WMU J Marit Affairs (2015) 14:7–24
DOI 10.1007/s13437-015-0082-4

ARTICLE

Towards understanding the stepwise dissemination of shipping technologies

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Received: 19 August 2014 / Accepted: 16 February 2015 / Published online: 10 March 2015

Abstract In the years to come, the maritime industry will have to improve its energy efficiency and soften its environmental footprint to meet higher energy prices and more stringent regulations. Shipowners, managers, and operators are often reluctant in installing new technologies even though they may already have successfully been applied in other industries. By analyzing historical data for the adoption of steel hull and diesel engine technology in the worldwide fleet, we find an indication that dissemination of new technologies happens in a step-like manner. That is, the underlying dynamics does not change continuously but rather abruptly. We argue that this phenomenon could be explained by the fact that any new technology has to function within given structures in a given context; if not, structures will act as barriers. We provide a new explanatory model where the concept of structures is central, i.e., tangible or intangible constructs, usually human made, in the form of infrastructure, regulations, competence, norms, behavior, etc. Constructs can limit (barriers) or support (enablers) a new technology. Once the structures and/or the (new) technology (which itself is a structure) are adapted to each other, they have an enabling effect and thereby change the underlying dynamics in a stepwise way. We support our view by comparing the proposed concept with other published approaches on technology adoption.

Keywords Technology adoption · Structural changes · Barriers · Enablers

1 Introduction

More than 90 % of global trade is carried on sea where economies of scale in freight transport allow the shipment of large volumes of cargo. This offers relatively low energy consumption as well as CO_2 emissions compared to other modes of transportation (Fig. 1). Although the shipping industry may be regarded as a small contributor with respect to global CO_2 emissions (3 %; IMO 2012), it still needs to reduce its

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energy consumption and emissions (CO_2, SO_X, NO_X, CO, etc.) and air pollutants (especially particulate matter).

Significant improvements towards higher engine efficiency, better hull designs, or larger cargo carrying capacities have already led to emissions reduction. The shipping industry is also exploring other possible alternative energy sources, but for the foreseeable future, fossil fuels will continue to be the predominant source of power for the majority of vessels (RAE 2013). Technologies such as fuel cells, hybrid propulsion, or full-scale system monitoring have so far not been adopted widely.

History shows there is often a very long time gap, measurable in decades, between an invention, its first piloting, and then, even longer down the road, the innovation, i.e., a successful business implementation. This rate of adoption is often qualitatively described by an S-shaped curve, i.e., Verhulst model, where the number or fraction of adopters of a new idea/technology is plotted against time. In this model, the adoption rate is proportional to the number of first adopters (leaders) and to the number of remaining potential adopters (followers). For many of these followers, the use of a new

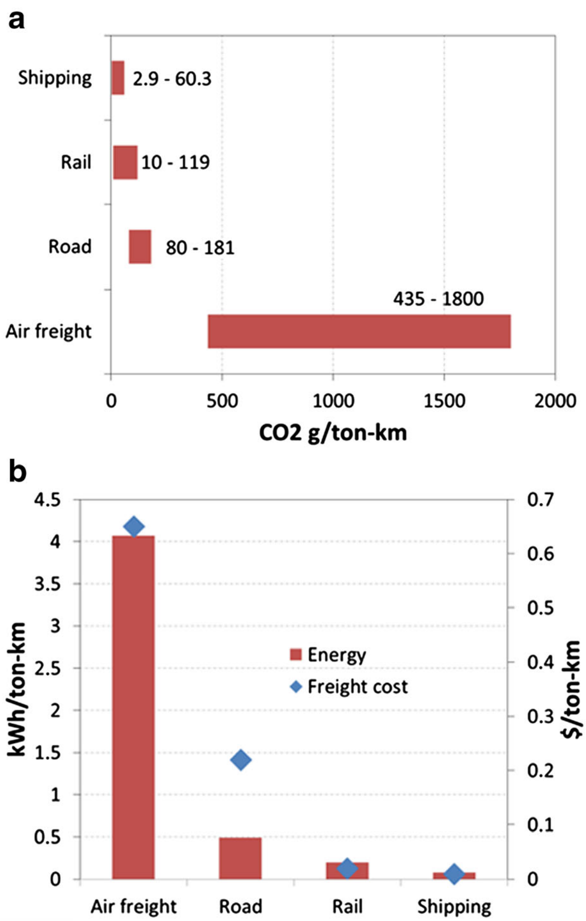

Fig. 1 Comparison of different transport modes and their CO_2 emissions range. (Source: World Ocean Review (WOR) 2010; International Chamber of Shipping (ICS) 2013)

technology may not be profitable yet, or they may need more information to be convinced (Battisti 2008; Plaza et al. 2010; Kucharavy and De Guio 2011).

Paap and Katz (2004) argue that technology substitution only occurs when there is an unmet need in the dominant driver and the existing technology is incapable of competitively addressing it. With dominant driver, they understand the performance characteristic to which an improvement will be perceived as having the greatest value to potential users. According to them, there are three distinct patterns for technology adoption: (i) the existing technology matures relatively to the dominant driver; (ii) the previous driver matures, a new driver emerges and the existing technology is unable to meet unmet needs of the new dominant driver; and (iii) the environment changes, creating a new dominant driver.

