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Shipbuilding Innovation: Enabling Technologies and Economic Imperatives

Paul W. Stott

Newcastle University, Marine Science and Technology, Newcastle Upon Tyne, United Kingdom

Commercial shipbuilding in the 21st century is dominated by large suppliers, constructing series' of ships in highly efficient shipyards. The industry would be unrecognizable to shipbuilders from a century ago and this raises the question as to when the modern form developed. Much development has been incremental but there have also been seminal triggers, both technical and economic, that have led to major shifts in the nature of the industry. This paper traces these shifts from the building of SS Great Britain to the current day. The modern industry saw its beginnings in the United States in World War II (WWII), follows a build strategy that was developed in Japan (under U.S. guidance) and a pattern of shipyard design that originated in Europe in the early 1960s. The most significant influences have included developments in iron and steel manufacturing processes, the expansion of the British Empire in the second half of the 19th century, the Liberty Ship program in WWII, Japan's "great reverse" post-WWII, and the "Bretton Woods" conference that initiated the process of globalization in the second half of the 20th century. The greatest steps forward have arisen out of economic imperatives and been assisted by influence from other industry sectors. The most important influences were those from government contractors in the introduction of welding into shipbuilding in WWII and in the influence of the aircraft manufacturing industry in Japanese shipbuilding post-WWII. The greatest barriers to innovation have arisen from conservatism.

Keywords: economics (shipbuilding); history; shipbuilding

1. Introduction

In an article in the *New York Times* of October 28, 1921, Henry Ford coined his famous phrase: "History is bunk." He was paraphrasing an earlier article in the Crawfordsville Review of June 6, 1916, where he had said: "History is **more or less** bunk" and the three additional words make all the difference in understanding this famous quotation. What Henry Ford did not mean was that we cannot learn the lessons of history. What he did mean was that we cannot reliably predict the future by extrapolating the past and this leads to a very optimistic view of the power of innovation in industry. What innovations might be around the corner that will change everything? Henry Ford is also often quoted in support of this view as saying, relating to the period before his innovations that made the motor car an affordable mode of transport for the masses in the United States: "*If I had asked people what they wanted, they would have said faster horses.*" In reality, Henry Ford is nowhere recorded as actually having said this, but it is a popular misquotation because it illustrates the principle perfectly (Vlaskovits 2011).

Innovation in shipbuilding technology has in the main been incremental over the past 50 years, responding to changes in ship design, technological capability, and the market. In aggregate, these incremental changes have led to an industry that would be substantially different but not unrecognizable to an observer from 50 years ago. There have in the past, however, been a number of revolutionary developments that have radically changed the nature of the industry and redefined what shipbuilders can achieve. The aim of this paper is to provide context for

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innovations in shipbuilding by taking the long view and identifying these radical innovations and key developments over the past 200 years. In identifying these shifts, it is hoped that perspective can be given to the future of the industry: is the status quo the ultimate state of the shipbuilding art or might there be future radical shifts that could take the industry to the next level? If so, where should we look for such innovations?

In the following review, the salient characteristics of the modern shipbuilding industry have been assessed, at the highest level, to relate to the build material (steel), the joining process (welding), the shipbuilding strategy (block building), and the facilities (building docks and large assembly cranes), and each is examined in turn below. In addition, reference is also made to radical shifts in the industry's economic context, in particular the development of globalized competition and the pursuit of economies of scale that have characterized the industry in the most recent thirty years: it is impossible to separate the industry and its technologies from the surrounding market, economics, and politics.

It will be seen that the United Kingdom and United States were preeminent in the developments up to the end of World War II (WWII), but with innovation then moving East, in particular to Japan in the 1950s and 1960s, where the shape of the modern industry was finally defined.

2. The evolution of steel as the building material: the significance of Henry Cort, the Siemens–Martin process, and the expansion of the British Empire

It could be posited that the modern commercial shipbuilding industry commenced with the first "modern ship," which is generally accepted to have been Brunel's SS Great Britain, built between 1839 and 1845 (launched 1843): "*which can claim to be the fore-runner of all ships of significance afloat today*" (Corlett 1971). Great Britain was made of iron, a shipbuilding material that had been made possible by improvements in the manufacturing process patented in 1783 and 1784 by Henry Cort, which led to the availability of iron of sufficient quality and quantity to produce an economic supply of rolled plates (Fairbairn 1861).

Without the availability of iron plates at an economically affordable price, the material did not come in a form that could be riveted together to form the shell of a ship's hull. In his book "The Iron Ship," Corlett notes that before Cort's improvements: ". . . *British wrought iron had been inferior in quality, mainly because of the relatively poor ores which were available; in any case iron was produced in very small quantities, virtually by hand. The only plates available were hammered from small ingots by trip hammers, a process invented in 1725. Naturally, these plates were very small, of poor quality and uneven thickness. As a result practicable engineering plates and sections were simply not available*" (Corlett 1975, p. 21).

It was almost 40 years, however, before the improved iron was used in significant shipbuilding. Iron boatbuilding commenced in 1812 with the construction of canal boats in the United Kingdom (Walker 1989), but the first iron sea-going ship, the Aaron Manby, was not constructed until 1822 (Fairbairn 1865). The industry in the United States was a little later in adopting iron because the cost was so much higher than in United Kingdom while timber was cheap and in plentiful supply: "*The first iron steamboats were probably the river paddlers John Randolph, 122 tons, Chatham, 198 tons and Lamar, 196 tons, which were put together at Savannah between 1828 and 1834 of materials imported from England*" (Fassett 1948, p. 43).

The Industrial Revolution, and Henry Cort's developments in particular, came to the rescue in providing the solution to a problem that had the potential to limit Britain's economic growth and curtail the mighty Empire that was under development in the second half of the 19th century. Hardy and Tyrell note: "*Before 1850 the Americans were supreme in shipbuilding, but in the second half of the nineteenth century Britain adopted the new techniques of the Industrial Revolution and overtook all other countries until she produced over 80% of the world's ships*" (Hardy & Tyrell 1964). By the 1850s, Britain was running short of wood from which to build ships to protect and serve the commerce of the expanding Empire, and certainly could not compete with U.S. builders on direct terms for wooden vessels (Slaven 2013). The growth of the empire, therefore, provided a major impetus for the development of iron shipbuilding and the resulting British dominance of the industry, founded on a substantial home market for both commercial and war ships.

