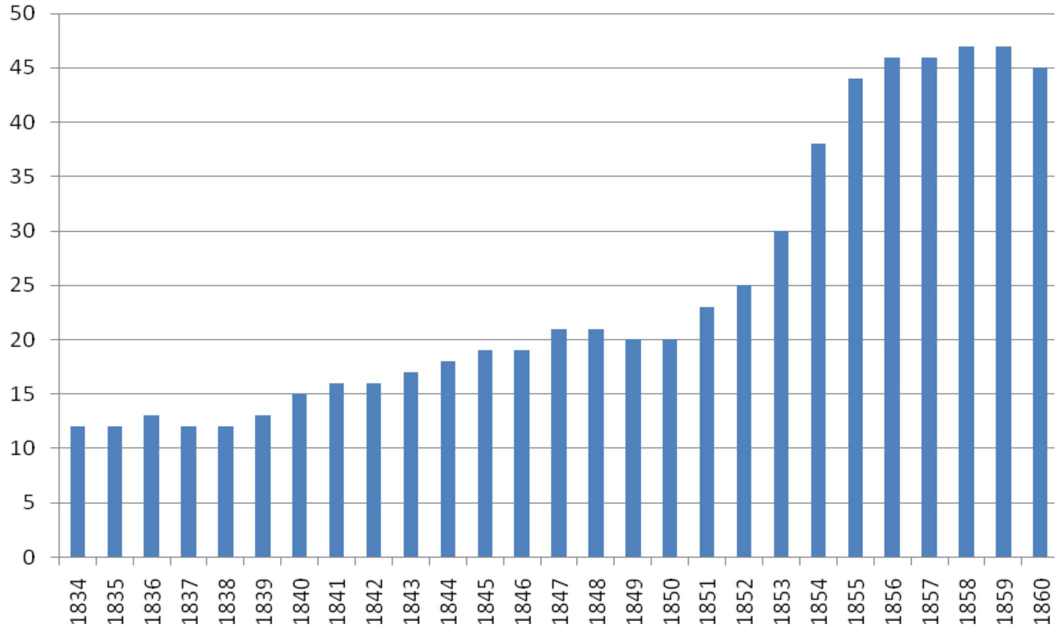
Graham, Secretary, who had served in the Admiralty. The recruitment through advertisement attracted highly qualified “shipwrights” and “practical nautical men” to work as Surveyors or inspectors of ships’ quality of construction and maintenance, a number of them foremen from naval dockyards (Fenton and Jones 2009, p. 15). The already mentioned George Bayley epitomises LR hiring policy. Bayley came from a family of shipbuilders, and was the Principal Surveyor in London between 1834 and 1844, a crucial period from the point of view of the society and from that of ship technology history. Integrity of surveyors was of the essence and the story is told how once, when offered a bribe to smooth his report, Bayley threw the corrupter overboard (Watson 2010, p. 23). A crucial aspect of the work organisation was that Surveyors did not class the ships they inspected. To ensure consistency and to keep external pressures at bay, this was to be done by the Classification Committee, or the Sub-Committee of classification, on the basis of the surveyors’ written reports and according to the Rules.

The first *Rules for the Classification of Ships* adopted in 1834 were framed for the construction of sailing ships; they recognised the steam propulsion approach but contained only a brief reference to it (Lloyd’s Register 1934, p. 63). A ship’s class depended on the quality of workmanship and the materials of the hull and equipment, as well as the state of repair. Then the ship’s details were recorded and her classification was entered in the *Register Book*. The top class to which a vessel could be assigned was denoted “A1” for a maximum period of 12 years. This certificate of excellence was only granted if the ship underwent surveys three times while under construction. The General Committee alone had the power to issue certificates of classification but, with business increasing, a Sub-Committee for Classification of Ships was formed just to attend to that task. The Rules themselves were under continuous development as more experience accumulated and as investigations brought further results. Machinery is a significant example. The Rules of 1834 specified the strength of boilers, and appear to follow the recommendations that came out of the 1817 Select Committee on boiler explosions.

Who where the Surveyors and where were they stationed?

From an undated LR manuscript notebook (referred to as the *Staff Bible*) containing information about officers working from 1834 to 1950, we obtain useful information about the employment dynamics of LR. Figure 7.9 plots the net number of Surveyors (in full-time and part-time employment) working for LR between 1834 and 1860.

Figure 7.9 Number of Surveyors in active service duty between 1834 and 1860



Source: elaborations on LR's archive *Staff Bible*, unpublished records

In the 1830s the average number of Surveyors in any year was around 12, it grew to 18 in the 1840s and jumped to 37 in the 1850s. LR hiring policy was certainly responding to the ever increasing numbers of the British merchant fleet and to LR's growing popularity among the shipping community. But what also emerges from this picture is the geographical reinforcement of Surveying. LR started out with a staff of Surveyors stationed in London, Liverpool, Bristol, Sunderland, Glasgow, Leith, and all other major ports of the country. Soon, though, there were several surveyors located in the same ports due to the large amount of business to attend to (for instance, in Hull, Sunderland, Bristol, and Liverpool). From the *Staff Bible* we can also infer LR's developing policy of making their Surveyors circulate among different ports. Bayley, for instance, stated in 1836 that he was posted in London but visited “other ports several times.” (*BPP* 1836, p. 181) But Surveyors also rotated between the posts they were stationed in. An example is John Maxwell (1830-1869): hired in 1854 at the port of Glasgow, he was placed in Newcastle in the following year and then in London in 1859 where he remained. This practice was increasingly enforced by LR management in order to guarantee Surveyors’ independence from local shipbuilders (see Watson 2010, p. 25), but it was a practice that also fostered the circulation, benchmarking and diffusion of expert knowledge and best practice.

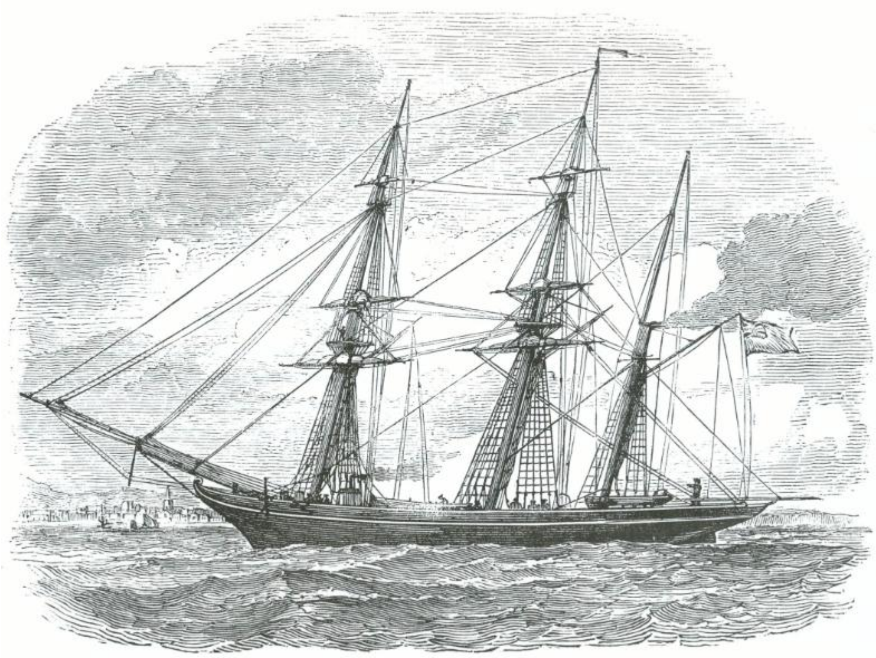
LR’s routine operations and its confrontation with novel iron-screw combinations

Routine work can be accessed through manuscript material that was, fortunately, preserved to current day in LR’s library. A key body of evidence are the *Minutes Books of the General Committee*. They carefully record the current matters dealt with by the Committee: letters of the Surveyors were read, outgoing post was decided upon, particular vessels or inspections were considered, deviations from the *Rules* were discussed, and so on. Evidence extracted from this source is apparently unavailable in the extant literature, with the notable exception of MacGregor (1988) who used it (he cites the volume between July 1855 and June 1856) in his discussion of sailing ships.

Regarding the *Minutes*, we sampled all volumes for the 1840s (when progress in iron and screw propulsion was making way; a search of the volumes was guided by the thematic index in the beginning of each volume) and took a deeper look at the years 1853 and 1854 (by which time iron-screw steamers were more visible; the search of the volumes was extensive and not confined to the pointers available in the index). An important finding is that experience with iron ships was being actively monitored during the 1840s. An iron sailing trader called *Ironside*, a 270 tonner, appears in a meeting of June 10, 1841 (*Minutes Books*, Volume referring to July 1840/June 1841). A report by the Liverpool Surveyor stated that at the time she could "carry dry and perishable cargos with safety"; she had had only few rivets replaced. Significantly, the Committee was still interested in observing the *Ironside* many years on, as an entry of March 19, 1846, shows. In the *Minutes* of the following year, i.e. July 1841/June 1842, references to iron vessels are more abundant. Interestingly, the Principal Surveyor, George Bayley, reported on the *Iron Duke* which was stranded and suffered considerable injury (November 24, 1841) and a note is made of the *Great Britain* being built at Bristol (February 2, 1842). By 4 January 1844, the construction of iron ships appeared to be growing markedly, and inspections were yielding "much valuable information".

It is, moreover, useful to cross-check this same period from a complementary angle, i.e. from the reports of the Surveyors themselves, which are held together as *Reports & C. of Surveyors No. 1, Nov1846 – Sept1852* (contents unpaginated). This source supplies abundant evidence that exemplary iron-screw projects (vessels embodying the "dominant design" of the future) and key selection events ("summative evaluations") were closely observed (as defined in Chapter 2, Section 2.2). There is in this source, for instance, a letter sent by the Surveyor of Bristol dated December 22, 1842, containing a wealth of data on the *Great Britain,* including details of her plates and drawings of the shape of the hull. In another document, a small but remarkable vessel received extensive attention, including comments and drawings of her parts. It was the *Q.E.D.* (see Figure 7.10), an "Iron Barque, built by Mr. Coattes to be propelled with a screw when necessary, particularly when ascending the Seine to Rouen." Several of her details were noted like her "alternate frames or ribs", her "complete internal skin" (double bottom), "two watertight bulkheads", and the "opening for the propeller".

Figure 7.10 "The iron steam screw collier, 'Q.E.D.'"



Source: *The Illustrated London News*, 28th September 1844 (in MacRae and Waine 1990, p. 9)

Surveyors and their networks

Another key archival resource are *Letter Books* (duplicates of issued mail) of the Surveyors working in the outports. These registered letters written by the Surveyors provide a perspective from actual activities on the ground. Sadly only three of these books appear to have survived: one covering August 1840 till February 1842, the most interesting one, and written by John Barr Cummings who had worked in Glasgow and Greenock and the other ports of the Clyde under his responsibility; and two slimmer ones by Walter Paton on Leith and ports on the Firth of Forth.

Cummings was employed by LR in April 1834 and stayed in Greenock until his death. Between 1835 and 1844 his yearly wage increased stepwise from £150 to £350 and then stabilised at £500 in the 1850s (cf. *Staff Bible*). This put him on a similar level to professions such as doctors, lawyers and senior clerks. Unsurprisingly the two single persons he wrote to the most, during the 18 odd months covered by the *Letter Book*, were LR staff: 59 times to Charles Graham, LR's Secretary, and 18 times to Walter Paton, his colleague in the North East. Letters to the Secretary are dominated by house-keeping issues, such as complaints of “great trouble in collecting the fees” (1st September 1840) or indications that particular vessels were “well fastened and entitled to her class.” (2nd January, 1841). Other entries are more interesting. A letter dated May 1st, 1841, affords some evidence of an increasingly systematic method of collecting technical data: Cummings writes to the Secretary that in the future we will keep a record on the “greatest and smallest spaces” between beams, not only the number of beams. In his correspondence with Walter Paton we often see preparations for visits of one surveyor to the other’s port for the purpose of conducting a common survey. Aside from Patton, the Clyde Surveyor sent letters to 14 other surveyors. It does appear, therefore, that circulation of technical knowledge and novelties occurred not only vertically in the organisation (to and from London) but also horizontally (among surveyors who would converse in letters or directly). We also learn that know-how was flowing between North Western and North Eastern shipbuilding ports through the close connections between, and the joint work carried out by, the surveyors.

