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.

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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 contenerization 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

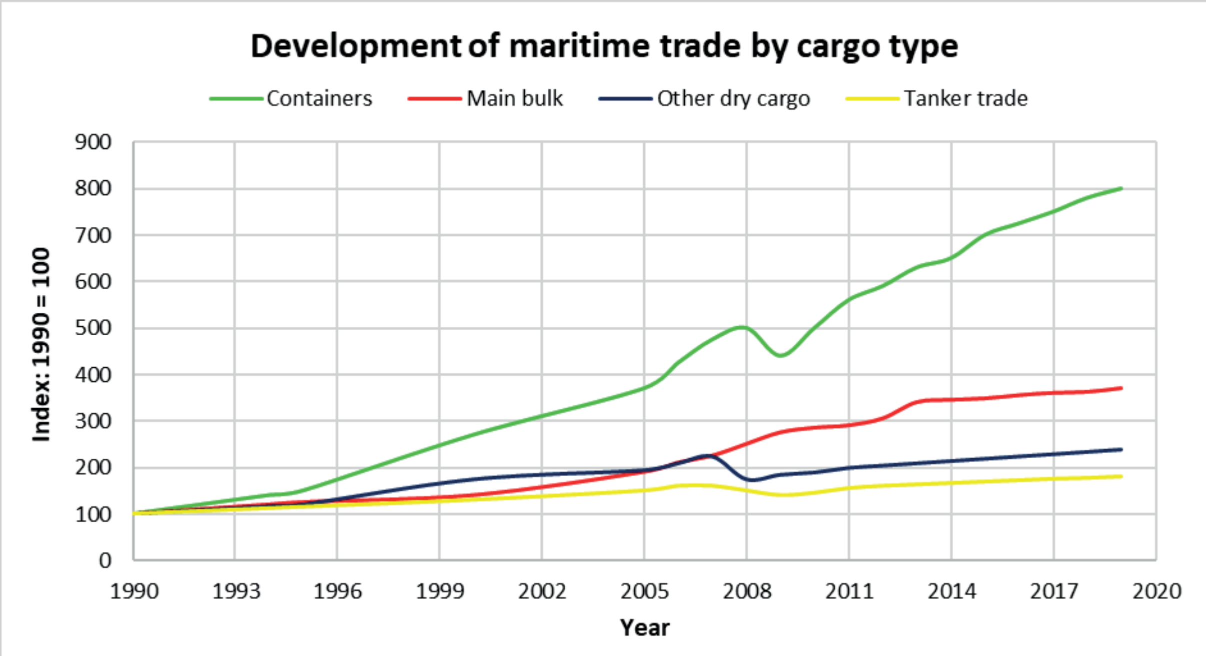

Figure 1 *Development of international maritime trade by cargo type [1]*

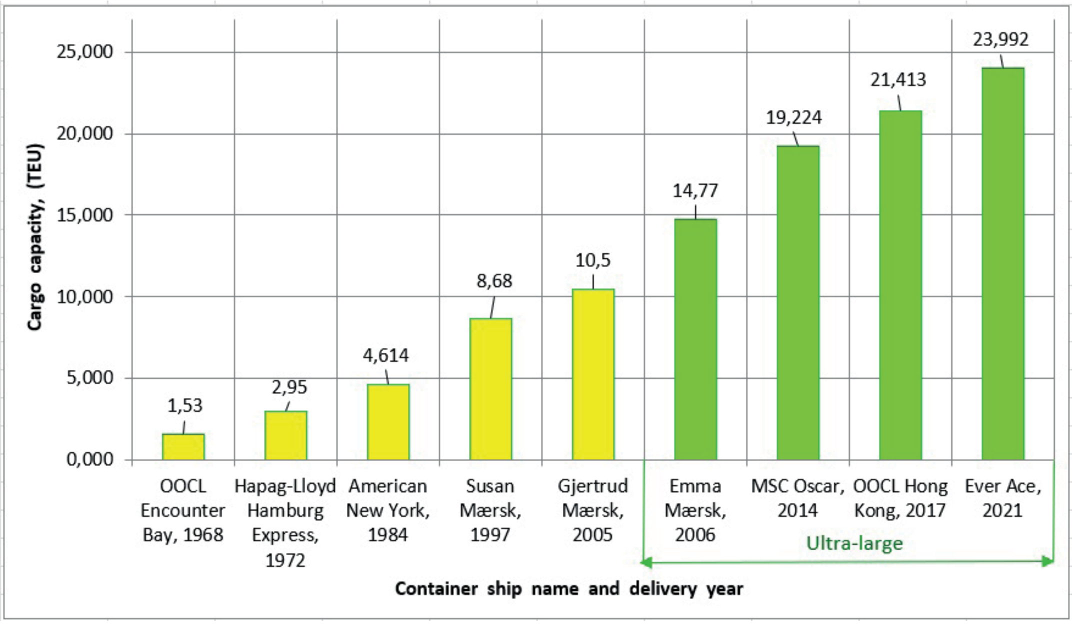

Figure 2 *Increase of the container ships' cargo capacity [3-4]*

Table 1 *The most capacious container ships [3, 5]*

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].

