Industrial and Corporate Change, 2021, 1–20
doi: 10.1093/icc/dtab021

OXFORD

The "sailing-ship effect" as a technological principle

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Abstract

The "sailing-ship effect" is the process whereby improvements to an incumbent technology (e.g. sail) are intentionally sought as a new competing technology (steam) emerges. Despite the fact that the *effect* has been referred to by quite a few scholars in different technological battles, the effect itself seems to have been taken for granted rather than organically defined and investigated. In this paper, within the context of evolutionary "appreciative theorizing" *à la* Nelson and Winter, through in-depth study of technological battles between old and new technologies, we transform what was an unfinished concept into a structured, fully-fledged, tool of analysis.

JEL classification: O33, O14, O31, L26

1. Introduction

The aim of this work is to systematize the "sailing-ship effect" concept. The *effect* owes its name to the 50-year long technological battle between sail and steam as a means of providing propulsion to ships in the 19th century. This phrase has become the standard expression to address the process whereby an incumbent technology experiences a wave of improvements when a new competing technology appears. These improvements are the result of intentional efforts, aimed at enhancing the "old" incumbent technology, and are activated *because of* the appearance of the new competing technology. These efforts, if successful, generate advancements which give the old technology a new lease of life through improved performance—cargo capacity in the eponymous case—so that the overtaking by new technology of the old takes place later in time and at a higher level of performance. It is important to stress the fact that the occurrence of the effect alters the diffusion process of the new technology, changing continuously through time the cost-benefit dimensions on whose basis agents have to decide in which technology to invest.

The phrase "sailing-ship effect" was first used by Ward (1967), and has been used by a few authors—e.g. Freeman and Soete (1997)—while from the 2000s, the *effect* has experienced renewed attention (De Liso and Filatrella, 2008, 2011; Adner and Snow, 2010; Liesenkötter and Schewe, 2013; Sick *et al.*, 2016; Miyamoto, 2019).

As so often occurs, the concept has raised interest as well as controversy. Despite the fact that the *effect* is referred to by a few scholars, its very existence has been questioned by Howells (2002), Edgerton (2007), and Mendonça

(2013). In a nutshell, these authors propose that the *effect* is not a technological principle which is (sometimes) at work, but is an uncritically accepted conjecture or a construction of hindsight. In particular, Howells and Mendonça explicitly try to retrace the route which should lead to a demonstration of the existence of the effect in the eponymous case, i.e. sail vs. steam. They each do this in a different way. The former by reconsidering the literature usually quoted to demonstrate the existence of the effect, and the latter by re-reading the literature and by testing econometrically whether an acceleration in innovation in sailing ships can be found in data relating to shipbuilding in the 19th century. The two authors conclude that the effect, if it exists, has not actually been accurately identified (Howells, 2002) or verified (Mendonça, 2013).

And here we come to the research question of this work. We have articulated it into two dimensions. In the first, we single out cases in which we can say that the effect has undoubtedly taken place and, in the second, we identify those features which lead to a theorization of the *effect*.

In particular, the first dimension considers the question of whether the "sailing ship effect" is an illusion. The main difficulty lies in demonstrating the nexus between the emergence of a new technology on the one hand, and improvements of the incumbent-old technology on the other. We do this by considering five cases in which the effect is unambiguously at work and by reassessing the eponymous case (see Sections 3 and 4). Worthy of an immediate comment is the fact that two of the cases which we address have never been considered before: the first concerns coal-based vs. oil-based mass production in the post-1945 (West) German chemical industry; the second concerns a nascent field, namely traditional vs. quantum computing.

The second dimension concerns the "theoretical" definition of the phenomenon. The reason for putting the word *theoretical* in inverted commas lies in that, at this stage, we consider our own analysis under the heading of "appreciative theorizing"—that is theorizing not on an abstract view of economic activity in general, but on particular sets of phenomena and economic questions (Nelson , 2018: 9; see also Nelson and Winter, 1982; Nelson *et al.*, 2018; Malerba *et al.*, 1999). This having been said, if the effect can be demonstrated to exist in more cases, then it is worthwhile investigating if there exist common characteristics among the various technological battles which can lead to elaboration of a general principle—where "general" does not mean that it always occurs.

Scholars who consider the sailing-ship effect as real, are content with saying that it consists of the improvement of an incumbent technology when a new one, potentially supplanting it, appears. However, if the effect is to be transformed into a real tool of analysis, it must be capable of answering questions such as: When does the real competition between technologies actually begin? For how long is it meaningful to fight? Can the old technology be improved sufficiently as to keep the new at bay, thus generating lock-in cases? Is the battle (ir)rational? Can we disentangle the specific *effect* from other aspects which induce technical progress anyway? Some of these questions may not have clear-cut answers, but it is an important step to be aware of the need to ask these questions.

In order to try to provide an answer, it is important to make explicit our theorizing strategy. In this work, we provide a historically embedded qualitative analysis which aims at building a conceptual model capable of explaining the "sailing-ship effect," thus transforming it from an intuition—or *vision*, as Schumpeter (1949) would have it—into a structured technological principle.

Our appreciative theorizing is *verbal*. Despite the fact that in the social sciences, and particularly in economics, "models" are increasingly associated with mathematical formalizations, models themselves need not be formal. Verbal theorizing has its own advantages in that "the language used can be rich and nuanced while expressing the understandings and beliefs of economists knowledgeable about the empirical phenomena under study regarding the key facts and mechanisms" (Malerba *et al.*, 2016: 25–26). Obviously, verbal models have drawbacks, but too often there exists a bias in favor of formal models, sometimes following the illusion that to cast a mathematical mantle over a problem is tantamount to solving it (Letwin, 1964).

Our analysis develops according to the following reasoning. In Section 2, we refer to the scholars who can be addressed as the precursors of the concept in different ways, from describing the phenomenon to trying to provide a formal model capable of describing the battle. In Section 3, we reassess the eponymous case, addressing also the non-trivial criticisms of Howells, Edgerton and, in particular, Mendonça. In Section 4, we consider five cases which can unambiguously be read under the heading "sailing ship effect"; two of these cases have never been addressed before. In Section 5, we carry out the decisive step, which consists of providing the structured sailing-ship effect technological principle which addresses the questions raised above. Section 6 contains the final discussion and the conclusions, hinting at further research possibilities.

A final remark is necessary to conclude this introductory section to clarify what we are *not* studying in this work. In battles between technologies, hybrid technologies have sometimes been developed, while at other times the two technologies have complemented each other. The case of sail vs. steam in certain phases actually shows both characteristics, i.e. hybridization and complementarity. We will just hint at these features and this limited attention to these aspects is not explained by the fact that they are unimportant but, on the contrary, because they deserve separate investigation. Some works on these themes are already available: Furr and Snow (2015) study the development of intergenerational hybrids, while Damásio and Mendonça (2019) actually study the period of complementarity between sail and steam over the first five decades of coexistence of the two technologies. However, as we have said, we will focus on that part of the process which sees the two technologies as alternatives to each other, as it turned out to be, in the end, in sail vs. steam and in the other cases considered throughout our work.

2. Literature review

The copyright on the phrase "sailing-ship effect" apparently belongs to the physicist Ward. He refers to it as to a process that can be applied to more fields:

> "This is the 'Sailing Ship Effect'; time, energy, intelligence, and money are spent in improving a concept, a branch of knowledge or a device that is inevitably being supplanted by the fruit of more original thinking" (Ward, 1967: 169).

