Propulsion trends in container vessels

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Future in the making

Contents

Container vessels are some of the biggest contributors to the shipping market. These vessels distribute goods, consumables, and components all around the globe. The owners of these vessels are some of the most renowned in the shipping business. This creates a vast interest in container vessels and also intensifies the competition within the segment.

The future development in freight rates, fuel prices, and environmental restrictions will challenge the container vessel design to ensure that the propulsive demand can be met while still complying with future restrictions. Fuel prices have a significant influence on the future of the container segment along with energy efficiency demands, which have been implemented to a greater extent for this segment than for other commercial vessel segments. This paper outlines the propulsion demands and possibilities regarding the future of container shipping for various sizes of container vessels. It also discusses how upcoming fuel types and propulsion aids can improve the efficiency of propulsion and help cope with the demands of present and future environmental restrictions while keeping operational costs at a minimum.

Introduction

Container vessels are one of the main contributors to the transportation of dry cargo. Dry cargo is often divided into two segments: Break bulk cargo and bulk cargo. Bulk cargo is mostly coal and grain which is transported by loading it directly into the hull of bulk carriers. Break bulk cargo is different, as it is often already manufactured goods transported in packages. In the early 1900s, these packages or goods were loaded single-handedly onto the cargo ships. This was common practice before container vessels revolutionised this market segment.

The use of container vessels started during the Second World War. The first vessel designed for container transportation was launched in 1960, the *Supanya*, which could carry 610 twenty-foot containers. In that connection, the typical measure of twenty-foot equivalent units (teu) was introduced. Since then, the amount of cargo shipped in containers has only increased, especially over the last 30 years. This has resulted in a rapid increase in both the number and size of container vessels.

With the introduction of the Post-Panamax size container vessels in 1988, the size of container vessels passed the ‘Panamax’ maximum breadth of 32.2 m. The largest container carriers continued to grow in size, today reaching a capacity slightly above 24,000 teu within a length of 400 m and a breadth of approx. 61.5 m.

Along with the increase in size and speed reductions came a drastic cut of the energy consumed per container transported, from 300 tonnes HFO a day for the 2,272 teu containers carried on board the triple-screw vessel *Selandia* at more than 28 knots in 1972 to less than half the amount for a modern 20,000 teu container carrier at 18 knots.

Despite these historical facts, the container shipping industry will still face challenges in the current and upcoming years, both regarding freight rates which are again under pressure, and stricter regulations:

- Energy efficiency regulated by design, regulations of EEDI and EEXI
- Energy-efficiency regulated operation – carbon intensity indicator (CII), FuelEU Maritime, and EU emissions trading scheme (ETS) regulations – and possibly even more and stricter regulations in the future.

At the 74th Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO), they agreed to advance EEDI Phase 3 from January 2025 to April 2022 for container vessels.
Furthermore, a graduated reduction rate for EEDI Phase 3, depending on deadweight tonnage, was agreed on, maintaining 30% as the reduction requirement for the smallest container vessels, gradually increasing to 50% for the largest vessels above 200,000 dwt, which corresponds to approximately 21,000 teu and above.

In January 2023, the CII was implemented to make sure carbon emissions during operation were kept at a minimum. This new index incorporates the carbon emitted during the operation of an entire year, where the EEDI and the EEXI were implemented as a design measure. An agreement has been reached on reductions for CII until 2026, and in 2025, a further evaluation will be done for upcoming future regulations.

In 2025, new regulations will be implemented within the EU as well. The ETS and FuelEU Maritime will regulate greenhouse gas (GHG) emissions, not only for the fuel burned on the vessel in a tank-to-wake perspective, it will also include emissions from the fuel production in a well-to-tank perspective. The ETS and FuelEU Maritime is unlike the EEDI and CII, only applicable within the borders of the EU though they also include half of emissions on journeys to and from ports in EU member states. These restrictions are enforced on a fleet basis and not based on a single vessel.

Since the financial crisis in 2008, the design speed of Panamax and larger vessels has dropped significantly from approx. 25–27 knots to presently 20–22 knots. As the freight rates are continuously under pressure and regulations set a limit for emissions, the design speed is not expected to increase within the near future – if ever again. Actually, many vessels delivered within the latest decade are operating at speeds 3–4 knots lower than their intended design speed, the maximum speed was exploited during the peak of container freight rates in 2021–2022.

The reason for the change is that the lower speed lowers the resistance, and thereby also lowers emissions and fuel consumption. This decrease in speed has been necessary to keep up with regulations for GHG emissions, but fuel prices have also contributed to the lowered speeds. With alternative fuels in mind, the power could increase slightly if utilised properly. However, an increase in speed and power is yet to be seen, the reason being that the operational prices of the consumed alternative fuels would increase significantly. And as prices of alternative fuels are expected to be higher than for traditional bunker fuels, the speed would most likely be kept unchanged, or lowered to keep operational expenses at a minimum.

Despite the lower design speed, a powerful main engine with a large engine margin is still desired by many owners to be able to catch up with delays and meet the scheduled time of arrival. Reaching the terminal at the expected time is very important for liner traffic in order to be sure to get the allocated spot along the quay, and to ensure that resources for cargo handling are available at the terminal.

But operational emission regulations, such as CII, FUEL EU, and EU ETS, might complicate this since a higher speed will increase emissions. So far, it is required that the decrease in carbon emissions (CII) must be lowered by 11% in 2026.

A lower service speed, and slow steaming even below this, along with a large engine margin challenges the ship designer to perform a limbo: A powerful engine is required along with a propeller that can absorb the high power. At the same time, the efficiency of the propulsion plant should be as high as possible during normal operation at lowered speeds.

Modern container carriers carry many refrigerated containers around the globe, and it is important to consider the vast electricity consumption of these giants as well. Since the speed is reduced, the electricity consumption will constitute an ever-increasing amount of the total energy spent on a voyage. Especially, some of the alternative fuels result in increased electricity consumption, since cooling is needed for the storage of certain fuels. This paper evaluates methods and possibilities for lowering the specific energy consumption for producing electric energy on board the vessel, including power take-off systems and waste heat recovery systems.

In addition, the paper shows how EEDI Phase 3 compliance can be reached for various vessels ranging in size from 400 teu to 24,000 teu. Specific examples of larger container feeders and New-Panamax vessels are also outlined for design purposes.
In this paper, traditional single-screw propulsion plants are considered along with an evaluation of twin-screw propulsion plants. Some of these solutions might be better suited for the limbo demanded of a modern container carrier design than others.

Characteristics related to container vessels

Definitions

The capacity of a container vessel will normally be stated by the maximum number of teu sized containers that can be stacked on the vessel. The size is sometimes also stated as ‘feu’ which is ‘forty-foot equivalent unit’. The most common size is teu and it is the size measure used in this paper.

The length of 20 feet corresponds to about 6 m, and the width and the height of the almost quadratic container is about 2.44 m. The vessel dimensions, especially the breadth, therefore depend on the number of containers placed abreast on deck and in holds. One extra container box abreast gives an increased vessel breadth of about 2.5 m in a given design.

In former days, an average-loaded teu container weighed about 10–12 tonnes, so the container vessels were often dimensioned for 12–14 dwt per teu. Historically, some owners also stated the teu capacity of their vessel according to this weight carrying capacity definition.

The maximum number of teu that can be stacked on the vessel is an important marketing parameter. Therefore, the cargo capacity used today by most yards and shipowners is equal to the maximum number of teu containers that can be stacked on the container vessel independent of the weight of the containers. Dwt is still a defining parameter, as the ship is designed to carry a specified dwt regardless of the allowed number of containers.

Development in vessel size

The reason for the success of the container vessel is that containerised shipping is a rational way of transporting most manufactured and semi-manufactured goods. This rational way of handling the goods is one of the fundamental reasons for the globalisation of production. Therefore, containerisation has led to an increased demand for transportation, and for further containerisation.

The commercial use of containers (as we know them today) started in the second half of the 1950s when the first vessels prepared for containerised goods were delivered.

Fig. 1 and Fig. 2 show container vessels delivered in 2000–2022 expressed as the number of vessels and the teu capacity, respectively. The figures also include orders placed for 2024 and 2025, showing a significant increase in the number of vessels and teu capacity in 2023 and 2024.

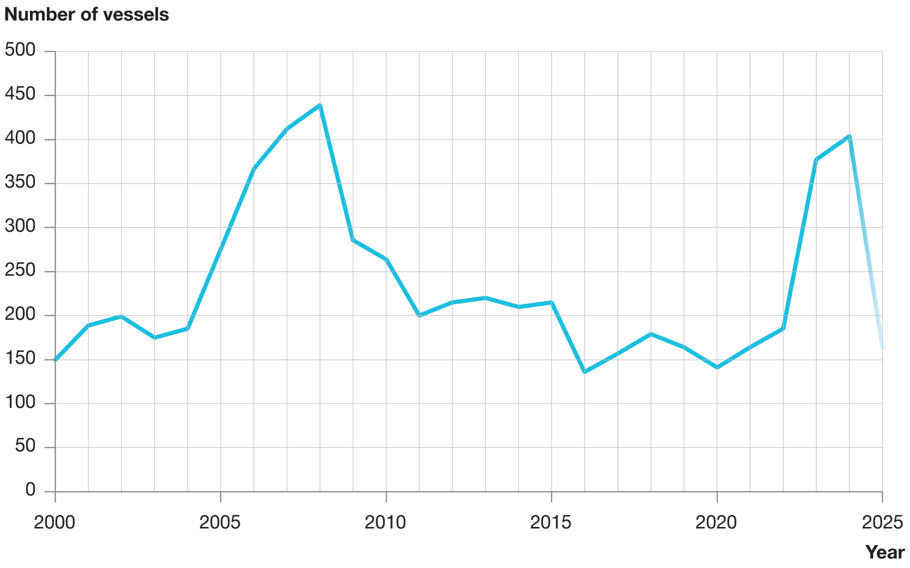

Fig. 1: The number of delivered container vessels through the years

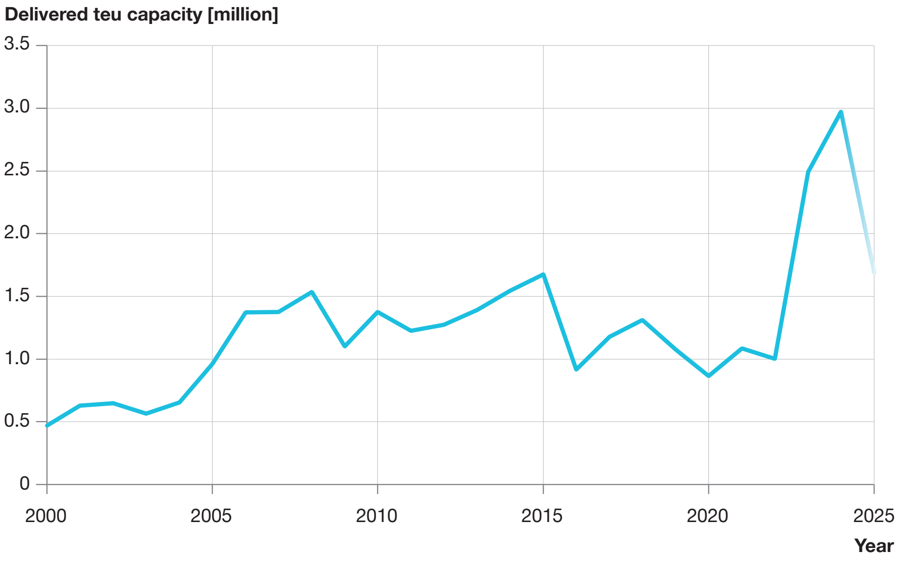

Fig. 2: Teu capacity delivered through the years

To relate teu capacity with the naming of container vessel classes, Table 1 gives an overview of the different classes and sizes.

Through the years, the container market has developed significantly. At the beginning of containerised shipping, the development of the container market was slow until the delivery of 30 vessels in 1968. Nine of these vessels were in the lower range of the category today defined as container feeders. In 1969, 22 vessels were delivered and the size of the largest vessels increased to around 1,500–2,000 teu.

In 1972, the first container vessels with a capacity above 3,000 teu were delivered from the German Howaldtwerke Shipyard. These were the largest container vessels until 1981 when Odense Staalskibsværft – Lindø delivered a 3,900 teu container vessel. An increase in size followed with the vessel *American New York* delivered in 1984, where the container vessel size surpassed 4,600 teu. For the next 12 years, the typical maximum container vessel size was in the range of 4,500–5,000 teu. All of these had a breath restricted by the Panama Canal which at the time allowed a breadth of 32.2 m. At that point, the number of vessels delivered had reached a level of 50–70 vessels per year and, with minor fluctuations, it stayed at this level until 1994 when 145 vessels were delivered. However, in 1996, *Regina Mærsk* exceeded this limit with an official capacity of 7,400 teu and a new development in the container market was started with the Post-Panamax category.

Since 1996, the maximum size of container vessels has increased rapidly. In 1998, the largest vessels reached a capacity of 9,600 teu. By 2007, the capacity had almost doubled for the largest container vessels, reaching 17,800 teu. This was the largest size for a nine-year period until 2016 where a new vessel size with a capacity of 20,000 teu was introduced to the market, followed by a 23,000 teu ULCV in 2019. As this paper is written, the largest container vessels have a capacity just above 24,000 teu and were first seen on the market in 2022, and it seems that many more vessels of this size segment are to come in the upcoming years.

Since the early 2010s, and the anticipation of the completion of the new Panama Canal which took place in 2016, the New-Panamax type of container vessel has been a popular category. The dimensions of the two Panama locks are shown in Table 2 along with the maximum permissible vessel dimensions.

Compared to the old Panama lock dimensions (also shown in Table 2), larger margins are required between the vessel and the lock walls, as the vessels are moved into the new locks by tugs instead of being pulled by locomotives running along the locks.

Class	Teu capacity	Approximate dwt	Overall length (LOA) [m]	Breadth (B) [m]	Draught (T) [m]
Small	<1,000	<15,000	<145	<22	<8.6
Feeder	1,000–3,000	15,000–40,000	160–215	23–32.2	11.5
Panamax	3,000–5,100	40,000–65,000	215–295	32.2	12–13
Post Panamax	5,100–10,000	65,000–115,000	272–325	42.8–45.6	12–15
New Panamax	10,000–15,500	115,000–160,000	325–365	48.2–50.8	15.5
ULCV	15,500<	160,000<	400	59–61.5	16–16.5

Table 1: Capacity and sizing of container vessel classes

Dimensions	Length [m]	Breadth [m]	Draught [m]	Height [m]	Teu capacity
Panama Canal lock	320	33.5	14.5	-	-
Panamax vessel	295	32.2	12	57.9	5,100
Lane three lock	427	55	18.3	-	-
New-Panamax vessel	366	51.25	15.2	57.9	13–15,500

Table 2: Dimensions of Panama locks and maximum permissible vessel dimensions [1]

	Length [m]	Breadth [m]	Draught [m]	Maximum cross section [m²]
Suez Canal limits	400	50–77.5	12.2–20.1	1,005

Table 3: Restrictions of the Suez Canal [3]

In 2018, the maximum permissible breadth of a vessel passing the new Panama locks has been extended from the original limit of 49 m to 51.25 m, permitting an additional row of containers. For in-depth knowledge on the propulsion of New-Panamax vessels, see the separate paper “Propulsion of 14,000 teu container vessels” [2].

Until 2010, the limits on the maximum area of the vessel cross-section to transit the Suez Canal posed a limit to the size of the largest container vessels. After the deepening and widening of the canal, these limits no longer pose a challenge for container vessels since a draught of 16.75 m is permitted for 60 m breadth. However, the container vessels are restricted by design to be able to navigate through the canal. If vessels continue to grow in size, these dimensions may again impose a limit. The size limits of the Suez Canal can be seen in Table 3.

The restrictions regarding breadth and draught are not specified at a certain point of the vessel but rather as a cross-sectional area of a maximum 1,005 m^2, which is the limiting factor for a vessel to pass through the canal.

Furthermore, the breadth of container carriers is limited by the range of the container cranes at the terminals. The first vessels to breach the 59 m breadth mark by an additional container row were delivered in 2019, reaching a breadth of 61.5 m which has not been surpassed so far.

The ultimate upper size limit for ultra-large container vessels is imposed by the Strait of Malacca between Malaysia and Indonesia. This is the passage between the Indian Ocean and the South China Sea which many container vessels have to pass and it allows a draught of no more than 20 m.