The bulk of Cummings’ entries, however, relate to local shipowners and shipbuilders, and to engineers and naval architects supervising the yards. We see Cummings corresponding with a number of names that would become references in the story of the steamship, such as John Wood (the builder of *Comet’s* hull), John Scott Russell (then a manager at Caird & Co. marine engine builders but already famous as an expert on science-based shipbuilding), John Elder (then just 17 years old but already a prominent apprentice at Robert Napier’s & Sons’ Lancefield and Vulcan engine works in Glasgow), Robert Menzies & Sons (shipbuilders at Leith), and Robert Napier (one of the most successful and respected steamship builders of the day).

Several of these interchanges, of which we know just a truncated part, refer to the normal business of having the ships visited and classed but several others reveal deeper and wider aspects. Let us note three instances. First, to Scott Russell, in a letter dated

December 4th, 1841, the Surveyor observed some of the seams to be rather wide and recommended diagonal iron strapping if the steamer were to go to a foreign station. In other words, Cummings had opinions on technical matters that he saw fit to forward to iron steamship designers and builders. Second, letters to Menzies and Elder, for instance (19th and 22nd of March, 1841), strike us as displaying a quite familiar tone and they show the Surveyor to be willing to “give any information” in his power on matters ranging from ships’ usage to underwriting. That is to say, Cummings saw no problem is acting as an information broker in matters not strictly related to the ship inspection business. Finally, Cummings’ interchanges with Robert Napier are interesting, not least because they involve John Wood. To Napier alone Cummings sent eleven letters over a period from 23rd January to 13th July 1814. They concerned several steamers that John Wood was building at Napier’s specifications and the general impression is that the surveyors seemed to act as a sort of middleman between the designer and engine maker (Napier) and the hull subcontractor (Wood). The Surveyor shows himself anxious to keep Napier pleased and abreast of the progress of the work at Wood’s yard as well as setting down several notes regarding the quality of the materials and workmanship.

Surveying the activity of surveying, and recombining best practice

It was decided after 1840 that visits from the General Committee to the outports should take place every year (Fenton and Jones 2009, p. 21). A different route was chosen every time so as to ensure that each shipbuilding area was visited once every three years. The visits served a number of purposes: guaranteeing the application of the Rules; appraising the standard and quality of a surveyor’s work; examining the financial records; looking for opportunities to expand business; and demonstrating to local operators that Surveyors were part of a broader organisation (Fenton and Jones, 2009; Blake 1960, p. 173). But, vitally important, these visits also allowed members of the General Committee to witness first-hand the directions of development taken in different regions and to obtain direct feedback from shipbuilders on technical aspects of the Rules. A detailed report was compiled while on the journey containing all the observations deemed appropriate, including quotations from individual shipbuilders.

Tangible evidence of such tours of inspection are to be found in the journals of the visits.[22] A visit, which started on July 28, 1853, appears to have represented something of a turning point. The LR team was composed of five members, entitled the "Sub-committee", and it was headed by Thomas Chapman, LR's Chairman, who signed the last page as of September 27. The Sub-committee visited a large number of shipyards and invariably entered into conversations with shipbuilders. Numerous impressions were recorded of shipbuilders being "civil and obliging" (at Hull, *Visitation Committee* 1853, p. 1d)[23] and of receiving the party "with much kindness" and "courtesy" (on the Clyde, *Visitation Committee* 1853, p. 7c and 7d). On August 9 they were "very well received" at the premises of Alexander Hall & Co., the celebrated pioneers of the Aberdeen bow, where it was noted that "(t)hey readily acknowledged that the Society had undoubtedly done much good to the general improvement of shipbuilding." (*Visitation Committee* 1853, p. 6c) Then, on August 11, the Sub-committee departed for the Glasgow area, where the visits to luminaries of the emerging shipbuilding industry (the Scotchs, the Steeles, the Thompsons, the Dennies) "appeared to afford much satisfaction" (*Visitation Committee* 1853, p. 8a). Here "visits could not fail to produce a deep impression of the rapidity which the substitution of iron for wood in shipbuilding is progressing and of its great importance." (*Visitation Committee* 1853, p. 8a) On the Clyde "the general activity that prevailed was truly astonishing." (*Visitation Committee* 1853, p. 8b) Before concluding their report, the Committee noted the "great extent to which Iron ship building is now carrying" and the expectation that it "will still be increased at Hull, in the Tyne, and at Greenock, Dumbarton, and Glasgow", and arrived at the following recommendation:

[22] These records too have traditionally been a rarely utilised source. Notable exceptions are Macgregor (1988), Corlett (1990), and Clark (1997).

[23] Each sheet numbered, each face noted here as "a", "b", "c" or "d".

> "The subcommittee considers that a review of the proceedings taken to obtain information upon this important subject if possible to frame rules is highly desirable." (*Visitation Committee* 1853, p. 9a)

The appearance of the first iron rules

Thus, LR officials seem to have to been finally convinced of the inevitability of introducing appropriate rules to judge iron ships from what they saw in the summer of 1853. It is significant that in the last pages of the report the 1853 Visitation Committee decided go back many years in order to report that:

> "In the year 1846 the attention of Mr. Creuze was particularly directed to this object. He then visited the several iron shipbuilding yards, having collected much useful information, he made a very interesting report, shewing, by Diagrams, the various combinations in the essential parts of a ship, by which the whole fabric was brought together. (*Visitation Committee* 1853, p. 9a)

Augustin Bullock Creuze (1800-1852) was the able successor of George Bayley as the Chief or Principal Surveyor in 1844, a position he held until his death. Creuze, a Fellow of the Royal Society, had solid scientific credentials and a close association with the Admiralty, being one of the 41 graduates of a short-lived school of naval architecture established in Portsmouth (Pollard and Robertson 1979, pp. 142-3; Watson 2010, pp. 154-5). Like Bayley, Creuze was something of a "public intellectual" in matters of maritime technology. By 1839 Creuze was "a gentleman already favourably known to the public, by his papers on naval architecture." (*The United Service Magazine*, 1839, Volume 31, p. 337) And by 1846 Creuze had written an article on shipbuilding for the *Encyclopaedia Britannica*, and several articles in *The United Service Journal* where he wrote on issues such as shipwrecks and the merits of iron ships.[24] The Principal

[24] Creuze contributed to the increasing availability of information on iron steamship construction by reporting (favourably), in particular, on Laird's *Nemesis* in 1840, a vessel he examined on the request of the Admiralty (see Brown 1990, p. 76; Rodgers 1996, p. 10; Lambert 1999c, p. 48). In the Great Exhibition of 1851, Creuze was involved in the selection of the exhibits having to do with naval architecture (Watson 2010, p. 155). His books and models were bequeathed to LR before he died, becoming the trigger to the formation of the Society's library. Incidentally, the Great Exhibition has been studied from a variety of angles (Greenhalgh, 1998; Auerbach, 1999; Davis, 1999), but so far the maritime exhibits showcased there have not been the subject of an explicit analysis. This is work worth pursuing in the future.

Surveyor's hands-on study visits led to a revision of the terms for reporting iron ships and to the adoption of a survey form calling the attention of Surveyors to several important points for classifying such vessels. The following year, Creuze's exertions to find out more regarding the properties of iron steamers continued:

> In September 1847, the Committee deeming it desirable that as much information as possible should be obtained regarding the 'Great Britain', after the perilous position in which she had been placed dispatched Mr. Creuze to Liverpool. After reporting upon her condition he states 'I went Mr Laird's Ironship building yard at Birkenhead partly to see the vessel he is now building, and partly also to talk with his foreman who I consider <u>one of the best</u> if not <u>the very best ship-</u>smith <u>in the Kingdom</u>. My object was to see whether anything, as a further test of workmanship, could be added to the new form for Ironships which has been issued, and I was pleased to find, that, after a long conversation with him, nothing further suggested itself to me." (*Visitation Committee* 1853, p. 9b-c, underlining in the original)

We thus see the *Great Britain*, which had just been refloated after her long period of being stranded in the sands of Dundrum Bay, emerging as a case study (see Figure 7.11). And we also see John Laird's shipyard, to which this LR's officer seemed to have unfettered access, working as a sounding board in the process of developing surveying methods. That LR was paying so much attention to Brunel's vessel is a powerful finding and corroborates the view of the *Great Britain* as a technological exemplar influencing an institution that helped to frame innovative shipbuilding in Britain. The report continues with events of September 1850, with Creuze again being sent to several iron shipyards "to obtain as much information as might be in his power to procure."

LR's first *Rules for Iron Ships* appeared in 1855, but the first formal steps had started a decade earlier. The *Rules* of 1845 required that iron ships classified A1 should be subject to an annual survey (Fenton and Jones 2009, p. 33). In 1852 a small section on "Ships Built of Iron" was inserted into the existing *Rules*. Before the end of 1853, it fell to the Joint Principal Surveyors, James Martin and Joseph Horation Ritchie (co-appointed in the sequence of Creuze's death in 1852) to head a special Sub-committee which began the efforts of framing new rules (Jones 2000, p. 22). After another tour of inspection and a process of debate the rules were finally published in the 1855 *Register Book*. The *Rules* started with a cautionary observation:

> "Considering iron Ship-building is yet in its infancy, and that there are no well understood rules for building Iron Ships, it is *not* desirable at present to frame a scheme *compelling* the adoption of a particular form or mode of construction, but that certain general requirements should be put forward, having for their basis, thickness of Plates and substance of Frame, shewing a *minimum* in each particular, to entitle Ships to the character A for a period of years, subject, however, to certain periodical surveys; (...)."

Figure 7.11 "SS 'Great Britain' ashore in Dundrum Bay, Ireland, 1846"

Credit: The Science Museum

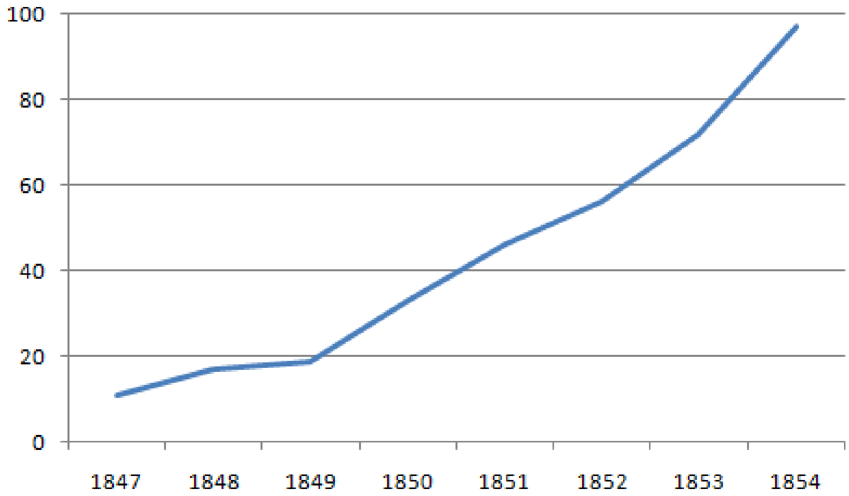
An example of this general and minimalist approach was the requirement of having at least two watertight bulkheads at a reasonable distance from of each other. Shipbuilders tended to follow local practice and the durability of iron as a shipbuilding material was still a matter of speculation. Given the divergence and uncertainty in the details of design and construction methods, LR's regulations were still tentative. This tact and prudence paid off as the Visiting Committee of 1855 found few objections on the part of iron shipbuilders (MacGregor 1988, p. 133). The Rules were amended in 1857 and small modifications continued to be introduced thereafter until a substantially revised version was adopted in 1870 (Fenton and Jones 2009, p. 35).