It is important to stress the fact that Ward's is a one-page article, and takes sail vs. steam as *the* example, but does not provide any supporting substance to his analysis. Maybe the process can be taken for granted in subsequent physics theories (this is why we mention above that he was a physicist), but it requires specific investigation when we deal with technological progress as the variables which must be considered are complex, necessarily interacting with institutional, social, and economic aspects.

Musing about old and new technologies, David Landes uses the phrase *Indian summer* which is basically synonymous with sailing-ship effect:

> "This Indian summer of growth and achievement in obsolescence is a common economic phenomenon: witness the golden age of coaching after the coming of the railway; or the development of the clipper and the large intercontinental schooners after the introduction of the steamship." (Landes, 1969: 260)[1]

However, like many other contributors to the economics of technological change who enunciate the concept, Landes does not substantiate it with the necessary additional investigation.

From a chronological point of view, the early intuition on the occurrence of the sailing-ship effect could be attributed to Gilfillan (1935) even though he never used the phrase. To Gilfillan we owe one of the most quoted passages about the fifty-or-so-year battle in the second half of the 19th century between sail and steam:

> "It is paradoxical, but on examination logical, that this noble flowering of the sailing ship, this apotheosis during her decline and just before extermination, was partly vouchsafed by her supplanter, the steamer." (Gilfillan, 1935: 156)

He "simply" recalls the battle sail vs. steam without asking or implicitly answering the questions we ask in the introductory section of this work. Furthermore, according to Mendonça, "Gilfillan, who is often cited in association with the 'sailing ship effect', cannot be understood as one of its proponents" (Mendonça, 2013: 1725)[2].

Similar criticisms can be extended to two more scholars who have dealt with the process of the substitution of steam for sail, and who are always referred to in the literature, namely Graham (1956) and Harley (1971). They study the process in a different way: the former uses a history of technology approach, while the latter develops his analysis of the displacement of sail by steam in an economic theory setting in which production functions are used.

Graham's point is well synthesized in the title of his work: the ascendancy of the sailing ship, *1850–85* (Graham, 1956). Here we have stressed the range of years considered by the author. The ascendancy of the sailing ship, in fact, took place during the period in which marine steam engines, as well as ancillary components in steamships, were being continuously improved. Harley notes how technical and economic conditions led to steamships gradually

1 Curiously enough, despite the fact that Landes' studies on technology are widely referred to and that the words he uses are very close to the idea of the "sailing-ship effect," he is never quoted in studies concerned with the effect itself.

2 For similar criticisms see also Howells (2002: 891–895).

displacing sail ships, starting from short trading routes and then on the longer ones—even though some sail-served micro routes remained active well into the 20th century[3]. Sail ships, though, continued to be produced in large quantities by British shipyards until the early 1890s: "the largest tonnage of sailing ships launched in Britain in a single year was launched in 1892" (Harley, 1971: 226)[4]. Both authors, by referring to the eponymous case, provide useful insights which lead to the generalization of the sailing-ship effect.

The list of further contributors recounting specific cases to read through the sailing-ship effect lens is rather large. Rothwell and Zegveld (1985) refer to the alkali industry in the late 19th century in which the British producers kept improving the old Leblanc process to contrast the new and better Solvay process. Cooper and Schendel (1976, repr. 1988) consider seven different cases—the most important being steam locomotives vs. diesel and electric, fossil fuels vs. nuclear power plants, aircraft propellers vs. jet engines, and vacuum tubes vs. transistors—and note that systematically the old technologies reached their zenith *after* the new had been introduced. Incidentally, on the subject of vacuum tubes[5] vs. transistors, it is worth pointing out that it may be "argued that the exhaustive research which went into semiconductors helped stimulate new valve work at a scientific rather than a technical level with such revolutionary results as the klystron traveling wave tube." (Braun and Macdonald, 1978: 69).

Utterback (1994) studies how the transportation and storage of naturally harvested ice improved as mechanical ice-making technology spread in the late 19th century. Snow (2004) and Furr and Snow (2012) refer to the Carburettor's twelve-year-long "last-gasp" series of improvements as electronic fuel injection came about. Further analyses relevant to our work are the ones by Henderson (1995), Tripsas (1997), Kaplan and Tripsas (2008), and Adner and Kapoor (2016): in all of these contributions forces and factors which prolong the life of incumbent technologies are considered.

De Liso and Filatrella (2008, 2011) are the first to provide a formal model capable of reproducing the process of competition between an old and a new technology. They do it in a simplified setting, based on simulations, in which both the old and the new technologies invest in R&D in order to improve their own performance—e.g. cargo-carrying capacity. The model reproduces the sailing-ship effect, i.e. one sees that the new technology eventually overtakes the old, and overtaking takes place later than it would have without the presence of the effect, at a level of performance which would not have been reached by the new technology without that process of competition with the old. However, once more, the reasons why incumbents should stick to the old technology are not properly investigated.

One of the criticisms of Howells (2002), Edgerton (2007), and Mendonça (2013) is that there is a lack of evidence of a causal nexus between the emergence of a new technology and the response of the old technology.

Mendonça, in particular, assesses the eponymous case sail vs. steam through an econometric study based on a time series, which ranges from 1814 to 1915. Through this time series the evolving performance, in terms of average tonnage cargo capacity, of both sail and steam can be evaluated. One of the main results is that the divarication between the two technologies occurs in 1861, while sailing ships experience an acceleration in carrying capacity in 1837, i.e. too "soon." Put another way, if there exists a causal nexus according to which improvements in the old technology occur *because* of the increasing competitiveness of the new technology, those same improvements should take place when the new technology becomes really competitive. Given that the latter condition occurs in 1861, improvements experienced by sail ships in the mid-1830s cannot be considered a response to improving steamships, but progress which would have taken place anyway (Mendonça, 2013)[6]. Should this analysis be considered as final, the "sailing-ship effect" is misnamed.

In order to arrive at our theoretical construct in Section 5, let us first reassess the eponymous case, and refer in Section 4 to cases in which the effect has unambiguously taken place.

3 We thank one Referee for pointing out the fact that sail ships continued to serve these micro-routes into the 20th century.

4 Of interest is also Harley's essay on the persistence of old techniques which concerns American shipbuilders sticking to wood between the mid-1850s and the 1880s when more efficient and dominant British producers had switched to metal (Harley, 1973); for a broad analysis of improvements of old technologies see also Rosenberg (1976).

5 Also referred to as *valves*.

6 This synthesis does not do justice to Mendonça's well crafted, historically based econometric analysis. However, as we show in this and in the next section, there are critical issues to be raised.

3. Toward the theoretical construct: reassessing the eponymous case

Why so much emphasis on the original case of sail vs. steam? The main reason is that this case presents an aspect of complexity which can make it a good benchmark for other relevant cases[7]. We are talking about two technologies which were evolving rapidly for 70 years, and institutional, social, and economic—as well as technological—considerations were part of the game. In more detail, the first point to consider is that if the *effect* exists in this case—together with the ones mentioned in the previous section and the further ones synthesized in the next—then it gives further confirmation of the transformation of an intuition which becomes a full *analytical concept* or *technological principle*, i.e. a tool to assess and understand other technological battles (and the effect was not misnamed). Secondly, it is thus important to identify its existence in a satisfactory way rather than assuming it. Third, it provides a benchmark concerning technological substitution between dynamic evolving entities: both sail ships and steamships were being greatly improved in terms of materials, size, reliability, longevity, reduction of crew, etc., as steamships displaced sail ships over a 50-year period. Fourth, different types of complementary assets and tributary innovations played a role in strengthening each technology—and, mutatis mutandis, systemic components may be at work in other cases. Fifth, the institutional set-up also played a role: for example, the changes in "Tonnage Laws" (Graham, 1956) or the abolition of the monopoly of the British East India Company (Geels, 2002) affected ships' design, while the repeal of the Navigation Acts in 1849 removed the security of an assured home market for British shipbuilders, thus fostering competition (MacGregor, 1973; Harrison, 1990). Sixth, by reassessing the eponymous case one finds a lot of technical and historical materials which must be selected and interpreted. When an abundance of sources and materials concerning technologies exists, evidence may be difficult to interpret, and this is true in sail vs. steam, but it is true in more instances in the chemical industry (e.g. Leblanc vs. Solvay and coal vs. oil as feedstock for organic chemistry), or, in iron production, in the open-hearth process vs. Bessemer. Seventh, there are policy implications.

