ModiYacht: Intelligent CAD tool for parametric, generative, attributive and interactive modelling of yacht hull forms

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ABSTRACT

This work proposes ModiYacht, a novel design tool for modelling optimised and customer-centred yacht hull forms. The proposed system incorporates parametric, generative, attribute-based and interactive design models. Parametric modelling uses high-level shape modifiers as quality operators to generate smooth and feasible designs. Because innovative and creative design is essential to a successful product, we also introduce an N-subpopulation-based teaching learning-based optimisation model that generates a variety of solutions to meet user design and performance requirements. Design attributes are developed using machine learning to shorten the communication gap between customers and designers. The generative designs can be used to provide interactive models for customers so that they can fully appreciate the hull-form's features and appearance prior to manufacturing. For this purpose, ModiYacht uses a design-space-shrinking technique during optimisation that guides the exploration process to focus the computational workload on user-preferred options.

KEYWORDS

Yacht hull design; computer-aided design; parametric design; generative design; interactive design; attribute-based design; optimisation.

INTRODUCTION

The fourth industrial revolution, Industry 4.0, has transformed contemporary design and manufacturing techniques, and many industries have adopted intelligent digital systems that integrate machine/deep learning to create robust design alternatives for innovative, optimised and customer-centred solutions. Despite such advancements, deep learning for maritime shipbuilding has been slow in adoption compared with other engineering fields. Typically, naval architects and designers use existing hull forms and apply mirror adjustments to obtain the desired features. The physical performance is then checked using high-fidelity computational simulations. If the results are insufficient, the process is repeated iteratively until a passable solution is found. This trial-and-error method depends greatly on designer experience; hence, it is subject to human fallibility. In short, a globally optimal design is rarely found. More importantly, with the need to reduce the worldwide carbon footprint, designers now require highly innovative design approaches that consider full lifecycle expectations. Notably, scholars have made considerable strides toward the modernisation of preliminary ship design (Cui et al., 2012; Van Bruinessen et al., 2011; McDonald et al., 2012; Duchateau, 2016); however, the results are not keeping pace with demand.

In this work, we propose ModiYacht, a novel computer-aided design tool (Khan et al., 2017; Khan and Gunpinar, 2018; Khan et al., 2019; Khan, Gunpinar & Sener., 2019; Khan and Awan, 2018; Dogan and Gunpinar, 2017) that supports designers at the preliminary yacht-hull design stage to provide innovative, optimised and customer-centred designs. ModiYacht comprises five functional parametric modules (Khan et al., 2017): attributive (Dogan and Gunpinar, 2017), generative (Khan and Gunpinar, 2018; Khan and Awan, 2018) and interactive (Khan et al., 2019). Parametric modelling is key to ModiYacht's power as it applies an innovative framework that ensures rapid and plausible shape modifications. During parametric modelling, the parent hull is divided into thirds, each constructed using Coons patches between characteristic lines (e.g. keel, deck, chine and station). Two sets of shape operators are provided to alter major and minor features, providing great flexibility with design variations.

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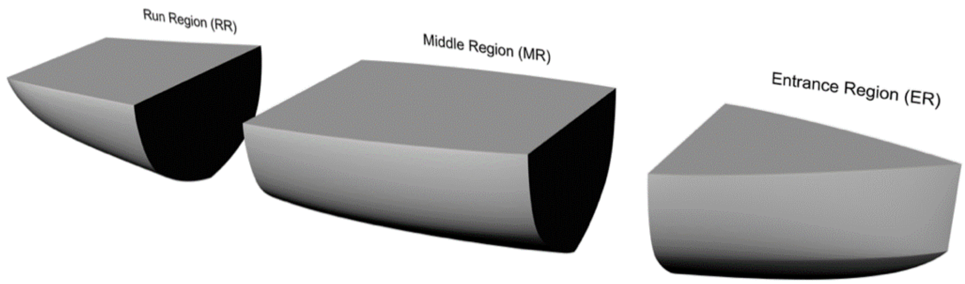

Figure 1: Segmentation of the parent yacht hull used with ModiYacht's parametric design method.

Attribute-based modelling is integrated into ModiYacht to provide rapid hull deformations based on a set of predefined attributes (e.g. aggressive, compact and modern). The preliminary relationships between hull attributes and forms are evaluated using a crowdsourced dataset that is used to train a group-method-of-data-handling (GMDH) polynomial neural network. Explicit mathematical formulations are thus provided to deform the hull to meet the desired attributes. Hence, communication between designers and customers is greatly facilitated, contributing to greater satisfaction.

Generative modelling is a critical component of ModiYacht, as it empowers both experienced and novice designers to generate all desired optimisation and performance alternatives for boilerplate 'parent' hulls. ModiYacht's generative approach samples the design space using a space-filling and non-collapsing optimisation strategy. Minimisation of these criteria ensures that diverse features are uniformly distributed within the design space. Interactive modelling allows designers to perceive the three-dimensional (3D) representation of the hull during the generative process, capturing the targeted regions of change. Generated designs are then presented to the customer, and attribute options are selected and combined based on the requirements. Afterwards, the design space is further refined using a novel space-shrinking technique (SST), which isolates the available design features based on iterative customer specifications. The altered features are then fed back into the generative design model (GDM) for the next iteration. This shrinkage process reduces the overall computational cost by providing only the expected design options at each phase. The experiments conducted in this study show that ModiYacht can be used as a complete yacht-hull design system. Its underlying components provide notable benefits to maritime vessel architects and designers over contemporary techniques.

PROPOSED DESIGN FRAMEWORK

In this section, we briefly explain the proposed design methodology for each ModiYacht module.

Parametric Design Module

ModiYacht parametrically assists designers in creating a diverse set of hull-form alternatives for different purposes, such as for motor-driven vessels, sailboats, expedition vehicles and open yachts. Using this system, designers can generate displacement, planing or semi-displacement hulls. To implement this approach, a parent yacht hull is divided into an entrance region (ER), a middle region (MB) and a run region (RR), as shown in Figure 1. Each region consists of an independent set of feature curves representing characteristic lines (i.e. deck, keel, chine and station). The station consists of keel-thickness, chine-thickness and two sub-station lines, as depicted in Figure 2.

All feature curves are represented as cubic Beziers, whereas bow, chine-thickness and keel-thickness lines are linear Beziers. With this cubic and linear combination, flexible hull modification can be achieved by changing the positions of the control points along the feature curves with the integration of high-level shape modifiers based on predefined rules. These modifiers allow the modification of all parameters defined on the overall shape while satisfying design constraints and quality criteria, as follows:

1. **Geometric continuity:** G^0 and G^1 continuities must be maintained between two adjacent feature curves. Otherwise, 3D surfaces generated from these curves will not be watertight and smoothly connected at the points between regions.
2. **Hull fairness:** Fairness of feature curves and the surface should be maintained so that infeasible and unrealistic design modifications are avoided.
3. **Independent modification of parameters:** The alteration of any parameter must provide variation to only local design features without affecting those defined by other parameters.

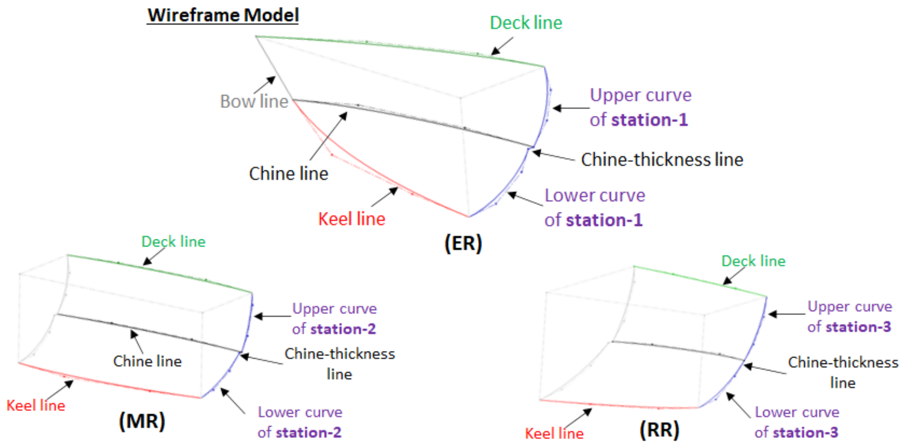

Figure 2: Description of the feature curves used to represent each region of ModiYacht's parent yacht hull.

