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Reducing CO_2 Emissions during the Operation of Unmanned Transport Vessels with Diesel Engines

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Abstract: Environmental protection is one of the most challenging tasks facing mankind. Reducing CO_2 emissions in the global economy, including maritime transport, is being pursued in various ways, one of them being the design work leading to the construction and operation of unmanned ships. Unmanned vessels operating on longer routes will still have internal combustion propulsion. However, they will not have the superstructure and the various systems and equipment necessary for the crew. This will result in an unmanned vessel having less weight, less displacement and, therefore, less size, resistance and propulsion power than a manned vessel for the same transport capacity. Consequently, the unmanned vessel will emit less CO_2. This paper presents a novel method for predicting fuel consumption and CO_2 emissions for unmanned container ships. The method uses regression relationships of geometric and operational parameters for manned container ships developed for this purpose to determine such relationships for unmanned ships. On this basis, it is shown what the level of CO_2 reduction will be compared to manned container ships.

Keywords: manned and unmanned container ships; carrying capacity; speed; propulsion power; fuel consumption; emissions

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1. Introduction

Despite its largest share in the global transport of goods (more than 80% of the global trade) [1], maritime transport contributes only about 4.7% [1] of the global atmospheric CO_2 emissions. Nonetheless, the measures being taken to reduce CO_2 emissions also apply to maritime transport. In maritime transport, the reduction of CO_2 emissions is implemented through:

- the optimisation of the ship's hull to reduce resistance and propulsion power, and consequently reduce fuel consumption and exhaust emissions [2],
- the use of alternative fuels with a smaller carbon footprint [3–5],
- the use of various auxiliary wind propellers on vessels [6–8],
- the replacement of internal combustion propulsion with battery-powered electric propulsion [9,10].

Battery-driven electric propulsion completely eliminates exhaust fumes; however, the existing ships with this type of propulsion have a short range of ca. 200 Nm. Therefore, in the near future, the vast majority of ships will continue to be powered by internal combustion engines, using various alternative fuels which, although less harmful, still emit exhaust fumes.

The ongoing research into unmanned vessels can also contribute to reducing CO_2 emissions in maritime transport. Unmanned vessels will not have the superstructure and all of the systems and equipment required on their manned counterparts. An unmanned vessel of the same carrying capacity (or number of containers), operating speed and sailing range as its manned counterpart should:

- have smaller dimensions, and thus a smaller displacement,

- have smaller resistance, and thus need less powerful propulsion,
- if equipped with an internal combustion engine, produce fewer exhaust emissions, including CO_2 emissions.

In order to determine the possible reduction in exhaust emissions, a comparison must be made between an unmanned and manned vessel, where:

$$\text{payload capacity: } W_{LO} = W_{LOA},$$

$$\text{operating speed : } V = V_A, \tag{1}$$

$$\text{sailing range: } R = R_A,$$

are the same for both types of ships.

The following values should be calculated for both types of ships:

- resistance: R_T and R_{TA},
- propulsion engine power: MCR and MCR_A,
- fuel consumption, e.g., daily: FC and FC_A,
- exhaust emissions (CO_2): CO_2 and $(CO_2)_A$,

(where index A refers to an unmanned, autonomous vessel).

The most likely type of vessel to be built in an unmanned version is the container ship. Unmanned vessels which are currently at the design stage, such as the already existing Yara Birkeland [11], are container ships.

Since unmanned container ships are still practically non-existent, there are no data on their energy efficiency or emissions produced (the abovementioned Yara Birkeland has electric propulsion [11]). However, there is a large fleet of manned container ships for which energy efficiency and exhaust emissions can be calculated as well as design parameters, such as light ship weight, deadweight, displacement or propulsion power of the ship, estimated based on the existing data. These data are sufficient to develop mathematical relationships between geometrical and weight parameters (main dimensions, light ship weight, deadweight) and operational parameters (resistance, propulsion power, speed, fuel consumption, exhaust emissions) for manned vessels. However, using the structural differences between a manned and unmanned container ship for criteria (1) and the abovementioned mathematical relationships for manned ships, it is possible to develop such relationships for unmanned ships.

A relatively small number of publications dealing with the topic of conceptual or preliminary design of container ships contain regression formulas for estimating geometrical, weight or operational parameters. The first analyses of this type date back to 1980, Piko [12]. The specifications described therein include basic dimensions, such as length, width and design speed, dependent on deadweight or capacity expressed as a number of TEUs. The regression studies concerned container ship parameters which are now considered obsolete. Kirstensen [13] and Papanikolaou [14] examine linear and non-linear regression relationships for more modern container ships, but not the latest ones. Kirstensen used a database of container ships built between 1990–2010, i.e., not subject to the mandatory reduction of emissions through compliance with the EEDI design efficiency factor introduced by the International Maritime Organisation (IMO) in 2013 [15]. The publications available deal mainly with the basic dimensions of container ships, since such parameters are used at the initial stage of ship design. There are few publications which include regression functions for, e.g., light ship weight or weight classes comprising an empty vessel, propulsion power or fuel consumption in relation to the displacement or deadweight of modern container ships.

Few publications contain regression formulas for calculating, e.g., light ship weight of a container vessel, propulsion power or daily fuel consumption (Kirstersen [13], Chądzyński [16], Cheirdaris [17]). More recent publications which propose regression relationships for calculating propulsion power and fuel consumption for container ships are presented by Cepowski [18]. The formulas contained therein are insufficient for the estimation of geometric, weight or operational parameters for unmanned container ships. The database of ships used in those studies contained vessels built up to 2018, and most of them were not subject to the IMO (EEDI) requirements.

In this paper, the authors propose a method to assess CO_2 emissions for unmanned vessels. Regression formulas for manned container ships will be presented in such a form that the same geometrical and operational parameters for unmanned container ships can be estimated from them. Subsequently, it will be possible to estimate the propulsion power, fuel consumption and exhaust emissions for unmanned container vessels and compare the results obtained with the same parameters for conventional (manned) container vessels. Based on the literature research, it can be stated that the authors propose a novel approach to assessing exhaust emissions of unmanned container ships. The method makes it possible to determine the reduction in exhaust gas, which can be achieved in the operation of unmanned, diesel-powered vessels, compared to manned container ships.

Reduced fuel consumption, and thus, lower exhaust emissions by unmanned vessels will make it possible to comply with the International Maritime Organisation's (IMO) Energy Efficiency Design Index (EEDI), the value of which is reduced every few years [19]. The largest reduction in the EEDI value concerns container ships, which makes it all the more justifiable to conduct research in this area.

2. The Aims of Research

Unmanned vessels can have many different advantages. During ocean voyages, unmanned vessels will continue to be diesel-powered. Therefore, the possibility of reducing CO_2 emissions with internal combustion propulsion of unmanned ships compared to manned ships is a very important advantage for the development of maritime transport and environmental protection. Unmanned vessels will not have a superstructure and the various systems and equipment necessary for a crew. This will result in an unmanned vessel having less weight, less displacement and, therefore, less size, resistance and propulsion power than a manned vessel for the same transport capacity. Consequently, the unmanned vessel will emit less CO_2. In order to ascertain what the reduction in exhaust emissions can be, it is necessary to develop possibly accurate equations for the still practically non-existent unmanned container ships.

Therefore, the research objective of this paper is to develop a novel method to calculate exhaust emissions for unmanned container ships. By comparing exhaust emissions for manned and unmanned container vessels meeting the criteria (1), it will be possible to determine, at the design stage, the reduction in emissions which will be achieved in the operation of unmanned, diesel-powered container vessels. In order to reach the main objective of the research, it is necessary to:

- develop approximation functions for manned vessels: light ship weight LDT, resistance R_T, propulsion power MCR as a function of deadweight DWT,
- develop a calculation method and approximation functions for unmanned vessels based on manned vessels: resistance R_{TA}, propulsion power MCR_A as a function of deadweight DWT_A, taking into account criteria (1),
- calculate the exhaust emissions for manned and unmanned vessels,
- develop functions to determine the reduction, in percentage points, in exhaust emissions by an unmanned vessel compared to a manned vessel using criteria (1).

For the last task, we formulated a hypothesis that the greatest reduction in exhaust emissions would be for small vessels and that the larger the unmanned vessel, the smaller the reduction in exhaust emissions would be. The predicted reduction in CO_2 exhaust emissions is shown in Figure 1. The reduction in the difference in CO_2 emissions between a manned and unmanned container ship as a function of the number of TEUs is due, among other things, to the decreasing share of superstructure weight in the total weight of the ship when the number of containers is high.