3.1 The stretching and differentiation of vessels

Two scholars who arrived at the "sailing ship effect" concept even though neither uses the phrase and who do *not* refer to Gilfillan are Björn Landström (1961) and Richard T. Harrison (1990). The former writes:

> "The three-masted barque was the most important vessel in northern merchant fleets at the end of the 19th century. *When the steamship came into general use and competition increased, many earlier barques were rigged so that maintenance would be cheaper and the number of crew reduced*. [. . .] Twentieth-century full-riggers and barques were only built for really long-distance trading . . . . In order to make seafaring under sail at all profitable even for coastal work, large barquentines were built which could be manned by a very small crew. Thus came the four, five, and six-masted ships *to continue the battle with the steamship*." (Landström, 1961: 203, emphasis added)

The stretching of vessels reminds us of the stretching process of the DC-8 aircraft series recounted by Rosenberg (1982) on the one hand, and the general idea of capacity stretching (Aylen, 2013), applied, in our case, to shipyards, on the other hand.

Harrison writes that substitution between an old and a new technology may take a long time because the old continues to be improved *after* the new has been introduced, and he refers to this phenomenon as the "process of inter-technological competition" (Harrison, 1990: 40).

A third author who studied the evolution of technological change in transport, and who uses explicitly the phrase "sailing-ship effect," is Grübler (1990, 1998). He writes that an old technology, when challenged by competition, may improve its technical and economic performance, thus:

> "*Challenged by the appearance of steamships, sail ship technology was improved* to such an extent that even a new clipper age began. Sail ship construction continued and the gross tonnage of sail ships increased even after the appearance of steamships." (Grübler, 1990: 83–84, emphasis added)

The three authors mentioned thus far are observers specializing in the shipbuilding and transport industries, who arrive at the same conclusion.

7 Incidentally, let us note that the transition from sail to steam was used as the case study by Geels (2002) in his multi-level perspective article on technological transitions—in which the sailing-ship effect is touched upon.

An aspect which is not sufficiently acknowledged concerns the improvements in the sail technology due to those actors who could not afford or were unwilling to adopt—and *adapt*[8]—steam technology, and who nevertheless had “to do something” to remain in the business. Here “to do something” necessarily means some form of innovation, however frugal. This is what happened in the Nordic countries.

Studying the work on the transition from sail to steam in Sweden (Fritz, 1980), Norway (Gjølberg, 1980), Denmark (Hornby and Nilsson, 1980), and Finland (Kaukiainen, 1980) it invariably emerges that sail shipbuilding was fundamental during the second half of the 19th century, vessels being incrementally improved, made bigger in cargo capacity and manned by smaller crews.

In the same vein, Ojala finds that the Finnish “years of glory” extended up to the 1870 s, and are characterized as *the age of sail* (Ojala, 1997). As steam competition became harder and harder, technological change in sail shipbuilding took this form:

> “The different sizes, types, and hull shapes became differentiated functionally: some for routes and cargoes that required more speed than cargo capacity, some for longer routes, and others for coastal or short-sea trade.” (Ojala, 1997: 122)

A preliminary conclusion, considering the works of Landström, Grübler, Harrison, and of the other scholars who refer to the Nordic countries, is that it is impossible *not to correlate* changes of sail ships to the emergence and development of steamships. The latter statement does not mean that before steam competition vessels were not improved: simply, steamers added competitive pressure, which further stimulated sail technology.

3.2 The timing of the battle

An important issue consists of the timing of improvements as pointed out by Mendonça, the question being: when did steam start to bite? According to him, steam started to be competitive after 1860 (Mendonça, 2013: 1729). Further historical evidence suggests a different, earlier, timing[9].

The *Nautical Magazine and Naval Chronicle* (NMNC hereafter), first published in 1832, contained lots of information which anyone concerned with ships—shipbuilders, merchants, insurance companies, investors, experts on patents, naval officers, etc.—wanted to know, from technology improvements to mapping of currents, from the presence of pirates to the modes of determining longitude.

The *actual* and *potential* role played by steamships is systematically acknowledged. For instance, at p. 752 of the 1837 issue of NMNC one finds comparisons between the performance of two steamers, the *Atalanta* and the *Berenice*, in terms of speed, engine performance, and coal consumption. The pros and cons of steam navigation find systematic room in each issue. A long article dedicated to “American Steam-Boats” begins with the words: “All the world has heard of the extraordinary speed of the steam-boats of the United States; the fame of their passages . . . and the accounts of their wonderful velocity, have long since reached the shores of Europe, and have formed the subject of discussion among many . . .” (NMNC, 1838: 536)[10].

Steam navigation on the high seas already existed as one can read, for instance, in an article on “steam navigation to India” (NMNC, 1839: 631–634).

There are too many examples to be recalled, and we wish now to emphasize two key aspects: one has to do with the relative importance of steam in mercantile United Kingdom tonnage in the mid-1830s, while the other has to do with the strategic military potentialities of steam vessels.

8 Technologies can rarely be adopted simply, but often they have to be adapted; the latter process is a costly activity; for shipbuilders who had built sail ships for ages, the adoption of steam-engines as the prime mover was not necessarily an easy task.

9 We have to stress that we have benefited from materials which are now easily accessible, and which were not when Mendonça submitted his article for publication. These are the multi-volume “Nautical Magazine and Naval Chronicle” reprinted by Cambridge University Press in 2013 and a key collection of research papers by Armstrong and Williams (2011). The former is made up of volumes each of which exceeds 700 pages; the first original *Magazine* appeared in 1832 and was relaunched in 1837.

10 The article includes a table (p. 537) in which 22 steamboats are listed, and for each, the main technical characteristics are indicated, including the date on which they were completed—the oldest in this list was completed in 1827. These steamboats were mainly used on big American rivers, and their use for transoceanic voyages was considered simply a matter of time.

On the former aspect, one can read that, starting from 1835, the "mercantile steam tonnage of UK, *progressing as it is in a prodigious ratio*, presents the most stupendous element of Naval power (by giving facility of operations) that the world ever witnessed" (NMNC, 1840: 736, emphasis added).

The aspect concerning military applications of steam to ships has attracted too little attention: scholars studying technical progress are ready to emphasize the role played by governments in shaping technologies (e.g. Mazzucato, 2015), particularly defence-related ones, that often find civilian applications—just think of the Internet. The British Navy started to invest heavily in steam vessels from the mid-1830s as steam navigation had "palpable merits and advantages" and "enables the country possessing it in the greatest force to harass an enemy's coast with a small but well-appointed army" (NMNC, 1840: 736).