Today, container vessels are not expected to grow much beyond the 24,000 teu capacity already being delivered because of the size limitations for navigating specific canals and straits but also because of port capacities. If any increases in size can be seen, only smaller increases, like adding an extra row, bay or tier, will be expected to enable the terminals to adjust with taller and longer reaching cranes and deepening of harbours and canals.

Concerns are furthermore raised that on routes with smaller cargo amounts than on the main routes, e.g. Shanghai–Rotterdam, the reduction in cost per container is almost insignificant when comparing a 24,000 teu vessel with a 15,000 teu New-Panamax vessel. Keeping up the utilisation rate will simply be more challenging. Furthermore, operational challenges related to draught restrictions and stacking order on the larger vessels can, along with an increased need for feeder services, cancel out potential savings of operating ULCVs on the smaller routes.

Today, most goods are transported by the larger segment since the vessels larger than Panamax contribute with 67.6% of the teu capacity. The increase in the maximum size of container vessels does not mean that the demand for small feeder and coastal container vessels has decreased. The large vessels do not fit into smaller ports, straits and canals and, therefore, the need for the smaller segments to feed the smaller ports is definitely not negligible. On the contrary, vessels with capacities of less than 3,000 teu, i.e. small and feeder container vessels, account for approx. 55.7% of the number of vessels in the world container fleet, and for 17.8% by teu capacity, as will be elaborated on in a later section. For in-depth knowledge of the propulsion of feeder vessels, see the separate paper “Container feeder” [4].

Naming of vessel size categories

Container vessel classes

The container vessels are throughout this paper divided into main groups or classes depending on teu capacity and hull dimensions. However, adjacent groups overlap and for some teu ranges there are not built any container vessels. Table 1 shows the classes based on teu and approximated dwt, and the most typical range of hull dimensions used in the segments. Table 1 also shows the approximate sizing of the different container vessel classes.

Small (feeder)

Small container vessels are normally applied for short-sea container transportation. In general, the breadth of the small feeders is less than 22 m. The small segment is also utilised as feeders for the larger container vessels in smaller harbours.

Feeder

Feeder container vessels larger than 1,000 teu are normally used to feed very large container vessels but they are also servicing markets and areas with a low demand for large container vessels, e.g. South America – coast of East Africa. In general the breadth of the feeders is 23–30.2 m, sometimes extending to the Panamax breadth of 32.2 m.

Panamax

Until 1988, hull dimensions of the largest container vessels, the Panamax-size vessels, were limited by the length and breadth of the lock chambers of the Panama Canal, see Table 2. The corresponding maximum capacity of a Panamax vessel lies between 4,500–5,100 teu. The maximum dimensions in Table 2 are also valid for passenger vessels but for other vessels, the maximum length is limited to 289.6 m (950 ft).

However, it should be noted that bulk carriers and tankers in this size segment have different size definitions of length and draught. The reason for the smaller length used for these vessel types is that a large part of the world’s ports and corresponding facilities are based on these. More information about the sizing of these segments can be found in the papers “Propulsion trends in bulk carriers” [5] and “Propulsion trends in tankers” [6].

Post Panamax

In 1988, the first container vessel was

built with a breadth of more than 32.3 m. This was the first Post-Panamax container vessel. The Post-Panamax size definition is still often used even after the completion of the new Panama locks. The typical main dimensions of Post-Panamax vessels have varied greatly but in the coming years, the Post-Panamax on order as of 2023, carrying 7,000–8,200 teu, seem to have the standard dimensions:

- Length, L = 272 m
- Breadth, B = 42.8–45.6 m, and
- Draught, T = 13–15 m.

New Panamax

To accommodate a larger proportion of the fleet, the Panama Canal Authority decided to extend the existing two lanes with a bigger third lane with a set of larger lock chambers, see Table 2.

After the increase of the maximum breadth to 51.25 m in 2018, the capacity of New-Panamax vessels has increased from approx. 14,000 to approx. 15,500 teu, making New-Panamax vessels even more interesting since they offer a sufficient economy of scale for other routes as well. In this paper, 15,500 teu is implemented as the upper size limit of New-Panamax vessels since it is the most common at the writing of this paper.

Ultra-large container vessel

The first ultra large container vessels (ULCV) were delivered in 2006–2008 with a capacity of approx. 15,500 teu, and later modified to carry 16,800 teu. After 2008, the idea behind these giants was discarded for some years, but in 2011 the industry picked up the idea and the next segment of ULCVs were delivered.

In 2019, the 23,000 teu limit was breached. Compared to the main dimensions of the earliest ULCVs, these vessels have not increased dramatically in size. The increase in capacity is primarily attained by increasing the fullness of the hull and by separating the deck house from the machinery casing in a twin-island design. Moving the deck house forward, allowed containers to be stacked higher on the hatches. The increased fullness reflects the reduction in service speed experienced since the financial crisis. Container vessels larger than 21,000 teu are sometimes referred to as MGX-24 or megamax-24, where container vessels in the range of 18,000–21,000 teu are referred to as MGX-23. The numbering 24 and 23 is based on the number of container rows allowed in breadth, MGX-23 with 23 container rows in breadth and MGX-24 with 24 containers in breadth.

Orders and deliveries

The development in the number of vessels in the world fleet can be seen in Fig. 3 and Fig. 4 for the period 1990–2025.

Peaks in the number of vessels delivered can be identified around 1998, again around 2006–2008, after which the financial crisis struck the world, and then again in upcoming years where a significant increase in orders can be seen in 2023 and 2024.

When considering the teu capacity of the vessels in Fig. 4, the peaks are not as significant as seen for the number of vessels in Fig. 3.

After 1998, the number of Post-Panamax vessel deliveries took off and after the financial crisis in 2008, the size of the vessels increased, also driven by the high fuel price at the time. At first, many New-Panamax vessels were delivered and since 2012, a significant capacity has been delivered as ULCVs. A significant drop in the number of Panamax vessels can also be seen after the opening of the larger and new Panama lock in 2016.

As of January 2023, the world container fleet consists of some 5,678 vessels in operation with a combined capacity of close to 25.7 million teu – more than a doubling compared to

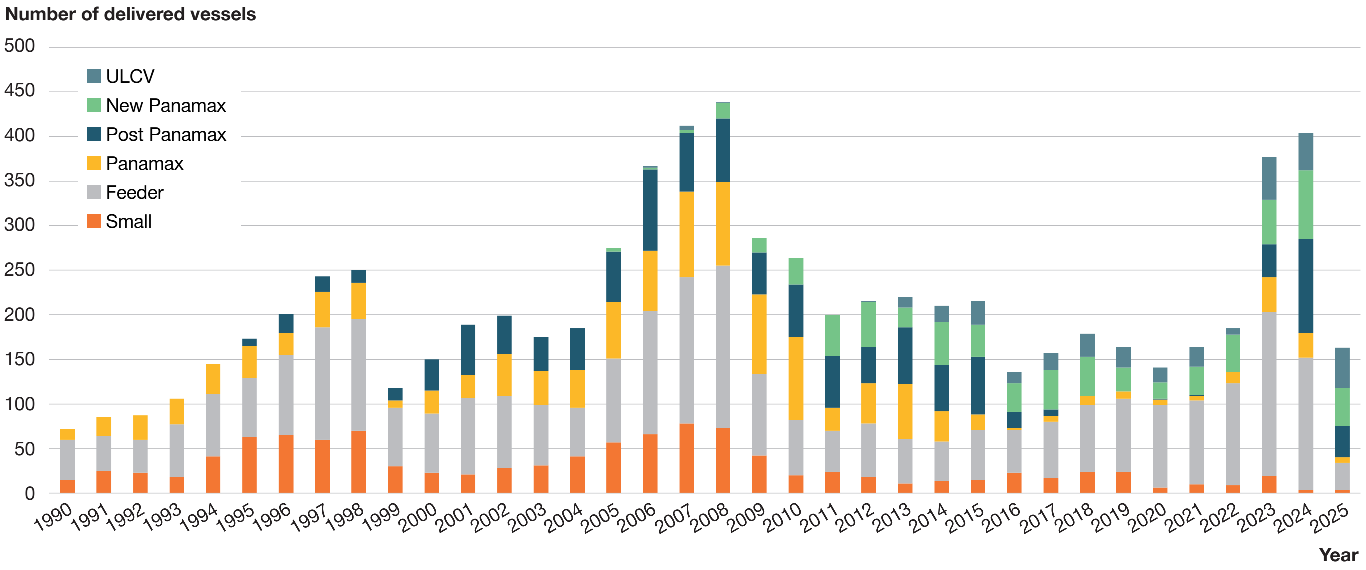

Fig. 3: Number of vessels delivered through the last 60 years

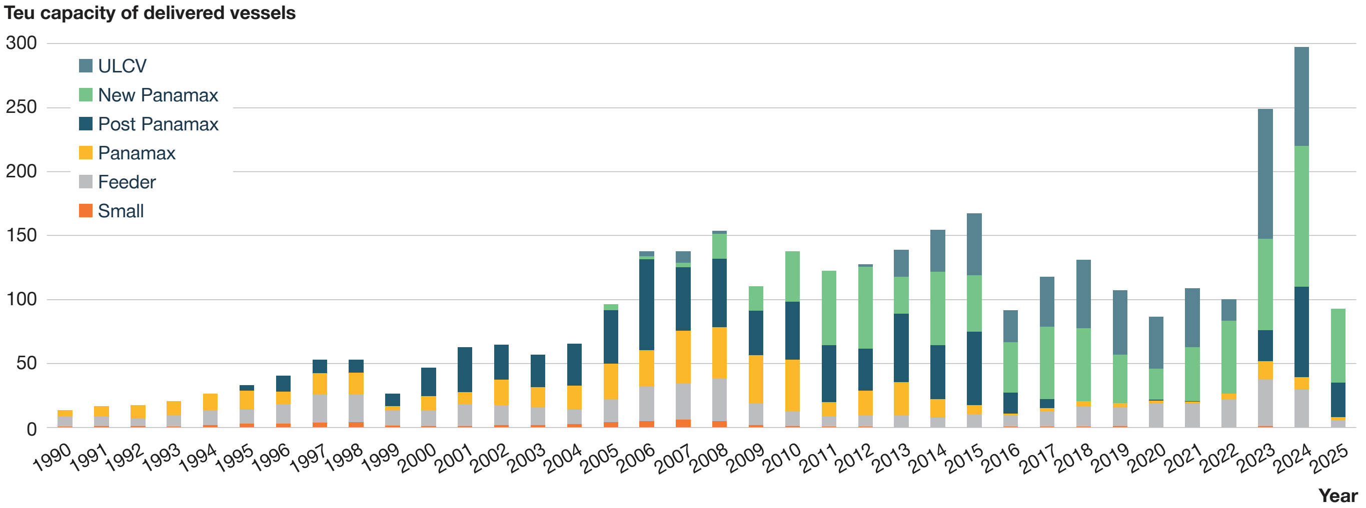

Fig. 4: Teu capacity delivered through the last 60 years

11.8 million teu in 2008. In the same period, the number of vessels in operation has grown by approx. 20%.

Fig. 5 and Fig. 6 describe the percentage distribution of the numbers of vessels in service and the teu capacity within the classes of container vessels, respectively.

In 2008, ULCVs represented 1% of the total teu capacity, whereas in 2023, ULCVs represent 15.1% of the teu capacity. Fig. 5 and Fig. 6 also show that 28.5% of the vessels are larger than the Panamax limit but as stated earlier, these segments contribute to 67.6% of the teu capacity of the global container market.

Age of the container fleet

The lifetime of a vessel is a very important factor for the owner and contractor of the vessel, Fig. 7 shows the number of container vessels delivered since 1960 in five-year periods.

A boom in the late nineties can be identified along with a boom in the years before the financial crisis in 2008. Fig. 8 shows the age of the current fleet. In fact it shows the upcoming demand for new vessels as the figure shows that not many vessels are in operation after 30 years.

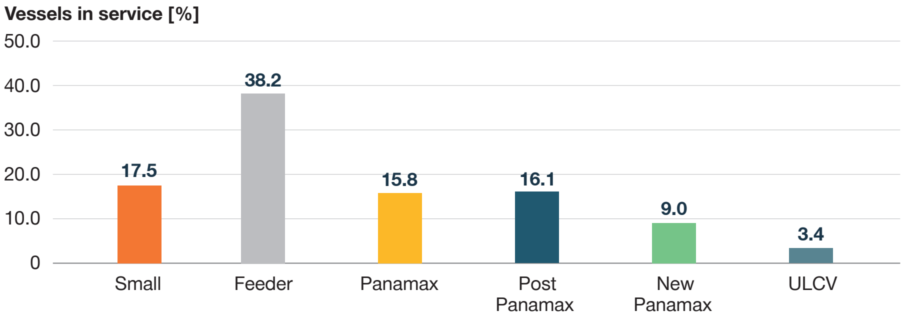

Fig. 5: Percentage distribution of the number of vessels in service

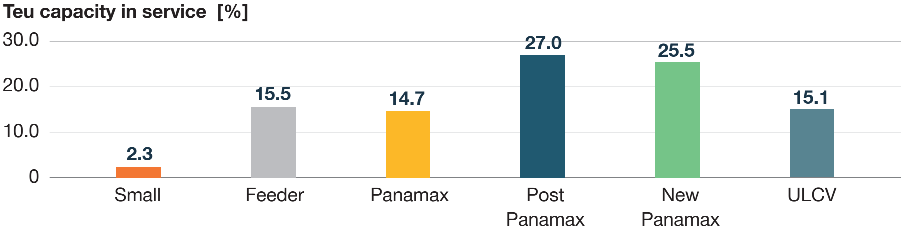

Fig. 6: Percentage distribution of teu carried by vessels in service

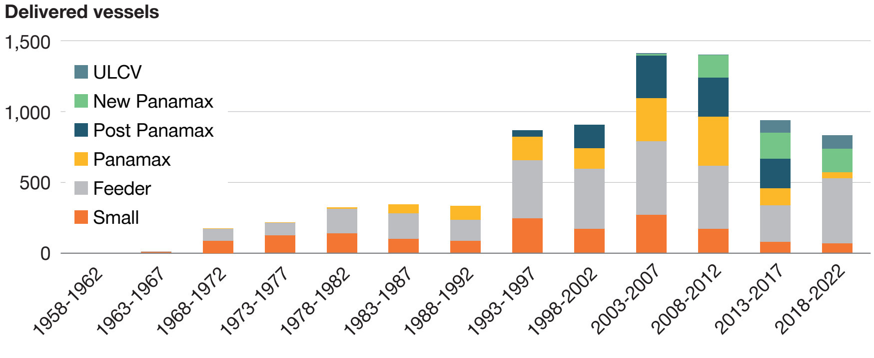

Fig. 7: Number of vessels delivered through the years since 1960

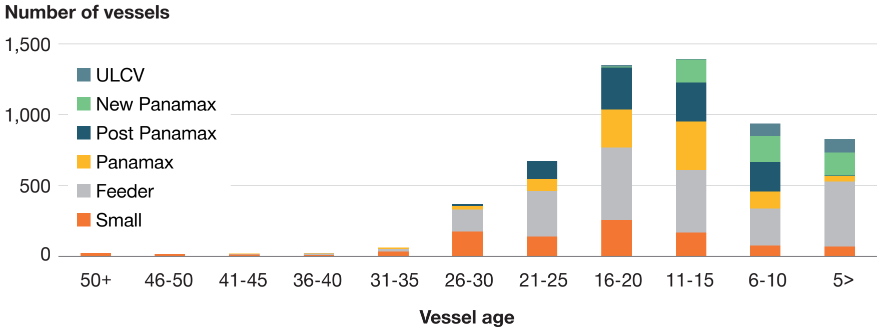

Fig. 8: Age of vessels still in operation

Fig. 9 shows the percentage of vessels still in operation, indicating that around half of the vessels delivered more than 25 years ago are now scrapped, which is also highlighted in Fig. 8 with the decrease in vessels still in service.

Even some of the vessels delivered during 2003–2007 have been scrapped, a faith especially experienced for Panamax vessels, as is also reflected in Fig. 10.

In 2010–2017, when these vessels were released from their initial charter contracts which extended for seven or ten years, charter rates for Panamax vessels had dropped significantly, resulting in some being scrapped.