Others relate this gradual dissemination to the existence of barriers which slow down a technology's wider application. These barriers have been categorized in five entities: (i) risk and uncertainty, (ii) cost and financial aspects, (iii) unreliable information, (iv) split incentives, and (v) bounded rationality (Geroski 2000; Jaffe et al. 2002; Stoneman and Battisti 2010; Fleiter and Plötz 2013). With respect to maritime industry, we may refer to the work on technology adoption done by Johnson and Andersson (2011), Arduino et al. (2011), Rehmatulla and Smith (2012), as well as Styhre and Winnes (2013). Kontovas and Psaraftis (2013) have special emphasis on split incentives. Jenssen and Randøy (2006) propose the opinion that bounded rationality could be overcome through forming relevant groups, competences, as well as relationships (contacts) in shaping the managerial strategy towards adoption. A wider perspective on bounded rationality is also offered by Tenold and Theotokas (2010), claiming that new technology adoption is determined from threats and opportunities in an international context (i.e., globalization, scale economies, etc.), regulations and the planned objectives of companies in relation to competences needed, acquired knowledge, networks, and business culture.

This article presents a new conceptual model providing hopefully a better qualitative understanding of the reasons (barriers) why shipping often struggles with the adoption of new technologies—and energy-efficient technologies in particular—and what could be done to overcome it. The article's structure is as follows: Section 2 presents historical data for the adoption of diesel engine and steel hull technology in the worldwide fleet. We argue why the Verhulst model and the work of Paap and Katz (2004) provide an inadequate explanation for technology adoption. In Section 3, we propose a new explanatory model and we argue for its logical validity. In Section 4, we use the proposed model to explain the adoption of energy-efficient technologies in shipping, and Section 5 concludes with some final remarks.

2 Historical data for dissemination of diesel engines and steel hull

It is widely acknowledged that the dissemination of new technologies (or new ways of working) often happens not in a constant, gradual manner but rather abruptly, i.e., over a short time interval. In general, it is difficult to get actual usage/dissemination data of specific shipping technologies as such data either are often not collected or not kept, or are proprietary or are spread everywhere. Class Societies, on the other hand, do painstakingly collect certain data over long time intervals. For instance, recordings of the use of diesel engines and the use of steel hulls are examples of two technologies (Lloyd's Register of Shipping). The data show that both technologies had a long dissemination time, i.e., in the range of 60 years, before they became the preferred technologies globally. The degree of dissemination, i.e., the fraction of vessels in the world fleet with steel hulls and with diesel engines (dots and triangles), is shown in Fig. 2 together with a fit to the Verhulst model.

Observe the effect of World War I (WWI) and World War II (WWII) had on the dissemination of these two technologies. The negative effect of the Great Depression on world trade, starting with the Wall Street Crash of 1929 and lasting until the late 1930s (nation dependent), is also evident as a lowering in the dissemination rate of steel hulls. Interestingly, WWI resulted just in a minor setback of 2–3 years with regard to dissemination of steel hull, and it may even be disputable if WWII had any significant effect at all (as most ships were already using steel hull). Following the end of WWI in 1918, there was a need to replace the mercantile shipping that was lost providing work for many yards during the immediate postwar period. The general decline in world trade after the Wall Street Crash resulted in a reduced demand for shipping services, overcapacity, and a consequent significant reduction in the number of new buildings. Consolidation was apparent and closure of two thirds of shipyards occurred. Although world trade began to recover towards the end of 1933, it was not until rearmament prior to WWII that the industry became fully revived. Despite the slow ship design evolution in the interwar period, there was a general desire to raise efficiencies of propulsion machinery and the diesel engine came gradually into prominence. The "Eisenhower recession" (August 1957–April 1958) caused by tightening of monetary to curb inflation coincides with marked change in steel hull dissemination. The same is the case for the "Rolling Adjustment" recession (April 1960–February 1961) and "Nixon

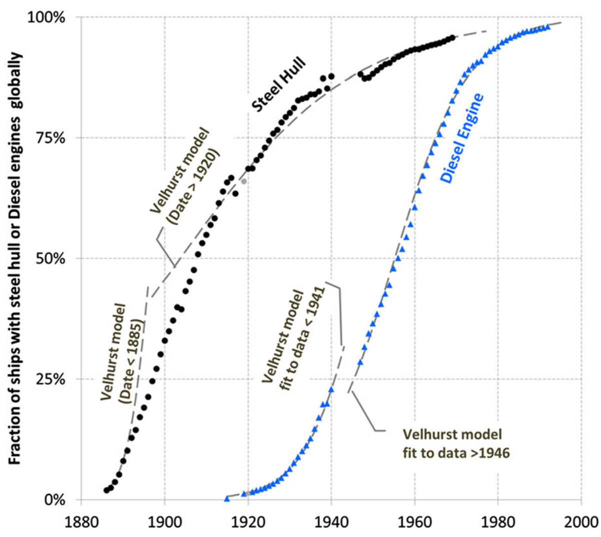

Fig. 2 Dissemination of steel hulls and diesel engines technologies in shipping. The degree of dissemination is measured as fraction of ships with steel hulls and marine diesel engine in the world fleet. The *gray dashed line* is a Verhulst model fitted to the data. The raw data are extracted from the annual reports from Lloyd's Register in the years 1886–1969 (steel) and 1915–1992 (diesel). No data were recorded for years 1941–1946. (Data source: Lloyd's Register of Shipping)

recession” (December 1969–November 1970) which match observed rate of change in dissemination of steel hulls and diesel engines. In parallel, the advantage of diesel engines was proved decisive when they were adapted to run on low-grade residual oil. In addition, the introduction of larger engine bores as well as high-pressure turbocharging made diesel engines the preferred (more profitable) choice before steam. In the last quarter of twentieth century, diesel engine designs became more compact, two-stage turbocharging and loop scavenging were introduced to increase efficiency, and components were standardized to allow worldwide provision of interchangeable spares.