Surveying radical innovation – LR and the coming of iron-screw cargo traders

What was LR's actual surveying experience with steamships, especially those cargo traders of the iron-screw type? One source to explore is the corpus of available *Register Books*, where surveyed and classified ships (above 100 tons) were listed along with their details (name, year and place of build, owners, classification, etc.) starting in 1834. Interestingly from the point of view of this thesis, the *Register* displays a separate section for "Ships navigated by steam" from 1838 onwards. For instance, in that year 55 steamers are listed. In addition, the *Register* lists "Vessels built of iron" broken into steam and sailing vessels from 1843 until 1854, hence covering the key period of transition we are examining. For example, in 1843 eight iron-steamers and eight iron sailing ships are listed. Between 1847 and 1854 the list also separates out iron-screw steamers. For instance, in 1847 there appear 97 steamers, 21 of which are iron steamers, and 11 are iron-screw steamers.

How wide and representative was LR's survey work? In the previously mentioned year of 1854 there are 227 steamers on LR's record, which represented only 2.1% of all listed ships. But this can hardly be taken as a sign of a prejudice against steam on the part of LR. According to Brian Mitchell (1988), there would have been only 1524 steam vessels afloat in 1854 (compared with a total of 25,335 sailing ships), meaning that LR had inspected something approaching 15% of all steamers in operation at that time (as compared with about 41.8% of all sailing ships in operation). On the contrary: if anything it would seem that LR tended to report on the most sophisticated of the steamers: from 1850 onwards, the majority of steamers listed are iron steamers; during 1847-50 54% of all listed iron steamers were iron-screw, that percentage rising to 59% in 1851-54. Figure 7.12 illustrates this by showing the increasing trend of surveyed iron-screw steamers in terms of absolute numbers. In 1847 less than 20 iron-screw steamers were on record, whereas only seven years later that number was approaching 100.

Figure 7.12 Number of iron-screw steamers listed by LR between 1847 and 1854



Source: elaborations on LR's *Register Books*

Another important question has to do with what kind of steamers where being surveyed and classified from the point of view of their economic function. Table 7.1 offers a view on the distribution of the different types of trade specialisation being surveyed by cross-referencing LR's data with Robin Craig's database (which, to recall, has been only digitised for the letters A to M). Hence, the table is a sample of ships listed by LR corresponding to roughly half of the total number of steamers for which economic particulars are available. The results are nonetheless suggestive: the majority of surveyed steamers were consistently cargo traders from the mid-1840s to the mid-1850s. This is significant as it shows that LR's attention was not homogenously allocated across commercial activities. LR was following more closely cargo traders than any other type of steamer. What is more, the relative importance of the surveyed cargo traders only stands out when set in context with the broader population of ships: on the one hand, from the table we see that in 1848 traders were 45% of all surveyed ships, and 57% in 1851; on the other hand, we know from the Craig-Mendonça database that cargo-traders represented a smaller proportion of the population of newly-built ships, 8% in 1840-44, 23% in 1845-49, and 43% in 1850-54. That is, LR's operation focused heavily on "humble" (but modern) cargo carrying steamers, not on "premium" (but subsidised) steam packets during the crucial years of the modern ship revolution.

Table 7.1 Sample of steamers listed by LR according to their commercial duties

	Traders	Tugs	Packets	Ferries	Experimental	Unknown	Total
1845	3	1		1		2	7
1848	9	2	2		1	6	20
1851	27	2	9	2	1	6	47
1854	45	6	18	6		15	90

Source: elaborations on LR's *Register Book* and the Craig-Mendonça database

Another exercise that the cross-check between LR's lists and the Craig-Mendonça database allows us is to focus solely on traders. We can, for instance, address the number and proportion of traders that were surveyed according to their design and ports of build. Table 7.2 summarises the numbers of cargo traders built in the late 1840s and the early 1850s (again, these figures are a sample as they correspond to the about half of the population built between 1846 and 1854).

Table 7.2 Sample of iron-screw traders built and surveyed, 1846-53

		Clyde	North East	Thames	Swansea	Ireland	Liverpool
1846-1849	**I-S**	5	3	1	1	2	2
	I-P	1	1	1			
1850-1853	**I-S**	19	2	2			1
	I-P	1		1			

Source: elaborations on LR's *Register Book* and the Craig-Mendonça database
Note: I-S, iron-screw; I-P, iron-paddle cargo steamers

We learn several things. First, a general observation: of the 38 iron-screw traders built in 1846-49 (and reported in the Craig-Mendonça sample) 17 were surveyed, that is about 45%. And of the 75 iron-screw traders built in 1850-53, 26, or 35%, were surveyed. In other words, Chapter 5 (Section 5.5) had shown that the radical iron-screw reconfiguration took hold decisively in the cargo steamer niche in the first place; it is now clear that LR studied a by-no-means insignificant proportion of this new variety of steamship from the outset. Second, what we also find is that iron-screw traders dominated in LR's surveys when compared with iron-paddle ones. That is, 82% of the surveyed steam traders of 1846-49 were of the iron-screw design, and 92% in 1850-53. Third, we find that LR was approached for service and carried out surveys in a number of ports, including peripheral ones (especially in the early exploratory years, before regional specialisation set in). In fact, although LR had its head-quarters in London, it did most of this advanced survey work in the Northern ports, particularly on Clydeside, during these years.

Finally, we see that LR was studying and learning from quite pioneering and influential ship projects from a number of regions from the very beginning. Innovative steamers like the experimental *Archimedes*, the North Eastern iron-screw *Bedlington*, the *John Garrow*, the *Q.E.D.*, the *Collier*, the *Fire Fly* and the *Augusta*, all came under the close scrutiny of LR's highly knowledgeable, networked and communicative Surveyors in this pivotal moment in the evolution of the industry. In other words, the core iron-screw architecture did not emerge unaided; it seems to have benefited from the assistance of that most expert, disinterested, and geographically dispersed institution of commercial shipping: Lloyd's Register.

The impact of LR in times of intense technical change

What effects did LR's work produce on general shipping? Some hints can be gleaned from contemporary statements recorded in parliamentary and other public events. One key instance of LR's recognition comes in 1836, merely two years after LR had been reformed. A Select Committee on Shipwrecks acknowledged that "there is good reason to believe that the ultimate result of this new system of classification will be to effect a great improvement in the general character of the ships of the United Kingdom" (*BPP*, 1836, p. vi). Evidence suggests that this hope was soon to be materialised.

As an indication of their recognition, Surveyors were asked to appear as witnesses in several parliamentary hearings. In the 1836 Select Committee on Shipwrecks, Nathaniel Symonds, the Society's first Secretary, and George Bayley, the Principal Surveyor, were called to give evidence. Symonds described to the Select Committee how LR was a private society governed by a committee constituted, on "equal proportion", by the interested parties of the shipping industry – merchants, shipowners, and underwriters – and went on to explain what classification procedures were followed (*BPP* 1836, p. 157). Bayley, also present at these hearings, emphasised the rigour of LR's work by saying that a ship was to be inspected and reported upon at least three times during her construction according to the rules, but that monitoring was actually much more frequent than that (he was checking ships at least once every week, *BPP* 1836, p. 181). Bayley also noted that he, "as matter of courtesy, during the progress of building, [would] state to the builder the objections which arise to the work, leaving him to the full exercise of his own discretion; I never interfere to dictate to him what course he shall pursue, that is not my province." (*BPP*, 1836, p. 181) Questioned if this system of classification contributed to the building of better ships, he stated: "I have not the least doubt of it; I know it to be the fact." (*BPP*, 1836, p. 181)

Charles Graham, George Bayley, John Barr Cummings, Walter Paton, and others from LR answered a call by another Select Committee in 1839, this time on steamship accidents, along with eminent builders and architects such as John Laird, Scott Russell, David Napier, Tod and Macgregor, John Wood, John Seaward and William Fairbairn. It is worth noting that in his testimony Bayley refers the Select Committee to the *Mechanics' Magazine*, since it gave a "very correct representation" of a fractured cylinder after the accident of a particular steamer, the *Victoria* of Hull (*BPP* 1839, p.

140). Incidentally, John Seaward also refers the Select Committee to the *Mechanics Magazine* in his own communication (*BPP* 1839, p. 125). This is significant: that the top LR Surveyor and a key member of the Civils both suggested that the Select Committee look at the *Mechanics' Magazine* provides an instance in which all these three institutions are linked together at the same time; an instance that, moreover, took place within a framework of public interest for the entire shipping industry.

Speaking in public in 1860, when the major advances regarding iron-screw merchant steamers had already been made, during the inaugural debate of the Institute of Naval Architects,[25] John Scott Russell praised LR's "very wise policy" of tolerance for experimentation that had notably been exercised in the realm of iron shipbuilding in the 1850s, and which was "Lex non Scripta":

> "They have made a rule, which, if you like, I will call the 'Rule of Exceptions.' They say, 'If you build your ship in your own way, and satisfy us that the ship you have built is stronger than the ship built according to our Rules, we will give a good classification as if you had conformed to those Rules." I say, if they will continue to act on that system, neither Mr. Fairbairn, nor Mr. Napier, nor Mr. Grantham, nor myself, will ever say a word more against Lloyd's Rules. But, if they will not so act, then, as far as our influence will reach, we will say, 'You have no business to put restrictions on us shipbuilders.'" (*TINA* 1860, p. 83)

Summary of Section 7.4

The activity of quality inspection was somewhat of an idiosyncrasy of the shipping industry and was pioneered in the British national system of innovation in its modern form. LR was a privately managed not-for-profit organisation of national scope that represented a wide array of stakeholders. This development was to prove timely: LR watched over the rise in importance of the steam fleet, the radical transition from wood-paddle to iron-screw technology, and the birth of the iron-screw cargo trader as a new

[25] The prestige of LR was recognised publicly by INA by making LR's Chairman, Thomas Chapman, founding Vice-President and the Joint Principal Surveyors Martin and Ritchie founding members of the new Council.

species of merchantman. This Section has brought together, systematised and examined a diverse body of little used archival material that sheds new light into LR's complex role during the critical years of the maritime industrial revolution.

LR was a custodian of good shipbuilding standards but it also kept abreast of innovation. LR was already surveying steamers on a routine basis from 1838. From the mid-1840s the *Register Books* reveal the particular attention paid to iron as ship-building material and the screw as a form of propulsion. By the 1850s LR had accumulated a wealth of experience in surveying iron-screw cargo traders, the revolutionary techno-economic combination central to the wave of industrial globalisation that would place Britain at the centre of the world economy for the remainder of the century. LR was actively examining the earliest iron-ships and iron-screw ships, large and small, experimental and trading, from the earliest days, during construction and during decisive events involving them. The evidence suggests that LR absorbed the new iron-screw know-how from the most audacious and experienced builders and proceeded to diffuse it to builders throughout Britain. Surveyors visited several ports during the course of a year, often changed port during their careers, were in constant communication with London's central headquarters, received Visitations Committees, and kept in regular correspondence with the best shipbuilders as well as with fellow Surveyors at other ports. LR provided free advice to all shipbuilders willing to listen, tentatively pushed for new rules in close connection with the shipbuilding community, and appointed Chief Surveyors who were in effect "public intellectuals" contributing to the most pressing technical debates of their day. In brief, LR monitored the evolving best practice and actively diffused it.