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

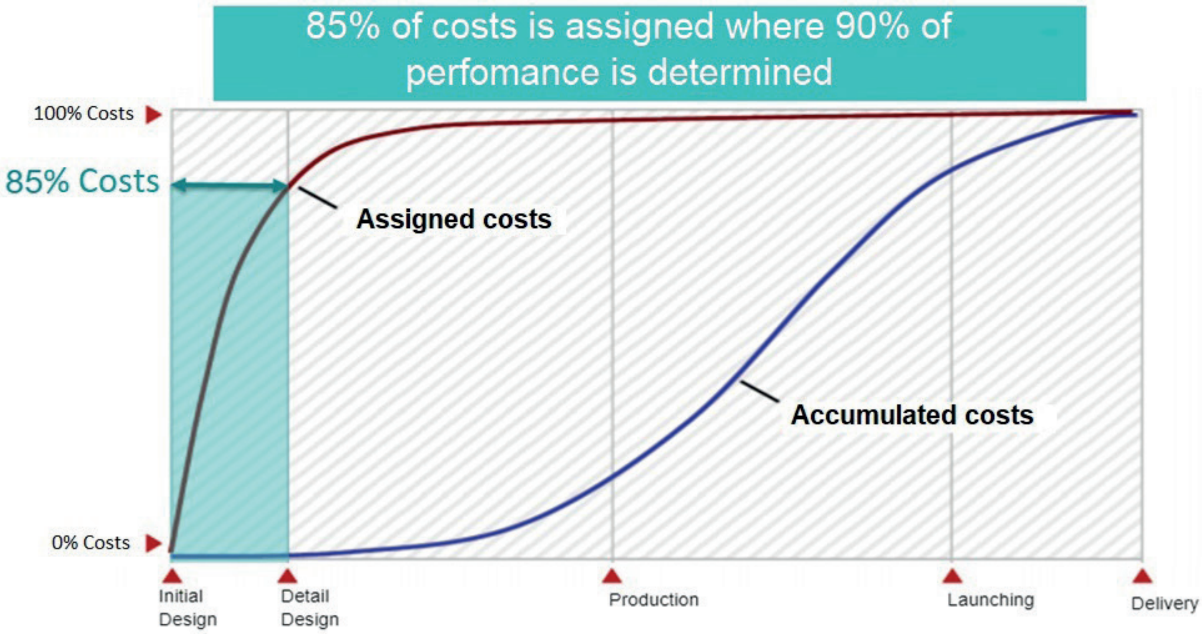

Figure 3 *Stages of the shipbuilding process [11]*

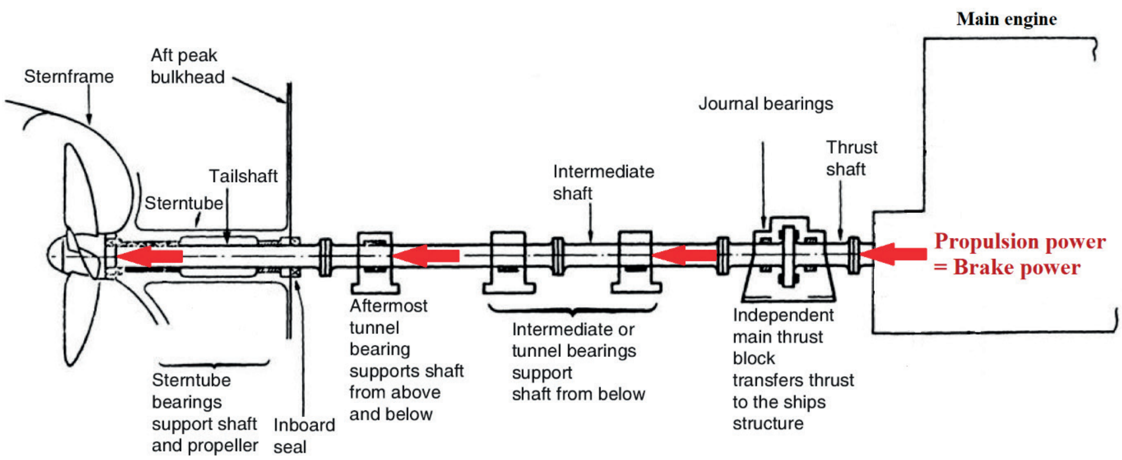

Figure 4 *Conventional direct-drive container ship main propulsion system [13]*

the technical or working design stage, which results in additional work, a significant increase in total costs and a significant delay in delivery. This means that design offices and shipyards cannot afford to have significant errors in the initial design of a given ship [10]. Stages of the shipbuilding process are shown in Figure 3.

Therefore, it was necessary to develop a method for predicting the propulsion power in a quick and simple manner with sufficient accuracy. Methods based on statistical modelling for a specific type of container ship, its cargo capacity, its age and the configuration of its main propulsion system can be an effective tool for predicting the propulsion power of a given ship.

The aim of this paper is to determine the empirical mathematical relationship based on a simple cubic regression model and obtained by comparing the real parameters of actual ultra-large container ships no older than the average age of all the container ships in service - i.e. 13 years [1]. This guarantees both a representative research sample and a focus on configurations of the main propulsion system still in use.