Note that due to the growth in world fleet size, the relative change in the fraction becomes smaller and smaller, which effectively hides any finer signals. By plotting the upper part of the graph in a log plot (logarithm of fraction), these finer signals become apparent (see Fig. 3). Observe the piecewise linear nature of the curve. In these straight line sections, the evolution of the adoption is best described by an exponential function with constant parameter values. This also means that the underlying dynamics does NOT change within these sections. Only at the break point between two lines, however, the underlying process changes into a new one, again represented by a straight line, but now with other parameter values. Observe that the transition from one straight line section to another happens surprisingly fast, i.e., usually within a year or two, implying that the existing structures are quickly adopted or new structures put in place in order to stay competitive. This observed phenomenon can be qualitatively explained by a structural perspective as once a structure is adapted it becomes an enabler and thereby also affects the dynamics of, i.e., technology adoption or business development.

We believe historians will appreciate these break points as they could provide information at what point in time they should focus on to understand what it was that changed and what it was that caused the change. It is not necessarily technology that may have changed; the observed changes in the underlying dynamics may have been caused by alterations in the regulatory structure, the market structure, or some new infrastructure, i.e., shipping line, port, or by some political causes.

2.1 Macroscopic behavior described by the Verhulst model

The Verhulst model is often used to describe the dissemination of an innovation through its life cycle as a logistic function. The argument is that in the beginning of a new product, dramatic quality improvements and cost reductions through research and development lead to a rapid industrial growth. Later on, either improvement or cost reductions are no longer easily obtainable, nor are there large market growth potentials as the product is widely used. The Verhulst model is a deterministic model explaining macroscopic behavior; hence, fluctuations or finer patterns seen in measurements cannot be explained by this model.

A Verhulst model fitted to the beginning of the steel data would suggest a much faster adoption than what actually occurred, whereas a fit based on the “end” of the data underestimates the early adoption rate (even when “removing” WWII). This points to a major shortcoming, as the Verhulst model assumes that the underlying dynamics remain unchanged, i.e., constant parameter values. It is quite utopian to assume that the processes governing the diffusion of steel hull technology should remain the same over a 100-year period including two world wars. Also, the Verhulst model assumes

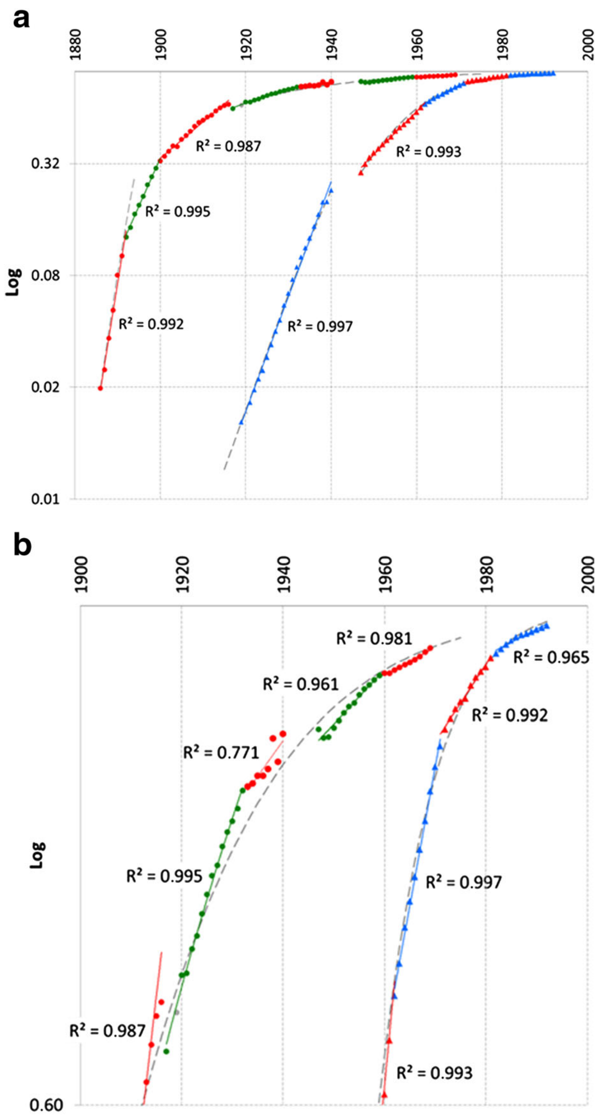

Fig. 3 Logarithmic representation of fraction of ships with steel hulls and diesel engines (*right figure* is a close-up of the upper part of the left figure). Note the *piecewise straight lines* in the curve indicate that the diffusion is best described by an exponential development. Note also that at the transitions between two straight lines, a change in the underlying dynamics occurred, i.e., we argue a structural change has happened. The regression coefficient, R^2, for goodness of fit is also provided. (Data source: Lloyd's Register of Shipping)

that the dynamics are symmetrical, which is clearly not the case for the steel data. The fast spread of steel shipbuilding at the end of the nineteenth century may be explained by the fact that for smaller vessels, the required infrastructure was already present (shipyards, ports, etc.). For the construction of larger ships by the first quarter of the twentieth century, the adaptation of shipbuilding infrastructure as well as port structures resulted in a slowdown of the adoption process.

