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The effect of main dimensions on the preliminary design of motor yachts

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ABSTRACT

The design process of motor yachts mainly relies on the experience of designers, who have confidence in the knowledge acquired from designing units with similar hull-form characteristics. However, once a new concept needs to be developed, the acquired experience on a standard platform is no longer sufficient to achieve in a short time a successful design. The design of a motor yacht implies considering multiple aspects of ship hydrodynamics: resistance, propulsion, seakeeping, and manoeuvring. Such factors have been widely discussed individually on different kinds of ships, but an appropriate joint investigation of hulls like motor yachts is missing in the open literature. Therefore, the present paper intends to cover this gap, providing guidelines for the design of motor yachts in a length range between 20 and 40 meters. As a preliminary study, a series of 15 yacht hulls has been developed, starting from a reference hull form. Seakeeping, manoeuvring, and propulsive performances have been evaluated at a reference environmental condition and speeds according to the ISO 22834:2022 guidelines. Such calculations allow for developing response surfaces of the hydrodynamic properties for the series of yachts as a function of the hull's main dimensions. As a final result, the obtained responses allow for identifying the best compromise solutions for the main dimension selection of a new motor yacht in the length range of 20-40 meters.

KEY WORDS

Large-yacht; ship design; multi-attribute design; hydrodynamic performances

INTRODUCTION

Designing a motor yacht involves several key considerations, including the size of the yacht, its intended use, materials, propulsion system, interior layout, and aesthetic features. More precisely, it is necessary to identify since the beginning of the project the primary use of the vessel (cruising, entertaining, fishing or a combination of them) to evaluate the operative profile of the large yacht, the estimation of crew and passengers and a preliminary definition of the internal spaces (number of cabins, living rooms, etc.). Afterwards, a crucial part of the design process concerns the estimation of the vessel's size and style. The sizing focuses on the selection of the main dimensions of the unit (length, breadth, draught, and a preliminary estimate of displacement), the style is the design theme of the yacht, which means, as an example, if it is a conventional bow, vertical bow, a sport yacht or an explorer unit (Ansaloni et al, 2024). Subsequently, all the decisions concerning the propulsion system (conventional, podded or hybrid electric solutions) and the definitive hull design need to be taken, before considering the definitive internal layout and the aesthetic of the external shape and interiors (Mancuso & Tumino, 2022, Mauro et al. 2021a). However, for the specific case of concept design, the most essential part is to determine the sizing of the vessel, which means choosing the best combination of hull dimensions leading to a given displacement and granting the achievement of some performance criteria concerning relevant attributes for the vessel (Papanikolaou, 2014, Papanikolaou et al., 2022).

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The design is generally based on the designers' confidence in the knowledge acquired from the design of units with the same hull-form characteristics. This approach is worthy once sister units must be built but is not advisable for the development of a new concept. Therefore, general guidelines are needed to achieve a successful new design in a short time.
The design of a motor yacht implies considering multiple aspects of ship hydrodynamics: resistance, propulsion, seakeeping, and manoeuvring, respectively. Such factors have been widely discussed individually on different kinds of ships (Tonelli et al., 2015), but an appropriate joint investigation of small hulls like motor yachts is missing in the open literature. The only guidelines available in the recent literature concern solely the vertical motions in waves (Ivanova & Gyurov, 2022, Begovic et al. 2023a, Begovic et al. 2020) or dedicated studies on the hybrid-electric propulsion (Geertsma et al., 2017, Bucci et al. 2020, Coppola et al. 2022, Begovic et al. 2022) or dynamic positioning of such units (Mauro et al. 2021b). A comprehensive analysis of the effect of different hull forms on the overall hydrodynamic performances of a motor yacht is not yet available, also considering that the relations between hull form parameters and hydrodynamic performance may lead to counteracting solutions while considering, as an example, propulsion or seakeeping characteristics.
To fill the gap between designers' needs and what the actual literature offers, this work presents a preliminary investigation of the effect of main dimensions on the hydrodynamic performance of a motor yacht. The study covers the estimation of some peculiar hydrodynamic attributes of a motor yacht, concerning resistance, seakeeping and manoeuvring characteristics. To this end, it is necessary to build a design space, starting from a reference hull and changing parametrically the main dimensions; here the variations are limited to the length, the breadth and the immersion, keeping, the hull form coefficients constant. With this approach, a design space has been built with the design of experiment techniques, applying a central composite design. From the process, 14 hulls have been derived from the initial hull form, by systematically changing the length, the breadth and the draught. For all hulls, resistance, seakeeping and manoeuvring calculations have been carried out for speed and heading conditions derived from the ISO 22834:2022 guidelines. More precisely, resistance parameters have been calculated with viscous flow CFD calculations. Seakeeping performances have been assessed with a linear 2D strip theory code and manoeuvring performances with rigid-body time domain simulations. The results formed a database of hydrodynamic attributes that can be analysed with multiple linear regression techniques and finally regressions of the attributes as exclusive functions of the main dimension of the vessel have been performed.
The present paper describes in the first section the definition of the design space. Section 2 describes the hydrodynamic calculations performed on the 15 hulls composing the design space. Section 3 reports the multiple linear regression analysis and, finally, section 4 reports an example of the applicability of the obtained regression to identify the effect of hull forms on the hydrodynamic performances of the large-yacht.
The results reported in this paper are promising for the definition of hydrodynamic performances in the early design stage of a motor yacht and encourage future studies on a wider range of hull form variations, including also hull form coefficients.

THE DESIGN SPACE

The present study investigates the hydrodynamic performances of motor yachts for optimal dimension investigations during the concept design phase of a new unit. To this end, it is necessary to develop mathematical instruments, like response surfaces, for capturing the variations of relevant hydrodynamic quantities with the vessels' main dimensions. In this sense, it is necessary to select a reference vessel and a set of geometrical transformations for the main parameters (applying the design of experiments) to form a design space suitable for regression analyses. In the following sections, the reference hull form is described, together with the parametric variations leading to the definition of the 15 hull forms composing the database.

Parent hull form

The reference hull form has been designed specifically for the present study. The main dimensions of the parent hull have been determined based on a preliminary analysis of the yacht database available at MARIN. The main particulars of the hull are listed in Table 1, while the transversal sections of the vessel are given in Figure 1.

