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EVOLUTION OF MARITIME TECHNOLOGY: ADVANCEMENTS IN SHIP DESIGN

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The evolution of ships has occurred through significant improvements in their design, materials, propulsion systems, size, navigation, and military capabilities. Ships were first built using simple, flat wooden hulls and were only suited for traveling short distances. Hull designs gained sophistication over time, taking on curved lines and later being built from steel and other composite materials that would improve their durability and efficiency. As for ship propulsion systems, these were initially powered by humans or the wind before evolving to steam engines, diesel engines, gas turbines, and nuclear power, vastly increasing their speed, range, and reliability. Ship size has also drastically improved, with modern supertankers and container ships now capable of transporting enormous loads across oceans. Developments in navigation technology, including the invention of radar, sonar, and GPS, have greatly improved marine safety and positional accuracy. Meanwhile, modern naval vessels now possess advanced defense systems, electronic warfare capabilities, and missile technologies. The drive toward sustainable practices have led to the adoption of green technologies such as hybrid engines and renewable energy and the adoption of more environmentally friendly ships. Ongoing innovations regarding maritime technology are reflected in these advancements and are helping shape the future of global shipping.

Keywords: Maritime evolution; Ship design; Propulsion systems; Constructal law; Energy efficiency.

1. INTRODUCTION

Driven by the need for increased speed, stability, and efficiency, ship hull designs have significantly evolved throughout history. In early times, hulls were simple and flat, a suitable design for navigating rivers and coasts, but they needed to be better suited for sailing the open seas. In the Middle Ages, curved hulls began being developed, which improved ship stability and lowered water resistance, thus letting ships navigate rougher seas more effectively [1]. With the Age of Exploration (15^{th}–17^{th} centuries), light sailing ships and galleons began to be designed with more sophisticated hulls to endure long transoceanic journeys. Modern times have seen fluid dynamics and materials science advancements, resulting in streamlined hulls being developed and optimized for reducing drag and improving fuel efficiency [2].

Shipbuilding materials have also undergone impressive evolution. Ships were initially wooden vessels, as trees were readily available and easy to shape, but wood has certain limitations regarding durability and resistance to marine environments. The Industrial Revolution introduced iron and steel to shipbuilding, significantly improving ships' strength and size. Being lighter and more durable than iron, steel allowed much larger and more robust vessels to be constructed [3]. In the 20^{th} century, aluminum and composite materials such as fiberglass and carbon fiber further revolutionized shipbuilding by reducing overall weight and improving performance, particularly for high-performance and military vessels [4].

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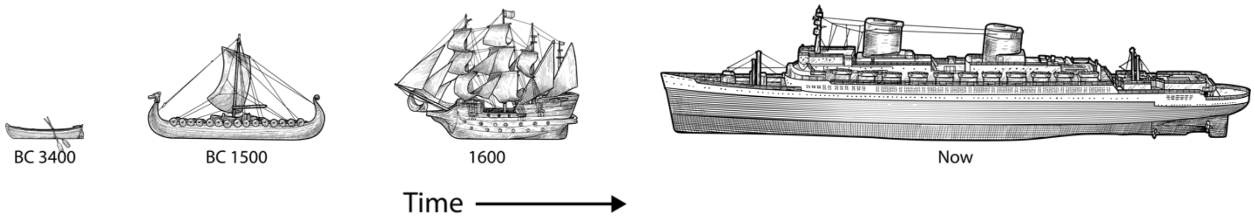


Fig. 1 – Evolution of ship design over time [5].

Sail and rigging systems have evolved to reflect the shift from wind-based to engine-powered vessels. Earlier ships relied on square sails hung from a single mast, which limited a ship's maneuverability and speed [6]. The Middle Ages saw more complex rigging systems being developed, such as multiple masts and sails. This allowed ships to harness wind from multiple directions [7]. Later, the steam engines of the 19th century marked a decline in sail-powered ships because steam power was more reliable and offered more powerful propulsion [8].