Converting Panamax vessels for future purposes by increasing their capacity is challenging. Due to stability requirements, the long and typically very slender hull does not allow containers to be stacked higher than they already are. Lengthening or widening will often also be challenging considering the structural integrity of the hull.

Fig. 7 also shows that many feeder vessels have been delivered from 1993 through 2002, and these are now 20–30 years old, leading to the increase in orders for feeder vessels. Furthermore, it shows that the lifetime of most small and feeder vessels extends beyond 25 years. Most Panamax vessels older than 25 years are vessels operating under the Jones Act in the US and this segment seems to have a shorter lifespan than the rest of the vessels. Regarding the ULCV and the New-Panamax segment, these were built later and therefore almost all of them are still in operation to this day. This explains the drastic decline in Fig. 10, since these vessels were built only 20 years ago.

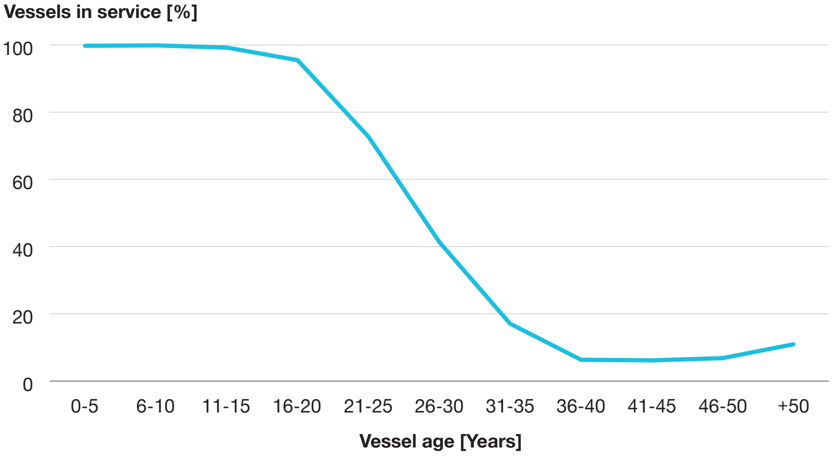

Fig. 9: Lifetime of container vessels in percentage

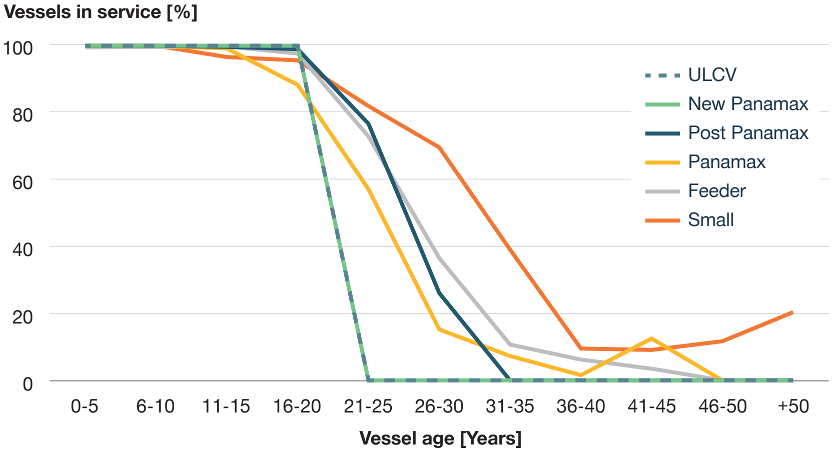

Fig. 10: Lifetime of container vessels in the different classes

Market outlook

As of January 2023, almost 900 container vessels are on order. A number that has increased from 372 orders in 2019 though the number does still not exceed the 1,400 vessels on order in 2008.

The 900 vessels on order correspond to about 15% of the existing fleet in numbers (5,678) and 27% of the existing fleet in teu capacity (25.7 million), indicating a coming significant increase in capacity. Fig. 11 and Fig. 12 show the percentage distribution of ordered vessels and teu across the classes of vessels, respectively.

Considering the number of vessels, feeder vessels outnumber any other size. The current feeder fleet is coming of age with a substantial number of vessels being more than 25 years old, which explains why orders are now placed for new vessels in this segment. By numbers, the Post and New Panamax constitute the second and third largest segments of vessels ordered, whereas by teu capacity, the ULCVs by far represent the majority of the teu capacity ordered.

Interestingly, a low number of small container vessels are ordered which corresponds to only 2.0% of the number of vessels compared to the current fleet, where the small segment contributes to 17.5% of the fleet. For the Post-Panamax segment, the number is increasing as the percentage of vessels on order is 20.8%, where Fig. 5 shows that this contributes to 16.1% of the current container fleet. For Panamax, the share seems to decrease, but this might be related to the massive increase of the ULCV segment from 3.4% of the current fleet to 20.2%. Furthermore, the increase in ordered New-Panamax vessels has gone from 13.1% to 20.7%. The increase in market share for these segments shows that the large segments are getting very popular.

A substantial part of the Panamax vessels on order as of 2023 will not be built to the maximum breadth limits of the old lock dimensions and could also be considered as large feeder vessels. Some of the vessels ordered for the 2,800–5,100 teu Panamax category are even constructed with a specific trade in mind, which is far away from the Panama Canal, and some of these may not fit the old canal locks. This corresponds to the tendency towards increased vessel sizes, as these vessels also may grow in capacity and enter the Post-Panamax class and it would describe why this class segment is increasing.

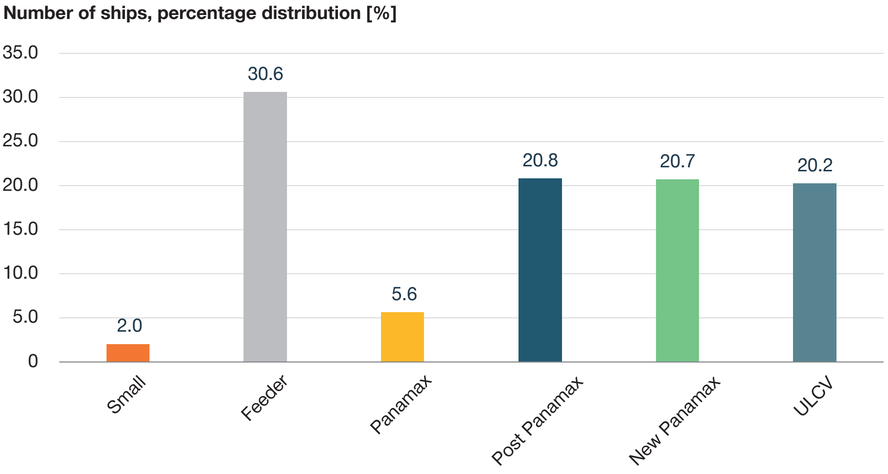

Fig. 11: Percentage distribution of vessel types ordered

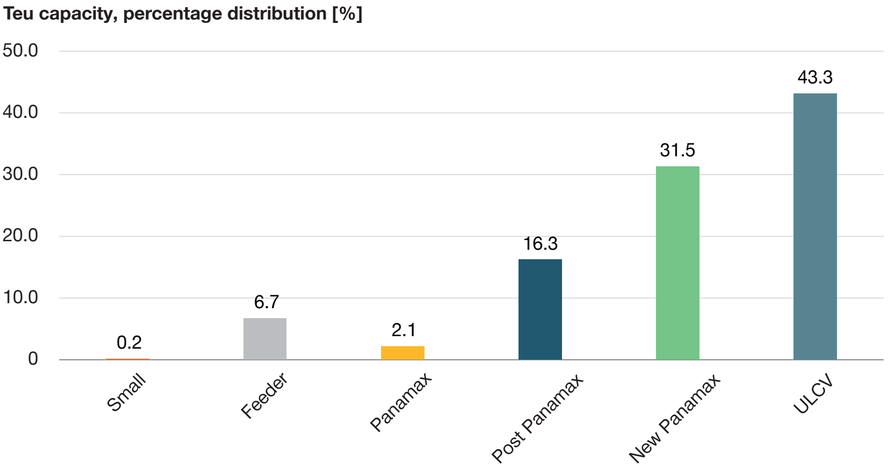

Fig. 12: Percentage distribution of teu ordered in the classes

Vessel sizes

The sizes of the container vessels are given as an approximation in Table 1. The average vessel particulars have been estimated based on container vessels built, or contracted, in the period 2010–2022 as reported in the Information Handling Services (IHS) Fair Play World Register of ships. Compared to previous editions of this paper, some changes in power and speed can be seen as the EEDI Phase 3 has now been fully implemented.

Relation between teu and deadweight

As the sizing of the container vessel depends on the number of teu, it can sometimes be hard to relate to restrictions and how much deadweight these huge vessels can carry. Fig. 13 shows approximated dwt carried and teu allowed for the different ship classes. As Fig. 13 shows, the curve tends to flatten out as the vessel capacity increases but it still seems to be fairly linear.

Fig. 14 shows how the teu/dwt ratio decreases as the size gets larger, this means that the allowed average dwt stored per container will be lower as the vessel increases in size. In the small segment, the ratio starts at 14 dwt/teu and for the largest ULCVs, it has decreased to around 9.5 dwt/teu.

Average hull design factor

Based on the above statistical material, the average design relationship of vessel particulars called the average hull design factor, F_{des}, can be calculated with Eq. 1, see also Fig. 15.

Eq. 1

$$F_{des} = \frac{L_{PP} \times B \times T_{scant}}{teu_{max}}$$

- L_{pp} is the length between perpendiculars
- B the breadth of the vessel
- T_{scant} is the scantling draught
- teu_{max} is the maximum capacity of the vessel expressed as the maximum number of containers that can be stacked on the vessel irrespective of the weight.

Fig. 15 shows that hull dimensions decrease as the allowed teu increases.

Because the hull dimensions are multiplied, the factor $L_{PP} \times B \times T_{scant}$ can be seen as a block, and it means that the size of the ship relative to the number of teu carried is decreasing. This indicates that larger ships can carry more teu in relation to the dimensioning, just as Fig. 14 indicates a lowered dwt per teu carried.

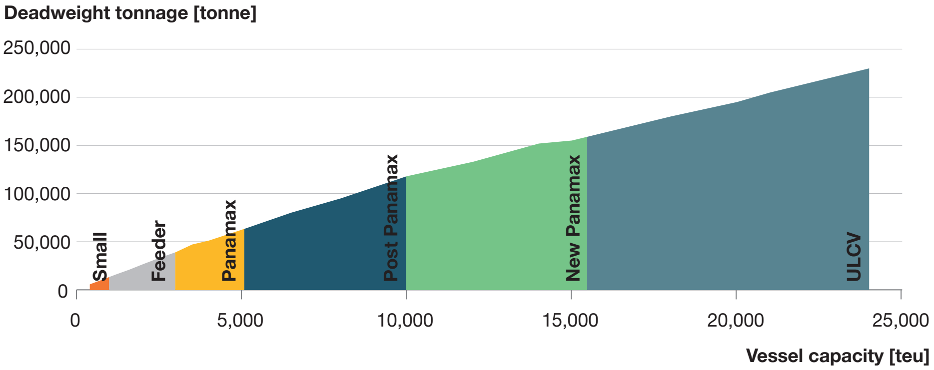

Fig. 13: Approximate relation between vessel deadweight and capacity

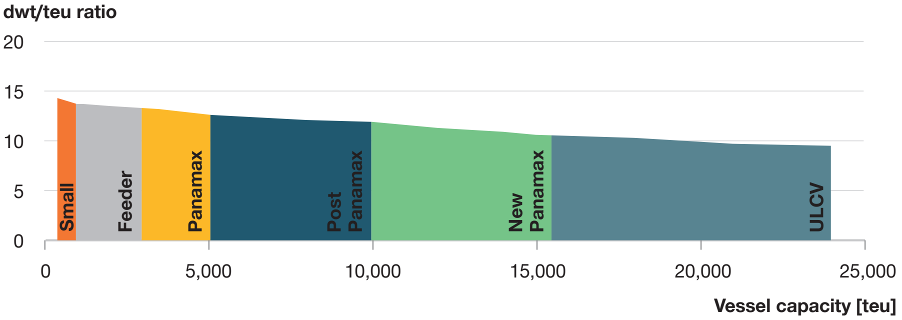

Fig. 14: Approximate dwt per teu as a function of vessel capacity

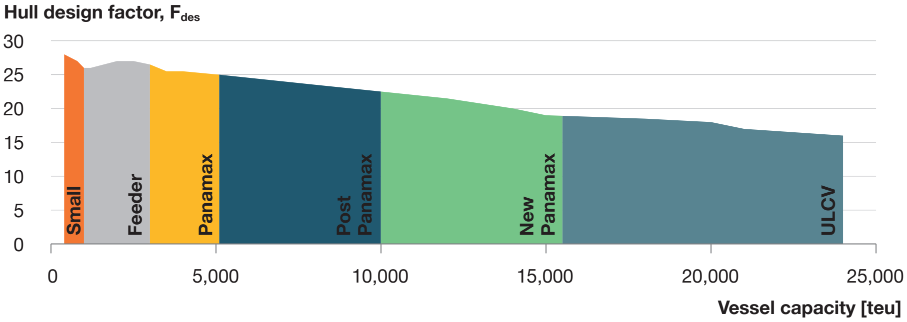

Fig. 15: Hull design factor, F_{des}, as a function of vessel capacity

Hull dimensioning

Regarding the dimensioning of the hull, certain factors set a limit for how these dimensions evolve. Factors such as port sizes, water depths, and straits and canals, all influence the design of the vessels to allow them to fit into desired routes.

Length between perpendiculars

The length of a vessel is heavily influenced by the Panama Canal. Fig. 16 shows that the increase in length for ships of the Panamax range is happening fast, because the limiting factor for the Panama Canal is the breadth. These vessels are very slender until reaching the Post-Panamax segment.

The length of a vessel seems to hit a plateau when exceeding the Panamax segment. This happens when the segment applies a less sleek hull because the breadth of the vessel increases in size, now that the vessel cannot possibly fit within the old Panama Canal locks. It allows extra rows of containers in the breadth of the vessel and gives more stability as the vessel gets wider.

An additional measure for keeping the overall length of the largest ULCVs below 400 m is to design the hull with a straight bow. This can be done either by eliminating the bulbous bow or integrating it in the straight bow, as the maximum allowed length for the largest ports is 400 m.

Breadth

The points made for the length are also valid for the breadth. Fig. 17 shows that all old Panama vessels have the same breadth of 32.3 m as this is the allowed breadth to fit into the older Panama Canal locks.

And for the Post-Panamax segment, the increase in breadth is very significant which perfectly reflects the design measures taken to fit the canal. Fig. 17 shows that for a 24,000 teu ULCV, the breadth is larger since another row is added for this segment.

Draught

When evaluating the development of scantling draught as a function of vessel size, Fig. 18 shows that before the old Panama limit, the draught showed a very steep increase for smaller vessels, whereas for larger vessels the curve flattened out.

And for the ULCV segment, the draught seemed to be steady at 16 m with the largest of them at 16.5 m for 24,000 teu. This tendency shows the importance of operating through the straits and canals since the designs all fit through the Suez Canal since the scantling draught is kept at 16.5 m maximum.

