PREDICTION OF THE ULTRA-LARGE CONTAINER SHIPS’ PROPULSION POWER AT THE INITIAL DESIGN STAGE

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Resume

Container ships represent the fastest growing segment of maritime transport. The need to reduce unit transportation costs and environmental impact has led to development of the most capacious ultra-large container ships operating on the world’s major shipping routes. A representative database of ultra-large container ships was created and further subdivided according to the main technical parameters. Using a simple cubic regression model, based on the least squares method, an equation, compliant to the general propeller law, was developed to predict the propulsion power of ultra-large container ships as a function of their sailing speed. The results obtained using the developed equation should be sufficiently close to the results of the exact verification calculations at the technical design stage. Then this prediction would find application in the design of both main propulsion, as well as waste heat and cold recovery systems.

1 Introduction

Maritime transport currently handles around 80% of the volume of global trade in goods. Its fastest-growing component is container transport. The weight of cargo transported by containers between 1990 and 2019 recorded a massive nine-fold increase, shown in Figure 1 [1]. The popularity of containerization results from easier distribution and shorter loading time of cargo on board ships, the protection against external factors and, most importantly, the possibility of transporting further without having to reload the goods in the container - known as intermodal transport [2].

The enormous progress in ship technology has helped to increase the dimensions and performance of container ships. In the period 1968-2021, the loading capacity of the largest container ship increased from 1,530 to 23,992 TEU (Twenty-foot Equivalent Unit), i.e. by a massive 1,468 % (Figure 2). This development continues unabated. In the next few years, new records are expected to be broken and previously unattainable limits of capacity to be exceeded.

The economic benefits of operating ever-larger ships on the world’s major shipping routes (East Asia - Northern Europe and East Asia - Northern America) has led to creation of ultra-large container ships (ULCS) of unprecedented size. The ultra-large generation appeared in 2006 with the Emma Maersk, the first container ship with an overall hull length of nearly 400 metres and a cargo capacity of 14,770 TEU [4].

Initially, this generation included all container ships with a cargo capacity of at least 14,501 TEU. However, this criterion has become obsolete with the more effective use of hull space and the location of more and more containers within the same area. The first container ships with dimensions corresponding to the slightly smaller very-large type and with a larger capacity than Emma Maersk were the UASC A15-class (15,000 TEU, delivery year 2014, length overall 368 m, beam 51 m). The largest very-large ones are currently the HMM Nuri-class (16,010 TEU, delivery year 2021, length overall 366 m, beam 51 m). Therefore, when comparing the parameters of all the ultra-large container ships in service, it can be conventionally assumed that their unique feature is a length overall of more than 390 metres. The parameters of the most capacious very- and ultra-large container ships are presented in Table 1 [3].

Despite the constantly growing demand for ultra-large container ships, the literature still does not include methods whereby the propulsion power may be approximately predicted. Available methods of predicting propulsion power are limited to the main engine rated power only and do not take into account the

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At the initial design stage, it is impossible to precisely determine the required propulsion power due to the lack of model tests results [9]. At the same time, decisions made at this stage of a project have a fundamental impact on its total cost and duration. Each mistakenly selected parameter requires adjustments at the initial design stage, it is impossible to precisely determine the required propulsion power due to the lack of model tests results [9]. At the same time, decisions made at this stage of a project have a fundamental impact on its total cost and duration. Each mistakenly selected parameter requires adjustments at

![Figure 1 Development of international maritime trade by cargo type](image1)

![Figure 2 Increase of the container ships' cargo capacity](image2)

| Type          | Delivery year | Name        | Cargo capacity, TEU | Reefer plugs | Length overall, m | Beam, m | Draft, m |
|---------------|---------------|-------------|---------------------|--------------|------------------|---------|---------|
| Very-large    | 2021          | HMM Nuri    | 16,010              | 1,200        | 366              | 51      | 16      |
| Ultra-large   | 2021          | Ever Ace    | 23,992              | 2,200        | 399.9            | 61.5    | 16.5    |

latest ultra-large container ships over 20,000 TEU [6]. It is therefore not feasible on their basis to predict the propulsion power required for any sailing speed, which is particularly important for, among others, calculations of waste heat and cold recovery, whose amount is growing with increasing of the propulsion power [7-8].
2 Database of the ultra-large container ships

A ship's propulsion power, required for sailing at any service speed, at the initial design stage can be predicted by comparing the actual parameters of ships in operation. For this purpose, a list of selected real parameters was prepared in the form of a database including 20 different classes of the ultra-large container ships, represented by 144 ships, not older than the average 13-year lifetime [1].