Iron and wood continued to be used for shipbuilding through much of the 19th century until steel, the material used in the modern industry, was introduced in the latter decades of the century. Wooden shipbuilding saw its peak in terms of tonnage built in 1855 (ibid., p.18) but the switch to iron (then steel) and to steam, rather than sail, was rapid. The first steel ship was a small river vessel built "*for Niger expedition*" by J. Laird of Birkenhead in 1858 (Newcastle University Marine Technology Special Collection 2014). A number of other smaller vessels followed but the first sea-going cargo vessel built of steel was the 452 ton Jason built in 1859 by Samuda Brothers of London (ibid.). The use of steel became more common in the 1880s, with Lloyd's Register's (LR) first set of rules for steel ships being published in 1888 (Blake 1960). Steel became more widely available after the invention of the Bessemer process in 1855 but early Bessemer steel was of variable quality. The trigger for the viability of steel as a shipbuilding material was the development of the Siemens–Martin process for steel manufacture:

> *Siemens–Martin open hearth steel of consistent quality became available from about 1878, with production rapidly expanding. The transition from iron to steel hulls took only ten years. Small quantities of cast steel had been available from the late 1850s but its high price of around £20 per ton compared with £9 for wrought iron limited its use to lightweight vessels like river steamers and blockade runners for the American Civil War, although it had been used to build masts and spars of lighter topweight. But bulk manufacture in Scotland and north-east England soon reduced the price of steel to about £6 per ton, even below that of iron. Its greater strength reduced steelweights by around 15% and its greater ductility improved survivability in the event of grounding or collision, while the larger size of plates possible (up to 8ft wide in place of 4ft) reduced riveted joint length and construction cost*. (Buxton 2010)

Thus the modern industry, in terms of its construction material, was established by the late 19th century but the industry of the

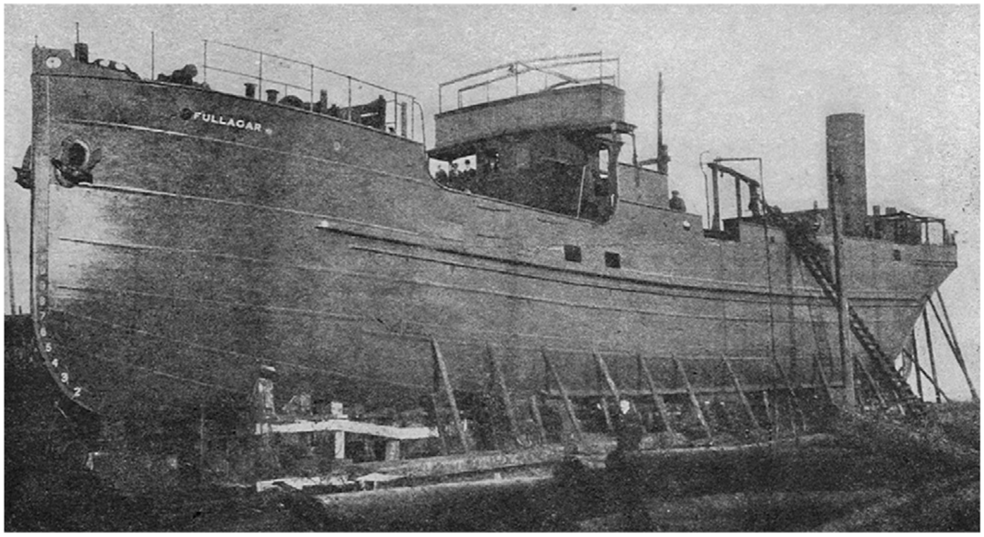

Fig. 1 MV Fullagar, the world's first all welded ship (Lords Commissioners of the Admiralty, 1943, p. 283)

21st century has little else in common with the industry of that time. The material remains more or less the same but the building technologies and methods, the producers, the products, and the scale of the modern industry would have been unrecognizable to shipbuilders from a century ago. Technically and economically, therefore, the modern industry started at some point in the 20th Century.

3. The evolution of welding as the joining process and the introduction of block building: the significance of WWII, United States Maritime Commission (USMC), the "Liberty Ship," and "Wendy the Welder"

Technically, the great change in the 20th century came with the advent of welding as a viable joining method for steel. Riveting was the prior method, which had many downsides. From the point of view of ship design, welding is superior due, inter alia, to the saving of weight in the structure, eliminating large numbers of heavy rivets, and because the smoother hull form derived without the overlapping seams required for riveted joints leads to less hull resistance. From the shipbuilders' perspective riveting was labor-intensive, heavy, and skilled work, which would be very difficult to automate and welding offers significant advantages in all these areas.

LR introduced experimental rules for welded shipbuilding in 1918 and the first experimental all welded ship, MV Fullagar (Fig. 1), was built at Cammell Laird in Birkenhead in 1920 (Blake 1960).

The use of welding to repair stern frames prior to this time had been only partially successful and LR indicated that "*until experience had been gained with welded vessels at sea, the classification would remain experimental. The principal deterrent, at that time, to the fuller use of electric welding was the distrust of the ductility of the welds*" (ibid., p. 172). This was despite MV Fullagar sailing successfully for 17 years before being sunk in a collision off Mexico. After this time, welding was used for certain parts of the ship only: *"Lloyd's Register of Shipping issued revised rules for the application of electric welding in 1932. In these rules, it was contemplated that the improved electrodes could be used for welding parts of the vessel of primary importance"* (ibid.).

The improved electrodes referred to in this quotation were the flux-coated welding rods that would be recognizable today, prior to which welding had been achieved with bare wire and was less reliable. As well as technical reservations on the part of the classification society, part of the problem limiting early adoption was that welding was significantly expensive. Labor unions sought additional pay for the skills needed and manufacturers of welding equipment tried to develop welding as a specialist subcontract, rather than promoting its use by shipyard workers.

Swan Hunter & Wigham Richardson of Newcastle built an all welded Great Lakes tank barge, the Peter G Campbell, for Dominion Tankers Ltd. Of Toronto, in 1933[1] (The Shipbuilder 1933), preceding the first all welded ship in the United States, also a great lakes tanker, Poughkeepsie Socony,[2] built by United Dry Docks Inc., (Staten Island Plant) at Pt. Richmond, NY, in 1934 (Lloyd's Register of Shipping 1934). It was not until WWII, however, that welding became more common as a process for joining the structure of the ship. In 1940, a British shipbuilding delegation visited the United States to order "*about 60 vessels of the tramp type of about 10,000 tons deadweight*" (Thompson & Hunter 1942). The delegation was ambivalent about welding but concluded: "*To suit USA practice, to ensure a good supply of labor, to facilitate production and to get the best value for money, it was decided that ships must be mainly welded*." The extensive Liberty Ship construction program saw welding become the norm for U.S. shipbuilding. The Liberty Ship was a standard 7210 ton general cargo ship that was built as quickly and cheaply as possible to replace allied tonnage that was being lost at an alarming rate to enemy action: "*the . . . demands of*

[1]"*The electrodes used were of the mild-steel and uranium type, manufactured by the Quasi-Arc Co., Ltd., of London*."

