TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Research Article

Transportation Research Record
2020, Vol. 2674(9) 177–190

DOI: 10.1177/0361198120927395
journals.sagepub.com/home/trr
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Predicting the Future Capacity and Dimensions of Container Ships

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Abstract

Since the introduction of the container ship, there has been an impressive increase in its use to take advantage of economies of scale. In the last two decades, the capacity of vessels has trebled. Currently, vessels of 23,000 TEU (20-ft equivalent unit) sail the seas. With the exponential growth experienced in this sector, the question arises if it is possible to reach a peak capacity, as has occurred with bulk cargo vessels and, recently, aircraft. This paper aims to predict the possible size and dimensions of a new generation of mega container ships. Based on economies of scale, port infrastructure, demand, environmental trends, and naval design criteria, the limit to ship size has been estimated. The results suggest that additional increases in ship size are still possible. The aim of this study is to help port authorities to understand the needs of the shipping container industry and to calculate the expansion and investment necessary.

Fueled by the Industrial Revolution in the nineteenth century, globalization and international trade started to take off. After a period of stagnation and decline during the First World War, the Great Depression, and the Second World War, global trade boomed again around the 1950s with the introduction of container boxes. The container shipping market was born, significantly reducing transport costs. In the following decades, container ships became an important part of the global logistics chain. An increase in efficiency and ship size followed. UNCTAD (*1*) estimated that 752 million TEUs were moved at container ports worldwide in 2017. The global trade growth experienced in the last decades has had an impact on container ship size, resulting in six waves of substantial changes, each represented by a new generation of container ships.

The first generation of container ships were primarily modified bulk vessels with a capacity up to 1,000 TEU. Rapid evolution followed. The ships continued to increase in capacity and size until the Panama Canal limitations came into effect in 1985, with a maximum capacity of around 4,000 TEU. Accordingly, these ships came to be known as the Panama generation. In 1988 a beam of 32.3 m was first exceeded and the generation of post-Panama container ships began. This new generation created infrastructure problems for most ports worldwide, requiring ports to invest in wider gantry cranes and dredging to accommodate these ships.

At the beginning of the 2000s, demand and volume were still growing. From 2001 to 2006, growth in trade volume was, on average, three times higher than the growth of GDP. Therefore, the top shipping lines, which started to form strategic alliances, saw the need for a new generation of container ships. In 2006, the introduction of Emma Maersk, the first very large container ship (VLCS), marked a new generation. Bigger container ships reduced the cost per TEU even further, which in turn increased demand and therefore incentivized bigger ships. This positive feedback loop ended in 2008 with demand decreasing because of the financial crisis. However, the market power of alliances and the

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rise of emerging markets like China stimulated the growth of container ships even further, despite demand not yet catching up. Therefore, around 10 years later in 2013, ultra large container ships (ULCS) with capacities above 20,000 TEUs were introduced. The current biggest container ship, in relation to capacity, is 23,000 TEU, 400 m in length, with 61.5 m of beam and 16.5 m of draught. Even though the capacity has noticeably risen, the dimensions of the newest container ships have not changed significantly in recent years. In the last 15 years capacity has trebled and length increased by 20%, beam by 43%, but draught only 10%. It is a consensus that both maximum capacity and ship size will increase over the next years (*2–4*). But how long these increases will take remains unclear. In this paper, potential ship dimensions are studied from the point of view of naval design principles and regulations.

The most modern cranes currently available can reach 23/24 rows across the vessel. If this limit is exceeded, then one must either load cargo for another port in the extra rows or take time to turn the vessel around part way through the operation. This is both costly and time-consuming and thus not a practical option if required in every port. If the capacity of container ships increases, some ports will struggle to handle their cargo because of the limitations of container yards. Extending the container yard is often limited by the surrounding infrastructure. According to the International Transport Forum, bridges can become an obstacle if the height of container ships continues to grow. It is important to note that the increase in the capacity of container ships can congest ports that do not have sufficiently fast logistics chains.

In light of all this, this paper analyzes the future evolution of container ship size and dimensions. It asks if the exponential growth that the sector has experienced in the last decades is approaching a peak. The paper is structured as follows. The second section contains a literature review of existing research related to the evolution of container ship size and influencing factors. Taking into account state-of-the-art technologies, a methodology is proposed in the third section to estimate the container ship size of the future, identifying possible limits in growth as viewed through naval design principles. The fourth and fifth sections analyze the past evolution of container ship size, according to the Lloyd's database, and define a set of future optimal alternatives according to naval design restrictions and capital costs. The sixth section analyzes the economies of scale of running bigger ships, considering vessels from the past and a set of alternatives for the future. Finally, the impact of world economic and demand trends on ship dimensions is analyzed in the seventh section. General results, discussion, and conclusions are drawn at the end of the paper in the final two sections.

State of the Art

The exponential growth in recent decades of container ship size has motivated several authors to model the industry's evolution and the possible limits for upsizing vessels.

According to Malchow (*2*), container ships with a capacity of 30,000 TEU are expected to be launched in 2025, with approximately 20 m draught, which should be the ultimate limit because of the constraint of the depth of the Malacca Strait. But Malchow questions if we are following this path and compares it with the development in the tanker sector, where a counter-movement occurred after a certain tanker ship size was reached. Malchow concluded that container lines will not benefit from further upsizing of container ships, and, moreover, other stakeholders, like ports and terminals, will suffer the consequences of additional investments.

The International Transport Forum (*5*) points out that the current generation of container ships can be marginally optimized by adding a top layer or an additional container row. Beyond that, however, a new generation of container ships will be needed, with bigger dimensions to generate sufficient cost reduction. This new class could start with a maximum capacity of around 24,000 TEU and require a length of 456 m as well as a beam of 65 m. The same report questions whether further ship size increase would be desirable if the potential cost savings to carriers were outweighed by high infrastructure costs. The introduction of a new generation with 24,000 TEU capacity would require substantial investments for the ports where they will operate first (Far East, North Europe, Mediterranean). In addition, because of cascade effects, 19,000 TEU ships would operate in North America and 14,000 TEU ships in South America and Africa, where investments will eventually have to take place.

In a similar way, Tran (*6*) concludes that bigger vessels could help container shipping lines to increase their revenue, but at a lower ratio than capacity growth. Nevertheless, Tran's paper shows evidence that the scale economies at sea create scale diseconomies in port. A comparison of port operating costs shows that serving post-Panamax vessels of 18,000 TEU is 17% more expensive than serving 4,000 TEU vessels (*7*). Taking into consideration external costs, Veldman (*8*) shows that economies of ship size exist for vessels above 15,000 TEU capacity. For existing fleet up to 15,000 TEU the economies are lower than expected.

