

# Surrogate Models for Propulsive Performance in the Feasibility Study of Cruise Ships

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**Abstract.** Propulsive issues are of utmost importance for determining a successful cruise ship design. Estimating the propulsive power and associated propeller revolutions needed in trial conditions is one of the key aspects for writing the contracts between yards and shipowners. Then, it is relevant to be capable of predicting the propulsive performances of the vessel in all the phases of the vessel design. In the present work, the focus is on the feasibility study of the vessel, when main dimensions should be selected before starting any other consideration on the hull form, internal layout and machinery equipment. Therefore, the study proposes the generation of surrogate models for the propulsive characteristics of the ship as a function of the vessel's main dimensions. Starting from an initial design space discretised with a Box-Behnken methodology, dedicated calculations have been performed by employing validated empirical-statistic methods on each member of the design space. Relevant quantities, like absorbed power, propulsive efficiency and optimal propeller characteristics have been collected in a database to perform a multiple linear regression analysis. The obtained models have all high quality of fit indicators, highlighting the good fitting performances of the regressions. As such, the study provides a good instrument for designers, allowing for estimating propulsive performances in the feasibility study of ships, before the concept design phase begins. Further improvements could be achieved by extending the initial design space.

**Keywords.** concept design, cruise ships, regression analysis, propulsion

## 1. Introduction

Passenger ships and especially cruise ships are complex objects to design, as they require knowledge of plenty of subsystems all concurrent to the operability of the vessel [1,2]. However, in the first stages of the design process not all the attributes relevant to the design are known and only the main Key Performance Indicators (KPIs) are assessed as a function of the vessel main dimension and general particulars [3]. This is the specific

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case of the feasibility study, where the main dimensions and geometrical coefficients have to be selected and where a wrong decision could compromise the success of the entire project [4,5,6]. To this end, it is extremely important to have mathematical instruments (i.e. surrogate model) capable of estimating vessel attributes with just a few input parameters [7].

Then, it is relevant to identify the principal attributes required by the shipowner in the feasibility study of the ship and evaluate proper surrogate model to estimate it [8]. Generally, in a feasibility study the driven parameter of the design is related to propulsive issues, which means achieve the target of a certain speed with a given power at certain rate of revolution [9]. Those are the principal KPIs required by the shipowner, therefore a designer should be capable of quickly estimate such performances with just a few inputs. In Naval Architecture there are multiple methods suitable for estimate the propulsive performance of a ship [10]. Namely, a designer has at disposal: basic regressions, empirical-statistic methods, numerical calculations and model tests. However, not all the methods are applicable in the feasibility study of a vessel. In fact, model test and numerical calculations require the availability of a detailed geometry to build the model or perform the calculation mesh. Furthermore, the processes need calculation and execution time not applicable to the really early design stages of a ship. Empirical-statistic methods require the knowledge of a lot of geometrical parameters, means require also a reference hull form or dedicated regression models for all the relevant geometric quantities. The best option is to adopt simple regression formulae, requiring just few inputs correlated to the vessel main dimensions [11]. Such instruments are at disposal for several kinds of ships and derive from database analyses, employing different levels of regression techniques [12,13,14].

However, just a few models are available for cruise ships and most of them are only related to the estimation of main dimensions rather than propulsive performances [3]. To feel this gap, the present work proposes a surrogate model for propulsive performances of cruise vessels as a function of the ship main dimensions. The model is based on an initial database of 13 hulls created by means of design of experiments techniques to cover a precise range of dimensions representative of the modern cruise ship market. As the model should not be extremely accurate as the uncertainty in a feasibility study is still high, no high fidelity tools (like CFD computations) have been employed but just a modified version of the state-of-the-art Holtrop & Mennen method for ship propulsion [15]. The reliability of the method is sufficiently high to cover the issue of a feasibility study, as the powering prediction with empirical-statistic methods is normally used in more advanced phases of the initial design [3].

Starting from dedicated powering calculations having as a target the speed of 21 knots, a database of propulsive performance parameter has been build as a basis to start regression analyses. Employing multiple linear regression techniques with length  $L$ , breadth  $B$  and immersion  $T$  as independent variables, surrogate models have been derived for vessel absorbed power, rate of revolution, efficiencies and propeller characteristics. The obtained models represent a novel tool for the feasibility study of cruise ships as no similar example is available in the literature. The employment of this instrument in the feasibility study is discussed with its implications and impact on the possible design choices.

Notwithstanding the above, it should be stated that the model has some limitations due to the relatively low number of hulls employed for this exploratory study. However,

the problem can be overcome by increasing in the future the amount of vessels in the initial database. All these issues and the methodologies employed for the surrogate model generation are further discussed and detailed in the following sections.

## 2. Ship Database

The initial point for the development of a surrogate model is the availability of a database populated with sufficiently reliable sets of data. Unfortunately, the literature cannot provide available open databases containing propulsive data of existing ships; therefore, alternative methodologies should be used.

The straightforward strategy to overcome the lack of data is to generate it by applying Design of Experiments (DOE) techniques in order to optimise the number of projects to populate a new database [16]. Prior to start with the DOE generation, it is necessary to identify which are the independent variables of the process and what are the interval of interest for these variables. The identification of the independent variable is simple. Targeting a feasibility study, the designer is interested in knowing the main dimensions of the ship; therefore, it has been decided to consider the following set of independent variables: the length between perpendiculars  $L_{PP}$ , the breadth  $B$  and the design draught  $T$ .

For determining the ranges, an investigation has been carried out on the dimensions of the cruise ships built in the recent years. Table 1 reports the data of the cruise vessels, which allows for determining the following ranges (expressed in meters) for the independent variables:

$$221.50 \leq L_{PP} \leq 325.04 \quad (1)$$

$$28.80 \leq B \leq 49.39 \quad (2)$$

$$6.80 \leq T \leq 8.80 \quad (3)$$

The data range capture almost all the medium and large sized cruise ships actually sailing around the world. The Table reports also other quantities relevant to cruise ships like the deadweight  $DWT$  and the number of passengers  $N_p$ , even though they will not be further considered in the analysis.