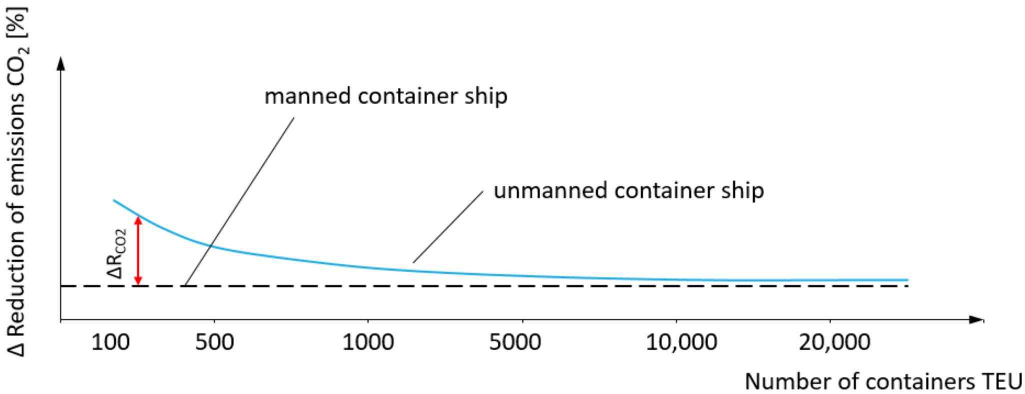


Figure 1. Forecast CO_2 reduction ΔR_{CO2} by unmanned container vessels, compared to their manned counterparts (diesel engines).

3. Research Method

The Sea-web Ships database [20] used in this research contains technical specifications of more than 200,000 ships and is considered an up-to-date and reliable database of the world fleet. However, the mentioned database does not contain detailed technical data on the individual weight classes that could be used to estimate the light ship weight of an unmanned vessel. For this purpose, the data collected for ships designed and built in the Szczecin Shipyard were also used [16].

The data retrieved from the Sea-web Ships database include technical specifications of modern container ships built between 2013 and 2022. The year 2013, as the adopted cut-off point in time, resulted from the fact that from 2013 onwards, newly built ships are required by the IMO to obtain a certificate confirming that they meet the required EEDI, which puts a limit on exhaust emissions. The introduction of the EEDI has forced ship designers and ship owners to implement solutions which ensure reduced exhaust emissions and greater environmental care. The same requirements will apply to unmanned, diesel-powered container ships.

Regression analyses should be conducted using representative data of the highest quality. Inaccurate predictive analyses and the resulting mathematical models of poor accuracy are typically attributable to the use of poor-quality data. Hence, the data retrieved from the Sea-web Ships database were thoroughly revised, and sister ship data with the same or similar characteristics were removed. Since unmanned container ships will not be equipped with deck cranes such as those on the vast majority of older manned container ships, the data were further sifted through to retrieve only data on container ships without cranes. The [20] database contains data on container ships of a capacity of 100 to 20,000 TEUs, and these have been divided into 11 groups (Table 1).

The container ship groups under analysis have internal combustion engines running on light or heavy fuel. The type of fuel used and the resulting exhaust emissions, including CO_2, were considered in further analyses.

Once the necessary approximation functions were developed for manned container vessels, they were used to develop such relationships for unmanned container vessels. The method for completion of this task, using criteria (1), is shown in the flowchart in Figure 2.

The developed method for calculation of CO_2 emissions for unmanned container vessels was used to calculate the predicted reduction in CO_2 emissions compared to manned container vessels, which is the main objective of this research.

Table 1. Range of parameters for the subtypes of container ships under analysis [20], *MCR*—total engine power, *V*—speed, TEU—number of TEU containers.

	Number of Ships Built in 2013–2022	TEU			MCR [kW]			*V* [knots]		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Small Feeder	137	100	963	504	850	9000	2942	9	19	13
Regional Feeder	460	1000	1984	1526	2648	19,420	9973	10	22	18
Feedermax	264	2034	2940	2489	4200	30,000	14,563	12	23	19
Panamax	14	27,420	36,560	33,949	4253	4335	4276	22	24.5	24
Baby post-Panamax	137	3013	5300	4104	9500	42,700	23,515	14.1	23.5	21
Sub Panamax	11	3100	3635	3415	25,040	31,710	26,441	20.5	23	22
Sub New Panamax	0	-	-	-	-	-	-	-	-	-
Post Panamax	207	5466	9962	8540	24,680	68,666	44,883	20	26	23
New Panamax	342	10,034	1610	12,923	34,223	72,240	48,475	18	24.7	22
ULCS	76	15,226	19,870	18,065	46,620	75,275	58,771	14.5	24.1	20
Mega Container	102	20,038	24,004	22,037	54,950	75,570	62,233	18	24	20

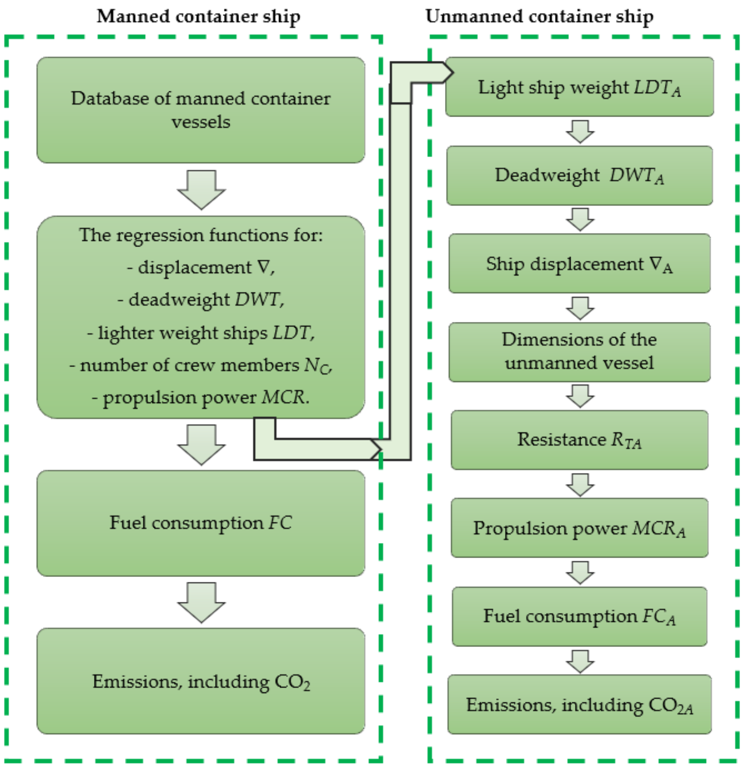


Figure 2. Sequence diagram for calculating CO_2 emissions for an unmanned container ship using the developed method.

4. Results and Analysis for Manned Container Ship

In order to prepare the necessary functional relationships which would be used to develop a method for calculating CO_2 emissions for unmanned vessels, the ship parameters which would have a significant impact on achieving the research objective had to first be determined. In the first step, we investigated which quantities have a decisive influence on the ship's displacement and deadweight capacity, and then developed regression functions appropriate for this research for manned container ships.

4.1. Ship Displacement and Deadweight

The buoyancy D of the vessel is equal to [14,21]:

$$D = LDT + DWT + B \tag{2}$$

where:

LDT—light ship weight,
DWT—deadweight,
B—ballast.

The deadweight of a ship is derived from the weight of all supplies, crew and cargo (i.e., containers, in the case of a container ship) [14,21]:

$$DWT = M_F + M_{PR} + M_C + M_{LO} \tag{3}$$

where:

M_F—weight of fuel and lubricating oil,
M_{PR}—weight of fresh water and provisions,
M_C—crew weight,
M_{LO}—weight of cargo containers.

The light ship weight is represented as the sum of weights of particular classes [21,22]:

$$LDT = M_1 + M_2 + M_3 + M_4 + M_5 + M_6 + M_7 + M_8 \tag{4}$$

where:

M_1—weight of the hull with superstructure,
M_2—weight of the deck equipment (e.g., steering gear, anchoring and mooring equipment),
M_3—weight of accommodation fittings,
M_4—weight of the engine room,
M_5—weight of piping and ship's systems (e.g., air-conditioning and ventilation),
M_6—weight of electrical equipment,
M_7—weight of special equipment (e.g., refrigerated pantry),
M_8—weight of spare parts.

