Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study

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Abstract
This paper addresses the following questions: How do technological transitions (TT) come about? Can we distinguish particular patterns and mechanisms in transition processes? TT are defined as major technological changes in the way societal functions are fulfilled. TT do not only involve changes in technology, but also changes in user practices, regulation, industrial networks (supply, production, distribution), infrastructure, and symbolic meaning or culture. To answer the questions, this paper practices ‘appreciative theory’ (Nelson and Winter, 1982) and brings together insights from sociology of technology, evolutionary economics, and innovation studies. This results in an evolutionary perspective on TT where reconfiguration processes are important. The dynamics of these reconfiguration processes are conceptualised by distinguishing three analytical levels: i) technological niches, where variation is generated, ii) sociotechnical regimes, which represent a ‘deep structure’ and account for stability, iii) a sociotechnical landscape, representing the wider context and ‘longue duree’. TT occur as the outcome of linkages and interactions of developments at multiple levels. The perspective on TT is empirically illustrated with a longitudinal qualitative case-study, the transition from sailing ships to steamships, 1780-1900. Three particular mechanisms in TT are derived from the case-study: niche-cumulation, technological add-on and hybridisation, riding along with market growth.

Keywords: Technological transitions, sociotechnical regimes, co-evolution, multiple levels, steamships

Note. If thought necessary for publication, I am willing to look for possibilities to shorten the paper.

1. Introduction

In this paper technological transitions (TT) are described as major technological changes in the way societal functions are fulfilled. An example for oceanic shipping is the transition from sailing ships to steamships (1840-1890). An example for land-based transportation is the transition from horse-and-carriages to cars (1880-1920). TT do not only involve changes in technology, but also changes in user practices, regulation, industrial networks (supply, production, distribution), infrastructure, and symbolic meaning or culture. Extending the innovation typology by Abernathy and Clark (1985), technological transitions can be described as ‘architectural innovations’. In their typology architectural innovations involve both changes on the user dimension (relationship with customer base, customer applications, channels of distribution and service, customer knowledge, modes of customer communication) and the technology/production dimension (design/embodiment of technology, production systems/organisations, managerial and technical skills, materials/supplier relations, capital equipment, knowledge and experience base). TT are different from changes in the ‘techno-economic paradigm’(Freeman and Perez, 1988), in the sense that the latter refer to pervasive technologies on the level of the entire economy, while the former are localised on the level of societal functions. TT are closer to Freeman and Perez’ category of changes in ‘technology systems’. These changes are based on a combination of radical and incremental innovations, together with organisational and managerial innovations. TT, however, do not necessarily match the criterion of “affecting several branches of the economy” (Freeman and Perez, 1988: 46). Long-waves in the economy or changes in the techno-economic paradigm take place through a cumulation of TT. Electricity, for example, affected the economy through subsequent technological transitions in transport (electric trams), lighting (in theatres, factories, households), power (electric motors in factories), and heating (e.g. melting in factories). The understanding of technological transitions is thus helpful in the long-wave debate.

This paper addresses the following questions: How do TT come about? Can we distinguish particular patterns and mechanisms in transition processes? To answer these questions I will start with describing a configuration perspective on technology, and reformulate TT as a reconfiguration process. In section 2 I will elaborate a multi-level perspective on technological transitions.

Technology, of itself, has no power, does nothing. Only in association with human agency and social structures and organisations does technology fulfil functions. It is the combination of ‘the social’ and ‘the technical’ that is the appropriate unit of analysis. In this respect Hughes (1986, 1987) coined the useful metaphor of a ‘seamless web’ in which physical artefacts, organisations (e.g. manufacturing firms, investment banks, research and development laboratories), natural resources, scientific elements (e.g. books, articles), legislative artefacts (e.g. laws) are combined and work together. Building on the tradition of sociology of technology, Fleck (1993) analyses technological systems as configurations of technological and nontechnological components. Rip and Kemp (1998), too, analyse technology as ‘configurations that work’. While the term ‘configurations’ refers to the alignment between a heterogeneous set of elements, the addition ‘that work’ indicates that the configuration can stabilise in ‘fulfilling a function’. Configurations that work cannot easily be bounded from the rest of society in a simple and obvious way. Things and skills are part of routines, of patterns of behaviour, of organisations. They work only because they are embedded in this way. Such a configuration perspective involves a move from the domain of ‘technical artefacts plus social relations’ into the domain of sociotechnology or ‘sociotechnical ensembles’ (Bijker, 1995). Figure 1 portrays the sociotechnical configuration for transportation. Artefacts' are described a as a *technical hierarchy,* consisting of components (e.g. materials, nuts and bolts), devices (e.g. a pump, a switching circuit), functional artefacts (e.g. a machine, a bridge, a radio) (Disco *et al.*, 1992). The transportation function can be fulfilled, because the heterogeneous set of elements is linked.

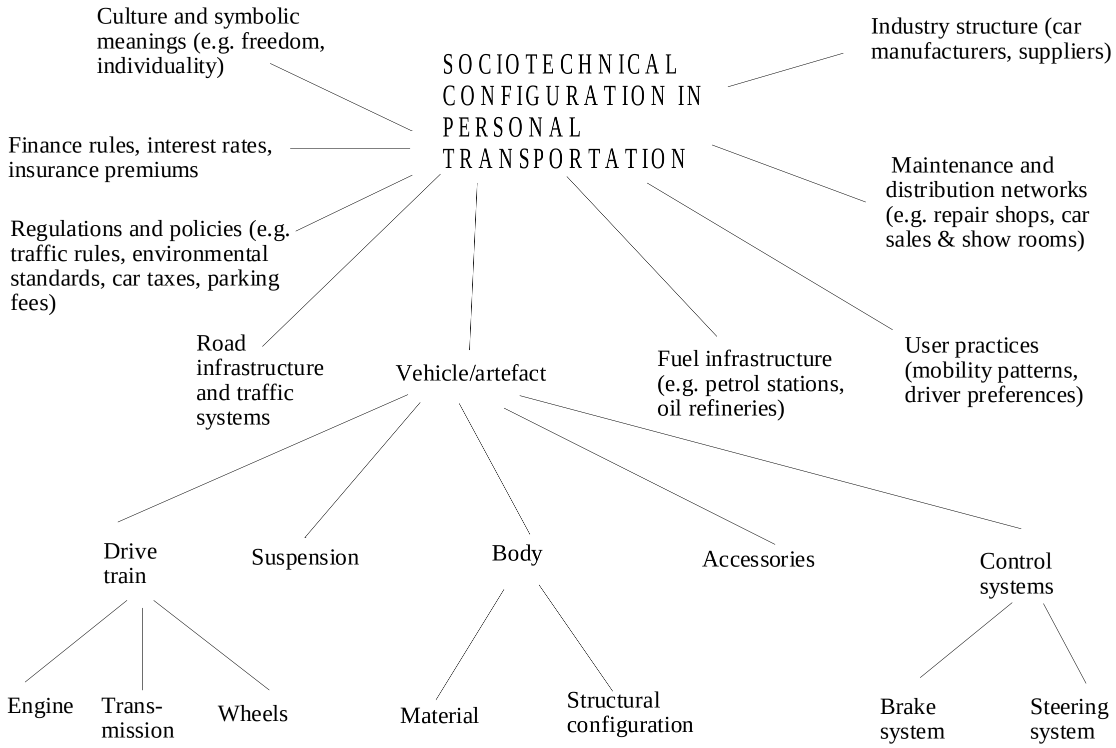


Figure 1: Elements from the sociotechnical configuration in transportation

A technological transition consists of major changes in the sociotechnical configuration, involving at least substitution of technology. TT are reconfiguration processes, which involve the breaking of established linkages and the creation of new ones. Such reconfiguration processes need not be of a rapid or revolutionary nature. Instead, what initially might appear to be a 'revolution' can in fact be the outcome of a series of small, incremental adaptations over time. The cumulative effect of these steps can be at least as substantial as the effect of abrupt innovations (Summerton, 1994: 5). Reconfiguration entails that multiple elements co-evolve. "Complexity and structural change can be explained only as historical developments, as co-evolutionary processes" (Freeman and Louç• , 2001: 122). Regarding these reconfiguration and co-evolution processes I distinguish two extremes, depending on whether one element takes the lead or many. One extreme is that a TT starts with a change in one element, and then subsequently transform others. The transition from piston engine and propeller aircraft to turbojets is an example. The idea of the turbojet was conceived by outsiders in the scientific community, on the basis of aerodynamics and thermodynamics (Constant, 1980). Although the young scientists promoted their ideas in the 1930s, the technical aeronautic community was not interested, because it strongly believed in the potential of the piston-engine propeller aircraft. It was not until World War II that their ideas were picked up. After the war, airframes were gradually adapted to the new engine, and landing strips were lengthened. As jet aircraft became more common, repair and maintenance procedures at airfields were changed. The noise of jet aircraft led to protests by local residents, and helped change the symbolic perception of aircraft. Slowly, policy makers reacted and issued regulations. As air traffic grew and jet aircraft flew faster, air traffic control systems had to be changed to increase safety at landing. Thus, the transition started with a component change, but gradually transformed the entire flying configuration. The other extreme is that TT take place because changes in many elements accumulate, link up and reinforce each other. The transition from horse-and-carriage to private gasoline cars may be a case in point. In many sub-regimes changes were occurring *before* the wide diffusion of the gasoline car. The popularity of the safety bicycle in the early 1890s not only helped to spread the new mobility practice of private transport (Flink, 1990), but it also gave rise in the US to the Good Roads Movement which lobbied for better roads. The rise of the electric tram in the 1890s had changed housing patterns by stimulating sub-urbanisation (Nye, 1990). Thus, the process of sub-urbanisation had already started *before* it was further stimulated by private cars. The process of sub-urbanisation had effects with regard to the perception of the function of streets. For suburban residents, streets were mainly 'arteries for transportation'. Hence they demanded better and faster roads (McShane, 1994). The administration of streets in the US changed in the 1890s from local residents to municipalities. Local authorities developed greater ambitions and interventionist attitudes, and became one of the main agents of technological change in the urban built environment (Chant, 1999). Because of this change, they could respond to demands for better roads. With regard to technology, alternatives were sought for horses, because of problems with manure, congestion, and high operating costs. Cars, propelled by steam, electricity or internal combustion engines, were initially developed as toys for rich, adventurous people. They were used for car races in the 1890s and touring the country side in the early 1900s. Only after the T-Ford established a dominant design, did more 'instrumental' use become common (e.g. commuting). One reason that the T-Ford spread relatively quickly after 1908 was that the elements of user practice, policy interventions, technology and societal groups changed simultaneously and, in retrospect, prepared the way for the car. As a dominant design emerged these changes linked up and stabilised into a new configuration. The T-Ford can be seen as a stimulus around which the other elements crystallised.

Reconfigurations resulting in TT do not occur easily, because the different elements in a sociotechnical configuration are linked and aligned to each other. Established technologies cannot easily be replaced by radically new technologies, when this also involves changes in other elements. Perez (1983) and Freeman and Perez (1988) have noted that new (pervasive) technologies often face a mismatch with the established socio-institutional framework, e.g. consumer attitudes and legislative environment. In their analysis of long-waves in the economy Freeman and Louç• (2001) analyse crises in terms mis-match and mal-adjustments between subsystems (science, technology, economy, politics and culture). In short, established configurations are characterised by inertia, which makes it difficult for radically new elements to be taken up. The stability of ST-configurations, however, is not ever-lasting. Configurations rarely remain 'closed' for good. Previously achieved closure can be undone by breaking established linkages. The undoing of closure opens up the potential for transformation and the creation of new linkages which may stabilise into a new ST-configuration.

In section 2 I will analyse the issues of stability and change in technological transitions with a multi-level perspective. This perspective aims to combine insights from sociology of technology with an evolutionary view. While the stability of configurations will be explained with the concept of sociotechnical regimes, variation and change are understood with the concept of technological niches. The multi-level perspective aims to integrate findings from different literatures as an 'appreciative theory' (Nelson and Winter, 1982). In section 3 I will illustrate this multi-level perspective with a historical case-study, the transition from sailing ships to steamships. In section 4 I will analyse this case-study and derive some further insights in technological transitions. The paper ends with some discussion and conclusions.

2. An integrative evolutionary multi-level perspective on technological transitions

In this section I will address the question: how do TT come about? To answer this question I will use a multi-level perspective (Rip and Kemp, 1998; Kemp, 1994; Kemp, Schot and Hoogma, 1998; Schot, Hoogma and Elzen, 1994; Geels and Kemp, 2000). This multi-level framework consists phenomena at three levels: i) a 'micro'-level of *technological niches*, which are 'protected' spaces in which actors search and learn in various ways about new technologies and their use; niches are precarious and require work by protagonists to be upheld ii) a 'meso'-level of *sociotechnical regimes*, which are rule-sets that are built up around a dominant technology and grant it stability; it refers to the 'common sense' activities of actor groups, ii) a 'macro'-level of *sociotechnical landscapes*, consisting of a range of contextual factors that influence technological development but that cannot be changed directly by actors. These levels are meant as analytical concepts, not ontological descriptions of 'reality'.