The basic workflow of ModiYacht's parametric model is illustrated in Figure 3. When feature curves are defined, the 3D surface of the hull is generated by separately interpolating Coons patches between the curves in each region. As the G^0 and G^1 geometric continuities are maintained between the feature curves of two adjacent regions, and the generated Coons patches are smoothed at the connection points. In each region, four Coons patches are applied if double chines and keel thicknesses exist.

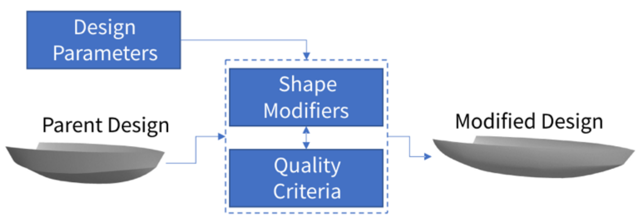

Figure 3: Workflow of the ModiYacht parametric model.

A diverse set of hull-specific design parameters is provided based on the parent hull, as listed in Table 1. Each region has its own set of independent parameters. For instance, lengths (L_e, L_m and L_r), beams (B_e, B_m and B_r) and drafts (D_e, D_m and D_r) are defined for entrance, middle and run regions, respectively. H_e is the vertical height of the bow, and F_e, F_m and F_r are the vertical positions of the chines at stations 1, 2 and 3, respectively. C_e, C_m and C_r specify the thicknesses (distances) between inner and outer chine lines for double-chine hulls. To explore the variety of design alternatives, the designer can alter a specific parameter without affecting others. A shape modifier is available for each parameter type to ensure plausible modifications. For example, an elongation modifier is employed when any parameter related to hull length (L_e, L_m or L_r) is altered.

Table 1: Design parameters defined on the ER, MR and RR of the hull for parametric modelling.

Parameters	Description	Parameters	Description
L_e, L_m and L_r	Length of ER, MR and RR	R_{m1}, R_{m2}	Minimum radius of curvature for the upper and lower lines of station 2
B_e, B_m and B_r	Beam of ER, MR and RR	R_{rs1}, R_{rs2}	Minimum radius of curvature for the upper and lower lines of station 3
D_e, D_m and D_r	Draft of ER, MR and RR	H	Vertical length of the bowline
F_e, F_m and F_r	Vertical chine position of stations 1, 2 and 3	K	Keel thickness
C_e, C_m and C_r	Chine thickness at stations 1, 2 and 3	β	Bow angle
R_{ek}	Minimum radius of curvature of the feature curve defining the keel in ER	θ	Entrance angle
R_{es1}, R_{es2}	Minimum radius of curvature for the upper and lower lines of station 1	α	Sheer angle

Each modifier is iteratively optimised using an objective function based on the curvature created by the set of points on the feature curves. Considering the page constraints of this article, we discuss only the elongation modifiers of the ER. The remaining modifiers follow similar procedures. When the ER's length is changed from L_e to $L_e + \Delta L_e$, the first control points of all feature curves are moved to $L_e + \Delta L_e$. Figure 4 depicts the evaluation process of the internal control points, CP_1 and CP_2, of the modified curve. To evaluate the positions of these control points, we first calculate angles $ang1$ and $ang2$ of the first and last segments of the polygon of the original cubic Bezier curve. The first segment lies between the CP_0 and CP_1 control points, and the last segment lies between CP_2 and CP_3, as shown in Figure 4. Two-line segments are then formed (i.e. $Lines$ 1 and 2) on the control points CP_0 and CP_3 of the modified curves at angles $ang1$ and $ang2$, respectively. The point at which these line segments intersect is the critical point. The distance between CP_0 and the critical point on $Line$ 1 is the candidate space for the CP_1 of the modified curve, whereas the distance between CP_3 and the critical point on $Line$ 2 is the candidate space for CP_2. To locate the positions of $CP_1$and CP_2 within their respective spaces, we run an iterative optimisation in which the objective is to minimise the cosine similarity (Equation 1) between the set of radial curvatures of the equally spaced points on the original (R_I) and the modified (R_M) feature curves and the final optimal positions of $CP_1$and CP_2, where the cosine similarity is minimised.

$$F = \frac{\boldsymbol{R}_I \cdot \boldsymbol{R}_M}{|\boldsymbol{R}_I||\boldsymbol{R}_M|} \qquad [1]$$

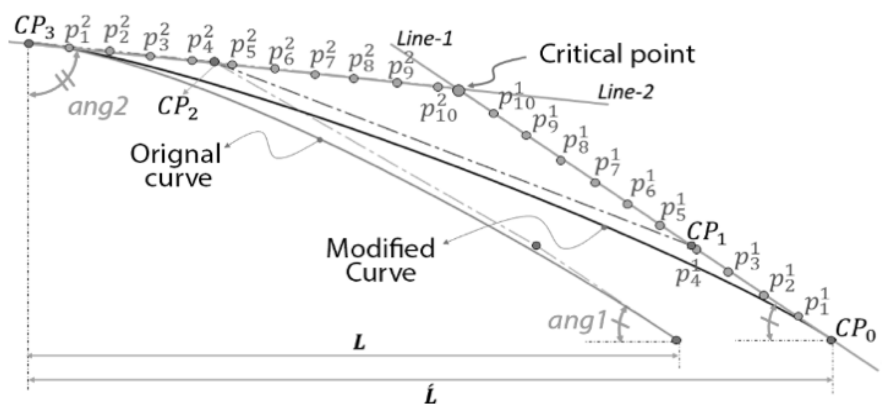

Figure 4: Workflow of the ModiYacht parametric model.

Generative Design Module

Generative design uses an algorithmic process to assist both experienced and novice designers in creating the desired number of optimal alternatives. Instead of a single solution, the generative process results in various satisfactory design alternatives that improve aesthetics and performance (Krish, 2011). To develop an effective GDM for ModiYacht, the proposed method should perform the following activities:

1. Provide an efficient exploration strategy to generate optimum design alternatives.
2. Create a diverse set of design alternatives containing the full design space.
3. Efficiently explore both constrained and unconstrained design spaces.

To achieve these objectives, an *N*-subpopulation-based teaching learning-based optimisation (N-TLBO) model is introduced. Although genetic algorithms have been widely used with generative design, their performance largely depends on the appropriate selection of tuning parameters (Eiben et al., 1999), which requires expertise not possessed by many designers (Krish, 2011). The basic flow of the generative process is shown in Figure 5. The proposed GDM takes the design parameters and their user-defined ranges to form the design space within which a set of N user-specified design alternatives is uniformly distributed to represent all design possibilities of the given space. All designs shall satisfy the specified performance requirements. When N designs are obtained, the previously described iterative parametric design process is used to generate 3D shapes.

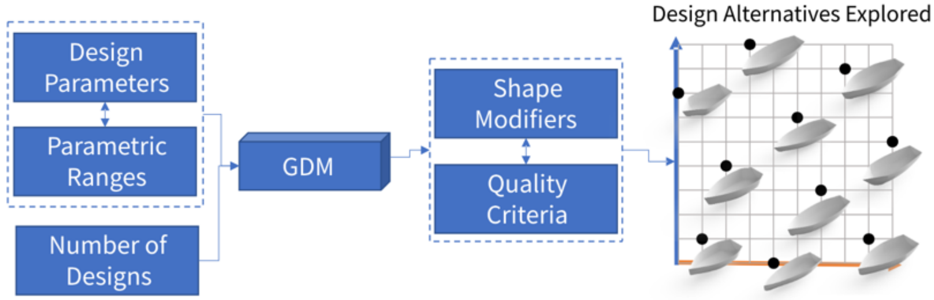

Figure 5: Workflow of the ModiYacht generative design method. GDM: Generative design method.