Table 1: Reference hull main particulars

Quantity	Value	Quantity	Value
Length between perpendiculars (m)	30.00	Block coefficient (-)	0.563
Length on waterline (m)	29.99	Midship coefficient (-)	0.846
Breadth (m)	7.5	Prismatic coefficient (-)	0.665
Draught (m)	1.625	Waterline coefficient (-)	0.817
Volume (m^3)	205.768	Vertical prismatic coefficient (-)	0.689

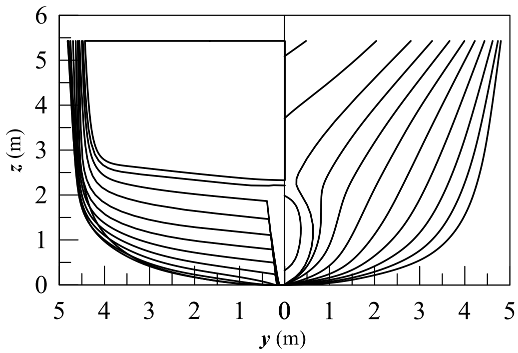

Figure 1: Body sections of the reference hull form.

Table 2: Hull form variations starting from the original hull form.

Hull Number	L_{BP} (m)	B (m)	T (m)	$Volume$ (m^3)
HULL 1	20.0	6.0	1.250	84.418
HULL 2	20.0	6.0	2.000	135.068
HULL 3	20.0	9.0	1.250	126.626
HULL 4	20.0	9.0	2.000	202.602
HULL 5	40.0	6.0	1.250	168.835
HULL 6	40.0	6.0	2.000	270.137
HULL 7	40.0	9.0	1.250	253.253
HULL 8	40.0	9.0	2.000	405.205
HULL 9	20.0	7.5	1.625	137.179
HULL 10	40.0	7.5	1.625	274.357
HULL 11	30.0	6.0	1.625	164.614
HULL 12	30.0	9.0	1.625	246.922
HULL 13	30.0	7.5	1.250	158.283
HULL 14	30.0	7.5	2.000	253.253
HULL 15 (original)	30.0	7.5	1.625	205.768

The initial hull represents an example of a yacht that can be used to study parametric variations of the main dimensions ranging from a length of 20 to 40 metres. In the following section, more details are given about the ranges and transformations performed on the reference hull form.

Hull form variations

Starting from the parent hull form, a set of 15 hull forms has been developed by systematically changing the main dimensions. As a simplification, the hull form coefficients have been kept constant and equal to the parent hull, as reported in Table 1. Then, by applying the design of experiment techniques (DoE) (Chang, 2008, Myers et al. 2008), a Central Composite Design (CCD) has been chosen to represent the 15 design variations (Beaver et al, 1977, Montgomery, 2009). The main dimensions of the resulting matrix of hull forms are reported in Table 2 and in Figure 2. The variations performed on the original hull forms led to the following range of main dimensions:

$$\begin{aligned} &20.0 < L_{BP} < 40.0 \\ &6.0 < B < 9.0 \\ &1.25 < T < 2.00 \end{aligned} \qquad [1]$$

This is an approximation that may affect the final results, as coefficients may influence the hydrodynamic performances. From a manoeuvring point of view, the choice of keeping the coefficients constant is in line with typical preliminary studies, as for instance, Clarke's diagram (1977) that shows the dynamic stability boundaries per block coefficient as a function of the length to breadth L/B and breadth to draught B/T ratio. However, this is a starting point to develop a methodology for the preliminary design stage that may be improved with time by adding more hull form variations considering also changes in the hull form coefficients.

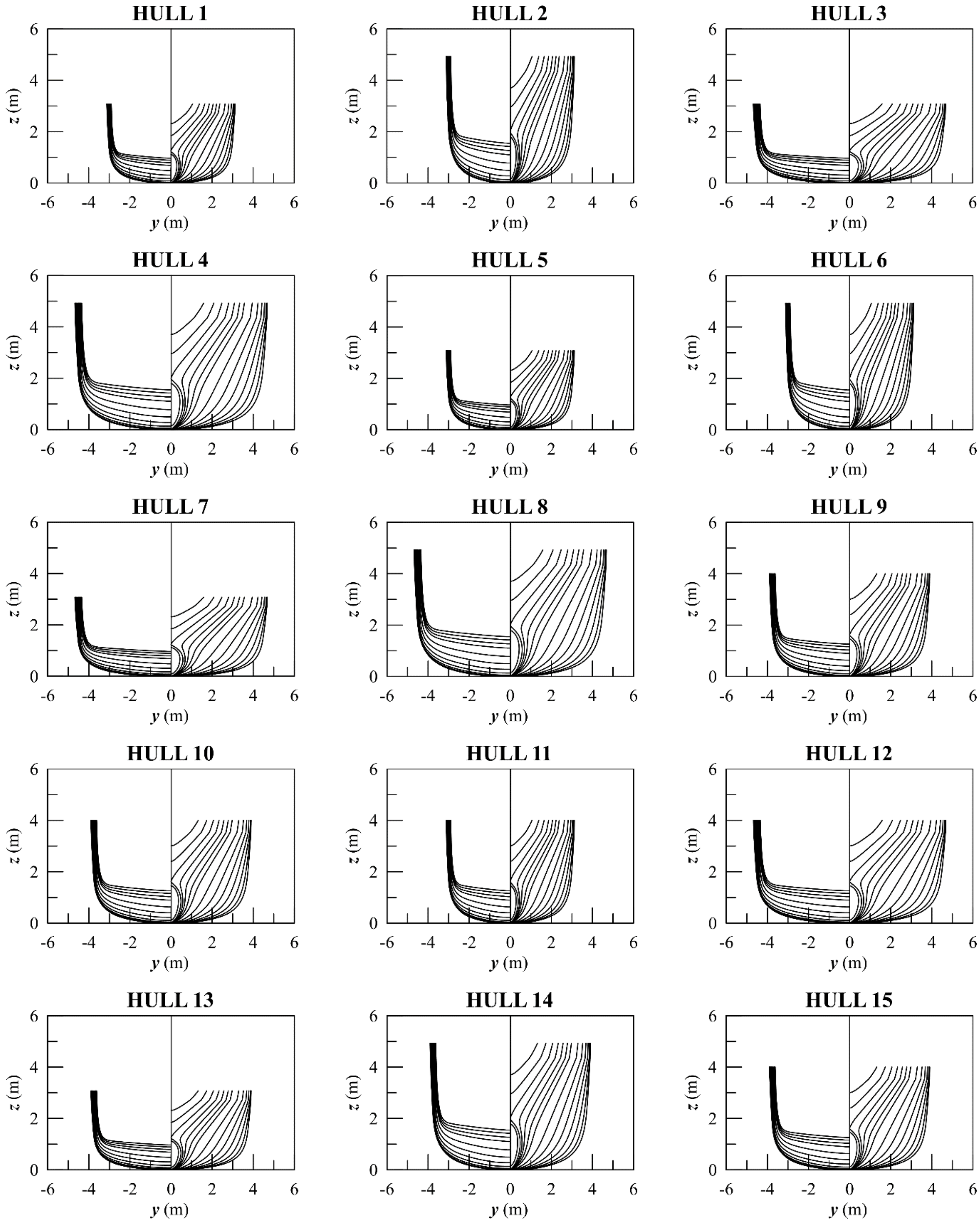

Figure 2: Body sections of the 15 hull forms.