In addition, depending on the desired level of resolution, one can see from Fig. 3 that the Verhulst model cannot explain the fine patterns apparent in, i.e., steel or diesel data. On the other side, the Verhulst model gives a good description of the diesel engine data on a macro level even with the gap in WWII. This may, however, also be its main disadvantage as all fine granularities (information) in the data are discarded in favor of a high-level view (ref. Fig. 3). The fact that a Verhulst model may offer a rather poor phenomenological description is best seen in the logarithmic plot in Fig. 3. Here, we can clearly see that the data points do not exactly follow the Verhulst model. They are actually much better described by sections of piecewise straight lines which supports our argument that the dynamics of technology dissemination is heavily influenced by structural changes. As many structural changes, i.e., regulations and production capacity, are discontinuous processes, in time they will also change the underlying dynamics discontinuously, hence the observed "breakpoints" between the piece-wise linear sections in Fig. 3.

2.2 Inadequacy of the explanation provided by Paap and Katz (2004)

Paap and Katz (2004) give in our opinion an inadequate explanation for technology diffusion as they fail to sufficiently explain why technology replacement occurs. The dominant drivers in industry are profit (business aspects) and regulations. Regulations do change, although rather infrequently, but the importance of the main driver, i.e., profit, seems only to increase. It is not the driver that has changed, but the surrounding structures, i.e., the business environment, and in particular, the infrastructures, production capacity, available competence, demand, etc. that can offer a higher profit margin (reduced cost and/or increased revenue) with the new technology compared to the existing ones. One might argue that technology dissemination in the private sector may mainly be explainable by the drive towards higher profits. For governmental or nonprofit organizations, the term profit should be replaced by benefits or values.

We further concur with Assink (2006) as well as Yu and Hang (2010) that Paap and Katz's (2004) model examines enablers, while it has not managed to investigate the interrelationship and interdependence on structural adaptation (barriers). In addition, it is weak to capture the perspective on the constraints organizational challenges put in place (i.e., resources, culture, processes, norms, behaviors, etc.). Without this understanding, it is hard to address potential mechanisms that could overcome the strong inertia forces given by the existing technology and its supporting base.

Using the approach suggested by Paap and Katz (2004), in their first pattern, wood would be the existing technology that matures and gradually becomes incapable of satisfying the requirements as a shipbuilding material, i.e., no longer providing the desired profit. In their second pattern, the dominant driver is replaced by a new one offering, or promising to offer, a higher profit margin. The Paap and Katz (2004) model does not provide any assistance in explaining the underlying mechanisms that favor/prohibit the replacement of the dominant technology.

Similarly, in the dissemination of the diesel engine, steam was the existing technology that matures in relevance to Paap and Katz's (2004) first pattern. With respect to the second pattern, it is not the dominant driver that is replaced by a new one (the dominant driver is still profit)—but an old technology is replaced by a new one offering a higher profit potential. The interesting question is, Why was the new technology not used earlier as its invention usually happened decades earlier? The Paap and Katz (2004) model provides little help in addressing barriers that prevented the technology's earlier introduction.

3 Technology adoption explained by structural changes

Our explanation model for technology dissemination is based on the following three fundamental observations:

- Existing structures: everything (including ourselves) is part of structures which are time, space, and context dependent. All structures are more or less interlinked and will change over time. Structures can be *physical*, i.e., a technology, hill, river, road, power supply, and operating system; or *functional*, i.e., work process and operation; or *social*, i.e., human relationships, hierarchy, behavior and psychological aspects, taste, fashion, and regulations; or *cultural*, i.e., language, written/unwritten norms, regulations, religion, and so forth. Structures internal to a company, i.e., organizational structures and company building, will be smaller compared to external structures such as regulations, other companies, societal aspects, infrastructures, etc. External structures will also have more connections to other structures, meaning that if an external structure is changed, it will affect many others. Any technology has to work within the existing structures in a given application context.
- Structural adaptation=barrier: if a new technology does not fit into existing structures, costs will arise as structural changes are then required, i.e., either the technology (which itself is a structure) or the surrounding structures, or both. These costs are often referred to as either switching costs (from one technology to another) or as investment costs or sometimes even as losses. Hence, structures can act as barriers to the introduction of a new technology that does not fit in. Changing internal structures within your company, i.e., organizational processes, training, and other technology adoption, can happen relatively fast with a correspondingly quick transition to a new technology. That is, shipowners will quickly adopt a new technology if they can realize a high profit with low investment cost (=structural changes). On the other hand, changing external structures will require a lot of effort in form of time, money, resources, lobbying, etc. to influence a change in the desired direction. Since external structures are outside your control sphere, the outcome will also be uncertain. Therefore, the larger the structure and the more connected it is, the slower will be the achievable rate of change and consequently also the slower the adoption of a new technology. This is often the reason why issuing new regulations within the International Maritime Organization can take many years.
- Structural utilization=enabler: most structures are human constructs which require energy, resources, time, and manpower to operate and maintain, i.e., structural costs. A new technology that could result in a higher output without changing the existing structures, or could result in lower structural costs, or preferably both, will be conceived as beneficial and ultimately could drive the user/investor towards these new technologies. A structure is therefore a barrier to a new technology if they do not fit together, but realize that once the technology or the structure (or both) are

adapted to each other, the structure does no longer represent a barrier; in fact, it becomes an enabler as it now supports the use of this technology with lower structural costs.