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 142 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_s, (km/h)	40.74
Engine type	WinGD 12X92-DF
	LNG-fueled
P_{Bmax}, (kW)	63,840
P_{Bs}/P_{Bmax}, (%)	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_{Bmax} - 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 Gulsun	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_s, (km/h)	41.49	41.21	42.97	43.06
Engine type	MAN 11G95ME-C			
	LNG-ready			
P_{Bmax}, (kW)	75,570			
P_{Bs}/P_{Bmax}, (%)	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_s, (km/h)	40.74	40.37	36.86
Engine type	MAN 12S90ME-C	MAN 11S90ME-C	MAN 10S90ME-C
	LNG-ready		
P_{Bmax}, (kW)	69,720	63,910	58,100
P_{Bs}/P_{Bmax}, (%)	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

***Table 4** Representative database of the HFO/MGO-fueled ultra-large container ships [5, 12, 14, 16-17]*

Ship class	Ever Ace	OOCL G	CMA CGM Antoine de Saint-Exupery	MOL Triumph	Ever Golden	MSC Olympic
P_{Bs}, (kW)	58,600	61,530	59,370	59,160	59,300	56,250
v_s, (kn)	22.20	22.50	22.25	22.20	22.50	21.90
v_s, (km/h)	41.11	41.67	41.21	41.11	41.67	40.56
Engine type	WinGD 11X92	MAN 11G95ME-C	WinGD 11X92	MAN 11G95ME-C		MAN 11S90ME-C
	HFO/MGO-fueled					
P_{Bmax}, (kW)	70,950	75,570	70,950	75,570		63,910
P_{Bs}/P_{Bmax}, (%)	83.01	81.42	83.68	78.29	78.47	88
L_{OA}, (m)	399.9	399.9	399.9	399.9	399.9	395.5
L_{PP}, (m)	393	383	383	383.6	387	379.4
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	2017	2016