Sociotechnical regimes and stability

I claimed that the stability and inertia of sociotechnical configurations resulted from the linkages and alignments between heterogeneous elements. These linkages are not automatic, however, but the result of activities of groups of actors which produce and reproduce them. Their activities create and maintain the elements of ST-configurations. Road infrastructures, for instance, are built and maintained by transportation ministries. Car regulations are made by public authorities, e.g. environmental departments, traffic departments, local municipalities. Cultural and symbolic meanings of cars are produced in the interaction between users, media and societal groups. Financial rules such as interest rates and insurance premiums, are created by banks, capital venture firms, insurance companies. User practices and mobility patterns emerge from the daily use of cars by different user groups. Industry structures are the outcome of mutual positioning and strategies of car manufacturers and their suppliers. The petrol infrastructure is created by petrol companies and their outlets. The technological knowledge embodied in cars is created by designers and engineers, while cars as artefacts are produced by firms (Constant, 1987).

The activities of these different groups are co-ordinated and aligned. To understand this co-ordination I use the concept of 'sociotechnical regime'. This concept builds upon that of 'technological regimes', as used in evolutionary economics (Nelson and Winter, 1977, 1982). Using insights from cognitive theory and organisation theory, Nelson and Winter (1982) conceptualise co-ordination as the outcome of organisational and cognitive routines. Organisations and the actors involved, *remember by doing*. "The routinization of activity in an organization constitutes the most important form of storage of the organization's specific operational knowledge" (Nelson and Winter, 1982: 99). What is required for the organisation to continue in routine operation is simply that all members continue to 'know their jobs', as those jobs are defined by the routine. As Nelson and Winter (1977) observed this also goes for engineers. Because of their cognitive routines (e.g. search heuristics) they focused on particular problems and had certain cognitive notions of how to deal with them. Because routines provide stability, Nelson and Winter (1982: 134) compare them with (biological) genes. This metaphor has been elaborated in organisation studies with terms such as 'genetic structure', 'deep structure', 'organisational DNA', 'genealogical structure' (see e.g. Baum and Singh, 1994). In so far as firms differ in their organisational and cognitive routines, there is variety in the technological search directions of engineers. In so far as different firms share similar routines, these form a *technological regime*. Technological regimes produce *technological trajectories*, because the community of engineers search in the same direction. Technological regimes thus create stability in the direction of technical development.

Building upon this conceptualisation of actors and their co-ordination, I widen it in two ways. First, I use the sociological concept of 'rules' over routines in order to include wider aspects than search heuristics. Rip and Kemp (1998: 340), for instance, define a technological regime as:

> "A technological regime is the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures."

While the cognitive rules of Nelson and Winter are embedded in the practices and minds of engineers, the rules of this new definition are embedded more widely: in the knowledge base, in engineering practices and beliefs, in management systems and corporate governance structures, in manufacturing processes, in the characteristics or products, institutions and infrastructures that make up a technological regime. Some examples of these wider rules are 'guiding principles' (Elzen *et al.*, 1990), 'expectations' (Van Lente, 1993), 'design criteria', 'product specifications', 'functional requirements', 'technical problem agenda', 'reverse salients' (Hughes, 1983), 'bottlenecks' (Rosenberg, 1976), 'technological guideposts' (Sahal, 1985), problem solving strategies and design tools (e.g. technical models).

Second, I would like to take on board more social groups than engineering communities. Technological trajectories are not only influenced by engineers, but also by users, policy makers, societal groups, suppliers, scientists, capital banks etc. As mentioned above, these groups also make up and maintain the elements of sociotechnical configurations. Because the activities of these groups are also guided by rules, I understand sociotechnical regimes as a semi-coherent set of rules. Although these rules are coherent, because the activities of different groups are aligned, I add the term 'semi', because at times there can be 'tensions' and misalignments between the different rules.

By providing orientation and co-ordination to the activities of relevant actor groups, sociotechnical regimes account for the *stability* of configurations. In evolutionary terms, regimes function as selection and retention mechanism (deep structure). Selection is not to be understood as a 'one off' decision, but as a gradual process of learning and articulation, situated in social networks. This way insights from innovation studies are incorporated. While early phases are characterised by uncertainty, search and experimentation, learning processes, this gradually gives way to stabilisation and crystallisation. While the rules in the regime guide action, they are also reproduced and refined. It is this refinement that gives rise to trajectories, as the work of engineers progresses 'down the design hierarchy' (Clark, 1985).

The wider context of sociotechnical landscape

Technological trajectories are situated within a *socio-technical landscape*, consisting of a set of deeper structural trends and changes (see Rip and Kemp 1998). The metaphor 'landscape' is chosen because of the literal connotation of something around us that we can travel through. This 'something' refers to the large-scale material context of society, e.g. the material and spatial arrangements of cities, factories, highways, land-use, gas and electricity infrastructures. The socio-technical landscape further contains heterogeneous factors, such as macro-economic factors (e.g. oil prices, economic growth), wars, emigration, broad political coalitions, cultural and normative values, environmental problems. Both regime and landscape are structures or contexts for interactions of actors, but in a different way. Regimes refer to social structures and rules that enable and constrain activities within communities. The function of the concept ‘socio-technical landscape’ is that it accounts for technology-*external* factors that influence its development. With regard to technological trajectories, the landscape provides a ‘gradient’ (Figure 2).

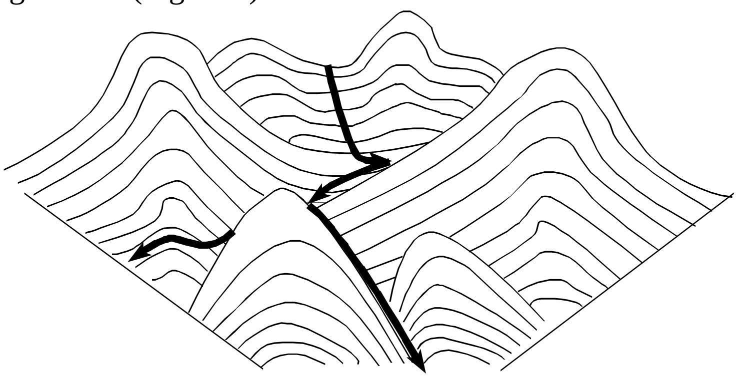


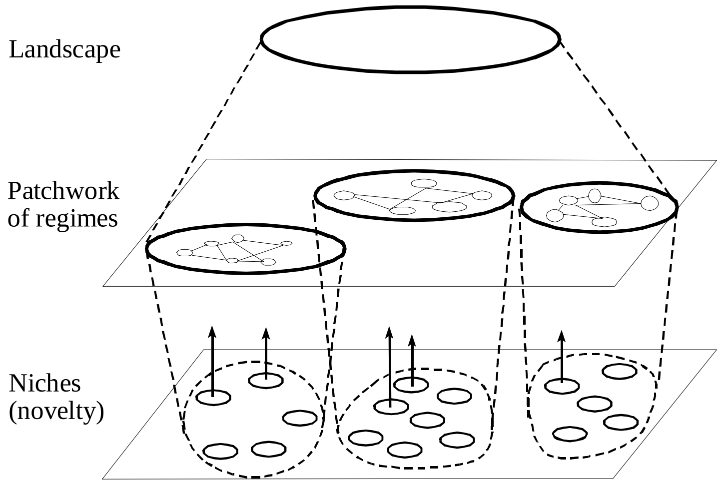
Figure 2: Topography of technological development (Sahal, 1985: 79)

Niches and variety

A technological niche is a specific application domain in which producers and users (sometimes together with third parties such as governments) form an alliance to protect new technologies against too harsh market selection. Niche developments happen in two (partly overlapping) forms: technological niches and market niches. Technological niches are ‘protected spaces’, where regular market conditions do not prevail because of special conditions created through subsidies and alignments between various actors. These *technological niches* are often played out in the form of experiments like those with electric vehicles in various European countries and cities (e.g. La Rochelle, Rugen, Gothenborg). These experiments with real-life users are suitable locations for learning processes, e.g. learning by doing, learning by using (Rosenberg, 1976; Von Hippel, 1988) and learning by interacting (Lundvall, 1988). Technological niches can develop into *market niches*, applications in specific markets in which regular market transactions prevail. In terms of rules and social networks, niches are different from regimes in two ways. First, while rules in regimes are stable and specific, rules in niches are fluid, broad and diffuse. In niches, there are only general guidelines and broad visions to guide activities. Protagonists are typically guided by ‘diffuse scenarios’ about the potential of future technologies. These general rules and visions become more specified and stable as more is learned about the technology and its use. Second, while regimes consist of large social networks, niches are carried by small and precarious networks. An important part of the work of niche protagonists is thus to manage and expand the social networks, to enrol other actors. As networks grow, they may turn into communities, with their own conferences, journals, societies etc. In short, niches are important for the development of new technologies, because they provide space for key processes such as the articulation and refinements of visions, interactive learning processes, and network formation by which a social constituency can be build up behind a new technology (Kemp, Schot and Hoogma, 1998; Kemp, Rip, and Schot, 2001; Hoogma, 2000). Niches are crucial for technological transitions, because they are the locations where variety is created. While sociotechnical regimes account for stability, niches are the seeds for change, building blocks for transitions. All historical TT started in technological or market niches. As technology became an explicit object of management in the 20th century, first in private R&D labs and later in government sponsored technology programs, technological niches became more prominent. Before the 20th century, small market niches were more often the incubators. Plenty examples of niches are available from the history of technology (Schot, 1998). The steam engine was developed to pump up water from mines. Steamboats were first developed as steam tugs to manoeuvre sailing ships in ports (e.g. the *Charlotte Dundas*, 1802). Gasoline cars were first developed for car races in Europe and touring in America. Freeman and Perez (1988) describe how niches are initially developed within the old framework. At first these innovations may appear as means for overcoming the specific bottlenecks of the old technologies. In later phases these innovations may develop into new sociotechnical regimes.

Relation between multiple levels

The relation between these three concepts can be described within a multi-level perspective (Figure 3). Niches are the locations where innovations emerge, where variety is generated. This is not a simple or blind process, but requires work from system builders. They have to form and manage a network of actors that share certain expectations about the future success of the innovation, and are willing to fund further development and maintain learning processes. The technological niche is formed against the background of the existing regime and landscape. The opportunities and problems in both kinds of context shape ideas about possible applications of the innovation. Radically new technologies usually have a hard time to enter established sociotechnical regimes, because of misalignments with other elements or because of strategic opposition from firms with vested interests in the old technology. Regimes and niches are both situated in a wider landscape, consisting of regime-external influences. Landscape developments occur slowly, and cannot be influenced directly by



regime actors.

Figure 3: Multi-level perspective on innovation

Understanding technological transitions

The dynamics of technological transitions can now be understood as follows. On the niche-level there is always work being done on innovations. The supporting networks and constituencies may be so small, however, that they are not noticed on the regime-level. The innovations then remain ‘hidden novelties’. The supporting constituencies may shift over time or fall apart. Callon (1980), for instance, described how development work on fuel cells for electric vehicles was done in France in the mid-1970s, and how the constituency gradually fell apart. Supporting networks may also grow larger under particular circumstances and gain widespread visibility. The strict emission mandate for cars the California Air Resources Board (CARB) proclaimed in 1990, for instance, was a major boost for the niche of battery-electric vehicles. Although there are always innovations being developed, they usually have a hard time breaking through, because of the inertia of the incumbent sociotechnical regime. The innovation may be under-developed, there may be a mis-match with other elements.

On the level of sociotechnical regime there are usually incremental processes ‘down the design hierarchy’, resulting in trajectories. As a heuristic I have distinguished seven dimensions in the sociotechnical regime: technology, user practices and application domains (markets), symbolic meaning of technology, infrastructure, industry structure (networks of suppliers, producers, distributors), policy and scientific knowledge. Although these dimensions are linked and co-evolve, they also have internal dynamics. These internal developments may result in ‘tensions’. There may be periods when linkages are weakening or ‘loosening up’. Such periods form windows of opportunity for innovations to break out of their niches and be incorporated in the regime. Metaphorically, the sociotechnical regime is a mosaic of heterogeneous elements and the niche-level as location where new elements are generated (variation). Once the mosaic starts shifting, these new elements can be introduced. The introduction of new elements may, in turn, trigger further shifts. Eventually such a process can result in a complete reconfiguration of the sociotechnical regime.

Tensions in the sociotechnical regime can also emerge as a result of changes on the landscape level. A cultural change such as increasing environmental awareness has put pressure on regimes such as transportation and electricity generation. The broad political trend towards liberalisation brought forward tremendous changes in the electricity sectors, introducing new technologies (e.g. gas turbines), new actors (e.g. organisations for trade in electricity) and new markets (e.g. green electricity).

The major point of this multi-level perspective is that technological transitions occur as the outcome of linkages and interactions of developments at multiple levels. Processes on the levels of regime and landscape create a ‘window of opportunity’ for innovations to break out of niches. Metaphorically this dynamic is like a ‘peatmoor fire’. While innovations may smoulder below the surface in niches, the fire only breaks through under particular circumstances, when multiple processes link up and accumulate. I have schematically represented this complex process in Figure 4.