7.5 Discussion of the empirical findings

Summary of the findings

Explaining the effective and fast-paced rise of the modern steamer without bringing in the Institution of Civil Engineers, founded in 1818, would be a hard task. This was the intellectual theatre of operations in which all the separate lines of steamship development converged and the fundamental uncertainties regarding their combination were addressed. The Civils are directly connected to the success of the first sea-going iron steamer in the early 1820s, the *Aaron Manby*. This connection to a founding radical innovation is important. It has been a somewhat underappreciated one even though it was the very son of the builder, Charles Manby, who played a continuous central role in the institution until the 1880s, that explicitly acknowledged it. From the outset, the Civils were guided by scientific values of justified argumentation, open debate and free disclosure of relevant information concerning new technologies and engineering events. The Civils emerged as the organizational platform that allowed influential knowledge integrators, such as Brunel, to make the most of the fresh complementary possibilities of steam, iron and the screw propeller. This was a safe conversational setting in which innovators could take advantage of informal criticism. There were numerous occasions in which particularly innovative projects were discussed, namely the iron-screw design details of paradigmatic ships ranging from the Atlantic packet *Great Britain* to the steamer collier *Sarah Sands*. In Buchanan's (2002, p. 220) felicitous phrase, the Civils emerged as "a focal point for consensus" at a time of unprecedented technical change. A number of other similar voluntary associations were formed along similar lines that reinforced this culture of sharing and collective self-education. We find reasons to believe this type of quasi-academic, collegial-like institutions deserves not a small share of the credit in the steamship story.

In this story, however, more than just direct or face-to-face engineer-to-engineer communication was at stake. Specialised, technology-oriented print media was another institutional innovation of the time. This intermediation platform made available insights and practices to a more general and dispersed audience. The magazine reported faithfully on experiments and experiences and, in that way, brought them to a much broader constituency than otherwise would have been possible. Even taking into consideration the very visible physical nature of steamships and the institutionally open nature of interactions within the engineering communities, we find reasons to believe that such outlets made a difference in spreading further the knowledge spillovers. The technical press collected raw data and diffused updated engineering facts and figures in an era in which information still circulated relatively slowly. Key innovators and surveyors used it to request and provide advice on steamship technology, and to discuss new solutions and failures concerning steamship design. The fundamental issues of screw-propulsion, iron shipbuilding, and real-world tests of evolving iron-screw ships were among the most publicised engineering news of the 1840s. Indeed, a case can be made that the technical press accelerated change and contributed to the cumulativeness of steamship innovation. The evidence suggests that the *Mechanics' Magazine*, founded in 1823, played such a role during the critical years of steamship evolution.

Finally, LR synthesised the interests of downstream sectors (shipowners, merchants and underwriters) and was instrumental in raising the quality of modern shipbuilding in Britain. Always in the background of the shipping sector, this not-for-profit institution justified its existence by providing sound technical information regarding the structural characteristics of merchant ships. Although keen in asserting its impartiality and the rigour of its standards, it had a cooperative attitude towards innovators after it was re-launched in 1834. LR developed a sure but delicate approach to technical change: it identified and followed up experiments that deviated from the Rules; it gathered systematic evidence of shipbuilding practice from all British ports; it recommended the adoption of particular solutions to steamship builders so that they could catch-up with best practice; and it worked toward eliminating the friction between engine and hull builders, ship designers and subcontractors. Between the mid-1840s and the mid-1850s, LR's collective knowledge of iron-screw cargo steamers developed tremendously and was indeed probably unsurpassed. Its surveyors followed an *ethos* of quiet and un-interfering professionalism. Nevertheless, they were able to write for the *Mechanics Magazine*, to interact intensively with naval architects and marine engineers communities, and to serve as expert witnesses in parliamentary hearings on steam navigation. There can be little doubt that LR effectively contributed to validating working innovations and to promoting knowledge dissemination at a most critical juncture for the modern steamship.

The technological public sphere

It is difficult to separate the rise of the modern steamer from the remarkable institutional developments taking place in the broader "national system of innovation". Changes in the infrastructure for innovation converged between the mid-1830s and the mid-1840s. New institutions acted as "moving parts" of a learning machine that aggregated dispersed knowledge and, subsequently, disseminated, filtered and systematised it. Taken as a whole, these partially overlapping arenas of an institutionalised and distinctively British collective agency worked as a learning accelerator and knowledge re-distributor: they encouraged new thinking in steamship design (i.e. they stimulated innovation and variation), they discussed engineering news (i.e. they evaluated technological selection events), and they developed the collective memory concerning standards of construction (i.e. the retention of working solutions). During this temporal hotspot, a major breakthrough occurred, the shift from the small wooden side-paddler design to the large, powerful, iron-hulled, screw-propelled, ocean-going steamship.

We believe that the case of early steamship development illustrates how, in a fundamental sense, debating became a form of learning. The modern steamship was a challenge of knowledge integration in the presence of radical uncertainty. It was also an expensive capital good in which failure often had catastrophic consequences. Something more than just informal "technological communities" evolved during the transformation process which the steamship underwent from the 1830s to the 1850s. As William Fairbairn put it in the 1851 patent hearings: "we are largely indebted to each other" (*BPP* 1851, p. 174). The fraternal cross-consultation among engineers in the dedicated professional associations (primarily the Civils) exhibited many composite features that the extant literature associates with "invisible colleges", "epistemic communities" and "communities of practice" (Chapter 2, Section 2.4). But learning gained new momentum after the *Mechanics' Magazine* and LR also got under way. Steamship development occurred largely at the margin of the patent system (Chapter 6). But the process of knowledge exchange was more structured than the concept of "collective invention" would lead us to anticipate (Chapter 2, Section 2.2). Cooperation involved formal institutions, plenty of explicit publication of technical information, and more actors than simply the inventors themselves.

When we consider together the existence of various independent, but overlapping, voluntary institutions oriented towards the mutual benefit of their members (like the Civils), the promotion of unrestricted dissemination of ideas and technical information (like the *Mechanics' Magazine*), and the activity of non-profit organisations (like LR), we arrive at the conclusion that we are talking about a distinctive form of social behaviour and active participation within British civil society of the time. Each type of civil society institution centralised knowledge and retransmitted it broadly back to those individuals and firms working on the same or complementary problems. A new combination of institutions emerged to become a unique (i.e. British) infrastructure for stimulating innovation (i.e. variation), speeding the flow of information regarding the appropriateness of the technology to its domains of application (i.e. selection), and creating a repository for the accumulating stock of knowledge (i.e. retention).

This was a flexible but consistent institutional framework. Seen in this light, one is led, quite intuitively, to consider an extension to the notion of Jürgen Habermas (whose key contributions were originally published in 1962 and later in 1981) of a "public sphere". To this space, as distinct from market competition and state bureaucracy, where engagement in the technological dimension of public life develops in a spirit of cooperation and openness, we may attach the label of the "technological public sphere". That is, individual engineers made available to others their insights and results but they did this through an institutionally rich realm of interaction. Through a set of novel institutions, engagement occurred in the form of a genuine, vibrant and self-organised rational-critical public debate on the vital technological issues of the day, i.e. a technological conversation relating to industrial-age navigation.

In this realm, and again to appropriate the terminology of Habermas (1964, p. 59), something approaching a "public opinion" between the participants and stakeholders in the technological process was formed. That is, a consensus understanding of the "modern ship" emerged through free exchanges as well as formal debates among individuals organised through a set of complex personal relationships and finely balanced institutional arrangements. The process through which general opinion concerning steamship design changed involved a dramatic departure from conventional wisdom. That is to say, technological conversations generated light, but they also produced heat: animosities in the Civils, polemics in the *Mechanic's Magazine*, and tension between LR and shipbuilders are examples of the latter. The introduction of a new steamship design, which was not simply a refinement of a pre-existing archetype, implied the tearing down of a "barrier of opinion" (King 1907, p. 299). That is, the technological conversation was not merely about information circulation but also about a transformation of interpretative structures and the capabilities of participants.

This study has attempted to show how the voluntary release of technical information took place in open-science-like institutions (learned societies of engineers), with the flow of technical disclosure being tracked though media channels (the technical press), and innovative contributions being certified by a non-profit organisation (an assurance corporation bringing in the interests of stakeholders). What we call a technological public sphere can be seen as an example of (following Mokyr 2010, p. 184), an enlightenment-like way to "channel creativity into productive activities". The institutional change we refer to resonates with what von Tunzelmann (2004, p. 330) has termed UK's "long history in 'third' way activities", i.e. Britain's early formation of voluntary knowledge-based associations bridging activities between invention and commercialisation. These findings may have implications for a recent debate among economic historians: on one side, those emphasising the role of "relative prices" as the ultimate trigger of the Industrial Revolution (Allen, 2009); on the other those referring to "industrial enlightenment" to describe the growing culture of applying rational knowledge to a widening range of technological and economic puzzles being increasingly defined as mechanical in nature (Mokyr, 2010). Our case study seems, quite naturally since it shares with it an emphasis on technology and evolution, to lend more weight to Mokyr's perspective. But, in what way?

One specific way has to do with the particular influence of the "Scientific Revolution" in general, and the Enlightenment in particular, on the Industrial Revolution. The consensus among historians seems to be that any linear causation arrow from science to invention cannot be proven, the argument goes, as France was much more advanced in terms of science and the aloof Royal Society was not geared up to pursuits in applied mechanical knowledge (see von Tunzelmann 1995, p. 120; Allen 2009, p. 10). Our findings show, however, that in the steamship case study an indirect role of research routines on industrial innovation can hardly be excluded. Smeaton was a member of the Royal Society that carried the practice of empirically informed theoretical debate to the realm of engineering gentleman clubs, something enshrined in the constitution of the Civils, an institutional innovation that provided the intellectual environment of openness and learning in which the idea of the modern steamship came to be nurtured. As it happens, at a time when no established university system existed for technical subjects in Britain, “speculative thinkers and experimenters” were much less isolated than it has previously been common to assume (Pollard 1989, p. x). The proverbial “practical men”, after all, built a research-based “collective self-help” system for themselves. New technologies and innovative projects benefited from the mutual assistance among engineers. This was also an efficient practice since it minimised “duplicate inventing”, to use Gilfillan’s (1935a, p. 76) term, and fostered cumulativeness in the case of steamship innovation. This set of mechanisms which we label the “technological public sphere” became established at a time when the traditional apprenticeship system was still very much in use and formal education in Britain was still generally weak. There is considerable empirical support for the argument that academic-like collegial routines were instrumental in helping innovators to keep up with the increasing scientific sophistication of marine engineering and naval architecture.

An impact of the “technological public sphere” on the economy as a whole was probably to strengthen the cohesion of the British national system of innovation in general, and to launch British shipbuilding as the world’s first such modern industry in particular. This observation provides operational content to Mokyr’s claim that, as Allen (2009, p. 10, italics in the original) puts it, in Britain there was more “[c]ommunication between *savants* and *fabricants*”. British shipping as a whole was a singularly efficient industry and an unprecedented success story because it was a particular case of a “mixed economy” (see Nelson, 2011), i.e. it was cooperative in its technological “back-office” but competitive in the service “front-office”. In the light of the quantitative and qualitative evidence uncovered and assembled in this thesis, however, the birth modern ship was apparently more a product of collegial collaboration than of patent-seeking entrepreneurs, isolated shipbuilding firms, or market-based competition.