The choice of a CCD design has a consequence on the type of analysis that can be carried out on the resulting hull series. In fact, any attribute relevant to a single hull can be described with at most a full quadratic model. Therefore, having in mind to derive multiple linear regressions on the resulting datasets, such a limitation should be taken into strict consideration as a bound for the research.

HYDRODYNAMIC CALCULATIONS

The crucial part of building design instruments for the preliminary design of a new vessel concerns the reliability of the initial dataset used to form the tools themselves. As such, the modern methodologies employed for the numerical estimation of hydrodynamic performances grant reaching high level of reliability, enhancing the accuracy of initial prediction. In the open literature, it is not common to find methods aiming at preliminary design relying on first-principle calculations
The main aspects to focus on for this study, concerning the hydrodynamics of large yachts, relate to the behaviour of the vessel while sailing in calm water, in waves and during a manoeuvre. Different tools have been used to evaluate the hydrodynamic performances for the specific characteristics needed to describe the behaviour of the vessel. In the specific, for the behaviour in calm water, i.e. resistance and dynamic trim, viscous flow CFD (Computational Fluid Dynamics) calculations have been performed. The behaviour of the vessel in waves has been assessed through strip-theory calculations, with a focus on the comfort characteristics of the yacht. Concerning the manoeuvring, time-domain simulations have been carried out to determine the yaw, checking turning ability of the vessel. In the following sections, a more detailed description of the performed calculations is given together with the parameters selected as principal attributes for the hydrodynamic description of a yacht.

Resistance Calculations

Resistance calculations have been carried out with the MARIN's in-house CFD (package ReFRESCO (https://www.marin.nl/en/facilities-and-tools/software/refresco).ReFRESCO is a community-based, open-access CFD code for the maritime sector. It solves multiphase unsteady incompressible viscous flows using the Navier-Stokes equations, complemented with turbulence models, and volume-fraction transport equations for different phases. The equations are discretised using a finite-volume approach with cell-centred collocated variables. A pressure-correction equation based on the SIMPLE algorithm is used to ensure mass conservation. Time integration is performed implicitly with second-order backward schemes. ReFRESCO is currently being developed, verified and its several applications validated at MARIN in collaboration with several worldwide known non-profit organisations.
The computational grids used in this study were generated using the software Hexpress. Surface refinements were used on the ship hull itself to provide space resolution to resolve the near-wall flow. The surface refinement was then complemented with three groups of boxes, defined to further improve space resolution in the near and far-field flow. The computations were performed at full scale and the computational domain size was chosen sufficiently large to ensure that the influence of the boundary conditions on the flow solution was negligible
For the specific case study, CFD simulations have been carried out in calm water, at a speed of 12 knots and results are presented in terms of total resistance (Larson and Raven, 2010) and dynamic trim. Resistance results include a correlation allowance (C_A) which incorporates the drag due to hull roughness, still-air drag of the hull and superstructures. For the dynamic trim, positive values indicate a bow-down trim, while negative values indicate a stern-down trim.

Seakeeping Calculations

To evaluate the seakeeping characteristics of the developed series of yachts, the new regulation ISO 22834:2022 has been applied to estimate the global comfort level. ISO 22834:2022 considers the Effective Gravity Angle (EGA) and the Motion Sickness Incidence (MSI) as key performance indicators for global comfort, which is afterwards translated into a star rating system ranging from one star (poor) to five stars (excellent). The assessment is performed by evaluating the EGA and MSI, at a reference heading of 135 deg and for speeds of 0 and 12 knots, across five locations along the yacht: the beach club (BC), the crew area (CA), the dining area (DA), the owners' cabin (OC), and the wheelhouse (WH).
The coordinates of the locations onboard the 15 vessels have been assumed according to the reference used by the authors in previous publications (Begovic, et al. 2023a, Mauro et al 2021). Table 3 reports the coordinates used for the calculation in non-dimensional form, as a function of the length between perpendicular L_{BP}, the breadth B and the draught T.

Table 3: Nondimensional coordinates for considered locations.

	BC	CA	DA	OC	WH
x/LBP	0.06	0.90	0.43	0.83	0.73
y/B	0.00	0.00	0.00	0.00	-0.23
z/T	1.81	1.09	2.54	3.26	3.99

For all the hulls, the longitudinal position of the centre of gravity has been set to have a zero-trim condition at rest. The vertical position of the centre of gravity has been calculated by taking the transverse metacentric height equal to 10% of the breadth at the waterline, to guarantee a uniform application of seakeeping calculations.
The evaluation of EGA and MSI for each location and speed requires knowledge of the Response Amplitude Operators (RAOs) of the ship motions for the 5 locations at a heading of 135 deg and the speeds of 0 and 12 knots. For this purpose, use has been made of the software ShipX, based on the strip theory as developed by Salvesen et al. (1970).
For each vessel the comfort level has been evaluated according to a number from 0 to 100, reflecting the percentage scale of the star system reported in the ISO rules. The final level of comfort is then assessed with the following weighted sum:

$$ISO_{TOT} = \sum_{i=1}^{2}\sum_{j=1}^{N_l}\sum_{k=1}^{N_{T_z}} w_{v_i} w_{lj} w_{T_{z_k}} I_{ijk} \qquad [2]$$

Where w_v, w_l and w_{Tz} are the weights for speed, locations and wave periods, respectively. I is the functional that accounts for the satisfaction of the criteria imposed by ISO 22834:2022. The functional is equal to 1 when both EGA and MSI are under the given thresholds (2 deg for EGA and 10% in one hour of exposure time for MSI). The functional is equal to 0 if at least one criterion is not fulfilled.
To have a more detailed description of the trends in EGA and MSI in different locations, the assessment can be performed also at a local level, considering each location individually and for each sea state, reducing equation (2) to just a summation of the weights for the reference wave periods. Alternatively, the comfort can be assessed globally per each speed, reducing equation (2) to the some of weights for locations and wave periods.
In this study, the global evaluation of comfort given by equation (2) has been considered for the calculations.