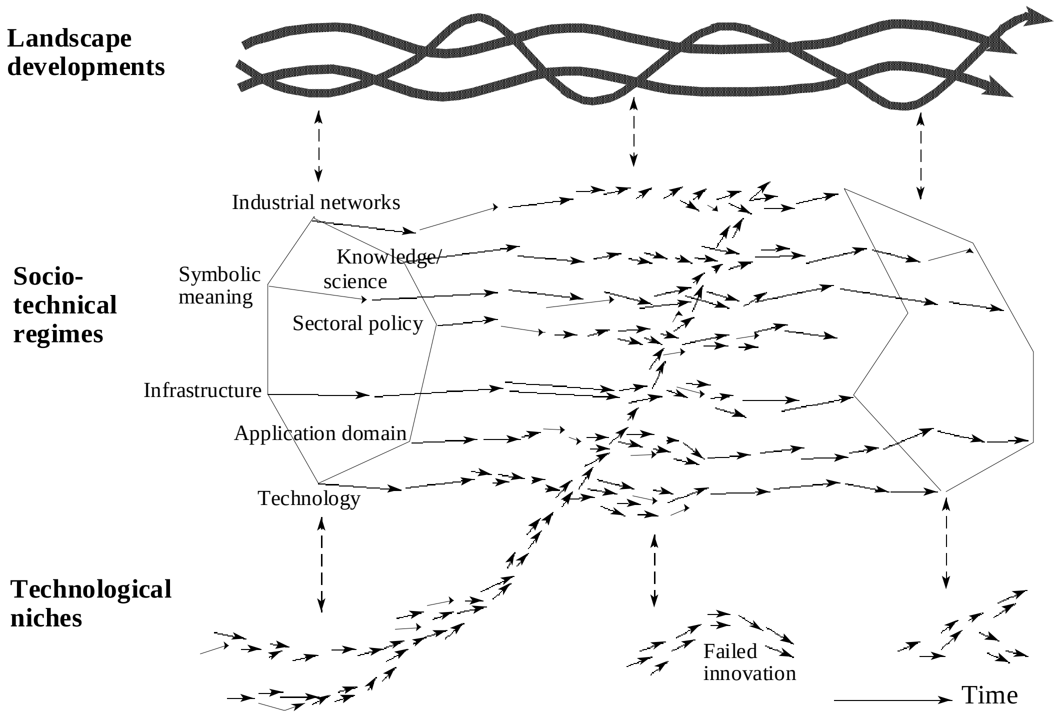


Figure 4: A dynamic multi-level perspective on technological transitions

It shows that innovations can remain in niches for a long time or even die out. Innovations break out of niches when they can link up with processes at regime- and landscape-level. An innovation can link up with processes on one or more of the regime dimensions. It may be linked to the established technology as auxiliary device (add-on); it may be linked to new regulations or newly emerging markets, etc. TT are about the linking of *multiple* technologies. TT do not only involve technology and market shares but also changes on wider dimensions such as regulation, infrastructure, symbolic meaning, social and industrial networks (represented by the increased density of arrows). Once established, a new sociotechnical regime may contribute to changes on the landscape level.

3. Empirical case-study: From sailing ships to steamships, 1780-1900

The aim of this case-study is to illustrate the multi-level perspective and provide material to further analyse reconfiguration processes (section 4). Traditional analyses describe this transition in terms of a life-cycle of steamships, a hero fighting against sailing ships ('David versus Goliath'). To prevent a heroic storyline I will start the analysis with the established sailing ship regime, and show how steamships emerged within this context. The first steamships did not compete with sailing ships, but actually improved the sailing ship regime, addressing particular bottlenecks. I aim to tell the story in terms of complexity and reconfiguration processes. To this end, I will use a mosaic style of writing, shifting between different elements of the sociotechnical regime (markets, ship designs, insurance rules, actor groups, institutions, mail subsidies, persistent and emerging problems, management practices). I underline the mosaic style by using captions to describe dynamics in particular elements. From a reconfiguration perspective, changes in one element trigger changes in another. Unconnected developments eventually link up and align. The story does not focus much on actors, but, instead, on somewhat aggregated processes. I will try to show Figure 4 in action, and describe for four subsequent periods which processes occurred at the landscape, regime and niche levels, and how they linked up and reinforced each other. The empirical description focuses on Great Britain, because this was the dominant shipping nation in the 19th century. Figure 5 presents an aggregate representation of the transition from sailing ships to steamships.

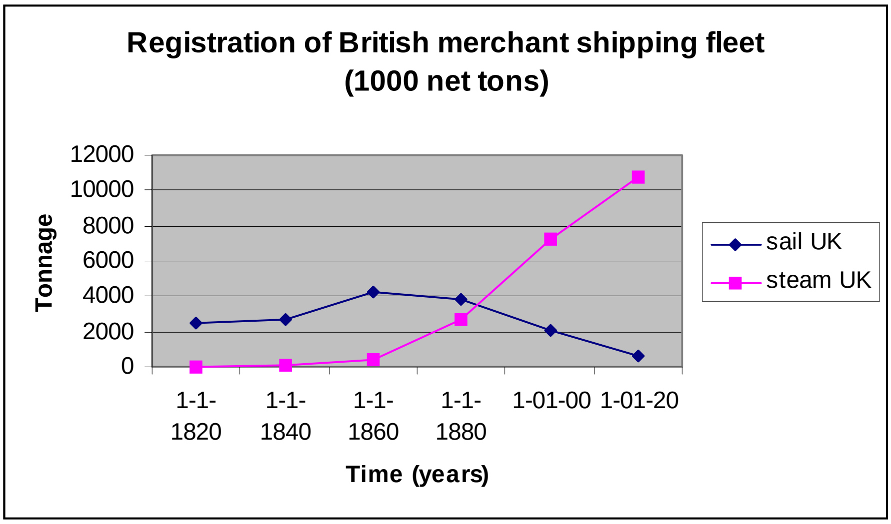


Figure 5: Fleets of steamships and sailing ships for two European countries (1000 net British tons) (data are based on Ville, 1990: 68-71; see appendix 1 for some data on other countries)

Steamships existed long before they took off in shipping. In 1850 the percentage of steamships in terms of British registered tonnage was only 4.7%, in 1860 it was 9.7%, in 1869 16.6%, and 51% was reached in 1883.

While Figure 5 represents the transition in terms of tonnage by sail and by steam, much more was involved, as becomes clear when late 18th century shipping is contrasted with shipping around 1900. In the late 18th century there were mainly two types of ownership: chartered companies, for whom the use of ships was instrumental to colonial trade, and the captain shipowner, usually operating one ship. Shipping expeditions were financed by charted companies or by ad-hoc collections, selling in advance possible revenues in 64 parts. Captain shipowners sailed to ports without knowing in advance if there was any trade. They relied on personal networks to acquire information about foreign markets, goods and prices. If there was no trade in a foreign port, the captain either sent a letter home to ask for further instructions or sailed to another port in search for trade. Mail was a crucial means for tele-communication and co-ordination. Both passenger and freight shipping were characterised by uncertainty and irregularity. Ships left ports when they were full and the time of arrival depended on winds and currents. The building of wooden sailing ships involved skilled craftsmen, e.g. carpenters. Intuition was more important than calculations for shipbuilders, and they took pride in their craft. Ports were relatively small, and unloading was done by hand.

In 1900 there were also two other types of ownership, liner companies and tramps. Liner companies were large firms, operating a fleet of vessels on the basis of fixed departure and arrival schedules. This introduced new functionalities in shipping, regularity and predictability. This was possible because steamships were independent of winds. Tramp steamers on the other hand roamed around the oceans, sailing from port to port in search of cargo to be shipped. Both liner and tramp fleets were managed from central offices. The telegraph was used to instantly acquire information about foreign markets and to (re)direct ships to the most profitable ports. Because steamers were more expensive than sailing ships, raising money was an important issue, especially in the case of fleets. A new institution was developed to raise money, the joint-stock company. This also meant that management and ownership were separated, and that managers had to pay much attention to financial accounting. Ships were built of iron and steel, and naval architects designed ships in advance. Engineers and scientists calculated optimal hull designs. As ships became ever larger, ports were enlarged and deepened. Because of their high capital cost, ships had to be unloaded quickly. Hence, new cargo-handling machines were introduced on docks. A world-wide coal infrastructure was created so that ships could refuel.

As this brief contrast shows, shipping in 1900 was very different from shipping in 1780. New functionalities had been introduced, new management and operating practices, new design practices, new infrastructures etc. In this section I will investigate how the sociotechnical regime in shipping changed. To understand these changes, I will describe relevant developments on the landscape and niche-level.

3.1. Pre-steam developments in shipping (1780-1830)

American innovations: Baltimore clippers

The shipping and trading regimes were dynamic and innovative in the early 19th century, particularly in America. Before the American War of Independence (1776-1783), American colonies provided cheap timber to Britain. After the War, the British punished America by denying access to British and colonial markets. Hence, American shipowners and traders had to find alternative markets. They turned their attention to the Atlantic, Mediterranean islands as well as to Mauritius and to China. In the small-volume, high-value China trade (e.g. opium, silk, opium) American merchants became competitors of the British East India Company, and needed fast ships to evade patrols. These particular market niches stimulated the emergence of the ‘Baltimore clipper’, a fast but relatively small ship. The Baltimore clipper emerged from a particular design practice which dated back to the time that America was still a British colony. One characteristic of this practice was to make the hull not flat-bottomed and full-bilged but with considerable deadrise, i.e. with the hull angling sharply up from the keel to where it curved into the sides (Calhoun, 1973). Another characteristic was that American construction methods remained light. This in itself tended to make medium-sized American vessels faster than comparable British models. The fast and manoeuvrable Baltimore clippers were used in the French Wars (1789-1815) to escape or get around French or British warships, and provide shipping services to obstructed ports (Dirkzwager, 1993). This had a great demonstration effect and stimulated demand for Baltimore clippers in those application domains that needed speed and manoeuvrability more than cargo capacity, e.g. smuggling, pirating, slave trade.

European shipping depression

The French Wars (1789 –1815) pushed up freight prices as demand for ships increased (for the transport of troops, provision). Entrepreneurial shipowners were attracted into shipping, resulting in a near doubling of the registered tonnage of the European fleet (Ville, 1990). When the war ended and demand fell back, this led to an oversupply of ships causing the European shipping depression of the 1820s and 1830s. The European depression was also caused by poor international trading opportunities. International trade with the colonies was hampered by a protectionist trade regime. Many countries had created monopolies which restricted colonial trade to their own ships. Britain, for instance, had the British Navigation Acts. British protectionism encouraged the building of a particular type of ships. Because shipowners paid more attention to a large cargo-holding capacity than high speed, this resulted in wide, heavy and sluggish ships. The design heuristics were not only encouraged by guaranteed markets, but also by government regulations, in particular the Tonnage Laws of 1773. Because considerable economies could be obtained by deepening the hold, without increasing the breath, these laws stimulated the building of deep, sluggish, flat-bottomed, flat-sided vessels (Graham, 1956).

New social groups and institutions

European colonial trading had been the province of chartered trading companies, operating within protected monopolies. Trade was the main business of these companies and shipping was merely an instrument. By the end of the 18th century a new social group emerged, the professional shipowner, offering shipping services to traders and merchants. This specialisation process signified a development in which shipping emancipated itself from trade. The emergence of professional shipowners was stimulated by the high profits made in the French Wars. Professional shipowning was also stimulated by the emergence of two other social groups: insurance companies and ship-brokers. Insurance companies offered a new way of dealing with the risks of long-distance trading trips. The function of ship-brokers was to mediate between demand (traders) and supply (shipowners) of shipping services. The mediation of the ship-broker increased the efficiency in shipping, as captains spent less time in ports looking for cargo. It especially increased efficiency in piece goods and general cargo, as ship-owners no longer had to negotiate with all traders individually (Broeze, 1977).

This specialisation in shipping and the emergence of new actors also depended on the extent of the market. Expanded markets, in turn, enabled increased specialisation and differentiation of the trading function. Beniger (1986) describes how a range of new actors and market institutions emerged in the expanding American export of cotton and import of textiles and machine-made goods from Britain. Goods were moved through increasingly denser networks of specialised middlemen, e.g. factors, financiers, brokers, advertisers, wholesalers, exporters and manufacturing agents. Increases in both the number of merchants and the density of their interactions encouraged specialisation in the information functions. An infrastructure for the circulation of information was created with a series of innovations in communication: journals of prices (1795), commercial newspapers (c. 1815), mercantile libraries (1820), trade journals (1831), ship-to-shore semaphore systems (1830s), agencies for advertising (1841), and credit report books distributed by subscription (1844) (Beniger, 1986: 200). New commercial institutions were also developed, e.g. formal exchanges to conduct market transactions, concepts of commercial law, and more sophisticated instruments of credit. Commercial capitalism established the essential infrastructure for the movement of matter on a world-wide scale. This included not only material technology like port facilities and ships, but also nonmaterial infrastructures like inter-personal channels of information gathering, processing and exchange, commercial law, and innovations like credit instruments and inventory techniques. These innovations occurred *before* the arrival of steamships.