[2]I am grateful to SNAME's reviewer for pointing out that this vessel was in the fleet of the Socony Vacuum Oil Company, the predecessor of Mobil Oil.

WWII, when a capacity output of approximately four times that of normal peace time operations was mandatory" (Fassett 1948, p. 202). In total 2468 Liberty Ships were built in U.S. shipyards between 1941 and 1945 and welding in place of riveting was one way of achieving the speed of construction needed. "*Since riveting had previously been the limiting factor in construction time, it was possible to decrease substantially the time necessary for all hull work*" (ibid., p. 59). Tassava argues persuasively that it was the experience of two major contractors in particular, Kaiser and Bechtel, working with the U.S. Maritime Commission, which introduced the revolution into the shipbuilding process: "*Both Kaiser and Bechtel had long experience working closely with government officials, for the two firms had—individually, jointly and in consortia with other construction companies—won numerous enormous contracts to build dams, roads, bridges, and other heavy infrastructure throughout the American West . . . Starting from their heavy-construction experience, Kaiser and Bechtel extended* [Maritime Commission] *ideas about building cargo vessels out of prefabricated units and about replacing riveting with arc welding*" (Tassava 2005).

Shipbuilding, therefore, benefitted from the accelerating effect of technologies introduced from other industries under the guidance of the Maritime Commission. Tassava further argues that it was not only technological developments that led to the step change in shipbuilding production in WWII, but also "*an amalgam of administrative, technical and social innovations that allowed merchant shipbuilders to produce ships at a breathtaking pace*" (ibid.). The lower level of skills required enabled thousands of new industrial workers to enter the industry, including female workers. The introduction of women into the workforce in WWII was in part made possible by the less manually demanding joining process. The British Admiralty, which was highly skeptical of welding, noted in relation to the developments in the United States: "*One of the principal reasons for welding the vessels . . . was, of course, the shortage of skilled labor . . . It was recognised that much less time would be necessary to produce efficient welders than to train reliable riveters and caulkers. The present war time policy of the British Admiralty is to increase production by developing merchant ship construction along similar lines . . . That policy has to a very large extent been dictated by the same considerations which operated in America—namely, the insufficiency of proficient labor, and the necessity for the rapid training of dilutees, including women*" (Lords Commissioners of the Admiralty 1943, p. 173).

Thompson and Hunter noted in 1942, following their visit to the United States, that: "*It is much easier to train good welders than good riveters. Females can and do weld, but they cannot rivet. The average man would prefer to weld rather than rivet*" (Thompson & Hunter 1942). It is significant, and not a little ironic, that the WWII U.S. cultural icons of "Rosie the Riveter" and "Wendy the Welder" represent a root cause that significantly accelerated the progress of the industry, which was theretofore almost entirely male dominated, overcoming the innate conservatism of shipyards, classification societies, and ship owners, not least the British Admiralty. The apparent strategic "weakness" of using "dilutees" (to use the Admiralty's rather pejorative terminology) led to the industry considering, out of necessity, how the process could be done better. This led to spectacular results rather than the fall in productivity that would undoubtedly have been anticipated by many prior to the event.

This is not to say that welded shipbuilding introduced during the war was without its difficulties, in particular due to the alarming "epidemic" of catastrophic cracking in Liberty ships and T2 tankers, which came to the fore with the breaking in two of SS Schenectady while under construction at the Swan Island shipyard in Portland, OR, in 1943, and which led to significant questioning of the viability of welding for shipping (Tassava 2003). The problems were solved, however, and welding was here to stay.

A further significant advantage of welding over riveting is that it permits prefabrication of sections of the vessel, something that could only be achieved for small parts using rivets. "Traditional" shipbuilding involved the joining of individual pieces to form the structure of the ship at the final assembly site (i.e., on the slipway). A shift of build strategy to the prefabrication of blocks of steel in covered workshops, prior to assembly on slipway or in dock, is an essential key to productivity in the modern industry. The origins of prefabrication were also seen in the United States in WWII: "*Mass production: In adopting these methods, wartime shipbuilders were following American industrial experience. Whenever it desired to turn out more identical units in a given time at reduced cost, the American mind inevitably devises mass production processes—whether it be for pins, automobiles or ships*" (Fassett 1948, p. 226). Koenig and Narita further note that "*Production processes were not modelled after the world's most commercially competitive shipyards (British), but instead were inspired by a different industry in which U.S. companies were the innovators and leaders—automobile mass production*" (Koenig & Narita 2003).[3]

The shipbuilding process was revolutionized, therefore, in WWII and the design of facilities developed to follow suit: "*The United States Emergency Shipyards have been specifically planned for mass production of standard welded merchant ships. As these yards are laid on vacant sites it has been practicable to provide extensive areas and depth of space above the head of the berths—essential for rapid production by prefabrication. Typical of these yards is the Todd California Shipbuilding Corporation in Richmond, near San Francisco. This yard laid down in 1941 . . . the assembly and welding of large preconstructed units, including double bottom structure, panels of the bottom shell . . .*" (Lords Commissioners of the Admiralty 1943, pp. 142–146).

Such preassembled units were actually very small by modern standards with assembly cranes of only 25–30 tons, compared to 1000 tons plus for a modern final assembly crane in large shipyard. It is also interesting to note the emphasis placed on land area ("*extensive areas and depth of space*") supporting the slipway in this quotation, which facilitated the new build strategy. Shortage of land for use in the storage and manipulation of blocks in the physically constrained shipyards of the United Kingdom was to become a problem in trying to adapt prewar investment to this new technology in the postwar period.

Prefabrication of standard products enabled substantial productivity of shipbuilding berths in the United States: "*the target of at least one ship per berth per month*" (Thompson & Hunter 1942). It would be wrong, however, to suppose that the United States was

[3]Some caution is needed in the use of the term mass production in relation to shipbuilding and Tassava notes: *"my analysis of Kaiser-Richmond and Marinship emphasizes that merchant shipbuilding sometimes looked like mass production and sometimes looked like flexible production"* (Tassava 2005).

alone in developing welding and prefabrication at this time. Tassava notes, in relation to naval shipbuilding in Germany in the 1930s, that "*German pocket battleships carried a thousand more tons of armament because their all-welded hulls weighed that much less than the equivalent riveted hulls*" (Tassava 2003). Block fabrication technology was also being developed in Germany, for submarine construction where dispersion of production, building "U-boats" in ring sections at disparate locations to avoid allied bombing, required that block construction be developed. It is possible that block building technology may have been more advanced in Germany than in the United States. The significance of U.S. developments in this context, however, was that it was U.S. technology that went on to be developed following WWII and which was therefore seminal in the development of the modern industry, even if more advanced technology had been developed elsewhere during the war years. In shipbuilding terms, therefore, it could be argued that the "Liberty ship" was the first modern ship, just as Great Britain had been in terms of ship design a century earlier.