Many examples of evolution regarding ship design are found. For example, the bulbous bow is a specialized design feature found on many large vessels, particularly cargo ships and tankers. The purpose of this shape is to reduce wave resistance and improve hydrodynamic efficiency. This protruding structure is positioned just below the waterline to change the pattern of water flows around the hull. The shape creates a wave that offsets the bow wave generated by a ship's forward motion. This, in turn, reduces drag and increases fuel efficiency [9]. Studies have shown a bulbous bow can decrease fuel consumption significantly and increase speed, especially on ships operating at higher speeds over great distances [10]. Moreover, this specific design also improves ship stability by lowering its center of gravity, which helps inhibit pitching and rolling in turbulent seas. However, a bulbous bow is only effective when designed in line with the vessel's specific dimensions and operational conditions.

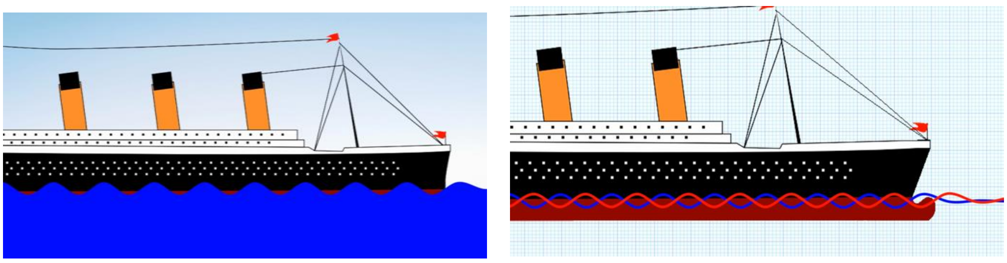


Fig. 2 – How a bulbous bow offsets wave resistance (credit: [11]).

2. **PROPULSION AND POWER SYSTEMS**

Ship propulsion first occurred through the power of human effort and wind. Rowing with oars was the common means of propulsion for smaller vessels, particularly in calm or inland waters. This method is labor-intensive, however, and has limited applications. Sails were first used to harness wind power. This became the primary means of propulsion for larger vessels and allowed ships to remain at sea longer. The drawback to this method, though, is that it greatly depends on wind conditions, and the predictability of winds could be better by nature.

The 19th century saw the introduction of steam power, which revolutionized maritime travel. Steam engines allowed ships to move independently of wind, greatly improving the reliability and speed of a journey. Early steamships mostly traveled on rivers and lakes, but not much time passed before technology advanced to allow them to cross oceans. Steam-powered vessels could maintain consistent speeds regardless of weather conditions, marking a significant shift in how maritime commerce and warfare were conducted [12].

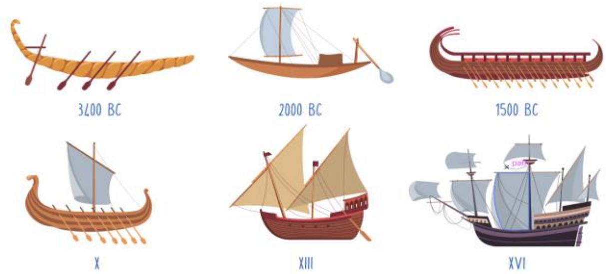


Fig. 3 – Ship designs up to the 16th century (credit: Shutterstock).

The 20th century witnessed further developments with the creation of diesel engines, which are more efficient, powerful, and reliable than steam engines. For this reason, diesel engines became the preference for most commercial and military vessels. Gas turbines were invented alongside diesel engines and are commonly used in military vessels that require higher speeds. Because of the greater power gas turbines offer, they consume more fuel than diesel engines. Thus, their usage is primarily limited to specialized applications [13].

The 1950s saw nuclear power emerge as a revolutionary propulsion technology for the navy, providing a unique edge for submarines and aircraft carriers. Nuclear power offers vessels virtually unlimited range and the ability to operate for extended periods without the need to refuel. This makes nuclear-powered vehicles strategically ideal for military applications. Nuclear propulsion has greatly improved modern naval fleets' operational capacities [14].

