Prediction of the very- and ultra-large Container Ships' Electricity Generation Capacity at the Initial Design Stage

Predviđanje kapaciteta proizvodnje električne energije velikih i vrlo velikih kontejnerskih brodova u početnoj fazi dizajna

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Abstract

Container ships represent the fastest growing segment of global shipping. Tackling such challenges as the constant pursuit of reduction of unit transportation costs and negative effects on the environment has led to the development of very- and ultra-large container ships, which dominate transport on the world's major shipping routes. Very-large container ships are conventionally assumed to have a cargo capacity above 10,000 TEU and an overall hull length below 369 meters, whilst the unique feature of ultra-large container ships is an overall hull length over 390 meters. The ship operational states and the main electric power receivers such as reefers and bow thrusters are mentioned and formulae to predict their electricity demand are given. Contemporary configurations of ships' electric power stations are presented and discussed. Cargo capacity expressed in 20-foot equivalent units (TEU) was identified as the main predictor of the electricity generation capacity based on a representative very- and ultra-large container ships database. Using a simple linear regression model based on the least squares method, a formula was developed to predict the electricity generation capacity of very- and ultra-large container ships at the initial design stage. The prediction will find application in the design of very and ultra-large container ships' electric power stations. The use of the developed formula at the initial design stage enables obtaining results that are sufficiently accurate to the results of the exact verification calculations at the technical design stage.

KEY WORDS
container ship
VLCS
ULCS
electricity generation
electric power station
generating set

Sažetak

Kontejnerski brodovi predstavljaju najbrže rastući segment svjetskoga brodarstva. Boreći se s određenim izazovima, kao što su npr. neprestano reduciranje troškova prijevoza i negativnih učinaka na okoliš, potaknuo se razvoj velikih i vrlo velikih kontejnerskih brodova koji dominiraju prijevozom na svjetskim glavnim pomorskim rutama. Smatra se da vrlo veliki kontejnerski brodovi obično imaju kapacitet nosivosti tereta iznad 10,000 TEU i ukupnu duljinu trupa preko cijeloga broda ispod 369 m, dok je jedinstvena značajka vrlo velikih kontejnerskih brodova ta da je ukupna duljina trupa preko 390 m. Navode se radna stanja broda i spominju glavni prijemnici električne energije, kao što su hladnjaci i pramčani porivni strojevi, a prikazuju se i formule kojima se predviđa i raspravlja o potražnji za električnom energijom. Identificirano je da je glavni čimbenik predviđanja kapacitet nosivosti tereta izražen u TEU jedinicama za kapacitet proizvodnje električne energije koji se temelji na bazi podataka reprezentativnih velikih i vrlo velikih kontejnerskih brodova. Koristeći se modelom jednostavne linearne regresije, koji se zasniva na metodi least square, razvijena je formula kojom se može predvidjeti kapacitet proizvodnje električne energije velikih i vrlo velikih kontejnerskih brodova u početnoj fazi dizajna. Predviđanje će naći svoju primjenu u dizajna postaja proizvodnje električne energije na velikim i vrlo velikim brodovima. Korištenje razvijenom formulom u početnoj fazi dizajna omogućava dobivanje rezultata koji su dostatno točni prema rezultatima ekstra verifikacijskih kalkulacija u fazi tehničkoga dizajna.

KLJUČNE RIJEČI
kontejnerski brod
VLCS
ULCS
proizvodnja električne energije
postaja električne energije
set proizvodnje

1. INTRODUCTION / *Uvod*

Maritime transport has been the main pillar of international trade for many decades, currently serving approximately 80% of the volume of worldwide trade in goods [1, 2]. Container transport is developing the fastest globally and is an extremely important element of trade. In 2019, the global merchant fleet transported 11,076 million tonnes of cargo, of which containers accounted for as much as 1,955 million tonnes. The weight of the cargo transported by container has undergone an unprecedented ninefold increase since 1990, in line with the continuing upward trend [2]. The popularity of containerisation 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 [3].

Shipping makes optimum use of economies of scale, so that sea transport costs have been reduced to a negligible minimum in a significant proportion of commercial calculations. This has become possible due to the tremendous progress in ship technology, which over the years has helped to increase the dimensions and performance of container ships. In the period 1968 ÷ 2021, the cargo capacity of the largest container ship increased from 1,530 to 23,992 TEU, i.e. by a massive 1,468% [4]. This development continues unabated. The economic benefits and reduction of the environmental impact of operating ever-larger ships on the world's major shipping routes have led to the creation of ships of unprecedented size (VLCS – Very-Large Container Ship and ULCS – Ultra-Large Container Ship). The continuous development of ship technology enables ever more effective use of the hull space and the location of more and more containers within the same area. When comparing the parameters of ships in service, very-large container ships are conventionally assumed to have a cargo capacity exceeding 10,000 TEU and an overall hull length of up to 369 meters, whilst the unique feature of ultra-large container ships is an overall hull length of more than 390 meters [5].

Despite the constantly growing demand for very- and ultra-large container ships, the literature still does not include methods whereby the electricity generation capacity of both of these latest types may be approximately predicted [6, 7]. At the initial design stage, it is impossible to precisely determine the required electricity generation capacity due to the lack of accurate electrical balance. At the same time, decisions made at this stage of a project have a fundamental impact on its total cost and duration due to 85% of the total cost is assigned where 90% of performance is determined [7]. Each mistakenly selected parameter requires adjustments at 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 error in the initial design of a given ship.

Therefore, it was necessary to develop a method for predicting the required electric power in a quick and simple manner with sufficient accuracy. Methods based on statistical modelling for a specific type of container ship, cargo capacity, age, and the configuration of its electric power station can be an effective tool for predicting the electrical power of a given ship. The aim of this paper is to determine the empirical mathematical relationship based on a simple linear regression model and obtained by comparing the real parameters of actual very- and ultra-large container ships no older than the average age of all container ships in service (i.e. 13 years) [2]. This guarantees both a representative research sample and a focus on the ship power station configurations still in use.