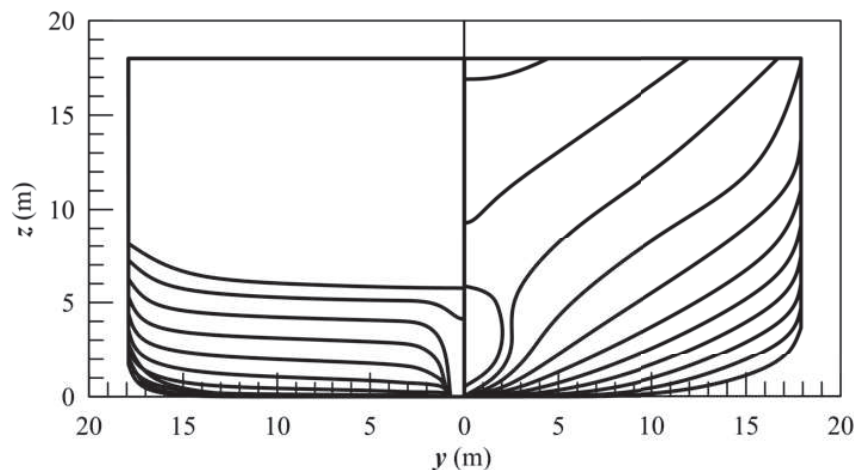
From the above-reported intervals, the midpoint of the database has been found corresponding to the following triplet of values:  $L_{PP}=273.27$  metres,  $B=39.09$  metres and  $T=7.80$  metres. Starting from these values, a reference hull has been developed reflecting the base ship for the database of hulls to be generated. Figure 1 shows the transversal body plan of the reference hull. Starting from the reference hull a design space has been created employing design of experiments (DOE) techniques.

### 2.1. Design of experiment

A suitable technique to minimize the number of elements necessary to populate a design space is the design of experiments (DOE) [16]. These techniques based on DOE are selecting the combination of parameters needed to properly stratify the design space, while keeping significantly high the quality of the results across the data set. For such a

**Table 1.** Reference database of cruise ships built between 2012 and 2022.

Ship ID	Year of build	$L_{PP}$ (m)	$B$ (m)	$T$ (m)	$DWT$ (t)	$N_p$
CRUISE_1	2022	266.90	38.00	8.30	10000	2800
CRUISE_2	2022	282.10	40.50	8.70	9547	3099
CRUISE_3	2022	297.00	37.00	8.60	9880	4000
CRUISE_4	2021	325.00	42.00	8.80	16450	6880
CRUISE_5	2021	266.90	38.00	8.30	10000	2770
CRUISE_6	2020	320.10	42.00	8.80	16887	6685
CRUISE_7	2020	305.83	38.38	8.60	11658	3660
CRUISE_8	2020	266.90	38.00	8.30	12741	2816
CRUISE_9	2019	305.83	38.38	8.57	11772	3660
CRUISE_10	2019	287.10	37.20	8.55	11963	4683
CRUISE_11	2019	287.10	37.20	8.55	12000	5260
CRUISE_12	2019	325.04	42.00	8.80	17000	4200
CRUISE_13	2018	324.95	42.00	8.80	17986	6654
CRUISE_14	2018	296.09	41.00	8.80	19209	5429
CRUISE_15	2018	287.10	37.20	8.55	12164	4683
CRUISE_16	2017	296.09	41.00	8.88	19209	5429
CRUISE_17	2017	306.00	38.40	8.55	11277	4450
CRUISE_18	2016	287.10	37.20	8.55	13415	4683
CRUISE_19	2016	265.79	35.00	8.26	9480	3152
CRUISE_20	2015	306.07	38.40	8.55	11793	3674
CRUISE_21	2014	269.10	37.20	8.00	11118	4928
CRUISE_22	2014	306.00	38.40	8.57	12193	4250
CRUISE_23	2013	306.00	38.40	8.50	12512	4250
CRUISE_24	2013	296.00	37.92	8.65	12614	4345
CRUISE_25	2013	225.70	32.20	7.30	7833	2194
CRUISE_26	2012	296.00	37.92	8.65	13188	4345
CRUISE_27	2012	269.70	37.18	8.20	10250	4633
CRUISE_28	2012	225.00	32.20	7.30	7757	2686
CRUISE_29	2012	297.00	37.00	8.62	9500	4000
CRUISE_30	2012	245.90	28.80	6.80	7952	2795
CRUISE_31	2012	221.50	37.00	8.07	8000	3052

**Figure 1.** Transversal sections of the reference hull form.

**Table 2.** Sample hulls main dimensions according to BBD.

Ship ID	$L_{PP}$ (m)	$B$ (m)	$T$ (m)	Ship ID	$L_{PP}$ (m)	$B$ (m)	$T$ (m)
Hull_01	221.50	28.80	7.80	Hull_08	325.04	39.09	8.80
Hull_02	221.50	49.39	7.80	Hull_08	273.27	28.80	6.80
Hull_03	325.04	28.80	7.80	Hull_10	273.27	28.80	8.80
Hull_04	325.04	49.39	7.80	Hull_11	273.27	49.39	6.80
Hull_05	221.50	39.09	6.80	Hull_12	273.27	49.39	8.80
Hull_06	221.50	39.09	8.80	Hull_13	273.27	39.09	7.80
Hull_07	325.04	39.09	6.80	-	-	-	-

reason, these methods are widely used in engineering for the generation of design spaces aimed at obtaining response surfaces for a set of dependent variables.