Problems in trading and shipping

Despite these innovations, the shipping and trading regime continued to be plagued by persistent problems. The infrastructure of distribution remained unchanged on the dimension of *speed*. Until the 1830s goods still moved at the speed of riding horses, draft animals, and water and wind power. Teams of horses and mules powered canal boat lines, on which sustained speeds of 4 mph proved rare. A transatlantic crossing under sail took 7 weeks plus or minus a month. Another major problem in oceanic shipping, particularly for traders and merchants, was the lack of *regularity* and *predictability* (Broeze, 1977: 135). The uncertainty about times of arrival and departure made it difficult for them to plan transshipments and further distribution. Another major problem in long-distance trade was the *lack of control and co-ordination*, due to primitive telecommunications. Mail was the main means for resident merchants to instruct their captains or agents to buy goods or sail to another port. Because mail was transported as slow as merchant vessels, the possibilities for feedback and communication were limited. Letters between America and London typically took two months in each direction, meaning that any response to a change in market conditions could only be effected a minimum of four months after the fact. Since there could be huge variations in prices over time or between different ports, merchants were confronted with the chance for both profits and ruin.

The innovation of fixed departure schedules

A major innovation in shipping was pioneered by four American traders: fixed departure times. In 1818 they founded the first scheduled packet service, the *Black Ball Line*, which ran between Liverpool and New York on a regular departure schedule. Customers willing to pay extra money for more regular services included merchants who needed to have certain shipments sent punctually, civil servants who had to fulfil special assignments, or anyone wanting to send an official postal item. The *Black Ball Line* not only offered more regularity, but also higher speed. By carrying much sail, the ships cut the eastern crossing from 1 month to 24 days and the western crossing from 3 months to 40 days (Maddocks, 1982). Because the experiment proved successful, other liner companies followed. The packet boats carried urgent shipments, pressing mail and hurried passengers. The fast Baltimore clippers came to be widely used in this niche, reaching their peak between 1825 and 1850 (Pollard and Robertson, 1979). These new transportation services also improved telecommunications.

Because mail transport was decoupled from trading vessels, it gave merchants more control in the co-ordination of trade. Although the departure of packet boats was fixed, their time of arrival was still uncertain because sailing packets depended on winds.

Steamboat experiments

In the late 18th and early 19th century an interconnected network of inland waterways was created. Rivers were deepened and long curves cut off. Because many artificial canals were constructed to connect rivers, lakes or cities, it was the period of canal-booms. In Britain the first canal boom was in the 1760s, and the second in the early 1790s (Ville, 1990). The first American canals were built in the 1780s, after the American War of Independence (1776-1783). A real canal craze set in after the Erie canal was completed in 1825, connecting Lake Erie with the Hudson river. The improvements in inland waterways were an important step towards the creation of national markets, as bulky low-value cargoes (e.g. coal, iron ore, grain, timber) were transported easier and cheaper over longer distances.

Within the context of the canal boom a *steamboat niche* emerged. In Britain several experiments occurred since the late 1780s. The envisaged application was a steamtug to pull sailing ships through canals or manoeuvre them in ports. Although the experiments proved technically successful, the shared opinion was that commercial success was impossible. In France, too, there were steamboat experiments, but these were ended by the French Revolution. American experiments took place on rivers and in ports.

American market niches

The first market niche for steamboats was created by Robert Fulton on the Hudson River in 1807. His *Clermont* made an average speed of 5 miles per hour (against the flow of the Hudson), and was initially used for passenger services. The Hudson River was a perfect niche for the primitive steamboat.[1] After Fulton's success the steamboat diffused to other inland waterways, e.g. Lake Champion, the Delaware, Mississippi River. Steamboats spread easily, because of two landscape elements, the poor state of American roads and the process of westward settlements. Pioneers travelled westward, creating settlements as they went along. Via inland waterways industrial goods and products could be delivered, while produce could be taken to eastern cities. Particularly in the Mississippi basin the steamboat flourished. The Mississippi basin became the central American waterway, because it linked up with the westward expansion of settlers. Because of relatively shallow streams, the Mississippi steamboat was flat-bottomed with its characteristic boxy appearance.

British market niches

The steamboat was re-introduced into Britain by Henry Bell in 1812, who used his *Comet* to offer commercial passenger services on the river *Clyde*. Following Bell's success, early steamboats were introduced on the placid and calm waters of canals or rivers. Wider applications were found on the greater waters of harbours, ports and estuaries. Tugboats helped manoeuvre large sailing ships into ports. The next step was from estuaries to coastal routes and crossing small seas, for which the Irish Sea, North Sea and Channel provided natural opportunities (Broeze, 1982). These early steamboats were relatively small vessels,

[1] The Hudson had poor winds, and high and wooded banks which reduced the airflow. It had no towpaths like many European rivers, which exluded horse-drawn boats. The Hudson flowed between large centers of commerce and the area between them was hilly and roads were bad. The fuel supply (wood alongside the river) was cheap. The route was 150 miles long and very straight, without rapids.The current was not too strong, making up-stream travelling possible (Gilfillan, 1935).

because of the limited strength of steam engines. The space for the power plant and its coal supply greatly reduced the capacity to transport freight. Thus, steamers could only exist commercially in places where there was large-scale passenger and mail traffic, supplemented by special low-volume high-value cargoes.

Steamboats were also used in the Navy, not as warships, but for minor, additional functions such as towboats and internal mail carriage. Mail steamers improved the co-ordination of the fleet. Another use was to fight pirates. The Dutch Navy, for instance, articulated a need for such anti-pirate ships for its East Indies colonies (Dirkzwager, 1993).

On the European continent the scope of useful functions for steamboats was small, because passenger and mail traffic between ports on the continent was limited. Steamboat services also faced tough competition from European road infrastructures (Broeze, 1982).

Oceanic steamboat experiments

In Britain steamboats came to be used not only on rivers, but also on seas (e.g. Irish Sea, North Sea and Channel). The use of steamers on oceans, however, was thought impossible up until 1835 (Dirkzwager, 1993: 73). Although there had been some isolated experiments with oceanic steamers before 1835, these were not heralded as the beginning of a new age. These early experiments were important, however, in the sense that they proved the possibility of oceanic steamships. The *Savannah* (320 ton) was the first steamship to make the Atlantic crossing in 1819. One of the earliest steamers to cross the Atlantic in a west-bound direction was a little vessel called the *Rising Star*, 1822 (Figure 6).

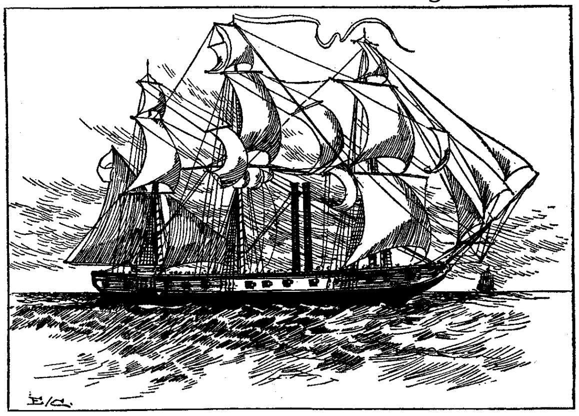


Figure 6: The Rising Star of 1822 (Fletcher, 1910: 130)

Steam engines were clearly used as an auxiliary add-on to sailing ships. For several years, no further attempts were made to send a steamer across the Atlantic. Many schemes were formed but also abandoned, as pioneers had difficulty in finding financial backing.

3.2. Functioning of steamships within the context of oceanic shipping (1830-1848)

Expanding markets

Starting in the mid-1830s a new era of shipping and trade expansion opened up. This was related to the landscape process of liberalisation in Britain. Businessmen and industrialists acquired more economic power and representation in parliament, and they pressed for economic liberalisation to stimulate their businesses. Britain became the ‘workshop of the world’, selling manufactured goods, coal, textiles, ships and financial services to the rest of the world. On the other hand, it imported raw cotton, metallic ores (e.g. iron, copper), meat, wool, guano and rubber. International and colonial trade were stimulated by the relaxation of the Navigation Laws in the 1830s. The market for luxury products such as tea, coffee, sugar, expanded, just as the transportation of passengers to Australia, New Zealand and America. Packet boats flourished in the expanding passenger markets, reaching their peak between 1825 and 1850. During the 1820s and early 1830s packet boats mainly transported first-class passengers, travelling in luxurious cabins on the upper deck. During the 1840s the increasing number of poor emigrants to America provided the greater part of income for sailing packets. The expanding freight markets and the liberalisation of colonial trade stimulated the emergence of professional shipowning.

Continuing problems and mail steamers as solution

Long-distance freight shipping continued to be troubled by problems of limited control. The most important constraints affecting the development of freight markets in the 1830s and 1840s were the *quality and speed of communication* and the *stock of information* which could be found in different localities (Kaukiainen, 1998). Market information in foreign ports was not publicly available, and could not quickly be send to merchants back home.

In the 1830s and 1840s steam began to offer solutions to the problems in the freight regime. The railway was of practical importance for postal connections in Britain, Belgium, Northern Germany and the Habsburg Empire, and steamships were making coastal traffic and the crossing of the Channel speedier and more regular. After 1838 the British government began stimulating the use of steamships by paying *mail subsidies* to shipping companies. Already by the mid-1840s mail was arriving in Batavia by steamer via the Mediterranean and the Red See, a faster route than by the Cape. Thus, the first use of oceanic steamships was aimed at improving the communication and co-ordination in the freight shipping regime. Mail steamers made possible a more flexible and faster carrying system by freeing it from physical partnership with mercantile transactions. This stimulated the gradual differentiation of commodity and freight markets (Kaukiainen, 1998).

New American ship designs: Sailing clippers

In the high-value freight markets new ship designs emerged, as the monopoly of the British East India Company was abolished in 1834. Because of the high value of its trade (opium, tea), China was an attractive market. High speed was an important criterion, because the quality of tea declined during transport. This new market was quickly explored by new American ships, the so-called *opium clippers*. These ships were larger than Baltimore clippers and more designed for cargo, but still fast and manoeuvrable. Their main period of activity was between 1830 to 1850, after which they were superseded by steamers and tea clippers (Pollard and Robertson, 1979). In Britain, the Tonnage Laws were altered in 1836, simplifying methods of measurement, making earlier tax evasions impossible. Because the new Tonnage Laws were not compulsory until 1855 improvements in British ship designs came about slowly.

As new routes and trades emerged, the hull forms of American clippers were adapted and differentiated. In the 1840s this resulted in the development of the long, flat-bottomed cargo-carriers, known as *clipper ships*. Though noted for their sharp lines, the American clipper ships were essentially a reversion to the flat-bottomed style of large-ship design that had prevailed just before 1815 (Calhoun, 1973). The most important era of the tea clippers extended from 1840 to 1860 (Pollard and Robertson, 1979). In the 1840s and 1850s the United States turned out the finest wooden sailing ships afloat. After the repeal of the Navigation Acts in 1849, American clipper ships were employed on around-the-world routes.

Problems in wooden sailing ships

By 1850, however, American shipbuilders began experiencing construction problems. As ships increased in size, they met problems of longitudinal strength. It was becoming more difficult to get large enough timbers, so that builders had to compound to beams out of smaller pieces. While British shipbuilders in the 1850s gradually moved to partial and total *metal construction*, American shipbuilders continued to use wood.

Mail subsidies for oceanic steamboats

Steamboats came to be used on oceans after 1838, when the British government decided to pay mail subsidies to steamship companies on particular routes. Because mail steamers delivered mail faster than sailing ships, they improved long-distance communication and co-ordination within the British Empire, beneficial to both public servants and private merchants. The *Cunard Line* and the Great Western Steamship Company were awarded mail transports to America. Line services to America not only increased on the dimension of speed, but also greatly improved the regularity and reliability of services, thus introducing new functionalities in oceanic shipping. Between 1838 and 1862 a global network of British intercontinental steam companies was created on the basis of imperial mail subsidies (Broeze, 1982). Although the American Congress awarded mail subsidies to steamship companies in 1847, this policy was attack in Congress during the 1850s (Fletcher, 1910).

Problems in steamships

Oceanic steamships suffered several problems. First, the net carrying capacity was reduced, because much coal had to carried on board. This was caused by the high coal consumption of steam engines. Second, paddle-wheels did not remain in contact with the water in conditions of rough weather and large waves. This not only reduced the functioning of the paddle-wheels, but also the ship's stability and manoeuvrability. Third, the heavy weight of boilers, condensers and steam engines caused the wooden hull to bend and stretch. As steam engines and boilers grew more powerful and heavier, also to increase coal efficiency, this problem grew worse.

Experimentation and learning

The decade of the 1840s was remarkable for innovation and experimentation with new technical elements. The mail subsidies and gradual expansion of market niches provided 'space' for innovations. It was a period of experimenting and learning. The direction of innovative effort was guided by the problems on the technical agenda. New elements such as screw propulsion, iron hulls, more efficient steam engines progressed by a tortuous process of trial and error. In the 1840s the different technical trajectories were relatively separate and uncoupled. It was not until the late 1850s and early 1860s that the different trajectories linked up, resulting in a new technical regime.