The parameters of the ships in service were obtained from the registers of classification societies [12]. This database does not include ships with unconventional main propulsion system configurations - i.e. Maersk Triple-E-class equipped with a pair of main
### Table 2 Representative database of the LNG-fueled ultra-large container ships [14]

| Ship class          | CMA CGM Jacques Saade |
|---------------------|-----------------------|
| $P_{bs}$, (kW)      | 57,456                |
| $v_{s}$, (kn)       | 22.00                 |
| $v_{r}$, (km/h)     | 40.74                 |

| Engine type         | WinGD 12X92-DF        |
|---------------------|-----------------------|
| $P_{max}$, (kW)     | 63,840                |
| $P_{bs}/P_{max}$ (%)| 90                    |
| $L_{oa}$, (m)       | 399.9                 |
| $L_{pp}$, (m)       | 383                   |
| Cargo capacity, (TEU)| 23,112               |
| Quantity            | 9                     |
| Delivery year       | 2020                  |

*where:*
- $L_{oa}$ - Length overall, (m),
- $L_{pp}$ - Length between perpendiculars, (m),
- $v_{s}$ - Service speed, (kn) or (km/h),
- $P_{bs}$ - Service propulsion power, (kW),
- $P_{max}$ - Main engine rated power, (kW).  

### Table 3 Representative database of the LNG-ready ultra-large container ships [15-16]

| Ship class          | HMM Algeciras | HMM Oslo | MSC Guleun | MSC Mina |
|---------------------|---------------|----------|------------|----------|
| $P_{bs}$, (kW)      | 60,380        | 59,360   | 66,650     | 66,220   |
| $v_{s}$, (kn)       | 22.40         | 22.25    | 23.20      | 23.25    |
| $v_{r}$, (km/h)     | 41.49         | 41.21    | 42.97      | 43.06    |

| Engine type         | MAN 11G95ME-C |
|---------------------|---------------|
| $P_{max}$, (kW)     | 75,570        |
| $P_{bs}/P_{max}$ (%)| 79.90         | 78.55    | 88.20      | 87.63    |
| $L_{oa}$, (m)       | 399.9         | 399.9    | 399.9      | 399.9    |
| $L_{pp}$, (m)       | 383           | 383      | 383        | 383      |
| Cargo capacity, (TEU)| 23,964        | 23,820   | 23,756     | 23,656   |
| Quantity            | 7             | 5        | 6          | 10       |
| Delivery year       | 2020          | 2020     | 2019       | 2019     |

| Ship class          | COSCO Shipping Universe | COSCO Constellation | UASC A18 |
|---------------------|--------------------------|---------------------|----------|
| $P_{bs}$, (kW)      | 57,900                   | 54,960              | 41,800   |
| $v_{s}$, (kn)       | 22.00                    | 21.80               | 19.90    |
| $v_{r}$, (km/h)     | 40.74                    | 40.37               | 36.86    |

| Engine type         | MAN 12S90ME-C | MAN 11S90ME-C | MAN 10S90ME-C |
|---------------------|---------------|---------------|---------------|
| $P_{max}$, (kW)     | 69,720        | 63,910        | 58,100        |
| $P_{bs}/P_{max}$ (%)| 83.05         | 86            | 71.94         |
| $L_{oa}$, (m)       | 399.9         | 399.7         | 399.9         |
| $L_{pp}$, (m)       | 386           | 382           | 385.4         |
| Cargo capacity, (TEU)| 21,237        | 20,119        | 18,800        |
| Quantity            | 6             | 11            | 6             |
| Delivery year       | 2018          | 2017          | 2015          |
The smallest of these (below 18,000 TEU) are no longer being built due to the steady increase in capacity of the next generation of very-large container ships with an overall length of up to 370 m, which has now already reached 16,010 TEU (HMM Nuri, overall length 366 m, width 51 m, 16,010 TEU). The construction of medium-sized ultra-large container ships of the order of 18,000 ÷ 22,000 TEU is also not continuing due to insufficient compensation for increased investment costs.