2. MAIN ELECTRIC POWER RECEIVERS / *Glavni prijemnici električne energije*

Number of active electric power receivers and their energy consumption depend directly on the ship operational state. Electrical balance of a given very- or ultra-large container ship without its own handling equipment is carried out for the following operational states [7, 8]:

- At sea including reefers,
- At sea excluding reefers,
- Manoeuvres including reefers,
- Manoeuvres excluding reefers,
- In port including reefers,
- In port excluding reefers.

Main electric power receivers in previous mentioned operational states are shown in Table 1.

A comparison of the data contained in Table 1, assuming the same number of refrigerated containers (reefers) in all operational states, shows that by far the largest demand for electric power occurs during manoeuvres. In this operational state, the generation of electricity by means of a shaft generator, if fitted, is severely limited due to the reduced power of the main engine. At that moment, if the reefer plugs are in full use, the actual electric power consumption almost coincides with the electrical output of all generating sets [7, 8].

By far the largest electric power receivers on very- and ultra-large container ships are refrigerated containers (reefers) and bow thrusters, which at full load can consume up to 80% of the electricity generation capacity [8]. Therefore, in order to prepare the electrical balance for a given ship, it is necessary to determine the actual electric power demand of each of them. This is discussed in detail later in this paper. Other receivers have been omitted due to their much smaller share in the electrical balance, as well as the lack of detailed information provided by the classification societies, and methods of predicting their energy demand.

Table 1 Main electric power receivers in various operational states

Tablica 1. Glavni prijemnici električne energije u različitim radnim stanjima

Operational state	Main electric power receivers						
	Reefers	Bow thruster	Steering gear power unit	Auxiliary machinery	Engine room control systems	Navigation equipment	Accommodation equipment
At sea incl. reefers	☒		☒	☒	☒	☒	☒
At sea excl. reefers			☒	☒	☒	☒	☒
Manoeuvres incl. reefers	☒	☒	☒	☒	☒	☒	☒
Manoeuvres excl. reefers		☒	☒	☒	☒	☒	☒
In port incl. reefers	☒			☒	☒	☒	☒
In port excl. reefers				☒	☒	☒	☒

Source: Charchalis, A. and Krefft J.; Nielsen, B.Ø. [7, 8]

2.1. Refrigerated containers (reefers) /*Rashlađeni kontejneri (hladnjaci)*

Refrigerated containers (reefers) are equipped with device to create and maintain the desired internal temperature. This type of device consists of one or more refrigerating units, pipelines and control systems, regulation and monitoring. The refrigerating unit consists of one or two compressors, one or two condensers, an evaporator and the necessary fittings and control devices. Major characteristics of refrigerated containers are listed below [3]:

- The use of compressed air for cooling,
- Cooling capacity ensuring continuous maintenance of the appropriate set temperature inside the container, even assuming a minimum of six-hour breaks in operation per day,
- Full automation,
- Resistance to mechanical and weather impacts occurring during transport.

The actual electric power consumption of a single refrigerated container is determined by its internal temperature, which defines the required evaporation temperature of the refrigerant and the influence of the ambient temperature and the properties of the circulating refrigerant. Generally speaking, the higher the inside temperature, the higher the electric power requirement and the larger the available cooling capacity. Typically, after the cargo has been cooled, the electrical power consumption drops. In freezing mode, the refrigeration appliance works in on/off mode; in cooling mode, the capacity of the refrigeration circuit is regulated continuously (e.g. using suction modulation valve). The energy demand of a container completely filled with refrigerated cargo (e.g. fresh fruit requiring a temperature of 16°C) will be up to approximately two times larger than that of a container completely filled with deep-frozen cargo (e.g. fish stored at –21°C) [9].

The literature mentions an empirically obtained average specific electric power of 2.1 ÷ 3.6 kW for a 20' container and 4 ÷ 7 kW for a 40' container [14, 15]. The electrical balance of Maersk A-class container ships in worldwide operation indicates that the total electric power consumption of all 817 refrigerated 40' containers is 4,280 kW [8], which yields a per unit value of $5.24\,\frac{\mathrm{kW}}{\mathrm{FEU}}$. Its reliability is confirmed by the fact that, in the view of the results of the latest available research, for preliminary calculations it is recommended to adopt an average value of $2.7\,\frac{\mathrm{kW}}{\mathrm{TEU}}$ for refrigerated 20' containers [10].

Table 2 Average specific electric power consumption by refrigerated containers

Tablica 2. Iznos prosječne specifične potrošnje električne energije hlađenih kontejnera

Refrigerated container size	Specific electric power consumption
20-feet	$2.7\,\frac{\mathrm{kW}}{\mathrm{TEU}}$
40-feet	$5.24\,\frac{\mathrm{kW}}{\mathrm{FEU}}$.

Source: Nielsen, B.Ø., Fitzegrald, W. et al. [8, 10]

Following formulae can be used to predict total electric power consumption of refrigerated containers [9]:

$$\sum \mathrm{P_{RU_{40}}} = \mathrm{P_{RU_{40}}} \cdot \sum \mathrm{RU_{40}} \tag{1}$$

and:

$$\sum \mathrm{P_{RU_{20}}} = \mathrm{P_{RU_{20}}} \cdot \sum \mathrm{RU_{20}} \tag{2}$$

where:

$\sum \mathrm{P_{RU_{40}}}\ [\mathrm{kW}]$ - Total electric power consumption of refrigerated 40' containers

$\mathrm{P_{RU_{40}}}\ \left[\frac{\mathrm{kW}}{\mathrm{FEU}}\right]$ - Specific electric power consumption of refrigerated 40' container

$\sum \mathrm{RU_{40}}\ [\mathrm{FEU}]$ - Reefer capacity expressed in 40-foot equivalent units

$\sum \mathrm{P_{RU_{20}}}\ [\mathrm{kW}]$ - Total electric power consumption of refrigerated 20' containers

$\mathrm{P_{RU_{20}}}\ \left[\frac{\mathrm{kW}}{\mathrm{TEU}}\right]$ - Specific electric power consumption of refrigerated 20' container

$\sum \mathrm{RU_{20}}\ [\mathrm{TEU}]$ - Reefer capacity expressed in 20-foot equivalent units

2.2. Bow thruster / *Pramčani porivni stroj*

Bow thruster is an electric motor-driven lateral thruster fitted in an athwartships tunnel near the bow to improve manoeuvrability. Schematic diagram of bow thruster power supply and control system is shown in Figure 1 [11].