Manoeuvring Calculations

To predict the dynamic variation of the motion of a ship, specific manoeuvring simulations have been carried out employing the software ANYSIM XMF. The software computes the motion of a ship resulting from non-linear hydrodynamic and mechanic loading. Ship-specific results from model-test, semi-empirical methods (such as slender body and cross-flow drag theory), and linear frequency domain tools are used for modelling hydrodynamics. Other elements such as rudders, propellers, thrusters, etc. are modelled in the time domain. The equations of motion are integrated through a fourth-order Runge-Kutta method with a fixed time step of 0.1 s. Such a time step is sufficient to have a converged solution. The software can handle the use of both propellers and rudder or pod for the manoeuvring of the vessel.
The simulations need the definition of a linearised stiffness matrix composed of terms derived by the hydrostatics of each one of the 15 hull forms. Besides, the simulations require the definition of a resistance curve or in general a resistance value for the speed of interest. For the specific case of this study, the speed of 12 knots is the target speed for the simulation and the resistance used for the simulation derives directly from the ReFRESCO simulations described in the previous sections. Hydrodynamic forces (damping and added mass) are then computed according to the sectional approach employed in the slender body theory and cross-flow drag theory (Toxopeus, 2006, Hooft, 1994).
The propeller model is based on the B-series, employing for all the hulls the same wake fraction (w=0.05) and thrust deduction (t=0.15). This is a reasonable approximation for the determination of general guidelines for the preliminary design stage.
Simulations performed include speed runs, zig-zag manoeuvres (both 10-10 and 20-20, i.e. the steering-yaw checking angles) and turning circles. The simulation process has been performed in two steps, employing a tuning process for the yaw moment calculated by the slender body theory. The tuning process employs empirical coefficients derived from the correlation between simulations, model tests and sea trials available at MARIN.
From manoeuvring simulations, there are a lot of parameters that can be used as a main attribute for ship design purposes. Between them, particular attention should be given to the initial turning ability and the yaw checking ability. The initial turning ability, also called course-changing ability, describes the responsiveness of the ship to initiate a turn with a moderate helm. The yaw-checking ability is a measure of the ship reaction to counter steering. It is identified by the response delay when reversing the helm angle of a turning ship. The most relevant manoeuvring characteristics related to these abilities are the overshoot angles and the initial turning distance. The overshoot angle is the heading deviation from the moment the steering device is

reversed to the moment the heading rate of turn is zero. The initial turning distance is the distance travelled in the direction of the original course by the ship from the moment the first steering order of, e.g., 20° is given (first execute) to the moment the heading has changed 20° from its original course.

Parameter Selection

The simulations performed to determine the hydrodynamic characteristics of the hulls can define multiple attributes as an output of the simulations. However, to proceed with the definition of the design guidelines for the large-yacht in the preliminary design stage, it has been decided to select a reduced number of attributes. Such a decision aims to give a more focused overview of global attributes for the preliminary design, instead of going too much into capillary details in a phase where most of the final details of the project are not defined yet. In any case, the procedure that will be shown in the next section can be applied to all possible attributes derived from hydrodynamic analyses.

The following attributes have been then selected to proceed with the multiple linear regression analysis:

- Resistance at 12 knots, (kN)
- Trim at 12 knots, (deg)
- Global ISO_{TOT} index for comfort, (-)
- Initial turning ability (from a 20-20 zig-zag manoeuvre), (-)
- Yaw checking ability (from a 20-20 zig-zag manoeuvre), (-)

This set of preliminary attributes grants a comprehensive vision of the operational profile of a motor yacht of small dimensions, capturing issues related to resistance, comfort and manoeuvring. Therefore, the regression analysis has been conducted on the sets of data describing such attributes, by employing a process that will be described in the following section.

MULTIPLE LINEAR REGRESSION ANALYSIS

In the field of engineering, the Design Of Experiments (DoE) is frequently used to analyse the response of a certain variable as a function of others by reducing the number of observations necessary to describe the variations. This results in a lower effort for experimentation or calculation work. In parallel, Response Surface Methodology (RSM) quantifies the relationship between the controllable input parameters and the obtained response variables. To this end, the following working principle should be pursued:

- Design a set of experiments for an adequate and reliable measurement of the analysed response.
- Develop a mathematical model of the response surface by applying a best-fitting technique.
- Represent the direct and interactive effects of processed parameters through multidimensional plots.

The first step has been already tackled by the definition of the design space of the motor yachts, which is choosing a CCD design for the 15 hulls developed in this study. Therefore, it is necessary to better define the mathematical models employed to identify the response surface for the selected parameters for the hydrodynamic properties of the yachts.

A response surface of a generally measurable variable can be identified by the following equation:

$$y = f\left(x_1, \cdots, x_n\right) \tag{3}$$

where y is the output of the process and x_i are the n variables of the problem to describe. Under the assumption that the independent variables are continuous and adherent to experiments with negligible errors, a suitable approximation for the relationship between the independent and the independent variables should be found. Adopting a CCD design, it is possible to use a complete second-order model to describe the surface response, following the subsequent general regression model:

$$y = \beta_{0,0} + \sum_{i=1}^{n} \beta_{i,0} x_i + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \beta_{i,j} x_i x_j + \sum_{i=1}^{n} \beta_{i,i} x_i^2 + \varepsilon \tag{4}$$

Where $\beta_{i,j}$ are the unknown parameters and ε is the regression error. In the literature, there are several methods available to evaluate the unknown parameters. However, in the specific case of relatively simple models, it is convenient to employ a least square method. Then, equation (4) can be written in the following matrix form:

$$\mathbf{Y} = \mathbf{b}\mathbf{X} + \varepsilon \tag{5}$$

Where $\mathbf{Y}$ is the matrix of the measured values and $\mathbf{X}$ is the matrix of the independent values. The matrix of independent variables includes not only the variables themselves but also their combinations up to the second order. The matrices $\mathbf{b}$ and ε

are the regression coefficients and the errors, respectively. Adopting this matrix formulation, the coefficients matrix can be determined by applying the least square method technique, deriving in the following expression:

$$\mathbf{b} = \left(\mathbf{X}^T \mathbf{X}\right)^{-1} \mathbf{X}^T \mathbf{Y} \tag{6}$$