7.6 Conclusions

Any account of the pivotal period of 19th century shipping from the point of view of innovation studies has to consider its wider institutional context. This thesis is an attempt to establish a connection between the rise of an institutional setting we have termed the "technological public sphere" and the mid-century "take-off" of steamship technology. The present chapter has sought to argue that a combination of institutionally networked engineers, the systematic publication of community news, and the public-good agenda of a non-profit organisation mattered in terms of innovative outcomes in the field of steam navigation. It is hard to conceive as a mere coincidence that the steamship flourished precisely as all the pieces of what we have called a "technological public sphere" fell into place. On the contrary, this institutional and cultural setting cannot be decoupled from the dramatic rethinking of the fundamentals of the steamer between the mid-1830s and the mid-1850s. An array of qualitative evidence, some unearthed and presented here for the first time, shows how critical institutional innovations preceded and were involved in the emergence of the large and efficient, iron-hulled and screw-driven – or in one word, the "modern" – ship.

This thesis started from the observation that, while the literature took it for granted that the steamship was a robust capital good by the 1860s, the early process by which it evolved was still rather inadequately understood. In our research we have attempted a detailed analysis of the circumstances behind the quantitative patterns identified in Chapters 4 and 5. Relying heavily on direct contact with primary sources, we have become convinced of the necessity of understanding the role played by the particular ways in which a broad community of experts became organised around steam navigation. As shown in Chapter 3, it was not the availability of individual technological concepts *per se* that represented the key novelty: after all, the screw propeller, iron plates, and reliable steam engines each made their debut well before the mid-1830s. What happened was a change in certain institutions (a bottom-up set of developments) that stimulated knowledge integration and made innovation cumulative. As other technological learned societies and technology-oriented media started to proliferate from the mid-1850s onwards, the corpus of steamship technology was already forming a well-connected and growing whole around which incremental and modular innovation could progress along an economically useful "trajectory".

There was community of steamship engineers and architects who were increasingly self-aware and free to use each others' work. They operated under shared norms of open and reciprocal cross-consultation practices moulded by the Civils' ethos, often mediated and informed by the print media and LR's operations. This set of intertwined practices seems to have been a major driver of innovation. These technologists and other experts entered the dialogue in a variety of ways. Section 7.2 provided an account of how engineers met and interacted in a friendly and inclusive environment like the Institution of Civil Engineers. Section 7.3 showed how observers and actors tracked the course of experiments and contributed news to outlets like the *Mechanics' Magazine*. Section 7.4 described Lloyd's Register as an impartial but engaged organisation, a prudent but frank mirror of the engineers' innovations. Section 7.5 discussed how each institution, in its own way, contributed to the engineer's ability to access, retrieve, validate, and accumulate new practical scientific and technological knowledge.

In this work we have found that complex institutional innovation and complex technological innovations went hand in hand. As the concept of the modern steamship matured, so the institutional conditions that helped engineers to innovate increasingly developed in a form that could be described as a "technological public sphere".

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Chronology

The following is a listing of selected events and developments in steam shipping compiled from several sources. The idea for this chronology came for two early books on steam navigation which contained time-lines of events and developments in steam navigation and which proved very useful for the work conducted in the current Dissertation (Boyman, 1840; Dodd, 1868; Kirkaldy, 1914).

Note about sources: entries not displaying a specific source are to be found in multiple books, book chapters or papers, i.e., they can be assumed to be general knowledge in the extant literature; those entries that are referred to a specific source are less commonly acknowledged features and issues.

Date	*Description of event or development*	**Source**
1618	- First English patent on matters related to steam navigation	Woodcroft 1848, p. 4
1690	- Denis Papin presents first clear proposal for steam-driven locomotion. It related to the application of steam on a boat.	Spratt 1958, pp. 23-4
1736	- First clear steamboat English patent and steamboat illustration, by Jonathan Hulls	Spratt 1958, pp. 26-7
1775	- First attempt at a practical trial of a steam boat. It took place on the Seine but was unsuccessful. The author of the experiment was Jacques Constantin Périer	Spratt 1958
1783	- First successful experiment in steam propulsion, by Marquis de Jouffroy d'Abbans the *Pyroscaphe*	Gilfillan 1935b, p. 92
1788	- First experiments in Britain. A steamboat by William Symington, a twin-hulled with paddles in between, 15 feet in length, made five miles an hour. It was commissioned by Patrick Miller, a well-off Edinburgh Banker and land-owner	Woodcroft 1848, p. 35-58; Smith 1938, pp. 12-2
1790	- The American John Fitch becomes the first individual to operate a steamboat for commercial purposes, on the Delaware river.). The boat was propelled by three paddles at the stern at a speed of up to 8 mph, carrying passengers and cargo between Philadelphia and Trenton	Gilfillan's 1935b, p. 82; Spratt 1958, p. 41-2; Trace 2003, p. 238
1802	- Successful tests in a canal of the *Charlotte Dundas*, a tugboat built in 1801 and engined by Symington, often described as the first practical steam boat ever built	Woodcroft 1848, pp. 35-58; Gilfillan's 1935b, p. 82

1807	- The *Clermont*, commenced in 1806 by the American Engineer Robert Fulton in association with a well connected American politician, started operating on the river Hudson and became the world's first commercially active steamboat	Spratt 1858, p. 81
1812	- Henry Bell's *Comet* is launched on the Clyde and becomes Europe's first steamer put into commercial service	
1813	- Introduction of iron cables for mooring purposes - The East India Company looses its Indian monopoly (*)	(*) Corlett 1990, p. 9; Woodman 1997, p. 190
1814	- First steam-powered war vessel, *Fulton the First*, is launched in 29 October 1814 at New York. Robert Fulton referred to this vessel at least once as *Demologos* ("The Voice of the People"), this being the name most historians have used to refer to her (*) - The *Richmond* becomes the first steamer to carry passengers on the Thames (**) - the Clyde-built *Duke of Argyle* performs the first long coastal passage (***) - The *Industry* is launched in May. First intended for the passenger transportation she was converted for the *cargo* trade on the Clyde. She began to work as tow boat making her the generally regarded first steam tug. She would be laid up in the 1870s (****) - First steamer owned by a government launched in the USA. Fulton's *Demologos* had an internal paddle-wheel and was intended for harbour defense (*****)	(*) Hutcheon 1981, p. 129, (**) Dear and Kemp, 2007, (***) Greenhill and Giffard 1994, p. 29 (****) Thomas 1983, p. 2 (*****) Lyon 1980, p. 16
1815	- The *Margery*, a little wooden vessel built on the Clyde in the previous, becomes the first steamer to work on the Thames	Spratt, 1958, pp. 92-5l
1816	- Black Ball line enters the passenger and emigrant trade on the Atlantic. It introduces a new form of organisation in the long-distance trade, the "packet" (or "liner") concept, by sailing regularly to definite dates. It becomes the first of a series of new fleets of well-built ships.	Corlett 1990, p. 8; Pollard and Robertson 1979, p. 9
1817	- First inquiry into boiler explosions leads to first government regulation over steam ships - The *British Caledonia* is the first steamer to cross the Channel	Tyler 1939, p. 5
1818	- Joseph Price, the first owner of a Tyne-built steamboat tries to introduce the towing system. Price claimed he entered the tug trade for the first time having the first sailing vessel is successfully towed down from Newcastle into the sea for 13 miles against the wind in 2 hours and 10 minutes in July 1818 (*) - First iron vessel is the *Vulcan*, built in the Clyde (**) - Launch of first steamer in the world to enter regular service first between Greenock and Belfast, the *Rob Roy*, built by William Denny of Dumbarton (***) - David Napier is reported to conduct experiments with model ships in especially build tanks.	(*) Dougan 1968, p. 28 (**) Clark 1912, p. 313 (***) Hume and 1975, p. 9 (****) Rowland 1970, p. 52

	(****)	
1819	- First steamship crosses the Atlantic, the auxiliary wooden New York built steamer *Savannah*, she had originally been built as a sailing ship in 1818 at New York but was equipped with a single-cylinder engine and boiler on deck driving two retractible and portable paddle-wheels that could be stowed on deck in bad weather, she left Savannah, Georgia, on the 22nd of May 1819 and arrived to the Mersey on the 20ht of June, her engine was in use only 80 hours during the voyage (*) - The Tonnage Law of 1773 is re-enacted (by the Act of 59 Geo. III, c. 5) and revised to allow the deduction of machinery (engine and boiler) space in the case of steam vessels (**)	(*) Clark 1912,p. 313 (**) Graham 1956, p. 78
	- Marc Brunel is supposed to have conducted in circular tanks or canal made in which the various models were made, some by screw-propellers	Corlett 1990, p. 46
1821	- The *Aaron Manby* becomes the first iron steamer. Built in Britain for traffic on the Seine (*) - The *Rob Roy* inaugurates regular steam cross-Channel traffic linking Dover and Calais (**)	(*) Baker 1965, p. 30; Dumpleton 1973, p. 18-9 (**) Cox 1979
1822	- First steamers serving the British government, the Royal Navy, two tugs called the *Comet* and the *Monkey* - First steamer to enter the Pacific, the *Rising Star*, arrives at Valparaiso in April (*)	Spratt 1851, p. 21
1823	- The *James Watt* is one of earliest steamships to figure in the *Lloyd's Register of Shipping*, built by John Wood of Port Glasgow, she was a wooden ship, used sails and was driven by a Boulton and Watt 100hp engine, classed A1 (*) - By this year there were 80 steamers in the *Lloyd's Register* - First time a steam vessel takes part in naval action, the paddle-steamer *Diana* during the First Burmanese War (**)	(*) Jones 2000 (**) Lyon 1980, p. 25; Roff 1993, p. 28
1824	- The British system of Navigation Acts begins to relax with negotiation of reciprocal treaties with northern European countries (**) - It becomes a statutory requirement that vessels are registered in 64ths by force of the Merchant Shipping. This practice dates back to 1786 onwards, when most vessels shares were already divided in 64ths (***)	(*) Corlett 1990, p. 9 (**) Craig 2004, p. 1
1825	The *Enterprise* is the first steamer to go from the UK to India, round the Cape of Good Hope	Woodcroft 1848
1831	- The *Sophia Jane*, 256 tons register and 50 hp, built by Barnes and Miller in 1826, enters the Sydney harbour on the 13th of May and is the first steamer to arrive to Australia. Previously she had been employed carrying passengers between England and France (*)	(*) Gregory 1928, p. 27 (**) Flint 2004; Greenhill 1993b, p. 25