The objective/cost function of the GDM is the weighted sum of residual resistance (R_{res}), space-filling and non-collapsing criteria. Residual resistance is the physical criterion, whereas space-filling and non-collapsing types are quality criteria used to ensure uniform distribution and diversity. The space-filling criterion is formulated based on the method of Audze and Eglais (1977), which employs an analogous method from physics, in which molecules in space exert repulsive forces on one another, leading to potential energy within the system. These molecules are in an equilibrium state when their potential energies are minimised, which guarantees their uniform distribution over the system space (Audze and Eglais, 1977). In the case of high-dimensional design problems, the space-filling criterion may place a large number of designs at the boundary of the design space. Therefore, the non-collapsing criterion is incorporated into the objective function to ensure an even proportion of designs over the space. This criterion divides the design space into N subspaces and prevents the placement of more than one design in each. Figure 6 presents a comparison of randomly generated designs and those found using space-filling and non-collapsing criteria. It can be seen that the latter designs are uniformly distributed.

The objective function, F, used during GDM optimisation is defined as follows:

$$\text{minimise} \quad F = \sum_{i=1}^{N} R_{res} + \sum_{p=1}^{N-1} \sum_{q=p+1}^{N} \frac{1}{\left\|\mathbf{x}_p - \mathbf{x}_q\right\|_2} + \sum_{p=1}^{N} \sum_{q=p+1}^{N} \left(f(\mathbf{x}_p, \mathbf{x}_q) = \begin{cases} 1 & \text{if } \mathbf{x}_p = \mathbf{x}_q \\ 0 & \text{otherwise} \end{cases} \right). \qquad [2]$$

Here, in F, the first term is the sum of residual resistance of all N designs, and the second and third terms are space-filling and non-collapsing criteria, respectively. $\mathbf{x}_p$ and $\mathbf{x}_q$ are the p^{th} and q^{th} designs within the design space. The optimisation is performed using the N-TLBO algorithm, which generates a population of randomly sampled designs from the design space and performs training operations to reach global optima or a single optimum. Interested readers should refer to (Rao et al., 2011) for details on the generic teaching learning-based optimisation process. In our case, using its conventional setting does not result in optimal solutions as the objective function can only be evaluated using the set of N designs. Therefore, instead of commencing with only one population, we begin optimisation with N different subpopulations. Thus, each design has its own subpopulation, and during convergence, all subpopulations are guided to their respective optimum positions.

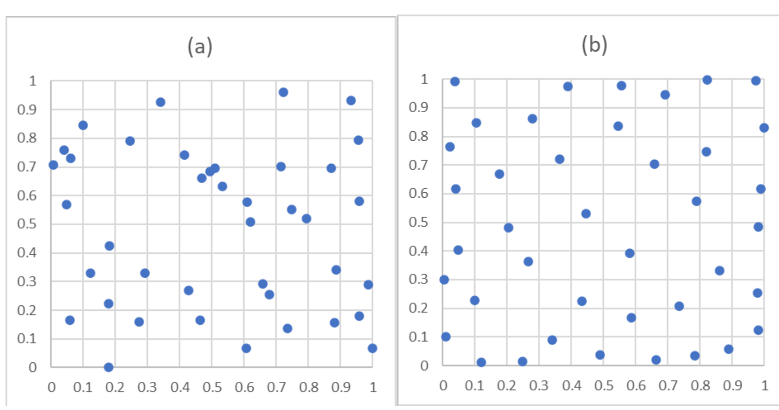

Figure 6: Designs (blue dots) in the two-dimensional design space generated (a) randomly and (b) using both space-filling and non-collapsing criteria.

In the presence of design constraints, Deb's heuristic constrained handling method (Deb et al., 2002) is adopted to avoid N-TLBO from selecting designs from constrained spaces. This method uses a tournament selection operator to designate design p as constrained-dominating another design, q, if any of the following heuristic rules are valid:

1. Design q violates constraints, but design p does not.
2. Designs p and q both violate constraints, but design p violates a smaller number.
3. Neither p nor q violates constraints, but design p has a better objective function value.

Attribute-Based Design Module

To enable ModiYacht to perform attribute-based yacht-hull modelling, the GDM is executed within the constrained design space, where the constraints are design attributes learned offline via machine learning and embedded within ModiYacht. The workflow of the attribute-based design method is shown in Figure 7.

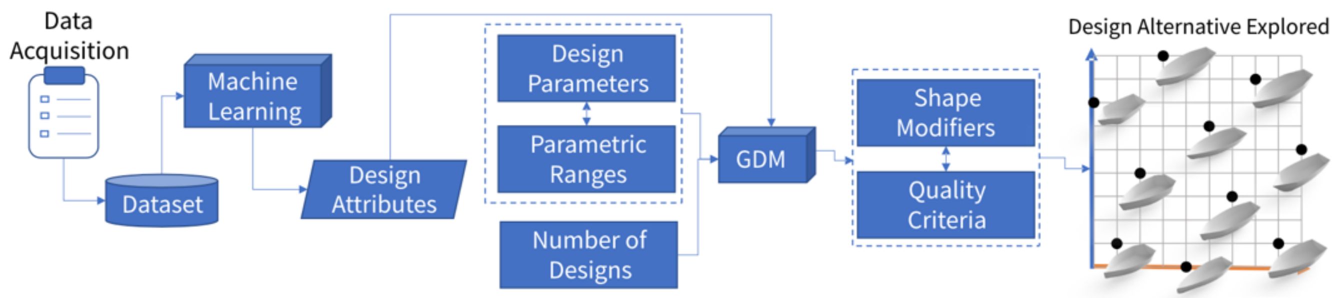

Figure 7: Workflow of the ModiYacht attribute-based design method.

The first step of attribute-based modelling is finding suitable attributes for yacht hulls and learning the relationships between these attributes and the hulls' 3D shapes. An attribute dataset was constructed from four sets of survey results collected previously. First, a large dataset of existing yacht hulls was retrieved from the internet, and the parent hull was modified using our previously defined parametric model to represent each boilerplate option. Afterwards, for each, specific attributes were obtained via crowdsourcing student participants at Istanbul Technical University in Türkiye. From the first survey's results, we chose attributes that sensibly represent yacht hulls. We initiated this process by selecting a diverse range of adjectives representing yacht shapes. Afterwards, we asked participants to apply appropriate adjectives from the set to each hull in the dataset. When completed, the following top adjectives were retained:

1. **Strong**: A design that looks powerful, heavy or difficult to break.
2. **Speedy**: A sharp design with apparently good hydrodynamics and aerodynamics.
3. **Comfortable**: A design that will provide a pleasant and comfortable feeling during a voyage.
4. **Aesthetic**: A design that shows great physical beauty.
5. **Usual**: A normal, mundane or commonly used design.
6. **Aggressive**: A bold-looking, assertive and forward design.
7. **Compact**: A tidy, efficient and economical design.
8. **Modern**: A design with a contemporary or unique style.
9. **Charismatic**: A captivating design with allure and charm.
10. **Cute**: An endearing design that inspires adoration.

From a second survey's results, we eliminated parameters lacking impact with respect to the chosen hull adjectives. From a third and final survey's results, we obtained the final attributes. Then, the design parameters of the hulls in the dataset were used as independent variables, and their attributes were used as dependent variables. The coupled relationships were then learned using a GMDH neural network model (Ivakhnenko and Ivakhnenko, 1995). GMDH is an inductive algorithm that uses the Kolmogorov–Gabor polynomial in Equation 3. $Y(x_1, \dots, x_2)$ is represented by a parameter set $(x_1, \dots, x_n)$ with coefficients $(a_0, \dots, a_n)$. It uses a feedforward procedure wherein mathematical models are progressively enlarged by the addition of training layers. Unlike typical neural networks, GMDH does not require much pre-processing for the given network layers, the neurons in hidden layers or thresholds for passing information to consecutive layers. Instead, it automatically organises the neural network architecture.

$$Y^z(x_1,\dots,x_n)=a_0+\sum_{i=1}^{n}a_ix_i+\sum_{i=1}^{n}\sum_{j=i}^{n}a_{ij}x_ix_j+\sum_{i=1}^{n}\sum_{j=i}^{n}\sum_{k=j}^{n}a_{ijk}x_ix_jx_k+\cdots \quad [3]$$

In Equation 3, $x_1,\dots,x_n$ represents n yacht-hull design parameters. Function $Y^z(x_1,\dots,x_n)$ denotes the attribute index of the z^{th} hull attribute. If the value of the attribute index, $Y^z(x_1,\dots,x_n)$, for a given hull model with $x_1,\dots,x_n$ design parameters is greater than a threshold of 0.5, then that hull model can be represented using the z^{th} attribute. The preference index, Y^z, is learned separately for each attribute via GMDH. A k-fold cross-validation technique is used to verify the performance of the obtained models by partitioning the dataset into k subgroups, between which cross-validation is executed. One of the groups is set aside as testing data, and the user preference models are obtained with k - 1 subgroups. The cross-validation process is repeated k times by taking the other subgroups as testing data. During the iterative process, a criterion value is calculated for the error between the actual and predicted outputs. Attributed models are then generated and updated iteratively until the prediction results cannot be improved further, and the error value is smallest.