Indirect support of our structural perspective can be found in the product lifecycle (PLC) approach describing occurring changes associated with the introduction and usage of any product (technology). In the PLC approach, the infrastructure development and its expansion rate play a key role in enabling and creating opportunities facilitating or inhibiting technology adoption. It is recognized that the technology may not mesh adequately with the existing infrastructure, or the needed infrastructure may not yet be in place to support it, or the investment for development would be too high given the doubts in the perceived benefits. As experience accumulates, it may be beneficial to provide a different version of the technology taking into account the level of change (radical or incremental) as well as where the stimulated interests to be concentrated (either for profit realization or long-term survival). Consequently, the infrastructure is modified over time until equilibrium is achieved. Further changes both with respect to technology, work processes, etc. aggregate and the whole construct advances and modifies again (Utterback and Abernathy 1975; Day 1981; McIntyre 1988; Werker 2003). Note that superior performance and lower costs can be attained when internal organizational and functional structures are nested providing privileged access to knowledge and resources, i.e., industrial networks. These nested connections introduce interdependencies hardening the involved structures and making them more resilient to changes. This resistance to change builds up opportunities towards incremental improvement of technology (alignment) or is linked and aims at solving the bottlenecks of the established paradigm (radical) (Geels 2002; Greve 2009; Brentani et al. 2010).

Literally speaking, we all somewhat agree that there is a significant difference between radical and incremental innovation (technology changes). One obvious difference may be the length of time interval over an innovation occurs. A temporal characterization would be to term a technology innovation as radical if the time interval is rather short, whereas incremental if it is long. What is considered a long or short time will be somewhat subjective as it depends on the typical dynamics in the system, i.e., what is expected to be a normal rate of change.

A different perspective, the one advocated by us, would be to relate the innovation to the existing structures. In our view, an incremental (technology) innovation would not (or just very little) affect the existing structures such as organization, work processes, business model, other technologies, infrastructure, etc. The aim of such an incremental innovation is therefore to optimize (output, performance) on existing structures, i.e., do things better. In contrast, a radical innovation will significantly affect and modify the surrounding structures, i.e., do things differently. For instance, the introduction of Liquefied Natural Gas (LNG)-powered vessels might be considered as rather radical since it requires a suitable change in existing structures, i.e., LNG bunkering infrastructure, on-board LNG tanks, new expertise/training, etc. Scrubbers on the other hand may be regarded as rather incremental since they do not affect/require as large changes as the LNG technology. It might be pointed out that any changes to structures come with a cost, and this explains why many economists/business leaders favor incremental innovation as it offers increased income with minimum investments. But sooner or later, optimization will bring the system to its natural carrying capacity/limits and further optimization may only achievable by disproportionately large investments.

In case of a radical innovation, the carrying capacity/limits of the system will also be different due to new or significantly modified structures. The initial investment (for technology and structural changes) may be higher compared to incremental innovations, but it may offer higher income (due to new technology) and reduced operating expenditures (due to new structures), and maybe the most important, it may offer larger growth potential in the longer run (new system limits).

3.1 Arguments supporting the structural change concept

This structural model naturally explains the observed phenomena of the piecewise straight lines in Fig. 3. It argues that the underlying processes governing the system dynamics will remain unchanged as long as existing structures are the same. Once an old structure is modified/replaced by a new one, the underlying processes will also change and hence also the system dynamics. This is seen as bends/breakpoints between the piecewise straight lines in Fig. 3.

3.1.1 Example no. 1: steel hull adoption

The dissemination of steel hull technology began in the midst of the 1880s and at the end of the 1960s, more than 95 % of all ships classed had a steel hull, i.e., it took more than 80 years to be adopted. This transition required large changes in the existing structures both for yards as well as for ports. At that time, the existing yard structure consisted of a large number of small shipyards (industry structure) with workers experienced in wood crafting (knowledge structure) using only simple tools (tool structure) based on domestic grown timber (supply structure). Building steel ships required other raw materials which could not be satisfied by the existing supply structure. The physical and functional structure of the existing shipyards had to be changed with expensive, heavy machinery and cranes. All these structural changes came at a cost and required time—but once they were implemented, they allowed building bigger ships. Larger ships, in turn, were facing other obstructions as the existing ports were originally designed (structured) for smaller wooden vessels. Again, investments were required to change port structures (increasing maximum size of cargo delivery or the port draught) before they were suitable for the new steel ship technology (Stopford 2009). The effect of this implementation could be seen as the bend points in the logarithmic plot of Fig. 3.

3.1.2 Example no. 2: diesel engine adoption

At the interwar period, diesel-powered ships were still lacking the structures necessary to produce suitable materials and the structures needed to manufacture the highly stressed engine components. Also the global shipping fuel supply structure was tuned in on coal, which required that most bunkering stations around the world had to be adapted to the new fuel. Again, WWII caused rapid and vast structural changes enabling oil as the main transportation fuel in shipping. Then, with the development of turbochargers in the 1950s, a major boost to engine output and reductions in engine size and weight was achieved. Internal combustion engines became enabling structures for turbochargers, and turbochargers in turn associated with cylinder lubricants became enabling structures for burning cheaper heavier fuel oils. And again, as the world fleet competes with each other, any business advantage gained by one actor due to new technology is quickly mirrored by the other actors resulting in a stepwise nature of diesel engine dissemination.