Lightweight

The actual weight of the vessel without containers and fuel is termed

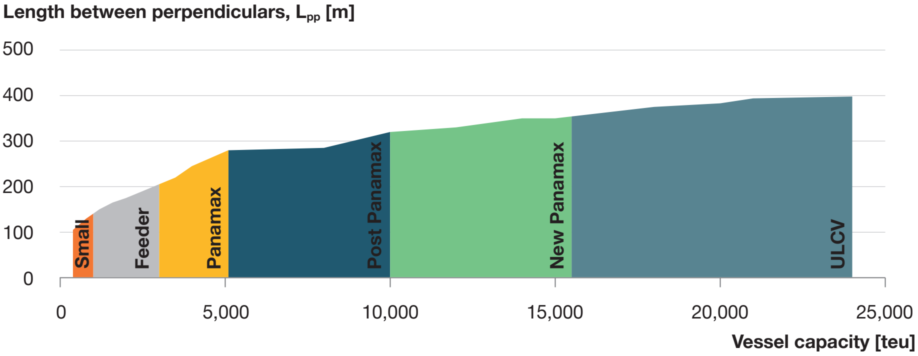

Fig. 16: Length between perpendiculars as a function of vessel capacity

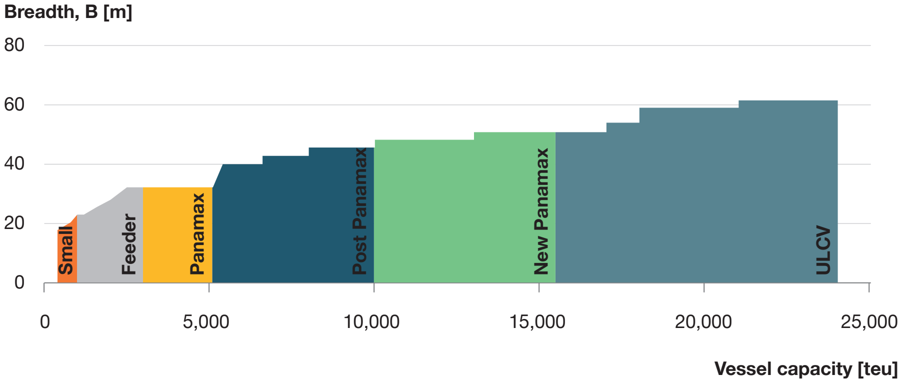

Fig. 17: Breadth as a function of vessel capacity

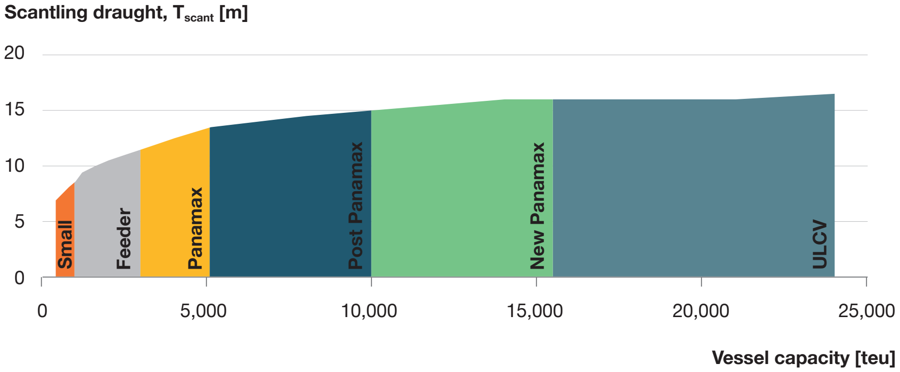

Fig. 18: Scantling draught as a function of the vessel capacity

lightweight, sometimes stated as LWT, and an estimation of the development is illustrated in Fig. 19.

The lightweight denotes steel, appendices, auxiliary systems, outfitting, cranes, and the main engine, etc. As a rule of thumb, the containership lightweight is almost always around 30% of the deadweight, but it fluctuates depending on the vessel type and class. If for example, the vessel operates in icy waters, it has to meet certain standards to be an ice-classed vessel. This means that thicker steel plates are needed to withstand the ice which permits an increase in lightweight. For more information about ice-classed ships, see the paper “Ice classed ships” by MAN Energy Solutions [7].

Block coefficient and Froude number

As the ship is not built as a square block but with a hydrodynamic profile, a coefficient that describes the fullness of the hull is defined as the block coefficient C_b, see Eq. 2 and Fig. 20.

Eq. 2

$$C_b = \frac{L_{pp} \times B \times T_{scant}}{dwt + lwt}$$

Fig. 20 shows that the block coefficient fluctuates around 0.7 for container vessels and that it decreases towards the old Panama Canal limits because of the resctricted breadth allowed in the canal. Then it is kept constant until it reaches a point around the Post-Panamax segment, where it increases again. The largest of the vessels, the MGX-24, has the highest block coefficient which also means that this segment has a fuller hull, compared to smaller vessels with a sleeker hull, to fit more containers within the hull. The block coefficient does not change a lot in magnitude. Other vessels, such as tankers and especially bulk carriers, have a higher block coefficient due to the lower demand in design speed.

Fig. 20 also shows the Froude number, a dimensionless number defined by the speed-length ratio. As the Froude number increases so does the resistance on the vessel induced by water. The reason is that an increased Froude number means increased wave-making resistance. The figure shows a fast decrease in Froude number for the smaller segment and up to the Panamax segment, highlighting the decrease as the teu increases. The reason being that the resistance due to wave making gets lower and the fullness of the vessels decreases as well. Afterwards, the Froude number continues to decrease. Looking back just 5–10 years, the Froude number would not have shown this continuous decrease since the large segments had higher design speeds. Since the large segments have decreased the speed to lower fuel consumption and expenses, and to cope with environmental restrictions, this has caused the Froude number to decrease for the large segment.

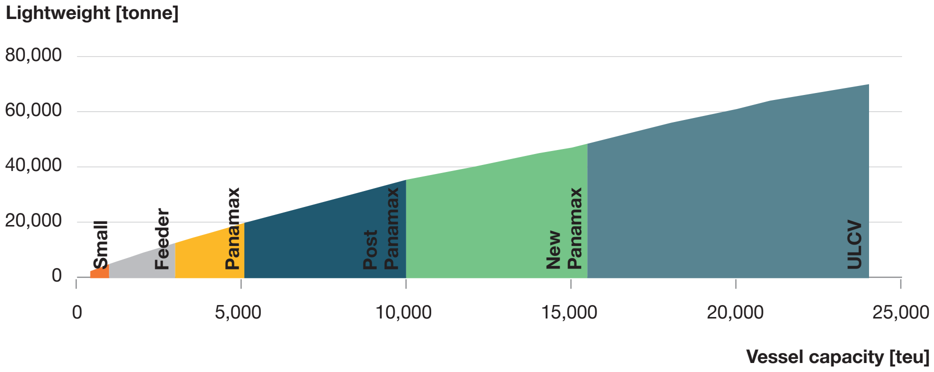

Fig. 19: Vessel lightweight as a function of vessel capacity

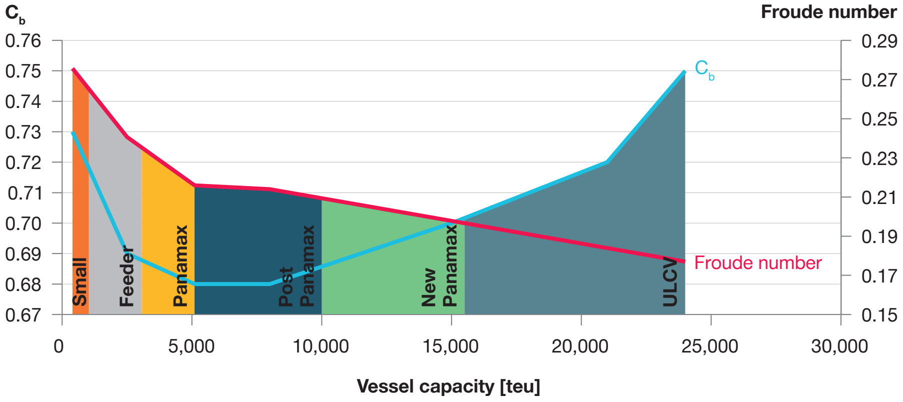

Fig. 20: Block coefficient and Froude number as a function of vessel size

Propulsion

The design speed of container vessels has dropped significantly from 2014 to 2023. The reason is the large consumption of fuel and EEDI restrictions, and the design speeds are lowered to save operational expenses and to cope with the restrictions. Fig. 21 shows that today, most vessels are delivered with a design speed around 22 knots.

For the largest ULCVs, a tendency to reduce the design speed below 22 knots can be identified, breaching the tendency of the past that the service speed would only increase with an increase in vessel size.

Naturally, the reduced design speed implies a reduction of SMCR power as illustrated in Fig. 22, which shows the approximate SMCR for complying with EEDI Phase 3 restrictions of 2023.

This means that vessels using LNG or methanol will be allowed higher SMCRs than vessels designed for VLSFO operation, since these fuels have a lower carbon content, and higher design speeds are possible while still complying with regulations.

Today, this is not the case, as design speed and SMCR is unchanged for alternative fuels as well. The reason that the allowed extra power is not utilised for a higher speed is that the alternative fuel prices are too high. Adding power would result in increased fuel consumption which, in the end, would increase operational costs of propulsion remarkably.

The increased fullness of ULCVs is reflected in the fact that despite similar main dimensions and a lower service speed, around the same power is installed to propel a 24,000 teu vessel and a 20,000 teu vessel. Fig. 20 shows this as an increased block coefficient. Despite this, the kW per teu still reduces with increasing capacity as reflected in Fig. 23, and therefore larger vessels will transport more teu compared to the SMCR power installed.

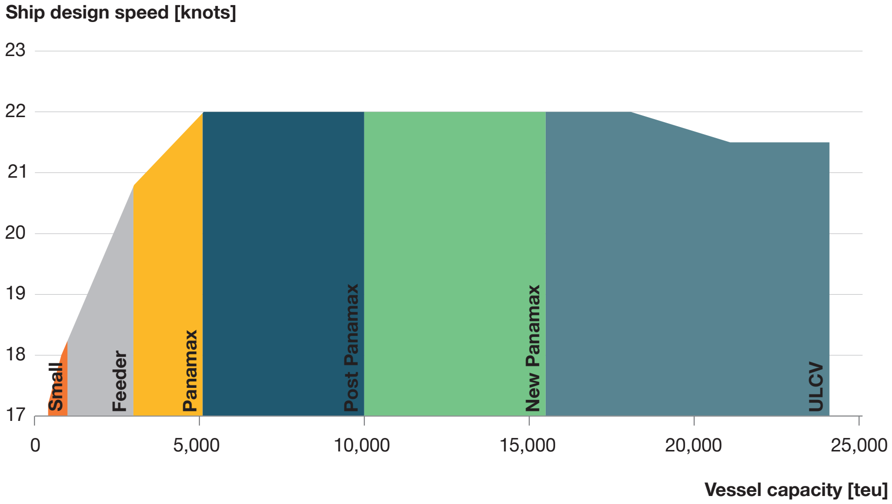

Fig. 21: Design speed in relation to teu

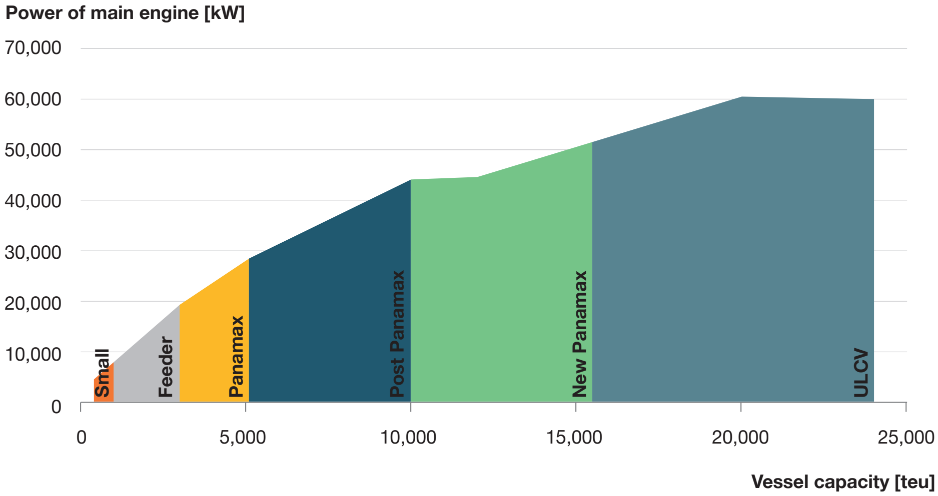

Fig. 22: SMCR power in relation to teu

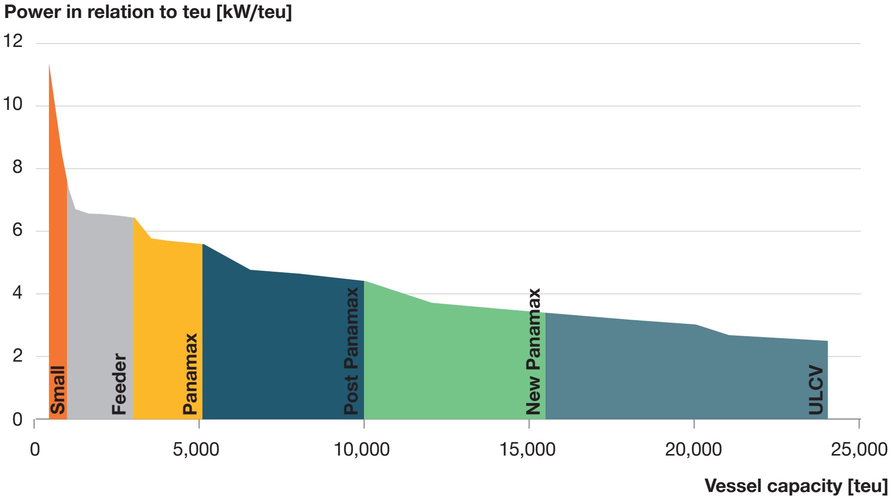

Fig. 23: kW per teu as a function of vessel capacity in teu

For further insights into the propulsion and power requirements of container vessels, the next section about propulsion of container vessels discusses current and future demands and restrictions.

Propulsion of container vessels

Regarding propulsive power, a minimum requirement for the installed power is stated by the IMO for bulk carriers and tankers, but container vessels are by default installed with such high power that the minimum propulsive power is not considered for this segment. The propulsion power of container vessels is determined by balancing fuel costs, environmental regulations, and the desire for a maximum speed to capitalise on demand peaks.

Fuel types

When looking to reduce fuel consumption and emission of greenhouse gases, the obvious choice is to focus on the fuel for main engine combustion.

MAN B&W dual-fuel engines can burn various kinds of fuel depending on the engine design and the desired fuel solution. During the last few years, dual-fuel engines have proved to be very popular and the fuel oil engine has seen a significant decrease in orders in the same period. In recent times, the ME-GI engine operating on LNG has been very popular due to the lowered CO_2 emissions and the extremely low methane slip. The ME-GI is still a popular solution for the largest container vessels in strong competition with the LGIM methanol engine. As of November 2023, methanol engines make up more than 60% of all the dual-fuel engine orders for container vessels, measured in Power and it offers a direct path towards net-zero emissions.

The MAN B&W dual-fuel engine has the possibility to operate on traditional bunker and the second fuel selected. The LGIM engine combined with a scrubber has been specified in some projects since it would be possible to reach a net-zero emission potential along with the fact that the ship can burn HFO and gradually change to methanol when the availability of green methanol increases and the price decreases. However, the vast majority of the LGIM engine orders are not specified with a scrubber and will rely on compliant fuels. An application of a vessel sailing on green methanol has been delivered in 2023 called *Laura Mærsk*.

When considering methanol as a tool for reducing greenhouse gas emissions, it is very important to consider the production pathway of methanol. In the past, methanol has mainly been produced using a combustion process and natural gasses and in a well-to-wake (WtW) perspective, GHG emissions of fossil-based methanol produced in this way are higher than for traditional fuels.

To attain an actual GHG reduction on the WtW level, sustainably produced methanol has to be used. This is a well-known fact and the production of green methanol is picking up fast as a result of the high demand from the maritime sector.

In 2023, MAN Energy Solutions demonstrated the first successful combustion of ammonia (NH_3) in a two-stroke marine engine. MAN Energy Solutions is developing dual-fuel engines capable of operating on ammonia to ensure another option for carbon-neutral shipping in the near future. For the combustion of ammonia, a pilot oil amount will be required to ensure satisfactory ignition, however, minimising the pilot oil amount is a strong focus of the continuous developments. Currently, pilot oil is a requirement for all two-stroke dual-fuel engine types regardless of the fuel type.

This paper compares MDO, HFO, LNG, methanol, and VLSFO, and Table 4 shows the properties of the five fuels together with the properties of ammonia for future reference.

The values for ammonia in Table 4 represent storage at −33°C in liquid form and cooling to keep it liquid at atmospheric pressure, similar to how ammonia is presently transported in NH_3/LPG carriers.