4. The development of block building post-WWII: the significance of Japan's decimation and the "great reverse"

Modern joining methods and block production technology, therefore, were established in WWII. The methodology of block or unit construction in commercial shipbuilding was then developed further in Japan in the 1950s. Shipbuilding, was one of the key industries involved in what came to be known as Japan's "economic miracle," that being the recovery of the economy that was decimated during WWII. Hardy and Tyrell note that the postwar recovery of the Japanese shipbuilding industry was "*aided largely by American capital, engineers, and production planning*" (Hardy & Tyrrell 1964, p. 105). Under the influence of the United States (after 1948 under the "great reverse" following General McArthur's initial reform policies that were aimed at curtailing militarism [US Department of State Office of the Historian 2014]), shipbuilding was selected as a priority industry, along with steel, coal mining, electricity generation, railways, chemical, and others, for the rebuilding of the economy (Otsubo 2007). Shipbuilding was an obvious choice for inclusion because lack of natural resources meant that Japan would need to build a large fleet to serve the planned economic recovery. By building these ships at home the country's economy was able to take advantage of the substantial economic multiplier effect that shipbuilding provides by virtue of the network of supplier industries it generates. The same multiplier was later used to great effect in South Korea, in the 1970s (Kang et al. 2015) and more recently in China.

The effectiveness of Japan's post-WWII industrial policy was spectacular and by the mid-1960s Japan had established itself as a major exporter. The progress of Japan in what is sometimes referred to shipbuilding's "*market hegemony*" (Bruno & Tenold 2011), that being the predominance or ascendency of one group to the exclusion of others, is shown in Fig. 2.[4]

[4]I am grateful to Tom Lamb for pointing out that care is needed in reviewing this graph in that it addresses the putative "hegemonies" only. In the period of the decline of the United Kingdom industry and the establishment of the Japanese industry, e.g., both Sweden and Spain became, temporarily, market leaders.

The industry developed in Japan after 1948 would be recognizable today as the modern commercial shipbuilding industry, establishing the build methods that would be used to develop industries in both South Korea and China, as well as most other modern shipbuilders. In this way, the development of the shipbuilding industry in Japan post-WWII could be regarded as the birth of the modern commercial shipbuilding industry, building on the success of the "Liberty Ship."

Japanese shipbuilding absorbed the production methods developed in the United States in WWII, assisted notably by U.S. entrepreneur Daniel Ludwig and his company National Bulk Carriers (NBC). NBC leased the Imperial Navy Dockyard at Kure in August 1952 and "*NBC's Kure shipyard quickly became acknowledged as the leader in the diffusion of the new technology and the originator of a fresh system for Japanese shipbuilders*" (Koenig & Narita 2003). At the same time the U.S. wartime emergency shipyards were dismantled. Over the following two decades Japanese shipbuilders developed the strategy and technology further and eventually the situation reversed and the United States sought to learn from Japan. In a citation accompanying the award of the "Solberg Award" by the American Society of Naval Engineers to Louis D. Chirillo in 1985 it is stated: "*Under the auspices of the National Shipbuilding Research Program, he studied Japanese shipbuilding methods and through management of research projects with Japanese shipbuilders he gained a complete understanding of the logic and principles of their methods*" (American Society of Naval Engineers 1985).

In addition to the U.S. influence, contributing also to the strategic development of the industry in Japan, was the appointment of the head of the Japanese aircraft industry, which was industrially significantly more advanced than shipbuilding, to lead the development of the shipbuilding industry: "*Interestingly, the development of the modular construction system for shipbuilding which the Japanese developed came as a result of the now popular benchmarking concept of studying parallel industries. In this case, following World War II, the head of Japanese aircraft construction was appointed head of shipbuilding. In those days, the traditional method of building ships was to lay the keel and then build the ship from the bottom up. Aircraft construction was different; in this case, a modular construction method was used...This method required greater accuracy in the manufacture of units but overall it reduced construction times by a factor of ten. The same improvement resulted when the method was applied to ship construction*" (Hutchins 2008). As with the influence of external agents (Kaiser & Bechtel) in the United States in WWII, therefore, shipbuilding benefitted again from external influence to move the industry to a new level.

5. The development of modern shipbuilding strategy and facilities: the significance of building docks, "goliath" cranes and the development of Hyundai Heavy Industries (HHI)

The introduction of welding and the development of block construction led to a new form of shipyard designed to efficiently apply the new methods. Many tried to adapt old investment to these new methods but ultimately this would not be economically successful (Kang et al. 2015). Similarly, attempts to "shoehorn" old labor paradigms of high skill levels and demarcation by trade

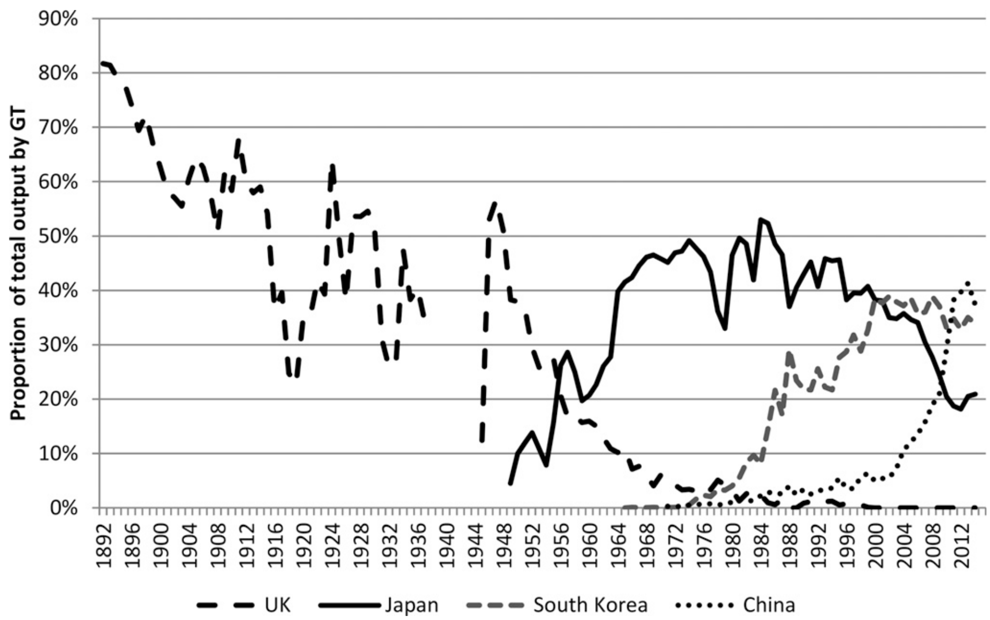

Fig. 2 Proportion of GT delivered by market leaders 1892–2014 (compiled by the author from various sources)[4]

into the new order would also be doomed to failure, these two aspects playing a significant role in the demise of commercial shipbuilding in United Kingdom and elsewhere.