The upsizing of container ships is mainly restricted by sailing routes. Charchalis and Krefft (*9*) point out that the length and beam of a container ship for current mega vessels, from an engineering point of view, are limited by the expected sailing route. In the long term, Saxon and Stone (*3*) conclude that the upsizing of container ships is limited by three main factors: declining return on investment, physical constraints of the sailing routes, and port infrastructure. However, they hypothesize that container ships with 50,000 TEU are possible for the next half-century. Even though in the next 5 to 10 years the development could slow slightly because of overcapacity, the upsizing could continue when demand catches up. Gomez Paz et al. (*10*) use the Delphi method to determine which factors will slow down the growth of container ships in the long term. Interviews with experts across the logistics chain led them to conclude that the port infrastructure and the canals would be the limiting factors.

In view of the increasing environmental pressures over the next decades, bigger ships could be favored in the future. On the one hand, upsizing the ships could reduce the environmental impact by using less energy per TEU (*8*). On the other hand, from the point of view of ports, bigger ships produce more air pollution emissions than smaller ships. If ports are starting to charge container ships based on their emissions, at one point it could become uneconomical to operate those bigger vessels (*11*). Therefore, the regulatory framework of ports could also have an impact on further ship size development (*12*).

Tran and Haasis (*6*) suggest that because of the interdependencies of stakeholders, decisions should not be made looking from only one side of the problem. Instead, a more holistic view is needed when decisions about ship size are taken. For example, besides shipping costs, port costs, inventory costs, inland transportation costs, and so forth should also be considered. Merk (*13*) concludes that port relocation because of bigger container ships could favor non-urban ports with deep sea access. Nevertheless, a port relocation is consequential for existing ports and inland connections. Thus, these decisions must be carefully considered.

Ports will have to react to the constant upsizing of container ships and to the trend to shipping alliances. Merk (*14*) suggests that ports should coordinate more to build their own alliances to balance the power in the container market in their own favor. This could lead to a slower ship size growth.

Related to the container ship size, the relationship between carrying capacity and ship dimensions has been studied in several research projects. Predictions of mega ships' dimensions are formulated via regression analysis by Kristensen (*15*). The author analyzes container ships from the IHS Fairplay database and creates regression formulas, which are used to calculate further length, beam, and draught based on capacity. However, this analysis is based on data from the past and does not consider that, for example, technological disruption or a dramatic ship redesign could change the evolutionary trajectory. Park et al. (*4*) and the Korea Maritime Institute (*16*) construct similar regressions with updated data to predict the tendency toward mega container ships.

The literature suggests that bigger container ships are still possible, with a capacity size ranging between 30,000 and 50,000 TEUs. In relation to the ship dimensions, authors indicate that, depending on capacity, the length estimated is between 453 and 517 m, beam between 65 and 72 m, and draught between 17 and 20 m.

Methodological Approach

To study the evolution of container ship size and define the possible limits on growth, various approaches or criteria have been considered at the same time: the evolution of the principal dimensions of container ships; the naval design restrictions and regulations; the geographic and port restrictions; the economies of scale of container shipping lines; the CO_2 emissions of vessels; and finally the world economy, demand, and global trends.

This paper contributes to the state of the art because it defines a methodology to design alternatives of possible bigger container ships according to naval design regulations. Additionally, different criteria are analyzed to identify the boundary restrictions of growth. Several studies predict the future ship size dimensions with regressions, based on data of the existing world fleet. Nevertheless, in this paper the container ship capacity and its dimensions is predicted by identifying alternatives of possible bigger vessels and selecting the optimal ones. Figure 1 describes the main steps of the methodology used.

Evolution of the Dimensions of Container Ships

To predict further development, first the authors analyzed container ship dimensions from the past, based on Lloyd's database. Figures 2–4 illustrate the evolution of the length, beam, and draught in relation to the capacity of all container ships built since 1944.

Analyzing the relationships, some comments can be made:

- Draught does not change significantly once a limit of 12,000 TEU is passed. In fact, draught for these larger ships seems to be stabilized around 16.0–16.5 m.
- Length is stabilized around 400 m for vessels bigger than 15,000 TEU.
- Beam is the dimension that experiences the largest proportional growth. Currently, the bigger vessels are 60 m in length.

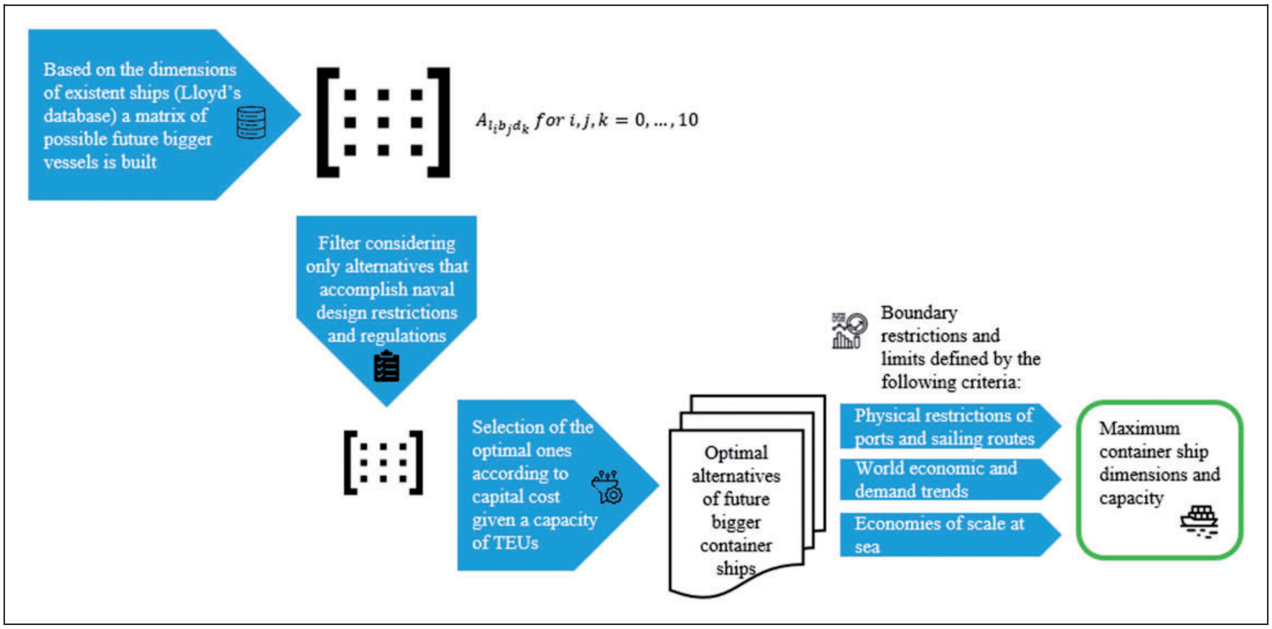

Figure 1. Simplified methodology approach.