Alternatives to paddle-wheels

The problems with paddle-wheels gave rise to several search directions. Incremental changes were tried with regard to the position of the paddle-wheels, e.g. on the side of the ship, or at the back. An alternative propulsion option was jet propulsion, where water was drawn in by a turbine wheel and ejected through propulsion pipes and nozzles (Fletcher, 1910). Another alternative propulsion system was screw propulsion. Two early inventors, Ericsson and Smith, aroused great interest with five screw vessels for demonstration purposes in 1836 and 1837 (Gilfilllan, 1935). Although the basic principle of screw propulsion was demonstrated, many practical problems and issued required further experimentation and learning. Because screw propulsion required a higher number of revolutions, a device had to be worked to drive the screw fast enough. The higher number of revolutions, however, caused the so-called *vibration problem*. Wooden ships suffered from being shaken apart. The vibration problem aggravated problems with wooden hulls, and stimulated a gradual shift towards iron hulls. Vibration also stimulated a change in the lay-out of the ship, as cabin passengers were moved from the back to midship. Traditionally, the stern had been the place of honour, and changing the established custom was not an easy matter (Gilfillan, 1935). Furthermore, a large variety of screw forms had to be tried out in practice (see Figure 7). These practical problems had to be worked out, before screw propulsion became more acceptable in the 1850s. An indication of the increasing belief in screw propulsion was the reduction in insurance premiums on screw ships from 4% tot 1.25% in the 1850s (Lambert, 1999).

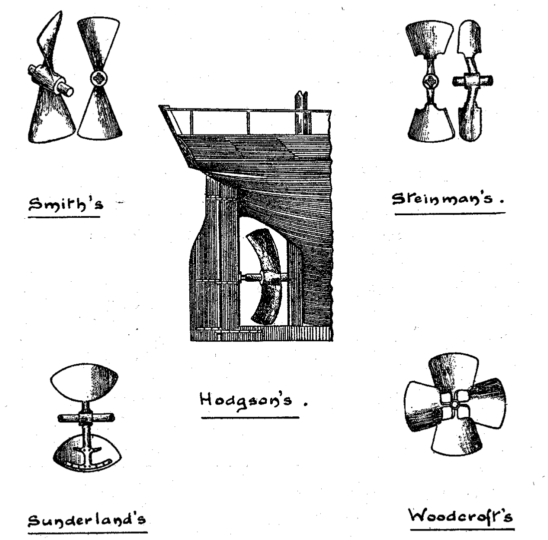


Figure 7: Screw propellers tried in the Rattler, 1845 (Smith, 1937: 76)

Search directions in marine steam engines

The evolution of marine engines was that of a slow sequence of innovations. The most important way to higher coal efficiency was higher boiler pressure. In the 1830s the ordinary steam pressure in marine boilers averaged 5 psi (pounds per square inch); in the 1840s 10 psi; and in the 1850s with the introduction of the tubular boiler 20 psi (Graham, 1956). Higher boiler pressure was achieved by making boilers heavier and stronger, using stronger metals. Another search direction was boiler design. Between 1840 and 1850 tubular boilers were generally adopted, being lighter and more compact (Fletcher, 1910). Better lubricants, reducing friction between moving parts, further improved the efficiency of steam engines.

Learning to work with new materials: Iron hulls

Enterprising shipbuilders began experimenting with iron ships in the 1830s. The building of iron ships required new skills and competencies. Initially, iron plates came in small dimensions, about 3 meters long and 1 meter wide (Wimmers, 1998). These iron plates had to be connected together by rivets, a difficult task requiring specialised competencies. Iron also required different process techniques, e.g. heating, hammering, flattening, punching. Shipbuilders used to working with wood, possessed neither the required skills nor the machines to build with iron. Hence, the construction of iron ships depended on outsiders, iron workers and boiler makers (Smith, 1937).

The first iron ships encountered great scepticism. Some people believed that iron ships would sink because iron was heavier than water (Fletcher, 1910). If iron vessels did not sink under their own weight, the engines, it was said, would cause them to sag, while the reciprocating motion of the engines would cause fracture of the plates. The most difficult problems were due to the serious disturbance of the compass and the rapid fouling of the hulls by marine growths (Smith, 1937: 96). Because iron hulls disturbed the compass, iron ships were difficult to use on oceans. It was not until 1855 that a proper compensating arrangement for the compass was developed (Dirkzwager, 1993). Hence, iron ships were first used in the niche of inland waterways. The Navy also bought some iron steamships in the late 1830s, but turned sceptical after shooting tests showed that iron hull splintered and fragmented when hit by bullets (Dirkzwager, 1993).

The use of the new material for ship design set new problems, because many of the traditional building rules were no longer applicable. Initially, shipbuilders build iron ships on the basis of rules and criteria from wooden shipbuilding practices. But these early iron ships often suffered from instability, as described by Scott Russell, a shipbuilder and vice-president of the Institution of Civil Engineers, who wrote in 1875 about his experiences in the 1840s:

> "Ships were launched in my time, so ill calculated in quality, that their first evolution, on reaching the water, was to turn upside down and to stay that way. (..) We remember another fleet of iron ships, built for another great company, being all actually completed before their utter unseaworthiness was discovered; and we remember the cure to have been the building of a great brick wall, in cement, on the inside of the iron hull, on the bottom, so that the weight of the bricks should keep the bottom of the ship from turning upside downs in a sea-way, and for many years these ships were kept on end by these means alone" (Russell cited in: Garrat *et al*., 1973. 69-70).

Despite the early scepticism and design problems, it was gradually found that iron had some advantages over wood. It stood fires and vibration as well as the weight of steam engines. Because of its greater strength, the hull could be thinner, even to the point of being lighter than wooden ships (Gilfilllan, 1935). Official recognition of iron ships dates from 1837 when the steamer *Sirius* was classified in Lloyd's Register. High insurance premiums had to be paid and no rules for the construction of iron ships were issued by Lloyds until 1855 (Smith, 1937).

While iron ships were gaining acceptance on inland waterways and short-distance routes, iron ships for oceanic travel were still distrusted. In this context, the use of iron to build the Great Britain (1843) was a major experiment (Figure 8).

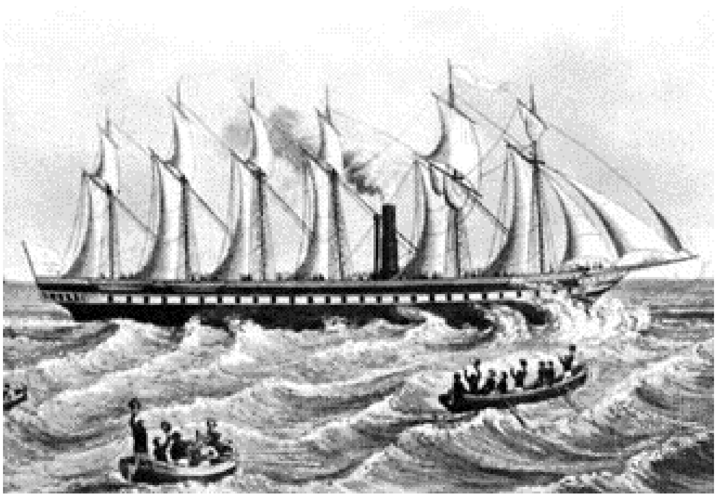


Figure 8: The Great Britain (1843) (Encyclopedia Britannica)

The ship (3618 ton) was much larger than contemporary iron vessels which were between 700 and 1000 tons (Smith, 1937). To reduce the chance of failure, the ship was built as strongly as possible, with relatively thick iron plates. Although the *Great Britain* successfully crossed the Atlantic, it took many more demonstrations before iron ships were widely accepted. As Figure 8 shows, the *Great Britain* was a hybrid form between sailing ships and steamships.

3.3. Sailing clippers and the take-off of steamships in passenger transport (1848-1869)

Expansion in passenger and freight transport

The shipping regime in the 1850s and 1860s was characterised by growth. The upward trend of demand for shipping services produced long-term optimism in the sector, indicated by the phrase ‘the Golden Fifties’ (Palmer, 1985). Passenger transport on the North Atlantic grew strongly because of European emigration. Between 1820 and 1920 about 60 million Europeans set sail for the America (60%), New Zealand, Canada, South America (O’Rourke and Williamson, 1999). The first wave of mass emigration occurred in the late 1840s. Between 1846 and 1855 more than 2 million Europeans left for America (Maddocks, 1982). Mass migration from Ireland was caused by the Irish potato famine (1845-1849). The European political revolutions of 1848 also stimulated people to leave. Many Europeans wanting to escape poverty were attracted by high American wages. This was reinforced by the goldrush in California (1848) and Australia (1851). Freight transport benefited from liberalisation, as the British Navigation Acts were finally abolished in 1849. Industrialisation in western countries also stimulated freight transport, as did falling freight tariffs. Between 1840 and 1887 there was a sevenfold increase in seaborne commerce (see Table 1). Because this increasing trade was carried by sailing ships, it is *not* true that the emergence of world trade depended on steamships. The growth of world trade was started by sailing ships and provided opportunities for steamships. Once steamships became larger and faster the growth in world trade was further stimulated, e.g. by decreasing transport costs.

COMMODITY	*1840*	*1887*		*COMMODITY*	*1840*	*1887*
Coal	1400	49.300		Jute	-	600
Iron	1100	11.800		Meat	-	700
Timber	4100	12.100		Coffee	200	600
Grain	1900	19.200		Wine	200	1400
Sugar	700	4400		Salt	800	1300
Petroleum	-	2700		Sundries	9180	33.750
Cotton	400	1800				
Wool	20	350		Total	20.000	140.000

Table 1: Merchandise carried by sea, annual totals, in ‘000 tons (Craig, 1980: 18)

Re-emergence of British shipbuilding: Towards iron sailing ships

While American clipper ships came to be employed on around-the-world routes, reaching their climax between 1840 and 1860, British shipbuilding enjoyed a new vitality. Stimulated by the growing opportunities, Britain’s pace of innovation quickened in the 1850s and 1860s. As the new Tonnage Laws became compulsory in 1855, British shipbuilders began building clipper ships. These British clippers were heavier and narrower than American clippers, which were generally cheaper and faster. The advantage in strength and safety lay with British ships (Pollard and Robertson, 1979). British shipbuilders gradually shifted from wood to iron as building material. This shift was related to problems of longitudinal strength. As wooden ships increased in size, they were approaching their ‘natural limit’ of 275-300 feet. Iron made its way into shipbuilding, because it linked up with this problem. Another was the increasing scarcity and rising price of timber in Britain (Harrison, 1990). Because of production improvements, iron actually became cheaper than wood in the 1860s. In America timber remained cheaper than iron, stimulating American shipbuilders to stick with wood (Harley, 1973).

Iron entered British shipbuilding in a gradual and stepwise proces. Iron was first used, as an *add-on*, to strengthen the existing wooden constructions in the form of knees or connections between the deckhouses and the ribs, and for the breast-hooks and pillars of the ship. As a second step composite sailing clippers were built in the 1850s, having an iron frame and wooden planking. These composite ships were a hybrid, intermediate form. In the late 1850s and early 1860s ships with all-iron hulls and steel masts emerged. This was accompanied by a substantial revision in 1863 of Lloyds Rules lowering the insurance premiums of iron ships (Harley, 1973). The shift towards iron was an important factor in the re-emergence of British shipbuilding. Another factor was the American Civil War (1861-1865), during which around 40% of American sea-going tonnage was lost (Harrison, 1990).

Steamships take off in passenger transport

The percentage of steamships in terms of British registered tonnage grew from 4.7% in 1850 to 9.7% in 1860 to 16.6% in 1869. Although steamships continued to be used in the Navy and on inland waterways, it was the transatlantic transport of passengers that accounted for this growth. The take-off of steamships was stimulated by European emigration. Most emigrants travelled on cheap packet boats in the 1850s. Rich passengers, however, chose for steamships to cross the Atlantic. Speed, regularity and comfort were important selection criteria for first-class passengers to which steamships could link up. Early steamship companies had little interest in poor emigrants, leaving them to sailing packets. This changed in 1850, when the steamer *The City of Glasgow* made a considerable profit, transporting 400 passengers. After the mid-1850s steamships quickly captured the emigrant market. While 45% of European emigrants travelled by steamer in 1863, this rose to 81% in 1866 (Maddocks, 1982).

New organisational forms and management practices

Steamship liner companies turned into large corporate and professional companies, operating fleets of liners which ran to a regular timetable connected with railway services (Ville, 1990). A major organisational change was the introduction of a new kind of ownership: the joint stock company. This new institution made it easier to acquire capital to buy steamships, which were more capital intensive than sailing ships. Particularly when steamships were operated as a fleet of liners, large companies were set up as joint stock companies.

Management practices also changed with the emergence of liner companies. Managers had to pay more attention to matters such as fleet management, financial accounting, cost control, detailed budgeting, long-range planning (Sloan, 1998). The shift to new management practices was a search and learning processes. Financial accountants tried to deal systematically with matters such as initial cost, useful operating life, replacement cost, vessel depreciation and residual value. New capital aspects related to steamships were not always appreciated, as accountants continued to rely on conventional financial standards. They often failed to grasp the matter of steam vessel depreciation (Sloan, 1998). Shipping management became an exclusive, specialised occupation, using trained professionals. Ownership and management were increasingly separated. The rise of professional shipowners, a trend which had begun in the early 19th century, was accelerated by the transition to steamships.