	- John Laird's works build the *Elburkah*, 70 tons and 15 hp. She would be used by his son, Macgregor Laird, to explore the river Niger. She became the first iron vessel to complete an ocean voyage in 1832 (**)	
1832	- Parliament orders a inquiry into schemes for a mail steam route to India (*) - The 100th steamer appears in the *Lloyd's Register*	(*) Gregory 1928, pp. 27-8
1833	- The of contracting private steamship companies to carry out the packet service is inaugurated in 1833 with mail carriage to the Isle of Man (*) - First steamer crosses the Atlantic	(*) Tyler 1939, p. 74
1834	- LR is reconstituted - The *Garry Owen* is the first iron steamer to introduce the system of transverse watertight bulkheads. Built by the Lairds of Liverpool (*) - One of the earliest LR machinery certificates, steamer *Sir Francis Drake* (**) - The East India Company monopoly is over after the Charter Act of 1933 and the tea and the China trades are now open (***)	(*) Corlett 1990, p. 25 (**) Jones 2000, p. 15 (***) Moyse-Bartlett 1937, p. 224; Corlet 1990, p. 9
1836	- *Archimedes*, a yacht, becomes the first seagoing vessel driven by a (Francis Petit Smith's) screw propeller. She was built by Henry Wimshurst and engined by the Rennie brothers - A Tonnage Law is comes into force, it amended the 1773 measurement system that did not take depth into account for port dues (*)	(*) Graham 1956, p. 78; Greenhill 1980a, pp. 9-10
1837	- Isambard Kingdom Brunel launches the *Great Western* - The first steam Royal Navy frigates are launched, the *Gorgon* and the *Cyclops* (*) - The Steam Department is set up at the Admiralty (**) - In February a Bill is passed putting assigning the control of the Post Office Packet service to the Admiralty (***)	(*) Greenhill and Giffard 1994, p.53 (**) Rowland 1970, p. 66 (***) Tyler 1939, p. 74
1838	- The *New Jersey* (formerly the *Robert F. Stockton*, British built), fitted with an Ericsson propulsion system, becomes the first (double-)screw steamer in commercial operation. Serves the Delaware and Raritan Canal Company (*) - The British & American Steam Navigation Company is the first company to start a steam service on the Atlantic and manages to launch the *Sirius* ahead of the *Great Western* (**) - Henry Bell is remembered by the erection of an obelisk in the grounds of Dunglass Castle, on the banks of the Clyde. This is "an early example of such an honour" (***)	(*) Woodcroft 1848, p. 101; Baker 1965, p.44, p. 49 (**) Bonsor 1975, Vol. I , p. 54 (***) Harvey and Downs-Rose 1980, p. 168
1839	- The schooner *Scottish Maid* is launched on 7th August 1839 by William Hall of Aberdeen. She was designed to reduce register tonnage dues and for speed. A sharply raked stem and a fine entrance were the means to simultaneously achieve both these goals. It became known	(*) Cable 1943; MacGregor 1988; *Lloyd's List* 1984, p. 220 (**) Bonsor 1955, p. 12

	as the Aberdeen Bow and contributed to earn ships the description of "clippers". The result came, at least partially, from tests in water tanks (*) - The *Liverpool* is the first steamer on the North Atlantic to display two funnels, she was advertised as providing "warm and cold baths" (**) - First steamship company organised in Australia, the Hunter River Steam Navigation Company. She made order for iron ships, two from Fairbain & co. at Millwall (the *Rose* and the *Thistle*) and the third by Paterson of Bristol (the *Shamrock*). The three arrived in 1841 (***)	(***) Gregory 1928, , pp. 35-6
1840	- The Royal Navy orders the first screw propelled warship, the *Rattler* (she was launched in the Spring of 1843) (**) - First two-funnelled ship is built by Humble & Milcrest at Liverpool for P&O, the Great Liverpool (**)	(*) Lambert 1993, p. 139 (**) Ingall 1997, p. 2
1841	- The *Novelty*, built by the same builder of the *Archimedes*, completes a voyage from Liverpool to Constantinople with 420 tons of cargo, making her the first screw steamer to carry freight into the sea. (*) - The *President* is the first steamship to founder in the Atlantic (**)	(*) Smith 1938, p. 72 (**) Spratt 1949, p. 41; Bonsor 1955, p. 595
1842	- The British Navy steam sloop *Driver* sets out for a circumnavigation voyage. It would be completed in 1847, the first circumnavigation made by a steam-powered vessel (*) - The *Iris*, built by Alexander Hall & Sons for the Baltic trade, is the first steamer to receive the "Aberdeen bow" (**) - HMS Bee is built. An instructional wooden steamer built with both wood and screw. Broken up in 1874 (***) - Ban on machinery exports, which had been in force since 1774, is lifted by Prime Minister Robert Peel (****)	(*) Graham 1956, p. 74; *Mech Mag*, 1849, January 13, p. 26; Woodcroft 1848, p. 89 (**) Boyd Cable 1943, p. 79; MacGregor 1988, p. 107 (***) Brock and Greenhill 1973, p. 14 (****) Bairoch (1989, p. 12)
1843	- Although not a warship the first iron screw steamer is launched and purchased by Royal Navy's, her name was eventually changed from *Mermaid* to *Dwarf*, built at the order of the Rennies - Isambard Kingdom Brunel floats the *Great Britain* at Bristol, the first ocean-going iron steamship, screw-fitted and the largest ship in world at the time - *Hibernia*, a Cunarder, is the first ship to cross the Atlantic in less than 10 days (*)	(*) Kemp 1978, p. 165
1844	- The *Q.E.D.*, a small sailing vessel of 271 tons, is built on the Tyne by John Coutts. She was the fist vessel build with double-bottoms for taking in water as ballast while not interfering	(*) Dougan 1968, p. 39 (**) Prebble 1895, p. 202

	with the cargo holds. At the time the banks of trading rivers were lined with heaps of chalk to be used as ballast by ships returning empty after service. She was later fitted with auxiliary engines by Mssrs. Hawthorn and was equipped with the first screw-propeller of the Tyne (*) - The first steam collier is built, the aptly called *King Coal*. She normally took six to eight days from Newcastle to London (**) - The idea of deep sea cruising is first put in practice. P&O had a network of regular connections between a number of ports in the Mediterranean (Malta, Athens, Alexandria, Constantinople, Rhodes, Jaffa and Egypt) so they offered round tickets, including on shore excursions on each of the ports of call. They offered one of such tickets to novelist William Makepeace Thackeray, who wrote a book about the trip using the name Michael Angelo Titmarsh, *Dieary of a Voyage from Cornhill to Grand Cairo*, 1846 (***) - Lloyd's Register describes the schooner *Queen of the Tyne*, built by Walter Hood of Aberdeen, as a clipper. This is the first time a ship, other than Alexander Hall's, is so described (****)	(***) Howarth and Howarth 1986, p. 47 (****) MacGregor 1988, p. 115
1845	- On April 3rd takes place a famous trial. The screw steamer *Rattler* (the first commissioned naval, screw warship 1078 tons, 437 nhp) and the paddle steamer *Alecto* (800, 200 hp engine), in which they are secured by cables. The *Alecto* gets moving first pulling the *Rattler* at full speed, but on this starting its engines she slows down and then is dragged on. The tug-of-war ends with a comfortable win of the *Rattler* towing the *Alecto* at 2.7 knots (*) - The *Massachusetts* is the first US steamer working on the Atlantic since the *Savannah*. She was a wooden screw steamer (**)	(*) Smith 1838, p. 73 (**) Bonsor 1955, p. 595
1846	- The Royal Navy's paddle steamer HMS *Penelope*, originally built in 1929, won considerable fame as she is cut at two and extended to accommodate a 650hp engine an increase its capacity to carry 600 of coal, she became bulkier but faster, for the Admiralty a conclusive proof of the superiority of the screw propeller - Act of parliament 1846 directing all iron steamers above over 100 tons burden to be divided into water tight sections by transverse bulkheads	
1848	- Repeal of the Navigation Laws in 1848, trade can now be carried by non-British owned vessels in and out of British ports (*) - Bennet Woodcroft publishes his book on the history of steam navigation, this is "one of the first attempts to survey the development of a particular technology" (**)	(*) Ville 2004 (**) Harvey and Downs-Rose 1980, p. 167

1849	- The 417 ton *Leviathan* becomes the first of the so-called train ferries. She serviced the North British Railway Company in the root across the Firth of Forth from Granton to Burntisland. The service was successful for many years until it was replaced by a bridge (*) - A Bill repealing the Navigation Laws is passed in The House of Commons and signed by the Queen in June 1849 (**)	(*) Rowland 1970, p. 133 (**) Moyse-Bartlett 1937, p. 227
1850	- The *Goliath*, a steam tug is chartered to lay the first telegraph cable connecting Britain and France. The task was carried out in a single day of August, 1850 (*) - Composite construction is patented by John Jordan of Liverpool (**)	(*) Thomas 1983, p.5 (**) Slaven 1992, p. 2
1851	- The first composite ship, "Iron frame and planked", Tubal Cain, 787 tons, sailing ship, appears in the 1851 *Lloyd's Register* (*) - In the UK census of 1851 the term "carpenter" no longer appears in the list of occupations. The dropping of the term may be related to the decreasing importance of timber in shipbuilding in comparison to iron. The label "shipwright/shipbuilder" was used for shipbuilding instead (**)	(*) Jones (2000), p. 24 (**) Neal 1993
1852	- The pioneer steam iron screw colliers and one of the most successful of its kind, *John Bowes* of 486-ton, she lasted until 1933 when she sunk (*) - P&O is the first line to adopt screw steamers for regular service, the *Chusan* and the *Formosa*, placed on the route between Hong Kong and Shangai (**) - Cunnard follows with its first screw steamer the *Andes* (***)	(*) Dougan 1968 p. 44 (**) Prebble 1895, p. 217 (***) Bonsor 1955, p. 596
1853	- The first steam yacht makes it appearance in the US, the 1,876-ton *North Star*, built for Commodore Cornelius Vanderbilt. The steam yacht becomes a standard for status. - The *Arabia* is launched, the last wooden Cunarder - In May the contract for building the *Great Eastern* in signed (*) - Underfloor steam heating is introduced in a passenger liner on the Atlantic (**) - The stipulation that mail steamers are to be built of wood is dropped by the government (***)	(*) Beaver 1969, p. 29 (**) Lloyd's List 1984, p. 66, p. 237 (***) Woodman 1997, p. 185
1854	- The first steamer fitted with a compound engine, the *Brandon*. She was an iron screw liner built on the Clyde for the London & Limerick Steamship Company. This was the first vessel to have a compound engine made by Randoplph & Eder after their joint patent of January 24, 1853 (another was taken in 1856) (*) - First circumnavigation by a steam ship: the *Argo*, a British screw-propelled ship of 1850	(*) Bonsor 1955, p. 82 (**) Prebble 1895, p. 218 (***) Moyse-Bartlett 1937, p. 227

	tons register (**) - John Penn, with F.P. Smith, suggest *lignun vitae* as remedy for the rapid wear occurred in the stern tube of screw-propelled ships (***) - Coastal trade, which had been reserved under the terms of the Navigation Laws, is declared open with the new Merchant Shipping Act, issued on 10 August 1854 (***)	
1855	- First *Rules for Iron Ships* construction issued by Lloyd's Register (*) - Passenger Act is passed, ensuring minimum safety regulations for emigrants in British ships (**) - The Act allowing the formation of joint-stock enterprise is passed and the shipbuilding industry is quick to embark in the formation of new companies (***) - The Panama isthmus railroad is opened. Construction works had started in 1850 in the wake of the traffic increase to California due to the 1849 California Gold Rush.	(*) Jones 2000, p. 22 (**) Pollard and Robertson 1979, p. 11 (***) Pollard and Robertson 1979, p. 75
1856	The first successful ships fitted with compound inverted engines: the Pacific Steam Navigation Co.'s paddle steamers *Valparaiso*, 1060 grt, and *Inca*, 290 grt, trading from Liverpool to South America (*) - Superheated steam, which increased thermal efficiency of the engine, is first demonstrated in Britain by John Wethered, an American. It was tried in the *Dee*, built and engined by the Maudslays. A 20 per cent decrease in coal consumption was achieved in the experiment. First superheater deigns were unreliable, so the approach was not immediately adopted (**) - The *Adriatic* is launched in April, a wooden side wheeler designed and built for the Collins Line by George Steers (the same designer of the yacht *America*). She had reportedly the first searchlight especially designed for use at sea, a calcium-powered searchlight at the stern (***)	(*) Jones 2000, p. 30 (**) Rowland 1970, p. 121 (***) Lloyd's List 1984, p. 215
1857	- The Brunel's *Great Western* is broken up after a working life of 20 years. - First attempt on November 3, unsuccessful as the ship only moved four feet sideways in the direction of the water, at launching the Great Eastern. Another attempt was made on November 19. Effort restarted on 28 November and would go on until the 17 of December. By this time Brunel had been joined by Robert Stephenson to advise him on the "mode of proceeding" (*) - LR rules of iron ships extended (**)	(*) Beaver, 1969, p. 29 (**) Corlett 1990, p. 198
1858	- Pioneering (mild) steel river boats: the *Ma Robert* built as river boat for the Zambezi and the *Rainbow* for the Niger (*) - Railway across the isthmus between Alexandria and Suez is completed (**)	(*) Pollard 1950, p. 329 (**) Maber1980, p. 20