As shown in figure 7, ships with a length between perpendiculars equal to 383 m, most often associated with an overall hull length of more than 399 m, constitute 45 % of the created database. Ships with a service speed of at least 22 knots constitute 73 % of the created database as presented in Figure 8. This group also includes all ships with a capacity of at least 23,000 TEU. Lower service speeds engines driving two fixed pitch propellers within twin-skeg hull [12]. It includes single-skeg ships with fixed pitch propeller directly-driven by diesel or dual-fuel low-speed main engine (Figure 4).

The created database includes LNG-fueled (Table 2), LNG-ready (Table 3), HFO/MGO-fueled ultra-large container ships’ classes (Table 4). It should also be noted that the classes are groups of sister ships. For example, the CMA CGM Jacques Saade class includes 9 ships built to the same design with exactly the same technical parameters. An explanation of LNG-ready term can be found further below Figure 11.

Figure 6 indicates that more than 35 % of the created database consists of ships with a cargo capacity of 23,000 TEU or more, all of which were built in the last three years. Ships of this size are also in the current order books for the coming years as the only ultra-large type. The smallest of these (below 18,000 TEU) are no longer being built due to the steady increase in capacity of the next generation of very-large container ships with an overall length of up to 370 m, which has now already reached 16,010 TEU (HMM Nuri, overall length 366 m, width 51 m, 16,010 TEU). The construction of medium-sized ultra-large container ships of the order of 18,000 ÷ 22,000 TEU is also not continuing due to insufficient compensation for increased investment costs.

As shown in figure 7, ships with a length between perpendiculars equal to 383 m, most often associated with an overall hull length of more than 399 m, constitute 45 % of the created database.

Table 4 Representative database of the HFO/MGO-fueled ultra-large container ships [5, 12, 14-17]

| Ship class         | Ever Ace | OOCL G | CMA CGM Antoine de Saint-Exupéry | MOL Triumph | Ever Golden | MSC Olympic |
|--------------------|----------|--------|----------------------------------|-------------|-------------|-------------|
| $P_{\text{max}}$ (kW) | 56,600   | 61,530 | 59,370                           | 59,160      | 59,300      | 56,250      |
| $v_r$ (kn)         | 22.20    | 22.50  | 22.25                            | 22.20       | 22.50       | 21.90       |
| $v_s$ (kn/h)       | 41.11    | 41.67  | 41.21                            | 41.11       | 41.67       | 40.56       |

| Engine type | WinGD 11X92 | MAN 11G95ME-C | MAN 11G95ME-C | MAN 11S90ME-C |
|-------------|-------------|---------------|---------------|---------------|
| $P_{\text{max}}$ (kW) | 70,950 | 75,570 | 70,950 | 75,570 |
| $P_{\text{HFO}}/P_{\text{max}}$ (%) | 83.01 | 81.42 | 83.68 | 78.29 | 78.47 | 88.00 |
| $L_{\text{ppl}}$ (m) | 399.9 | 399.9 | 399.9 | 399.9 | 399.9 | 399.9 |
| $L_{\text{ppl}}$ (m) | 383 | 383 | 383 | 383 | 383 | 383 |
| Cargo capacity, (TEU) | 23,992 | 21,413 | 20,954 | 20,170 | 20,160 | 19,437 |
| Quantity       | 14       | 6       | 3       | 6       | 11       | 6       |
| Delivery year  | 2021     | 2017    | 2017    | 2017    | 2016     |         |

| Ship class         | MSC Pegasus | CSCL Globe | CMA CGM Zheng He | CMA CGM Kerguelen | APL Temasek | CMA CGM Marco Polo |
|--------------------|-------------|------------|------------------|-------------------|-------------|-------------------|
| $P_{\text{max}}$ (kW) | 61,530 | 56,800 | 54,936 | 53,960 | 36,900 | 62,910 |
| $v_r$ (kn)         | 22.65 | 22.00 | 21.75 | 21.60 | 19.00 | 23.15 |
| $v_s$ (kn/h)       | 41.95 | 40.74 | 40.28 | 40.00 | 35.19 | 42.87 |