Where $\mathbf{X}^T$ is the transpose matrix of $\mathbf{X}$ and $(\mathbf{X}^T\mathbf{X})^{-1}$ is the inverse matrix of $\mathbf{X}^T\mathbf{X}$.
For performing the multiple linear regression analysis on the selected dataset of hydrodynamic parameters, use has been made of a stepwise selection process (Harrell, 2001). In the initial step, all the variables are included in the complete second-order model. Afterwards, at each step, a different variable is removed from the equation changing its status (from removed to inserted and vice-versa). For each variable whose status changes, the change in the sum of squared error (SSE) is evaluated and the variable is consequently removed or added to the final model. The process continues automatically until there is no more variable changing the SSE over a given threshold. Moreover, to keep the same threshold in SSE throughout the study, all the dependent and independent variables have been normalised in [-1,1] before starting the regression procedure. Then the threshold is set to 0.06. To judge the quality of the regression, a key performance indicator has to be selected. Here use has been made of the determination coefficient R^2 and the adjusted determination coefficient R^2_{adj}. The coefficients are defined as:

$$R^2 = 1 - \frac{SSE}{SS_{tot}} \tag{7}$$

$$R^2_{adj} = 1 - \left(1 - R^2\right)\frac{n-1}{n-p-1} \tag{8}$$

where n is the number of points to fit, p is the number of variables included in the model (after executing the stepwise procedure) and:

$$SSE = \sum_{i=1}^{n} \left(y_i - y_i^*\right)^2 \tag{9}$$

$$SS_{tot} = \sum_{i=1}^{n} \left(y_i - y_M\right)^2 \tag{10}$$

Being y_i the datapoint to fit, y_M the mean value of datapoint and y_i^* the fitted values derived from the application of regressions. The following section reports in graphical and tabular form the regression performed on the hydrodynamic attributes according to the process that has been here described.

Surface responses

The procedure for determining multiple linear regression and the associated surface responses described in the previous section has been applied to the data processing of the main attributes defined beforehand.
Table 4 reports the results of the regression analysis, reporting the coefficients together with the quality of the regression assessed through the performance indicators described by equations (7) and (8).
From the results reported in Table 4, it is evident that the general quality of the regression is high. All the values for the R^2 are above 0.9 and the unbiased estimator of R^2, the R^2_{adj}, is also high except for the dynamic trim regression. It is interesting to observe that none of the final regressions employ all the estimators of a full quadratic model. Such a matter is the effect of the stepwise iterative procedure used to develop the regression models, which automatically excludes the non-significant terms.
Analysing in detail the individual regressions, for the resistance, it is interesting to observe that the dependence from the vessel length is only linear, no significant higher order, coupled terms are present. Higher order dependency is observed only for the breadth and draught. For the dynamic trim, coupled terms became significant for the length, but still, the higher order is not present. Changing hydrodynamic quantity and going for the analysis of comfort, the regression for the ISO comfort considers all the coupled terms but is missing higher order terms for the length and breadth. The same situation is for the initial turning ability, while for the yawing ability the coupled term between breadth and draught is missing together with all the higher order terms. Such a trend in the significant coefficients does not have a direct explanation for the resulting hydrodynamic properties as the selection of coefficients is purely associated with the automatic selection procedure described in the previous section. It could be possible that with a different dataset as an input to the process, the resulting coefficients would be different, resulting in other conclusions. In fact, even though the multiple linear regression analysis can be classified as a white-box model, the relationship between the data remains difficult to directly analyse the effect of main dimensions on the hydrodynamic properties.

Table 4: Regression coefficients for the hydrodynamic attributes.

	RT	*Trim*	*ISO $_{TOT}$*	*Init_20*	*Yaw_20*
	(kN)	*(deg)*	*(-)*	*(-)*	*(-)*
	Coefficients				
Intercept	5.702E+03	-1.588E+02	5.006E+02	2.718E+00	5.551E+00
L	-1.193E+00	1.061E-01	5.241E+00	1.112E-01	-1.183E-01
B	-1.541E+03	4.122E+01	-5.793E+01	-1.194E-01	-2.756E-01
T	-7.175E+03	1.943E+02	-6.244E+02	-1.327E+00	1.341E+00
LB	-	-7.850E-03	-7.461E-01	-3.208E-03	7.975E-03
LT	-	-2.293E-02	-3.747E+00	-3.443E-02	-2.157E-02
BT	1.954E+03	-5.101E+01	8.821E+01	7.889E-02	-
L^2	-	-	-	-	-
B^2	1.030E+02	-2.667E+00	-	-	-
T^2	2.223E+03	-5.932E+01	1.998E+02	4.459E-01	-
R^2	**0.9526**	**0.9353**	**0.9669**	**0.9687**	**0.9661**
R^2_{adj}	**0.9052**	**0.8189**	**0.9228**	**0.9269**	**0.9407**

On the other hand, having an instrument like the regressions allows for visualising the behaviour of the dependent variables (i.e. the attributes) as a function of the dependent ones (i.e. the ship's main dimensions). Therefore, a particular set of diagrams can be derived to observe the variations of the attributes for a particular set of hull forms. The design space considers hull form variations that keep the coefficients constant. Then, all the hulls having the same volume can be plotted as a single surface in a diagram having *L*, *B* and *T* as principal axes. On this surface, it is possible to visualize in the form of a contour plot the value of a single attribute, highlighting the areas where the main dimensions have a good value for the reference attribute or not. Here, these graphs have been reported for the 5 main hydrodynamic attributes selected for the analysis, using as a reference a project constraint that imposes a reference volume of 225 m^3. The selection of this volume is purely arbitrary and is just a value that allows a good visualisation of the variations of the hydrodynamic properties along with the vessel main dimensions. The response surfaces are reported in Figures from 3 to 7. Figure 3 shows the response surface for the resistance, highlighting the area most favourable for hulls having main dimensions with a length of around 40 metres, breadth of 6.0 metres and draughts ranging between 1.6 and 1.8 metres. Such a combination of values is expected as the slender the ship is the lower is resistance. Figure 4 shows the behaviour of the dynamic trim. Here the behaviour of the data is different compared to the case of resistance, as not only one minimum or maximum are identified. In any case, for the trim the most preferable value for designers is the achievement of a neutral trim; therefore, for the reported surface, the best combinations refer to the saddle points populating the central part of the surface.

Figure 5 shows the response surface for the ISO_{TOT} comfort index. In this case, a maximum of the function is clearly identifiable for combinations of L, B and T around 30-35, 8.5-9.0 and 1.2-1.5 metres, respectively. This area is different compared to the area of minimum for the resistance, confirming that attributes for hydrodynamic characteristics are sometimes antithetic between each other.