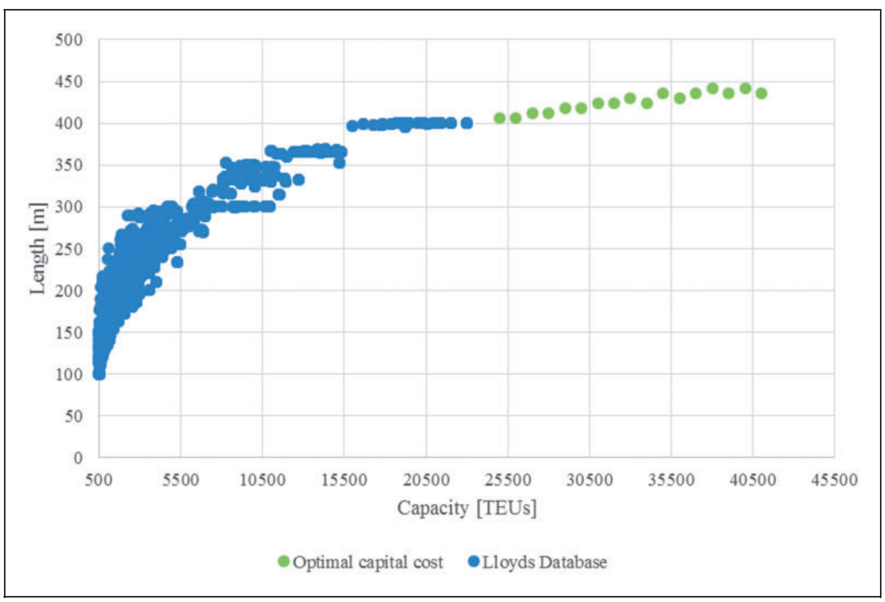

Figure 2. Relationship between the length and capacity of container ships built, with optimal alternatives selected according to capital cost.

- Increase in capacity for VLCS and ULCS is logically related to changes in length, depth, and beam, but significantly more so for beam than for length and depth. Draught is the dimension least affected in the new mega vessels.

Higher capacities are being achieved without a substantial increase in vessel dimensions. Based on recent vessel developments, the beam is the dimension that best accommodates extra TEU capacity when compared with the other measured dimensions.

Alternatives for Bigger Vessels According to Naval Design Regulations and Physical Constraints (Ports and Sailing Routes)

In this section, different scenarios of possible container ship sizes are represented according to different

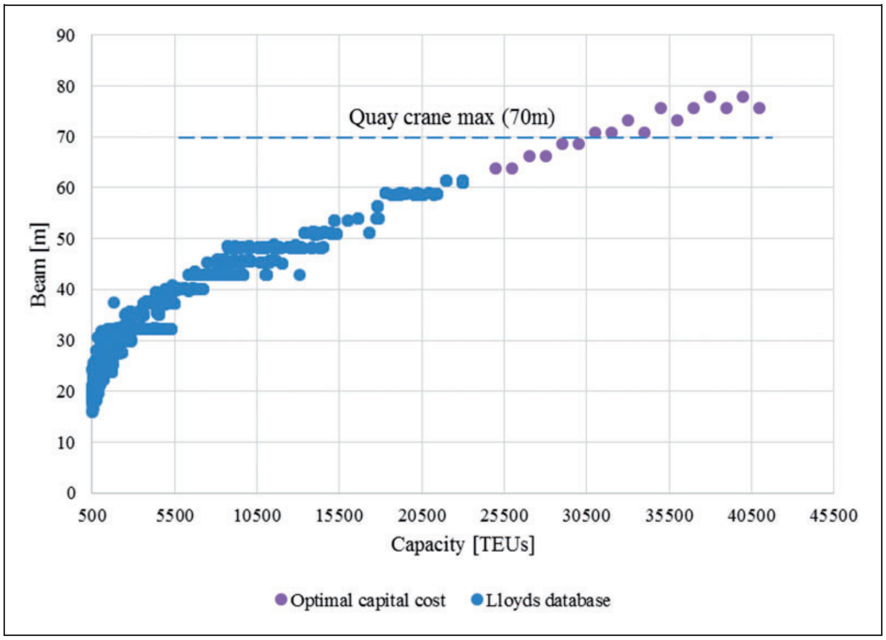

Figure 3. Relationship between the beam and capacity of container ships built, with optimal alternatives selected according to capital cost.

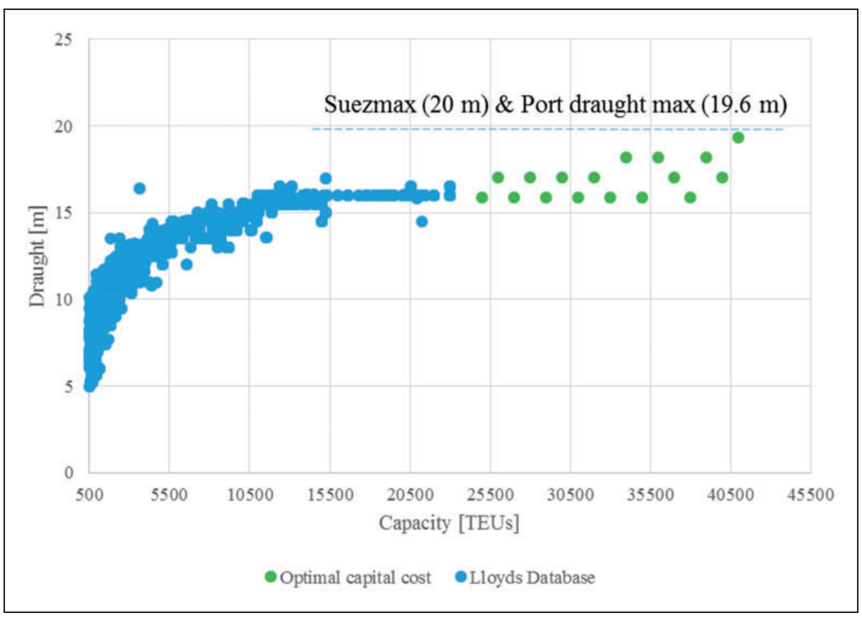

Figure 4. Relationship between the draught and capacity of container ships, with optimal alternatives selected according to capital cost.