The Sea-web Ships database does not contain as many details as were included in Formulas (3) and (4). Such detailed data are contained in the shipyard technical documentation drawn up for the ship under construction and are usually a business secret of the shipyard or the design office.

It can be seen from Table 2 that the hull with the superstructure (class 1), deck equipment (class 2) and engine room (class 4) account for the greatest share in the light ship weight. The total weight of the other classes is much smaller than the combined weight of classes 1, 2 and 4 (Table 3).

Table 2. Shares of weight classes in the light ship weight [%].

Weight Classes		Ship 1 *		Ship 2 **	
		Weight [T]	%	Weight [T]	%
1	Hull, superstructure, funnel including superstructure	9331	72.12	9337.1 1293.0	70.51
2	Deck equipment with hatch covers and cranes	1367	10.57	1227.0	9.27
3	Accommodation fittings	416	3.21	667.7	5.04
4	Engine room of which: main engine, generating sets	1073	8.29	964.8 376.0 62.0	7.29

Table 2. *Cont.*

	Weight Classes	Ship 1 *		Ship 2 **	
		Weight [T]	%	Weight [T]	%
5	Piping systems	505	3.91	602.4	4.55
6	Electrical equipment	170	1.32	299.4	2.26
7	Special equipment	44.5	0.34	114.1	0.86
8	Spare parts	31.5	0.24	29.5	0.22
	Total	**12,938**	**100%**	**13,242**	**100%**

* Container ship with hatch covers and four deck cranes [22] L_{BP} = 196.0 m, B = 32.26 m, H = 19.0 m, T = 10.0 m, 2700 TEU. ** Open-deck container ship without cranes [16] L_{BP} = 198.0 m, B = 33.40 m, H = 23.0 m, T = 12.5 m, 3000 TEU.

Table 3. Comparison of shares of specific weight classes in the total light ship weight.

Weight Classes	Ship 1 (*) from Table 2		Ship 2 (**) from Table 2	
	Weight [T]	%	Weight [T]	%
1, 2, 4	11,771.0	90.98	11,528.9	87.07
3, 5, 6, 7, 8	1167.0	9.02	1713.1	12.93
Total	**12,938.0**	**100%**	**13,242.0**	**100%**

* Container ship with hatch covers and four deck cranes [22] L_{BP} = 196.0 m, B = 32.26 m, H = 19.0 m, T = 10.0 m, 2700 TEU. ** Open-deck container ship without cranes [16] L_{BP} = 198.0 m, B = 33.40 m, H = 23.0 m, T = 12.5 m, 3000 TEU.

The components of the total deadweight *DWT* for exemplary container ships built in the Szczecin Shipyard are shown in Table 4.

Table 4. Components of the deadweight [%] [16].

DWT	Ship 1 *		Ship 2 **		Ship 3 ***	
	Weight [T]	%	Weight [T]	%	Weight [T]	%
Fuel M_F	450.0	11.05	880.0	8.65	4060.0	5.38
Fresh water + Provisions = M_{PR}	21.3 0.7	0.52 0.02	81.0 2.8	0.8 0.03	100.0 3.5	0.136 0.005
Crew M_C	2.0	0.05	4.2	0.04	6.5	0.009
Cargo M_{LO}	3600.0	88.36	9200.0	90.48	71,300.0	94.47
Total	**4074.0**	**100%**	**10,168.0**	**100%**	**75,470.0**	**100%**

* L_C = 102 m, V = 17 knots, R = 4100 Mm, MCR = 6400 kW, N_C = 13. ** L_C = 140 m, V = 19 knots, R = 8000 Mm, MCR = 8400 kW, N_C = 28. *** L_C = 285 m, V = 19.5 knots, R = 6800 Mm, MCR = 26,700 kW, N_C = 42.

It can be seen from Table 4 that the cargo carrying capacity M_{LO} has the greatest share in the total deadweight *DWT*, followed by the weight of fuel with a share of 5% to 11% (the larger the vessel, the smaller the share of fuel in the total deadweight *DWT*). The shares of other components of the deadweight are negligibly small.

The Sea-web Ships database does not contain complete data on the weight classes or deadweight components of the container ships included therein. For more detailed calculations, the data on a small population of container ships built in the Szczecin Shipyard were used, for which more detailed data were obtained [16].

4.2. Statistical Analysis of Geometric Parameters and Weight Groups of Manned Container Ships

Mathematical relationships between geometric, weight or propulsion power parameters for manned container ships as a function of number of TEU containers and speed *V* or displacement ∇ and speed *V* were developed using a multiple linear and non-linear regression model. Finally, the multiple linear regression was chosen due to the simpler form of the approximation function and sufficient accuracy. The general form of the multiple linear approximation function is as follows [23]:

$$Y = a_0 + a_1 X_1 + a_2 X_2 + a_3 X_3 + \cdots + a_k X_k \quad (5)$$

where:

Y—independent variable (in this case: deadweight, light ship weight, propulsion power),
X—dependent variable (in this case: number of TEU containers and speed or displacement and speed),
$a_0, a_1, \ldots, a_n$—regression coefficients.

A full description of the multiple linear and non-linear regression model is provided in many publications, e.g., [23,24], and in application to the mathematical search for relationships between vessel parameters, as presented by Cepowski [25].

The computer programme NdCurveMaster software (Version 8.2, SigmaLab, Mumbai, India, 2021) [26] was used to search for model equations and their coefficients.

As a result of an analysis, several mathematical models which provide the highest accuracy for the manned container ship parameters under analysis were selected. To assess the accuracy of the models, we primarily used the coefficient of determination R^2 and the standard error of estimation [23].

Table 1 shows basic groups of container ships, broken down by number of containers. In this study, data for the first three groups (Small Feeder, Regional Feeder and Feedermax) were used. Fuel consumption and exhaust emissions by container ships are primarily determined by their operating speed, as well as by dimensions and displacement. Hence, the approximation functions sought for manned container vessels, which were to be used to develop such functions for unmanned container vessels, depended on the number of TEUs or displacement ∇, and operating speed *V*. A statistical analysis of speed *V* as a function of the number of TEU containers for the first three groups in Table 1 is shown in Figure 3.

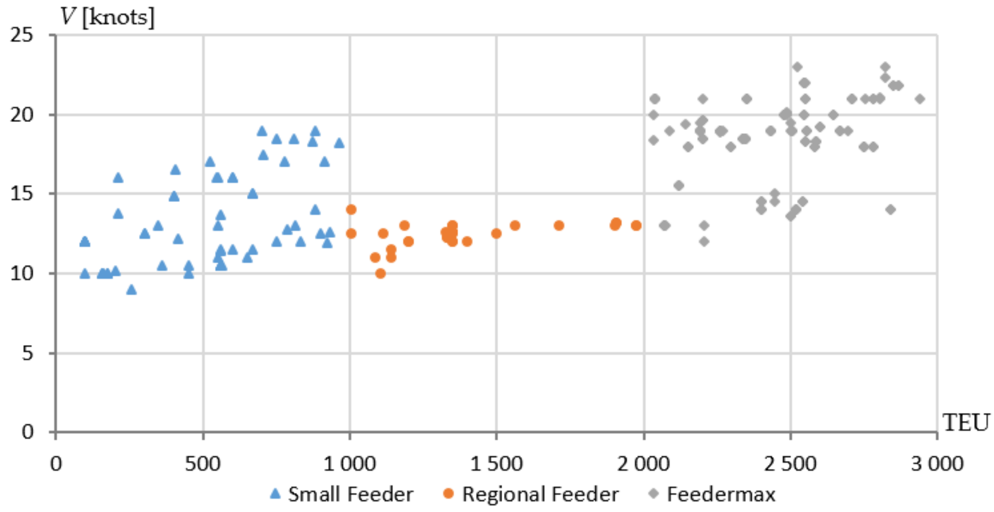


Figure 3. Operating speed and number of containers (first three groups from the Sea-web Ships database [20]).

In is clear from the data shown in Figure 3 that the speeds of the container ships vary across the groups. Hence, the approximation functions for manned container vessels had to be well suited and verified for each group.

The analysis of manned container vessel parameters was carried out for:

- displacement ∇ = f(TEU, *V*),
- deadweight *DWT* = f(TEU, *V*),
- light ship weight *LDT* = f(TEU, *V*),
- light ship weight *LDT* = f(∇, *V*).