Fuel	Carbon content	Carbon factor, C_F [t CO_2/t fuel]	Density [kg/m^3]	LCV [kJ/kg]	Energy density [MJ/m^3]	Carbon content per GJ	Relative EEDI
MDO	0.8744	3.206	~900	42,700	38,430	75.1	100%
HFO	0.8493	3.114	~980	40,200	39,396	77.46	100%
VLSFO	0.8493	3.114	~940	40,200	37,766	78.4	100%
LNG	0.75	2.750	~450	48,000	21,600	57.3	76%
Methanol	0.375	1.375	~792	19,900	15,760	69.1	92%
Ammonia (NH_3)*	0	0	~696	~18,600	~12,900	0	0%

* Properties are approximations for liquefied ammonia at −33°C and 1 atm (~1 bar) [8]

Table 4: Approximate values for carbon content, carbon factor, density, lower calorific value (LCV), energy density, carbon content per GJ, and relative EEDI for MDO, HFO, VLSFO, LNG, methanol, and ammonia [8], [9], [10]

When considering both the lower heat rate and density of the fuels, the values of Table 4 imply that for a vessel to operate on alternative fuels, the fuel storage space has to be increased.

VLSFO and methanol can be stored at room temperature whereas LNG requires special tanks to keep it in the liquid state below -163°C, at ambient pressure. This implies that storage of both LNG and ammonia requires special considerations for accommodating the fuel tanks onboard the vessels. Smaller vessels, such as container feeders, can store LNG or ammonia in fully pressurised type C tanks. Type C tanks can pressurise the fuel, which will minimise the power consumed for cooling. But there is a physical size limitation and the tanks are cylindrical or spherical. On larger vessels, refrigerated type B and A tanks are more common because of their space efficiency. The tanks have the disadvantage that they cannot withstand significant pressures and require cooling. For ammonia, semi-reradiated type C tanks, also utilised on smaller NH_3/LPG carriers, could be an option for container vessels though there are some extra safety measures to be considered when storing ammonia for combustion as it is toxic.

The comparison of carbon content per GJ for the fuels in Table 4 shows how much the EEDI can be lowered simply by changing the fuel type when considering a tank-to-well (TtW) perspective.

Eq. 3 can be used for calculating the potential EEDI reduction by switching fuel. The example shows a calculation for switching from MDO to LNG.

Table 4 shows the relative EEDI figures from a TtW perspective when switching fuel. Changing from MDO to LNG lowers the EEDI by 24%, whereas a decrease of 8% can be achieved by changing from MDO to methanol while keeping the SMCR speed and power constant. Ammonia does not contain carbon and carbon emissions would be lowered to 0%. The engine will still be emitting some carbon due to the pilot fuel necessary for ignition of the fuel. Note that MDO is used as a reference in the calculation of EEDI in Eq. 3, even though VLSFO or HFO is used in operation.

Eq. 3

$$Relation\ of\ saving\ for\ EEDI = \frac{C_{F,LNG}}{C_{F,MDO}} \times \frac{LCV_{MDO}}{LCV_{LNG}} = 0.76$$

Fuel prices

Prices of alternative and current fuels must be evaluated as well. The prices in Table 5 represent an estimate as of June 2023.

MAN B&W dual-fuel engines provide fuel flexibility. The engine can run on an alternative fuel, such as either LNG, methanol or ammonia and still has the option to burn VLSFO as the main fuel. During operation, the engine cannot burn the different fuels at the same time, but if desired it is possible to switch between the fuels and operate part-time on an alternative fuel and part-time on bunker fuels. This could be necessary to comply with operational restrictions such as CII, FuelEU maritime, and EU ETS while keeping operational expenses at a minimum. The engine can run on the fuel preferred on the current market, depending on fuel prices and regulations of the region.

LNG prices vary a lot depending on the region where it is bought. For methanol, the infrastructure is still under development and the prices will also develop as methanol becomes more common as a fuel for marine propulsion. HFO can also be used since it has the same properties as VLSFO, but it will require the installation of a scrubber due to the increased sulphur content of HFO.

In the future, dual-fuel engines will definitely be the preferred solution. This allows the owner to choose the cheapest fuel solution on the market and decide how to comply with future environmental restrictions, when operational measures, CII and Fuel EU maritime, get into stricter phases. And as the vessels are expected to have a lifetime of around 25 years, it is very important to consider future legislation when planning new projects.

Emission regulations

EEDI and EEXI

EEDI and EEXI guidelines are mandatory instruments adopted by the IMO that ensure compliance with international requirements on CO_2 emissions of vessels. Here, EEDI applies to newbuildings and Phase 3 was implemented in April 2022 for containerships, whereas for existing vessels, EEXI must be complied with on the first annual survey after 1 January 2023. The EEDI represents the amount of CO_2 as gram CO_2 emitted when transporting one deadweight

	USD per GJ	USD per tonne	USD per tonne HFO equivalent
MGO	21.15	903	903
HFO	12.9	551	551
VLSFO	14.9	600	637
LNG	14.1	675	600
Bio-methanol*	36.7	730	1,475
e-methanol*	68.8	1,370	2,770
Fossil/grey methanol	26.6	529	1,050
Green ammonia*	59.5	1,100	2,525

* Price is estimated from [11], [12]

Table 5: Prices of fuels on the market in September 2023 [13], [14], [15]

tonnage of cargo for one nautical mile. The same applies to the EEXI, shown in a simplified version in Eq. 4.

Eq. 4

$$EEDI \approx \frac{CO_2\ emission}{tranport\ work}$$

The EEDI is calculated based on cargo capacity, propulsion power, ship speed, specific fuel consumption and fuel type. However, certain correction factors are applicable for certain ship types, and reductions can be obtained by installing, for example, waste heat recovery systems (WHRS) or power take-off (PTO) systems. This is explained further in chapter 4 in “Basic principles of ship propulsion” [16].

The reference index for the specific ship type is calculated based on data from ships built in the period from 2000 to 2010. According to the EEDI guidelines implemented on 1 January 2013, the required EEDI value for new ships has been reduced in three phases. Phase 3 was later revised for container vessels due to the significant increase in engine power for larger container vessels in the reference period. This resulted in a final EEDI reduction of 15–50% compared to a reference value depending on dwt, which came into force on 1 April 2022. Table 6 shows how the reduction levels of Phase 3 are distributed for container vessels of different dwt values, and approximated teu size for both EEDI Phase 3 and EEXI.

For further information on the calculation of EEDI, and further details on the reduction of EEDI and other environmental regulations, see Chapter 4 in “Basic principles of ship propulsion” [16].

Carbon intensity indicator

The carbon intensity indicator (CII) was implemented by IMO on 1 January 2023, as an operational measure to assess the ship’s efficiency in transporting passengers or goods. Unlike the onetime design performance measurements of the EEDI, CII is a restriction for yearly emissions during operation. It is implemented for all vessels larger than 5,000 gt to reduce the annual carbon emission in operation. The CII calculation is approximately as stated in Eq. 4.

For the carbon intensity indicator, there will be a grading system consisting of ratings A, B, C, D and E. A is best and E is worst. Following three consecutive years of grade D, or one year of E, the owner must submit a corrective action plan on how to reduce carbon emissions. The boundaries shown in Fig. 24 are based on emission statistics of ships from 2019.

The data showed that when using the current CII definition, 15% would be rated E, 20% would be rated D, etc. If for example, a vessel complies with the reference value for 2023 requirements, which is a 5% CII reduction compared to the reference line, it will be graded C. Each year, the required emission reduction must be lowered compared to the reference line. At the time of writing, the extent of the annual reduction is only given until 2026, see Table 7.

As of 2023, Fig. 24 only shows assumptions about the future development of the factors after 2026. CII will be reviewed in 2025 to assess

Dwt	Approximated teu	EEDI Phase 3	EEXI container vessels
Above 200,000	<21,000	50%	50%
120,000–200,000	10,500–21,000	45%	45%
80,000–120,000	6,500–10,500	40%	35%
40,000–80,000	3,000–6,500	35%	30%
15,000–40,000	1,150–3,000	30%	20%
10,000–15,000	750–1,150	15–30%	0–20%

Table 6: Approximate teu relative to deadweight and the applied reduction to ensure EEDI compliance

Eq. 5

$$CII \approx \frac{Annual\ fuel\ consumption \times CO_2\ factor}{Annual\ distance\ travelled \times capacity} \times Correction\ factors$$

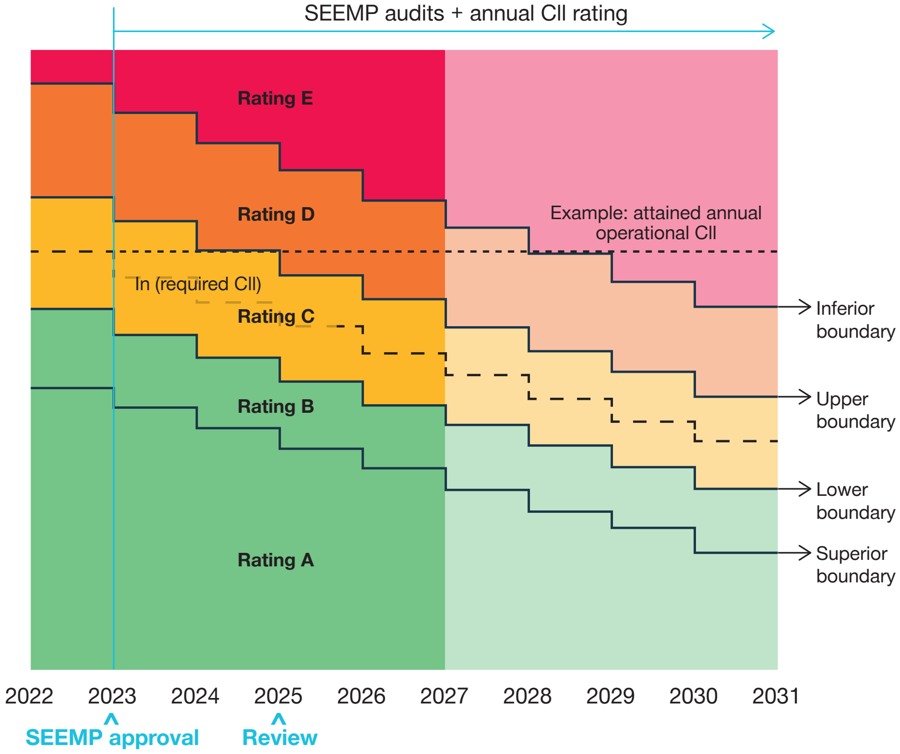

Fig. 24: A reduction of CII will proceed in the future – information about CII can be found in [17] and [18]

Year	Reduction compared to 2019 [%]
2023	5
2024	7
2025	9
2026	11
2027	-

Table 7: The magnitude of reductions [17]

Voyage	Included emissions [%]
Energy used when in berth in an EU port	100%
Energy used on voyages from one EU port to another EU port	100%
Energy used on voyages from a port outside the EU or to a port within the EU	50%
Energy used on voyages and at berths outside of the EU	Not included

Table 8: GHG percentage of the total GHG emitted for a voyage which is included in restrictions/limits [19], [20]

A transhipment port will not be seen as a port call if the port is within 300 nautical miles from a port under the jurisdiction of a European member state.

Neither will it count as a port call if the share of container transhipment exceeds 65% of the total container traffic during the most recent 12-month period.

Table 9: The definition of when a transhipment port is not accounted for

Year	2024	2025	2026
Phase-in factors	40%	70%	100%

Table 10: The percentage of the voyage included in the restrictions as the ETS is phased-in in the coming years

future restrictions. The faded area in Fig. 24 shows the period where the CII reduction has not yet been defined.

EU ETS

ETS is short for emissions trading system, a measure implemented to control the absolute amount of GHG emissions from combustion. Initially, EU ETS was a part of the European directory designed to lower GHG emissions. This included a ‘fit for 55’ package that aims to reduce emissions in the EU by 55% in 2030, compared to a baseline from 1990. For a long time, the maritime sector was not affected by EU ETS regulations, but by 2024 these changes and shipping will be included. As a starting point, regulations will control only carbon emissions, methane (CH_4) and nitrous oxide (N_2O) will be monitored as well, but not before 2026.

The overall goal is to reduce the total volume of GHG emitted. It will be implemented through a ‘cap and trade’ system with an upper limit for emissions, but it will allow involved businesses to buy emission allowances. This allows capacity to be bought and traded from others who have not used up their full allowance. These allowances are based on the shipping company’s identity and therefore not on individual vessels.

Restrictions only include emissions within EU areas plus 50% of emissions to and from EU areas as shown in Table 8.

If a vessel is going for a transhipment port, emissions will still be included and the voyage will not be regarded as a port call under certain criteria. These criteria can be found in Table 9.

The EU ETS will not be directly implemented, to make the transition easier, a phase-in strategy has been agreed on to implement the restrictions in the coming years. The reduction factors will increase in the years 2024–2026, as shown in Table 10.

For EU ETS, the costs of CO_2 emissions are approximately 100 USD per metric tonne equivalent emitted as of 2023 [21]. If this is not complied with, it could mean that an expulsive order is issued at the port of entry in case of non-compliance, or a flag detention order, until the shipping company fulfils its obligations.

Ice-classed ships of class IA or higher may surrender 5% less in allowances. More info about the ETS can be found in [19] and [22].

FuelEU Maritime

The FuelEU Maritime is part of the ‘fit for 55’ package, just like the ETS, aimed at the shipping industry. The purpose is to reduce the GHG intensity of vessels on a fleet basis considering all energy consumed by a vessel.

FuelEU is a new regulation for lowering overall GHG emissions. The FuelEU will come into effect in 2025, and the goal is not only to lower GHG emissions from the combustion of fuel on the vessel but for emissions seen in a full ‘cycle’ perspective from well-to-wake (WtW). This regulation covers, besides the emission of CO_2, also methane and nitrous oxide. It is divided into two parts, well-to-tank (WtT) and tank-to-wake (TtW). As both methane and nitrous oxide have a more severe global warming potential, factors reflecting this have to be included in WtT and TtW calculations for methane and nitrous oxide to be CO_2 equivalent. The global warming potential for these are shown in Table 11.

GWP	
CO_2	1
CH_4	25
N_2O	298

Table 11: Global warming potential for CO_2, methane, and nitrous oxide

WtT contains extraction, transport, refining and distribution contributions to emissions as it is also illustrated in Fig. 25. If the extraction is done from biofuels, or produced from products harvested, this can also be seen as a field-to-tank (FtT) process.

This means that the full life cycle should be evaluated, sometimes denoted as life-cycle assessment (LCA). To evaluate the specific fuel, these two intensities are combined in Eq. 6.

The unit is gCO_2eq/MJ, and the evaluation is done on a WtW basis which does not outline the energy used onboard, but rather the GHG intensity of the fuel used. The overall share of a single ship will influence the intensity on a fleet level, since the larger the emission share from the individual ship, the more it will influence the overall GHG intensity.

Regarding future reduction measures, Table 12 shows the development of reductions from 2025 to 2050.

If these reductive factors are not complied with, penalties can be applied to fleet owners, a fee will be added to make sure that companies do not neglect compliance. As for the ETS, the emissions included follow the same restrictions regarding port calls outside the EU and within the EU, as shown in Table 8. Furthermore, transhipments also follow the same regulations for when a transhipment can be seen as a port call, as shown in Table 9.

In 2030, container vessels and passenger vessels will be required to connect to shore power for stays longer than two hours. If owners do not comply with any of these regulations, it will result in penalties and could even result in vessels being banned from EU waters.