Figure 6 highlights the variations of the initial turning ability. Also in this case the most favourable is for the attribute to be clearly identifiable, with a maximum for long and slender ships and a minimum for short slender ships. Such a behaviour is totally opposite to the description of the yaw-checking ability shown in Figure 7. It is interesting to notice that the two attributes related to manoeuvring have antithetic behaviour, that in both cases do not match between optimal regions for resistance or comfort. This would apply even to the turning ability from the turning circle test. This is in fact most likely antithetic to the yaw-checking ability from zig-zag manoeuvres

From this qualitative analysis, it is evident that a designer can make his decisions based on empiricism by just interpreting the graphs with the associated surfaces. However, the adoption of more advanced mathematical techniques can give more quantitative help to designers. In fact, the obtained surfaces can be employed to feed a Multi-Attribute Decision Method (MADM) in order to find the best compromise solution between the given attributes, providing also weightings according to the desiderata of the designer. The following section reports the description and the application of this technique on a reference yacht size.

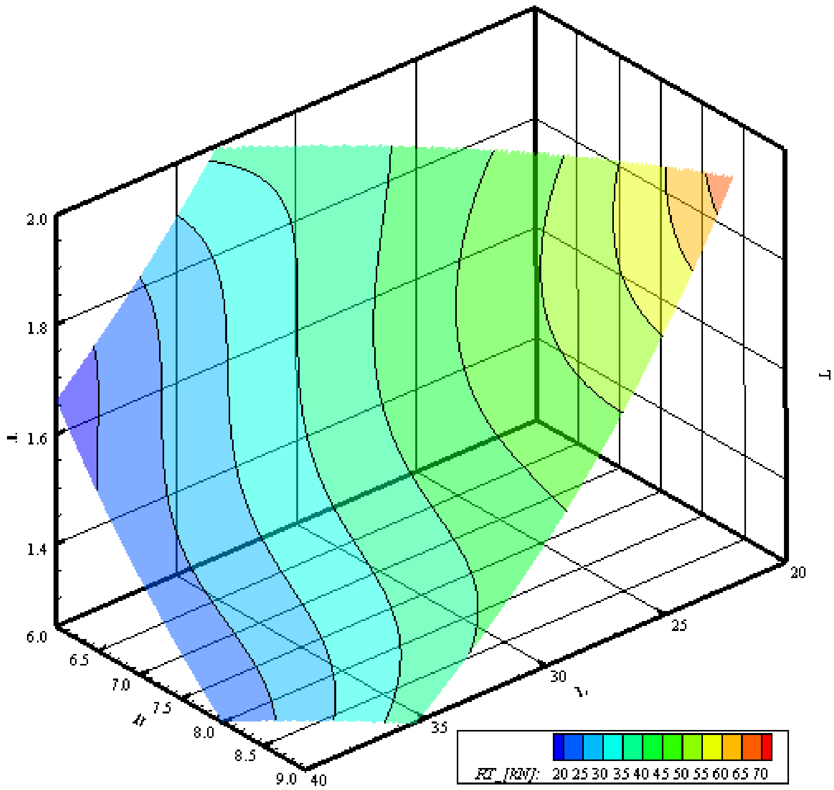

Figure 3: Response surface for the resistance at 12 knots for a hull of 225 m3 of displacement.

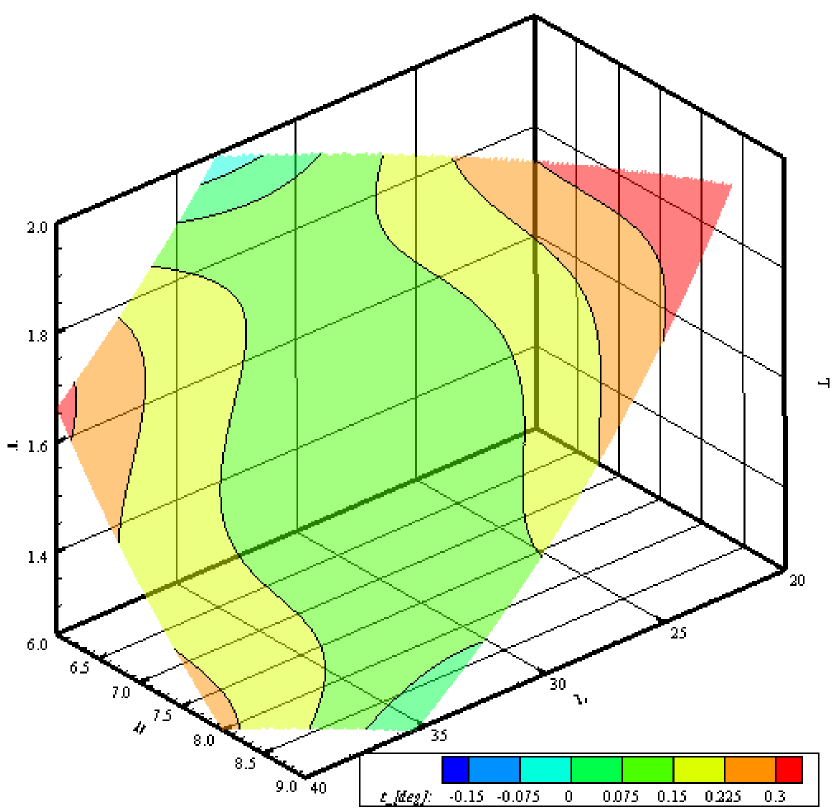

Figure 4: Response surface for the dynamic trim at 12 knots for a hull of 225 m3 of displacement.

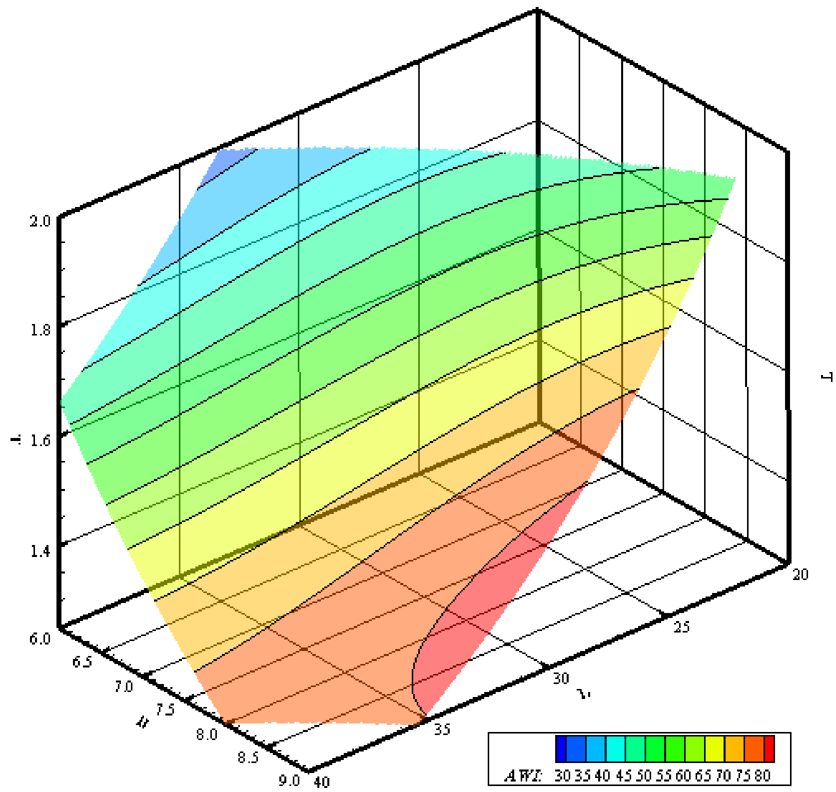

Figure 5: Response surface for the ISO comfort for a hull of 225 m3 of displacement.