Layout drawings of U.S. shipyards in WWII show that volume was achieved by utilizing multiple slipways. The more slipways the more ships built, with the "Liberty Ship" potentially (theoretically) achieving the maximum possible of about 12 ships per slipway per year but more commonly a slipway would produce less than 2 ships per year (Fassett 1948). Figure 3 shows a typical layout of a high volume U.S. shipyard of WWII vintage, showing the array of slipways (or "shipways" as referred to in this drawing) needed for high capacity.

Slipways are still commonly used in shipbuilding and a range of alternative build strategies has been developed, notably the "semitandem" method, whereby the stern end of a following ship is built alongside the preceding ship and skidded into place when the slipway becomes available, and "level land" building whereby launch is effected using a floating dock (which was pioneered at Ingalls Shipyard in Pascagoula Mississippi and used in Korean shipyards to temporarily expand launching capacity during the shipbuilding boom of 2003–2008). The most common strategy for a modern high volume shipyard, however, involves the use of a flexible large building dock served by very large "goliath" cranes, that is to say self-supporting gantry cranes. Hyundai Heavy's largest drydock, the no. 3 dock at Ulsan, e.g., has dimensions 672 m × 92 m and is served by three goliath cranes: one at 1290 tons swl and two at 450 tons. Cranes of this size, which are one of the keys to higher productivity of a shipyard, would be impractical on an inclined slipway and the extent of possible development of slipway capacity is therefore limited by, among other factors, the cranes.

The importance of large final assembly cranes to shipyard capacity and efficiency relates to the limitation of the amount of work undertaken at the final assembly site, which is relatively the most expensive stage of the process (prelaunch) due to problems of access and work orientation. The British Shipbuilders extensive productivity improvement program of the 1980s, conceived in conjunction with Louis D. Chirillo and IHI of Japan, estimated that the cost of a piece of work doubles once the block has left the workshops and that the same piece of work takes 8 times as many man-hours if undertaken at the final assembly site compared to at the early stage of the steel fabrication process and 12 times if undertaken postlaunch. Light cranes limit the size of block than can be erected from the workshops, thereby consigning more work to be undertaken at the final assembly stage. Light cranes also limit the extent of preoutfitting that is possible, outfit materials adding weight to the steel blocks. Large cranes mean that large blocks can be fabricated in workshops for erection into the dock, maximizing the potential for integration of steel and outfit work on the block, minimizing the amount of work left to the final, most difficult and expensive stages of the process. Fabrication workshops were designed specifically to support this strategy, defining the shape of a modern shipyard (Bruce & Eyres 2012, pp. 119–123).

Commercial shipbuilding in drydocks probably commenced in Germany in the late 1950s (although much earlier examples of dock-building of warships may be found). In 1960, Kieler Howaldtswerke was using ship construction facilities that included five slipways and four drydocks, two of which were sometimes used for repair (Verband Fur Schiffbau und Meerestechnik 2016). This is certainly an early commercial use of drydock building, although it has not been possible to confirm that this is the earliest adopter of this technology: Japanese shipyards were similarly building occasionally in repair docks (The Shipbuilders' Association of Japan 1961). Repair (or "graving") docks are limited in terms of their performance for newbuilding, in particular because they tend to have light and agile cranes, essential for productivity in ship repair but which severely limit block size for new construction, and because of limited working space around the ship and at the dock side. They are also limited

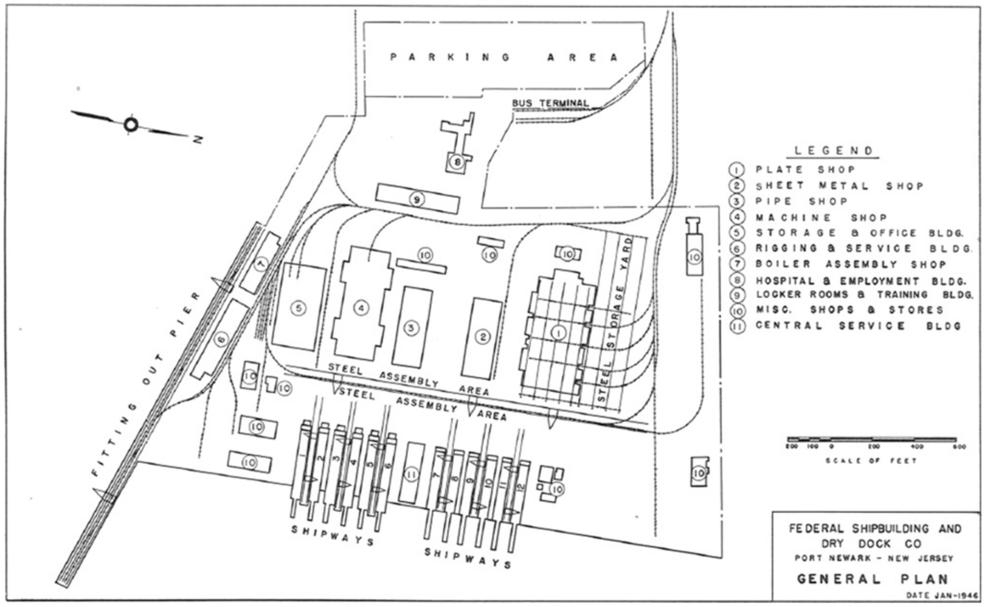

Fig. 3 Arrangement of a WWII U.S. shipyard showing slipway arrangements needed for capacity (Fassett 1948, p. 243)

to one ship at a time, rather than providing the flexibility for multiple parallel constructions of many ships within the area provided by a building dock.

Much larger dedicated newbuilding docks for commercial shipbuilding were first seen in the early 1960s in Europe. The United Kingdom "Patton Report" into productivity in shipbuilding in 1962 noted four shipyards using drydocks for building in continental Europe. This included the purpose-built dock in Burmeister and Wain of Copenhagen, and the large building dock at Gotaverken Arendal in Sweden. These two shipyards were highly influential in pioneering large block construction and dock-based build strategies ahead of Japanese shipyards. These dock-based strategies, along with the goliath cranes supporting the dock, became a model for the modern generation of building docks (Patton 1962). This pattern of large shipyard was made ubiquitous, however, by British consulting company "A&P Appledore," which designed and built Hyundai Heavy Industries in Ulsan in 1971 (Bruno & Tenold 2011). The form and technology of that shipyard was exported to many shipyards globally, including the latest generation built in China.