Among the different techniques that can be employed to generate a design space, here the Box-Behnken Design (BBD) [17] has been applied, being the one capable of covering a design hypercube with the lower amount of samples.

For the specific case of the cruise ship under analysis we have only three independent variables: the length  $L_{PP}$ , the breadth  $B$  and the draught  $T$ . Therefore, the BBD process generate 13 combinations of the above parameters covering the design space determinate by Eqs. (1), (2) and (3). Table 2 reports the main dimensions of the 13 hull forms.

After the generation of the main dimensions with BBD, the 13 hulls have been derived from the initial hull form presented in Figure 1, by scaling the main dimensions. Such a simplified approach conserve all the hull form coefficients of the initial hull, thus all the variations on attributes evaluated in the 13 hulls are only related to the change in main dimensions. To study the propulsive performances, after the generation of the hulls dedicated speed power performance predictions have been carried out on the data set.

## 2.2. Speed-power prediction

The evaluation of the propulsive performances of the 13 hull forms describing the reference design space have been performed by means of dedicated speed power predictions. Having as a reference only the hydrostatic characteristics of the hull, use has been made of empirical-statistic methods to estimate resistance, propulsive coefficients and matching between propeller and hull.

The analysis has been carried out employing an in-house code estimating resistance and propulsive coefficient with a modified version of the Holtrop and Mennen method [18], using Wageningen B-Series [19] propeller characteristics to estimate the optimal propulsor. To carry out the analysis, the following assumptions have been made:

- The speed-power prediction is made considering a target speed ad trials of 21.0 knots. Which means the onboard installed power has been iteratively changed until reaching the convergence on the trials speed.
- The propeller selection has been made assuming that the ships are equipped with a conventional twin-screw propeller system.
- Appendages of conventional twin-screw propelled ship have been considered plus the presence of bilge keels and active fins stabilisers.
- All the predictions consider 5-bladed propellers.

- The propeller selection has been made optimising the rate of revolution, by keeping the maximum diameter fitting in the aft ship according to advisable hull-propeller clearances [20].

The results of the speed power prediction allows for collect information concerning the power, the revolutions, the propulsive coefficients and propeller characteristics. Here, the main attributes that have been collected are:

- Propulsive power  $P_D$  at the trial speed.
- Rate of revolution  $N$  at the trial speed.
- Propulsive efficiency  $\eta_P$  at the trial speed.
- Propeller pitch/diameter ratio  $P/D$ .
- Propeller expanse area ratio  $A_e/A_0$ .
- Power coefficient  $CA_D$  at the trial speed.

These variables are the one selected for the execution of regression models to derive guidelines for designers for the feasibility study of cruise ships. All the selected variables are straightforward to understand, but a more detailed focus should be given to  $CA_D$ . The power coefficient is expressed as follows:

$$CA_D = 0.7477 \frac{\nabla^{2/3} V_s^3}{P_D} \tag{4}$$

where  $\nabla$  is the volume in cubic metres and  $V_s$  the speed in knots. This coefficient is useful to compare propulsive performance of hulls having different displacements, having an overview of the relative power absorbed by the hulls.

Other quantities, like the propulsive coefficients  $w$ ,  $t$  and  $\eta_R$ , are not considered as the speed power prediction method is already employing a regression formula to estimate them as a function of main dimensions.

### 3. Regression models

Dealing with a reduced amount of data, one of the most suitable techniques to build a regression model in cascade to a DOE definition of design space is the Multiple Linear Regression (MLR) analysis [21]. MLR is a statistical technique that models the relationship between a dependent variable and two or more independent variables. It is an extension of simple linear regression analysis.

The goal of MLR is to find the linear relationship between the dependent variable  $Y$  and multiple independent variables  $X_i$ . The underlying assumption is that the relationship between  $Y$  and  $X_i$  is linear, meaning the effect of each independent variable on the dependent variable is additive and proportional. According to the MLR model, the relationship between dependent and independent variables can be represented by the following equation:

$$Y = \beta_0 + \sum_{i=1}^{N_p} \beta_i X_i + \varepsilon \tag{5}$$

where  $Y$  is the dependent variable (i.e. the outcome we are trying to predict),  $X_i$  are the  $N_p$  independent variables (i.e. the predictors),  $\beta_0$  is the intercept of the model,  $\beta_i$  are the

**Table 3.** Regression outputs for the propulsive performances.

Variable	Number of predictors	$R^2$	$R_{adj}^2$
Propeller pitch/diameter ratio $P/D$	6	0.9458	0.9071
Propeller expanse area ratio $A_e/A_0$	12	1.0000	0.9999
Propulsive Power $P_D$	8	0.9713	0.9312
Rate of revolutions $N$	12	1.0000	0.9996
Propulsive efficiency $\eta_P$	8	0.9829	0.9591
Power coefficient $CA_D$	12	1.0000	0.9996

regression coefficients and  $\varepsilon$  is the error term (i.e. the difference between the observed and predicted value of  $Y$ ).

MLR model gives also the flexibility to employ polynomial expansions of the independent variables to increase the quality of fit of the regression. In any case, once the coefficients  $\beta$  have to be determined, it is convenient to rewrite Eq. (5) in matrix form:

$$\mathbf{Y} = \beta \mathbf{X} + \varepsilon \quad (6)$$

where  $\mathbf{Y}$  is the matrix of observed data,  $\mathbf{X}$  is the matrix of predictors,  $\beta$  are the coefficients and  $\varepsilon$  the matrix of errors. Employing this matrix formulation, the unknowns of the problem is matrix  $\beta$ , which can be derived as follows:

$$\beta = (\mathbf{X}'\mathbf{X})^{-1} \mathbf{X}'\mathbf{Y} \quad (7)$$

where  $\mathbf{X}'$  is the transpose of matrix  $\mathbf{X}$  and  $(\mathbf{X}'\mathbf{X})^{-1}$  is the inverse of  $\mathbf{X}'\mathbf{X}$ .