| Engine type | MAN 11G95ME-C | MAN 12S90ME-C | MAN 11S90ME-C | Wartsila 14RT-flex96C |
|-------------|---------------|---------------|---------------|---------------------|
| $P_{\text{max}}$ (kW) | 75,570 | 69,720 | 63,910 | 80,080 |
| $P_{\text{HFO}}/P_{\text{max}}$ (%) | 81.42 | 75.16 | 85.96 | 79.81 | 79.81 | 79.81 |
| $L_{\text{ppl}}$ (m) | 399.9 | 399.7 | 399.2 | 396 | 396 | 396 |
| $L_{\text{ppl}}$ (m) | 383 | 383 | 381.4 | 378.4 | 378.4 | 378.4 |
| Cargo capacity, (TEU) | 19,437 | 19,100 | 17,859 | 16,020 | 16,020 | 16,020 |
| Quantity       | 14       | 5       | 3       | 3       | 3       | 3       |
| Delivery year  | 2016     | 2014    | 2015    | 2015    | 2017 lengthened | 2012    |
Figure 5 Database divided into delivery year [3, 5, 12, 14-17]

Figure 6 Database divided into cargo capacity [3, 5, 12, 14-17]

Figure 7 Database divided into length between perpendiculars [3, 5, 12, 14-17]
are related to slow steaming of the main engine. This parameter was used as the main predictor of the required propulsion power due to its variability over the full range.
to more and more restrictive limits on the emission of harmful substances (i.e. NOₓ, SOₓ and CO₂ set by MARPOL Annex VI) and the development of bunkering infrastructure at ports [18].

3 Results and discussion

The values of the propeller curve constant coefficient, \(c\), of all the analysed ship classes, \(c\) were obtained by transforming Equation (1) resulting from the general propeller law [9, 13, 19]. They are contained in Table 5. The required service propulsion power and service speed values for each ultra-large container ship class was previously included in Table 4.

\[
P_s = c \cdot v^3
\]

(1)

thus:

\[
c = \frac{P_s}{v^2}
\]

(2)

Figure 9 announces that ships equipped with the MAN 11G95ME-C main engine, whose rated power is 75,570 kW in either a single or dual-fuel version, constitute 45% of the created database.

The service propulsion power of ultra-large type container ships is usually 78 ÷ 81% or 86 ÷ 90% of the main engine rated power. These ranges constitute 2/3 of the created database as demonstrated in Figure 10. The size of the used engine margin results from the applied variant of the main engine work optimisation, in which the specific fuel consumption and pollutant emission are the lowest.

Figure 11 outlines that, in total, 51 of the 144 ships assigned to 7 of 20 classes are equipped with propulsion suitable for running on LNG (Liquified Natural Gas). However, only nine ships CMA CGM Jacques Saade-class are currently LNG-fueled [14]. Ships marked as LNG-ready equipped with dual-fuel engines will burn LNG as soon as LNG tanks and fuel gas supply system are installed within the engine room. The popularity of the LNG as marine fuel will continue to grow due to more and more restrictive limits on the emission of harmful substances (i.e. NOₓ, SOₓ and CO₂ set by MARPOL Annex VI) and the development of bunkering infrastructure at ports [18].

### Table 5 Values of the propeller curve constant coefficient of all analysed ship classes

| Ship class       | Ever Ace | HMM Algeciras | HMM Oslo | MSC Gulsun | MSC Mina |
|------------------|----------|---------------|----------|------------|----------|
| \(c\) (kW ∙ kn⁻³) | 5.3560   | 5.3722        | 5.3889   | 5.3375     | 5.3030   |

| Ship class       | CMA CGM Jacques Saade | OOCL G | COSCO Shipping Universe | CMA CGM Antoine de Saint-Exupery | MOL Triumph |
|------------------|-----------------------|--------|-------------------------|---------------------------------|------------|
| \(c\) (kW ∙ kn⁻³) | 5.3959                | 5.4018 | 5.4376                  | 5.3899                          | 5.4072     |

| Ship class       | Ever Golden | COSCO Constellation | MSC Olympic | MSC Pegasus | CSCL Globe |
|------------------|-------------|---------------------|-------------|-------------|------------|
| \(c\) (kW ∙ kn⁻³) | 5.2060      | 5.3049              | 5.3554      | 5.2952      | 5.3343     |

| Ship class       | UASC A18 | CMA CGM Zheng He | CMA CGM Kerguelen | API Temasek | CMA CGM Marco Polo |
|------------------|----------|-----------------|-------------------|-------------|--------------------|
| \(c\) (kW ∙ kn⁻³) | 5.3042   | 5.3392          | 5.3544            | 5.3798      | 5.1513             |
Results of the regression analysis and equations describing relations between given parameters are included in Table 6 [20].