restrictions. Beam (B), length (L), depth (D), and draught (T) intuitively grow by intervals according to the new rows of TEUs added in each direction. For that reason, a matrix of alternative possible larger vessels has been built adding new rows in each direction to the current biggest container ship of 23,000 TEU (L = 400, B = 61.5, D = 33.2, T = 16.5). The matrix of alternatives is defined as:

$$A_{l_i b_j d_k} \quad \text{for} \quad i, j, k = 0, \ldots, 10 \tag{1}$$

where

$l_i = 400 + i*5.9$, is the length and increases accordingly to the length of a TEU (5.9 m)
$b_j = 61.5 + j*2.4$, is the beam and increases accordingly to the width of a TEU (2.4 m)
$d_k = 33.2 + k*2.4$, is the depth and increases accordingly to the height of a TEU (2.4 m)

To calculate draught, assume the same ratio of the current 23,000 TEU, T = 0.48*D. For example, the alternative $A_{l_0 b_3 d_1}$ is a container ship with 400 m length, 68.7 m of beam, 35.6 m of depth, and 17.08 m of draught.

The set of alternatives is calculated following to Alvariño (*17*). The formulation to define the load capacity considers, aside from the main ship dimensions, the power of the ship, the service speed at 85% of the maximum control rate and displacement of different vessels generated. The stability is verified using the assumptions defined by the International Convention for the Safety of Life at Sea (SOLAS) (*18*). To ensure that the alternatives generated are feasible, the initial stability of each of them has been calculated, by making sure that the metacentric height (GM) of the vessel is greater than zero.

$$GM = (KB - BM) – KG \quad (2)$$

where K is the intersection point between the ship baseline, the creaking plane, and the transversal section; B is the center of buoyancy where the thrust is applied; G is the center of gravity of the vessel; and BM the metacentric radius that can be defined as the ratio between the total inertia and the total volume of the ship.

$$BM = \frac{C_2 * B^2}{12 * C_b * T} \quad (3)$$

KB is the ratio between momentum of the volume in relation to the plane K and the total volume of the ship; C_b is the block coefficient which is the ratio of the volume of displacement at that draft to the volume of a rectangular block having the same overall length, breadth, and depth.

$$KB = C_1 * T \quad (4)$$

where C_1 and C_2 are constants obtained of Riddlesworth's and Normand's expressions (*17*). KG depends on the ship's displacement and the distribution of loads. It is estimated using weighted ratios obtained from Alvariño (*17*).

The set of alternatives defining future ship sizes was filtered, with selection of the vessel designs that optimize for capital costs of construction given a capacity. This decision is made because construction costs represent 42% of the major costs associated with running ships, according to Stopford (*19*). The capital cost formulation is defined in the sixth section. Figures 2–4 illustrate the historic dimensions of ships (length, beam, and draught) and the set of alternatives selected. The figures show that the alternatives selected follow the historic tendencies for all the dimensions.

The constraints of the port's infrastructure limit ship size development as well. Depth of draught, the limited arm-length of gantry cranes and the limited space for container yards make it impossible for some ports to handle the ever-growing vessels. The traditional reach of quay cranes in most container terminals is less than 70.4 m (represented in Figure 3); automatic container terminals opened after 2015 have a length of berth of over than 1,000 m (*4*). The maximum draught depths of the main ports of the world are listed in Table 1. As shown, the maximum draught of all ports is less than 20 m, with a range from 16 m to 19.65 m.

Relative height of mega ships or how high containers are stacked could be a limiting factor of growth, especially for maritime routes that need to pass under bridges to gain access to ports. The actual relative height is around 17.50 m for the current biggest container ships,

Table 1. Draught of the Main Ports across the World Sorted by Region and Country

Region	Country	Port	Draught (m)
South-Eastern Asia	Singapore	PSA Singapore	18
	Indonesia	New Priork (Jakarta)	16
North-Eastern Asia	China	Dalian	17.8
	South Korea	Busan	17
Middle East and South Asia	India	Bharat Mumbai	16.5
	Saudi Arabia	Saudi Global Port	16
North Europe	Belgium	Antwerp	17
	Holland	Rotterdam	19.65
	Germany	Hamburg	17.4
Mediterranean Sea	Italy	Savona	17.25
	Portugal	Sines	17.5
	Turkey	Mersin	15.8
	Spain	Algeciras	18.5
	France	Marseilles	16
	Morocco	Tangier	18
America	Panama	PSA Panama	16.3
	Colombia	Buenaventura	16.5
	United States	Los Angeles	16.7

Note: Authors' own elaboration based on the ports' website data.

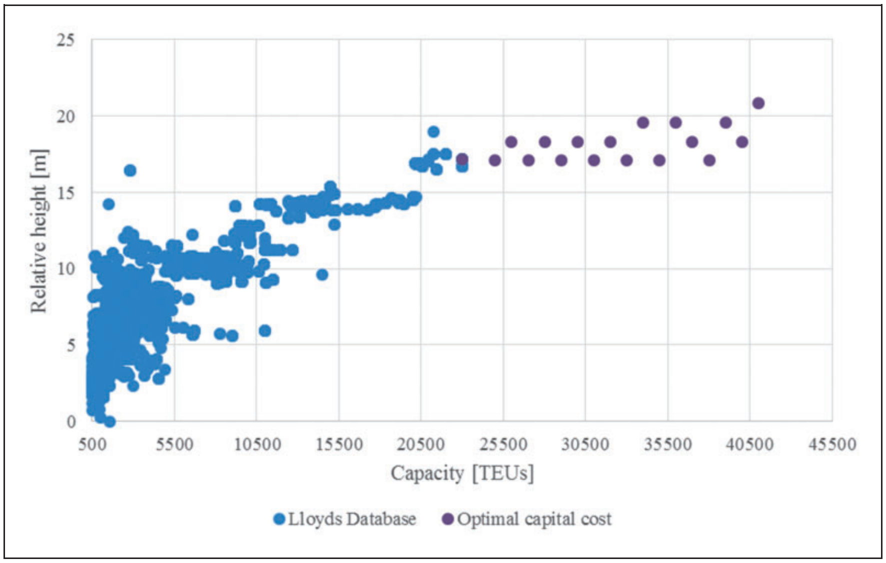

Figure 5. Relationship between the relative height and the capacity of container ships, with optimal alternatives selected according to capital cost.

and according to the results shown in Figure 5, it could stabilize around 20 m.