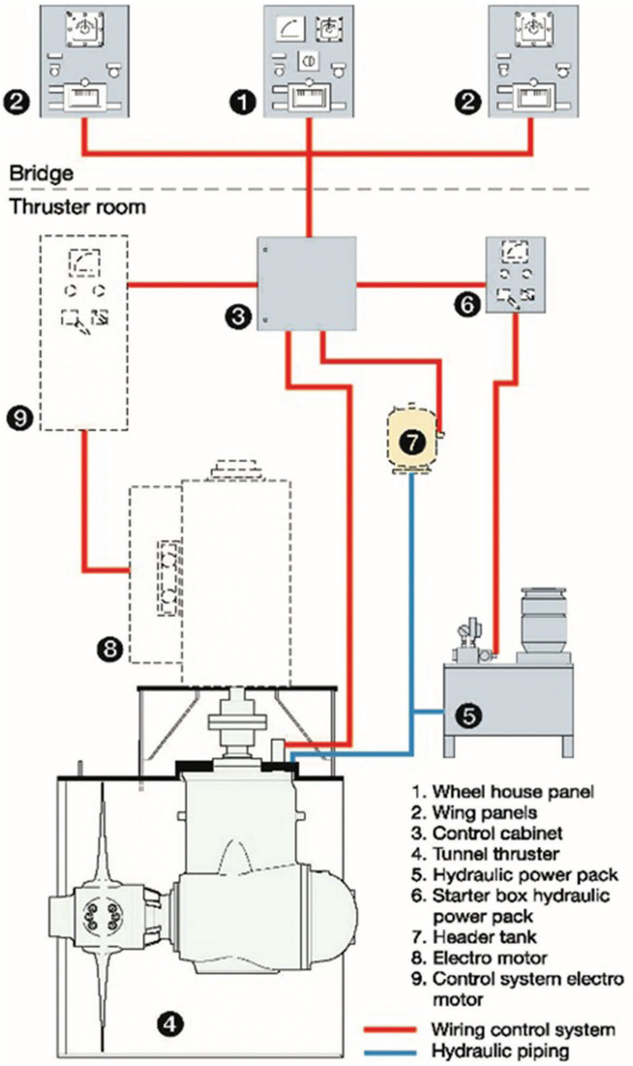

Figure 1 Schematic diagram of bow thruster power supply and control system

Slika 1. Shematski dijagram opskrbe energijom pramčanoga porivnoga stroja i sustava kontrole

Source: Wärtsilä Corporation [11]

When the bow thruster is used while the vessel is moving forward the thrust is partially counteracted by a vacuum created in the wake of the water jet emanating from the thrusters. The effect is worst when the vessel is moving forward at four to six knots. In such cases the vacuum on the hull can be relieved by the addition of an anti-suction tunnel [11] shown in Figure 2.

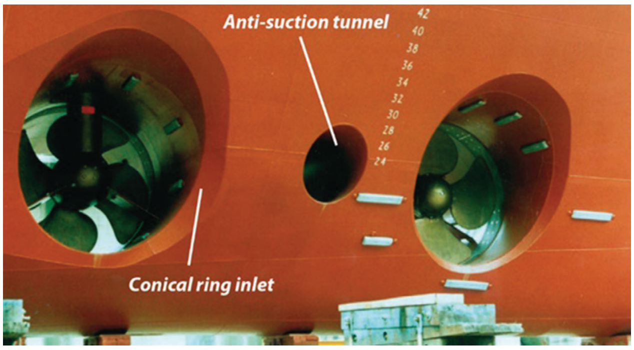

Figure 2 Bow thrusters

Slika 2. Pramčani porivni stroj

Source: Wärtsilä Corporation [11]

On the very- and ultra-large container ships, two bow thrusters of identical power (1,600 ÷ 3,000 kW) are installed. A pair of bow thrusters operating under rated load conditions are responsible for consuming up to 25% ÷ 30% of the electrical energy produced by generating sets. Wärtsilä recommends taking a value of 0.6 kW for each m^2 of windage area (Table 3) of a given container ship to approximate the total electrical power of the bow thrusters [11]. Formula (3) allows the total power of the bow thrusters to be predicted in relation to the total windage area of a given ship [12].

Table 3 Average specific electric power consumption by bow thrusters

Tablica 3. Prosječna specifična potrošnja električne energije pramčanoga pogona

Thrusters type	Total electric power consumption per projected windage area
Bow thrusters	$0.6\ \left[\frac{kW}{m^2}\right]$

Source: Wärtsilä Corporation [11]

$$\sum P_{BT} = 0.6 \cdot A_W = 0.6 \cdot \left(A_{W_H} + A_{W_C}\right) \tag{3}$$

where:

$\sum P_{BT}$ [kW] - Total power of bow thrusters

A_W [m^2] - Total windage area

A_{W_H} [m^2] - Hull windage area

A_{W_C} [m^2] - Cargo (containers) windage area

3. DATABASE OF THE VERY- AND ULTRA-LARGE CONTAINER SHIPS / *Baza podataka o velikim i vrlo velikim kontejnerskim brodovima*

A ship's electricity generation capacity 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 52 different classes of very- and ultra-large container ships, represented by 455 ships, not older than the average 13-year lifetime [2], i.e. built after 2008. It should also be noted that the classes are groups of sister ships built to the same design. The parameters of the ships in service were obtained from the registers of classification societies [13, 14, 15, 16, 17, 18, 19].

This database does not include ships with unconventional electric power station configurations or those designed to transport of specialised cargo. It includes ships with 4 ÷ 6 generating sets with the same or different active electric power, consisting of medium speed engine and generator.