	- The largest ship of the world is launched on January 30 after three months of attempts. She took the life of Brunel and led Russell to bankruptcy. She was underpowered it was ultimately considered a failure as a passenger ship as she never was put on the job she was designed for. She laid down the first transatlantic cable in 1866, scraped in 1888.	
1859	- First sea-going ironclad warship is the French frigate *La Gloire* - Last wooden battleship launched by the Royal Navy, the *Victoria* (*)	(*)Moyse-Bartlett, 1937, p. 257
1860	- Institution of Naval Architects is founded - HMS *Warrior*, first iron clad of the Royal Navy build as a reaction to *La Gloire*, launched the year before as the first ship of a building program to achieve naval supremacy. Launched at blackwall, designed by Isaac Watts, it was the first major warship with an armoured hull consisting of iron platting. The "iron clad" became the usual way to refer to any armoured warship until the launch of the *Dreadnought* in 1906 (*)	(*) Kemp 1978, p. 181-2
1861	- On November 19th a little sailing vessel, the 224 tons gross brig *Elisabeth Watts*, left Schuykill River Dock, Philadelphia. She had a cargo of 901 barrels of rock oil and 428 of coal oil in her hold, thus becoming the first reported ship to have transported this kind of mineral energy resource. In 1859 the first oil well had been drilled in the US, at Titusville, Pennsylvania. Apparently it was not easy to find a crew as seamen knew already mineral oil was a dangerous cargo. She arrived in London on the 9th of January 1862 (*) - Companies Act is passed, risk-taking is encouraged (**)	(*) Lloyd's List 1984, p. 188 (**) Greenhill 1980a, p. 22
1862	- Iron prevails for the first time in British ship construction, ending the domination of wood and composite (*) - First (inconclusive) encounter between ironclads, the *Merrimac* and the *Monitor* in the context to American Civil War - Cunard, the largest operator in the North Atlantic, receives its last paddle-wheeler, the iron-hulled *Scotia* (**) - First LR Rules for the testing of anchors and chain cables (LR established this year its own Proving House at Poplar, but in 1973 it became uneconomic) (***) - The *Formby*, a sailing ship of 220 ft length and 37 ft beam built by Jones, Quiggin and Co., is the first known sea-going vessel to be built. She was made of high tensile steel. On the same day, November 26th, she was followed by the Hope, a paddle blockade runner of 281 ft by 35 ft beam, capable of 18 knots (****) - J.&G. Dudgeon of Millwall starts building twin-screw craft. Between 1862 and 1865 he	(*) Maywald 1956, p.46 (**)Bonsor 1955, p. 597 (***) Jones 2000, p. 52-3 (****) Corlett 1990, p. 200 (*****) Rowland 1970, p. 127 (******) Moyse-Bartlett 1937, p. 227 (*******) Slaven 1992, p. 3

	some 20 craft of this type up to 1,500 tons displacement and 350hp, eight of which confederate blockade runners to elude the fleets of the Federal navy. Although twin-screws still did not become common after this period these numbers made this firm to be the first to construct a large number of such vessels (*****) - Railway companies are granted permission to run their own steamers in conjunction to train-services (******) - The "Scotch boiler" is introduced by John Howden capable of higher pressures, which allow the compound engine to be efficiently exploited (*******)	
1864	- First large steel ship, the *Altcar* of 1283t launched by Jones, Quiggin & Co. of Liverpool (*) - First steel vessel to be classed: screw steamer Annie, 430 tons, built in Hull 1864, designed as a blockade runner, recorded as A1 in the 1867 register book where she was described as "steel" and "experimental" (**) - Last paddle steamer is built for P&O, *Nyanza* (***) - The Royal School of naval Architecture and Marine Engineering opens at South Kensington (****)	(*) Pollard 1950, Vol. II., p. 330 (**) Jones 2000, p. 34 (***) Ingall 1997, p. 9. (****) Rowland 1970, p. 116
1865	- The first ocean-going steamers are introduced in long-range trades. They were the *Agamemnon*, *Ajax* and *Achilles*, built by Scott and Company of Greenock and introduced for the Ocean Steamship Company. The success came with the compound engine built by Alfred Holt & Co. for the Far Eastern Trade in 1865-66. The *Agamemnon* is the first to do a voyage to China in April, 1866 (*) - A trial on the compound engined his performed on the request of the Royal Navy. Three ships were tried and one of which, HMS *Constance*, engined by Randolph and Elder. A race from Plymouth to Madeira. All the three ships were without coal along the way, but when this happened to the *Constance* she was 120 miles ahead of the others (**) - The largest ever wooden merchant steamers are authorised by the US Postmaster General. They were to be four to be built for the Pacific Mail Steamship Co. to be linking San Francisco and Hong Kong on a monthly basis. These American vessels were enlarged versions of familiar estuary side-wheelers of the coastal states. They had no clipper stems like the last British deep-ocean paddlers, nor they were iron built as this material was expensive in the US while timber was readily available. The 3881-tonn *Great Republic* was floated in the see on 18 May 1867. She was redrawn from service in 1876. Two others, the America (4454 tons) and the Japan (4351 tons) went up in flames in 1872 and 1874,	(*) Bonsor 1955, p. 83; Brock and Greenhill 1973, p. 80 (**) Rowland 1970, p. 121-2 (***) Maber 1980, p. 11-2

	respectively. The fourth, called China, was decommissioned in 1879 and sold to shipbreakers in 1886. The era of ocean-going paddle-steamers was then over (***)	
1866	- First full fledged sea battle between steam-powered fleets, Batle of Lissa in which the Italians were defeat by the Austrians. In an episode that would influence naval ship design the Ferdinand Max accidentally rammed the Re d'Italia, which sank in five minutes (*) - The first ocean-going twin-screw vessel, *Ruahine* (**)	(*) Ellis 1957, picture 205 (**) Maber 1980, p. 19
1867	- The *Great Republic* enters service and together with the America, Japan, and China, marks then end of the ocean-going paddle steamers - The *Rules for Composite Ships* (drawn by Bernard Waymout) are published in 1867 (*) - Last crossing by a wooden paddle Cunarder, the *Africa* (**)	(*) Jones 2000, p. 24 (**) Bonsor 1955, p. 597
1869	-Opening of the Suez Canal on November 17. The first steamer through the Canal belonged to the British India Steam Navigation Company and it was also one of their vessels, the *India*, the first to arrive to England via Suez loaded with produce (*) - the most famous of all composite clippers is built, *Cutty Sark*, 963 grt, and classed A1 under LR. Her designer was Hercules Linton, son of a LR's surveyor at Belfast and then Aberdeen between 1853 and 1873, Alexander Linton (**) - The last specially built North Atlantic sailing packet is launched, the 1,600 Black Ball ship *Charles H. Marshall* (***)	(*) Porter, p. 540 (**) Jones 2000, p. 26 (***) Bowen 1932, p. 118
1871	- The *Oceanic* becomes the first ship of the White Star Line. She was an innovative ship, for instance by placing the first class accommodation and saloon amidships, with a length to beam ration of 10 to 1 (in contrast with the then customary 8 to 1) (*) - Willam Froude's experimental Tank at Torquay (**) - First steamer used as icebreaker is the *Eisbrecher* I and is tried out by Russian ship-owner Britneff (***) - HMS Devastation, the first ocean-going capital ship carrying no sails is launched. This mastless turret ship was also the first war vessel with main armament mounted on top of the hull rather than inside it (****)	(*) Bonsor 1955, p. 257 (**) Moss and Hume 1977, p. 92 (***) Rowland 1970, p. 132 (****) Brock and Greenhill 1973, p. 21
1872	- First gas lighting is installed in the White Star *Adriatic*, 300 gas-burning mantles (*) - Froudes' results with experimental naval architecture are published in a paper to the British Association (**) - The *Vaderland* becomes the first steamer especially designed to carry oil in bulk is built on	(*) Bonsor 1955, p. 598; *Lloyd's Lis*t 1984, p. 237 (**) Rowland 1970, p. 131 (***) Rowland 1970, p. 133

	the Tyne in Palmer's Yard (***)	
1873	First sailess seagoing Royal Navy war ship, HMS *Devastation*	
1874	- Lloyd's Register hires its first engineer surveyor, William Parker, after two suggestions in that direction, one in 1836 and the other in 1865, also first year that the *Register* listed a Ship's engine builder (*) - Triple-expansion engines are fitted to a seagoing vessel for the first time, the screw steamer *Propontis*. The engine-builder was John Elder & Co. (later Fairfield Shipbuilding & Engineering Co.) and the designer was A.C. Kirk responding to Elders request to build a vessel operating at 150psi, much higher pressure than the 80psi of common compound engines (**) - A steam launch built by John Thornycroft is probably the fastest vessel in the world. The launch No. 18 Sir Arthur Cotton built in 1874 achieves 21.4 knots on trials (***) - East India Company ceases to exist (****)	(*) Jones 2000, p. 30 (**) Moss and Hume 1977, p. 39; Slaven 1992, p.6 (***) Rowland 1970, p. 141 (****) Moyse-Bartlett 1937, p. 224; Slaven 1992, p. 6
1875	-The Admiralty orders the use of the new (mild) steel in the construction of two cruisers - First "conference system" is tried out on the Britain-Calcutta trade and had become the usual starting point for dating the emergence of this mechanism if association of shipping lines with a common interest in certain liner trade. The term would name those agreements directed at regulating "uneconomic competition" by defining rates for types of freight, allocate sailings to each company. It come sometimes under accusations of cartel behaviour against the public interest (*) - In a paper to INA Nathaniel Barnaby, the Chief Naval Architect of the Admiralty summarises current understanding relative to steel as a material for shipbuilding: Bessemer steel is distrusted (**) - Last British fully-rigged armoured ship, the *Nelson*, is launched (***)	(*) *Lloyd's List* 1984, p. 171; Kirkaldy, 1914; Deakin and Seward 1973; *Encyclopaedia Britannica*, "History of Transportation", p. 669 (**) Rowland 1970, p. 130 (***) Brock and Greenhill 1973, p. 21
1876	- Merchant Shipping Act decrees the draught level to which a ship could be loaded, the load line known as the Plimsoll Line, named after its most famous public campaigner Samuel Plimsoll, MO (*) - First (external only) electric light is installed in the *Amérique*, a French liner (**) - The Royal Navy uses steel for the first time in the *Mercury* and the *Iris* (***)	(*) Jones 2000, p. 30 (**) Bonsor 1955, p. 598 (***) Rowland 1970, p. 131
1879	- First mild steel merchant ship, *Rotomahana*, compound engine 2 500 hp, 17 knots, 1,727 tons, built by William Denny & Bros on the Clyde, Dumbarton, delivered to Union Steam Ship Co. of New Zealand (*)	(*) Jones 2000,, p. 35 (**) Bonsor 1955, p. 599; Rowland 1970, p. 165