Eq. 6

$$WtW = WtT\ (fuel\ and\ electricity) + TtW(fuel\ consumed, including\ emission\ slips)$$

Year	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Reduction of GHG intensity in 2020 [%]	2	6	14.5	31	62	80

Table 12: Reduction measures for GHG intensity [25]

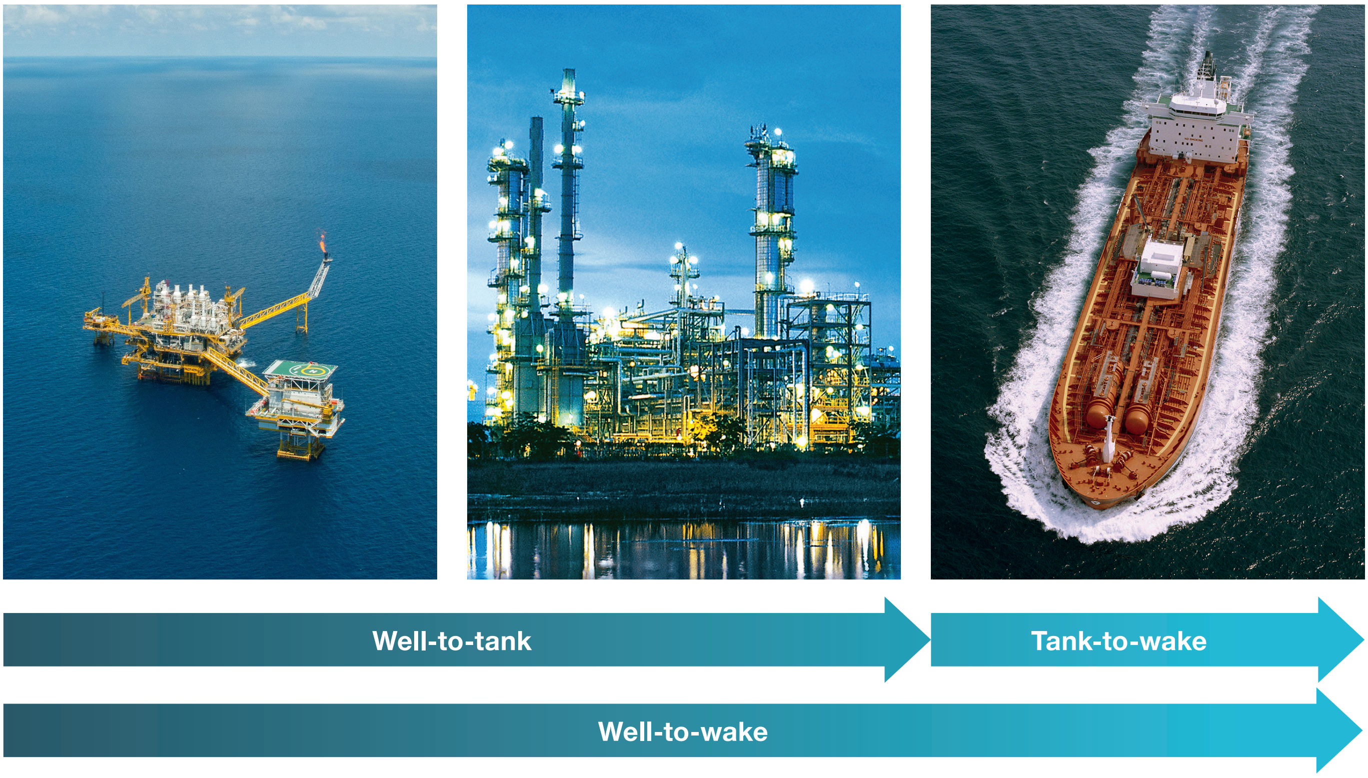

Fig. 25: Illustration of WtT, TtW, and the combined WtW [23]

To get an overview of which fuel types will be compliant, Fig. 26 shows approximate WtW values for 11 different fuel types, and for how long they will be able to comply with the FuelEU regulation if the engine can burn one fuel.

Fig. 26 shows that fossil fuels such as HFO, VLSFO, grey methanol and even grey ammonia will not be able to cope with the regulation from its implementation in 2025. LNG, bio-diesel, and LPG on the other hand seem to have a few more years before falling short of compliance at around 2035 to 2045, depending on which of the fuels are chosen. Almost all the remaining fuels illustrated seem to comply with restrictions until 2050. However, these illustrations include the burning of pilot fuels in the WtW evaluation, which could change as technology develops. VLSFO is commonly used as pilot fuel, and usually it increases the WtW intensity due to the higher GHG intensity. Note, that the dual-fuel GI-engine can run on any type of methane, i.e. fossil LNG, bio-LNG, and e-LNG. And the same is valid for the methanol engine and the fuel types grey methanol, bio-methanol, e-methanol, and blue methanol. This enables a change of fuel and the production path, depending on how fast the infrastructure develops.

The need for lowered WtW intensity again forms a pathway for dual-fuel engines. By operating part-time on different fuel types, the GHG intensity can be lowered as it depends on the gCO_2/MJ. This means that by operating part-time with a lowered WtW emission, or if part of the fleet were to operate on a fuel with lowered WtW emission, the overall GHG intensity will also be affected.

These regulations only apply within the restrictions mentioned above, which means that only operation between, and to and from EU ports will be included. An influential factor is the pricing of these alternative fuels and the development through the upcoming period, and as fossil fuels would impose a penalty, the evaluation of the price of alternative fuels compared to the price of the inflicted penalty is certainly going to be a big discussion point. However the regulation will definitely increase the demand for dual-fuel engines in the long run, depending on the desired lifetime of the vessels, to get the possibility to be FuelEU compliant.

Efficiency improvements

Improving the efficiency of the propulsion system has various benefits ranging from a possible speed increase, lower fuel consumption, and a decrease in emissions. There are several ways to improve the efficiency, but these improvements will come at the expense of the added equipment or interfaces that will allow for an overall increased efficiency of the propulsion of the vessel. The improved efficiency will lower EEDI, CII, and EU ETS costs, as less fuel is consumed and emissions decreased. A few of the possible improvements are outlined in the following sections.

Major propeller and engine parameters

In general, the larger the propeller diameter, the higher the propeller efficiency, and the lower the optimum propeller speed – here referring to an optimum ratio of the propeller pitch and propeller diameter.

The FPP propeller is the typical application in the larger segment since the FPP has a higher propeller efficiency due to the smaller hub. This does not mean that only large ships have an FPP propeller, it should also be evaluated for smaller ships whether port manoeuvrings will be done by bow thrusters or tug boats. The CPP propeller enables a change of the pitch and, thereby, has an advantage when manoeuvring. It makes the CPP the typical application for a vessel with frequent port calls, or ships with the need for improved manoeuvring capabilities. More information about propellers and propeller energy-saving devices can be found in “Basic principles of ship propulsion” [16].

The efficiency of a two-stroke engine depends particularly on the ratio of maximum (firing) and mean effective pressures (mep). The higher the ratio, the higher the engine efficiency, and the lower the SFOC which is exploited

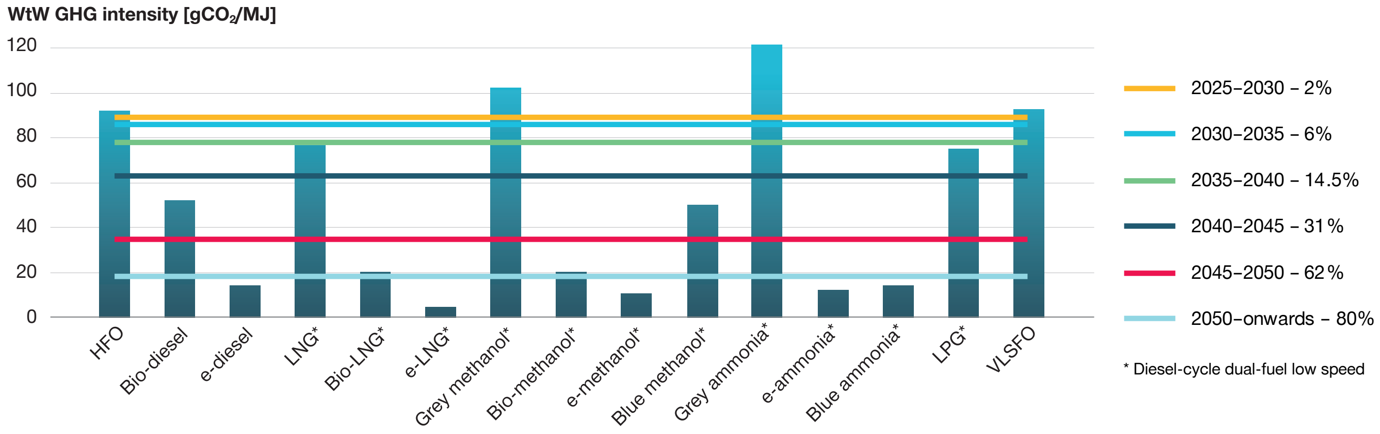

Fig. 26: Different WtW intensity values and an illustration of when it is not compliant with FuelEU regulations anymore

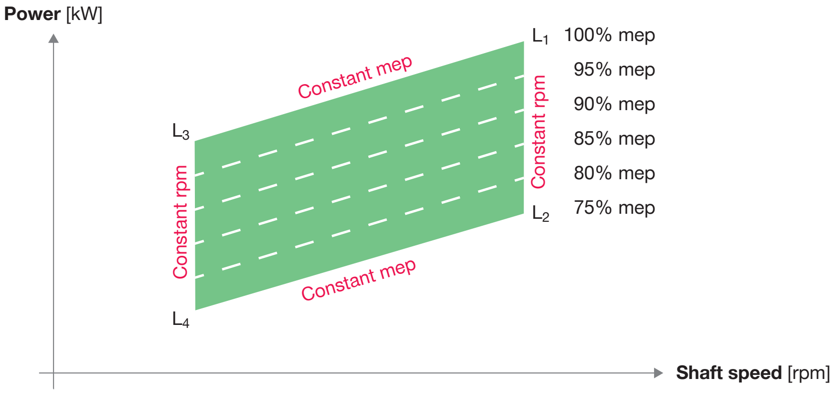

Fig. 27: Engine layout diagram with lines of constant mep and rpm

in a derated engine. For illustrative purposes and to show the derating of an engine in the engine layout diagram, Fig. 27 shows how to decrease the mean effective pressure.

Furthermore, the higher the stroke/bore ratio of a uniflow scavenging two-stroke engine, the higher the engine efficiency since the scavenging process improves with a higher stroke/bore ratio. This means that the ultra-long-stroke G-type engine design has a very high efficiency.

Shaft generator/power take-off systems

Another solution that can be implemented is a shaft generator with a PTO system. A PTO is an addition to the main engine shaft that enables electricity to be produced using the power of the main engine. The installation of a PTO will lower CII, EU ETS, and EEDI because electricity is produced with the efficiency of the main engine instead of auxiliary engines (gensets). The PTO system is relevant for all vessels, but especially for vessels operated on expensive alternative fuels because of the higher efficiency of the energy conversion in the PTO. However, auxiliary engines are still necessary while at port or anchored, as long as the vessel is not connected to shore power.

The power produced by the PTO is limited, though, and most efficiently produced at the highest main engine efficiency. Different parameters, such as the light running margin of the propeller and the power of the engine, limit the power produced. Container vessels would most likely be able to produce the desired power, but the PTO layout limit should be considered to make sure enough power is available. More information about the limitations and the efficiency improvements with a shaft generator can be found in “Shaft generators for low-speed main engines” [26].

Waste heat recovery system

Another way to improve the efficiency of the propulsion system is to implement a waste heat recovery system (WHRS).

The principle of the WHRS-tuned MAN B&W low-speed combustion engine is that part of the exhaust gas flow bypasses the main engine turbocharger(s) via an exhaust gas bypass.

As a result, the total amount of intake air and exhaust gas is reduced which results in an increased exhaust gas temperature after one or more main engine turbochargers and the exhaust gas bypass. This results in an increase of the maximum obtainable steam production power for the exhaust gas-fired boiler – steam, which can be used in a steam turbine for electricity production.

Also, the revised pressure drop in the exhaust gas bypass, which is part of the WHRS, can be utilised to produce electricity by applying a power turbine.

A WHRS can consist of different components and may vary from standalone installations to combined installations.

Choosing a system for a project depends on the power demand onboard the ship (electrical load at sea), the ship’s running profile (number of hours at different main engine loads at sea), the acceptable payback time for the proposed WHRS solution based on the running profile, and the space available on the ship, among others.

Often, the WHRS will be able to supply the total electricity needed as a standalone power source, but it can also run in parallel with a shaft generator, shaft motor, and auxiliary gensets. This type of advanced power system requires an advanced power management system (PMS) and that the engine control system of MAN Energy Solutions is designed to communicate with it.

More information about WHRS can be found in an upcoming WHRS paper [27].

Air lubrication system

One technology that can improve efficiency is an engine supported air lubrication system (ESAL). This is a system that can be implemented on vessels to lower the frictional resistance induced by the water on the hull as the vessel progresses through the water.

The working principle is that by injecting air bubbles underneath the ship’s hull, a layer of air is created which forms a cushion between the water and the hull. This reduces the drag on the flat bottom, as air is approximately 55 times less viscous than water, and thereby improves the hydrodynamic efficiency of the vessel.

As the frictional resistance is reduced, the ship can now move more efficiently through the water. The lower resistance enables an improved vessel speed while keeping either the loading of the engine unchanged or the speed constant but at a lowered load. This also means that less fuel is consumed to keep the desired speed, which results in a higher fuel efficiency. This induces a lowering of emissions and, thereby, also of EEDI, CII, and FuelEU indexes by lowering GHG emissions.

ESAL has already been implemented in a few cases and it was a great addition for lowering the resistance of the ship. See more in an upcoming paper about ESAL and WASP [28], or contact MarineProjectEngineering2S@man-es.com.

Wind-assisted propulsion

Wind-assisted ship propulsion (WASP) seemed to be a thing of the past before the motorised shipping industry took over. But in recent years, WASP has been studied as an application for lowering emissions since the usage of wind power will assist ship propulsion by adding to the main engine power. A conclusion about which technology is best depends heavily on sea state, wind direction and wind speeds. Installation solutions could be a design of traditional sails, wing sails, kites, Flettner rotors, etc.

A few designs have been seen on container vessels, but containers stacked on top of the vessel complicate most solutions because the sails occupy deck space and thereby decrease the teu capacity. However, some solutions with telescopic and retractable sails or kites could show up in the future, if an analysis of correctly fitted sails or kites turns out to be beneficial. More information about ESAL and WASP can be found in the upcoming paper [28], or by contacting MarineProjectEngineering2S@man-es.com

Twin-screw propulsion

Twin-screw propulsion is relevant for the largest ULCVs. They consume vast amounts of energy and face the largest challenges, performing the limbo between a large power margin and a low service speed.

Despite a higher construction cost, some ULCVs have been delivered with twin-screw and – skeg propulsion plants. Twin-screw designs may be relevant for future vessels operating on expensive alternative fuels since the configuration has multiple advantages.

Because the propellers are not located at the centre of the vessel, the speed of the water arriving at the propeller is in general slightly higher, as the flow to the propeller is less affected by the shadow of the hull.

Sharing the load between two propellers of a diameter equal to the diameter applied for a single-screw vessel will reduce the thrust loading coefficient, C_{th}, significantly, and hereby increase the propeller efficiency by approx. 8–9%. This is illustrated in Fig. 28.

However, the hull efficiency, η_{hull}, of twin-screw vessels will decrease by approx. 2–3% as the wake coefficient, w, decreases more than the thrust deduction coefficient, t, recalling the definition of the hull efficiency in Eq. 7.

$$\eta_{hull} = \frac{1-t}{1-w} \qquad \text{Eq. 7}$$

This effect reduces the combined efficiency of a twin-screw propulsion plant, see “Basic principles of ship propulsion” [16]. Twin-screw vessels with two propellers of the same diameter as on a single-screw vessel will typically be able to accommodate an engine of the same bore as the single-screw vessel, with the cylinder number divided between two engines. For low-speed twin-screw vessels, a reduction of the bore size compared to a single-screw vessel may be necessary, typically resulting in a slight reduction of engine efficiency.

Overall, twin-screw propulsion plants are estimated to be 4–6% more efficient for ULCVs compared to single-screw plants. However, as Fig. 28 shows, lowering the speed would cause C_{th} to decrease. If C_{th} decreases significantly, the propeller efficiency would then decrease as well, and a twin screw would not be beneficial.