Interactive Design Method

During interactive design, the design space is explored using subjective human evaluations. Doing so ensures the incorporation of human intuition without explicitly codifying human flaws into the design process. This process is carried out using interactive interfaces (Umetani and Bickel, 2018) or integrated optimisers within the interactive interfaces to semi-automate exploration (Mortazavi et al., 2018). In the latter approach, designers are interactively involved in each iteration to guide the exploration of promising regions. First, a population of randomly sampled designs is generated, and the customer selects one based on needs. The optimiser then iterates to generate designs like the selection, but with better performance in which the similarity among designs is measured using a distance-based metric (Poirson et al., 2013). This iterative, interactive process continues until the customer-preferred design is achieved.

During GDM, the designs created at each iteration of optimisation are based on designer selection(s) from the previous iteration; therefore, initiating the process with randomly generated designs hinders optimisation. Furthermore, contemporary distance-based design-space exploration methods can drive the optimiser towards fast convergence to similar designs without sufficiently exploring the design space. Therefore, the interactive ModiYacht process begins with designs generated by the GDM, as they are uniformly distributed and cover nearly all possibilities in the given space. Instead of using a distance-based metric to converge the interactive process to the customer-preferred solution, we apply the SST to detect and remove non-potential regions based on the selected designs so that a newly narrowed design space is created to greatly reduce computational costs. At each interaction, designs are created using the GDM and the parametric modelling method, in which physical properties are presented. The customer then selects a design based on the desired appearance and performance, and the design space is refined again using SST. This procedure continues until the optimal design is achieved. Figure 8 illustrates this approach in a two-dimensional design space. At each interaction, the design space created in the previous interaction shrinks based on the newest user-selected design. Thus, the region of the user's interest can be better explored.

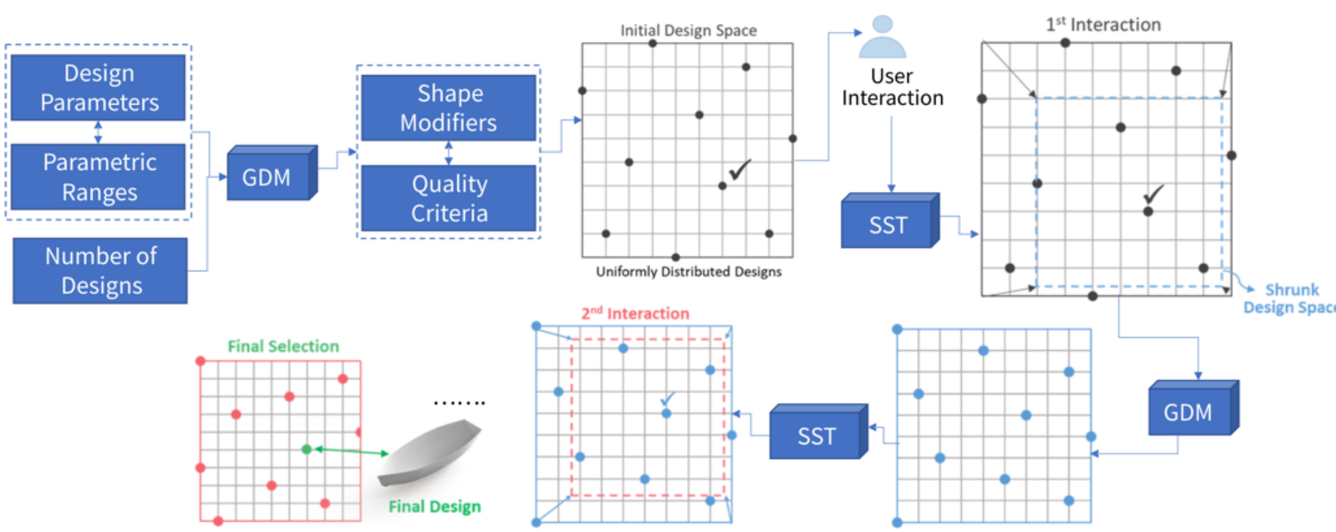

Figure 8: Workflow of ModiYacht's interactive design method.

Design-Space Refinement via SST

After obtaining the design set ($\mathcal{N} = [\mathrm{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_N]$) from the GDM, the designs in $\mathcal{N}$ are sorted in ascending order based on their R_{res} values. Afterwards, the sorted set is presented to the customer from which a design is selected. The sorted designs in $\mathcal{N}$ help the user judge which design has the best performance and aids in trade-off decisions (performance vs. appearance). After this interaction, design space $\mathcal{X}$, which is formed by the upper ($\mathbf{x}_m^u$) and lower ($\mathbf{x}_m^l$) limits of the parametric range of the parent hull design (m), is shrunk towards the user-selected design. Design-space refinement is carried out with Equation 4. Next, we summarise the space shrinking technique.

At the T^{th} interaction, a design set, $\mathcal{N} = [\mathbf{x}_{op}, \mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_N]$, is presented by the GDM, and the customer selects the t^{th} design ($\mathbf{x}_t$), where T is an integer. After the selection, a new design space, $\mathcal{X}^T$, is formed while shrinking the previous design space ($\mathcal{X}^{T-1}$) based on the selection, $\mathbf{x}_t = (x_{t,1}, x_{t,2}, \dots, x_{t,n})$, which is then used to generate designs for the next interaction. The design space is shrunk by calculating new lower ($\acute{\mathbf{x}}_m^l$) and upper ($\acute{\mathbf{x}}_m^u$) bounds with Equation ?? for $\mathcal{X}^T \coloneqq \{\acute{x}_{m,k}^l \le x_{t,k} \le \acute{x}_{m,k}^u,$ $\forall k \in \{1,2,\dots,n\}\}$).

$$\begin{cases} \acute{x}_{m,k}^l = x_{m,k}^l + \left|\kappa^T \times \ln\left(\frac{x_{t,k}}{x_{m,k}^l}\right) \times \frac{1}{T}\right| \\ \acute{x}_{m,k}^u = x_{m,k}^u + \left|\kappa^T \times \ln\left(\frac{x_{t,k}}{x_{m,k}^u}\right) \times \frac{1}{T}\right| \end{cases}, \forall k \in \{1,2,\dots,n\}. \qquad [4]$$

Here, κ^T is the shrink rate initialised by the customer during the T^{th} interaction, ranging between $0 < \kappa^T \le 1$. When κ^T is zero, the space-shrinking process terminates.

GRAPHICAL USER INTERFACE AND RESULTS

In this section, we discuss ModiYacht's graphical user interface and provide a brief overview of the utility of its three modules. We also provide practical results to demonstrate the system's feasibility.

ModiYacht was programmed using the Microsoft Visual Studio platform with C++ and Parasolid's[1] 3D geometric modelling application programme interface. A parent hull, shown in Figure 1, is initially stored in the database. During the interactive process, parametric shape modifications take place based on new sets of values. The main interface of ModiYacht, shown in Figure 9, consists of an OpenGL[2]-based graphical user interface for design visualisation.