In the present study, the independent variables are the length  $L_{PP}$ , the breadth  $B$  and the draught  $T$ . The regression have been performed starting from a 4<sup>th</sup> order model, eliminating automatically terms not significant for the global results in terms of quality of fit of the regression. This allows for obtaining a regression model with the minimum number of relevant predictors [22]. For the judgment of the quality of fit of the regression use as been made of the coefficient of determination  $R^2$  and of its unbayased estimator  $R_{adj}^2$ . Table 3 reports the output of the obtained regressions for the considered dependent variables. The value in the tables highlight the good quality of the obtained regressions, together with the goodness of the regression structure. In fact, the  $R_{adj}^2$  is high for all regressions indicating that the number of predictors is not determining a problem of overfitting for the presented models. For the sake of brevity, all the coefficients are not reported in the present work, but may be available on request.

#### 4. Response surfaces

From the models obtained with the MLR reported in Table 3, it is possible to obtain response surfaces to better visualise the behaviour of the dependent variables as a function of the independent ones. As the models have been developed as a function of three independent variables (i.e. the length  $L_{PP}$ , the breadth  $B$  and the draughts  $T$ ), they represent a volume of data for all the dependent variables.

To properly represent the trends of the dependent variable as a function of the independent ones, it is convenient to represent slices of the resulting volume at different significant values of one of the three independent values. Which means visualising the be-

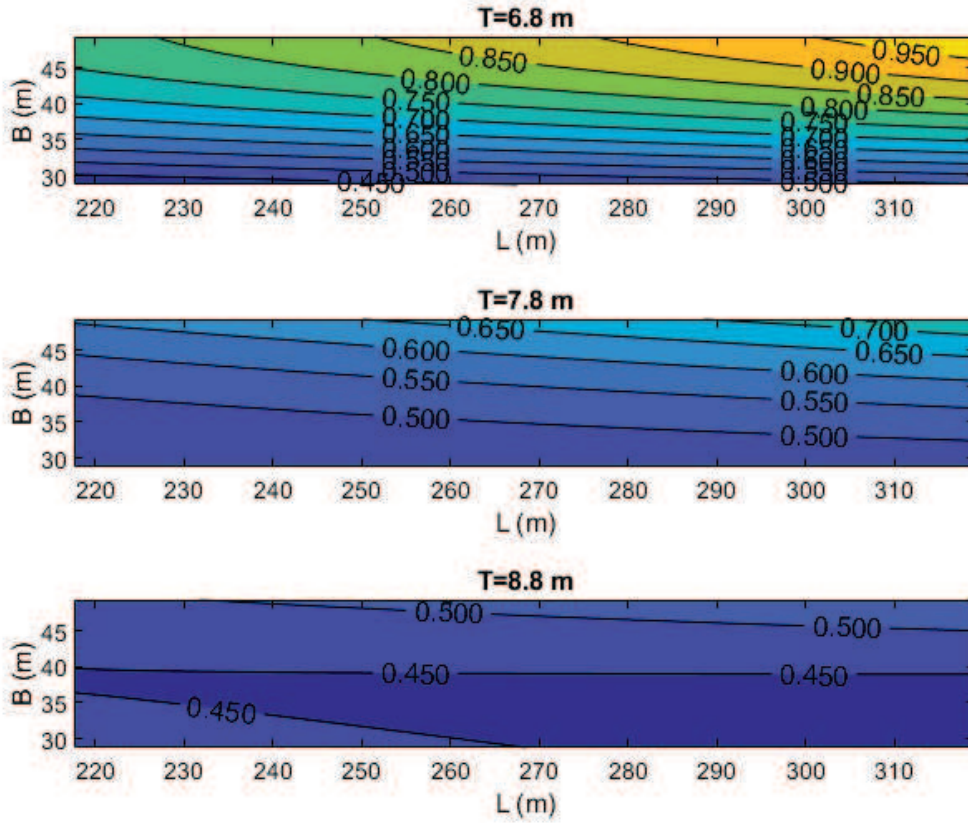


Figure 2. Response surface for the expansion area ratio  $A_e/A_0$  at three different draughts.