Ship size development is also limited by the physical constraints of sailing routes. The Panama Canal route is the most restrictive, with a limited length of 366 m, beam of 49 m, and draught of 15.2 m. For the Asia–Europe route through the Suez Canal, which is the shortest path for this itinerary, there is no limitation of length, a beam limitation of 50 m, and a draught limitation of 20 m or, eventually, 77 m of beam and 12.2 m of draught (*20*). It is important to note that, in accordance with the Suez regulations, as beam increases, draught decreases because of the trapezoidal cross-sectional geometry of the canal. For example, for the actual biggest container ship of 23,000 TEU capacity, with a beam of 61.5 m, the draught restriction is 16.28 m. It thus becomes clear that today's container ships should optimize their dimensions to increase capacity according to the Suez Canal's navigation regulations. Nevertheless, this paper aims to study future ship size and accordingly assumes that the cross-section of the Suez Canal could be increased, despite the high investment costs required. For the alternate Asia–Europe route, around the Cape of Good Hope, the only limitation for draught is in the Malacca Strait, which is constrained to 25 m. Finally, because of global warming, in the long term the Arctic Route is considered, even though according to a study by the Copenhagen Business School (*21*) the Northern Sea Route will not be commercially viable until 2040.

Analyzing the set of physical and geographical restrictions of sailing routes and ports, we can conclude that:

- According to capital cost optimization, ship length can grow up to 450 m, with no boundary restriction on this dimension.
- According to Figure 3 the beam can increase up to 80 m. This is because the beam is the cheapest dimension for increasing capacity. However, the canal and quay crane boundary restrictions could limit this dimension to around 70 m, which corresponds to a container ship of 30,000 TEUs.
- Finally, draught is the dimension that experiences least increase, growing up to 20 m for vessels larger than 40,000 TEU. Nevertheless, for vessels with capacity under 35,000 TEUs, draught fluctuates between 16 and 17 m. Current canal and port restrictions operate at around 20 m in depth.

In summary, draught or beam limitations could form the natural limits to further ship growth.

Economies of Scale at Sea

One of the main drivers for bigger container ships is economies of scale. Historically, increased capacity per vessel reduced the cost per TEU, so shipping lines strove over the last decades to enlarge their vessels. However, returns of scale are declining with increasing size. Therefore, it is not clear if the unitary cost will continue to decline with ship size.

Because container ship maritime trade is strongly dependent on the economies of scale, this section studies the main costs that influence container shipping lines: capital, fuel and operational costs (*19*).

Capital Cost

Capital cost is defined as the shipyard building price. To analyze capital cost according to the size of the vessel, this study used the methodology elaborated by Junco (*22*). The following costs have been taken into account to calculate a ship's total capital cost (*CC*):

$$CC = CMg + CEq + CMo + CVa \tag{5}$$

The bulk material cost (*CMg*) considers the materials used and their qualities, as well as the utilization coefficient. Junco (*22*) uses series of coefficients to take into account not only the steel of the ship's hull, but also all the metallic elements included in the structure (superstructure, metallic equipment, etc.). The ship equipment costs (*CEq*) have been calculated as the sum of the labor costs of assembling the equipment and facilities, cargo handling equipment, cost of equipment calculated as the cost per power units of propulsion and auxiliary equipment for the total propulsion power. Here we take into account the cost of propulsion equipment, calculated as 350 €/kW for the power installed in the vessel, as well as the cost of crew members' quarters and the price of the remaining equipment calculated by their weight. General labor costs of the ship (*CMo*) considers the costs of personnel necessary to carry out the construction in the ship yards, calculated as the hours needed to build the ship by weight of steel. Other construction costs (*CVa*) include the costs of the International Association of Classification Societies, insurance, channel tests, and so forth, where a value of 10% of the total construction cost has been assumed based on Junco (*22*).

Because fuel costs are calculated based on the EU-MRV (*23*) database for 2018 container ships, only the capital costs of these same vessels are analyzed. The operating life of the ships is assumed to be 20 years, with an operating time of 365 days per year.

Fuel Costs

To determine fuel costs based on ship dimensions, the Lloyd's database has been used in conjunction with available data from the European Union (EU-MRV) database, which reports ships' fuel consumption in 2018 according to EU Regulation 2015/757. Despite alternative fuels currently emerging, it is assumed here that container ships will continue to use traditional petroleum fuel throughout the next 30 years, based on the World Outlook Energy of 2018 (*24*). The impact of new Emission Control Areas (ECAs) and Sulfur Emission Control Areas (SECAs) regulations of the International Maritime Organization (IMO) for the next years is addressed in building three scenarios that consider the use of marine diesel oil and very low sulfur fuel oil.

To determine daily fuel costs based on the EU-MRV database, the following formulation is applied:

$$Daily\ Fuel\ Cost_{2018}\ \left[\frac{€}{TEU}\right] = \frac{Total\ fuel\ consumption_{2018}}{Total\ time\ spent\ at\ sea_{2018} * TEU\ capacity * Fuel\ Cost} \tag{6}$$

The total fuel consumption cost and the time spent at sea is obtained from the EU-MRV (*23*) database.

To estimate the fuel costs of the predicted ships of the future, the methodology of Alvariño (*17*) is used. The following formulation is used to calculate the ship's fuel consumption:

$$Consumption\ \left[\frac{m3}{hour}\right] = \frac{Power\ (kw) \cdot Specific\ consumption}{Fuel\ density} \tag{7}$$

where specific consumption is 0.189 $\frac{kg}{kWh}$ and fuel density is 991$\left(\frac{kg}{m^3}\right)$.

A constant cost of $571/tonne of heavy fuel oil is assumed, which represents the average cost during the first quarter of 2018 according to energy prices in selected OECD countries collated by the International Energy Agency (*25*). A U.S. dollar to Euro exchange rate of 1.1534 is assumed, being the 2018 average according the European Central Bank.

It is important to remark that the new generation Maersk Triple E, which practically doubled the capacity of its predecessors, achieved a cost reduction of 40%–50%. However, in recent years, it has been found that 60% of the reduction is because of the efficiency of the engines rather than the scale effect (*5*).

Operational Costs

Operational costs include manning, insurance, stores, spares, lubricating oils, repairs and maintenance, dry docking, management, and administration. They are estimated according to the 2015 regressions of Tran (*6*), which are based on Drewry data from 2012. The estimated regression model with respect to TEU capacity is:

$$Daily\ operational\ cost\ \left[\frac{€}{TEU}\right] = \frac{22{,}89{*}TEU\ capacity}{r} \quad (8)$$

where r is the U.S. dollar to Euro exchange rate of 1.1534.

Operating cost is the category that presents the least variation for ship size capacity. Doubling vessel capacity increases overall cost by 32% while decreasing unit operating costs by 34%.