Ship class	MSC Pegasus	CSCL Globe	CMA CGM Zheng He	CMA CGM Kerguelen	APL Temasek	CMA CGM Marco Polo
P_{Bs}, (kW)	61,530	56,800	54,936	53,960	36,900	63,910
v_s, (kn)	22.65	22.00	21.75	21.60	19.00	23.15
v_s, (km/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
	HFO/MGO-fueled					
P_{Bmax}, (kW)	75,570	69,720	63,910			80,080
P_{Bs}/P_{Bmax}, (%)	81.42	75.16	85.96	84.43	57.73	79.81
L_{OA}, (m)	399.9	399.7	399.2	398	397.9	396
L_{PP}, (m)	383	383	381.4	380	380.1	378.4
Cargo capacity, (TEU)	19,437	19,100	17,859	17,722	17,292	16,020
Quantity	14	5	3	3	8	3
Delivery year	2016	2014	2015	2015	2017 (lengthened)	2012

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 46 % of the created database.

Ships with a service speed of at least 22 knots constitute 74 % 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

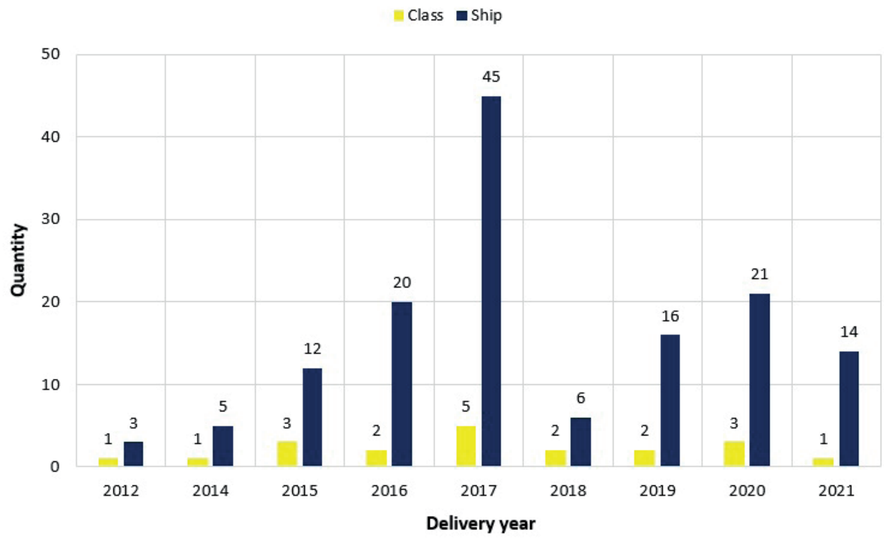

Figure 5 *Database divided into delivery year [3, 5, 12, 14-17]*

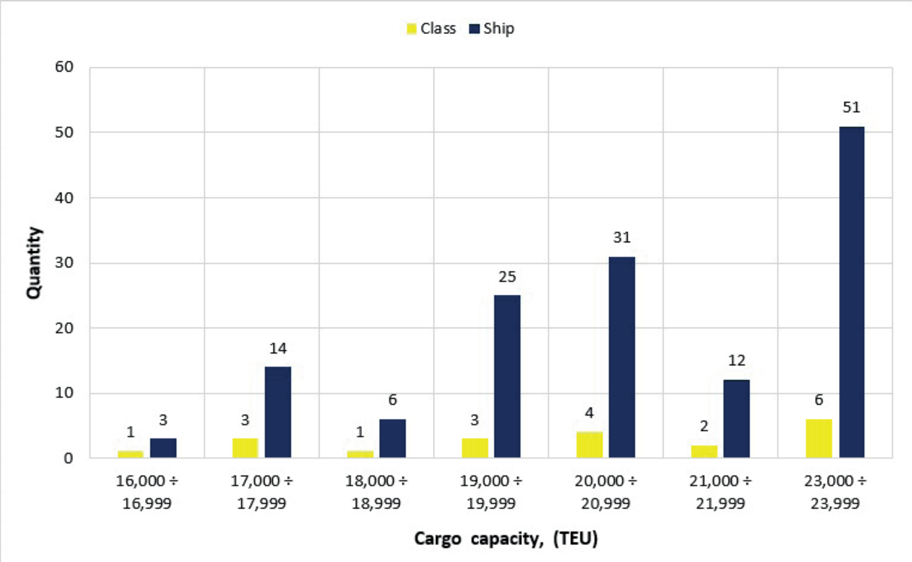

Figure 6 *Database divided into cargo capacity [3, 5, 12, 14-17]*

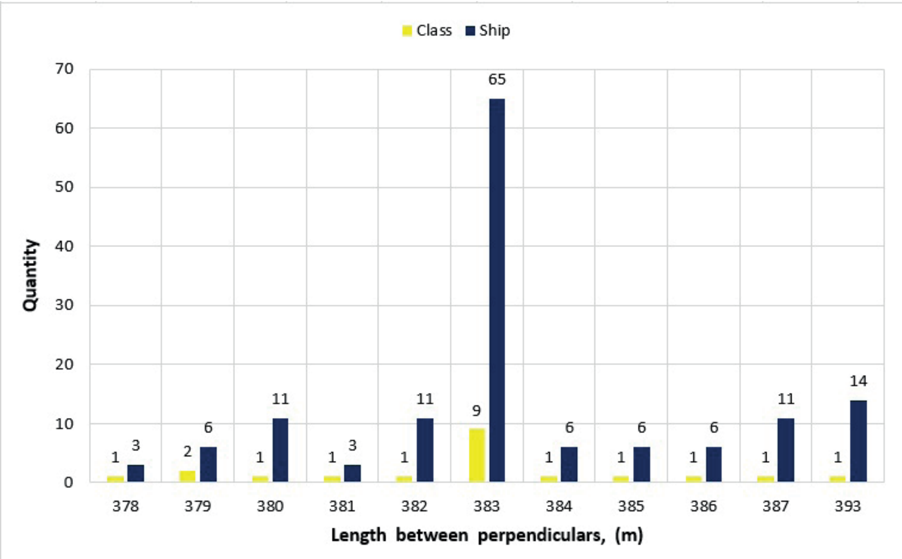

Figure 7 *Database divided into length between perpendiculars [3, 5, 12, 14-17]*

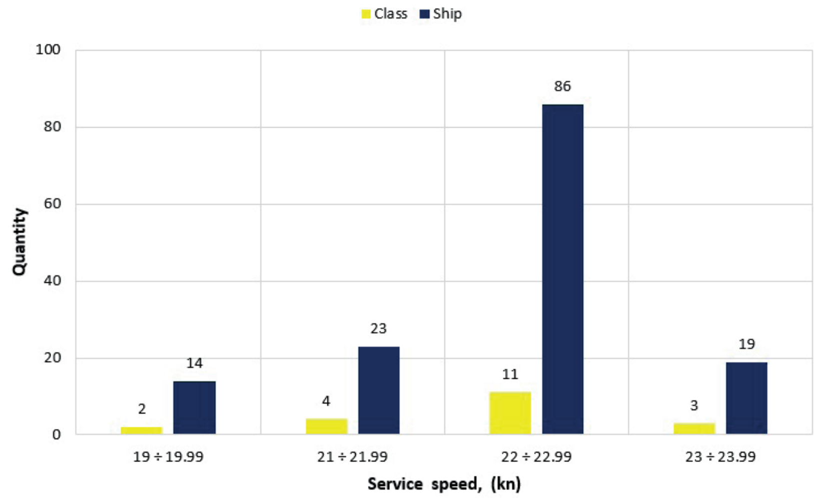