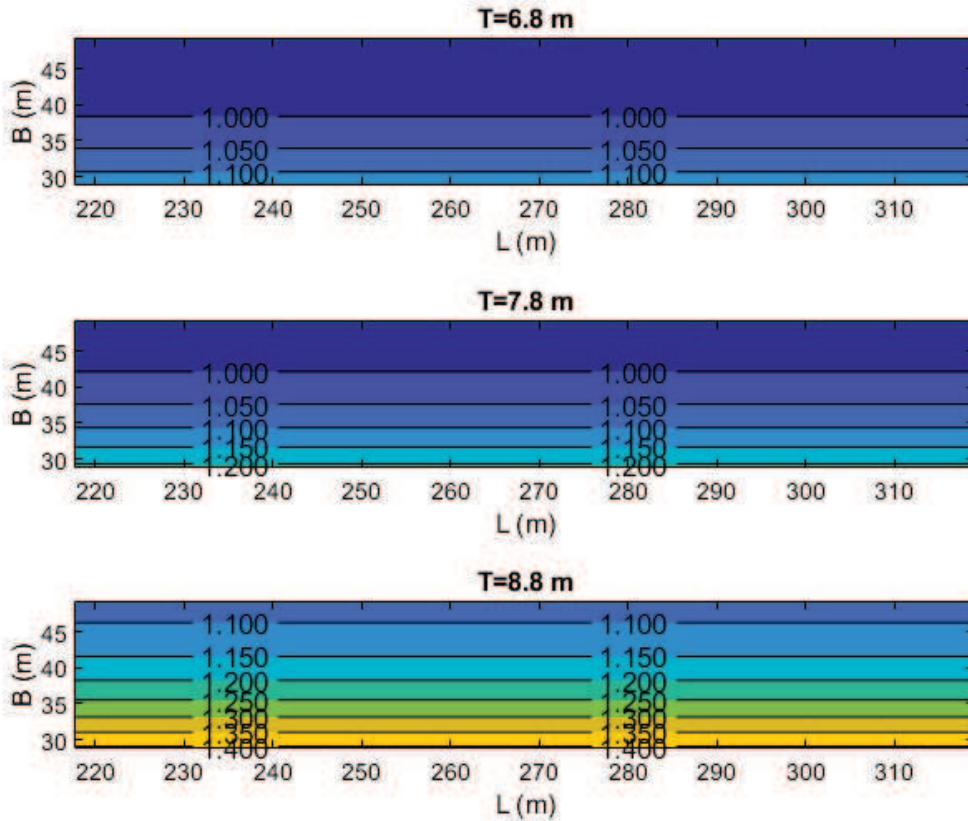


Figure 3. Response surface for the pitch diameter ratio  $P/D$  at three different draughts.

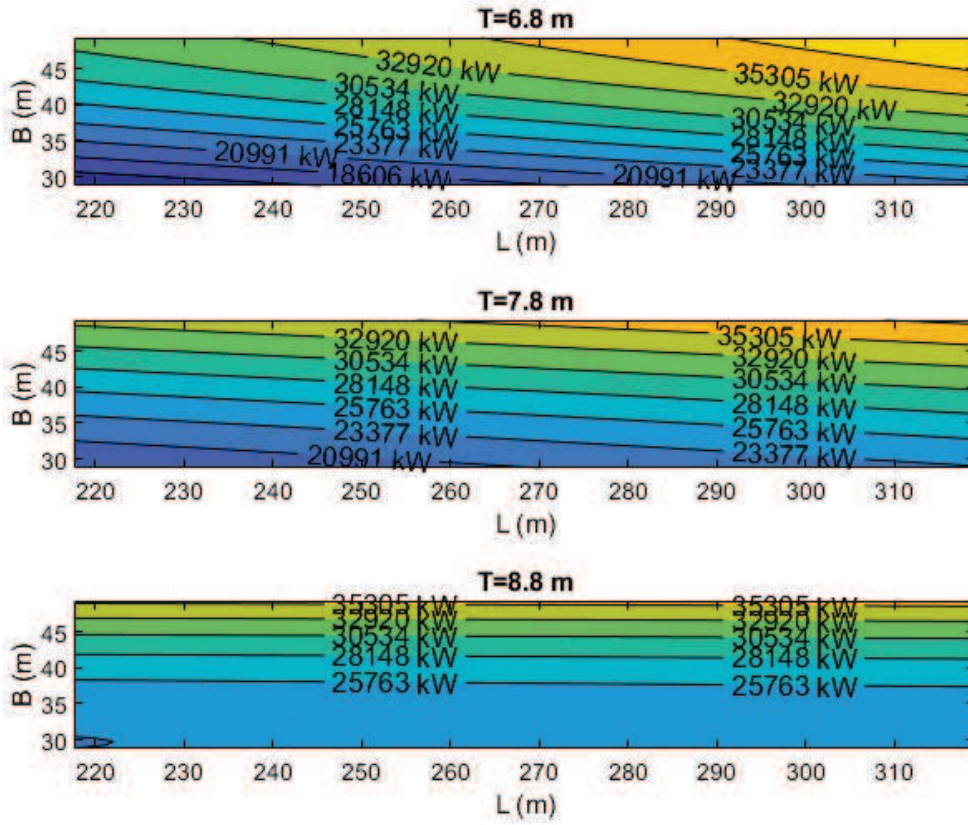


Figure 4. Response surface for the propulsive power  $P_D$  at three different draughts.

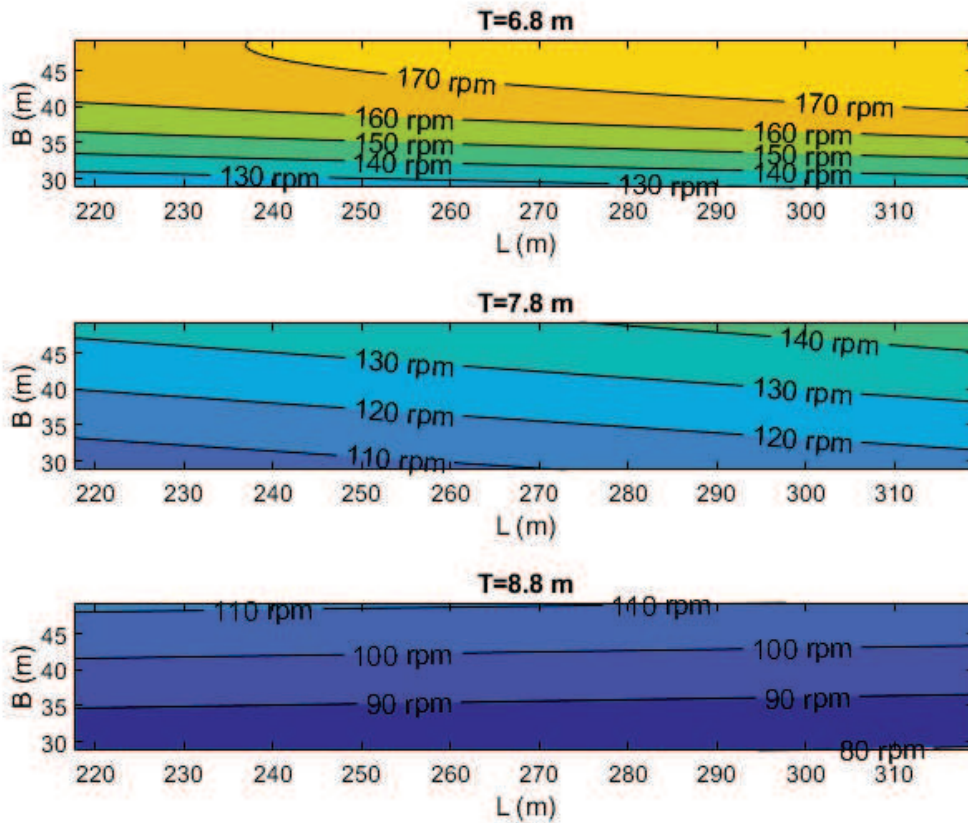


Figure 5. Response surface for the revolution rate  $N$  at three different draughts.