3.1.3 Example no. 3: oil tanker evolution

Let us consider the evolution of oil tankers as shown in Fig. 4. Until the 1940s, the average size of the oil tanker as well as the annual growth in the world oil production was constant, i.e., the existing structures of demand and supply remained the same. These structures were characterized by short-haul voyages favoring small tankers that spent more time in port and less at sea (operational structure). With the rise in industrial production and especially with the increase in privately owned cars after WWII, the demand for oil could no longer be fully met by the USA alone, being the world's largest oil producer pre-WWII. From the 1960s onwards, the Middle East gradually emerged as a main center of oil production requiring transportation of huge amounts of volumes of oil. This structural change in demand and transport patterns favored the development towards larger oil tankers. From a structural design point of view, bigger vessels had fatigue problems due to stresses and strains. At that time, the existing design rules and shipbuilding competence were not able to allow for larger sizes (knowledge barrier). The observed rapid increase in oil tanker size in the 1950s was only possible by attacking the barrier that hindered the construction of larger ships. Replacing the old empirical-based shipbuilding rules with ones based on scientific methods, i.e., laboratory tests, analytical and theoretical methods, and calculations; new/adapted structures were created that enabled new technologies (welding, corrugated bulkheads, etc.), which allowed ever growing tanker sizes. The design of tankers started to become more robust by reducing the size of cargo tanks and adding more transverse bulkheads (changing vessel structure). External infrastructures, i.e., shipyard size and port infrastructure had to adapt correspondingly. Initially, the switching costs were high, i.e., the existing structures acted as barriers, but with new processes and automation (organizational, process, and knowledge structures), the existing structures could be adapted to the new technologies and increased efficiency was achieved (Wijnolst and Wergeland 2009). Figure 4 shows clearly that WWII was a major event that had a large changing effect on the existing structures that were in place prior to WWII. It especially changed the structures governing oil production and demand.

3.1.4 Example no. 4: liberty ships

Another example supporting our view on the importance of structures both as barriers to the introduction of new technologies but also as enablers follows. WWII (or for that respect most wars) represents a major change in structures affecting the dissemination of technologies. In war (or crisis) situations, considerable changes to market and production structures can be achieved surprisingly fast. For instance, consider the US Maritime Commission's Emergency Shipbuilding Programme (Liberty ships) responsible for the massive merchant marine fleet expansion during the WWII period (1941–1945). By applying Paap and Katz (2004), this would be attributed to lack of ships (first

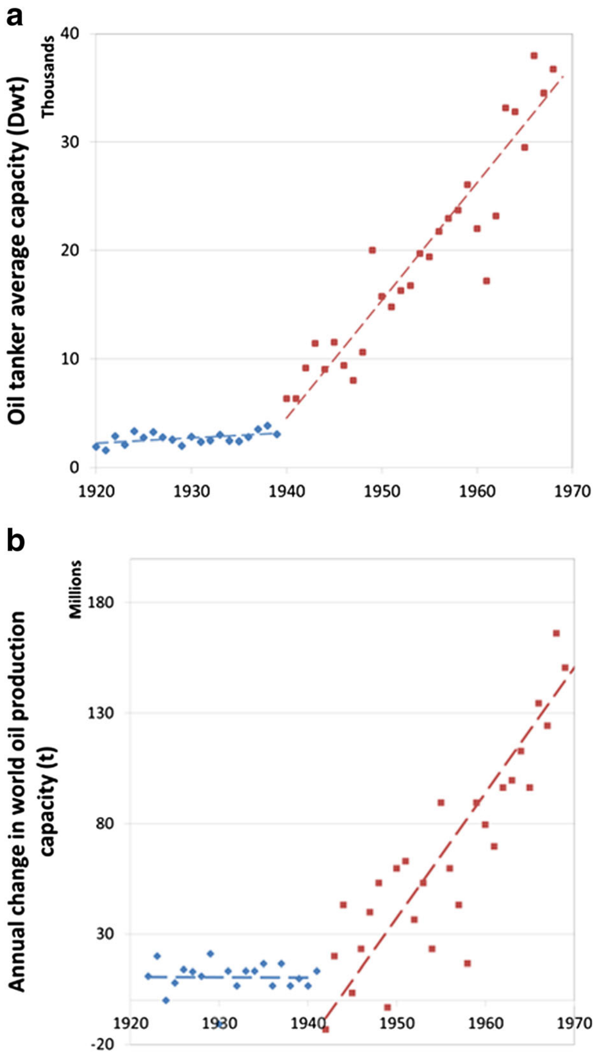

Fig. 4 Comparison of oil tanker capacity (**a**) and annual change in world oil production (**b**). (Source: (**a**) Stopford 2009; (**b**) British Petroleum (BP) plc 2013)

pattern) and lack of adequate shipyards to build ships quickly (second pattern). Though, in reality, the driver had always been to win WWII, and it was expedited by the regulatory structure in allocating budget (funding structure) for constructing new shipyards and expanding new facilities (reshaping the shipbuilding structures). The productive capacity of the yards was greatly increased by the assembly of prefabricated sections (reshaping the organizational structure) as well as the utilization of labor, equipment and material (reshaping the supply structure). The standard Liberty design was a modification of the British tramp vessel (oil instead of coal, welding instead of riveting, water-tube instead of Scotch boilers), utilizing the existing knowledge and tools structures of how to build quickly and cheaply ships that were easy to operate and had a long service life (Thompson 2001; Bourneuf 2008).

Realize that little to no additional structural changes (costs) were required when building the same type of ships leading to standardized ships, i.e., the existing structures were maximally utilized. The operation and maintenance cost of these shipbuilding structures could thereby be distributed over more ships. Any subsequent introduction of new technologies, such as welding instead of riveting, welding and assembly robots or processes such as advanced production engineering, required again changes of the existing structures or sometimes even creation of completely new ones. All these changes implied switching costs, and the structures appeared therefore as barriers, but once the new or adapted structures were in place, the benefit of large-scale economics allowed lower production costs.