	- The first ship to be fitted with internal electric arc lamps is the Inman Line vessel *City of Berlin* (**)	
1880	- First steel steamer on the Atlantic ocean trade the *Buenos Ayrean* (*) - the Ravenna becomes the first P&O steel vessel (**) - Electric lighting is introduced in several yards this decade (***)	(*) Bonsor 1955, p. 598 (**) Corlett 1990, p. 200 (***) Pollard and Robertson 1979, p. 121
1881	- Thomas Chapman, FRS who served for 46 years as elected as chairman of LR retires and his succeed by William Henry Tindal (served until his death in 1899) (*) - Cunarder *Servia* is the first liner to be all lighted by electricity (**) - First British naval vessel to be equipped with (swan) lamps is the HMS *Inflexible* (***)	(*) Jones 2000, p. 28 (**) Boumphrey 1933, p. 89 (***) Rowland 1970, p. 165
1882	- First triple-expansion maritime steam engine, *Aberdeen*. Here A.C. links his new engine to a high-pressure scotch boiler made with steel plates and using forced draught. This is often referred as the real breakthrough in reliable fuel economy (*) - The *Alaska* is the first ship ever to cross the Atlantic in less than a week (New York to Cobh in 6 days and 22 hours in June)	(*) Slave 1992, p. 6
1884	- The steam turbine engine is patented by Charles Algernon Parsons - First commercial test-tank in the world is introduced at William Denny & Bros, Dumbarton. It was modelled in Froude's earlier pioneering tank. It included devices such as wax models and moving carriages as instruments to record data on the movement of hulls through the water (*)	(*) Moss and Hume 1977, p. 92
1885	- First recorded ship in *Lloyd's Register* to use oil as fuel, the *Himalaya* (*) - Sir John Biles announces in the Iron and Steel Institute that for a ship of a given size the cost of iron and steel were identical and that steel allowed for larger carrying capacities, thus yielding a weight reduction between 13-14 per cent (**)	(*) Jones 2000 (**) Moss and Hume 1977, p. 41
1886	- From this year onwards steel supplants iron in ship construction in Britain (*) - Freeboard rules adopted and issued by the Board of Trade (based on the buoyancy research by LR's chief surveyor Benjamin Martell and after years of public campaigning against "coffin ships" by Samuel Plimsol, MP) (**) - *Bakuin*, 1,669 grt, "Carrying Petroleum in Bulk" is built in 1886 by Wm. Gray & Son, West Hartlepool. She becomes the first LR-classed modern oil tanker, launched one week after then Gluckhauf (generally regarded as the forerunner of the modern purpose-built tanker) (***) - Alexander Kirk the designer of the engines of the *Propontis*, now at Robert Napier & Sons, modifies the marine triple-expansion engine making it sufficiently reliable for general use	(*) Maywald 1956, p.46 (**) Jones 2000, p. 29 (***) Jones 2000, p. 39 (****) Moss and Hume 1977, p. 39, Mackinnon 1921, p. 99

	(****)	
1887	- The *Charles Howard* becomes the first oil-burning tanker. Her own fuel oil was carried in her double-bottom. She was nevertheless promptly converted to coal after a breakdown in her maiden voyage	Lloyd's List 1984, p. 192
1888	- First quadruple-expansion engine is patented by Walter Brock at Denny of Dumbarton and installed in the vessel *Phoenecian* (*) - New *Rules for Steel Ships* are published for the first time by LR (**) - *City of Paris*, by J. & G. Thomson, becomes the first double-screw liner, indeed, with her sister City of New York, they can be considered the first modern liners (***) - Deck cranes for cargo make their first appearance on board a carrier fitted by Swan, Hunter and Wigham Richardson of the Tyne (****) - The City of New York, placed in service in this year by the Inman Line, becomes the first of the large ocean liners to use twin screws (*****)	(*) Bonsor 1955, p. 599 (**) Jones 2000, p. 36 (***) Boumphrey 1933, p. 89 (****) Lloyd's List 1984,, p. 237 (*****) Johnson 1906, p. 29
1890	- LR classes a total of new 812 vessels, only 51 of them equipped with electric lighting (*) - A bust of William Symington is unveiled on 21 November at the then Museum of Science and Art, now the Royal Scottish Museum, by Sir William Thomson, the future Lord Kelvin (**)	(*) Jones 2000, p. 44 (**) Harvey and Downs-Rose 1980, p. 170
1891	Last ocean liner to have sails, *La Tourraine*	
1993	- First steamer built with quadruple-expansion steam engine is the *Southwark* (*) - Swan, Hunter shipyard pioneers installing electric powered machinery (**)	(*) Bonsor 1955, p. 599 (**) Pollard and Robertson 1979, p. 121
1894	- Charles Parsons introduces the turbine to public notice with his vessel *Turbinia* - First steamship having four funnels is the German-built *Kaiser Wilhelm der Grosse.* She become a Blue Riband holder for North German Lloyd's. She marks the moment in which German builder started competing with premier Clyde yards. Germany was not then as a major shipbuilding nation, let alone capable construct world class innovative designs (*) - In the trials of the *Daring*, the faster of two Thornycroft ships, she exceeds the Admiralty's stipulated speed by over a knot. It is during her trials that the problem of cavitation is first encountered. This is a phenomenon of lost of thrust that happens in a rapidly rotating propeller (**)	(*) Bonsor 1955, p. 599; Moss and Hume 1977, pp. 97-9 (**) Rowland 1970, p. 156
1898	- Admiralty orders the torpedo boat HMS *Viper* to Parson's Marine Steam Turbine Company - The last two paddle-steamers built to serve across the English Channel - Mild steel supersedes iron as the prime shipbuilding material and ships built of steel	(*) Jones 2000, p. 36 (**) Blake 1960, p. 81

	accounted for more than 90% of the LR-classed new building fleet (by 1883 LR was surveying and classing 90% of the British fleet) (*) - As the value of shipments of frozen meat grew from the 1880s onwards LR's decides that the problem of refrigeration at sea it its business releases *Rules for Refrigerating Machinery* (**)	
1899	- The *Oceanic* (II) is the first liner to surpass the *Great Eastern* in length, although not in tonnage	Bonsor 1955, p. 257; Beaver 1969, p. 9
1901	- The *King Edward*, a Clyde excursion steamer built by Denny Bros, becomes the first turbine-driven commercial ship (*) - The *Celtic* is the first steamer to exceed the *Great Eastern* in tonnage (**)	(*) Moss and Hume 1977, p. 100 (**) Bonsor 1955, p. 599
1902	- Lloyd's Register classed its 200th tank steamer (*) - The Hamburg-operated *Preussian* is built (**)	(*) Lloyd's List 1984, p. 192 (**) Baker 1965, p. 206
1904	- "Cruising" is started by P&O, travelling from Southampton to Malta and Athens. The company's vessel *Rome* is renamed *Vectis* and fitted for the new activity. Cruises had been entertained by P&O by 1844, but would only provide significant revenue after 1950 (*) - The *Vandal* is completed. She is the first Diesel-electric vessel to be built. She a river tanker vessel of 800 tons burden fitted with thee engines of 120 hp each. The engines were made by the Swedish firm A/B Diesel Motorer, which had been founded on April 21, 1898 (**)	(*) Ingall 1997, (**) Lloyd's List 1984,, p. 229
1905	- First major modern ship battle, Battle of Tsushima, 27 May, in the context of the Russian-Japanese war, fought between the Japanese and Russian fleets of armoured battleships, the first naval battle in history to be engaged independently of the strength and direction of the wind, Japanese victory overwhelming; - First destroyers to have oil-combustion boilers; - First turbine steamer on the North Atlantic line was the *Victorian* is launched. She is also the first triple-screw ship (*)	(*) Bonsor 1955, p. 599
1906	A total of six ships with turbines are on their stocks being built. The *Lusitania* and the *Mauretania* are two of them	Lloyd's List 1984, p. 215
1907	The *Lusitania* becomes the first-ever ship equipped with quadruple expansion and the largest ship in the world, the first to exceed the 30,000 tons. She also is the first to surpass the *Great Eastern* in displacement. Her sister, the *Mauretania*, had 4 million rivets on her	Emmerson 1981, p. 145; Dugan 1953, p. 219; Lloyd's List 1984, p. 209
1909	- Her sister the *Mauritania* breaks the record of speed in the Atlantic (the so-called "Blue Riband"), previously held by the *Lusitania*, holding it until July 1929 when the *Bremen*	(*) Jones, p. 40; Lloyd's List 1984, p. 188

	brakes it - 1909, LR accorded full recognition to the advent of the tanker by publishing separate *Rules for the Construction of Vessels intended for the Carriage of Petroleum in Bulk*. Petrol was then called "motor spirit". The liquid fuel was mostly transported by steamers and was developing into an important trades (*)	
1910	- First German battle-cruiser equipped with Parson turbines and the first with four shafts, *Van der Tann* - LR issues Rules for *Petrol and Parafine Engines* (*) - Conflicting accounts of the first ocean going motorship: some say it was *Vulcanus*, built in 1910 in the Netherlands, a tanker owned by Royal Dutch/Shell others say that it was the Italian twin-screw mailship *Romagna* is the first seagoing vessel to be built with (German made) diesel motors (**)	(*) Jones 2000, p. 50 (**) Jones 2000, p. 51
1911	- The *Selandia* becomes world's first ocean-going motor ship, built in Copenhagen for the East Asiatic Steamship Co. She was fitted with Burmeister and Wain diesel engine (*) - Charles Parsons is knighted - The five-masted barque *France*, 5633 gross tons and 418 feet in length, launched by Chantiers de la Gironde, she was the largest sail commercial vessel ever built. In 1919 she was chartered to take transport coal from the Tyne to the US. Taking a cargo of iron ore from New Caledonia to Europe she drifted into a coral reef in July 1922 because of lack of wind (**) - The *Toiler*, 2,600 deadweight, is reported to be the first motor ship to have crossed the Atlantic. She was built at Newcastle-Upon-Tyne by Swan, Hunter and Wigham Richardson Ltd. (Neptune Works) for the carriage of grain (***)	(*) Moss and Hume 1977, p. vii (**) Kemp 1978, p. 205; Fletcher 1928, p. 136. (***) Lloyd's List 1984,, p. 229
1912	- A series of battleships of the Queen Elizabeth class start to be laid down for construction (the *Barham*, the *Valiant*, the *Malaya*, the *Warspite* and the *Queen Elizabeth*), the first large warships using fuel oil, they were finished in 1915-1916; - First motorship built in the UK, the 5000-ton *Jutlandia*, for a Danish company (*) - The first large ships to have oil engines, the sister ships Sealandia and *Fiona*, built for the East Pacific Company by Messrs Burmeister and Wain of Copenhagen - *France*, 5632 grt, launched by Chantiers et Ateloirs de la Girond, Bordeux, generally accepted to be the largest sailing ship ever built - *Selandia*, 4,950 grt is the first large diesel propelled ocean-going merchant vessel. Built by Burmeister & Wain of Copenhagen, she was fitted with four-stroke single acting engines.	(*) Clarck 1960, p. 86 (**) Craig 1980; Lloyd's List 1984,, p. 229. (****) MacLeod 2007, p. 341

	She had three masts, a "four island profile" and no funnel (probably the first powered ocean-going ship to have no funnel) making her a most original looking ship. Another feature was that she accommodated diesel at her double bottom. She was lost in 1842. He sister of the *Fiona*. The builders had acquired a Diesel licence in 1897 (**) - The centenary of Henry Bells' historical vessel, the first British steamer to carry passengers for money, is celebrated in Glasgow. The three days of festivities included fireworks, illuminations, a model of the *Comet* and a naval parade of sixty vessels (***) - One hundred years after the *Comet* was launched on the Clyde the *Titanic*, 46,329 grt, sinks on the Atlantic	
1913	First diesel motorship to sail the North Atlantic, the Danish cargo vessel *California*	Bonsor 1955, p. 599
1914	- LR recognises the significant progress in marine heavy oil (diesel) engines by publishing its first *Rules for Diesel Engines and Auxiliaries*, 47 vessels are classed, either in service or building (*) - the *Mississippi* is the first British motor (cargo) ship - *Aquitania*, a Cunard liner, measures up to 869 feet in length - Opening of the Panama Canal ends with the American nitrate trade, the last stronghold of sail, just as the opening of the Suez took the tea trade out of the hands of clippers (**) - 89% of the world's merchant marine relies on coal (***)	(*) Jones 2000, p. 54 (**) Kemp 1978, p. 208 (***) *Lloyd's List* 1984, p. 224