6. Economic acceleration post-WWII: the significance of Bretton Woods

The other great change in commercial shipbuilding in the 20th century was triggered by economic shifts, specifically the move away from empires toward globalization, which was promoted by the Bretton Woods conference of 1944. Stopford argues that this was a key driving force for the modern shipping industry: "*At the Bretton Woods conference in 1944 the US Secretary of the Treasury, Henry Morgenthau, outlined the objective of creating 'a dynamic world economy in which the peoples of every nation will be able to realise their potentialities in peace and enjoy increasingly the fruits of material progress of an earth infinitely blessed with natural riches.' By the end of the meeting the World Bank and the International Monetary Fund had been founded and the groundwork had also been laid for the General Agreement on Tariffs and Trades (GATT). This policy had a profound effect on the maritime industry. By the end of the 1960s almost all of the European colonies had been given independence and they were encouraged to open their borders and transform their economies from self-sufficiency to export production*" (Stopford 2009, p. 37).

The "*profound effect*" on shipping had a knock-on profound effect on shipbuilding. The Bretton Woods conference in 1944 and the consequent globalization that followed, therefore, was the trigger for the development of modern shipbuilding as much as it was the trigger for the development of modern shipping. The following changes in particular should be noted:

1) Increased shipping demand to serve rapidly expanding globalized trade required more ships and the volume of production increased. In 1950, the world's shipbuilding industry produced 3.2 million gross registered tons. In 1976, the

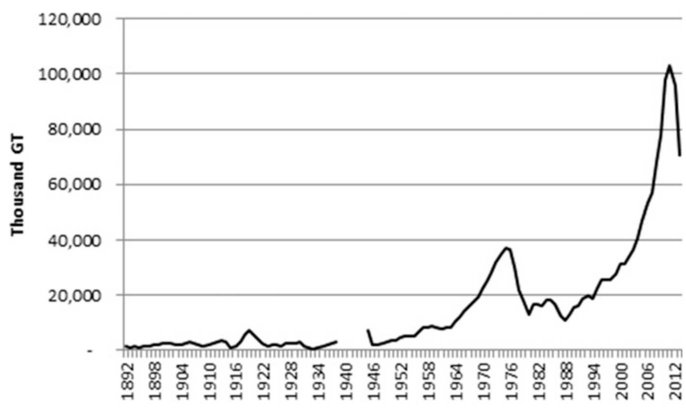

Fig. 4 Commercial shipbuilding output 1892–2013 (compiled by the author from various sources)

industry reached a peak of 34 million tons and in 2010 reached a peak of 103 million tons, 32 times the size of the industry post-WWII. Figure 4 shows the development of output of commercial shipping between 1892 and 2013, excluding output during WWII where statistics were not available. The explosion of volume is clearly seen in this figure.

2) The size of vessels increased in pursuit of economy of scale in shipping. Records for general cargo ship production in 1950, show that the average size of ship built in that year was 2868 deadweight tons and the largest was 13,632 tons. In the same year, the largest tanker produced was 42,295 tons and the average was 13,984 tons. Shortly after this, the first commercial[5] Panamax vessel, the 70,000 dwt crude oil tanker W Alton Jones, was built by Newport News, VA, in 1954. This was a large vessel in its day but commercial ship size peaked with the development of Ultra Large Crude Carriers in the 1970s, the largest having a deadweight of 555,000 tons (Stott 2014). Shipyards clearly needed to be bigger to handle this step change in ship size.

The scale of the industry developed post-WWII, in terms of both the size of products and the scale of production, which in turn was stimulated by economic globalization and facilitated by developments in shipbuilding technology, would have been unrecognizable to the prewar manufacturers, with the industry developing beyond recognition between 1939 and 1962, when the first modern generation of shipyards opened.

7. Developments since 1960 and economy of scale: the significance of standard ship types, Deng Xiaoping's "two cats" and high-volume production

The form of the modern commercial shipyard was thus established in the early 1960s. Since that time, developments in automation, equipment, and supporting systems have been predominantly incremental rather than seminal, although the adoption of computer technologies has revolutionized the design, planning, and logistics parts of the process and could be argued to represent a seminal shift. Key technological developments have included

1) direct links between design and production (eliminating traditional lofting and significantly improving accuracy);
2) automated panel production (with consequent improvements in accuracy and reduced skill requirements);
3) integration of outfitting and steelwork (facilitated by improved planning and larger cranes);
4) sophisticated planning and logistic control systems (enabling integration of outfit and steelwork);
5) automated steel cutting and marking (with consequent improvements in accuracy and reduced skill requirements);
6) improved welding processes to increase productivity and reduced heat input and distortion;
7) quality assurance to reduce rework.

In addition to these technological advancements there have been two key shifts in the nature of the commercial shipbuilding business that have been fundamental to the development of competitiveness, these being the pursuit of volume and standardization of the product. Essentially, these two factors together relate to "economy of scale" and it is the scale of the industry that has developed most in the past 50 years, leading to high economic efficiency, at least for the periods where the market provides enough orders to utilize the high capacity developed. To demonstrate the progress of the pursuit of volume in commercial shipbuilding Fig. 5 presents the output from the world's largest shipyards at the start of each decade from 1960, with output measured by both gross tons and number of ships delivered.

The movement of the market lead from Europe in 1960, through Japan in the 1970s to South Korea following 1980 can be seen in this Figure. What can also be seen is that the largest shipyard in 2010 produced 28 times the gross tonnage of the largest yard in 1960 and almost five times as many ships. It can also be seen that the pace of investment in volume picked up significantly after 1990, facilitated by the continuous growth in demand that developed between then and the market crash following the economic crisis of 2008,[6] a significant part of which can be attributed to the China's economic growth that stemmed from reforms that created Deng Xiaoping's "socialist market economy" (inextricably associated with his famous "two cats" quotation: "*It doesn't matter if a cat is black or white, as long as it catches mice*") and the consequent opening of China to the global market.

The significance of shipyard size relates to high levels of competitiveness that result from volume and standard products, enabling shipbuilders to develop high efficiency internally and highly efficient supply chains externally. Such ultra-large shipyards are vulnerable to market downturns that periodically recur in commercial shipbuilding, such as the one prevailing at the time this paper is being written. Whether this investment is justified in the longer term, remains to be seen.