4 Adoption of energy-efficient technology in shipping

The technological opportunities for energy efficiency in ships can be broadly divided into three strategies impacting on the design of (i) vessels (i.e., air lubrication, hull optimization, bulbous bow, aft waterline extension, etc.), (ii) engines, auxiliaries, and propulsion systems (i.e., waste heat recovery, diesel electric drives, counter-rotating propellers, propeller nozzle, kites and sails, wing thruster, solar panels, fuel cells, etc.), as well as (iii) operational strategies (i.e., propeller and hull cleaning, port turnaround time, slow steaming, voyage planning and weather routing, trim optimization, etc.). The combination of these options could provide an estimated CO_2 emissions reduction of 20–30 %, while operational measures could be viewed as the most cost-effective. The amount of energy saved depends on the actual measures implemented on a specific vessel segment, i.e., the highest potential is observed for bulk and general cargo vessels, followed by tankers and containerships; whereas offshore, passenger/cruise and RoRo/ROPAX vessels have the lowest potential. This is attributed to the diverse characteristics and practices among liner and tramp routes (Eide et al. 2011).

Implementation of energy-efficient technologies is usually not done out of save-the-world motives but is considered as a way to gain competitive advantages by reduction of fuel costs (stronger financial results, larger market share, reputation, etc.). In order for an energy-efficient technology to be successfully used, it may have to be conceived as the most profitable investment (at least within its normal investment space), if not, the shipowner will invest in something else, i.e., fleet expansion. Such a technology will gain highest profitability if technology and its surrounding structures (i.e., infrastructure, organizational, work structures) are perfectly adapted to each other. The main challenge may be the modification of these often very large and interwoven existing structures (i.e., LNG bunkering infrastructure, electricity supply for cold ironing) as large investments and a lot of collaboration is involved. Although the technical challenges pertinent to energy-efficient measures can easily be solved (i.e., we have the technology and the knowledge), the central problem lies in the adaptations of the existing structures as this may require changes in business models, re-prioritization, and collaboration between company silos or even with external players. Or expressed in other words, technology is already available being superior with respect to its green footprint, i.e., it uses less energy, compared to main stream technologies. The problem is that they are not profitable enough to be the technology of choice as the existing structures favor the old technologies.

For instance, the legal structure of the current shipbuilding and carriage of goods contracts do not provide any premise for investing into the most energy-efficient vessel, rather than giving merit to the standard design. Overcoming this split incentive dilemma where the shipowner carries the cost of energy-efficient technologies from which the charterer benefits can only be done by new forms of collaborations. Also, manufacturers of energy-efficient equipment rarely accept to share the cost with the shipowner (supply structure) or receive payment until the promised energy saving result is achieved. "Don't fix what ain't broken," i.e., minimum operational disruption is central in many industries. Hence, the authorities' and trade organization's role in providing motives cannot be emphasized enough. They have the power to initiate structural changes by issuing incentive schemes or new regulations that would support new (i.e., more environmentally friendly) technologies or that would convince maritime players to collaborate to overcome, i.e., split incentives. Only through (voluntary or forced) collaboration can existing sub-optimizations be overcome. The goal of structural changes is then to make new (more environmentally friendly) technology more profitable than the existing solutions. And once such a change has started, it benefits from the snowball effect as others will have to follow, otherwise they lag behind and become less profitable. In this case, conglomerates, investment funds, or equipment vendors may influence the functional, organizational, knowledge, and technology structures of maritime partners through regulatory structures (see no. 1 in Table 1).

Once a technology implementation has shown to be profitable, it can quickly spread through the market depending on the cost structure of companies and the technology

Table 1 Examples of possible mechanisms for the adoption of energy-efficient technologies in shipping

	Example	Comment
1	Clean Development Mechanism and carrier (fuel efficiency improvement of freight transportation) https://cdm.unfccc.int/Projects/DB/SIRIM1348642609.49/view Accessed 18 August 2014	Although this project refers to road freight, it could be well applied to shipping where regulation may act as an enabler for the adaptation of functional, organizational, knowledge and technology structures
2	Cargo owner, shipper, carrier and consignee (air lubrication) http://www.adm.com/Lists/PressRelease/Attachments/362/ADM%20Vessels%20News%20Release.pdf Accessed 18 August 2014	Energy efficient management across the whole supply chain network with the utilization of functional, organizational, knowledge and technology structures
3	Charterer, manufacturer and shipowner (wind assisted propulsion) http://www.cargill.com/news/releases/2011/NA3040908.jsp Accessed 18 August 2014	The cited partnership indicates how functional, organizational, knowledge and technology structures can be adapted to each other
4	Government and shipowners (scrubber funding) http://www.lloydslist.com/ll/sector/ship-operations/article429089.ece Accessed 18 August 2014	The investment aid (regulatory structure) lowers the economic burden of installation (organizational and technology structures)
5	Market-based measures http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Market-Based-Measures.aspx Accessed 18 August 2014	The regulatory structure can provide incentives for knowledge as well as technology adaptation

(switching cost). The cost of the new technology will fall correspondingly in relation with the learning, i.e., economies of scale. The critical factor is the successful demonstration of the technology in a real business situation, as an investment in the new technology is only done when enough reliable information is available to perform a reliable cost-benefit analysis (knowledge and tools structure). The example no. 2 in Table 1 demonstrates the commitment to improve the environmental footprint along the whole supply chain network through the confidence in the technology structure which is being supported by the flexible functional and organizational structures. In order to keep investment costs, i.e., potential losses down, piloting projects, joint ventures, or partnerships are the preferred ways of generating the necessary information and trust in them. In example no. 3 in Table 1, the involved parties do not only provide the required cofunding, they also strengthen their respective functional and organizational structures. Realize, the value of energy-efficient technologies may not only be apparent to the shipowner, to the charterer, or to the equipment manufacturer, but it may also offer value to, i.e., society at large, environmental organizations, or even to very unfamiliar parties, i.e., suitable for advertisement. The interesting point is that partnerships for promotion and implementation of more environmental friendly technologies may be related not only to traditional assets, i.e., vessels, terminals, equipment, etc. but also to more intangible society-related resources.