In more recent times, sustainability requirements have led to renewable energy sources being developed to power ships using wind, solar, and hybrid systems to combine traditional engines with electric motors. These novel developments aim to limit the impacts shipping has on the environment and to provide higher energy efficiency [15]. Hybrid systems have become ever more popular, particularly for short-distance shipping by sea and port operations, as these systems can operate on significantly less fuel and output fewer emissions.

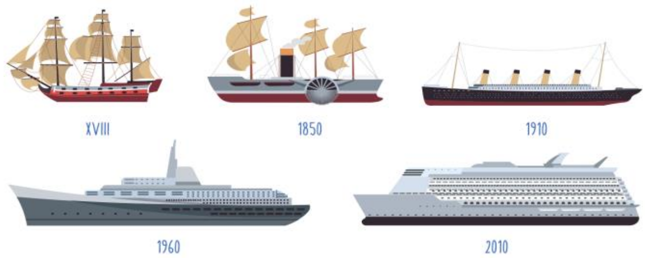


Fig. 4 – Ship designs from the 18th–21st centuries (credit: Shutterstock).

3. THE EVOLUTION OF SIZE AND CAPACITY

Ship size has increased greatly over the centuries. The first ships were relatively small, could only carry limited cargo, and were typically used for short-distance trade or navigating along coasts. Since the Age of

Exploration, incredible growth has been seen in ship size, with vessels now being able to carry tremendous volumes of cargo over the oceans. Since the Industrial Era, even larger steel-hulled vessels, such as modern supertankers and container ships, have been constructed. Some of these are over 400 meters long and able to transport tens of thousands of containers (one container can weigh 30 tons) or millions of barrels of oil (one barrel weighs 600 pounds) [16]. Currently, these giant ships of the sea have major roles in global trade.

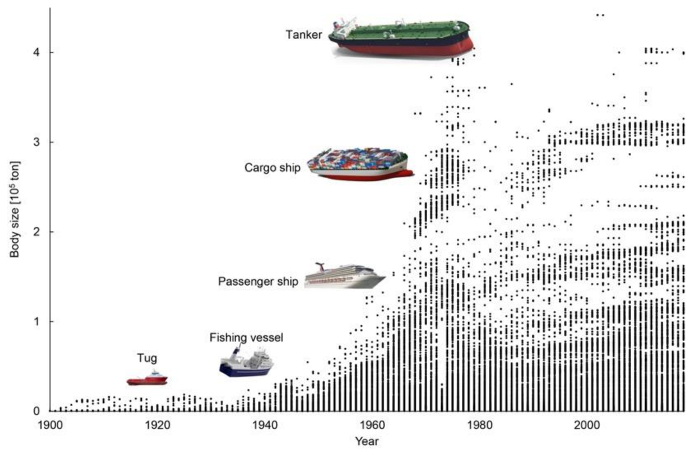


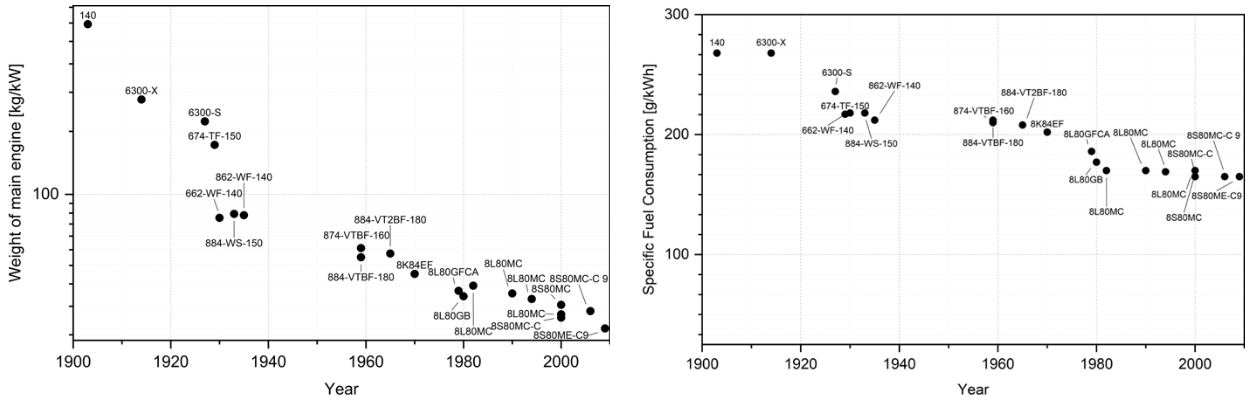
Fig. 5 – The emergence of ship models and sizes (1900–present) [18].