In the case of the OOCL G-class and Maersk H-class series of container ships, shaft generators were installed instead of a fifth diesel generating set, whilst the twin-screw Maersk Triple-E had shaft generators fitted instead of fifth and sixth diesel generating sets. The 48 container ships in these 3 classes are the only very- and ultra-large types that use shaft generators [18].

The electricity generation capacity featured in the database is the sum of the rated active electric power of all generating sets and shaft generators, excluding the combined steam turbine and gas turbine generating unit used for exhaust gas waste heat recovery. They were omitted due to their rarity in the Maersk Triple-E series and the fact that they operate when the main engine is under a sufficiently high load, when they can replace up to two existing diesel generating sets [20]. Therefore, if their electricity generation capacity were included in the total capacity of the ship's electric power station, the result would be artificially inflated. Electricity generation capacity as the sum of the electrical output of generating sets and, if applicable, shaft generators is represented in formula (4).

$$\sum P_{el} = \sum P_{GS} + \sum P_{SG} \tag{4}$$

where:

$\sum P_{el}$ [kW] - Electricity generation capacity

$\sum P_{GS}$ [kW] - Electrical output of generating sets

$\sum P_{SG}$ [kW] - Electrical output of shaft generators

The database features the delivery year (Figure 4), type of propulsion (Figure 5), overall hull length rounded to the nearest metre (Figure 6), cargo capacity (Figure 7), reefer capacity (Figure 8), and electricity generation capacity (Figure

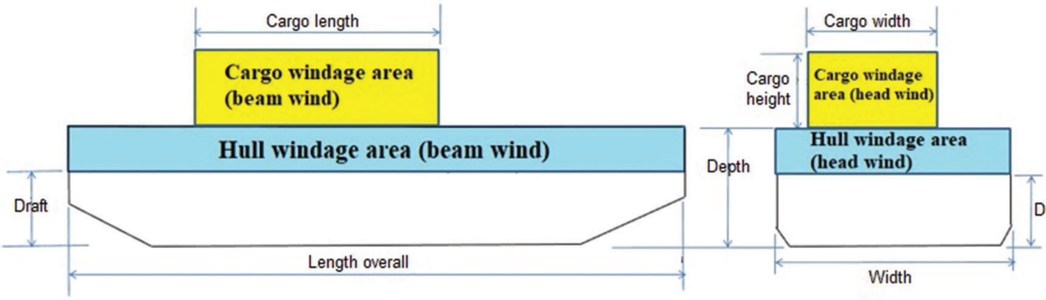

Figure 3 Windage area

Slika 3. Prostor izložen vjetru

Source: Own study on basis [12]

9) according to the formula (4). This list should not be treated as a list of similar ships due to the lack of available information on electric power consumers (some classification societies only give the power of bow thrusters), degree of engine room automation and brake power of the main engine. Ships equipped with main engines operating in slow-steaming mode and with a redundant cylinder tend to have an operating load within the range of 60 ÷ 75% of the rated power, which excludes the rated power from the parameters relevant to predict the electricity generation capacity.

In total, 103 of the 455 ships assigned to 11 of 52 classes are equipped with propulsion suitable for running on LNG, reflecting the trend of this low-emission fuel's increasing popularity. 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.

Ships just under 366 and 400 meters long are the most common. The former are related to the Panama Canal restrictions in effect until 2018 (max. overall length 366 m, max. beam 49 m). The latter reflect the largest permitted length for container ships today and are typical of the latest ultra-large container ships.

Over half (54.5%) of the database consists of ships with a capacity of at least 13,000 TEU, but less than 17,000 TEU. This is due to the progressive increase in the capacity of container ships whilst maintaining the given dimensions. The most capacious very-large container ship (HMM Nuri), put into operation in March 2021, has a capacity of 16,010 TEU [17], while the CMA CGM Marco Polo built in 2012 needed a hull 30 metres longer and 2.6 metres wider [15]. Ships with a cargo capacity of 17,000 TEU and above make up 33% of this database.

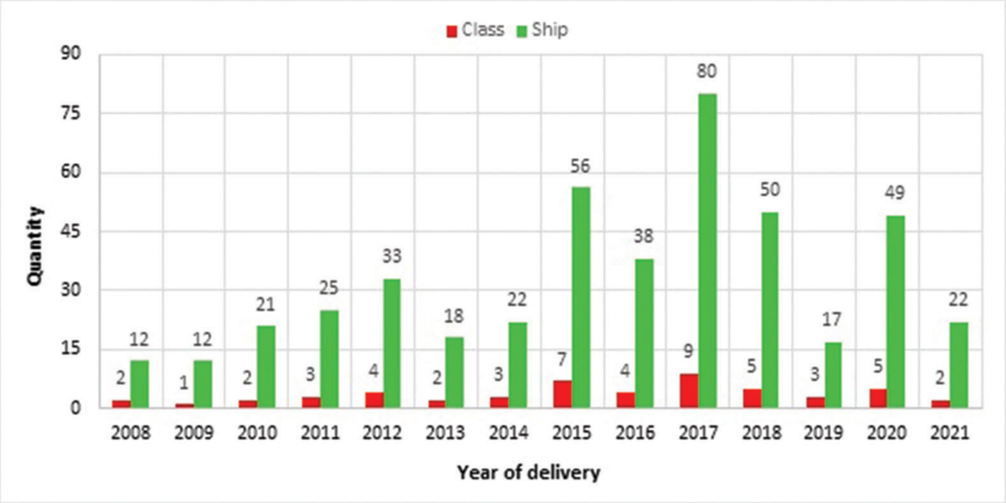

Figure 4 Database structure divided into year of delivery

Slika 4. Struktura baze podataka podijeljena prema godinama isporuke

Source: own study on basis [13, 14, 15, 16, 17, 18, 19]