Examples of results of the above regression analyses for manned container ships are shown in Figures 4–7.

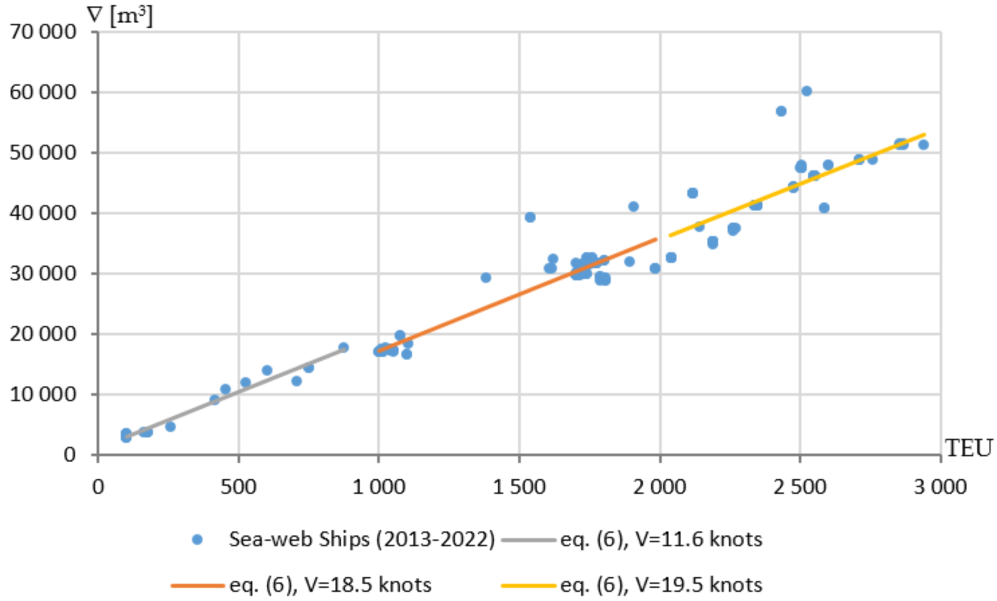


Figure 4. Displacement ∇ = f(TEU, *V*).

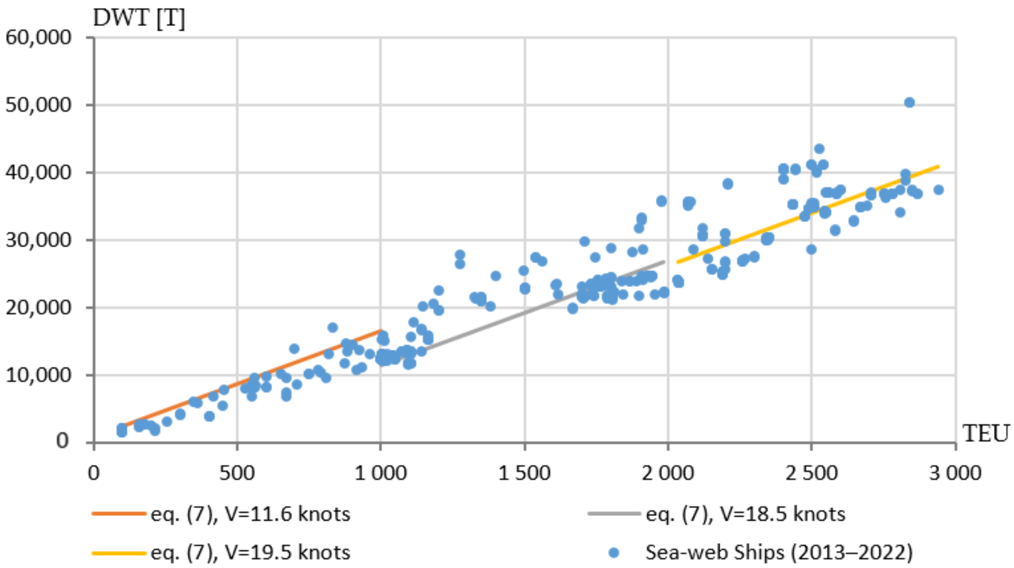


Figure 5. Deadweight *DWT* = f(TEU, *V*).

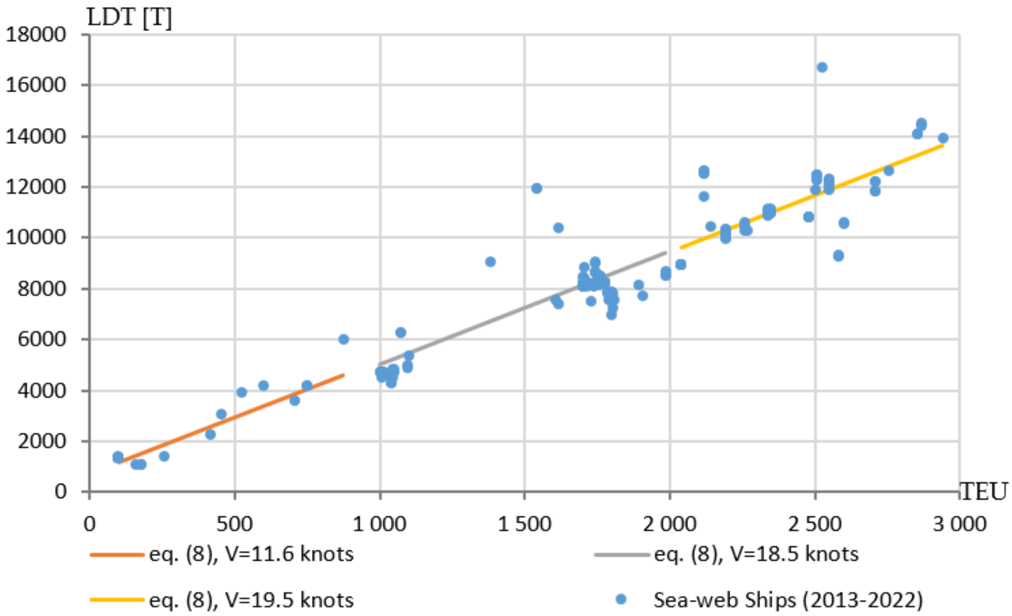


Figure 6. Light ship weight *LDT* = f(TEU, *V*).

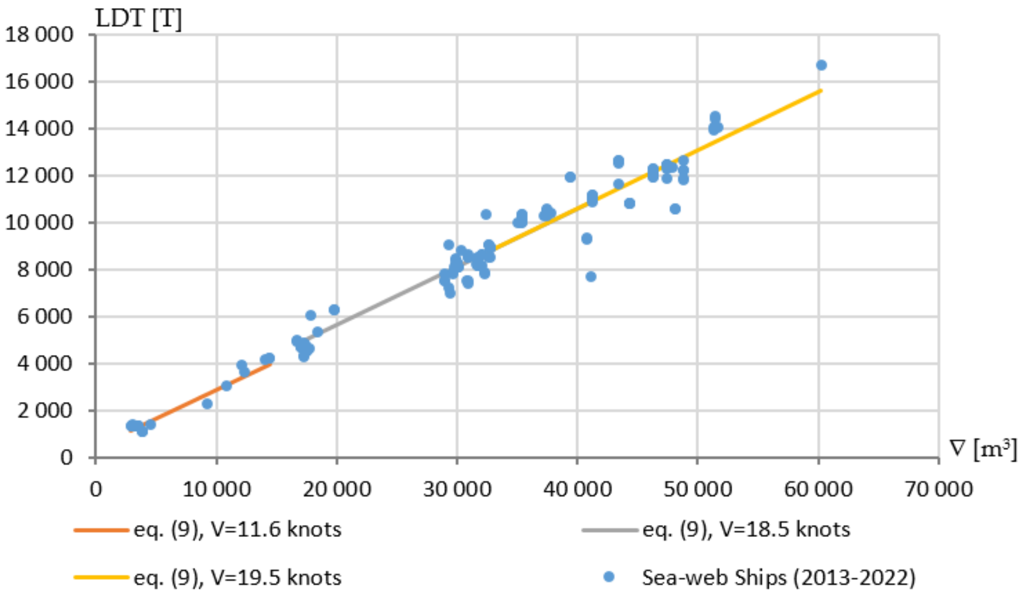


Figure 7. Light ship weight *LDT* = f(∇, *V*).