The evolution of passenger ships has seen small ferries and merchant ships that could only carry a few dozen people grow to modern cruise liners that can accommodate thousands of passengers. Steam-powered transatlantic liners became popular in the 19th century, offering reliable and relatively quick intercontinental voyages [17]. Luxury liners became more and more popular in the 20th century as ships were designed for comfort and entertainment rather than just transportation. Modern cruise ships are cities on the sea and have all the accompanying amenities of a city, such as theaters, swimming pools, and shopping centers. These vessels can accommodate up to 6,000 passengers.

4. **ENVIRONMENTAL AND ENERGY EFFICIENCY**

In the transition from sail- to steam- and then to diesel-powered ships, fuel efficiency has become more and more critical. Steam engines were first powered by coal, a heavy fuel that takes up considerable onboard storage, which in turn limits ships' operational range [19]. Diesel engines significantly improved fuel efficiency when they first appeared [20], and aerodynamic and hydrodynamic optimizations in modern times are employed to further reduce fuel consumption, providing ships with greater efficiency and lower environmental impacts.

In addition to fuel efficiency, the maritime industry has placed an extreme focus on reducing emissions. Ship engines produce harmful pollutants such as sulfur dioxide (SO_2) and carbon dioxide (CO_2) when burning fossil fuels, thus producing more air pollution and negatively affecting climate change. The International Maritime Organization (IMO) has tasked itself with addressing these issues and implementing strict regulations on emissions. This has helped technologies such as exhaust gas cleaning systems (scrubbers) to be adopted and low-sulfur fuels and liquefied natural gas (LNG) to be used. These regulations aim to reduce the large environmental impact of global shipping.



a) b)

Fig. 6 – The evolution of a) marine engines' specific fuel oil consumption and b) main engine weight [5].

Figure 6 shows the installed main engine weights in kg per kW. For producing the same unit power, the main engine weight has decreased significantly since the 1900s. The reasons behind this include technological developments in such areas as materials and production. When examining the time-based change in terms of specific fuel consumption per unit of main engine power, fuel consumption is seen to have also decreased significantly due to the development of technologies and systems that make movement easier. Figure 6b shows the specific fuel consumption for installed main engines. The specific fuel consumption required per kW of power has decreased over time. When considering how specific fuel consumption is inversely proportional to efficiency, a decrease in specific fuel consumption clearly results in greater engine efficiency.

5. **CONCLUSION**

Maritime technology has gone through major evolutions, a dynamic journey of continuous advancements regarding ship design, propulsion systems, and materials. All these developments have aimed to improve efficiency, safety, and environmental sustainability. Since the first days of simple wooden hulls operating under human power and the wind up to the modern era and its sophisticated vessels operating under nuclear power and renewable energy sources, the maritime industry continues to adapt to provide what global trade and exploration demand. The invention and implementation of advanced materials such as steel, aluminum, and composite materials have improved the durability of ships per unit weight while also allowing ship size to increase and ship performance and capabilities to undergo revolutionary changes.

In line with this, the evolution of propulsion systems has gone from less efficient hand-operated and wind-based mechanisms to much more efficient diesel engines, gas turbines, and nuclear reactors. This has significantly expanded ships' range and speed. Furthermore, the newer interest in sustainability has inspired green technologies such as hybrid engines to be adopted and alternative fuels to be used, further reducing the negative environmental impacts of shipping. As a response to the global environmental challenges the world is experiencing, these continuous innovations testify to the maritime industry and its commitment to increasing the energy efficiency of ships and reducing their emissions.

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