Figure 8 *Database divided into service speed [3, 5, 12, 14-17]*

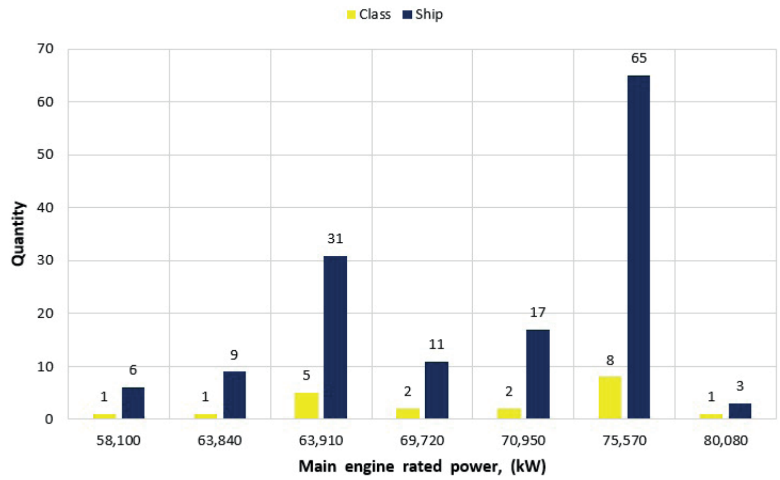

Figure 9 *Database divided into main engine rated power [3, 5, 12, 14-17]*

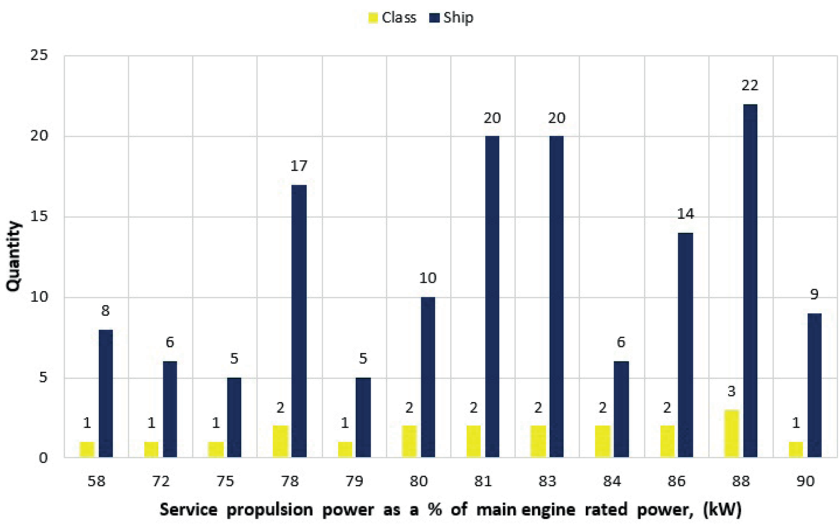

Figure 10 *Database divided into service propulsion power as a % of main engine rated power [3, 5, 12, 14-17]*

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.

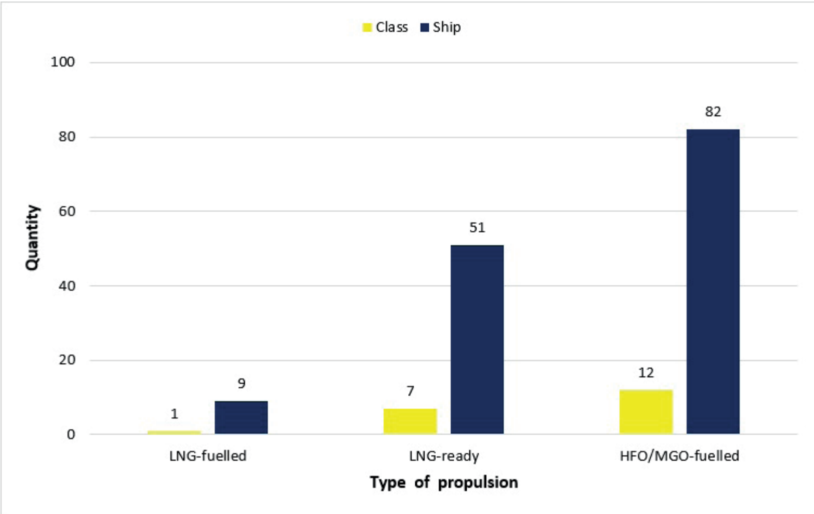

Figure 11 *Database divided into type of propulsion [3, 5, 12, 14-17]*

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	APL Temasek	CMA CGM Marco Polo
c (kW · kn^{-3})	5.3042	5.3392	5.3544	5.3798	5.1513