Finally, it is important to point out the inventory cost. Arrival of a mega ship in a port is associated with higher yard occupancy, more feeder traffic, truck and train movements that could increase the inventory costs because of delay (*5*). Tran (*6*) defined the inventory cost as USD20 per TEU carried. Inventory costs are excluded from the analysis because of the dependence on the sailing routes and port calls.

Total Costs of Running Container Ships

Given the set of alternatives selected in the previous section, shipping unitary costs are estimated to study economies of scale. Figure 6 illustrates the evolution of running costs of all 2018 ships as well as the prospective costs of future vessels.

Some comments can be made, arising from Figure 6:

- The total unitary cost is stabilized for a container ship of around 30,000 TEUs. Figure 7 details the relative life-time costs for a vessel of this capacity.
- For vessels larger than 20,000 TEU, the reduction in operational costs is negligible.
- From the point of view of construction and fuel costs, a stabilization of costs per TEU for vessels over 25,000–30,000 TEU is observed.
- There is a downtick in total costs of ships around 21,000 TEU, especially because of fuel costs. However, if historic ships (2018) up to 15,000 TEU are considered, then the trend of the historic data

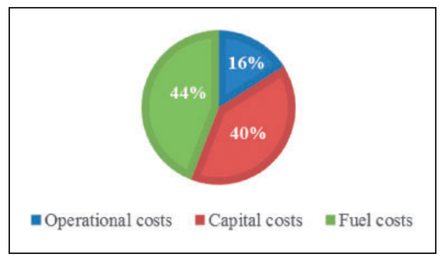

Figure 7. Relative life-time costs (fuel, operational, and capital) of running a container ship of 30,000 TEU.

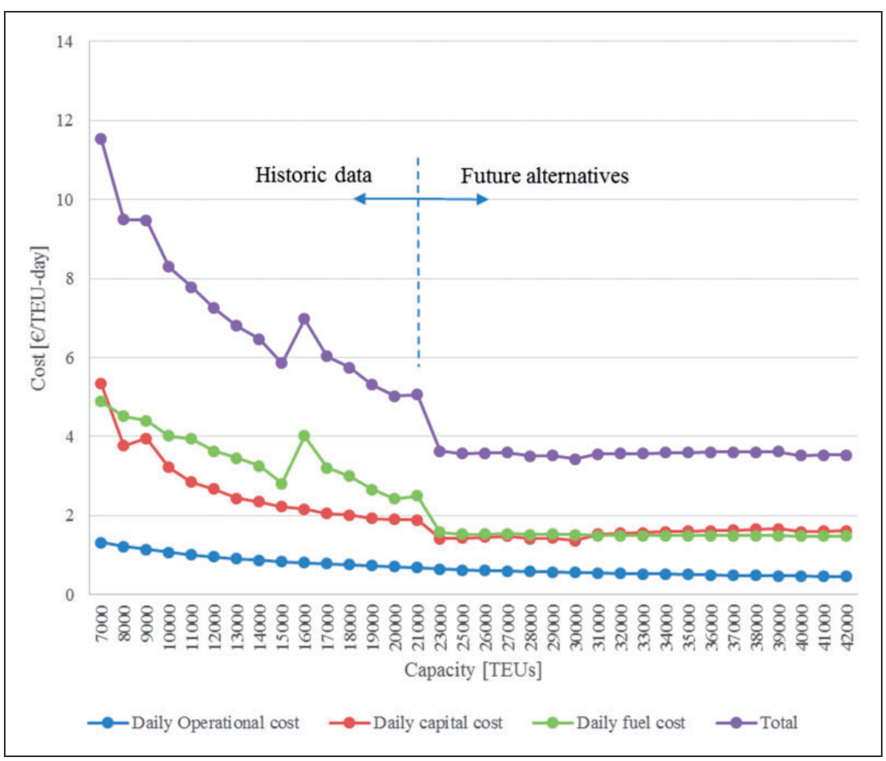

Figure 6. Fuel, capital, and operational costs of container ships in 2018 (7,000–21,000 TEU). Projection for vessels bigger than 23,000 TEU. Own elaboration with Lloyd's and EU-MRV databases.

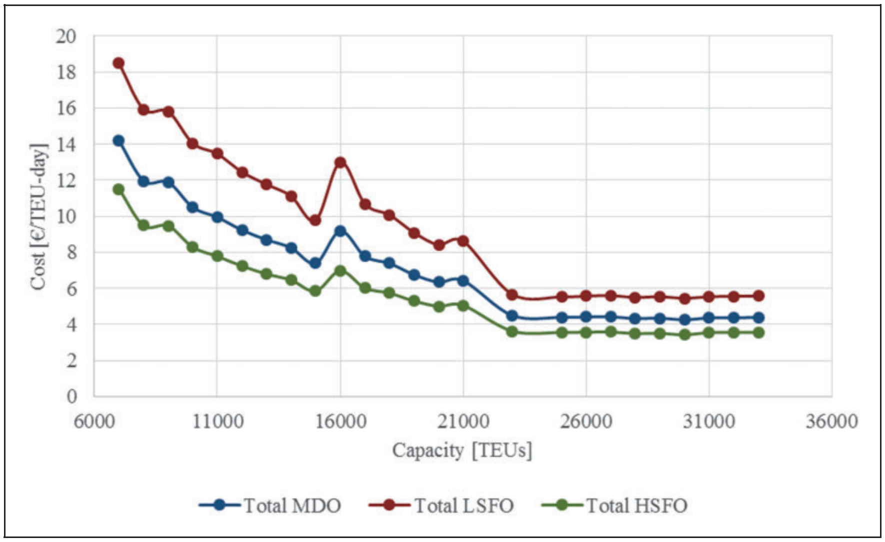

Figure 8. Total costs of container ships in 2018 depending on the type of fuel oil used (7,000–21,000 TEU). Projections for vessels bigger than 23,000 TEU. Own elaboration with Lloyd's, EU-MRV databases and Ship&Bunker data prices.
Note: MDO = marine diesel oil; LSFO = low sulfur fuel oil; HSFO = high sulfur fuel oil.