If serious direct investment in the new technology started in the 1830 s, attention to the strategic importance of the steam-engine as applied to vessels emerges explicitly in many earlier writings, not least in a letter of 1820 in which the Chancellor of the Exchequer speaks of the need to follow "the improvements of an invention [the steam-boat] which seems likely to be at the least very formidable" (quoted in Graham, 1958: 38).

The *Nautical Magazine and Naval Chronicle* provides a clear picture of the changing spirit of the time, which already considered steam as an important actual and potential technology for sea transport in the mid-1830s. A systematic analysis on the role of steam technology during the period 1812–1834, though, is contained in the works of Armstrong and Williams (2011)[11].

Armstrong and Williams provide a thorough analysis of the evolution of steam technology in the very early phase and their analysis is corroborated by many tables containing details on who produced marine engines, the number of steam vessels, their tonnage, in which ports they were registered, and many other data. Basically, it emerges that steam was seen as a threat much earlier than generally understood.

One short quote is particularly important, in which the authors note that their data reveal "that in the initial 22 years [1812–1834] of the steamship's existence, vessels were constructed in around 70 different locations"—a surprisingly large number indeed—while in 1834 the number of ports in UK in which one could find one or more steamboats providing regular services was 75 (Armstrong and Williams, 2011: 145, 149). If the first successful commercial steamboat built in Scotland and brought into use in 1812, the *Comet*, "had been powered by what was basically a land-engine pressed into marine service" (p. 293), then from 1820, we have a boom in steamboat construction. The latter was due to growing confidence in the new technology which was based on greater reliability and greater efficiency of engines (Armstrong and Williams, 2011: 283–284).

The timing of the emergence of steam as a threat to sail is further reinforced by Davis *et al.* (1997: 261) where they write that by the 1820 s steam-powered vessels were crossing the English Channel and the Irish Sea, while in the 1830 s *regular service* was established between England and Egypt and in 1835 between England and India.

Many authors ranging from Brunel (1870)[12] to Damásio and Mendonça (2019) confirm the fact that steam technology started to bite from the late 1820 s, so that, by the 1830 s it was clear to those who lived by sail technology that their technology had become *contestable*. This is a very important point: it constitutes one of the foundation-stones of the fully fledged "sailing-ship effect" principle which is that an awareness of contestability triggers a response by the incumbent technology. It is the threat, not the substitution, that sparks the effect[13].

4. Toward the theoretical construct: five cases in which the "sailing-ship effect" seems evident

In this section, we consider five cases in which one finds clear evidence of the incumbent technology being improved *because* a new, competing one, has emerged. In fact, as we shall see, the causal nexus is explicitly identified through quantitative statistical analysis or through explicit enunciation of the actors involved. The first two are case studies available in the literature on technological competition; the third has only been hinted at by Filatrella and De Liso

11 Useful references, looking at longer periods, are Mendonça (2012) and Smith (2018); worthy of a quote is also the book by Ferreiro (2007) in which he studies the birth of "scientific" naval architecture before the advent of steam technology.

12 This is the book written by Isambard Brunel, son of *the* engineer Isambard Kingdom Brunel, and published in 1870; see, in particular, chapter VIII.

13 The words of this sentence are taken verbatim from the report of one of the anonymous Referees, whom we thank.

(2020), while the fourth and the fifth have never—as far as we know—been considered. We provide a synthesis table at the end of this section.

Two recent cases studied under the "sailing-ship effect" heading, are those by Miyamoto (2019) and Sick *et al.* (2016). These cases are definitely uncontroversial. The latter concerns the diffusion of cleaner propulsion technologies in the automotive industry and the title contains explicitly the question if "the legend" about sailing ship effects is true or false—and it concludes that, in the case considered, it is true. Sick and colleagues were aware of Howells' sceptical view, thus their patent-based evidence concerning conventional vs. alternative propulsion technologies has been carefully investigated. Put another way, the authors look for the causal nexus of old technologies being improved as new ones emerge, and they find it.

Miyamoto also uses the phrase "sailing ship effect" in the title of his work, and he studies Sanyo's resistance to change in rechargeable batteries. In the 1990s, Sony developed new lithium-ion batteries which were clearly superior to old nickel-metal batteries on which Sanyo was the leading Japanese company. As the new technology appeared, Sanyo's first answer was to stick to the old technology, trying to improve it to fight the new one. As often occurs, the new technology is far superior to the old one so that, eventually, it prevails. However, once more, we have a case of the intentional improvement of the old technology as the new one appears (Miyamoto, 2019).

A third uncontroversial case concerns DSL—i.e. old modems-cum-copper wire—vs. fiber optics in specific areas. Fiber optics are much more powerful than modems-cum-copper wires in data transfer, and the former is becoming the dominant technology after a false start in the 1990s[14]. The Anglo-Canadian company Genesis Technical Systems, though, has intentionally improved the old technology to counteract the spreading of fiber optics in certain areas. The new version of the old technology is called "DSL rings," and is aimed particularly at rural and suburban locations and is explicitly designed to comply with the existing infrastructure. DSL rings deliver "fast, service-enhancing broadband over existing carrier networks, at a fraction of the cost of fiber" (GTS, 2019). The latter words provide a clear picture of the sailing-ship effect: the company is developing the old technology to fight the spreading of the new one.

Here we have to emphasize a point that will be addressed later as a general feature of the sailing ship effect: DSL can survive in these areas provided it can match consumers' data consumption, which needs higher data transfer capacity compared with previous DSL versions. Improvements in the old technology match consumers' needs reasonably well and are thus enough to render as uneconomical investments in fiber optics. Sometimes, it is the *relative* difference in performance which matters: even though the old technology's technical performance is not as good as that of the new one, it satisfies users' needs fairly well, thus not making investments by competing companies offering services based on a better technology worthwhile.

A fourth case in which the sailing ship effect has occurred, and that has never been considered under this heading before, concerns the (West) German chemical industry in the immediate post Second-World-War period. The case is studied by Raymond Stokes (1994) and concerns the transition from traditional coal-based chemistry to modern petrochemical technology—the latter being based on petroleum—in West Germany in the years 1945–1961. The author is *not* concerned with the "sailing-ship effect," nor does he use the phrase. Nevertheless, the analysis which he provides, considering the transition just indicated, fits very well with the sailing-ship effect reasoning.

As Stokes immediately clarifies, we are dealing here with an R&D-intensive sector. Since the 1870 s, the organic chemical industry's primary starting material, or feedstock, was coal—a raw material abundant in Germany. From the early 1920s, American chemical and oil companies developed petroleum-based technologies. In the same period, German researchers at the Kaiser Wilhelm Institute for Coal Research in Mülheim, developed the Fischer-Tropsch process, which produced high-value-added synthetic fuels and other basic chemical feedstocks using coal as the essential input. By the end of the Second World War, in 1945, petrochemical technology had gained a lot of ground and to many observers, it looked "obvious" that it would prevail. However, West Germany tried to stick to the "old" Fischer-Tropsch technology making many improvements to it in the late 1940s and 1950s. Improvements came on the one hand from R&D on the chemical side, and from mechanization of as many production phases as possible, on the other. Many improvements were made explicitly to fight petroleum-based technology, and those improvements had been so successful that in the mid-1950s American and British companies built three Fischer-Tropsch-process pilot plants to investigate if that could be the winning technology: in the early 1950s, a renewed wave of development

14 In the mid-1990s, the appearance of broadband modems actually delayed the diffusion of fiber optics (De Liso and Filatrella, 2008).

of the Fischer-Tropsch process was expected. In 1961, though, the fight was over—and it was won by petroleum-based technology (Stokes, 1994: 217–228).