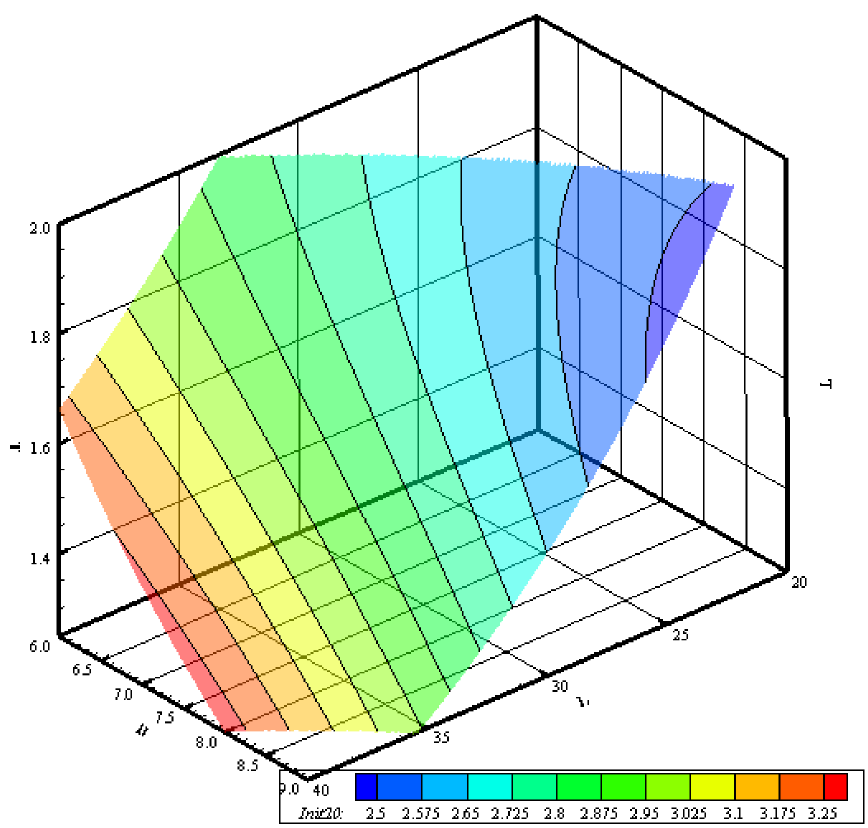

Figure 6: Response surface for the Initial turning ability for a hull of 225 m3 of displacement.

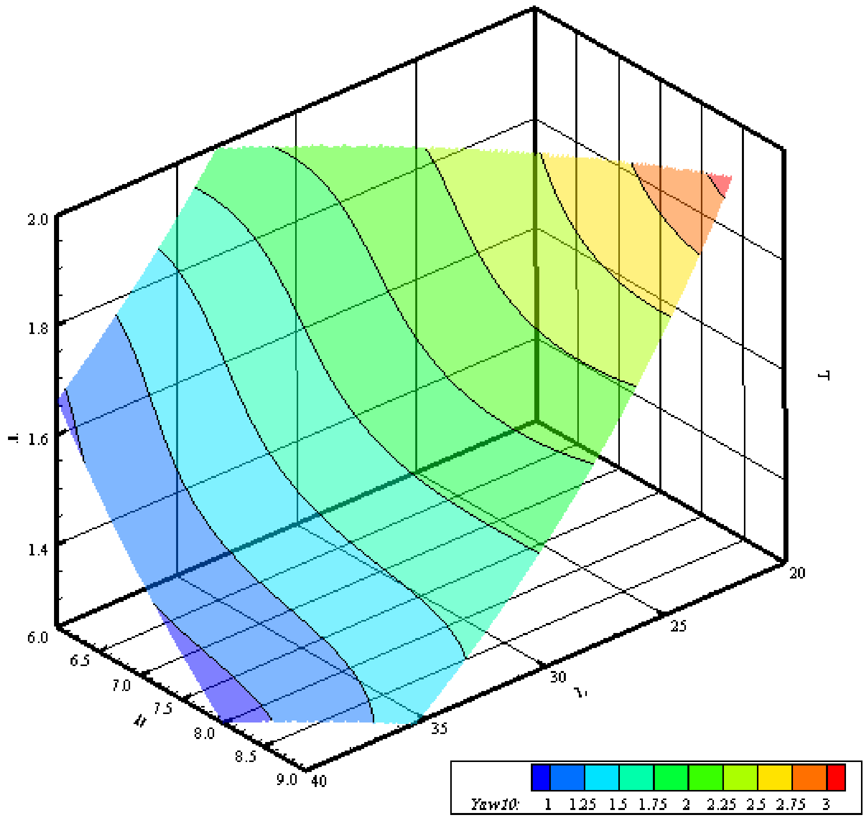

Figure 7: Response surface for the Yaw ability for a hull of 225 m3 of displacement.

APPLICATION TO CONCEPT DESIGN

The concept design of a new vessel implies the handling of different knowledge in Naval Architecture and Marine Engineering, ranging from resistance determination up to the estimation of the structural loads on a ship. As such, the designer should face a multi-criteria environment to find a proper design solution. Due to the complexity of the environment, a proper methodology needs to be applied in the early stages of design. In this respect, Multi-Attribute Decision Making (MADM) stands as an valuable tool for decision-makers facing complex and multifaced choices (Trincas, 2001, Kumar, 2010). In fact, by systematically considering multiple criteria and employing rigorous analysis techniques, MADM enhances the decision-making process, leading to more informed and effective choices in a complex environment as the design of a vessel.

Several methodologies can be employed to select the weighting attribute criteria, the decision matrix and the scoring of the best solutions. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is one of the possible methodologies that can be applied to the early design of ships as it has been recognised to be simple and effective for the problem (Behzadian et al. 2012).