Prestige in the innovation race: The Blue Riband Price

Because of its profitability the Atlantic Ocean turned into a competitive arena between liner companies. To distinguish themselves liner companies ordered ships that were ever larger, faster, safer, more luxurious and modern. The importance of speed was emphasised when the *Blue Riband* price was instituted in the 1860s for the fastest crossing of the Atlantic. This resulted in an innovation race, providing an incentive for further work on new technical elements such as iron hulls, screw propulsion and better steam engines.

The gradual articulation of new design possibilities with iron hulls

By the mid-1850s more iron ships were built, and shipbuilders began to rise above the experimental stage. The Navy changed its hesitant attitude towards iron after grenades were introduced in the Crimean War (1853-1856). Because this new weapon greatly increased the damage to wooden ships after the projectile entered the ship, Navies searched for alternatives After the French developed the frigate *La Gloire*, using heavy iron plates as armour, the British Navy decided in favour of all iron hulls in 1859 (Dirkzwager, 1978). This gave a further stimulus to iron hulls. Acceptance in the mercantile community was accompanied by Lloyds lowering of insurance premiums of iron ships in 1863 (Harley, 1973).

Because iron ships were plagued by fouling of the bottom, further innovations were sought. Experiments were done with anti-fouling paint containing salts of mercury, lead, antimony, zinc and copper. In 1860 Rathjen achieved world-wide success with his quick-drying alcoholic shellac solution (Gilfilllan, 1935).

With regard to ship design it was gradually learned that iron allowed for new functionalities. Early shipbuilders saw iron simply as a substitute for wood, translating wooden construction principles into iron. The iron keel, for example, was built identical to a wooden keel. Only later its shape and way of construction were changed (Dirkzwager, 1993). Other design innovations of the 1850s were: a) the double bottom, which was used both as a safety compartment and a set of containers for water ballast or oil fuel, b) water-tight bulkheads, which were used for safety and strength, c) bilge keels, lateral fins outside the ship to diminish its rolling (Gilfilllan, 1935). Furthermore, iron made it possible to build far larger ships. Iron also turned out to be longer lasting than wood, lengthening the life of ships. As screws became used in the 1850s, it turned out that iron hulls could much better stand the constant vibration.

Screw propulsion

Screw-propulsion gradually established itself as the dominant propulsion mode in the 1850s and 1860s. In the early 1850s, the Navy began adopting screws. The acceptance of screw propulsion is indicated by the lowering in the 1850s of insurance premiums on screw ships from 4% tot 1.25% (Lambert, 1999). Commercial steamship lines were somewhat slower in adopting the screw. The damage from vibration to wooden ships was an important issue, as it jeopardised the safety of ships. The vibration problem was solved as iron hulls came to be more accepted by the mid-1850s. The vibration of screw-propulsion also required changing the ship lay-out and moving passenger cabins to mid-ship, something which met resistance because tradition had it that the stern-post was the place of honour (Gilfillan: 1935). One of the first liner companies to adopt the screw was the Inman Line in 1850. The older and established Cunard Line continued to use paddle-wheels until 1862 (Dirkzwager, 1978).

Compound steam engines

A promising way to increase coal efficiency were compound engines, where high-pressure steam could be used twice to drive an engine. The steam from the first cylinder, where the initial pressure was great, would be passed to a second cylinder of greater bore, where there was naturally less pressure per unit of area. Thus the amount of power from a given amount of steam was increased considerably. Compound engines were first developed for land-based, stationary applications such as in mines and factories. In the late 1820s and 1830s compound engines were used to some degree on steamboats for inland waterways (Verbong and Van Overbeeke, 1994: 230). Compound engines were not used on oceans, because injection of salt water, to condense the steam, gave problems. Salt formed sediments on the inside of the cylinder, reducing its working and creating explosion problems. This stimulated a search for new ways of condensing steam. Already in 1832 Brunel obtained a patent for a surface condenser, where steam was cooled by letting it flow through small tubes cooled by water on the other side. Technical problems prevented its application at the time. Work on surface condensers picked up again in the 1850s. The first experimental compound engine with surface condenser was installed on board an oceanic steamer in 1854 and used successfully to cross the Atlantic (Broeze, 1982). This engine used about 3 ¼ lbs coal per horsepower per hour, compared to 4 to 4 ½ lbs hp. per hour for contemporary engines (Craig, 1980). The working of the compound engine was hindered, however, by the poor quality of boilers, making it difficult to sustain proper working pressure. Before 1860 steam pressures were generally not higher than 30 psi. After 1860 better surface condensers were introduced and higher pressures of steam generated: 40 psi in the early 1860s, 60 psi by 1866 and 70 psi by the mid-1870s. The compound engine was crucial for using steamships on long-distance routes, because it greatly improved coal efficiency, enabling reductions in fuel consumption of 60% (Graham, 1956).

A new technological steamship regime

In the 1850s and early 1860s the technical trajectories of screws, iron hull and compound engine were gradually linked together, resulting in a new technical steamship regime. The linkage between the different technical elements was no simple matter or linear process. It required many experiments and learning processes. One impressive but costly project was the *Great Eastern*, launched in 1858 (Figure 9).

Figure 9: The Great Eastern, 1858 (Encarta Encyclopaedia)

The *Great Eastern* (211 meters 18.915 gross tons), designed as a prestige object for the Great Western Steam Company, represented a gigantic leap forward, being six times larger than other ships of its time (Gilfillan, 1935). It was designed to steam to Ceylon, Australia and back. Its great size was dictated by the need to carry thousands of tons of coal as there was not yet a world-wide coal infrastructure. The peculiar combination of steam and sail was aimed to assist the ship around the Cape. Although the ship was admired for her engineering, if suffered some technical problems, e.g. high coal consumption, instability in bad weather. As a commercial venture the *Great Eastern* was a complete failure. It never made any money because it was too large and too progressive. There simply were not enough passengers, cargo and docks (Gilfillan, 1935).

The introduction of compound engines made it possible to use steamships in particular long-distance market niches in *freight* shipping. Alfred Holt not only developed compound engines, but also used them in his steamships. Because the quality of tea declined during transport, merchants were willing to pay a premium price for high speed transport. His pioneering steamship, the *Agamemnon*, steamed to China in 1866 via Cape of Good Hope. Because Holt's engine consumed 40% less fuel than earlier steamers, his ships were able to compete successfully with the 'tea clippers' that had dominated the tea trade (Craig, 1980).

3.4. Gradual diffusion of steamships in freight and wider transformations (1869-1900)

Steamship diffusion in freight markets

A major change in the physical landscape was the opening of the Suez Canal in 1869. The Canal not only shortened distances to the east, but also proved unsuitable for sailing ships, because of few and variable winds. Hence, the Canal gave steamships a great comparative advantage on routes to Bombay, Calcutta, Singapore and Shanghai. Although the impact of the Suez Canal was confined to a few routes, particularly the Chinese and Indian trades, it gave rise to *steamship mania* (1869-1874). The percentage of steamers in the British fleet rose from 16.6% of total registered tonnage in 1869 to 31.3% in 1874. A large part of this growth was caused by the diffusion of steamships in freight shipping. In the 1850s British steamers entered some trades with northern Europe and the Baltic countries, while they began competing in the Mediterranean fruit trade around 1865. With the introduction of the compound engine in the mid-1860s steamships came to be used in the special market niche of the Chinese tea trade. At the end of the 1860s the distance margin between sail and steam was raised to 3000-3500 miles (Harley, 1988). This enabled freight steamers to be used on the North Atlantic grain trade and increasingly in the grain trades from the Black Sea. The Suez Canal opened up the market niches of India and China trades. Already in 1871 virtually all cotton products to Bombay and almost 20% of all exports from Calcutta to Britain travelled through the Suez Canal. Javanese coffee and sugar could also be profitably carried by steam. As a result, by 1873 more than 20 new European steamship companies were formed for the Asian trades (Broeze, 1982). As coal efficiency improved, the distance margin gradually progressed and steamships came to be employed on longer routes (Table 2).

Date (approximately)	Voyage (route)	Distance (miles)
1855	Northern Europe	500
1865	Mediterranean fruit and cotton; Chinese tea trade	Up to 3000
1870	North Atlantic grain trade; Bombay via Canal	3000 6200 via Suez canal
1875	New Orleans cotton	5000
1880	Calcutta	8200 via Suez canal; 11.500 via Cape
1895	West Coast of America, grain, ore	13.500 to San Francisco

Table 2: Routes and dates on which steam became competitive with sail (Harley, 1985: 177)

Competition and prestige in passenger transportation

Passenger transportation continued to be a growth market for steamships. In the 1880s and 1890s emigration speeded up again, when about 600.000 people left per annum. After the turn of the century the emigrant stream increased even further to about 1 million emigrants per annum (O'Rourke and Williamson, 1999: 119). New liner companies were formed in the 1870s on the Atlantic and in the Indian Ocean, e.g. the White Star Line (1870), Norse American Line (1871), Red Star Line (Antwerp, 1872) and the Holland America Line (1873) (Broeze, 1982). Existing liner companies such as the Cunard Line, P&O, Royal Mail, Hamburg-Amerika Line, Norddeutcher Lloyd expanded their passenger services. In the emigration market to America, German lines such as the Hamburg-Amerika Line and Norddeutscher Lloyd challenged British hegemony. The competition stimulated technical development. As liner companies struggled for prestige, ever larger, faster and more luxurious liner ships were developed.

Why was steamship diffusion in freight markets gradual?

There are three complementary reasons for the fact that the diffusion of steamships in freight was so gradual: a) gradual technical change in steamships, b) defence by sailing ships, and c) changes on wider dimensions of the socio-technical regime, e.g. ports, coal infrastructure.

Technical change in steamships

The first reason for the gradual increase of the 'distance margin' of steamships were technical improvements reducing coal consumption of marine steam engines. Boilers improved, facilitating higher steam pressures. Higher pressures depended critically on better quality steel, as well as better lubricants improving airtight sealing (Gilfillan, 1935). Innovations such as superheaters and forced draught (which allowed the use of poorer quality coal) also enhanced coal efficiency. The compound engine was further improved, eventually resulting in the tripple-expansion engine which was quickly adopted in 1884. The cumulation of a host of incremental innovations greatly improved coal efficiency (Figure 10). Because these improvements lowered fuel costs, steamers were increasingly able to compete successfully on long-distance voyages.

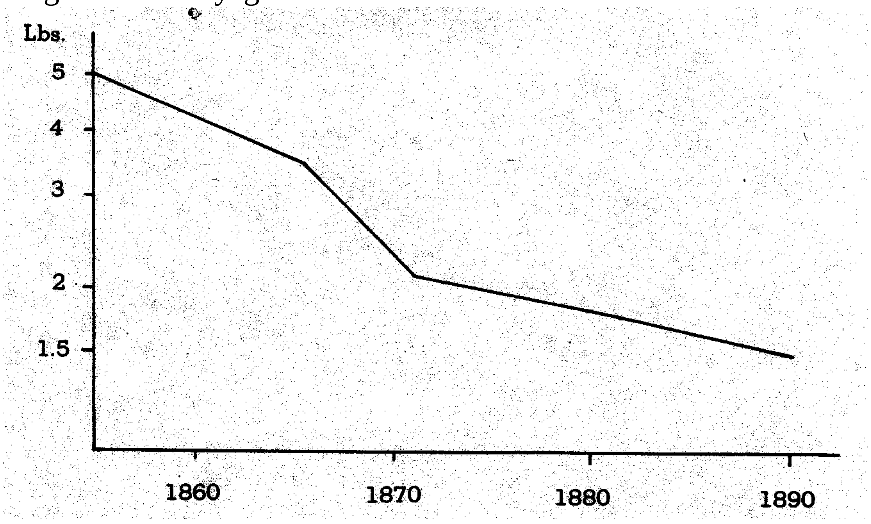


Figure 10: Coal consumption of steam engines per horsepower per hour (Harley, 1985: 176)

Other innovations also lowered operating costs of steamships. As ships grew larger, relative transport costs per ton decreased. Lower coal consumption meant fewer stokers to feed the boilers and reduced labour costs (Kaukiainen, 1992). Prices of iron shipbuilding decreased rapidly from the mid-1870s, because of better metal working machine-tools and cheaper metals. Improved port facilities and cargo handling, resulted in faster turnarounds in ports.

Defence by sailing ships

The second reason for the gradual diffusion of steamships were 'defence strategies' by sailing ships. The first defence strategy was technological innovation in sailing ships. Cargo capacity was increased by building larger sailing ships with composite hullsin the 1860s and with iron hulls in the 1870s (Harrison, 1990). By 1870 iron sailing ships had double the space for cargo in proportion to tonnage (Graham, 1956). To reduce crew costs labour-saving machinery (e.g. for rigging) was introduced. With these new machines, sailing ships could be manned and navigated by about 30% the number of men (Graham, 1956). Higher speed was achieved by new hulls, longer ships and additional masts. Large gains in speed were made by lengthening ships. These longer ships also allowed more masts and sail. More sail increased the speed of sailing ships but also reduced the ship's manoeuvrability. A culmination of the trend to more masts and sail was the steel-hulled schooner *Thomas W. Lawson*, build in 1902 (Figure 11). Although this giant sailing ship (117 meters) was fast, it had bad manoeuvrability. The ship was so unstable that it capsized while at anchor during a severe gale in 1907 (Foster, 1986).