The fifth case we focus on concerns a sailing-ship effect which is at its very beginning: the case is that of classical vs. quantum computers. Given that at the time of writing only two properly working quantum computers are acknowledged to exist in the world, this may sound awkward to some observers. However, as we shall clarify later, the *effect* has already started.

Quantum computing has been "in the air" for a while, and physicists, mathematicians, and computer scientists could already theoretically conceive universal quantum computers (Deutsch, 1985) as well as special algorithms for quantum computation (Shor, 1994). The problem, though, is to produce the hardware. The first signals in this direction arrived in 2007 when the Canadian company D-Wave announced that it had constructed the first working quantum computer while in February 2014 *Time* magazine devoted the cover to the "infinity machine," announcing that D-Wave had produced a prototype "commercial"—it would cost 10 m dollars—quantum computer.

The news itself was enough to stimulate some answers from the "classical" side. For a few years, in fact, a group of researchers at IBM[15] "T.J. Watson Research Center" had actually been carrying out research on how to speed up, through improved software and hardware, classical computers in such a way that they could somehow compete with quantum computers.

In a paper first published in 2017 and revised in 2018, IBM's Pednault *et al.* (2018) present a new approach for the calculation of complex amplitudes that extends the boundaries of what can be computed on a classical system. Building on that work, and further extending the field, in another paper, Pednault *et al.* (2019a) tackle an "entanglement pattern" which is a task specifically designed to challenge classical simulations algorithms; they conclude that what was previously thought to take years, could now take a couple of days.

In an article published in late October 2019 in *Nature* (Arute *et al.*, 2019) Google also claims to have produced a quantum computer leading to the so-called *quantum supremacy*, i.e. quantum computers which in a few minutes can solve problems that would take years, or even centuries, using classical computers. In a devoted IBM Research blog, the "quantum supremacy" explicitly recalled by Arute *et al.* (2019) in *Nature* is disputed. IBM's scientists-bloggers challenge the statement according to which a state-of-the-art classical supercomputer would require approximately 10,000 years to solve a class of problems which would take a matter of minutes for quantum computers. They "argue that an ideal simulation of the same task can be performed on a classical system in 2.5 days and with far greater fidelity," and that this is a conservative, worst-case estimate, i.e. with further refinements the computation time of the classical computer could be further reduced (Pednault *et al.*, 2019b).

The main point, though, is always the same: the threat of a competing technology stimulates improvements in the old.

5. The structured technological principle

If, from what precedes, we can conclude that the "sailing-ship effect" does exist, how can we transform it into a tool of analysis such as, for instance, the concept of "presumptive anomaly" as elaborated by Constant (1980)?

5.1 Triggering off the effect and the battle

The first question which we raised was "when does the effect begin?" This has already been answered at the end of Section 3, the answer being: when the new technology is perceived as a threat, i.e. the incumbent technology becomes *contestable*. One cannot necessarily fix a precise date, and the gestation period is technology-specific.

In the case of traditional vs. quantum computing, reaction of the "traditionalists" takes place essentially in real time, in particular when we look at the timing of IBMers reaction (Pednault *et al.*, 2019b) to Google (Arute *et al.*, 2019). Put another way, in the case of quantum computing, the availability of the first working quantum machine has been enough to trigger the sailing-ship effect.

In the eponymous case, the early cumbersome, unreliable, and sometimes even dangerous steamboats of the late 18th century were hardly a threat, and thus were not enough to trigger the effect itself. A symbolic event, though, was the first transatlantic crossing by the steam-equipped *Savannah*[16] in 1819. A serious threat started to be

15 Despite having abandoned the PC business in the mid-2000s, IBM is still a protagonist in supercomputing.

16 This was a hybrid sail-steam ship, but the fact that it was equipped with steam attracted a lot of attention.

perceived in the 1820 s, when steamers were *routinely* crossing the English Channel and the Irish Sea. Some of these steamers were special-purpose, i.e. they were "only" passenger ships or vessels transporting mail packets. However, what matters is the fact that the steam technology was applied to navigation, and it became clearer and clearer that it could be adapted to any kind of vessel.

In the case of (German) coal vs. (American) petroleum in the chemical industry, we have two rounds of competition, the strategic issue being for Germany to continue to make use of abundant coal as an answer to the American petroleum-based chemistry. The first round took place in the 1920s and saw the birth of the Fischer-Tropsch process in Germany; during this round, the old technology fought successfully. The second round took place in the period 1945–1961, and this time the old technology was defeated.

The second question is: Why should the old technology try to fight the new technology through its own improvements rather than trying to adopt (and adapt) it? This is *the* question, and the answer begins with the acknowledgment of the fact that technology is characterized by at least three dimensions: technology as knowledge, technology as skills, and technology as artifacts (Layton, 1974; Metcalfe, 1995).

Given that our reasoning concerns an incumbent dominant technology (sail ships, coal-based chemistry, traditional computers) our starting situation is one in which there exists a well-established technological paradigm together with a dominant design (Abernathy and Utterback, 1978; Dosi, 1982; Clark, 1985; Sahal, 1985). This dominant design is the sedimentation of all previous experience along the three dimensions of knowledge, skill, and artifacts which provides a standardized course of action, not only in order to reproduce the technology, but also in order to provide potential indications of the direction to be undertaken if we are to improve that technology.

While becoming dominant, the paradigm and the design provide a common-sense behavioral system to the firm, which, in turn, means that reactions to problems and opportunities is "automatic": previous experience provides a set of ready-to-use tools which can guide new action. Such a system makes possible a reproduction-cum-innovation of the incumbent technology, bearing in mind that the innovative possibility frontier is both technology-specific and firm-specific (Metcalfe, 1995: 33).

In all the cases we are considering, incumbent firms had to face a new technology which can be labeled as disruptive (Christensen and Bower, 1996) and competence destroying (Tushman and Anderson, 1986). In the language of Henderson and Clark (1990), we have radical innovations which concern both the components of the artifact *and* the architecture according to which those components are assembled. A further dimension concerns customers' reaction to novelties (Bower and Christensen, 1995).

Given these premises, it is rational to expect that some of the firms making use of the incumbent technology, when threatened by a new one, will stick to the incumbent itself devoting *extra efforts* to its development. There are many forces pushing in the direction of the incumbent technology.

First of all, by sticking to the old technology one can continue to build on safe ground exploiting those forms of *localized* technical change—due to learning-by-doing, learning-by-using, learning-by-interacting, and learning-by-purchasing—stressed by Antonelli (2003). Conversely, if an incumbent firm, in order to try to embrace the new technology, abandons the incumbent technology on which it has a well-established grip, it will lose a large part of its previous capabilities and learning, to which we have to add all the other sunk costs. Furthermore, one must also add the switching costs: producing steamboats, petrochemicals, or quantum computers requires new design, new work processes, new machinery, new skills, and so on.

As Furr and Snow (2012) point out, when threatened by substitution, incumbents may engage in old-technology-related investments that may not have been economically feasible when competing for marginal cost advantage, i.e. innovation efforts previously not justified by a marginal innovation return become acceptable in the face of the devaluation of all existing assets.