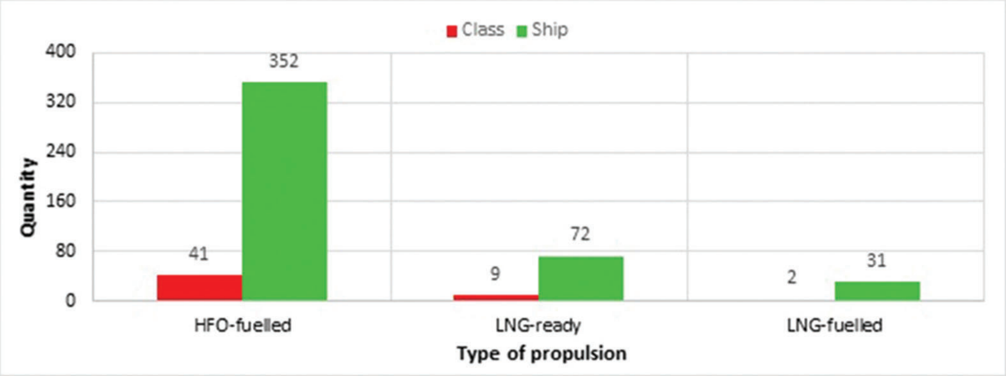

Figure 5 Database structure divided into type of propulsion

Slika 5. Struktura baze podataka podijeljena prema tipovima propulzije

Source: own study on basis [13, 14, 15, 16, 17, 18, 19]

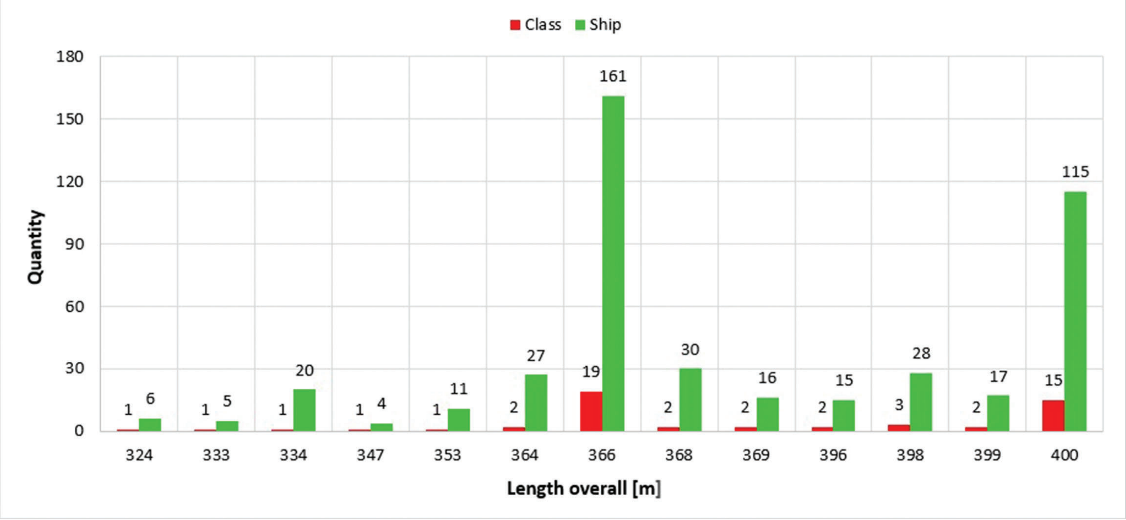

Figure 6 Database structure divided into hull length overall

Slika 6. Struktura baze podataka podijeljena prema ukupnoj duljini trupa broda

Source: own study on basis [13, 14, 15, 16, 17, 18, 19]

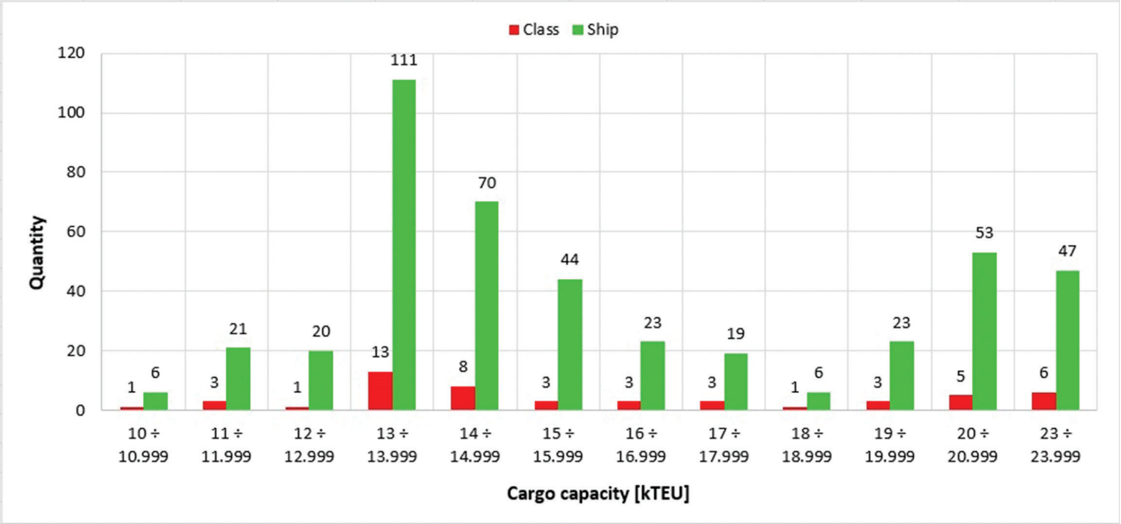

Figure 7 Database structure divided into cargo capacity

Slika 7. Struktura baze podataka podijeljena prema nosivosti

Source: own study on basis [13, 14, 15, 16, 17, 18, 19]

A huge 46% of the database consists of container ships capable of transporting 1,000 refrigerated 40′ containers. They include ships in both the smaller (i.e. Evergreen F-class, length overall 334 m, 12,188 TEU) [9] and larger classes (i.e. COSCO Universe-class, length overall 399.9 m, 21,237 TEU) [18]. It should also be noted that even smaller container ships (Hapag-Lloyd Valpalraiso Express-class, length overall 333 m, 11 519 TEU) can carry 2,100 refrigerated 40′ containers [14]. Taking into account the different energy demand of the bow thrusters and auxiliary devices installed on various ships, this indicates that there is not a sufficient correlation between the electricity generation capacity of very- and ultra-large container ships and the number of refrigerated containers (Table 5).