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 46 % 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 more than 2/3 (68 %) 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, 60 of the 142 ships assigned to 8 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. NO_X, SO_X and CO_2 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 were previously included in Table 4.

$$P_B = c \cdot v^3, \tag{1}$$

thus:

$$c = \frac{P_B}{v^3} \tag{2}$$

where:
P_B - 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:

$$P_B = 5.333 \cdot v^3 \quad (3)$$

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 $R^2 = 0.9959 \cong 1$, obtained when

***Table 6** Regression analysis results [20]*

Parameter	Symbol	Value	Equation	
Sample size	N	500	$N = n_v \cdot n_c$	(4)
Confidence level	CL	0.95	$CL = 1 - p$	(5)
Standard deviation	SD	22,046.57 kW	$SD = \sqrt{\frac{\sum_{i=1}^{N}(P_{Bi} - \overline{P_{Bi}})^2}{N-1}}$	(6)
Determination coefficient	R^2	0.9959	$R^2 = 1 - \frac{\sum_{i=1}^{N}(P_{Bi} - \widehat{P_{Bi}})^2}{\sum_{i=1}^{N}(P_{Bi} - \overline{P_{Bi}})^2}$	(7)
Standard error of propulsion power	SE	985.95 kW	$SE = \frac{SD}{\sqrt{N}}$	(8)

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 142 ships,
$p = 0.05$ - Assumed p-value (probability value),
P_{Bi} - Propulsion power, the actual value of the dependent variable, (kW),
$\widehat{P_{Bi}} = P_B$ - Propulsion power, the predicted value of the dependent variable based on the regression model, (kW),
$\overline{P_{Bi}}$ - Propulsion power, the mean value of the actual dependent variable, (kW).

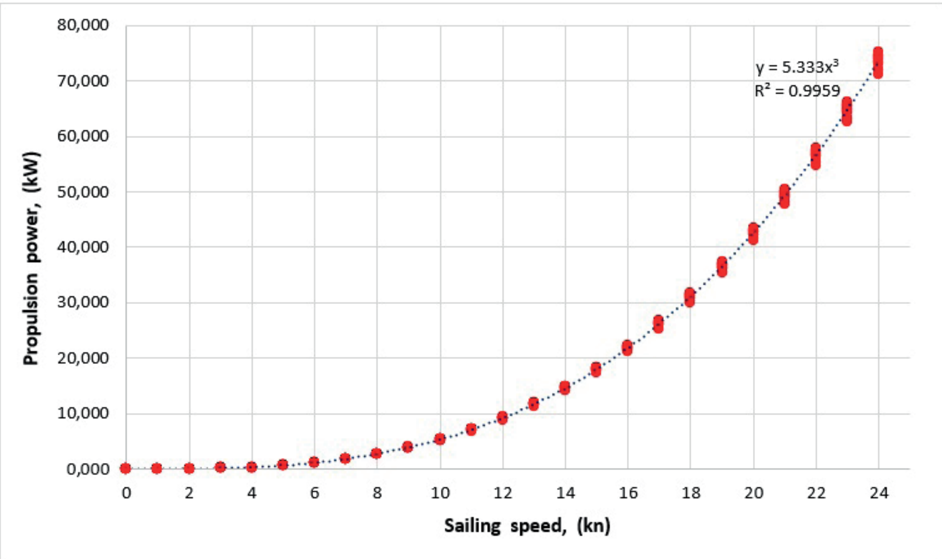

***Figure 12** Propulsion power of the ultra-large container ships' as a function of its sailing speed*

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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