The positive action of carrying out intentional activities to fight the new technology may be reinforced by two inertial forces. The first is simple resistance to change which is sometimes observed in all levels of the workforce, including top managers[17]. Worthy of quotation are a few words taken from Alphabet's—Google's parent

17 "Simple" resistance to change can be observed in many cases across sectors and time. Worthy of quotation is the following passage: "[It] is not unjust to say that the bane of British shipbuilding and ship-management in the 18th century had been an obstinate opposition to innovation, combined with a contempt for scientific learning, and a blind faith in 'practical experience'" (Graham, 1958: 35); for a study on common sense and science see Green (2019).

company—*Form 10-K*[18]: “Many companies get comfortable doing what they have always done, making only incremental changes” (Alphabet Inc., 2019).

The second fundamental force has to do with company culture and identity. This is a subtle force, as it plays a two-sided active role, one positive, in providing the environment in which improvements occur, and one negative, in that it can evolve in such a way as to hinder, or even inhibit, change:

> “One key reason for the persistence of the coal-based chemical industry in the face of the apparently overwhelming superiority of petroleum-based processes was that coal chemistry was part of a distinguished industrial tradition in Germany. Producing petrochemicals would require that German chemists and industrialists begin to think in ways completely different than they had before. [. . .] Design traditions had also to change, because the new technology required that German designers—who were trained primarily as chemists—abandon their traditional regard for ‘elegance’, that is, for processes in which the theory was well understood and the highest possible yields were obtained. [. . .] It took time to alter habits that had led to such success from the 1860s through the 1940s . . .” (Stokes, 1994: 5–6)

As Tripsas puts it, routines, procedures, capabilities, knowledge base, and beliefs come to form an organization’s identity; the identity thus developed serves as a lens that filters the firm’s technical choice, and may become an impediment to change (Tripsas, 2009: 454). The ideas just recalled are further reinforced by Foster:

> “A company’s product and production technology is an integral part of its corporate culture. Technology directs and conditions management’s intuitive strategic responses to opportunities . . . When the technology changes, the whole corporate culture frequently must change as well. And this is a difficult and painful process. . . . Expert vacuum-tube designers don’t necessarily become good solid-state [transistor] designers.” (Foster, 1985: 134)

We thus see at work the typical forces referred to by evolutionary economics which have to do with path-dependence, guided variation, self-reinforcing mechanisms, and cumulative features (Dosi, 1982, 1988; Arthur, 1989; Metcalfe, 1998; Nelson and Winter, 2002; Tripsas, 2009) which tend to prolong the life of a technology through developments along a given trajectory. Here we consider those extra stimuli which come from the emergence of an alternative technology which may supplant the old. Put another way, the sailing-ship effect accelerates and further differentiates innovativeness within the incumbent technology, as pressure from technological competition may lead in directions which would never have been undertaken, had that very competition not emerged.

When incumbents are confronted by competitors managing a new technology, incumbents themselves are necessarily influenced by a system of prior beliefs, and future action depends crucially on expectations concerning the potential of their own technology, expectations of the potential of the competing technology and of the evolution of the market for the good or service that they offer. Expectations though, are necessarily characterized by genuine uncertainty. Incumbent firms will have different expectations even among themselves concerning the maximum performance achievable by their old technology, while expectations of the new technology will be even more volatile.

Cognitive factors play a key role here, as neither the nature of a new technology, nor its trajectory is obvious ex ante; the relevant actors develop technological frames, where “frame” means the lens through which actors themselves make context-specific interpretations, decide, and act (Kaplan and Tripsas, 2008). Who can ex ante answer questions such as: Can a quantum computer *reliably* solve all the problems solved by classical computers *and* other problems unsolvable for the latter? Will we all have a quantum computer on our desks 20 years from now, so had we better invest in this technology today?

When we look at the eponymous case, we see that the use of steam-engines to provide motion to ships required a lot of experimenting. From the 1800 s to the 1840 s, a lot of money and effort was devoted to the paddle-wheel technique, i.e. the two giant wheels on the sides of ships. This arrangement implied special variations of ships’ design to accommodate the engine, the wheels, and the connecting mechanisms. In the 1830 s, serious experimenting was carried out on a completely different technique, i.e. the underwater screw propeller, which would provide motion in a completely different way, and would create different technical problems to be solved, from friction and vibration. The screw propeller necessitated different engine speeds and new gears; these changes implied partial re-design of

18 This is the Annual Report that American companies have to produce for fiscal reasons.

engines, gears, and of the hull. The change from the paddle-wheel to the screw propeller was an epoch-making change[19].

As so often occurs, in the early stages, the new technology is unreliable and inferior in terms of performance, and this is true in many cases. For instance, “Early transistors were not only noisier than valves, but they could handle less power, were more restricted in their frequency performance and were more liable to damage by power surges, radiation, and high temperature.” (Braun and Macdonald, 1978: 56). Thus, as a rule, the new technology does not arrive fully developed and its working principles are not fully understood, and its potential is somehow acknowledged only by some “visionaries”; it should thus not come as a surprise that many rational, risk-averse agents prefer to stick to the old technology, because they are and *feel* “comfortable” with it.

The sailing-ship effect gives the old technology a new lease of life, but in virtually all the cases considered above, the old technology eventually loses the battle and disappears or finds niche applications. However, one must always be careful not to fall into the hindsight trap (Kamin and Rachlinski, 1995): what ex post looks obvious, “the new technology wins”, is not so ex ante, i.e. it is rational to stick to the technology one has a good command of. As Furr and Snow (2012: 34) put it, “It is only *after* a successful technology transition has occurred that we can tell the rigidity narrative” (original emphasis).

The length of time for which the old technology survives depends on the evolving technological performance of both technologies on the one hand, and on market conditions on the other. In the sail vs. steam battle, it can be maintained that “advances in sail productivity kept pace with those of steam on the long-hauls, and the average cost curve of steam did not fall below those of sail until the mid-1880s” (Walton, 1970: 439). The old technology could survive a few more years because the *relative* difference in terms of performance between the two technologies was not so great. As we pointed out in Section 3, talking about DSL vs. fiber optics, sometimes the old technology, despite not being as good as the new, if it is improved so that it satisfies demand well enough, can still be *profitably* employed.

5.2 Some more forces which contribute to the final result of the battle

The final outcome of the battle is affected by other forces, which may be present in different forms and have different degrees of importance.

First of all, particularly when a technology has been dominant for a long time, there may exist an institutional set-up which favors the incumbent technology. Incidentally, let us point out that this is a process which takes place whenever a new technology emerges and threatens an incumbent one, i.e. it is not limited to cases in which the sailing-ship effect is taking place. An example, taken from Hargadon and Douglas (2001), clarifies what we mean.

When Thomas A. Edison attacked the gas lighting system with his electric alternative, he had to fight not only against a well-established technology, but with an industry inextricably woven into the cities’ physical and institutional environment made up of regulatory agencies, a web of suppliers to the gas industry and consumers who had to be convinced to switch to a new technology, however simple to use. In New York, where Edison began this battle, the gas companies “had integrated themselves deeply within the city’s social, economic, political, and physical infrastructure, from their many gas mains buried under the streets to their extensive corps of city-employed lamplighters, to their powerful influence over the aldermen and Mayor of New York” (Hargadon and Douglas, 2001: 484).

A second force which favors the incumbent technology is the presence of complementary assets and tributary innovations which reinforce the core technology. Complementary assets, as identified by Teece (1986), can be general purpose, specialized and cospecialized, and portray factors such as marketing, after-sales support, and specialized manufacturing. While general purpose assets do not need to be tailored to a specific technology/innovation, specialized and cospecialized assets—examples of which are repair facilities and containerization which meant bilateral dependence between ships and ports—do. As Tripsas (1997) demonstrates for the typesetter industry, the incumbent technology may benefit from the existence of a consolidated network of complementary assets which buffer incumbents from the effects of competence-destroying innovations.