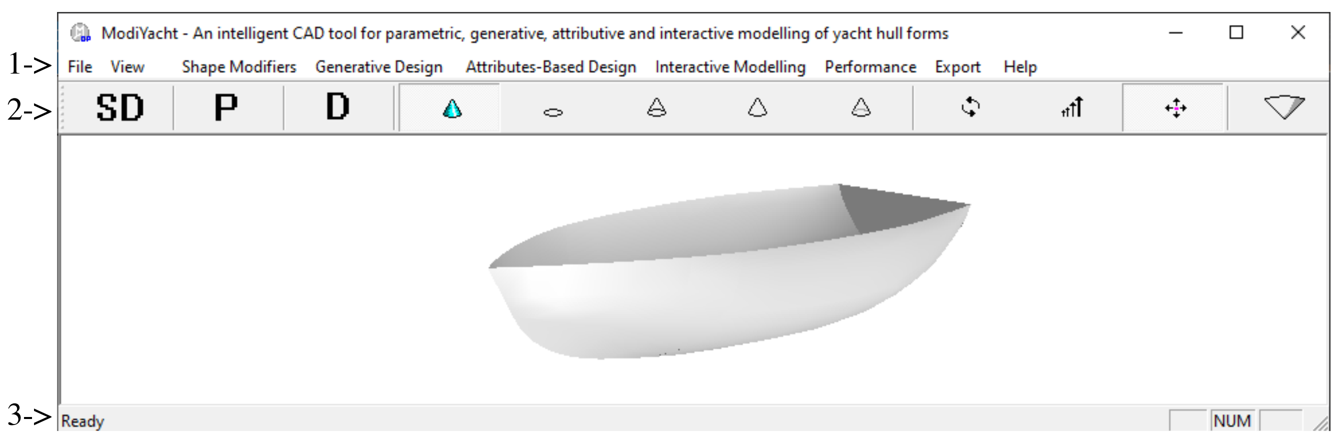

Figure 9: Main graphical user interface of ModiYacht, used to visualise results and access all design functionalities.

This interface is composed of operation, tool and status bars. The operation bar provides access to the three design modules, including the manipulation of shape and performance modifiers. The toolbar is used to choose from among semi-displacement, planing and displacement hull types. The toolbar also provides users with the ability to perform simple operations, such as

[1] https://www.plm.automation.siemens.com/global/en/products/plm-components/parasolid.html
[2] https://www.opengl.org//

rotating, panning, zooming and wireframe toggling. Lastly, the status bar at the bottom of the interface provides the current status and progress of all operations.

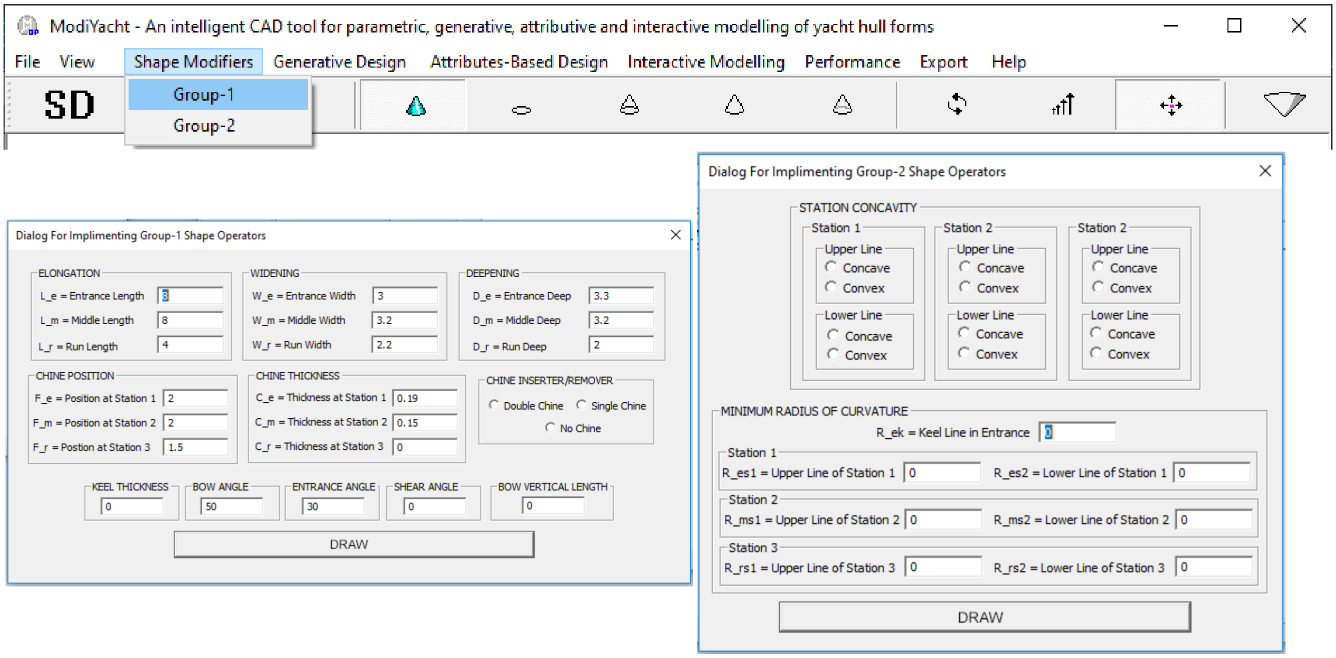

Figure 10: ModiYacht interface used for parametric design modelling.

Parametric Modeller

The shape modifier tab opens a drop-down menu that can be used to access two groups of shape modifiers, as shown in Figure 10. Group-1 modifiers are used to alter the major hull features (e.g. length, beam depth, entrance angle and bow height). Group-2 modifiers are used to alter local features (e.g. curvature radius and station concavity). To begin, the user first selects the type of hull desired using ‘SD’, ‘P’ or ‘D’ options on the toolbar.

Figure 11 displays sample shape modifications of the parent hull: length altered at MR L_m; draft altered at ER D_e; beam altered at ER B_e; bow angle altered at β; a combination of vertical heights of stations 1 and 2 at $[F_e, F_m]$; and a combination of vertical bow heights and angles at $[H, \beta]$). From these results, it can be seen that G^0 and G^1 continuity is maintained at the connecting regions of the feature curves; thus, surface transitions are smoothed throughout hull alteration.

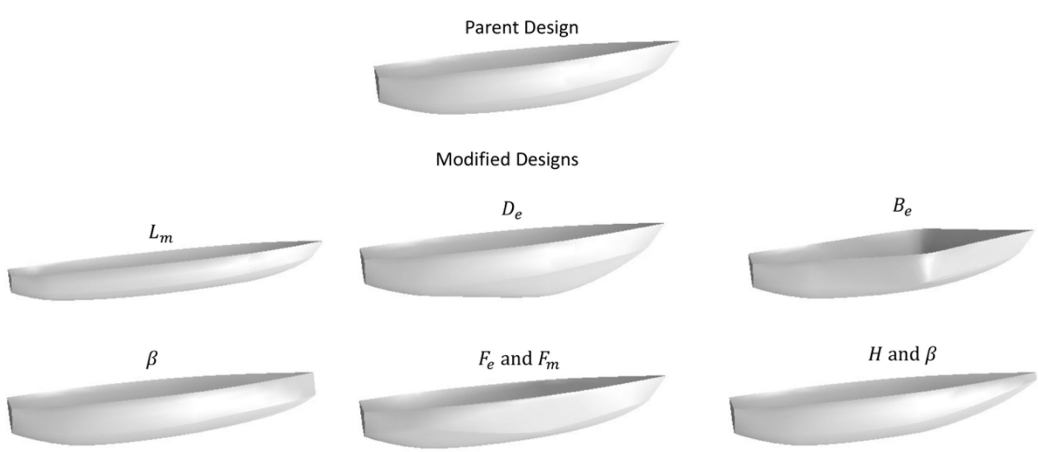

Figure 11: Results of performing parametric modelling using shape modifiers to alter hull shapes based on different parameters.

Generative Modeller

Like shape modifications, the generative design tab (Figure 12) also provides a drop-down menu, which leads to a simple dialogue box with which users set the input parameters (e.g. number of designs to generate, number of N-TLBO iterations to run, initial subpopulation size, customer-modifiable parameters and design-space limits). To create the initial design space, the user sets the upper and lower parametric bounds using the design-space dialogue box. These limits can be defined either by providing specific values or a percentage of the parent hull's parameters. Here, the user can select the components of the objective function (Equation 2) to be included during optimisation. By default, the objective function is the sum of all three component types (i.e. residual resistance, space-filling and non-collapsing).