TOPSIS is based on the concept that the best alternative is the one closest to the positive best ideal solution and the farthest from the negative ideal solution; where the maximum positive represents the best quality for all criteria and the negative the lowest quality. By calculating the proximity of these alternatives to the ideal solutions, TOPSIS assigns a score to each alternative, providing a rank among different solutions. To proficiently work, the TOPSIS procedure needs to go through the following steps:

1. Attribute definition: identifying the project attributes relevant to the design process.
2. Weight assignment: assign relative weights to each attribute according to the designer's preference.
3. Determination of Decision Matrix: normalise all the attributes and multiply them according to the given weights.
4. Determine the Positive and Negative ideal: find the best and worst case according to given weights
5. Rank the solutions: identify through Euclidean distance the closeness of each solution to the ideal and rank the solution accordingly.

The process is quite straightforward and allows for easily determining the rank among different solutions with sufficient flexibility for incorporating the desiderata weights for each attribute in a complex scenario.

While MADM offers valuable insights into complex decision scenarios, it has also a large number of challenges. These may include the data uncertainties, the susceptibility in criteria weighting, and the difficulties in capturing the dynamic nature of the decision environments. Therefore, also the application of these techniques requires an iterative approach and training before defining and refining the best decision model.
The adoption of first-principle tools for the definition of the main hydrodynamic attributes aims at reducing the uncertainties due to the methods employed to generate the initial database. However, even though the regressions show a high accuracy level, the resulting responses are still an approximation of the process and, therefore, the results should be interpreted by the designers with caution. Nonetheless, the implementation of the calculation process, automating the calculations and providing a graphical representation of the output help in streamlining the decision-making process and consequently enhance the efficiency.
In the present section, the TOPSIS process is applied to the example of the large yachts, employing the response surfaces described in the previous sections as an input to generate multiple design solutions for a given design space. For demonstration purposes, the design target is a large yacht with a displacement of 225 m^3. According to the definition of the TOPSIS process, it is necessary to assign weights to the different attributes, to incorporate designers' preferences into the project. For this initial calculation, the weights have been hypothesised to be evenly distributed among the attributes, afterwards they have been arbitrarily changed to reflect different kinds of design strategies. Table 5 reports the weights employed and the results for the main dimension obtained by applying the TOPSIS procedure on a dataset of 10,000 randomly generated projects.

Table 5: Example of TOPSIS procedure for different weighting factors.

Project	Weights [R_T, τ, ISO_{TOT},Init,Yaw]	L [m]	B [m]	T [m]
P1	[0.20;0.20;0.20;0.20;0.20]	39.446	7.857	1.303
P2	[0.20;0.10;0.50;0.10;0.10]	32.107	7.609	1.678
P3	[0.50;0.10;0.20;0.10;0.10]	30.161	7.645	1.725
P4	[0.10;0.10;0.10;0.35;0.35]	37.053	7.007	1.503
P5	[0.60;0.10;0.10;0.10;0.10]	33.595	6.003	1.968

From Table 5, it is evident how different weights identify different main dimensions for the same target displacement of the yacht. It has to be underlined that weights are arbitrary and do not reflect any design strategy derived from yacht designers but they have been used to reflect possible design strategies that favour more attributes related to resistance, comfort or manoeuvrability.
Even though the present method considers only the main dimensions of the yacht, the methodology proposed allows potential designers to make decisions on the main dimensions of a new project intrinsically considering attributes related to resistance, comfort and manoeuvring. Therefore, by adding further hull form variations to the initial dataset it would be possible to increase the flexibility of the current set of regression, by including also hull form parameters variations. In manoeuvring and seakeeping, only the main dimensions are often looked at, considering moreover large variations, and local modifications to the hull are often considered negligible. However, local modifications on the hull lines in the stern could produce different manoeuvring performance. Future studies as described in this paper could bring better insight.

CONCLUSIONS

The present study investigates the possibility of generating response surfaces for ship design purposes on a set of large-yacht hulls. An initial database of 15 hulls has been generated by parametrically changing the main dimensions in a specific range of values and by keeping constant the hull form coefficients. The changes have been performed according to a CCD design. On the resulting set of hull forms, CFD resistance calculations, strip theory seakeeping calculations and time-domain manoeuvring simulations have been carried out to evaluate the hydrodynamic performances of the yachts. Afterwards, multiple linear regression analyses were performed to determine the surface responses of all the hydrodynamic characteristics previously derived by first-principles calculations. Thanks to this process, the resulting responses can be employed in a MADM approach to find the best combination of main dimensions for a yacht having a predetermined target displacement, considering the weighting of attributes.
The resulting response surfaces from the first-principles calculations show the behaviour of the hydrodynamic attributes along with the changes in the main dimension, highlighting the antithetical nature of certain attributes. The developed graphs including the variations of hull form parameters for specific hull displacements could provide help to designers, in identifying the areas where the best solutions for each attribute are located. Besides, the development of response surfaces allows the application of such instruments to the selection process of main parameters through the application of MADM approaches. This allows for identifying the best tuple of dimensions taking into account also different weights among the attributes.

The process developed in this study is just a starting point for subsequent developments, since modifying only the main dimension is not sufficient to have a thorough understanding of the changes of hull forms on the hydrodynamic performances. The hull form coefficients strongly influence the hydrodynamic performances, and, in this case, they are kept constant as a preliminary assumption. Furthermore, progress can be made in the methodologies applied for the determination of the hydrodynamic coefficients, which means applying CFD also for manoeuvring purposes and 3D diffraction codes for seakeeping. Nonetheless, the methodology developed for this study can easily be implemented to a wider dataset that may become available by increasing the number of changes in the hull form generation.
In any case, the findings of this study are the first step to initiate a series of studies oriented to identifying response surface for the hydrodynamic performances of small and large yachts, taking finally into consideration all the aspects of ship hydrodynamics (i.e. resistance/propulsion, seakeeping and manoeuvring) plus additional attributes that are nowadays not included at all in the preliminary design of yachts like the Dynamic Positioning. The present work shows that this path can be pursued by employing the tools and methods described in the paper, ensuring promising results for the following research.

CONTRIBUTION STATEMENT

F. Mauro: Conceptualization; data curation, methodology; calculations, software, supervision, writing – original draft, writing – review and editing. **E. Begovic:** calculations; data curation, supervision; writing – review and editing. **E. Della Valentina:** Supervision **A. Dell'Acqua:** calculations, data curation, writing – review and editing. **B. Rinauro**: calculations, writing – review and editing. **G. Rosano**: calculations, data curation, writing review and editing. **R. Tonelli**: calculations, data curation, writing review and editing.

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