By tributary innovations, we mean both intentional and unintentional innovations which affect or benefit a given technology. An example for either—intentional and unintentional—case clarifies the point. The “Cunningham

19 In 1840, Isambard Kingdom Brunel wrote a technical report on the advantages arising from the use of screw propellers, among which we recall the saving of weight of the paddle-wheels, a better and simpler form of vessel, regularity of motion, and increased power of steering (Brunel, 1870: 552–553).

reefing system" was an intentional tributary innovation concerning exclusively sail ships, as such a system allowed the reefing of sails from the deck, thus reducing the time needed to perform the operation, eliminating risks to the sailors who previously had to do it from the mast, and allowing a reduction in the crew. Sail ships also benefited from systematic research on ocean currents, winds, and weather—all activities which were not necessarily carried out to favor sail ships[20].

A specification of a tributary intentional innovation is that which Ansari and Garud (2009) define *collateral developments*. While studying the competition between second (2 G) and third (3 G) generation mobile communication, they found that some incumbents actively sought the *collateral development* "packet switching technique" which enabled the old 2 G technology to be extended in such a way that it could be redefined 2.5 G. Let us emphasize that this example further clarifies the idea according to which the *relative difference* between two technologies may be the key point in keeping alive the old technology: 2.5 G was inferior to 3 G, but the improvements from 2 G to 2.5 G were enough to satisfy those consumers who wanted some extra services which could not be provided through 2 G but who did not need full 3 G services.

These forces help explain what Henderson addresses as the "unexpectedly long old age" of optical photolithography aligners used in the manufacture of solid-state semiconductor devices. In fact, despite the fact that two better and reliable technologies were developed in the early 1970s, the old equipment was constantly improved and was still dominant in the 1990s (Henderson, 1995). Also of interest is the work by Adner and Kapoor (2016) where they study 10 episodes of technological competition between different generations of semiconductor lithography equipment in the period 1972–2009. As the Authors clarify, each lithography generation had some opportunities to extend the resolution performance. In three cases, out of 10, the new generation took a longer-than-expected time to overtake the old.

A further force which must be considered lies in the possibility of the old technology taking advantage of some features of the new. In the case of sail vs. steam, shipbuilders applying the latter technology had to confront new problems in terms of the shape of the hull, materials' resistance to stress and vibration, and more. In particular, the use of iron, and later steel, was basically essential for vessels in which increasingly powerful marine steam-engines were installed. The solutions to the problems, which were typical of steamships, could generate a positive externality for traditional sail ships producers. Obviously, the reverse process was also at work, i.e. the new technology borrowing extensively from the technological results achieved by the evolving sail technology[21]. We must note that when the two technologies are based on completely different principles—as in the case DSL vs. fiber optics—the possibility of the old technology borrowing from the new, or vice versa, is not always available.

We can thus now summarize our argument in Figure 1, in which we highlight the main dimensions which characterize the incumbent technology and its persistence through the sailing-ship effect.

5.3 The epilogue

As we can see, there are many technological, institutional, and economic reasons for trying to fight the emergence of a competing technology. Thus, despite the fact that we know *ex post*—and this "ex post" must be strongly stressed—that, in all of the cases considered, eventually the new technology wins the battle, the fighting of the old has full technological and economic dignity.

Sail ships could compete with steamships until the 1880 s, then they lost ground. However, the relative difference in terms of performance between the two was not so great, so that further technological improvements together with a buoyant market for goods transportation allowed sail ships to remain competitive. Let us stress with Pollard and Robertson (1979: 132) that by 1860 science had entered steamship yards so that, in particular, marine engines became more reliable, more powerful, and more fuel-efficient, and thus more difficult to fight against. Steamships could grow in size in ways that were impossible for sail ships. The most technologically advanced sailing ship of all time—

20 Worthy of comment is the fact that steamships greatly benefited from the opening of the Suez Canal in 1869; the Canal was obviously not dug to favor steamships, but these were the biggest beneficiaries, given the difficulties experienced by sail ships in sailing through the Canal itself.

21 A phenomenon which sometimes takes place is the creation of intergenerational hybrids characterized by what Furr and Snow (2015) call *spillbacks* and *spillforwards* of knowledge.

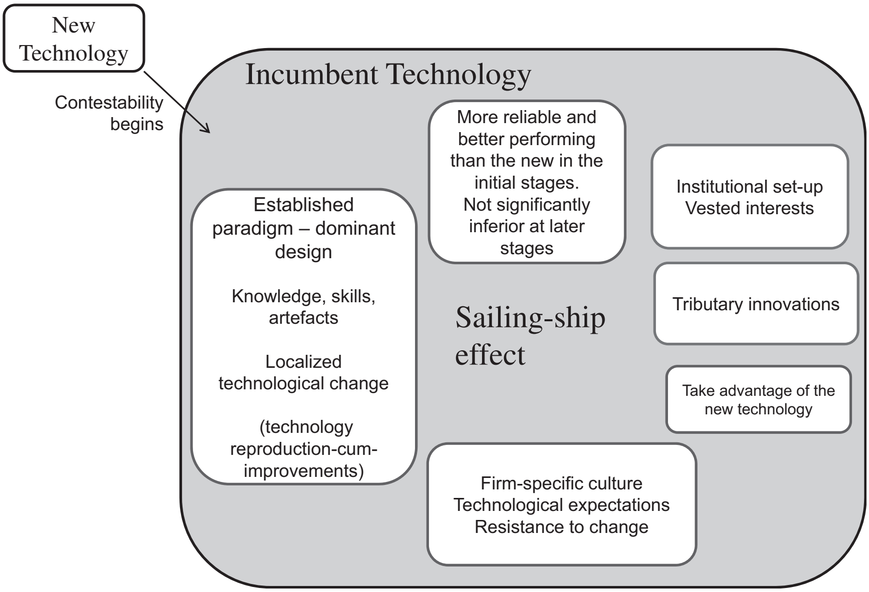

Figure 1. The incumbent technology and the main dimensions of the sailing-ship effect.

the huge German-built *Preussen*[22]—was a product of the 20th century (Davis *et al.*, 1997: 262), and was launched in 1902, but it represented the very last gasp.

6. Discussion and conclusions

The main aim of this work was to transform the "sailing-ship effect" from its embryonal stage into a structured technological principle. We believe that we have accomplished this objective. We consider our work to be a building block of a concept which can help to understand some cases of technological competition. We view this stage of the concept as a beginning rather than as a conclusion.

As usual, the starting point of one's own analysis is the works and intuitions of other scholars who pointed to the idea in various ways. We have mentioned many authors who, through different tools, provided a basis on which we could build our work.

The foundations of the sailing-ship effect as a structured principle, though, lie in the evolutionary principles, and in particular, in path-dependence, guided variation, self-reinforcing mechanisms, and cumulativeness. Put another way, we find a further confirmation of the fruitfulness of evolutionary theorizing. Stimuli coming from critics to the concept were also important in pointing to weaknesses or lack of sound analysis.

Let us now answer the questions we raised in the introduction. The battle between an incumbent and an emergent technology begins when the incumbent perceives the new as a serious threat, that is the incumbent becomes *contestable*. Despite the fact that the latter statement seems rather generic, the triggering stage of the sailing-ship effect can be identified through historical and quantitative analysis. How far the new technology represents a threat to be faced depends on the judgment of individual entrepreneurs, many of whom will prefer to try to make improvements to the technology of which they have a good command.