Below are the final forms of the regression formulas developed for manned container ships:

$$\nabla(\mathrm{TEU}, V) = 5172.67 - 353.715 \cdot V + 18.6289 \cdot \mathrm{TEU},\ \mathrm{R}^2 = 0.9714 \tag{6}$$

$$DWT(\mathrm{TEU}, V) = 9468.38 - 734.367 \cdot V + 15.5558 \cdot \mathrm{TEU},\ \mathrm{R}^2 = 0.9712 \tag{7}$$

$$LDT(\mathrm{TEU}, V) = 925.722 - 18.5126 \cdot V + 4.4492 \cdot \mathrm{TEU},\ \mathrm{R}^2 = 0.9554 \tag{8}$$

$$LDT(\nabla, V) = -84.2494 + 41.4843 \cdot V + 0.246921 \cdot \nabla,\ \mathrm{R}^2 = 0.9829 \tag{9}$$

4.3. Number of Crew Members on Container Ships

On manned vessels, some components of the weight classes (such as, e.g., superstructure), as well as some components of *DWT* (such as, e.g., fresh water, provisions for crew) depend on the deadweight and number of crew members. It follows from the data in the Sea-web Ships database that the number of crew members varies from 21 to 26, depending on the deadweight of the ship (number of containers). Based on these data, approximation functions between the number of crew members and number of containers were developed (Figure 8).

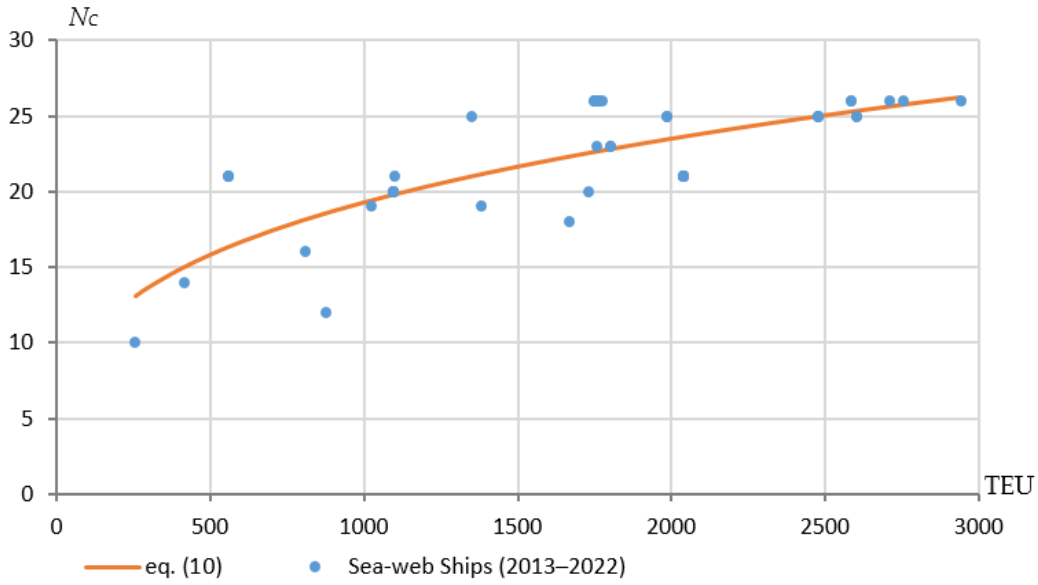


Figure 8. Number of crew members N_C = f(TEU).

The approximation formula for the number of crew members N_C depending on TEU is as follows:

$$N_C(\text{TEU}) = \text{ROUND\_TO\_INTEGER}\left(3.1037 \cdot \text{TEU}^{0.267}\right),\ R^2 = 0.5956. \quad (10)$$

4.4. Statistical Analysis of Propulsion Power for Manned Container Ships

On the basis of the data contained in the Sea-web Ships database [20], a statistical analysis for three groups of container vessels listed in Table 1 was carried out to examine:

- propulsion power *MCR* = f(TEU, *V*),
- propulsion power *MCR* = f(∇, *V*).

Using the same data, daily fuel consumption *FC* functions for manned container ships were also developed; however, the resulting statistical relationships were insufficiently accurate for research purposes.

To compare fuel consumption between manned and unmanned container vessels, the relationships recommended by IMO [15] were used, as follows:

$$FC = MCR \cdot sfc \cdot 24/1000,\ [\text{kg fuel/day}] \quad (11)$$

where *sfc* is the unit fuel consumption; the recommended value of *sfc* = 190 g/kWh was used in the comparative study [15].

To determine the CO_2 emissions during a ship's voyage, the IMO has developed an index for different fuel types [19]. CO_2 emissions, e.g., daily, are calculated from the following formula:

$$CO_2 = CF \cdot FC\ [\text{kg } CO_2/\text{day}] \quad (12)$$

where *CF* [g CO_2/g fuel] is the conversion factor, for heavy fuel (HFO) *CF* = 3.1144 g CO_2/g fuel [19].

To facilitate a comparison of the CO_2 emissions by manned and unmanned container ships, it was assumed that only heavy fuel would be used for propulsion.

Example results of regression analyses *MCR* = f(TEU, *V*) and MCR = f(∇, *V*) are shown in Figures 9 and 10.

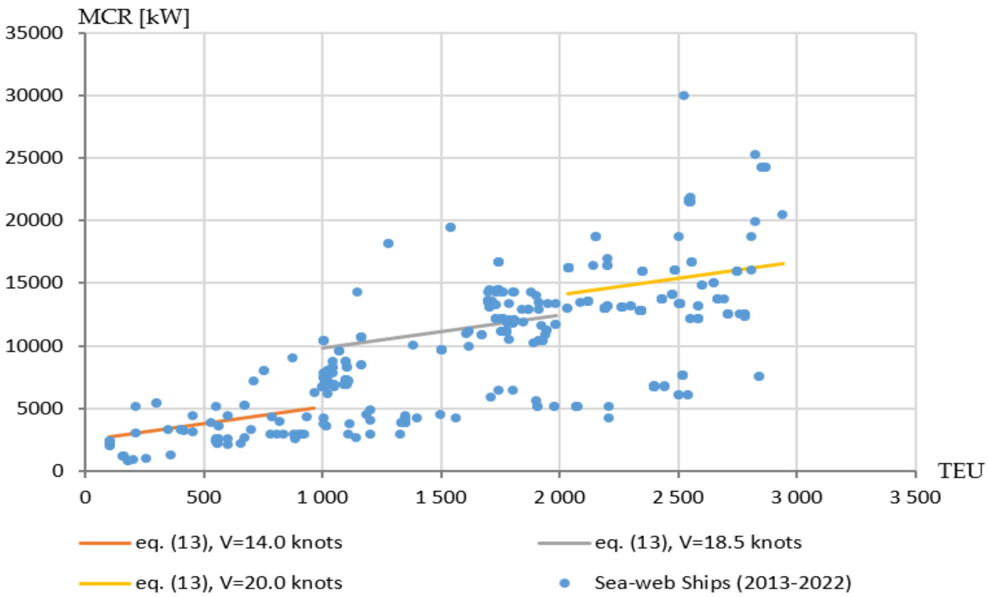


Figure 9. Propulsion power *MCR* = f(TEU, *V*).

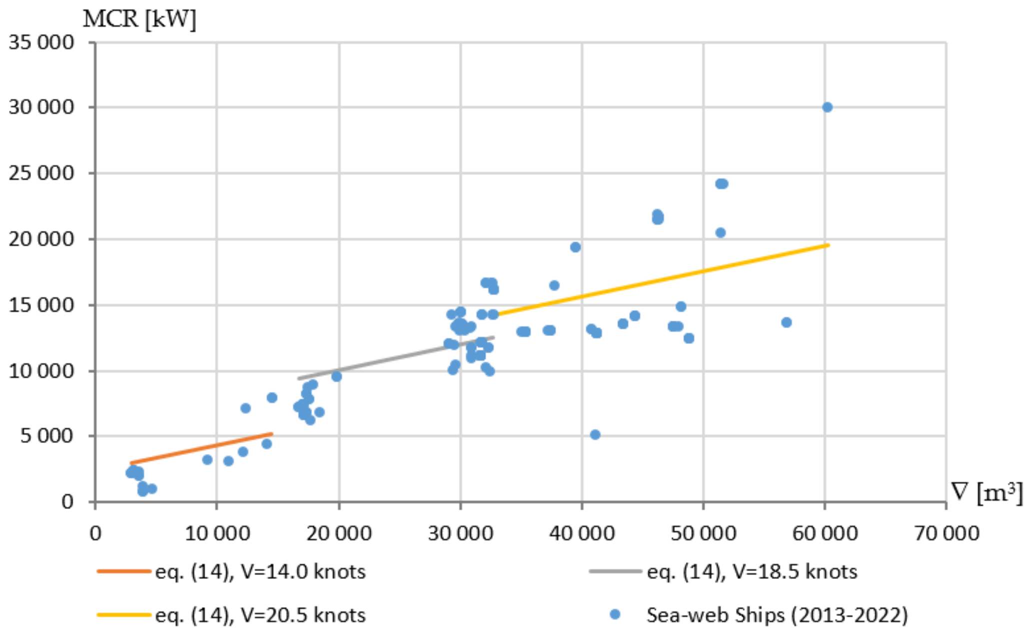


Figure 10. Propulsion power *MCR* = f(∇, *V*).