The benefits of product standardization have long been known, but were, and to some extent still are, rejected as being to some degree inapplicable in shipbuilding. Shipbuilders were very reluctant to let go of the notion that ships are predominantly unique products or, at best, built in relatively short series. This notion was particularly strongly held in United Kingdom shipyards, where product variety was seen by many as a virtue in marketing terms. Sturmey noted in his 1962 book on the decline of the British shipping industry, that one of the contributory factors was that British shipowners insisted on buying unique ships from British shipyards, ignoring the fact that standard ships could be purchased more cheaply from abroad: "*Standardization of tramps, bulk carriers and tankers has been largely neglected by British shipowners and shipbuilders, despite the knowledge that such standardization could cut costs*" (Sturmey 1962, p. 401). Four years later, however, the "Geddes Report" by the UK Shipbuilding Inquiry Committee published in 1966 describes in a section titled "*The kind of industry*," the conflict between craft and industry in shipbuilding in the United Kingdom and states that "*ships,*

[5]The first actual Panamax ships were the USS "Iowa" class battleships, of which four were completed in 1943 and 1944.

[6]Due to the order backlog, shipbuilding output peaked in 2012, four years after the general economic crash.

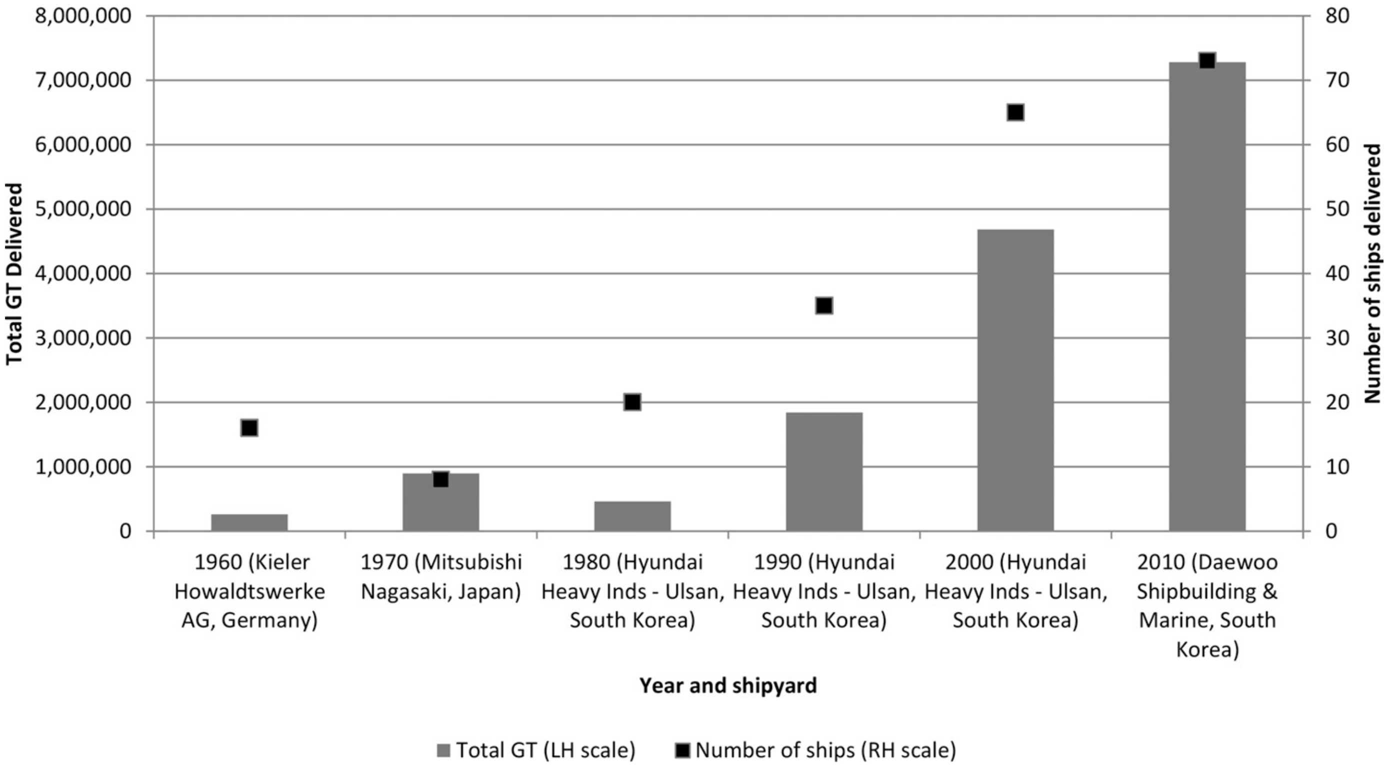

Fig. 5 Largest commercial shipbuilders by decade (output in the year indicated)

like buildings, are mostly 'one off' jobs" (Geddes 1966). The lesson was not being learned and the signs were missed. A popular textbook from 50 years ago, Hardy and Tyrell, echoed this increasingly outdated view, notwithstanding "liberty ships" and "T2" tankers that are noted as an exception: "*It must be remembered that seldom—except in the case of oil tankers—are more than six exact sister ships needed. Therefore the highly specialized assembly-line establishment may find difficulty in operating at maximum efficiency*" (Hardy & Tyrrell 1964, p. 4). Things started to change during the 1970s and in the "Booz Allen" report commissioned by the United Kingdom government into "British Shipbuilding 1972," an update to the previously mentioned "Geddes Report," it was stated that "*Standard designs, particularly for large ships in the oil and bulk trades, are becoming increasingly acceptable to shipowners*" (Booz-Allen & Hamilton International BV 1973). Realisation came too late for many and the introspective views of the industry, ignoring the progress being made elsewhere, contributed to the collapse demonstrated so clearly in Fig. 2.

It is true to say that up to the 1980s standard products were the exception, rather than the rule, and were sufficiently unusual as to be branded to identify the series. Examples include IHI's "Fortune" bulk carrier (61 built in total) and "Freedom" general cargo ship (178 built in total), and the highly successful "SD14" general cargo liner from Austin and Pickersgill, United Kingdom (208 built in total). Of 943 ships larger than 5000 GT built in 1975, however, only 10% (95 ships in total) were of a recognized standard design of this type, with the longest series over the year being 10 "Santa Fe" general cargo liners from AESA of Spain and 9 "SD14"s from Austin and Pickersgill. Such charismatic names are rarely used in the modern era but the use of standard designs has become more or less ubiquitous outside the niche sectors of the commercial industry, such as cruise ships or dredgers, or in warship building, where short series remain the norm.