As we pointed out, the gestation period is technology-specific, and it lasted about two decades in the eponymous case, while the response takes place almost instantly in traditional vs. quantum computers.

The length and meaningfulness of the battle depend on technological and economic aspects, profitability being the judge who decides how long fighting remains worthwhile. Sail ships as well as Fischer-Tropsch coal-based chemical processes, etc., were profitably doing the job until the alternative technology became so superior as to confine

22 For a concise description see also Landström, 1961: 201.

the old to substantial irrelevance. However, for longer or shorter periods of time, the battle indeed remains rational, and the profitability of the old technologies depends crucially on those sailing-ship-effect improvements which are actively sought in order to stay competitive.

This having been said, let us now comment on the usefulness and applicability of the "sailing-ship effect" theoretical concept.

Any theoretical concept provides a lens through which selected phenomena can be understood, interpreted and, sometimes, predicted. Special attention is usually devoted to the third dimension—typical of the "hard" sciences—but the first two dimensions are also fundamental and may be the ones which open the way to the third. A theoretical construct is useful if it is a reality-generating tool, i.e. it indicates in which direction to explore and what to look for.

The risk of a tool distorting, rather than improving, our understanding, is always present, and all fields are affected by the problem: limiting ourselves to one example in economics, we could think of the inability of neoclassical theory to take on board even in recent years the switches of techniques, i.e. the fact—demonstrated a long time ago (Pasinetti, 1966)—that it is *not* possible to order production techniques as a monotonic function of the rate of profit. General agreement on theoretical constructs, often used as a tool to reinforce one's position, may also be dangerous: the fact that for centuries the majority of astronomers found "evidence" that the Sun revolved around the Earth does not render that statement true.

Bearing in mind the statements above, we believe that the sailing-ship effect construct is both useful and applicable. A good argument for the effectiveness of such a concept is the case of coal vs. oil in the chemical industry. In fact, while the original study is not concerned with, nor mentions the idea of, the sailing ship effect, the latter concept provides a lens through which that study can be reassessed. More generally, we believe that more case studies concerned with technological battles can be read in this light. Put another way, do we have a common principle which unites and subsumes some technological battles? What unites sail vs. steam, coal vs. oil, DSL vs. fiber optics, and so on? The answer is: the sailing-ship effect.

Obviously, the fact that the principle is at work in some cases does not mean that it takes place every time a new technology, competing with an incumbent one, emerges. Simply, it seems to us that it can be shown to be at work in some cases.

The principle is characterized by different intensity and duration, where "intensity" concerns the improvements introduced as a response to the emerging and improving new technology. Both intensity and duration are technology-specific. Thus, for instance, in sail vs. steam the effect took place over a long period of time and was intense; in coal vs. oil the battle was very intense in the 15-year time span 1945–1961.

Delving into technologies one finds a whole range of reactions, from strong to timid, to completely lacking. An example of timid reaction is that of old television sets, based on rear-projection technology, vs. flat-panel displays. The back size of large-screen traditional televisions was substantially reduced in the early 2000s as an answer to emerging flat-panel displays; however, the old technology could not match, not even in relative terms, the new 5-cm depth TV-sets. Despite the "sailing-ship" improvements attained by Texas Instruments and Scram Technologies in the early 2000s in order to reduce the size of TV sets based on the old technology, the battle ended in less than a decade (Taub, 2008). We can thus identify a range of decisions, from fighting to doing nothing, taking into account that, as Schuetz (1953) clarifies, *purposive* abstention from acting must be considered as an action in itself.

Regarding further research, at least three lines are open. The first line consists of looking for unexplored technological battles in which the sailing-ship effect has played a role. Good candidates are steam vs. diesel motor for ship propulsion, with steam this time being improved as an answer to the appearance of diesel motors (hints can be found in Henning and Trace, 1975) and gas vs. electric lightning in the period 1880–1900 (hints can be found in Silverberg, 1967; Sacks, 2001; Hughes, 2003).

A second line consists of the exploration of the possibility to reassess cases which have not been studied under the sailing-ship effect light. An example clarifies what we mean. Among his case studies aimed at studying quantitatively the forces which accelerate or deter the process of technological substitution, Montroll (1978) considers the case sail vs. steam in America in the 19th century. He finds evidence of a "perturbation" in the take-over by steam, but in his analysis he does not consider the sailing-ship effect. The question is thus: could that "perturbation" actually be the sailing-ship effect?

The third line consists of investigating cases in which the demand side plays an essential role. For instance, vinyl records are kept alive by consumers who stick to the old technology even though their sound quality and resistance to damage is inferior to CDs and their price is higher than the digital competitor (Beckman *et al.*, 2016). However, despite the fact that many consumers would buy vinyl discs anyway (Schiavone, 2013), companies have actively

Table 1. Five cases in which the "sailing-ship effect" has taken place

Sector/industry	Technological competition over	"Effect" emerging from	Author(s)
Automotive	Cleaner propulsion	Statistical analysis	Sick *et al.* (2016)
Rechargeable batteries	Battery life	Case study and statistical analysis	Miyamoto (2019)
DSL	Data carrying capacity	Explicit statements in company report	GTS (2019)
Chemicals	Continued use of cheap abundant feedstock	Case study	Stokes (1994)
Computing	Speed of computation	Explicit statements in company reports/papers	Pednault *et al.* (2018, 2019a,b)

sought improvements: in 2016 the Austrian company *Rebeat Innovation* started producing "High Definition" vinyl records through laser-inscribed grooves, which means that the grooves themselves are now better cut thus providing better audio quality and longer playing time compared with previous vinyl records (Rebeat, 2018). How should we interpret these cases, which, mutatis mutandis, would include other products such as mechanical watches (Raffaelli, 2019)?

The final comments must be devoted to technology and innovation policy—limiting ourselves to providing some hints. Given that in virtually all of the cases considered above, the new technology eventually relegated the old technology to irrelevance, one would be tempted to conclude that the best policy, for companies and governments alike, is always to try embrace the new technology because the old technology's fate, as a rule, is sealed. Adopting such a view would be a mistake because it is entirely based on hindsight. It forgets that technological substitution is a process which takes place in a dynamical context in which more dimensions must be considered, and we provide only three hints. First of all, as a rule, in the initial stages the new technology is actually inferior to the old, both in terms of performance and reliability: this, by itself, makes any policy decision difficult to take in the early stages of technologies' coexistence. Secondly, it is impossible for all agents to quickly abandon their well-established knowledge, skills, and artifacts, to embrace a technology they are not familiar with. Thirdly—as a direct consequence of the previous point—one prefers to live longer rather than dying instantly and, by the way, in some cases it is not just surviving, but prospering: once more let us remember that the ascendancy of sail ships took place when steamships were also experiencing radical improvements, and the former thrived. Strange though the following comment may seem, the fact that the thriving of sail ships' transportation was also based on a series of other historical events—starting from buoyant international trade—does *not* matter.

During a large part of the 19th century, sail shipbuilders improved their beloved artifacts in such a way that their relative difference in performance from steamships was kept within a range that gave sail ships a long lease of happy, profit-generating life. In doing this, they kept technological diversity alive for decades—a typical evolutionary argument—while, unintentionally but meritoriously, avoiding carbon emissions.

Acknowledgments

We wish to thank the two anonymous Referees: their comments and suggestions have indicated clear ways to improve this paper. We are responsible for any remaining errors.

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