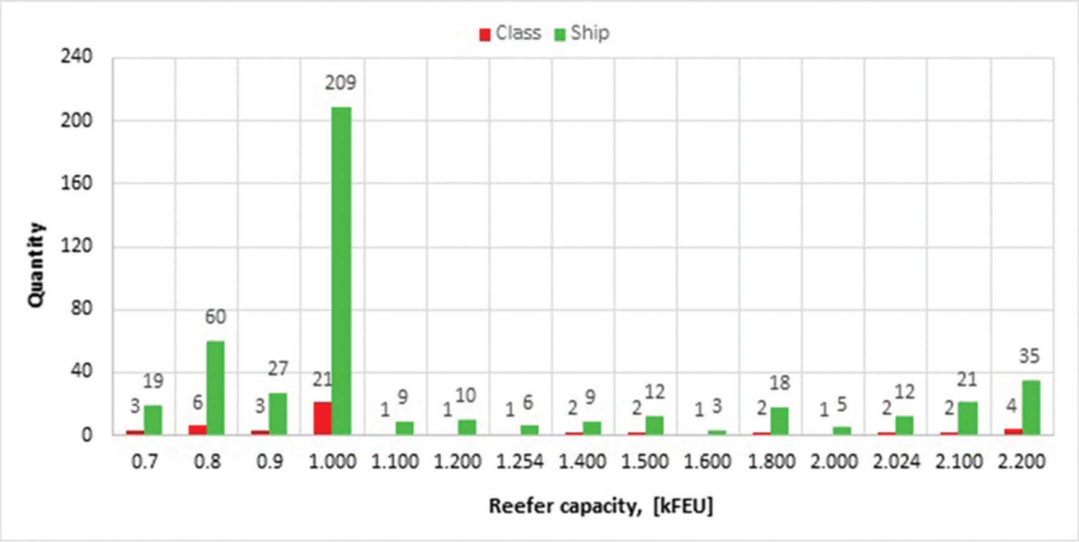

Figure 8 Database structure divided into reefer capacity

Slika 8. Struktura baze podataka podijeljena prema nosivosti hlađenih brodova

Source: own study on basis [13, 14, 15, 16, 17, 18, 19]

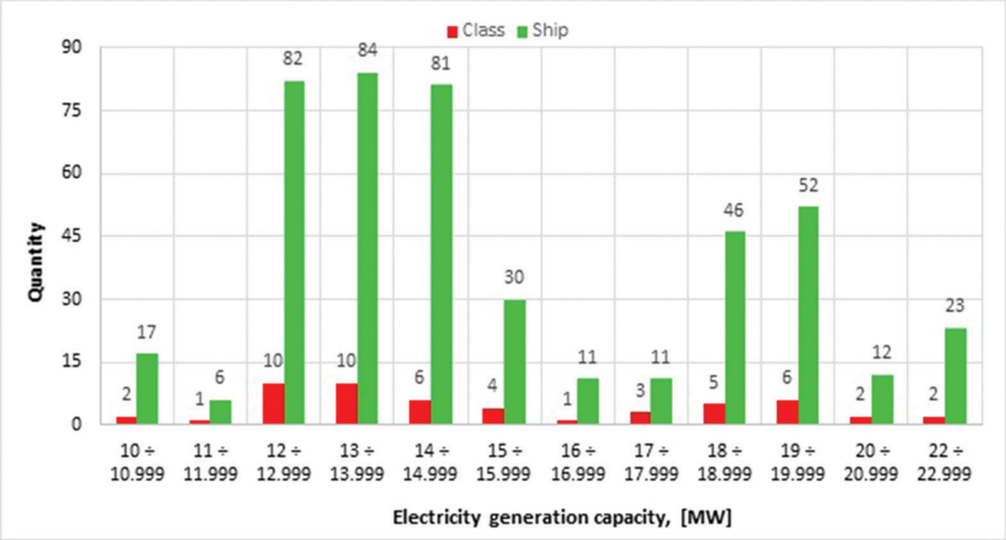

Figure 9 Database structure divided into electricity generation capacity

Slika 9. Struktura baze podataka podijeljena prema kapacitetu proizvodnje električne energije

Source: own study on basis [13, 14, 15, 16, 17, 18, 19]

An electricity generation capacity of less than 17,000 kW can be found on very-large container ships, while ultra-large ships have capacities above this limit. The histogram illustrating the electricity generation capacity (Figure 9) shows a significant similarity to the histogram that organises the database by cargo capacity, which suggests that cargo capacity (Figure 7) may be a significant predictor of electricity generation capacity. This was statistically verified in Table 5.

Exemplary configurations of the selected very- and ultra-large container ships' electric power stations are shown in Table 4.

Table 4 Configurations of the Thalassa Hellas and COSCO Shipping Universe electric power stations
Tablica 4. Konfiguracija Thalassa Hellas i COSCO Shipping Universe postaja električne energije

Type of the container ship	Delivery year	Name	Cargo capacity, [TEU]	Reefer capacity, [FEU]	Generating set			Electricity generation capacity, [kW]
					Quantity	Type	Electrical output, [kW]	
Very-large	2013	Thalassa Hellas	13,800	800	2	HiMSEN 8H32/40	3,667	12,834
					2	HiMSEN 6H32/40	2,750	
Ultra-large	2018	COSCO Shipping Universe	21,237	1,000	4	Wärtsilä 9L32	4,840	19,360

Source: Vessel Register for Det Norske Veritas [14]

4. METHODOLOGY / *Metodologija*

Methods based on statistical modelling for a specific type of container ship, cargo capacity and the configuration of electric power station can be an effective tool for predicting the electricity generation capacity. The formulas available so far were developed for container ships with a cargo capacity up to 10,000 TEU. Using a multiple regression model, the authors found that the most statistically significant predictors of electricity generation capacity are cargo and reefer capacities [6, 7]. The earlier findings were verified due to the lack of available methods for predicting the electricity generation capacity of container ships over 10,000 TEU.