The final forms of the formulas for container ships in Table 1 are as follows:

$$MCR(\text{TEU}, V) = -12062.7 + 1039.65 \cdot V + 2.65121 \cdot \text{TEU},\ \text{R}^2 = 0.8906 \quad (13)$$

$$MCR(\nabla, V) = -9427.6 + 0.192657 \cdot \nabla + 846.526 \cdot V,\ \text{R}^2 = 0.8908. \quad (14)$$

5. Method of Forecasting Propulsion Power, Fuel Consumption and Exhaust Emissions for Unmanned Container Ships

5.1. Assumptions for the CO_2 Emission Forecasting Method for Unmanned Container Ships

A database of geometric and operational parameters for unmanned container ships does not yet exist; hence, a method for forecasting propulsion power, fuel consumption and CO_2 emissions for these ships was developed under the assumptions that:

- the differences in design and equipment between manned and unmanned container vessels can be identified,
- knowing these differences, it is possible to adjust regression formulas for manned container vessels in such a way as to obtain relationships which describe unmanned container vessels,
- in the next step, using calculations according to Equations (11) and (12), it is possible to determine the fuel consumption and CO_2 emissions for unmanned container ships.

The main differences in the design and equipment of manned and unmanned container vessels are shown in Table 5. The regression formulas developed for manned container vessels are included in Section 4, whereas their application, as well as the sequence of analyses to determine the propulsion power, fuel consumption and CO_2 emissions, are shown in Figure 2.

Table 5. Comparison of manned and unmanned container vessels.

Number of Containers, Operating Speed and Sailing Range—the Same	
Manned container ship	Unmanned container ship
Light ship weight	Smaller weight: - no superstructure, - no systems necessary for the crew, - smaller energy requirements (smaller generator sets), - smaller power of the main propulsion.
Deadweight	Comparable to that of a manned vessel (Table 4)
Vessel dimensions, displacement	Smaller dimensions and displacement
Resistance, propulsion power, fuel consumption	Owing to a smaller size and displacement, the vessel has a smaller resistance, needs less powerful propulsion and has a smaller fuel consumption level

5.2. Geometrical and Operational Parameters for Unmanned Container Ships

The geometrical and operational parameters (approximation functions) for unmanned container vessels were developed on the basis of the approximation functions for manned container vessels, Section 4, taking into account the information in Tables 2–5. The developed relationships for unmanned container vessels are for the number of containers from 200 to 2800, corresponding to the first three groups in Table 1, and for the operational speed of the same container vessels.

5.2.1. Light Ship Weight of Unmanned Container Vessel

The hull with superstructure accounts for the largest share of the light ship weight—weight class 1, Table 2. An unmanned container ship will have no superstructure or accommodation for a crew.

The weight of the hull is the sum of:

$$M_1 = M_H + M_S, \tag{15}$$

where:

M_H—weight of hull without superstructure,
M_S—weight of superstructure.

Based on the parameters for the container ships built in the Szczecin Shipyard, the weight of the superstructure can be represented by the following relation [16]:

$$M_S = 83.5613 + 0.000569 \cdot DWT^{1.16888} + 0.001579 \cdot N_C^{3.51869}, \quad (16)$$

where:
N_C—number of crew members.

The light ship weight will be smaller, since an unmanned vessel will not have a superstructure or systems necessary for the crew, and the weight of the engine room will also be smaller (an unmanned vessel with the same number of containers as its manned counterpart will have smaller dimensions, thus a smaller displacement and less powerful propulsion).

Therefore, the light ship weight LDT_A of an unmanned vessel is represented as:

$$LDT_A(\text{TEU}) = LDT(\text{TEU}) - M_S - \Delta M_H - \Delta M_4, \quad (17)$$

where:
LDT(TEU)—light ship weight of a manned vessel, Equation (8) or (9),
M_S—weight of superstructure, Equation (16),
ΔM_H—reduction in the weight of the hull of a ship without a superstructure (the hull of an unmanned ship with the same number of containers as its manned counterpart will be lighter, as it will have smaller dimensions and displacement),
ΔM_4—reduction in the weight of the engine room, owing to a less powerful propulsion.

The weight of superstructure M_S is a function of DWT and the number of crew members N_C. Equation (7) DWT = f(TEU, V) and Equation (10) N_C = f(TEU) must be substituted into Equation (16).

The reduction in weight of the hull of an unmanned container ship ΔM_H relative to a manned container ship with the same number of TEUs, but for a smaller displacement ∇_A, is calculated from the following formula:

$$\Delta M_H = LDT(\nabla, V) - LDT(\nabla_A, V), \quad (18)$$

where:
$LDT(\nabla, V)$—light ship weight of a manned container vessel, Equation (9),
$LDT(\nabla_A, V)$—light ship weight of an unmanned container vessel, for displacement ∇_A.

The reduction in the weight of the engine room ΔM_4 of an unmanned container ship relative to the weight of the engine room of a manned container ship (for the same number of TEUs) is calculated from the following formula:

$$\Delta M_4 = M_4(MCR) - M_4(MCR_A), \quad (19)$$

where:
$M_4(MCR)$—weight of the engine room of a manned container ship for the propulsion power MCR,
$M_4(MCR_A)$—weight of the engine room of an unmanned container ship for the propulsion power MCR_A (the unmanned container ship has the same speed V as the manned container ship—criterion (1)).

There are several approximate formulas in the literature for calculating the weight of the engine room for a ship with an internal combustion engine, including Barrass [21], Molland [27], Papanikolaou [14]. As a result of an analysis of the abovementioned approximate formulas, verification of the scope of their application, and consideration of the weight of the engine room in container ships built in Szczecin Shipyard, the Barrass formula [21], which applies to the range of TEUs for the first three groups in Table 1, was used for further calculations:

$$M_4(MCR) = 0.075 \cdot MCR + 300. \quad (20)$$

In order to calculate the reduction in weight ΔM_H, Equation (18) and ΔM_4, Equation (19), the quantities of displacement ∇_A and propulsion power MCR_A for an unmanned container ship are required.

At this stage of the calculation, these quantities are not known. Therefore, it is initially assumed that:

$$\nabla_A = C_\nabla \cdot \nabla, \tag{21}$$

$$MCR_A = C_{MCR} \cdot MCR, \tag{22}$$

where:

C_∇—displacement ∇_A reduction factor for an unmanned container ship, initially assumed in the first iteration step,
C_{MCR}—propulsion power MCR_A reduction factor for an unmanned container ship, initially assumed in the first iteration step.

5.2.2. Deadweight of an Unmanned Container Ship

It follows from Table 4 that ca. 90% or so of the total deadweight is attributed to cargo deadweight, and from 5% to 11% (for this group of ship sizes) to the weight of fuel. For the purpose of further analysis, it was assumed that 10% of the total deadweight of an unmanned vessel is attributed to the weight of fuel, and 90% to the cargo deadweight.

Based on the data in Table 4, it was assumed that the deadweight of an unmanned vessel is the same as that of a manned vessel (i.e., the unmanned vessel will carry the same number of containers and will have the same fuel supply as the manned vessel):

$$DWT_A = DWT. \tag{23}$$

5.2.3. Displacement ∇_A of an Unmanned Container Ship

Calculating from Equation (16) the lesser light ship weight of an unmanned container ship, its displacement will equal:

$$\nabla_A(\text{TEU}, V) = \frac{LDT_A(\text{TEU}, V) + DWT_A(\text{TEU}, V)}{\gamma}. \tag{24}$$

where γ is the specific gravity of water, and for seawater, γ = 1.025 t/m^3.