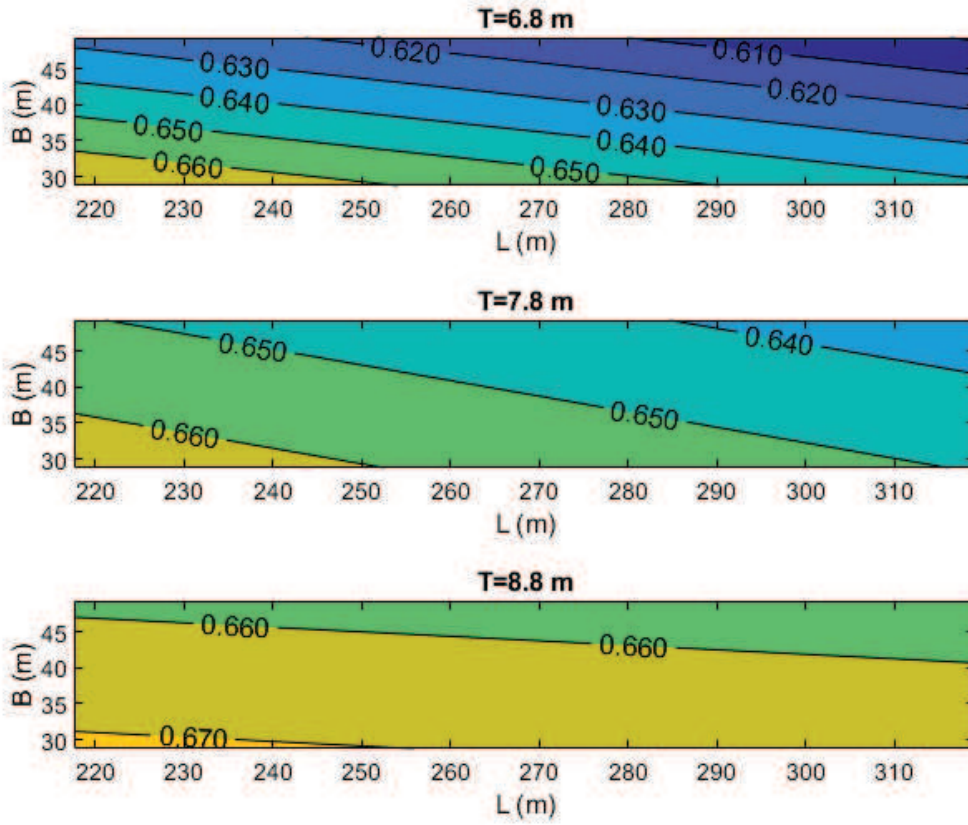
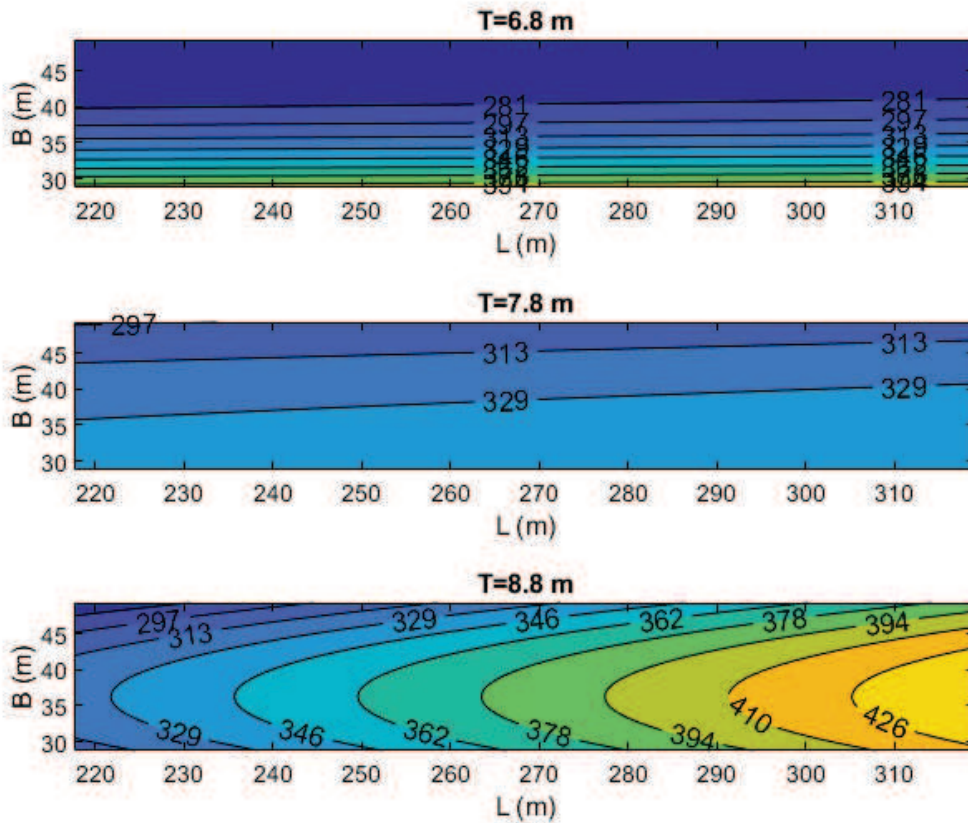


Figure 6. Response surface for the propulsive efficiency  $\eta_P$  at three different draughts.



haviour of a dependent variable while changing two independent variables while keeping the third constant.