Figure 12 shows the propulsion power of the ultra-large container ships’ as a function of its sailing speed.

The developed Equation (3) can be applied with very high accuracy to container ships with a length between perpendiculars of 378 ÷ 393 m and a sailing speed not exceeding 24 knots. It facilitates a quick and easy prediction of the ultra-large container ships’ propulsion power with sufficient accuracy, which is particularly relevant at the initial design stage, when model tests have not yet been performed.

It is worth noting the very high value of the determination coefficient \( R^2 = 0.9959 \equiv 1 \), obtained when

\[
P_B = P_a - C_v \cdot v^3
\]

where:

- \( P_a \) - Brake power for a given sailing speed, (kW),
- \( c \) - Propeller curve constant coefficient, constant value for a full range of sailing speed, (kW ÷ kn\(^{-3}\)),
- \( v \) - Sailing speed, (kn).

According to Equation (1), the values of the propulsion power were predicted for all the analyzed ultra-large container ships in the range of sailing speed up to 24 knots. Then, the simple cubic regression model, based on the least squares method, was applied. The following equation was obtained as a result of the calculations:

\[
P_B = 5.333 \cdot v^3
\]

Table 6 Regression analysis results [20]

| Parameter                        | Symbol | Value | Equation |
|----------------------------------|--------|-------|----------|
| Sample size                      | N      | 500   | \( N = n_v \cdot n_c \)  
| Confidence level                 | CL     | 0.95  | \( CL = 1 - p \)  
| Standard deviation               | SD     | 22.046.57 kW | \( SD = \sqrt{\frac{\sum_{i=1}^{N} (P_{Bi} - P_{B})^2}{N - 1}} \)  
| Determination coefficient        | \( R^2 \) | 0.9959 | \( R^2 = 1 - \frac{\sum_{i=1}^{N} (P_{Bi} - P_{B})^2}{\sum_{i=1}^{N} (P_{B} - P_{B})^2} \)  
| Standard error of propulsion power| SE     | 985.95 kW | \( SE = \frac{SD}{\sqrt{N}} \)  

where:

- \( n_v = 25 \) - Total number of points related to sailing speeds between 0 and 24 knots with an interval equal to 1,
- \( n_c = 20 \) - Total number of ship classes, including a total of 144 ships,
- \( p = 0.05 \) - Assumed p-value (probability value),
- \( P_a \) - Propulsion power, the actual value of the dependent variable, (kW),
- \( P_{Bi} = P_a \) - Propulsion power, the predicted value of the dependent variable based on the regression model, (kW),
- \( P_B \) - Propulsion power, the mean value of the actual dependent variable, (kW).

Figure 12 Propulsion power of the ultra-large container ships’ as a function of its sailing speed
developing an equation for predicting the propulsion power, which indicates a strong relationship between the dependencies under study and choosing the appropriate regression model. This enables the use of Equation (3) with a high probability that the initial calculations would be satisfactorily similar to the results of the exact verification calculations at the technical design stage.

4 Conclusions

A unique feature of all the ultra-large container ships is a length overall of more than 390 meters. The cargo capacity of the most capacious ship has already reached nearly 24,000 TEU and is still growing. The typical configuration of the main propulsion system of the ultra-large container ships consists of a fixed pitch propeller directly-driven by diesel or dual-fuel low-speed main engine. The service speed is the main predictor of the required propulsion power due to its variability over the full range. The calculations based on Equation (3), using a simple cubic regression model, allows the propulsion power to be predicted with sufficient accuracy at the initial design stage, when the model tests results are not yet known. The obtained results would be useful for the design of main propulsion systems, as well as waste heat and cold recovery, whose amount is related to the propulsion power.

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