Starting from the assumption that the variables under study relating to each class in the database have a normal distribution, relying on the central limit theorem and using a simple linear regression model based on the least squares method, a statistical analysis of three different independent variables was performed. For the statistical analysis, an intercept model was used, which includes parameters that may affect the final formula, and were not included in the process of statistical analysis [21]. In addition to the significance level, the statistical analysis also presents the Pearson's correlation coefficient and the determination coefficient in relation to the electricity generation capacity. The basic ship parameters which are known at the initial design stage, i.e. cargo capacity, reefer capacity and length overall, were taken into account as independent variables. Results of a basic linear regression analysis for three different independent variables were presented in Table 5.

In view of the very high significance level ($p \leq 0.001$) of all the independent variables considered, the selection of the predictor of ship power plant output in the simple linear regression model was made on the basis of a comparison of the values of Pearson's correlation and determination coefficients. Cargo capacity is the only parameter that demonstrates a very strong correlation (R » 0.9) with the electricity generation capacity. Moreover, the R^2 value included in Table 5 indicate that the cargo capacity explains 92.09% of the variance in the dependent variable. This means that this alone can provide a sufficiently accurate prediction and the use of multiple regression model is not necessary. Therefore, a formula was developed to predict the electricity generation capacity of very- and ultra-large container ships in relation to their cargo capacity.

5. RESULTS AND DISCUSSION / *Rezultati i rasprava*

The mathematical relationship that allows the total electricity generation capacity of very- and ultra-large container ships to be predicted, corresponding to formula (4), was developed jointly for electric power stations consisting of generating sets and ones fitted with a shaft generator. The following formula was obtained as a result of calculation:

$$\sum \mathrm{P_{el}} = 0.7503 \cdot \mathrm{TEU} + 3{,}215 \qquad (5)$$

where:
$\sum \mathrm{P_{el}}$ [kW] - Total electricity generation capacity
TEU - Cargo capacity expressed in 20-foot equivalent units

The obtained slope of 0.7503 states that an increase of 1 TEU in cargo capacity results in an increase of 0.7503 kW of electricity generation capacity, whereas the intercept of 3,215 kW refers to the limited range of applicability of the model. The linear regression statistics were presented in Table 6 for an assumed significance level of p = 0.001, which corresponds to the significance of the cargo capacity in predicting the electricity generation capacity. Detailed results of a linear regression analysis were shown in Table 6.

Table 5 Results of a linear regression analysis for different independent variables
Tablica 5. Rezultati analize linearne regresije za različite neovisne varijable

Regression model	Independent variable	Significance level	Pearson's correlation coefficient	Correlation strength	Determination coefficient
		p	R		R^2
Simple	Cargo capacity	≤ 0.001	0.9596	Very strong	0.9209
	Reefer capacity		0.6979	Moderate	0.4871
	Length overall		0.8307	Strong	0.6901

Source: own study on basis [13, 14, 15, 16, 17, 18, 19, 21]

Table 6 Detailed results of a linear regression analysis

Tablica 6. Detaljni rezultati linearne regresijske analize

Regression model	Parameter	Symbol	Value
Simple	Sample size (52 classes including in total 455 ships)	N	52
	Pearson's correlation coefficient	R	0.9596
	Determination coefficient	R^2	0.9209
	Significance level	p	0.001
	Confidence level	CL	0.999
	Confidence interval	CI	± 1,389.55 [kW]
	Standard deviation of the electricity generation capacity	σ	3,045.17 [kW]
	Standard error	SE	864.93 [kW]
	Range of applicability of the model	-	10,000 ÷ 24,000 [TEU]

Source: own study on basis [13, 14, 15, 16, 17, 18, 19, 21]

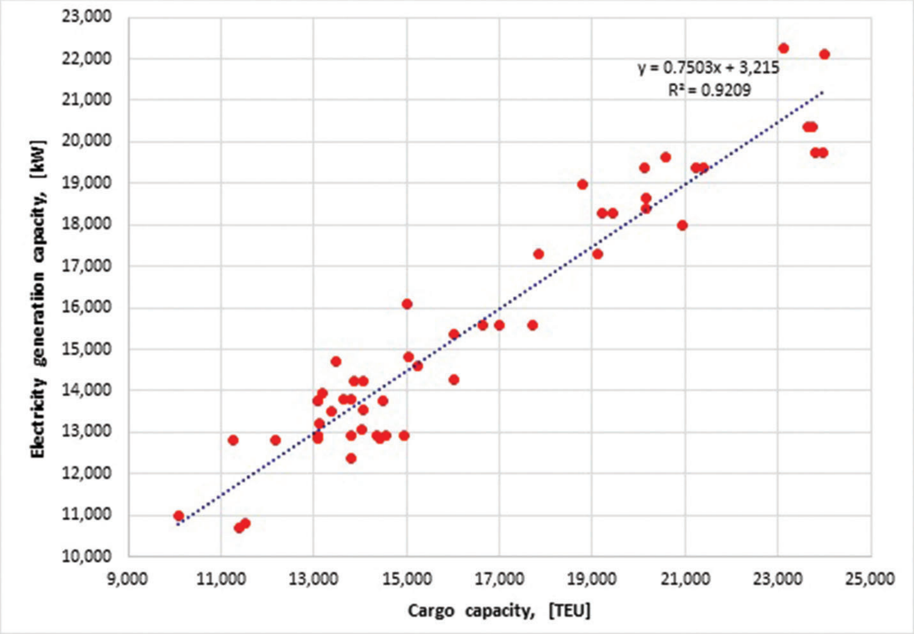

Figure 10 Electricity generation capacity as a function of cargo capacity

Slika 10. Kapacitet proizvodnje električne energije kao funkcija nosivosti tereta

Source: own study on basis [13, 14, 15, 16, 17, 18, 19, 21]

Figure 10 indicates the electricity generation capacity of the very- and ultra-large container ships as a function of their cargo capacity.