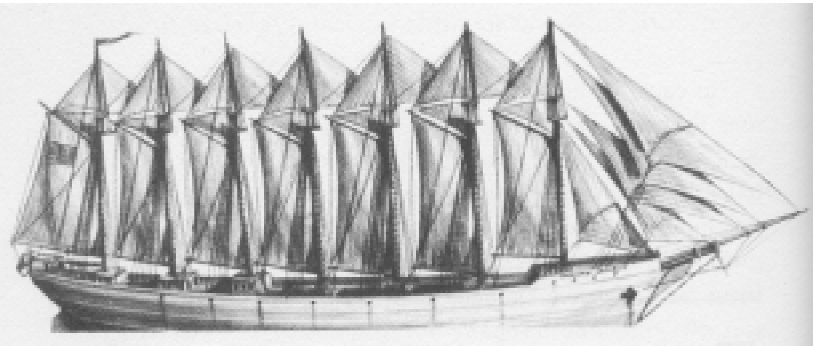


Figure 11: The Thomas Lawson, 1902-1907 (Foster, 1986: 28)

The renewed sailing clippers were strong competition for steamships in the ocean trades of the 1870s and 1880s. The improvements in sailing ships are an example of the general pattern that established technology is improved when it is challenged by a new technology. Because this pattern is so obvious with sailing ships and steamships, it is often called the *sailing ship effect*.

The second 'defence strategy' were wider technological changes that improved the operation of sailing ships. Steam tugs, for example, helped sailing vessels get to sea more quickly by combating adverse winds and tide (Ville, 1990). Steamers thus not only competed with sailing ships, but also helped them. Another innovation was the widening knowledge of oceanography and the creation of reliable charts of winds and currents. Maury's standard work of 1850 helped captains choose the best route in any particular month or week. Thus, the average passage to the equator was shortened by 10 days. The journey from England to Australia was shortened from 125 days to 92 days.

A third 'defence strategy' of sailing ships was to evade to new markets, as steamships threatened them. This strategy was made possible by market dynamics in world trade. World trade both grew and diversified. Between 1850 and 1913 world trade per capita grew at over 30% per decade (Ville, 1990). Britain imported raw materials (e.g. metallic ores, petroleum) and wheat, while coal, textiles, iron, and machinery were exported. The freight market also diversified, both in terms of shipping routes and the kind of freights. Shipping routes to new continents were opened up, while established routes were expanded. This resulted in a diverse freight market, consisting of many different market niches. Many of these new markets were bulk cargoes, consisting of raw materials, e.g. iron and coal, jute and rice of India and Burma, wool of Australia, nitrate fertiliser (guano) of Chile and wheat of California and Russia. Because low costs were a more important selection criterion in bulk markets than high speed, sailing ships found good employment. As a result, the predominance of sail was extended by more than a decade after 1870 (Graham, 1956). Particularly on routes with uniform and constant winds large sailing ship continued to be the cheapest freight carriers.

Wider changes in the sociotechnical shipping regime

The third reason for the gradual diffusion of steamships were changes on wider dimensions of the sociotechnical regime. In fact, a new sociotechnical regime was created around iron steamships. The development and alignment of these elements inevitably took time.

As the size of steamships increased, ports and harbours were enlarged and deepened. Longer, wider and deeper locks were needed (Pearsall, 1996). Steamshipping also called forth a new generation of port facilities, tailored to the need for a rapid turnaround. Docks were fitted with modern cargo-handling and unloading gear, e.g. grabs, cranes and conveyor systems. The move towards bulk handling of both commodities in ports first made significant progress in the 1860s (Jarvis, 1998). The introduction of bulk cargo-handling machinery was sometimes the object of controversy and battle between actors involved. Van Driel and Schot (2001) describe how the introduction of grain elevators in the Rotterdam harbour was accompanied by a struggle between labourers, merchants, weighers, shipowners, and elevator producers. A range of new transshipment facilities emerged to store cargo, which waited for further transportation. All these changes required huge investments. It is estimated that £ 159 million was spend in port facilities in Britain between 1850 and 1914 (Jackson, 1998).

As steamships spread to more routes, a world-wide network of coaling stations was created. Because there were not many suitable sites on the route to Australasia, the establishment of steamship services on this route was significantly delayed.

The shift from wooden sailing ships to iron steamship transformed the shipyards. Geographical location, job skills and workplace organisation were all altered as shipbuilding moved from its craft skill tradition to become a heavy engineering industry (Ville, 1990). The transition to iron steamships was accompanied by increases in both the scale and complexity of shipbuilding. As ships grew bigger, so did the size of shipyards and the scale of operations. The huge hull components forced yard-owners in the 1860s to expand their yards and adopt cranes for haulage. Many shipbuilders were unable or unwilling to make this change, and continued to build wooden ships. As a result, the centre of gravity in British shipbuilding moved north to the Clyde and the North East of England (Harrison, 1990). New jobs emerged on shipyards, e.g. metal and woodworkers, painters, plumbers, electricians, millwrights, engineers. Many of the new workers needed specialised tools and machines. In the 1870s and 1880s riveting machines and other kinds of machinery for working iron plates were introduced (Harley, 1973). The new machines often used new power-sources. In the 1860s most shipyard equipment was powered by steam engines. In the 1880s and 1890s hydraulic power was used and proved to be very suited for heavy sustained work. Pneumatic power was introduced in the 1890s for accurate and precision work (e.g. drilling, planing, riveting), and from the mid-1890s electric power became more common (Pollard and Robertson, 1979). Another major transformation in shipbuilding was the introduction of science and engineering. While shipbuilding had always been a craft-profession, it gradually turned into an applied science. Most shipbuilders initially looked with unveiled hostility on the attempts to substitute ‘rule’ for ‘instinct’ (Pollard and Robertson, 1979). Because most private builders in Britain were content to use rule-of-thumb methods, professional naval architects and mechanical engineers only gradually entered the shipyard (Pollard and Robertson, 1979). While many governments (particularly in Germany and America) built experimental tanks over the next decades, Britain lagged behind. The knowledge intensity of shipbuilding increased, and more attention was being paid to the circulation of knowledge. The technical trade press was made more available to the staff, together with standard textbooks and general works on naval architecture. A new training and education system was created for naval architects, scientists and mechanical engineers, such as the Institute of Naval Architecture in 1857 and the subsequent creation of chairs of Naval Architecture at the universities of Liverpool, Newcastle and Glasgow (Ville, 1990).

Users of steamships turned into large corporate and professional companies, offering regular liner services running to a regular timetable. A new kind of ownership was implemented (the joint stock company) and new management practices introduced. With regard to fleet management the introduction of the submarine telegraph cable in the late 1860s and early 1870s had an enormous impact. It not only provided up-to-date information on prices in commodity and freight markets around the world, but also made possible much tighter control of ships. It became possible to convey information and instructions in hours rather than days or weeks, as in the days of mail. Telegraphy made up-to-date market information available in quality local newspapers, and it allowed control to be centralised more effectively, with less reliance on ‘our man in Singapore’ (Jarvis, 1998). The telegraph thus enabled managerial activities to be concentrated with managing directors. Ships could be more easily directed away from markets with a surplus of shipping tonnage to those with a shortage. This not only increased the efficiency of deployment, but also changed the way the shipping regime functioned. Another change was the emergence of tramp shipping in the second half of the 19th century. While liners operated regular timetables on fixed routes, tramp steamers roamed around the oceans in search of cargo to be shipped. The rise of tramp shipping in the second half of the 19th century was made possible by the rapid expansion of international trade. Furthermore, British tramp shipping was stimulated by the growth of coal exports which gave them an initial outbound payload (Ville, 1990). And thirdly, the development of international telegraph cables provided up-to date information about freight markets, and enabled co-ordination of a fleet of tramps from a central office. Competition between liners and tramps was strong. While the liner offered certainty, reliability and speed, the tramp’s competitive edge was its cheapness. To control competition, liner companies created a new market institution: the *shipping conference*. These conferences were formal, often legally-binding agreements to restrict competition and stabilise market conditions, for the purpose of minimising destructive rivalries while maximising profits (Sloan, 1998). The first major conference regulated the Calcutta trade in 1875. By 1900 conferences covered most international trade routes.

Wider impacts on society

The steamship transition also had wider impacts on society. While globalisation started with sailing ships, steamships were involved in the great expansion of global trade in the second half of the 19th century. As steamships grew larger, faster, cheaper and more reliable they boosted the emergence of a world-market. The decline in international transport costs after mid-century was enormous, and ushered in a new era. Relative freight rates moved down from 100 in 1830 to 24 by 1910-1914 (Ville, 1990). These falling transport costs greatly stimulated globalisation. Globalisation, in turn, affected agriculture. From the 1860s onward ever larger quantities of cheap grain from America and Russia appeared on European markets, transported by trains and steamships. Because of these cheap imports, food prices went down, threatening the livelihood of many European farmers and contributing to the agricultural crisis of the 1890s. New flows of food influenced feeding patterns. As efficient refrigerator ships were developed in the 1870s and 1880s, large quantities of frozen meat were imported in Europe from Australia and Latin America. Other perishables such as apples and butter followed (Jarvis, 1998). This not only altered trading patterns, but also improved the standard of living of lower-middle and upper-working class people. Luxury products such as meat, dairy products, sugar and fruits came within reach of more people. This not only altered their feeding patterns, but also contributed to better health. Imports also changed agricultural practices. Cheap corn from America was used to feed cattle, contributing to the expansion of cattle farming, e.g. in the Netherlands. Guano from Latin America was used as fertiliser in agriculture and stimulated productivity. Steamships were indirectly involved in major social and economic transformations through their role in emigration. The great numbers of European emigrants in the late 19th and early 20th century were transported by steamships.

4. Analysis and some mechanisms in technological transitions

On the basis of the case study I would like to make several points to refine the conceptual perspective on technological transitions. The first point is that breakthroughs of innovations depend on processes on the level of regimes and landscapes, i.e. they are context-dependent. Much has been done in technology management, innovation studies and strategic niche management on internal niche processes, e.g. network formation, learning processes, product champions, the role of visions and expectations. While such internal niche processes are obviously important for breakthroughs of radically new technologies, they are not sufficient. Radical innovations also need to link up with wider contextual processes in order to break out of niches. Steamships broke out of the subsidised mail transport niche by linking up with the market of growing Atlantic passenger transport. This was created by European emigration after 1848, which, in turn, depended on the Irish potato famine, European political revolutions and the Californian gold-rush. Similarly, steamships were able to enter long-distance freight shipping, because a change in the physical landscape, the Suez Canal, opened up the India freight market. It is because of this aspect of technological transitions that the multi-level perspective is useful for analysing TT.

The second point is about reconfiguration processes. In the case-study I have shown how changes in one element may trigger changes in another, and so on. After the American War of Independence, for instance, Britain punished America by denying it access to markets in her Empire. This forced American shipowners to look for alternative markets, e.g. the China trade (e.g. opium, silk, opium). These particular market niches, in turn, stimulated the emergence of the 'Baltimore clipper'. This ship already existed but could now rise to prominence, particularly after it proved itself in the French Wars. This triggered a design trajectory from which the famous opium clippers and tea clippers emerged in the 1840s. The (re)configuration perspective thus looks like 'actor-network theory' on a macro-level. While 'actor-network theory' focuses on associations and chains between concrete human and non-human actors (e.g. between a key, hotel owner and his guests (Latour, 1993)), the (re)configuration perspective looks at linkages between more aggregate elements (e.g. markets, technologies, subsidies, infrastructure). Both, however, show that changes in one element also affect other elements. Latour (1991) uses the example of the introduction of the Kodak camera to show that this did not just involve a substitution of plates by film and of wet collodion by dry collodium, but also involved the creation of new users (amateurs instead of professionals) and new firms. The story is about shifing assemblies of associations and substitutions. It is about a reweaving of elements. "What we observe is a group of variable geometry entering into a relationship with an object of variable geometry. Both get transformed. We observe a process of translation" (Latour, 1991: 116).

Reconfiguration processes can occur in a somewhat haphazard and coincidental way, as in the Baltimore clipper example just described. But they can also occur in response to problems in the regime. When persistent problems trigger actors to look for solutions, this may generate new elements which can be incorporated in the regime. Because (American) merchants were troubled by the irregularity of sailing ships, they experimented with fixed departure schedules in 1818 (the Black Ball Line). When this proved commercially successful, other lines followed, thus introducing a new element into shipping. Steamships later linked up with this quest for more regularity, because they were independent of variable winds. Another example is that wooden sailing ships suffered problems of longitudinal strength, as they grew longer in order to sail faster. These problems allowed iron to enter sailing ships, first as auxiliary knees, then as composite ships and eventually as all iron ships. This, in turn, allowed the building of longer sailing which competed with steamers in the 1870s and 1880s. Persistent problems may thus result in a loosening up of the regime, creating windows of opportunity for new elements.

The steamship transition seems to fall in between the two extreme routes I distinguished in section 1. On the one hand, there is the pattern that first a new steamship regime stabilised (1855-1865) and then the wider sociotechnical regime was transformed, e.g. coal-infrastructure, shipyards, ports. On the other hand, there were several transformations occurring *before* steamships emerged. Steamships linked up with these processes, and further reinforced them. The emergence of professional shipowning, for instance, already started in the late 18th century. The process towards more regularity was already started in 1818 with sailing packets. Improvements in tele-communication occurred long before the telegraph, with the use of steamships and trains to transport mail.[2] The emergence of world trade began with sailing ships and was reinforced by steamships. In short, some reconfigurations started before the steamship; many others followed it.