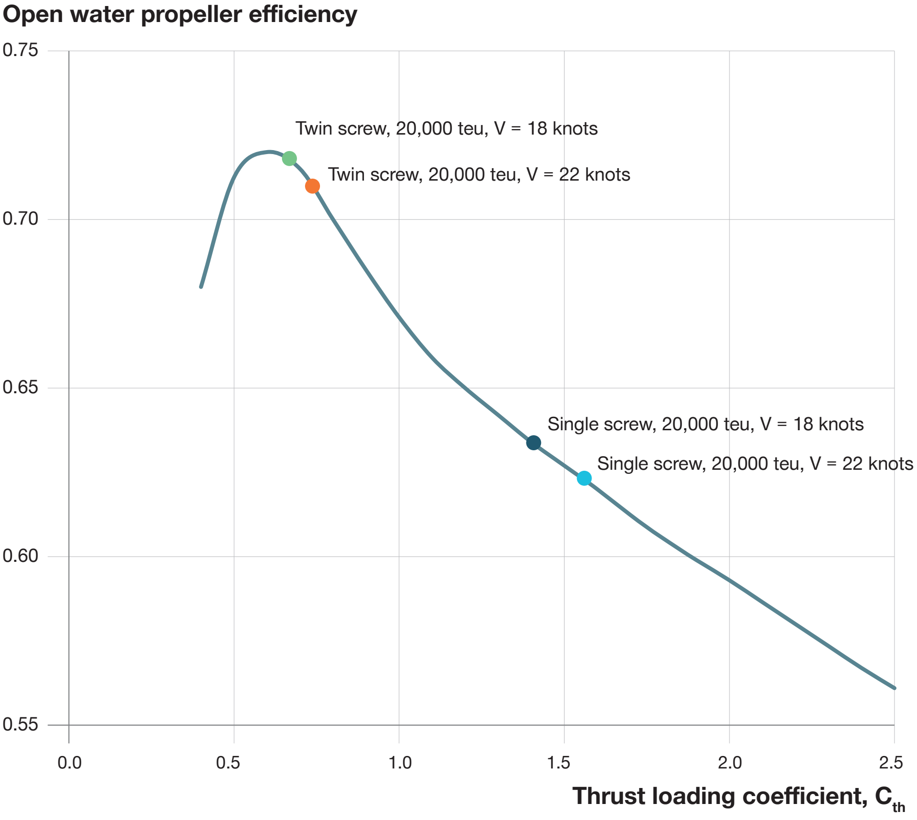

Fig. 28: Increase of propeller efficiency by applying a twin-screw FPP propulsion plant for a 20,000 teu container vessel designed for 18 and 22 knots, respectively

Examples

Container vessel propulsion systems

To put the information in this paper into perspective, examples have been included where a power prediction for various vessel designs has been performed for different sizes and classes of container vessels. The designs are estimated by using mathematical relations for vessel sizes and considering the influence from recently constructed designs. The estimated designs can be seen in the Appendix.

In the Appendix, EEDI has been calculated using a 6% tolerance for SFOC values. The SFOC values are obtained from MAN Energy Solutions' application for engine modelling – our computerised engine application system (CEAS). For auxiliary engines, SFOC values have been estimated at 50% load and an SFOC of 200 g/kWh.

The Appendix shows calculated EEDI values for MDO, LNG, and methanol, and the corresponding EEDI values with and without the application of a PTO. For the overview, only one propeller design is considered, but keep in mind that some designs could have either more or fewer propeller blades than the stated designs.

Another comment is that the SMCR point is not changed for LNG and methanol. This allows for a lower EEDI, compared to the calculation based on MDO, and an increase in engine power to optimise for EEDI Phase 3. The EEDI will be evaluated in 2025 and this could mean further design regulations regarding GHG emissions. Furthermore, operating expenses for these fuels will also influence and contribute to the fact that speed and power will most likely remain unchanged.

The high speed of around 20–22 knots will most likely be maintained at this level for as long as possible, and therefore the possibility of changing the fuel would probably be considered before lowering the speed even further.

Specified examples for given vessel sizes

To put some of the engines further into perspective, examples are given for two different size classes of container vessels. The size classes are a small Panamax vessel of 3,500 teu, which could also be regarded as a large container feeder, and a New-Panamax vessel of 14,000 teu. Parameters for these vessels are given in the Appendix.

Example of Panamax feeder vessel (3,500 teu)

A large part of the fleet is from the feeder segment, 38.5% of the current fleet as seen in Fig. 5. During the last couple of years, container vessels have increased in size, which also means that the Panamax segment not only includes ships going through the Panama Canal, but also the larger feeder segment. In this example, the propulsive system of a vessel of 3,500 teu will be evaluated. For this purpose, the four propulsive configurations in Table 13 have been chosen regarding the engine and propeller.

An important factor for container vessels is the operational expense (opex), as these vessels are expected to be in service for the next 25 years or more. For each engine, an evaluation of whether the different fuel types are an option has been made. The configurations are: Fuel oil engines (diesel) and dual-fuel GI-engines (LNG) and LGIM-engines (methanol). Specific fuel oil consumption (SFOC) is evaluated for fuel oil engines and for dual-fuel engines, specific gas consumption (SGC) and specific pilot oil consumption (SPOC) are evaluated. A comparison of the specific fuel consumptions can be seen in Fig. 29 which shows calculated relative SFOC-equivalents for the four engines. Using SFOC, SGC and SPOC for the different fuels, respectively, Fig. 30

Engine	SMCR [kW]	RPM	NCR [kW]	Dprop [m]	Number of blades
7S70ME-C10 – 19,000 kW	19,000	91	16,150	7.6	5
6S70ME-C10 – 19,000 kW	19,000	91	16,150	7.6	5
8G60ME-C10 – 19,000 kW	19,000	98	16,150	7.6	4
6G70ME-C10 – 19,000 kW	19,000	80	16,150	8.1	5

Table 13: Engine configuration, including propeller diameter and number of blades

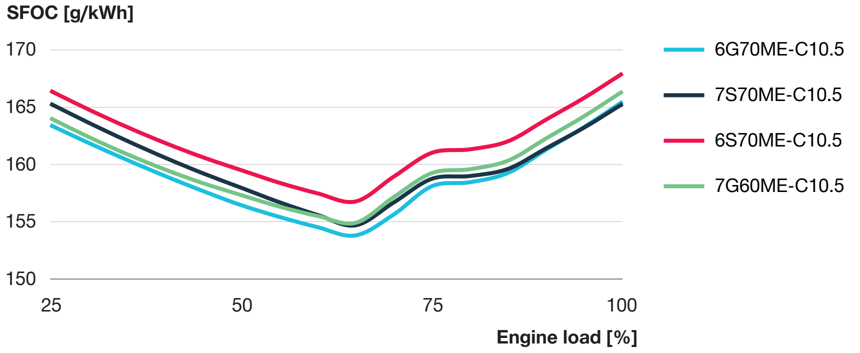

Fig. 29: SFOC values for the three engine configurations as a function of load

shows approximated consumptions. Note that S70 and G70 do not include methanol versions since the engine configuration is not available as of 2023, but for G70 it will become available.

If methanol is the desired option, it requires around twice the weight of LNG and VLSFO. If this is compared to Table 5, it shows that using alternative fuels requires an increase in storage space to accommodate the fuels. Furthermore, the fuel consumption for the GI engine running on LNG is slightly lower than for VLSFO, but as the density of LNG is much lower than for both methanol and VLSFO, the storage space still has to occupy a larger volume. LNG has the disadvantage that it has to be cooled to a certain point or/and pressurised, which complicates storage. If the storage configurations used today for the transportation of ammonia are used, then cooling will also be necessary for ammonia. Pressurising and cooling are not necessary for methanol and VLSFO.

Another thing to consider is the EEDI and future regulations regarding emissions. It is important that the propulsive system complies with current and future regulations regarding emissions, as these will be more strict in the years to come. For the 3,500 teu vessel, an estimation has been made using the relation in Fig. 13 that 3,500 teu corresponds to around 47,000 dwt. This means that for EEDI Phase 3, which was implemented in April 2022, the EEDI value has to be lowered to below 65% of the reference value as stated in Table 14.

The EEDI values in Table 15 have been calculated for the three engine configurations and three fuels, to see which engines can cope with EEDI restrictions. The EEDI has been calculated for each fuel type and engine with and without the implementation of a PTO.

As can be seen, the PTO enabled a reduction of the EEDI, and the margin for errors regarding the EEDI was before only 5.3% for the 6S70ME-C10 running on MDO, with a PTO it would have a margin of 8.7%. It would then be possible to cope with the restrictions due to the large margin. It should also be considered that by switching to alternative fuels, it will not be a problem to comply with the EEDI, and even if further reductions should occur, it seems that methanol and LNG engines would be able to comply. This is of course dependent on future restrictions. But even if the EEDI was not strengthened, other measures such as the FuelEU, CII, and EU ETS will enter stricter regulations. This will again make the dual-fuel engine a suitable solution since it will enable a fuel transition, both on a fleet basis and for single vessels. The dual-fuel engine almost seems necessary for coping with future restrictions, unless the vessels are supposed to go out of service before they are 20 years old.

EEDI	Percentage
Phase 3, 47,000 dwt	65%

Table 14: EEDI Phase 3 requirement for a 3,500 teu container vessel approximated at 47,000 dwt

	EEDI [%] – PTO not included			EEDI [%] – PTO included		
Engine	**MDO**	**LNG**	**Methanol**	**MDO**	**LNG**	**Methanol**
7S70ME-C10 – 19,000 kW	58.9	45.2	-	55.5	42.8	-
6S70ME-C10 – 19,000 kW	59.7	45.7	-	56.3	43.3	-
7G60ME-C10 – 19,000 kW	59	46.2	53.8	55.7	42.8	52.6
6G70ME-C10 – 19,000 kW	58.6	44	-	55.3	41.6	-

Table 15: Corresponding EEDI values in percentage for the 3,500 teu container vessel at a service speed of 21 knots

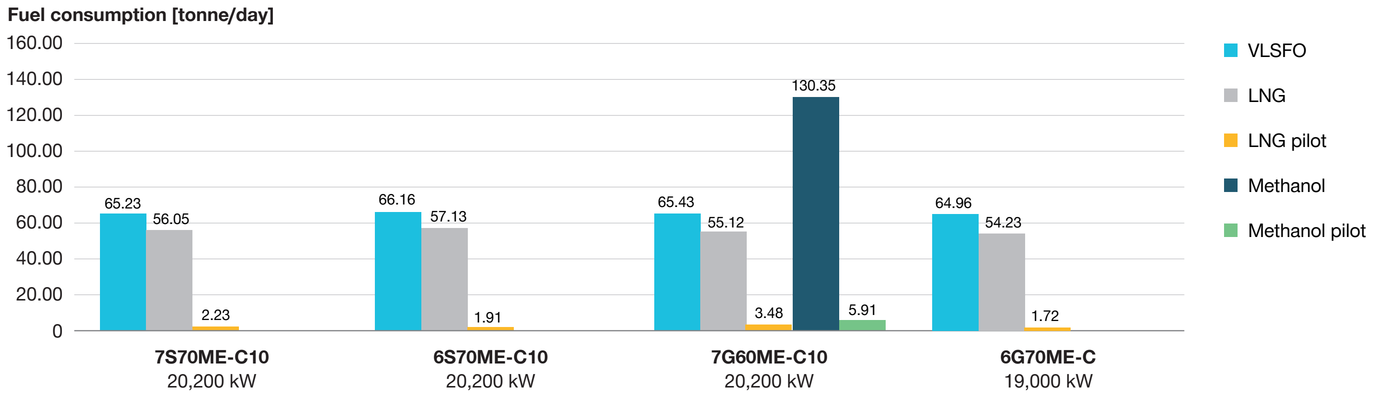

Fig. 30: Engine fuel consumption in tonne/day for each fuel

Operational costs (opex)

To make a proper estimate of the price of the fuel consumption, an operational profile has been developed for the evaluated vessel type. The load profile can be seen in Fig. 31.

To evaluate operational costs, the price of the fuel in Table 7 is taken into account. Mind that the analysis is based on the fact that the pricing of June 2023 will remain. This is of course a very rough assumption but it allows for a comparison of the pricing of the fuels and thereby operational costs.

A comparison of operational costs can be seen in Fig. 32.

Looking at opex, it is clear that the cheapest solution on the current market is the GI engine running on LNG. And as LNG also has a lowered carbon emission, this would enable a lower EEDI, CII, and ETS, regarding the FuelEU, it depends on how the LNG is produced and processed.

Example of New-Panamax vessel (14,000 teu)

The New-Panamax segment has been around for many years but was put into perspective when the new Panama locks opened in 2016. This segment is extremely popular as it can go through the Panama Canal while still fitting a huge number of containers. The New-Panamax segment has shown that the transport costs per teu do not change significantly if the vessel can carry 14,000 or 24,000 teu. This means that this segment is getting very popular and contributes 33% of the transported teu capacity on the current market.

For this segment, only the two engine types in Table 16 are chosen since there is a requirement for high power.

To evaluate the consumption of the engine, SFOC, SGC and SPOC are evaluated for each engine depending on which fuel type is chosen. For the two engines, the SFOC-equivalent values can be seen in Fig. 33 as a function of the loading of the engine.

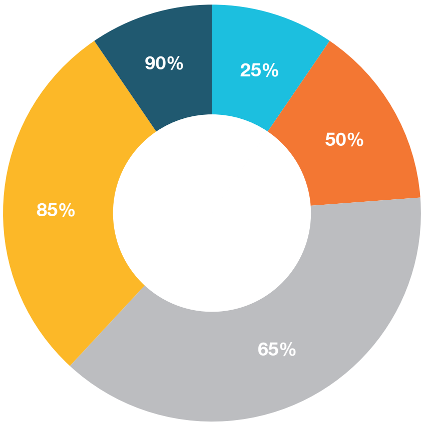

Fig. 31: Load profile of a 3,500 teu Panama container feeder

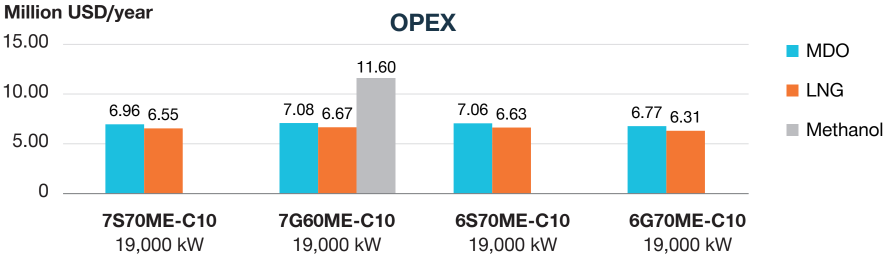

Fig. 32: Comparison of the fuel consumption price per year in million USD/year

Engine	SMCR [kW]	RPM	NCR [kW]	Dprop [m]	Number of blades
9G95ME-C10 – 49,400 kW	49,400	80	41,990	10	5
8G95ME-C10 – 49,400 kW	49,400	80	41,990	10	5

Table 16: Possible engine configurations for a New-Panamax vessel

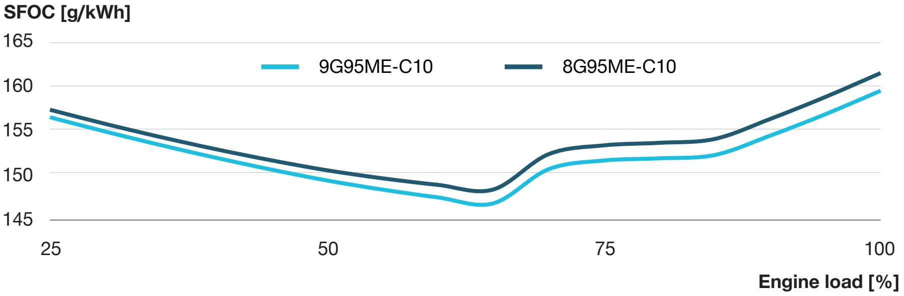

Fig. 33: SFOC values for the two engine configurations

Using SFOC, SGC and SPOC for the different fuels, respectively, approximate consumptions for the two engines can be seen in Fig. 34.

Again, the amount of methanol seems huge because of the low LCV of methanol, where MDO is still the easiest to handle regarding dwt space, storage temperature, and pressure.

Regarding carbon emissions, the EEDI has to be accounted for in the design process of the 14,000 teu New Panamax. An estimation of 152,000 dwt has been made for the 14,000 teu container vessel, which means that the EEDI should be lower than 55% of the reference value from April 2022, as stated in Table 17.

To evaluate the different engines regarding EEDI, an extended version of Eq. 4, also found in [16], has been used to calculate the EEDI value for the fuel types: Diesel, LNG and methanol. The EEDI values can be seen in Table 18.

Table 18 also shows how a PTO affects the EEDI value. If the value is close to the required point, a PTO will make it possible to comply with regulations.

Many more benefits can be found by installing a PTO which is also discussed in the earlier section "Shaft generator/power take-off systems" [26]. The PTO facilitates a reduction of carbon emissions, but changing the fuel type, or choosing a dual-fuel engine will have a much larger influence on GHG emissions. Furthermore, it will facilitate compliance with the other regulations: CII, FuelEU, and ETS and avoid penalties.

Operational expense

Lastly, operational expenses are also calculated. To calculate the operational costs of the vessel, a load profile has been estimated for a New Panama vessel to estimate the operating time at different loads. This can be seen in Fig. 35.