The developed formula has closed a gap in the methods of predicting the electricity generation capacity of container ships. The formulas available to date concentrate on ships up to 10,000 TEU, while the biggest demand today is for the very- and ultra-large container ships. However, as with previous analyses, it was shown that the most significant statistical predictor of electricity generation capacity is cargo capacity expressed in 20-foot equivalent units [6, 7]. It is worth noting the very high value of the determination coefficient ($R^2 = 0.9209$), obtained when developing the formula for the electricity generation capacity of a ship's electric power station, which indicates a strong link between the dependencies under study and choosing the appropriate regression model. The resulting formula (5) facilitates a quick and easy prediction of the necessary electricity generation capacity of very- and ultra-large container ships with sufficient accuracy, which is particularly relevant at the initial design stage, when a detailed electrical balance has not yet been prepared. The indicated value of R^2 enables the use of formula (5) with a high probability that the initial calculations will be sufficiently accurate to the results of the exact verification calculations at the technical design stage.

Moreover, Figure 11 shows the energy intensity of the analysed very- and ultra-large container ships' classes per 1 TEU.

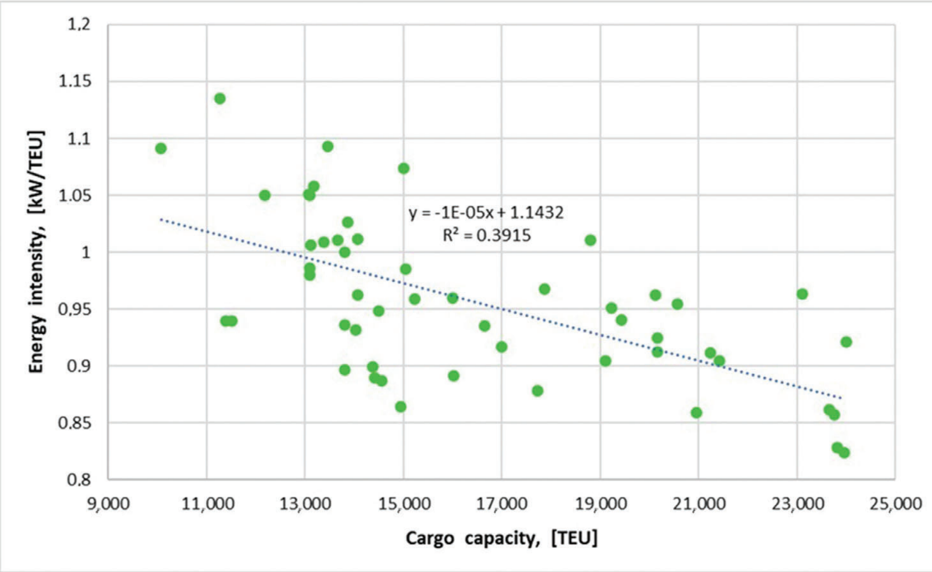

Figure 11. Energy intensity as a function of cargo capacity
Slika 11. Intezitet energije kao funkcija nosivosti broda

Source: own study on basis [13, 14, 15, 16, 17, 18, 19]

Based on the comparison of the data contained therein, it is evident that the energy intensity of ships decreases as their cargo capacity increases. This also means that, in line with the trend of increasing hull volume utilisation, newer ships are characterised by a noticeably lower electricity generation capacity per 1 TEU. However, the value of the determination coefficient obtained for this linear regression is quite low (R^2 = 0.3915) and indicates that more than 60% of the variance in the dependent variable is explained by factors other than cargo capacity. These include the degree of engine room automation, as well as energy-saving LED-based lighting systems, advanced energy management systems and recuperation technologies implemented on ships. It should also be mentioned that in the case of LNG-powered ships, increased electricity demand is caused by the need to power the fuel gas supply system, which is responsible for regasification of LNG and supplying natural gas to the engines at the required pressure [22, 23]. The use of these technologies on ships and the switch from fuel oil to LNG results from the need to reduce carbon dioxide emissions per ton-mile of cargo transported in accordance with current IMO regulations [24, 25].

Taking into account the impact of factors other than cargo capacity on the electricity generation capacity, another need in this area becomes the development of a formula that also considers other electric power receivers and the use of energy-efficient technologies, as well as the fuel gas supply system on LNG-powered ships in connection with the growing popularity of this low-emission fuel. Then it would become possible to precisely predict the required very-and ultra-large container ships' electricity generation capacity. However, this requires obtaining undisclosed information from shipowners, design offices, shipyards and classification societies.

6. CONCLUSIONS / *Zaključci*

When comparing ship operational states, it was found that the highest energy demand occurs during manoeuvres with reefers, and that the largest receivers of electric power on very- and ultra-large container ships are refrigerated containers and bow thrusters. The total electric power consumption by refrigerated containers is directly proportional to their quantity and the temperature of the stored cargo; in the case of bow thrusters, it is directly proportional to the windage area. Auxiliary devices, energy-saving technologies, LNG fuel gas supply system and the degree of engine room automation also have a significant bearing on a ship's electrical energy demand.

Electric power stations on very- and ultra-large container ships consist of 4 ÷ 6 generating sets with the same or different active electric power. In a relatively rare configuration, on ships of only 3 of the 52 analysed classes, a shaft generator is used instead of fifth or fifth and sixth generating sets. A combined steam turbine and gas turbine generating unit for waste heat recovery is only present on Maersk Triple-E series ships, and its operation depends on the main engine running under a sufficiently high load, which allows some of the generating sets to be temporarily shut down. Therefore, the required electricity generation capacity is the sum of the active electric power of all generating sets and shaft generators.

The analysis has demonstrated that the most significant statistical predictor of electricity generation capacity is cargo capacity. The calculations based on formula (5) using a simple linear regression model allows the electricity generation capacity to be predicted with sufficient accuracy at the preliminary design stage, when the electrical balance has not yet been precisely determined.

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