The regulatory structure is an effective way for enforcing or encouraging energy saving and emission reduction which might not happen otherwise. For instance, a new or stricter environmental regulation may force a company to look for new ways of operating or utilizing other technologies and in this way causes structural changes in the company's organizational and functional structures. Regulations should define the objective to be achieved, i.e., emission levels, but should leave it to the industry to find the optimal way. Examples no. 4 and no. 5 in Table 1 address the situation where regulatory structures affect the adoption of organizational and technological structures of shipping companies at a regional or even international level. The drawback of many regulations lies in the fact that there are no further incentives to comply beyond the minimum level as given by the regulation; once this minimum level is reached, a licence to operate is obtained. A company performing on a higher environmental level may therefore not be rewarded by receiving better charter rates or by better financing conditions compared to competitors. At the end of the day, it is the shipowners and shipyards (together with suppliers, i.e., engine manufacturers) that have to adopt energy-efficient technologies.

Shipping is characterized by regulatory compliance and fierce global competition. Adoption of new (more environmentally friendly) technology may most easily be accelerated by modifying existing financial structures, i.e., introduction of environmental taxes, fees, fuel taxes, emissions trading alternatives, government subsidies, etc., and for a review, see Corbett and Winebrake (2010) as well as Nikolakaki (2013). For instance, no. 4 in Table 1 is an example of a governmental investment subsidy lowering the economic burden when installing scrubbers. Outlining governmental initiatives of, i.e., Flag States and assessing them from a structural point of view is left for future work.

To this end, we may summarize our understanding of accelerating the dissemination of new (more energy-efficient) technology into the following schemata:

1. Identify the effects a new technology can potentially have on existing structures, i.e., reduced fuel consumption, reduced emissions, organization, internal reorganizations, training, new sub-suppliers, out-phasing of old suppliers, etc., i.e., *impact assessment*.

2. Deduce which structure is impacted, how much, and whether this effect is positive or negative, i.e., requires capital expenditure, leads to reduced operation expenditure, change in revenue stream etc., i.e., *value proposition*.
3. Identify what players are affected and are central in these structures, i.e., companies, authorities, nongovernmental organizations. Realize that a potentially affected part may not even be within your industry segment, a real-estate developer benefiting from reduced port emissions, i.e., partnerships.
4. Initiate collaborations among the affected parties such that the potential benefits can be experienced and any negative effects mediated.
5. Initiate changes to existing structures such that they become enablers of the new technology.

5 Concluding remarks

It is unambiguously accepted that due to stringent environmental regulations, shipping has to improve its environmental footprint and will increasingly have to relate its operation to the concept of sustainability. It should also be acknowledged that the adoption of energy-efficient technologies will not happen overnight, as sometimes considerable structural changes must be done before the benefits of these technologies can be realized. It was our aim to provide some new insights why large-scale adoptions are often delayed. We argue that it is because of the rigidity of established structures, i.e., invested interests in physical, functional, social, behavioral, psychological, and cultural arrangements that restrict and hinder our activities (barriers). To accept a (new) technology, it has to fit into the existing structures. Any modification of structures (technology is a structure itself) comes at a cost (investment, loss), but once adapted, the new structures will act as enablers of the (new) technology. We argue and show that the effect of these structural changes should actually be visible in the diffusion rate of the technology. We provide historical fleet data for the global dissemination of ships with steel hulls and diesel engines which indeed supports our view.

The data presented in our study is on a global level, and it should be pointed out that zooming on specific fleet segments, i.e., per country, might reveal further information. Also, any analysis is only as good as the available data, and the data are only as good as the process for collecting the data. Some of the observable breakpoints could be artifacts as they may have been caused by changes in how “steel hull” or “diesel engine” were recorded.

Regarding the adoption of new technologies in shipping, focus should be on how and with what industry or authority partners we can cheaply and quickly change the existing structures such that they actually favor and enable the use of more environmentally friendly technology.

Acknowledgments The work reported in this article has been carried out under the DNV GL Strategic research programmes and is an extended version of the paper presented at the International Association of MaritimeEconomists (IAME) 2014 Conference in Norfolk, Virginia, USA. The authors would like to express theirgratitude to Louise Sanger (Lloyd’s Register Group) for kindly providing the historical data. The article alsobenefitted from valuable discussions with Mark Schweitzer, Hans Christian Jensen (Archer Daniels MidlandCompany), Chiharu Kawakita (Mitsubishi Heavy Industries Ltd.), Jan Øivind Svardal, Roar Fanebust, AndersMoseid (Grieg Star), Preben Rasmussen (Jo Tankers), Lars Dessen, Gunnar Malm Gamlem

(Wilh.Wilhelmsen ASA). The authors thank Prof. Michele Acciaro (Kühne Logistics University) for providingrequested articles of IAME 2013, meeting participants at IAME 2014 for comments, the colleagues at DNV GLwho responded to their enquiries and the reviewers for the constructive feedback as well as the editors fortheir valid proposals to improve the manuscript.

The opinions expressed are those of the authors and should not be construed to represent the views of DNV GL Group AS or the referred individuals and their affiliated organizations.

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