By the time of the peak in output at the top of the most recent cycle, in 2012, the importance of standards had changed beyond recognition for a shipbuilder from an earlier era. Of the 2557 commercial vessels delivered in 2012, 28% (1848 ships in total) were of a branded and named standard design. Even where there is no named standard, however, standardization is now the norm in much of commercial shipbuilding, particularly for larger ships. For example, between 2007 and 2014 Daewoo Shipbuilding and Marine Engineering of South Korea delivered 59 VLCCs, all of which have length and beam of 333 m $\times$ 60 m and deadweight about 320,000 tons. Hyundai Heavy Ulsan delivered 46 VLCCs also with these dimensions and Hyundai Samho a further 37. Other Korean yards have delivered smaller numbers of VLCCs with almost identical dimensions. While these vessels are not specifically named as standards and there may be minor variations between ships, they constitute effectively quasi-standard ships that conform to size classes required by the shipping industry and conforming to the parcel sizes that shippers require for their trades (Stopford 2009, pp. 58–60).

Otuput data for Kieler Howaldtswerke AG of Germany, market leader in 1960, showed that no two vessels built by the yard in that year were the same. By the time of the peak of output in the mid-1970s, the market leader Mitsubishi Nagasaki was series building identical VLCCs as the only product. Market shifts between products over time, however, meant that focus on a single product was found to be unsustainable and shipbuilders had to find a mix of similar products to maintain output over the longer term and the development of strong size classes of ship (such as VLCC, Suezmax, and Panamax) has been a significant feature of the shipbuilding boom of 2000–2012, differentiating it from the previous boom that peaked in the mid-1970s.

Standardization of products has developed as a feature at the microlevel in shipbuilding, as well as in relation to the main products themselves. While the function of a ship built within a shipyard will vary according to its type, e.g., oil tanker compared to container ship, the interim products from which those two types are made, in particular the steel interim products, need not vary significantly. As Bruce and Garrard term it: "*One of the key features of design for production is the use of standards, for example for steel*" (Bruce and Garrard 1999). This concept is generally termed "group technology" in shipbuilding. This is described in SNAME's standard work on ship production as follows: "*The vast majority of shipbuilding involves the simultaneous production of multiple products of different types with some significant variation within product types. A key to this type of production is to recognise that even given product variety and variation, there is a high degree of similarity between most ships' intermediate products. Intermediate products are the subproducts that are produced and then concatenated through multiple production stages to create a final product*" (Lamb & Society of Naval Architects and Marine Engineers (U.S.) 2003).

The consequence of standardization and volume is the highly efficient, at least while the market can provide sufficient work to keep them busy, ultra-large yards of South Korea and China, which have increasingly come to dominate the market.

8. Conclusion

The seminal events in the development of commercial shipbuilding are summarized as follows:

1) Henry Cort's improvements to iron manufacture and plate rolling, 1783 and 1784, which led to iron plates of sufficient quality being available economically to facilitate iron shipbuilding.
2) Britain's expanding 19th century Empire and a national shortage of timber, which stimulated iron shipbuilding as an economic necessity for the country's economic development.
3) Commercialization of the Siemens–Martin steel manufacturing process from about 1878, which led to steel plates of sufficient quality being available economically to facilitate steel shipbuilding.
4) The introduction of welding as a necessity for speed of construction and to address the shift in gender balance of the workforce, overcoming the inherent conservatism of shipyards, classification, and buyers (including commercial ship owners and Admiralty) in WWII. Adoption of techniques from other industries was significant in this development.
5) The Bretton Woods conference of 1944, stimulating the decline of colonialism and the start of globalization, which in turn led to a rapid change in the nature of shipping and required new and larger ship types and a larger fleet, changing the shape of the investment needed to supply this tonnage.
6) Japan's "great reverse" and the resulting "economic miracle" following 1948, leading to modern shipbuilding methods, learned partially from U.S. wartime shipbuilding and partially from the aircraft industry, with adopted technology from another industry again being important.
7) The development of the modern form of large building dock supported by "goliath" cranes in Northern Europe in the early 1960s.
8) Dissemination of European shipyard design and Japanese shipbuilding technology, starting with the construction of HHI Ulsan in 1971.
9) The development of standard and quasi-standard ships from about 1970.
10) The explosion of output between about 1990 and 2012, stimulated by China's opening to global trade that resulted from Deng Xiaoping's reforms, leading to the creation of ultra-large shipyards in South Korea and China.

In summary, the modern commercial shipbuilding industry in terms of products, volume, producers, technology, materials, and investment, emerged post-WWII, was developed following technologies originated primarily in the United States and Japan in large building docks that originated in Northern Europe, and is the product of the process of globalization. The modern industry has little in common with the pre-WWII industry apart from the end product being a ship. The WWII experience triggered key developments in welding and block production, which radically changed the way that ships are built and had a consequential change on the investment required to compete in shipbuilding and the makeup of shipyard workers. Technical changes since that time have been important but constitute a refinement of the processes, rather than any radical shift, except, arguably, in the use of information technology. More recently, the most significant change has been the development of scale in the market leaders and the development of standardization of vessels, in place of the idiosyncratic designs of cargo vessels that characterized the tastes of ship owners in the colonial era.

Further to this, it is tempting to try to extrapolate the past to speculate on where the industry may go next. What new materials may be available, for example, or is it possible to develop a new joining process that eliminates the problems that welding presents to shipbuilders? We need to keep in mind Henry Ford's "faster horses," however, which councils against any attempt at such specific extrapolation. Rather than that, there are general lessons that can be learned from observing how the industry has progressed over the longer term.

The first observation is to recognize that the industry has perhaps been conservative in adopting new technologies. It took 40 years from Henry Cort's developments in iron manufacture to its first use in building a significant ship. It was 30 years after the construction of the first steel ship that class published the first rules for construction in that material. It took more than 20 years and the strategic imperatives of a global war for welding to proceed from experimental class rules to being generally accepted as a viable method for shipbuilding.

The second observation relates to the importance of technology transfer from other industry sectors in making more significant steps forward. The experience of U.S. contractors in WWII in adapting welding that had been successful in major infrastructure projects and the employment of aircraft techniques in Japan post-WWII are the best examples. Outside influence has acted to drive change and override the innate conservatism of the industry.

The third observation relates to the importance of the influence of economic and strategic necessity in pushing the industry forward. The shortage of wood in the United Kingdom in the 19th Century coupled to the imperative to build ships for the Empire is a good example, as is the experience of the United States in WWII, which led to the first modern ship from the perspective of the shipbuilder, the "Liberty Ship." The effects of globalization on the fleet are a third example.

Finally, it is worth noting the influence of the United States in the development of the industry over the past 100 years—a level of influence that may not be evident to modern observers from the perspective of the prevailing commercial output and global market share. The development and implementation of welding, the seeding of technology and capital for Japan's postwar miracle and the production of the first large commercial ship on the road to globalization (Newport News producing the first Panamax) being particularly noteworthy.

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