The displacement ∇_A calculated from Equation (24) is compared with the pre-assumed displacement ∇_A, Equation (21). If the difference is greater than the assumed accuracy, the new displacement ∇_A value from Equation (24) is substituted into Equation (18), and calculations are continued until the assumed accuracy of ∇_A is reached.

5.2.4. Dimensions of an Unmanned Container Ship

Based on the displacement ∇_A, it is possible to determine the basic dimensions that must satisfy the displacement equation:

$$\nabla_A = L_A \cdot B_A \cdot T_A \cdot C_{BA} \tag{25}$$

where:

L_A, B_A, T_A—the main dimensions of the hull of an unmanned vessel (length, breadth, draught, respectively),
C_{BA}—block coefficient of the hull of an unmanned vessel.

The determination of L_A, B_A, T_A, C_{BA} must be carried out in accordance with the ship's design rules so as to achieve compliance with Equation (25) and other design criteria.

5.2.5. Resistance and Propulsion Power of an Unmanned Container Ship

For the designed hull of an unmanned container ship, the resistance R_{TA} and the propulsion power MCR_A can be calculated from approximate methods for an assumed operational speed V. Since the MCR = f(∇, V) function was determined from regression analyses for an manned container ship, Equation (14), the propulsion power MCR_A for an unmanned container ship of displacement ∇_A was calculated directly from this function:

$$MCR_A = MCR(\nabla_A) \tag{26}$$

where $MCR(\nabla_A)$ is provided by Equation (14) for speed V and displacement ∇_A.

The propulsion power MCR_A for an unmanned container ship, calculated from Equation (26), is compared with the initially assumed one according to Equation (22). If the difference is greater than the assumed accuracy between the assumed MCR_A, Equation (21), and the one calculated from Equation (26), the new MCR_A value is substituted into Equation (19), and the calculation is continued iteratively until the assumed accuracy of the propulsion power MCR_A calculation is reached.

Since the displacement of an unmanned container ship ∇_A = f(TEU, V), Equation (24), then ultimately the propulsion power MCR_A can also be represented as a function of TEU: MCR_A = f(TEU, V).

5.2.6. Fuel Consumption and CO_2 Emissions

Based on Formulas (11) and (12), the daily fuel consumption and CO_2 emissions for an unmanned container ship are calculated from the following relationships:

$$FC_A = MCR_A \cdot sfc \cdot 24/1000 \tag{27}$$

$$CO_2 = CF \cdot FC_A \tag{28}$$

6. Design of a Manned and Unmanned Container Ship

Section 5 presents the developed method for predicting propulsion power, fuel consumption and CO_2 emissions for unmanned container ships. Since they are still virtually non-existent, their geometrical and operational parameters are unavailable. Therefore, the corresponding data for manned container vessels were used to calculate the fuel consumption and exhaust emissions of unmanned container vessels.

In order to verify the validity of the analysis results obtained, especially the estimated reduction in exhaust emissions between manned and unmanned container ships meeting criterion (1), two conceptual designs of both container ships were developed for the purpose of this paper. The designs made it possible to verify the predicted fuel consumption and exhaust emissions from the developed method with the calculations made during the design of the two container ships.

Both versions of the container ships were designed with the following assumptions:

- capacity 300 TEU,
- operating speed V = 17 knots,
- sailing range R = 4100 Mm.

The preliminary design and all design calculations were carried out in accordance with the commonly applied method for designing transport vessels [21,27–29].

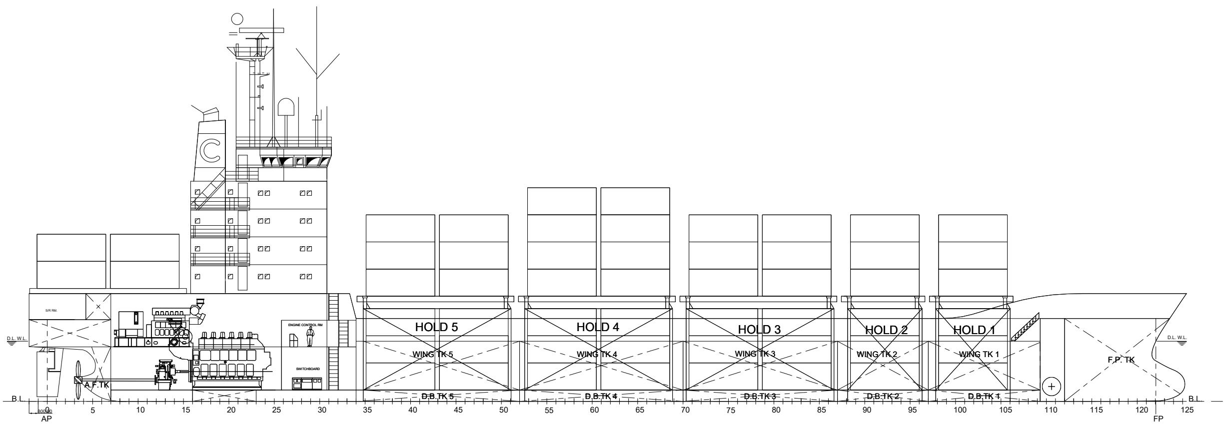
According to the adopted assumptions (TEU, V, R), hull shapes were developed, theoretical lines designed, final ship dimensions determined, and the buoyancy, equilibrium, and stability equations were verified. The spatial subdivision of the hull was carried out, and the arrangement of containers in the hull checked. In the next step, resistance and propulsion power were calculated for the designed hulls, using the Holtrop–Mennen method [30] for a predetermined speed, and the main engines selected. Daily fuel consumption and CO_2 emissions were calculated for each selected engine.

The geometrical and operational parameters of the completed designs are shown in Table 6.

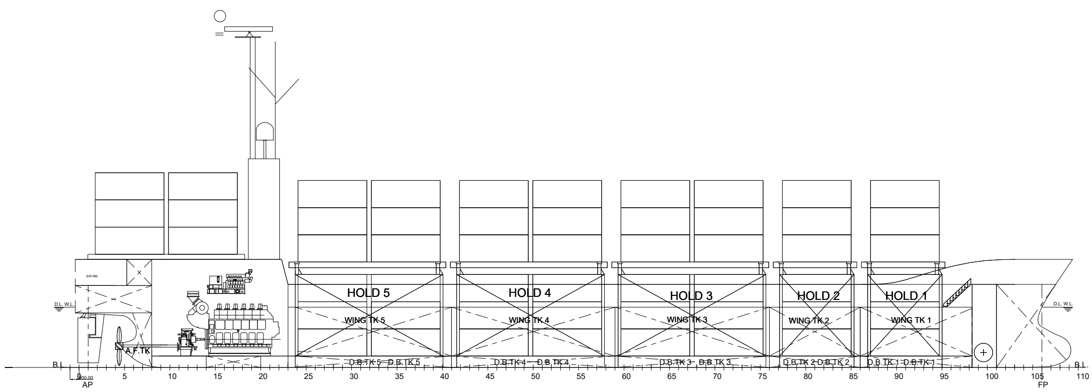
Table 6. Geometrical and operational parameters of a manned and unmanned container ship.

Container Ship: capacity 300 TEU, operating speed V_E = 17 knots, coverage R = 4100 Mm		
Parameter	**Manned**	**Unmanned**
Length L [m]	99.24	85.38
Width B [m]	19.00	19.00
Depth T [m]	5.30	5.30
Displacement ∇ [m^3]	6877.0	5907.0
Deadweight DWT [T]	4072.0	4012.0
Light ship weight LDT [T]	2233.0	2005.0
Resistance R_T [kN]	391.9	374.6
Propulsion power MCR [kW]	5800.0	5500.0
Daily fuel consumption FC [kg]	26,448.0	25,080.0
Daily CO_2 emissions [kg]	82,369.6	78,109.1

A general arrangement plan for each of the container ships (manned and unmanned) is shown in Figure 11.



(**a**)



(**b**)

Figure 11. General arrangement plan of a manned (**a**) and unmanned (**b**) container ship.

The results of calculations of the resistance and propulsion power, shown in Table 6, were obtained with the use of ship design software programs, based on the designed theoretical lines. The regression relationships of Equations (13) or (14) for a manned container ship and Equations (22) or (26) for an unmanned container were not used to calculate the propulsion power.

Thus, the results of calculations of fuel consumption and CO_2 emissions for both container ships could be used to verify the CO_2 calculations made by the developed method.