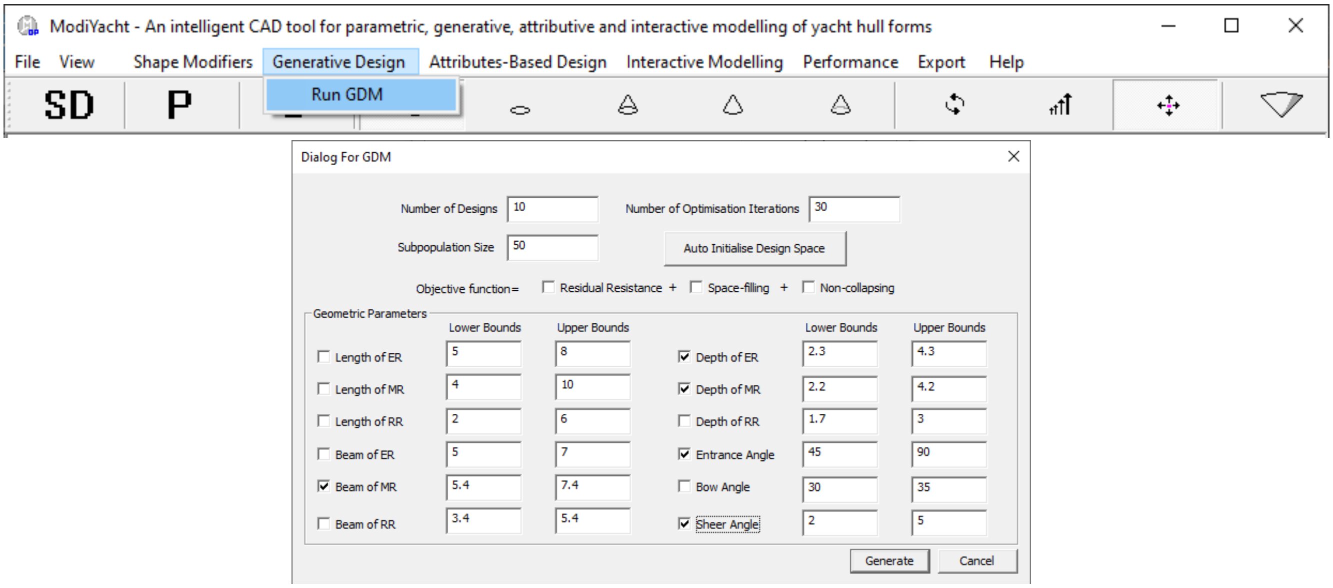

Figure 12: ModiYacht interface used for generative design modelling (GDM).

Figure 13 shows the GDM results for $N = 40$ when the number of optimisation iterations and subpopulation size are set to 20 and 5, respectively. The length, beam, draft, bow and entrance angles are subtly changed using a $\pm 5\%$ parametric variation. Thus, with only a few affected parameters and optimisation runs, substantial variations are provided. Care should be taken when defining the design space, as those with large parametric intervals will result in higher variations, including invalid or impractical ones.

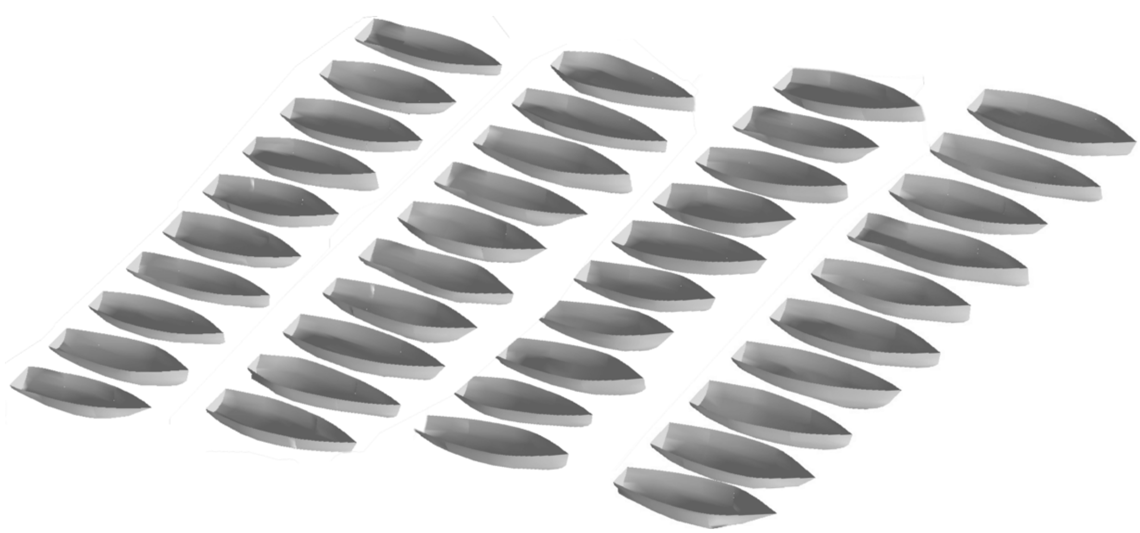

Figure 13: Designs generated by ModiYacht's generative design model.

Attribute-Based Modeller

The attribute-based design tab provides access to ModiYacht's adjective modeller, shown in Figure 14. Here, the user can open a dialogue for attribute-based modelling. The mathematical models of the previously described attributes are defined in ModiYacht's database. Users must first select the desired attributes (single or multiple) and specify the desired number of designs (N). Then, the user clicks the 'SAMPLE DESIGN' button, which launches the GDM. The status bar shows the status of 'Creating designs in defined design space using N-TLBO'. After the generative process completes, the status bar displays 'Designs have been created in design space by N-TLBO'. After the specified number of designs is created, the user may change the number using the slide control and by clicking the 'GENERATE' button.

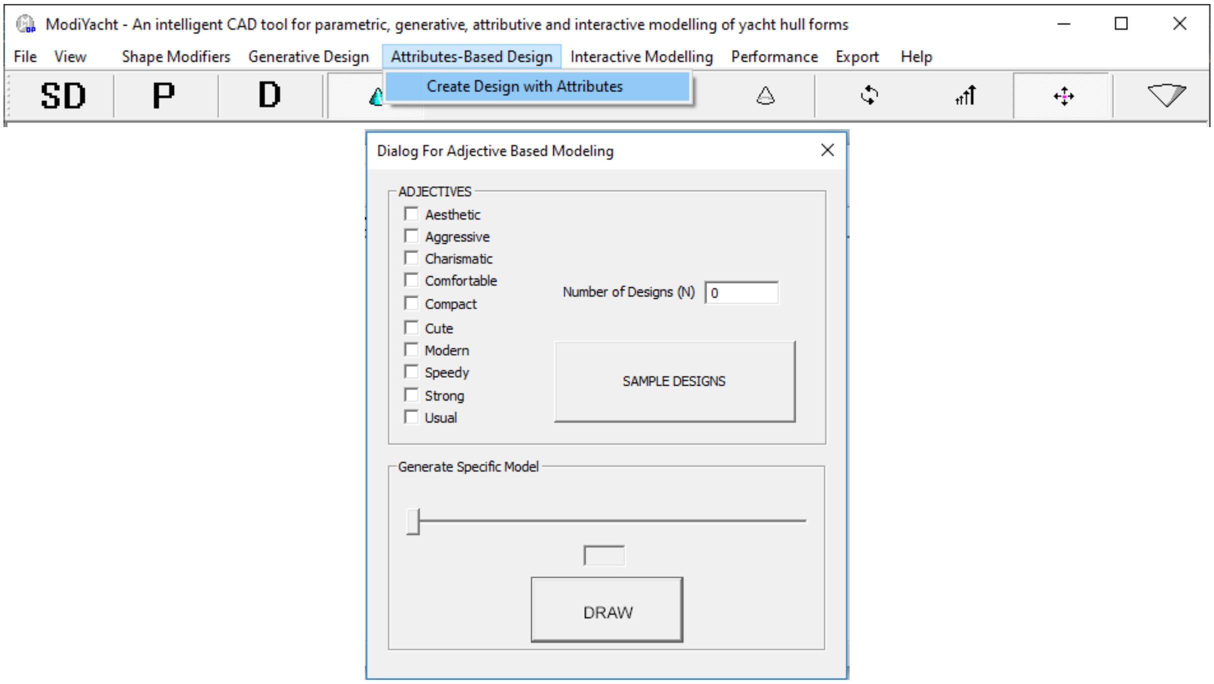

Figure 14: ModiYacht interface for attribute-based design modelling.