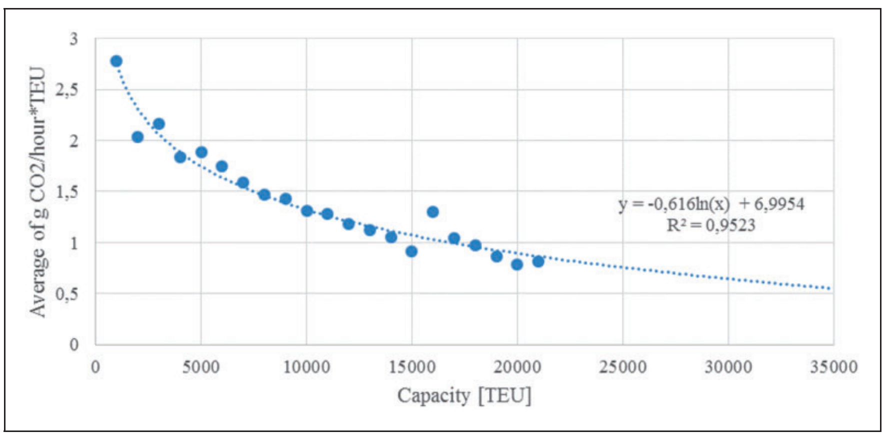

Figure 9. Evolution of CO_2 emissions per hour and TEU transported according to ship size. Own elaborations with the EU-MRV database.

follows that of the future alternatives, drawing a potential stabilization curve.

- The gap detected in the economies of scale that appears in Figure 6 is derived from the EU-MRV database, because 16,000 TEU ships present higher consumption of fuel.

To analyze the possible influence of the IMO 2020 regulation, Figure 8 represents the fluctuation of total costs, comparing the costs of high sulfur fuel oil, very low sulfur fuel oil, and marine diesel oil. The latter two have respectively +70% and +50% higher cost than high sulfur fuel oil (*29*). Analyzing the results, we can assume that in the three scenarios there is a stabilization of total economies of scale. Costs for running container ships bigger than 25,000 TEU fluctuate between €4 and €6 per TEU per day.

In light of climate change, it is worthwhile to analyze the evolution of CO_2 emissions produced by container ships. The evolution of CO_2 emissions is estimated related to container ship capacity. This is done using Lloyd's database as well as data available from the EU-MRV system, which reports ships' CO_2 emissions according to EU Regulation 2015/757. Figure 9 illustrates that there is a trend of reducing CO_2 emissions as container ship size increases. Even though there is a small uptick for container ships of 15,000 TEU, it can be assumed that environmental scale economies could favor an increase in ship size.

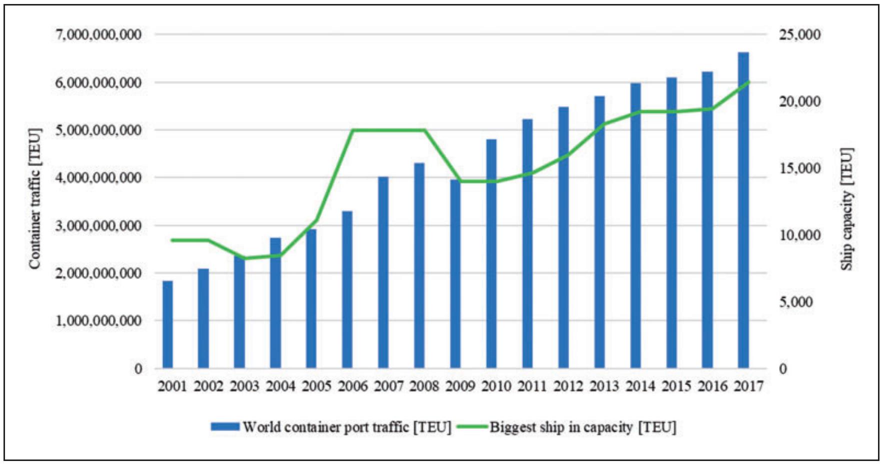

Figure 10. Global TEU trade evolution and biggest current container ship in capacity. Source: Own elaboration based on Lloyd's and the World Bank databases.

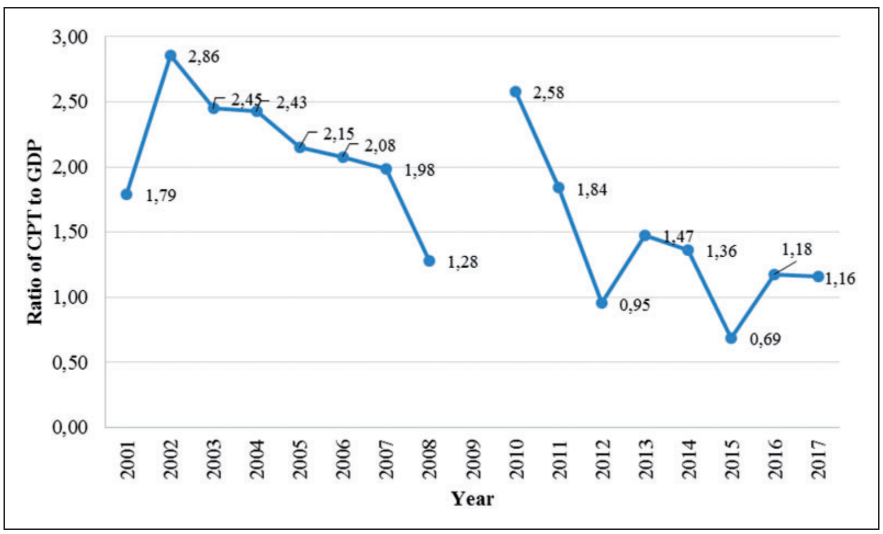

Figure 11. Ratio of annual container port traffic (CPT) to annual GDP growth (excluding 2009 because of the financial crisis). Source: Own elaboration with World Bank database.

World Economic and Demand Trends

GDP is usually a valuable indicator to anticipate future trade volume. From 1997 until 2007, the growth of the container trade was almost three times higher than GDP growth. Since the 2008 crisis, the volume of goods traded has increased approximately in line with GDP, with a ratio of TEU growth to GDP of 1.7 (*3*). Current estimates show global trade to be growing slightly quicker than GDP but to be on a downward path (*3*). Figure 10 illustrates the positive relationship between world container port traffic and the largest ship, in relation to capacity, in each year since 2001. Figure 11 indicates that the average ratio of container port traffic to GDP is decreasing from two to one. Moreover, in 2012 and 2015, the ratio was below one, which means that world container traffic is growing proportionally less than the global economy. According to Figure 10, it can be assumed that, if the global container trade is growing at a similar rate to GDP (as can be concluded from Figure 11), ship size is going to increase in the same proportion. The International Transport Forum (*26*) has estimated that the compound annual growth rate in the world 2015–2050 is 2.9%. Thus, if the biggest container ship in the world in 2015 was 19,000 TEU, in 2040 we could estimate a container ship of 39,000 TEU, based only on demand forecast and past ship size evolution. In addition to that, the downward trend in TEU growth to GDP growth could be an indicator of stabilization of container ship size.