7. Final Results and Analysis

The final results of calculations of CO_2 emissions for manned and unmanned container vessels for speed V = 17 kn and number of TEUs = (200–2000) obtained using the regression formulas are shown in Figure 12. The same figure also shows the daily CO_2 emissions for the designed container vessels (manned and unmanned). Figure 13, on the other hand, shows the difference between the CO_2 emissions of manned and unmanned container ships for the same range of number of containers carried and speed V = 17 kn. In this figure, the difference in CO_2 emissions for the designed container ships is marked with a point.

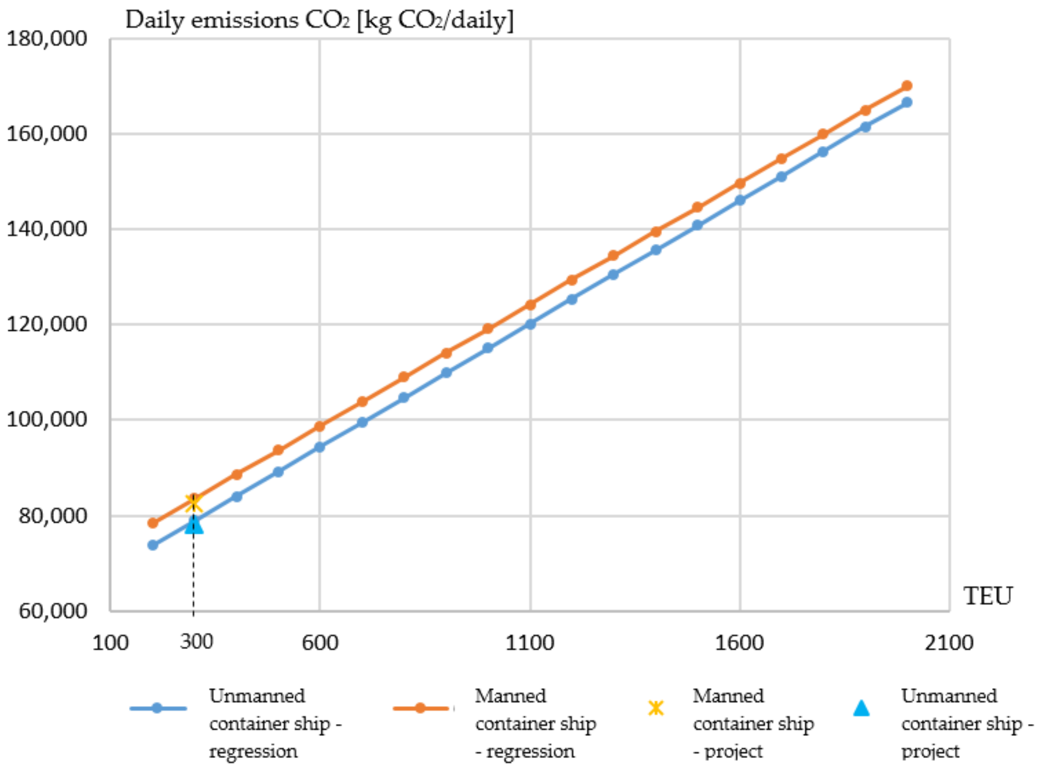


Figure 12. Daily CO_2 emissions, calculated for container ships of 200–2000 TEUs for speed V = 17 knots, and the designed container ships (manned and unmanned).

The graphs in Figures 12 and 13 show a clear decrease in CO_2 emissions for unmanned container vessels compared to manned vessels. The calculations were made using the method developed for unmanned container vessels, where regression relationships developed for manned container vessels were applied. The trend in the reduction in CO_2 emissions for unmanned container vessels confirmed the previously accepted hypothesis, namely, the larger the container vessel (greater number of TEUs), the smaller the reduction in CO_2 emissions, compared to manned vessels. In Figure 13, the reduction in CO_2 emissions is linear; however, it applies to small container ships between 200 and 2000 TEU. For large or very large vessels, the decrease in CO_2 emissions is expected to be smaller and represented by a non-linear curve.

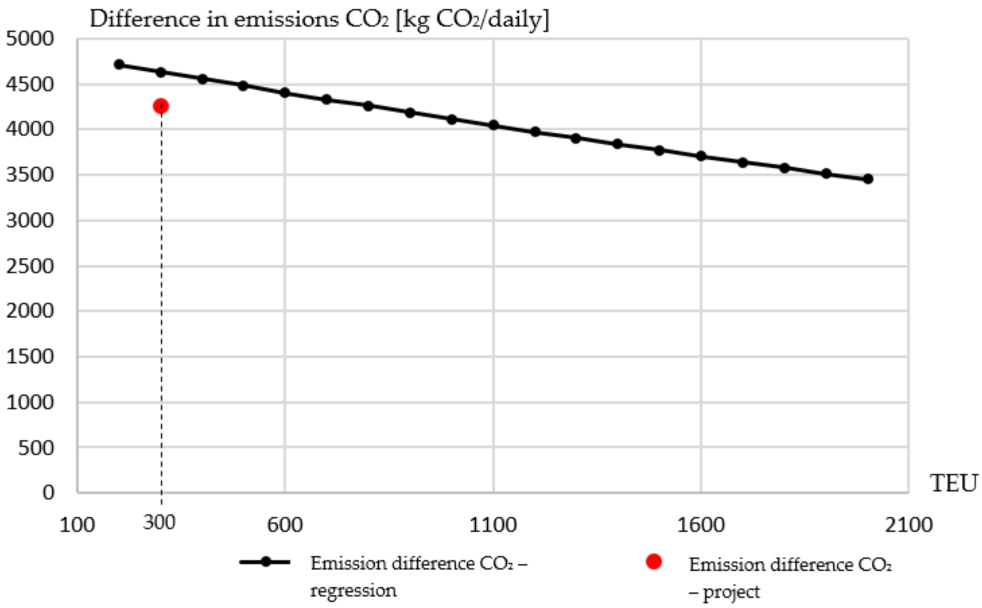


Figure 13. Difference in CO_2 emissions calculated for manned and unmanned container vessels with 200–2000 TEUs for speed V = 17 knots, and the designed container vessels (manned and unmanned).

The CO_2 emissions and their reduction calculated for the designed container ships shown in Figures 12 and 13 confirmed the correctness of the calculations according to the developed method for unmanned container ships.

8. Summary and Conclusions

The development of unmanned ships is an important measure that will contribute to reducing CO_2 emissions in maritime transport. Even if diesel-powered ships (also those burning alternative, less carbon-intensive fuels) continue to operate on longer routes, a reduction in CO_2 emissions is possible. The aim of this work was to develop a method to estimate the level of CO_2 reduction for unmanned versus manned vessels. As unmanned vessels do not yet exist (apart from experimental vessels for testing autonomous control systems), the developed method cannot be based on the design parameters of a large population of such vessels.

The method proposed by the authors is a novel solution for predicting CO_2 emissions for still non-existent unmanned ships. It follows from the literature research that such a method, which can also be used in the conceptual design of unmanned ships, has not been developed yet.

The proposed method uses regression equations developed for manned container ships. Since the accuracy of regression equations is highly dependent on the capacity (number of TEU containers) and speed of container ships, the method was developed for container ships of up to 2800 TEUs. Its elaboration required detailed data on container ship design, weight classes, and energy requirements for ship systems, including, without limitation, systems required for the crew. Such data are mostly unavailable in large databases, such as [20]. Therefore, data for a small population of container ships built in the Szczecin Shipyard were used [16].

The proposed method can be expanded and completed once more detailed data are obtained. However, the results obtained so far, and their comparison with the parameters of the container ships specially designed for this study, confirmed that sufficient accuracy was achieved to prove the hypothesis set out at the beginning of the paper about the reduction of CO_2 emissions for unmanned container ships.

Internal combustion engines on seagoing vessels will be increasingly powered by alternative fuels with a carbon footprint smaller than that of diesel fuel. The proposed method can also be used for predicting CO_2 emissions for these fuels.

As the method proposed by the authors is the first of its kind for analysis of CO_2 emissions by unmanned ships, research into the operation of unmanned ships and their environmental impact will be continued. Once more data are available on the weight classes, equipment, design, and energy balance (including, without limitation, the energy requirements for the crew) for existing manned container ships, the method can be improved to provide more precise calculations of fuel consumption and CO_2 emissions for unmanned container ships under development.

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