Using SFOC, SGC, and SPOC, operation costs are calculated for the different engines, see the results in Fig. 36.

Opex shows that the 9G95ME-C10 is slightly more efficient which is also shown in Fig. 33 for the SFOC values. For future operation on more costly low- or zero-carbon fuels, efficiency is paramount and the most derated engine would likely be applied. Likewise, the application of any of the dual-fuel engines enables the engine to endure future regulations and navigate the market as prices fluctuate in a desired lifetime of at least 20 years.

This paper does not include the operation of engines on ammonia, or how to convert a containership into operation on alternative fuels. A separate paper has been written about the adaptive measures to prepare a New-Panamax vessel for the operation or conversion towards green-fuel-based operation [29].

EEDI	**Percentage**
Phase 3 – 152,000 dwt	55%

Table 17: EEDI Phase 3 requirement for a 14,000 teu container vessel approximated at 152,000 dwt

	EEDI [%] – PTO not included			**EEDI [%] – PTO included**		
Engine	**MDO**	**LNG**	**Methanol**	**MDO**	**LNG**	**Methanol**
9G95ME-C10 – 49,400 kW	53	39.9	49.9	50.5	38.2	48.9
8G95ME-C10 – 49,400 kW	53.6	40.3	50.2	51.1	38.5	49.3

Table 18: EEDI values in percentage at an approximated speed of 22.4 knots

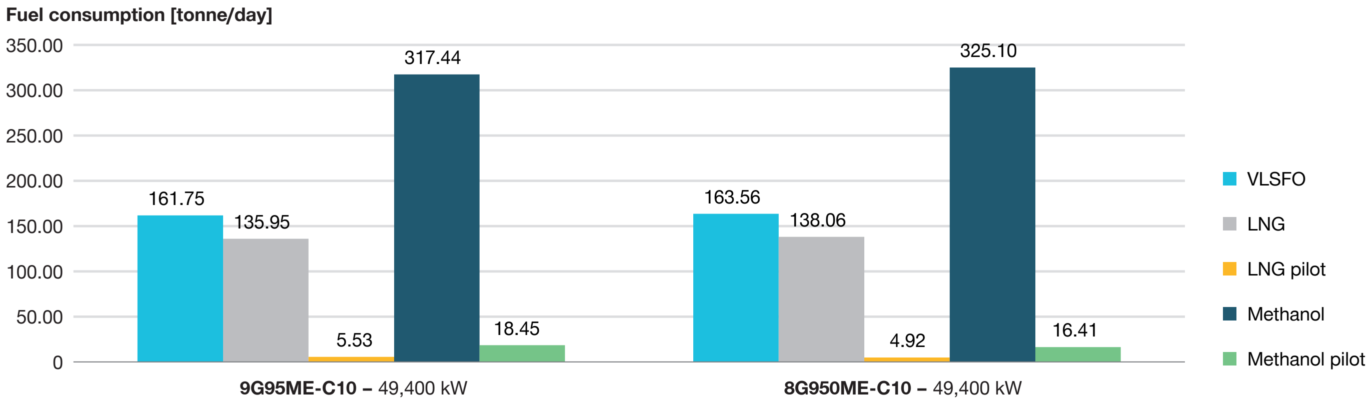

Fig. 34: Engine fuel consumption in tonne/day for the different fuel types

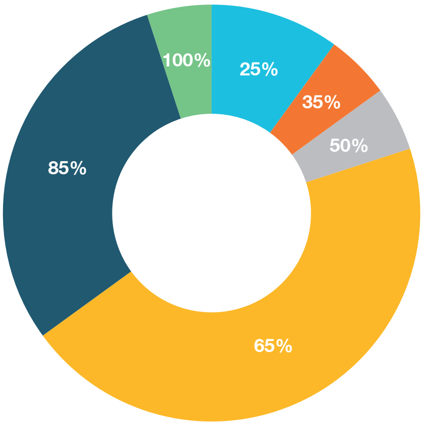

Fig. 35: Load profile estimate for a New-Panamax vessel

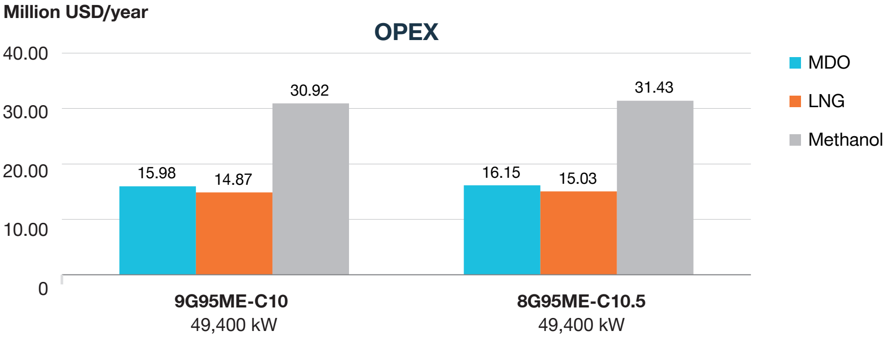

Fig. 36: The price estimate in million USD per year for the operation of a New-Panamax vessel

Summary

The volumes of containerised cargo continue to grow and along with it, the size of the world fleet of container vessels. Container vessels have grown significantly in capacity during the past decade, and ultra-large container vessels constitute 38.7% of the teu capacity on order as of 2023.

Besides ULCVs, New-Panamax vessels attract great interest together with the larger feeder vessels. These three types of container vessels constitute more than 80% of the teu capacity on order and around 70% of the number of ships on order.

For all of these three ship types, significant energy savings have been attained within recent years, and the road for future reductions is laid out: By implementing shaft generators, waste heat recovery systems, and other energy-assisting methods, fuel savings can easily be attained. Both the environment and the owner will benefit from such energy savings.

By installing waste heat recovery or a shaft generator, the overall efficiency of the propulsion plant may be increased even further. Waste heat recovery can be especially relevant for container vessels, as these operate at relatively high service speeds and require a large engine power with a potential for applying waste heat recovery. At the same time, these vessels carry many reefer containers demanding electric energy.

Because of the vast demand for electric energy from the reefer containers, the installation of a power take-off/shaft generator on a container vessel is especially meaningful, also due to the higher attainable efficiency of the main engine.

Besides this, MAN B&W engines offer a large variety of dual-fuel options for various alternative fuels. These alternative fuels can reduce emissions and set the course for lowering greenhouse gas emissions towards a net-zero emission future.

As a concept, it may be worth considering an installation of controllable pitch propellers on vessels in need of increased manoeuvring capabilities. This may give advantages for vessels slow-steaming in the harbour at even lower speeds in the future, but still having the fixed pitch propeller in mind because of the higher efficiency due to the smaller hub.

The implementation of new energy-saving technologies such as wind-assisted propulsion or air lubrication systems could potentially improve the propulsion efficiency of the vessel by lowering the fuel consumption and thereby lowering emissions from the main propulsion system.

An additional option for the largest container vessels is the application of a twin-screw propulsion plant. At increased construction costs, this solution offers the potential for operational savings as the propeller load may be shared between two propellers whereby the propeller efficiency increases under certain circumstances. Some examples were made for two ship types, including a New-Panamax vessel and a larger feeder.

For in-depth cases on the propulsion of feeder vessels and New-Panamax vessels, see the separate papers “Propulsion of 14,000 teu container vessels” and “Container feeder” [2], [4].

MAN B&W S- and G-type engines offer a significant variety of bores and stroke lengths for container vessels. This ensures that an optimum fit can always be achieved for each individual project and that an optimum rpm of a desired propeller always can be contained within the layout diagram of one of the many possible engine designs.

The ultra-long-stroke G-type engines have entered the engine rooms of the largest ULCVs, ensuring significant savings for these vessels. For the many feeder vessels facing renewal within the next few years, the G-engines will offer similar savings.

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Appendix

Category			Small
teu	400	800	1,000
T_{scant}	6.9	8.1	8.6
LOA	108	134	145
L_{pp}	105	130	140
B	17.8	20.4	23
Sea margin	15	15	15
Engine margin	10	10	10
LWT			
Dwt (based on statistics)	5,700	10,800	13,500
Average speed for EEDI Phase 3	17.1	18	18
SMCR power	4,350	6,750	7,350
SMCR speed	146	126	117
Propeller blades	4	4	4
EEDI Phase 3 reduction requirement	-	17.4	30
EEDI [% of reference]	93.4	78.1	71.4
EEDI [% of reference], incl. PTO	87.5	73.1	66.9
EEDI [% of reference] – LNG	69	57	52.5
EEDI [% of reference], incl. PTO – LNG	64.7	53.3	49.2
EEDI [% of reference] – methanol	84	71.1	65.8
EEDI [% of reference], incl. PTO – methanol	78.3	66.5	61.7
Engine options	7S35ME-C9	6S46ME-C8	5S50ME-C10
	6S35ME-C9	5S46ME-C8	7S46ME-C8
			6S46ME-C8

Category	Feeder				
teu	**1,200**	**1,600**	**2,000**	**2,500**	**3,000**
T_{scant}	9.4	10	10.5	11	11.5
LOA	160	175	185	198	215
L_{pp}	150	165	175	190	205
B	23	25.6	28	32.2	32.2
Sea margin	15	15	15	15	15
Engine margin	10	10	10	10	10
LWT					
Dwt (based on statistics)	16,000	21,000	26,500	33,000	39,000
Average speed for EEDI Phase 3	18.1	18.9	19.6	20.2	20.8
SMCR power	8,050	10,500	13,100	16,250	19,300
SMCR speed	111	107	105	104	93
Propeller blades	4	4	4	4	4
EEDI Phase 3 reduction requirement	30	30	30	30	30
EEDI [% of reference]	66.2	66.5	65.8	66.3	65.8
EEDI [% of reference], incl. PTO	62	62.2	61.9	62.8	62.5
EEDI [% of reference] – LNG	48.9	48.9	48.6	48.9	48.6
EEDI [% of reference], incl. PTO – LNG	45.8	45.9	45.8	46.4	46.2
EEDI [% of reference] – methanol	61.3	61.3	60.9	61.4	62
EEDI [% of reference], incl. PTO – methanol	57.4	57.6	57.4	58.2	59
Engine options	6G45ME-C9	7S50ME-C10	7S60ME-C10	7G60ME-C10	7S70ME-C10
	7G45ME-C9	6S60ME-C10	6G60ME-C10	7S60ME-C10	6S70ME-C10
	6S50ME-C10	5S60ME-C10	6S60ME-C10	6G60ME-C10	
	8G45ME-C9			5G70ME-C10	

Category			**Panamax**
teu	**3,500**	**4,000**	**5,100**
T_{scant}	12	12.5	13.5
LOA	235	260	295
L_{pp}	220	245	280
B	32.2	32.2	32.2
Sea margin	15	15	15
Engine margin	10	10	10
LWT			
Dwt (based on statistics)	47,000	51,000	63,500
Average speed for EEDI Phase 3	21	21.1	21.9
SMCR power	20,200	22,800	28,500
SMCR speed	98/91	88	84(80)/72
Propeller blades	4/5	5	5
EEDI Phase 3 reduction requirement	35	35	35
EEDI [% of reference]	62.4	61.7	61
EEDI [% of reference], incl. PTO	59.4	58.8	58.3
EEDI [% of reference] – LNG	46.1	45.5	45.1
EEDI [% of reference], incl. PTO – LNG	43.9	43.4	43.1
EEDI [% of reference] – methanol	57.7	58.5	55.8
EEDI [% of reference], incl. PTO – methanol	55	55.9	53.3
Engine options	8G60ME-C10	7S70ME-C10	6G95ME-C10
	7S70ME-C10	6G70ME-C10	8S70ME-C10
	6S70ME-C10	6S70ME-C10	7G80ME-C10
			6G80ME-C10

Category			**Post Panamax**
teu	**6,500**	**8,000**	**10,000**
T_{scant}	13.8	14.5	15
LOA	295	300	325
L_{pp}	280	285	320
B	40.9	45.6	48.2
Sea margin	15	15	15
Engine margin	10	10	10
LWT			
Dwt (based on statistics)	80,200	95,000	118,000
Average speed for EEDI Phase 3	21.8	22.3	22.7
SMCR power	31,350	37,150	44,100
SMCR speed	75	84(80)/72	84(80)
Propeller blades	6	5/6	5
EEDI Phase 3 reduction requirement	40	40	40
EEDI [% of reference]	56	56.2	56.5
EEDI [% of reference], incl. PTO	54.1	53.8	54.2
EEDI [% of reference] – LNG	41.7	41.5	41.7
EEDI [% of reference], incl. PTO – LNG	40	39.8	40
EEDI [% of reference] – methanol	52.3	52	50.1
EEDI [% of reference], incl. PTO – methanol	50.1	49.8	52.2
Engine options	8G80ME-C10	7G95ME-C10	8G95ME-C10
	6G95ME-C10	6G95ME-C10	7G95ME-C10
	7G80ME-C10	8G80ME-C10	
	7G95ME-C10		

Category			New Panamax
teu	**12,000**	**14,000**	**15,000**
T_{scant}	15.5	16	16
LOA	338	365	365
L_{pp}	330	350	350
B	45.2	50.8	50.8
Sea margin	15	15	15
Engine margin	10	10	10
LWT			
Dwt (based on statistics)	133,000	152,000	155,000
Average speed for EEDI Phase 3	22.3	22.4	22.5
SMCR power	44,600	49,400	51,600
SMCR speed	80	80	80
Propeller blades	5	5	5
EEDI Phase 3 reduction requirement	45	45	45
EEDI [% of reference]	51.4	53.6	51.7
EEDI [% of reference], incl. PTO	49.4	51.1	49.6
EEDI [% of reference] – LNG	38	39.9	38.2
EEDI [% of reference], incl. PTO – LNG	36.5	38.2	36.7
EEDI [% of reference] – methanol	47.6	49.9	47.8
EEDI [% of reference], incl. PTO – methanol	45.7	48.9	46
Engine options	8G95ME-C10	9G95ME-C10	10G95ME-C10
	7G95ME-C10	8G95ME-C10	9G95ME-C10

Category				ULCV
teu	**18,000**	**20,000**	**22,000**	**24,000**
T_{scant}	16	16	16	16.5
LOA	398	399	399	400
L_{pp}	375	383	394	398
B	59	59	59	61.5
Sea margin	15	15	15	15
Engine margin	10	10	10	10
LWT				
Dwt (based on statistics)	180,000	195,000	205,000	230,000
Average speed for EEDI Phase 3	22.6	22.6	21.8	21.7
SMCR power	57,200	60,500	56,300	60,000
SMCR speed	75	75	73	73
Propeller blades	6	6	6	6
EEDI Phase 3 reduction requirement	45	45	50	50
EEDI [% of reference]	51.6	51.9	47	47.3
EEDI [% of reference], incl. PTO	49.5	49.9	45.2	45.4
EEDI [% of reference] – LNG	38	38.4	34.7	34.9
EEDI [% of reference], incl. PTO – LNG	36.6	36.9	33.4	33.5
EEDI [% of reference] – methanol	47.7	48.1	43.6	43.7
EEDI [% of reference], incl. PTO – methanol	45.9	46.2	41.9	42
Engine options	11G95ME-C10	11G95ME-C10	12G95ME-C10	12G95ME-C10
	10G95ME-C10	10G95ME-C10	11G95ME-C10	11G95ME-C10
			10G95ME-C10	10G95ME-C10

Category		**ULCV**
teu	**twin**	**20,000**
T_{scant}		16
LOA		399
L_{pp}		383
B		59
Sea margin		15
Engine margin		10
LWT		
Dwt (based on statistics)		195,000
Average speed for EEDI Phase 3	Number of engines	22
SMCR power	x2	26,300
SMCR speed		66
Propeller blades		4
EEDI Phase 3 reduction requirement		45
EEDI [% of reference]		46.1
EEDI [% of reference], incl. PTO		44.3
EEDI [% of reference] – LNG		34.1
EEDI [% of reference], incl. PTO – LNG		32.7
EEDI [% of reference] – methanol		42.7
EEDI [% of reference], incl. PTO – methanol		41
Engine options		8G80ME-C10
		7G80ME-C10
		6G80ME-C10
		6G95ME-C10

Table 19: Various vessel designs, including an estimation of engine power and speed. Furthermore, an evaluation of the corresponding EEDI has also been carried out

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