Another factor favoring bigger container ships and reinforcing a 39,000 TEU capacity ship is the phenomenon of shipping alliances. Three global alliances represent the eight largest container carriers of the world. Together, the three alliances represent around 80% of overall container trade and operate around 95% of the total ship capacity on East–West trade lanes (*27*). Such alliances have allowed carriers to acquire and operate mega ships, thereby reducing unit costs.

However, even if ever-larger ships are increasing supply, demand is not catching up. This creates overcapacity in the container market. Although demand has increased since the financial crisis of 2007–2009, it is not keeping pace with supply. The supply/demand imbalance will persist, we predict, with revenue and pricing remaining under pressure as container ship sizes increase and global GDP only grows moderately. To take just one example, in 2016, the supply of the total fleet was 23% greater than the world demand (3).

In addition to the supply and demand unbalance, some additional trends can slow the increase in ship size. First, 3D printing could decentralize a bigger part of global production, which would have a negative impact on global trade. At the moment, nonetheless, the impact of new technologies on global trade is expected to be marginal: one analysis, by Petrick and Simpson (*28*), estimates that TEU volumes will fall by less than 1% by 2035. Another trend is the slowdown of the Chinese market, which is moving away from a development-based model centered on the export of physical goods and toward a consumption- and services-based model, negatively affecting world demand and therefore also the evolution of container ship size. Finally, emerging companies like Amazon and Alibaba could have a heavy impact on ship size developments by prioritizing time-to-market over cost per TEU. This would result in a demand for smaller vessels with more direct port-to-port connections, the opposite trend of that observed in recent years.

Results and Discussion

From the combination of the limiting factors described in the previous sections, it can be concluded that:

- Increase in capacity does not have a large impact on vessel dimensions. Beam is the dimension experiencing proportionally the biggest growth. In the last 15 years capacity has been trebled and beam has increased 43%, while length and draught have increased just 20% and 10% respectively.
- Draught or beam limitations of ports and sailing routes could form the natural limits to further ship growth. The results suggest that this limit will be reached with a container ship of 30,000 TEU capacity because of the physical restrictions of the sailing routes and port infrastructure (quay crane maximum reach of 70 m).
- From the point of view of the economies of scale, there is possible stagnation, with an eventual increase foreseeable for ships over 30,000 TEUs.
- The overall growth of world GDP and global trade favor the container ship upsizing beyond 30,000 TEU capacity. This is especially true as the container shipping market has become increasingly consolidated, with just a few shipping-line alliances controlling most trading routes. These alliances continue to use their market power to increase container ship size and capacity to achieve economies of scale. We predict the possibility of 39,000 TEU capacity ships in 2040, according to the GDP and traffic trends. However, the evidence of decline of global trends in relation to GDP indicates a possible peak of the container ship size. Other global trends, like 3D printing or the overcapacity of the world container fleet, could reduce the expectation of a 39,000 TEU capacity ship. In addition to that, according to Figures 2–4, dimensions of a 39,000 TEU ship are of 435 m of length, 76 m of beam and 18 meters of draught, which will limit the number of feasible ports of call and result in a beam larger than the current quay cranes.

It is necessary to note that, from the point of view of CO_2 emissions, there is no stagnation of economies of scale as ship size increases. If environmental scenarios are prioritized by the regulatory frameworks, larger container ships are more sustainable if the transport model is from hub to hub. These findings are consistent with Veldman et al. (*8*), who estimate that for a 6,000 TEU ship the external costs vary from 5.9% to 29.3%, while for a 25,000 TEU vessel they decrease slightly from 5.2% to 26.2%.

To sum up, the results suggest that there is a stabilization of ship growth around a capacity of 30,000 TEU. Malchow (*2*) and Park (*4*) predict that 30,000 TEU capacity ships will appear in the shipbuilding market in 2025. However, in the light of the global economic trends analyzed in this paper the findings suggest that the 30,000 TEU ship could appear in 2030. In the long term Saxon and Stone (*3*) hypothesize 50,000 TEU container ships for 2050.

The results of this study are consistent with and contribute to the state of the art by defining a methodology to predict future optimal vessel dimensions and capacity according to the naval design regulations (*17*) and considering different criteria to fix upper and lower limits.

Under the assumption of 30,000 TEU vessels, the results indicate that optimal ship size, according to capital cost, is 418 m length, 69 m beam, 35 m depth, and 17 m draught. To verify the accomplishment of naval design criteria, GM value is calculated. For the alternative selected this value is 3.01 m and, expressed as percentage of beam, 4.36%. A reasonable value would be between 4% and 5% (*17*), to avoid stability problems. These predictions are similar to those predicted in 2019 by Park (*4*): 453 m in length, 72 m of beam, and 17.3 m of draught. However, they differ from those predicted by the Korea Maritime Institute for a ship of 30,000 TEU: 517 m in length, 65 m of breadth, and 19.4 m of draft (*16*). A similar approach was built by Kristensen (*16*) who estimated that a hypothetical container ship with a capacity of 30,000 TEU would have 483 m of length, 71.5 m of beam and 18.7 m of draught. Malchow (*2*) estimates that a 30,000 TEU ship will have 20 m draught, while the results of the present study suggest that this dimension will be around 17 m.

This paper contributes to the state of the art of the evolution of container ship size offering some strategic key points to evaluate the need for investment in new port infrastructures to fit mega ships, considering also the possible unbalanced externalities. Nevertheless, the three existing shipping alliances (2M, Ocean Alliance, and The Alliance) represent 80% of all container trade, and they control the drivers of ship size optimization more than ports.

Conclusion

This paper deals with the possible growth path of container ships. A limit on capacity is estimated at around 30,000 TEUs. Analyzing historical data on container ships, it is apparent that an increase in capacity does not have a large impact on vessel dimensions, with the exception of beam, which has experienced the biggest growth in the last decades. If no technological disruption drastically changes container ship design, the results suggest that the world's largest vessel of 30,000 TEUs will be approximately 418 m in length, with 69 m of beam and 17 m of draught. It has been assumed that the cost of construction will prevail, over fuel costs, as the dominant shaping force, since it is expected that technological development will reduce fuel consumption as a result of increases in engine efficiency.

Acknowledgments

The authors thank the staff of the Port of Barcelona, Department of Innovation and Strategy, for their support in this paper.

Author Contributions

The authors contributed to the paper as follows: study conception and design: Javier Garrido, Sergi Saurí, and África Marrero; analysis and interpretation of results and draft manuscript preparation: Javier Garrido, Sergi Saurí, África Marrero, Ümit Gül, and Carles Rúa. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received the following financial support for the research, authorship, and/or publication of this article. This research has been conducted as part of a research grant from the Port of Barcelona (Agreement: BOE Núm.182 Sec. III Pág 75910).

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