Figure 15 shows the hull forms generated for aesthetic, aggressive, charismatic, speedy and a combination of modern, speedy and compact attributes, which are explored via the GDM while taking the given attribute as a constraint so that the index is higher than 0.5, ensured using Deb's heuristic constraint handling rules. Customers are encouraged to continue exploring alternatives until they find a design of interest.

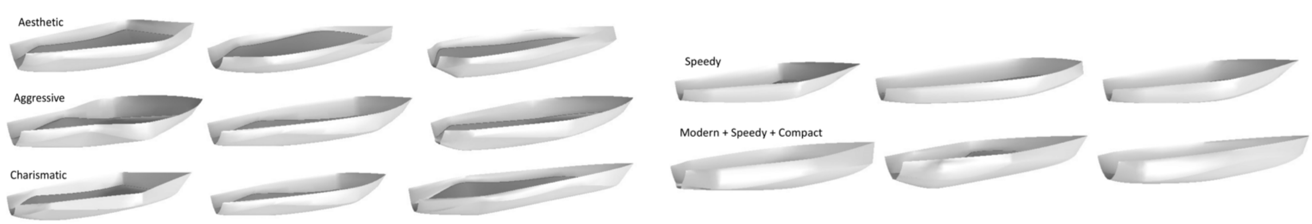

Figure 15: Yacht hulls generated using ModiYacht based on different attributes.

Interactive Design

To begin the interactive design, the user retrieves a parent hull and inputs the number of designs to be generated (Figure 16). Design parameters are then selected for alteration. ModiYacht creates the requested number of yacht hulls alongside their respected draft and Froude numbers. Based on appearance and performance, the user then selects a design for SST, which creates a new design space. The user also inputs a shrink rate, κ, which specifies the speed at which each iteration narrows the design space. User interaction continues until the desired design is obtained.

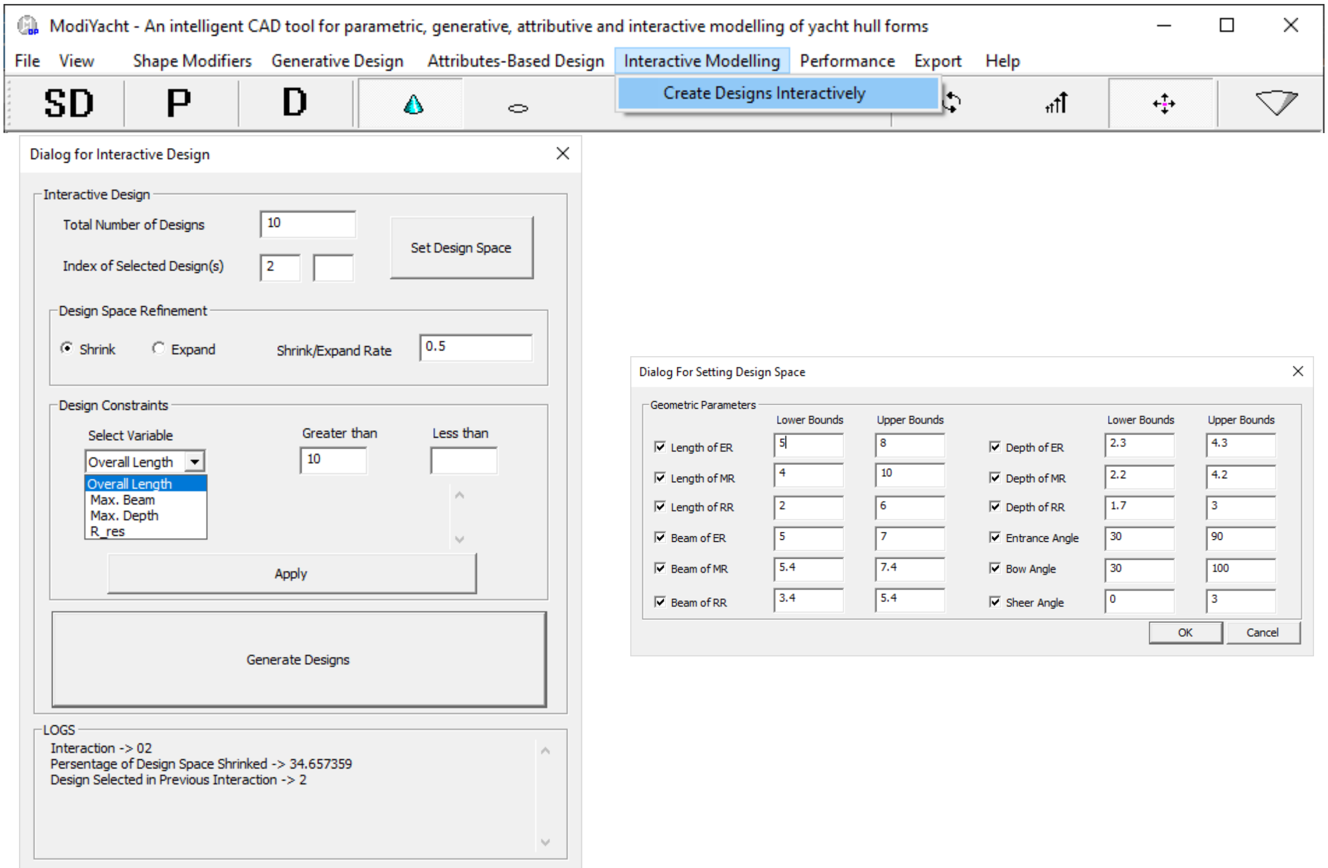

Figure 16: ModiYacht interface used for interactive design modelling.

ModiYacht also provides users the ability to define different geometric constraints (e.g. length, beam and depth) at any time during the interactive process. Design constraints may be added during any iteration; however, they should be carefully defined, as the hulls generated in a new design space based on a particular performance criterion may not allow certain attributes to be improved. ModiYacht notifies the user of the occurrence of this situation. Figure 17 shows the results of a seven-interaction process in which $N = 10$ designs are first generated. Afterwards, the customer selects a design based on aesthetics and required performance criteria, R_{res}. Given a shrinkage rate of $\kappa = 0.5$, $N = 5$ new designs are generated. It can be seen that the $T = 2$ designs are like those of the previous iteration. As the interactive process continues, the designs converge.

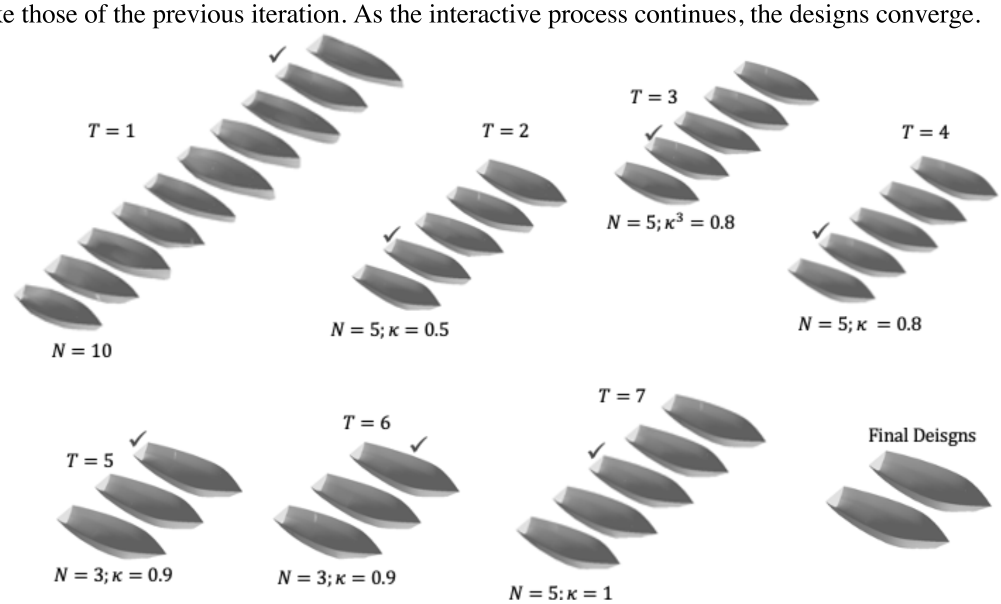

Figure 17: Yacht-hull design alternatives resulting from seven interactions.