Looking more specifically at the technical component of technological transitions, the case-study points to a particular pattern in reconfiguration processes, consisting of three phases. In the first phase the new technology linked up with the existing regime to improve it by addressing particular problems. Steam was used to improve the sailing ship regime in several ways. Steam tugs were used to manoeuvre large ships into ports. Steam engines were introduced on sailing ships as auxiliary device to overcome periods of calm winds. The first oceanic steamships were little more than sailing ships with additional steam engines and paddle-wheels. After 1838 steamships were subsidised and used to transport mail, thus improving long-distance communication and reducing co-ordination problems in trade and governance of the British Empire. In sum, the first steamships did not compete with sailing ships, but were used as improvements. In the second phase steamships gradually developed into distinct technical forms and gave rise to new, specific functionalities. As steamships came to be used on oceans and as steam engines got heavier, particular problems emerged with regard to paddle-wheels, coal consumption and the strength of wooden hulls. As the attention of technology-developers was focused on these problems, particular technical trajectories emerged. As a result, steamships increasingly differentiated themselves from sailing ships and developed into specific technical forms. As users learned more about steamships, new functionalities were generated. Steamships gradually gave rise to line services, first in mail and passenger transport, later in freight transport. This gave the shipping regime new characteristics such as regularity and predictability. The emergence of new technical forms and new functionalities went in tandem with changing professional management practices. These new functionalities and management practices were not entirely caused by steamships.

[2] The London-Bombay mail had taken an average of 108 days in the East Indiamen sailing ships between 1824 and 1832. By 1840 mail was carried to India by rail, steamship and overland in Egypt in 39 days; and by 1868 the P&O mail contract stipulated delivery within 24 days (Harley, 1985).

Professional shipowning gradually emerged since the late 18th century, and more regularity had already been introduced American sailing packets since 1818. Steamships both linked up and reinforced these processes towards more regularity and professional shipowning. In the third phase the diffusion of the new technical element occurred in tandem with a transformation of the sociotechnical regime, and with wider impacts on society. The diffusion of the steamship in the 1870s and 1880s was accompanied by changes in shipyards, ports, quays, cargo-handling equipment, coal infrastructure, etc. Steamships also stimulated the emergence of world trade, facilitated emigration to the US, and changed feeding patterns as well as agricultural practices. These three phases in the transition may be summarised as: a) fitting within the existing regime, b) emancipation of a particular technical form and generation of new functionalities, c) wider transformations. These three phases are a specification of the general idea that 'the new emerges by growing out of the old'. Van den Ende and Kemp (1999) showed how the computer regime grew out of the older comput*ing* regime, based on punched-card machines. This specification of reconfiguration processes also ties together some observations from innovation studies and history of technology. Clark (1985), for instance, noted that, when experience is limited, the customer's search for understanding is dominated by attempts to relate the new product to existing concepts. In the early stages, the new product is defined and interpreted largely in terms of the old. Only as learning occurs through real-life experience and interaction with the new technology, does it develop a meaning and definition of its own. New functionalities emerge gradually through probing and learning processes, working outward from established practices to explore new ways. In her social history of electric media Marvin (1988: 5) shows how "new practices do not so much flow directly from technologies that inspire them as they are *improvised out of old practices* that no longer work in new settings" (my italics). These three phases are also the explanation for the observed phenomenon that the ultimate potential of new technologies is rarely foreseen at the start.

> "Whenever a new technology is born, few see its ultimate place in society. The inventors of radio did not foresee its use for broadcasting entertainment, sports and news. They saw it as a telegraph without wires. The early builders of automobiles did not see an age of 'automobility'; they saw a 'horseless carriage'. Likewise, the computer's inventors perceived its role in society in terms of the functions it was specifically replacing in contemporary society. The predictions that they made about potential applications for the new invention had to come from the context of 'computing' that they knew. Though they recognised the electronic computer's novelty, they did not see how it would permit operations fundamentally different from those performed by human computers" (Ceruzzi, 1986: 196).

The third point is that technological transitions are often a cross-section of a wider transformation process. Many changes occurred *before* the steamship transition. New social groups emerged within shipping in the late 18th and early 19th century (e.g. shipbrokers, professional shipowners, insurance companies). Trading and shipping were gradually differentiated, giving rise to denser trading networks with specialised middlemen, e.g. factors, financiers, brokers, advertisers, wholesalers, exporters and manufacturing agents. New services were pioneered within shipping after 1818 by packet boats, leaving at fixed departure times. And new ship designs (e.g. Baltimore clipper) were developed.

Because the shipping regime was already changing on many dimensions, it would be wrong to describe the steamship transition with the concept of 'punctuated equilibria'. This concepts suggests that transitions are quick shifts from one stable state to another. For the relation between technology and industry structure this concept has been elaborated under the heading of 'technology cycle' (Tushman and Anderson, 1986; Anderson and Tushman, 1990, Rosenkopf and Tushman, 1994). The technology cycle is characterised by two periods: long periods of stability and incremental change and brief periods of ferment and discontinuity. While the technology cycle may apply if we look at technology and industry structure, it does not apply if we look at wider dimensions of the sociotechnical regime, at least in the case of the steamship transition. The emergence of steamships was itself part of wider processes of social and institutional change.

The fourth point is about mechanisms in technological transition, the topic of the second question I posed in the introduction. From the case-study I derive several mechanisms. By illustrating them with other examples, I try to make them more general.

The first mechanism is that TT occur via trajectories of *niche-cumulation*, i.e. new technologies are used in subsequent application domains (see also Levinthal, 1998; Schot, 1998). Steamboats were first used on inland waterways and for minor functions such as towboats, then as subsidised mail steamers, then for passenger transportation, and eventually also in freight shipping. Electro-magnetic waves were first used by Herz as a laboratory device to test Maxwell's theoretical work. Marconi developed this laboratory device into practical wireless telegraphy, used for communication with lighthouses and ships. As electromagnetic waves could be send over longer distances, wireless telegraphy began competing with wired telegraphy. After the development of vacuum tubes made it possible to transmit continuous waves, electromagnetic waves were used to transmit sound and voices. Eventually this led to radio-broadcasting and wireless telephony (Levinthal, 1998). Many more examples of niche-cumulation can easily be given.

A second mechanism is that technological *add-on* and *hybridisation* are important intermediary phases in TT. The first steamships (Figure 6) were actually sailing ships with additional steam engines. Steamships in the 1840s (Figure 8) were hybrid forms with both sail and steam propulsion. The introduction of iron in sailing ships also began as add-on, then progressed to composite ships (iron frame and wooden planking, and ended with all-iron hulls. In terms of reconfiguration processes this mechanism means that new technologies link up physically with old technologies. When the new technology is improved or when circumstances change, the new technology may gradually emancipate itself to a more hybrid phase or to an independent technical form. There may also be cognitive and economic reasons for this pattern, e.g. established views and sunk investments in the old technology. Devine (1983) describes how the transition in factories from steam engines to electric motors occurred via an add-on phase, where electric motors were placed *between* the factory's steam engine and the line shaft. Not only did factory managers gradually discover that electric motors could be used in a different way, namely as unit-drive, but also were factory owners hesitant to do away with their investments in the established millwork. Another example is the transition in aircraft from piston engines and propeller to jet aircraft. Gas turbines first entered aircraft as an auxiliary arrangement (add-on) to supercharge piston engines flying at high altitudes. Only in World War II was the gasturbine developed into a separate jet engine to power fighter aircraft. Islas (1997) describes how in electricity production the gas turbine was first used as auxiliary device to improve the performance of the steam turbine (combined cycle power stations). As gas turbines improved, gas turbines became the main component in the combined cycle, the steam turbine taking the role of auxiliary device.

A third mechanism is that new technologies break out of niches by riding along with growth in particular markets. The case-study showed that the take-off phase of steamships was associated with the strong growth in Atlantic passenger transportation. Similarly, electric motors rode along with the strong growth in large factories in the early 20th century (Hunter, and Bryant, 1991). Because problems with steam engines and millwork increased with the size of factories, large factories were an appropriate niche for electric motors.

5. Discussion and conclusions

In section 1 I phrased the following questions: How do technological transitions come about? Can we distinguish particular patterns and mechanisms? To answer these questions this paper described a conceptual perspective. Because a TT is a complex process the dynamics cannot be described easily. In fact, the proposed perspective is a composite one, understanding TT as evolutionary reconfiguration processes with multi-level dynamics. The different parts of the perspective highlight different aspects.

The reconfiguration aspect stems from sociology of technology and is useful to understand why TT involve more than technology and markets. Because it conceptualises the working of technology as the outcome of linkages between multiple elements, TT involve changes in linkages as well as elements. The reconfiguration perspective is also useful to understand stability and change. A configuration is stable, when the elements are closely aligned. If the linkages 'loosen' up, it becomes unstable, and more open to the introduction of new elements. Metaphorically, stable configurations are 'cold', while instable ones are 'warm' (Callon, 1998). The view on TT is that new configurations grows out of the old ones. TT do not occur because there is one sudden shift from one configuration to another, but through a stepwise process. First there is a change in one element of the configuration. As a result, dislocations and shifts occur in the linkages with other elements. This may result in a 'loosening up' of the configuration. If it creates enough 'space', a new element may be introduced. This results in further dislocations, etc. etc. This not only means that unstable situations provide opportunities for new elements, but also that the introduction of new elements may *cause* instability.[3] This may result in periods in which these changes succeed each other quickly. If these steps are close in time, the reconfiguration process may *look like* a sudden shift or revolution. But a TT may also occur as a gradual sequence of changes. The reconfiguration perspective also shows that old and new technologies are not always in competition with each other. Particularly in early phases a new technology is often used to address (minor) problems with the old technology. More specifically, the reconfiguration perspective is useful to distinguish three phases in technological transition: a) new technology fits within the existing regime, b) new technology emancipates and generates new functionalities, c) wider transformations occur.

The multi-level perspective is useful to understand where new elements come from and how they are generated. They come from technological niches and are generated through painstaking learning processes guided by visions and promises and supported by precarious networks of supporters. The multi-level perspective is crucial to understand breakthroughs of innovations as depending on processes in wider contexts (regimes and landscape).

The evolutionary perspective has not been elaborated well in this paper. I have metaphorically used the terms variation, selection and retention, without saying much about the object of these processes or their mechanisms. Nevertheless, these terms help to understand how the various levels contribute to change and stability. Niches are the locations of variety, where seeds of change are generated. Regimes provide stability and retention, thus

[3] The steam engine, for instance, was introduced on sailing ships as an incremental change. Over time, however, the steam engine gave rise to a particular problem agenda, resulting in design trajectories and a particular form of its own. The introduction of a new element resulted in shifts which triggered new developments.

functioning as deep structure. The social communities that carry regimes are the locations where selection occurs and where variations have to proof themselves.

I have illustrated the conceptual perspective with a single case-study, the transition from sailing ships to steamships. This case-study has a specific drawback, since it dates back to the 19th century. Not only is this a long time back, but also innovation occurred differently then than it does now. 19th century craft-based innovation had different dynamics than 20th century science-based innovation. In craft-based innovation, there was little means of predicting beforehand whether a new technology would work or serve its intended purpose, because of the absence of drawings and calculations. The only way to see if a new kind of artefact would work was to build it (McGee, 1999). While technology was not an explicit object of management in the 19th century, this changed in the 20th century with the emergence of R&D laboratories and state-funded technical programs. The network of social groups involved in technological development has become more differentiated in the 20th century. Although I cannot deny this drawback, its importance is not as great as it seems, because both the conceptual perspective and the case-study have been described on an aggregated and abstract level, without saying much about (the interactions between) actors. I think that the perspective and structural patterns also hold for transitions in the 20th century, as I have briefly indicated with some examples in section 4. Nevertheless, the perspective would become more robust if more case-studies were done, varied over different time-periods and sectors. In that sense, the perspective represents the beginning of a wider research programme.

Appendix 1: Registration of European merchant shipping fleets (1000 net British tons) (Ville, 1990: 68-71). For some countries before 1860 data are missing.

	UK	GERMANY	NETHERLANDS	FRANCE	NORWAY	ITALY
1780	882	123	398	729	386	235
1820:						
• sail	2436	-	-	-	-	-
• steam	3	-	-	-	-	-
• total	2439	-	-	-	125	-
1840:						
• sail	2680	-	-	653	-	-
• steam	88	-	-	10	-	-
• total	2768	352	-	663	205	-
1860:						
• sail	4204	754	485	928	-	664
• steam	454	23	11	68	-	10
• total	4658	777	496	996	532	654
1880:						
• sail	3851	927	264	642	1461	922
• steam	2724	177	64	278	58	77
• total	6575	1104	328	920	1519	999
1900:						
• sail	2096	584	78	510	1003	568
• steam	7208	1319	268	528	505	377
• total	9304	1903	346	1038	1508	945
1920:						
• sail	584	288	24	433	204	191
• steam	10777	1546	969	1085	1199	1589
• total	11361	1834	993	1518	1403	1780

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