Adopting this strategy, it has been selected to visualise the surfaces at iso-draught, thus keeping the draught fixed and changing  $L_{PP}$  and  $B$ . It has been selected to represent the surfaces at the three steps of the BBD generation of the design space, thus representing a surface for  $T = 6.8$  metres, a second for  $T = 7.8$  metres and the third for  $T = 8.8$  metres. According to this strategy, the response surface have been generated for all the dependent variables relevant to the propulsive characterisation of a passenger ship during a feasibility study, i.e. propeller  $A_e/A_0$  and  $P/D$  ( $D$  and  $Z$  are already fixed according to the assumption of the study), ship absorbed power  $P_D$  and rate of Revolution  $N$  at the trial speed, and propulsive efficiency  $\eta_P$  and propulsive coefficient  $CA_D$  at trial speed.

Figure 2 shows the response surfaces for the expanse area ratio  $A_e/A_0$ , highlighting a strong influence of all the independent variables on the selected parameter. Figure 3 shows the response surfaces for the pitch diameter ratio  $P/D$ , showing a dependency mainly to  $T$  and  $B$ . Figure 4 shows the response surfaces for the absorbed power  $P_D$ , highlighting a dependence from all the three independent variables. Figure 5 shows the response surfaces for the rate of revolutions  $N$ , highlighting a dependence mainly from  $T$  and  $B$  and partially on  $L_{PP}$ . Figure 6 shows the response surfaces for the propulsive efficiency  $\eta_P$  and Figure 7 for the propulsive coefficient  $CA_D$ . Both variables are strongly influenced by all the three independent variables.

The obtained response surfaces allow for make some design consideration that will be discussed in details in the following section.

## 5. Design considerations

The previous section presented the response surfaces of the dependent variables describing propeller and propulsive characteristics of the cruise ship dataset. However, the plots can be analysed more in detail, giving some indications of the most favourable combinations of  $L_{PP}$ ,  $B$  and  $T$  from a propulsive point of view. Therefore, the following considerations can be drawn for the propulsor and propulsive characteristics of a cruise ship:

- *Expanse area ratio  $A_e/A_0$* : the data behaviour shown in Figure 2 highlight a strong dependence of  $A_e/A_0$  from  $B$  and  $T$ . The influence of  $L_{PP}$  is minimal. From an analysis of the results it is highlighted that small value of the ratio are suitable for propeller with larger diameter, means for ships having a larger draught. The ratio decreases also by decreasing  $B$ , which means the narrower the hull is the lower is the impact of cavitation issues.
- *Pitch-diameter ratio  $P/D$* : the data shown in Figure 3 highlight a dependency only from  $B$  and  $T$ . The effect of  $L_{PP}$  is negligible. The  $P/D$  increases by increasing  $T$  and  $B$ , resulting in having the propeller with higher pitch for the cases with lower  $A_e/A_0$ . Such an effect is reasonable as propeller with lower  $A_e/A_0$  may be more loaded without occurring in cavitation problems. Of course, these propellers have a lower revolution rate  $N$  as it will be observed afterwards.
- *Propulsive power  $P_D$* : the response surfaces shown in Figure 4 highlight a strong dependency from  $B$  and  $T$ . The influence of  $L_{PP}$  is relevant at low  $T$  and negligible at higher  $T$  values. As a general trend, hulls with larger  $B$  have an absolute higher value of  $P_D$ , specially at lower  $T$  values. However, no generic guidelines

can be drawn on the efficiency, as the  $P_D$  is not taking into account the change of displacement between the hull. However, the regression allows for estimate with sufficient accuracy the  $p_D$  allowing an initial estimate of the propulsive power needed onboard.

- *Propeller revolution rate  $N$* : the data visualised in Figure 5 highlight a dependency of  $N$  by all the three considered independent variables. Generally,  $N$  is decreasing by decreasing  $B$  and by increasing  $T$ .  $L_{PP}$  has a different trend between lower and higher draughts. At low  $T$  values by increasing  $L_{PP}$ ,  $N$  is increasing with  $B$ . At deeper draughts the gradient with  $B$  is opposite. It can be observed that at higher  $T$  values with low  $B$ , the  $N$  are extremely low for a cruise ship. However, such combination of parameters are unusual for cruise ships.
- *Propulsive efficiency  $\eta_P$* : Figure 6 indicates a dependency of  $\eta_P$  from all the three main dimensions of the ship.  $\eta_P$  increases with  $T$  while is decreasing with  $B$  and  $L_{PP}$ . As such, the most efficient propulsive system is for ships shorter, narrower and deeply immersed. This is mainly due to the high performances found for the propulsor at these main dimensions combinations. It can be also observed that the gradient of increase/decrease of  $\eta_P$  decreases by increasing  $T$ .
- *Propulsive coefficient  $CA_D$* : the data reported in Figure 7 shows a strong dependence of  $CA_D$  from  $B$  and  $T$ . At low  $T$  there is no effect of  $L_{PP}$  on the  $CA_D$ , with most efficient ships identified by lower  $B$  values. At intermediate values of  $T$ , there is a small influence of  $L_{PP}$ , but generally the values of  $CA_D$  are lower compared to lower immersions. Different is the case at higher  $T$  values. Here the  $CA_D$  increases with  $L_{PP}$  and the higher  $CA_D$  values are for high  $L_{PP}$  and intermediate  $B$  values.

From the analysis of the response surface, a designer could have a lot of useful information on the propulsive characteristics of a new cruise vessel already in the feasibility study. In fact, it is possible to have information concerning the propeller parameters, the power needed for propulsion and the efficiency of the whole propulsive system.

Particular attention should be given to the analysis of the  $CA_D$  coefficient, which is assessing the quality of the propulsion system of a vessel, the higher the  $CA_D$  is the most favourable are the propulsive performances. Therefore, according to the provided regression, a designer could clearly identify the best combination of main dimensions that may ensure good propulsive performance for a new vessel,

## 6. Conclusions

The present work describes the development of regression models to estimate propulsive characteristics of cruise ships during a feasibility study. As such, the independent variables considered during the study are the length of the vessel  $L_{PP}$ , the breadth  $B$  and the draught  $T$ .

Starting from an initial database of existing ships built from 2012 to 2022, a data set of hulls has been developed with a Box-Behnken Design (BBD), by systematically varying  $L_{PP}$ ,  $B$  and  $T$ . The BBD process allows for determining 13 hull forms conserving the main geometrical coefficients while changing the main dimension only, thus allowing for evaluate the pure impact of main dimensions on the propulsive performances. On the 13 hulls, dedicated speed-power predictions have been carried out supposing a target trial speed of 21 knots and imposing adequate clearance constraints for the propulsors.

Starting from the speed-power results, Multiple Linear Regression (MLR) analysis has been performed to determine the response surfaces of the principal propulsive characteristics of the cruise vessels. Quality of fit indicators highlights a really good quality of the obtained MLR model, giving confidence in the reliability of the obtained results.

The analysis of the response surfaces allows a designer to evaluate the best combinations of main dimensions that could be beneficial for the propulsive performance of the ship, obtaining also information on the propeller characteristics and the power required for the propulsion.

Even though the methods employed for the speed=power prediction are empirical-statistics, the obtained set of regression is useful for designers at a feasibility study stage, where a lot of uncertainties are still present and fast methods should be employed for having a reliable evaluation of ship main attributes. The described methodology will be employed in future studies, using wider data sets of hulls as input to the MLR analysis, allowing to take into consideration also variations in the hull form coefficients.

## References

- [1] Andrews DJ. A Comprehensive Methodology for the Design of Ships (and Other Complex Systems). Proceedings of Mathematical, Physical and Engineering Sciences, 1998 454(1968): 187-211.
- [2] Caprace JD and Rigo P. Ship complexity assessment at the concept design stage. *J. Mar. Sci. Technol.* 2011; 16: 68-75.
- [3] Papanikolaou A. *Ship Design: Methodology of Preliminary Design*. Springer, 2014.
- [4] Papanikolaou A. *A Holistic Approach to Ship Design*. Springer, 2019.
- [5] Trincas G. Survey of design methods and illustration of multiattributes decision making system for concept ship design. Proceedings of MARIND; 2001; Varna, Bulgaria.
- [6] Bucci V, Sulligoi G, Chalfant J and Chrysostomidis C. Evolution in Design Methodology for Complex Electric Ships. *Journal of Ship Production and Design*. 2021; 37: 1-13.
- [7] Mauro F, Begovic E, Della Valentina E, Dell'Acqua A, Rinauro B, Rosano G and Tonelli R. The effect of main dimensions on the preliminary design of motor yachts. In proceedings of the 15th International Marine Design Conference; 2024, June 2-6; Amsterdam, The Netherlands.
- [8] Papanikolaou A, Lee BS, Mains O, Olufsen O, Vassalos D and Zaraphonitis G. GOALDS- Goal Based Ship Stability and Safety. *Proceedia Social and Behavioural Sciences*. 2012; 48: 449-463.
- [9] Mauro F, Braidotti L and Trincas G. Determination of an Optimal Fleet for a CNG Transportation Scenario in the Mediterranean Sea. *Brodogradnja*. 2019; 70: 1-23.
- [10] Lewis EV. *Principles of Naval Architecture: Volume II - Resistance, Propulsion and Vibration*. SNAME, 1988.
- [11] Abramowski T, Cepowski T and Zvolensky P. Determination of regression formulas for key design characteristics of container ships at preliminary design stage. *New Trends in Production Engineering*. 2018; 1(1): 247-257.
- [12] Clausen HB, Lutzen M, Hansen AF and Njorneboe N. Bayesian and neural networks for preliminary ship design. *Mar. Technol.* 2001; 38(4): 268-277.
- [13] Ekinci S, Celabi U, Bal M, Amasyali M and Boyaci U. Predictions of oil/tanker main design parameters using computational intelligence techniques. *Applied Soft Computing*. 2011; 11(2): 2356-2366.
- [14] Cepowski T and Chorab P. Determination of design formulas for container ships at the preliminary design stage using artificial neural network and multiple nonlinear regression. *Ocean Engineering*. 2021; 238: 109727.
- [15] Holtrop J and Mennen GG. A Statistical Power Prediction Method. *International Shipbuilding Progress*. 1978; 25(290): 253-262.
- [16] Fidalgo JL. *Optimal Experimental Design*. Springer Nature, 2023.
- [17] Box G, Hunter W and Hunter J. *Statistics for experiments: Design, Innovation, and Discovery (II Ed.)*. Wiley Interscience, New York, 2005.
- [18] Holtrop J. and Mennen GG. A statistical Resistance Prediction Method with a Speed-dependent Form Factor. In *Scientific and Methodological Seminar on Ship Hydrodynamics*, 1988, Varna, Bulgaria.

- [19] Kuiper J. The Wageningen Propeller Series. Maritime Research Institute of the Netherlands, 1992.
- [20] Holtrop J. An Introduction to hull form design. MARIN hydrodynamic course. 2015.
- [21] Seber GAF and Lee AJ. Linear Regression Analysis (II Ed.). Wiley, 2003.
- [22] Rinauro B, Begovic E, Mauro F and Rosano G. Regression analysis for container ships in the early design stage. *Ocean Engineering*. 2024; 292: 116499.