At each interaction, the user selects a design and, depending on the value of the shrink rate, κ, the new design space is limited. At higher values of κ, the design space shrinks faster, and the designs generated in this space share many similarities. When κ is set to a lower value, the designs converge more slowly. For example, the interaction results shown in Figure 18 were obtained using $\kappa = 0.9$ and $\kappa = 0.1$ for the same set of initial designs. When $\kappa = 0.9$, nearly all newly generated designs are like the previously selected design; however, $\kappa = 0.1$, then there is less similarity.

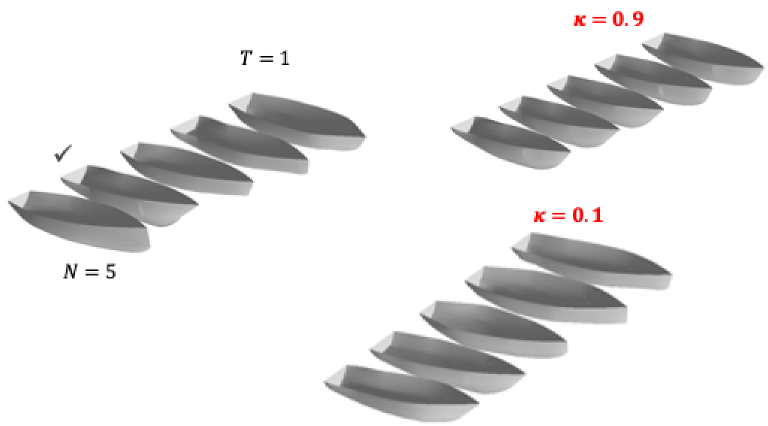

Figure 18: Hull alternatives representing different shrink rates, κ.

Yacht-Hull Performance Evaluation

During hull design, several hydrostatic and hydrodynamic analyses take place to determine whether the hull form can fulfill the customer's design requirements prior to final selection. Therefore, ModiYacht gives users the ability to evaluate hydrostatic properties, form coefficients and set Froude numbers (Figure 19).

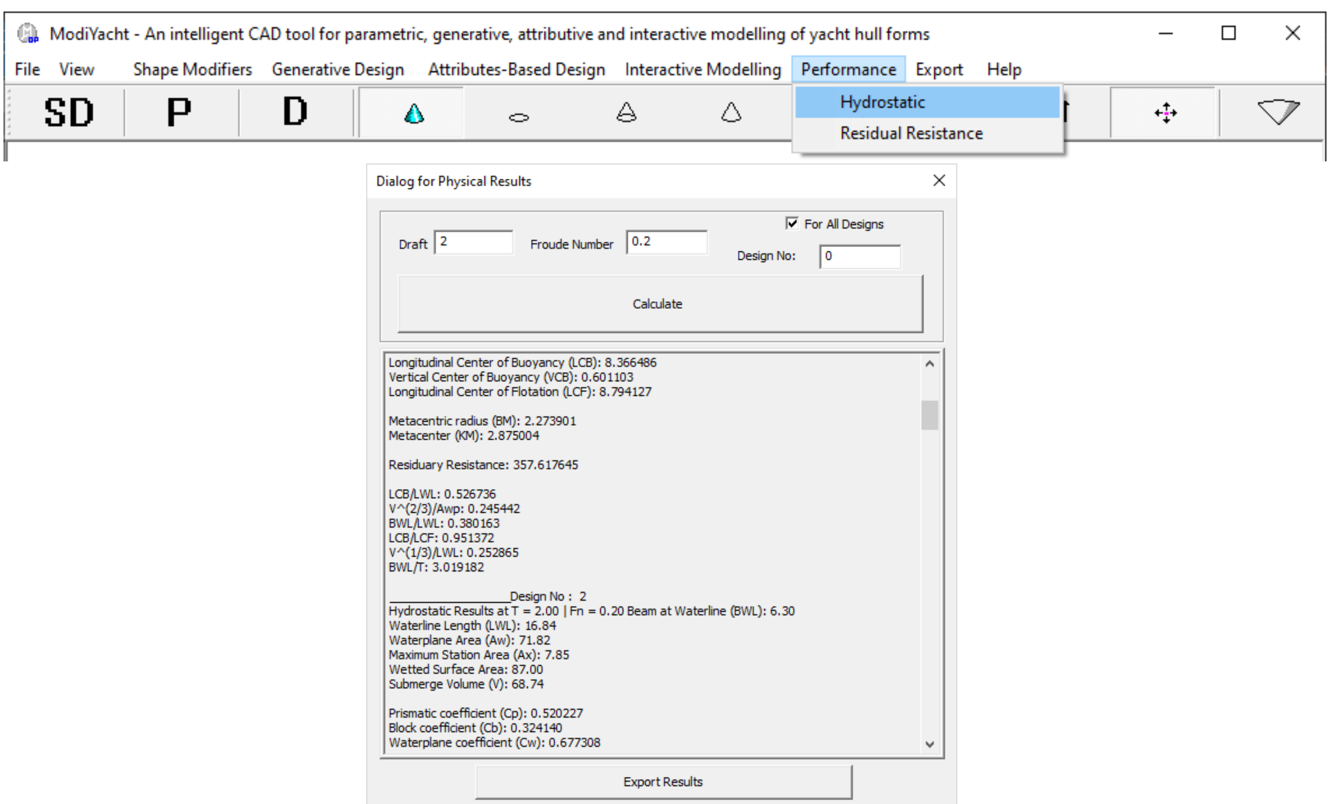

Figure 19: ModiYacht interface used to analyse yacht-hull performance properties.

Hull hydrodynamics include wave resistance, seakeeping, manoeuvrability and other factors, which typically require computational fluid dynamic (CFD) analyses. However, CFDs are computationally intensive and can result in long waiting times for customers between interactions, resulting in fatigue and poor choice-making. Therefore, we utilise the empirical equations proposed by Keuning and Katgert (2008) to calculate hull alternatives. Frictional resistance is calculated according to the 1957 International Towing Tank Committee formula (Lewis, 1988). The Reynolds number (R_n) and the frictional resistance coefficient (C_F) are calculated for a yacht navigating in seawater at 15 °C with a density and a kinematic viscosity of $1.189 \times 10^{-6}(m^2/s)$ and $1026.021\ (kg/m^3)$, respectively. The total resistance (R_T) is the sum of R_{res} and R_F. Currently, ModiYacht provides the properties listed in Table 2, evaluated at the given draft and Froude numbers. The final design may be exported into an **.IGES** file format, which can be used for additional physical analysis.

Table 2: List of hydrostatic properties evaluated using ModiYacht.

Waterline length (LWL)	Midship coefficient (Cm)
Waterplane area (Aw)	Longitudinal moment of inertia (IL)
Maximum station area (Ax)	Transverse moment of inertia (IT)
Submerge volume (V)	Longitudinal centre of buoyancy (LCB)
Wetted surface area	Vertical centre of buoyancy (VCB)
Prismatic coefficient (Cp)	Longitudinal centre of flotation (LCF)
Block coefficient (Cb)	Metacentric radius (BM)
Waterplane coefficient (Cw)	Metacenter (KM)

CONCLUSIONS

This work proposed a novel interactive and generative design-based system for the preliminary design of yacht-hull forms. The proposed system provides a maritime vessel architectural approach that enables architects, designers and novice users to integrate hull-design preferences using a design space visualisation and exploration method. Customers generate designs that best fit their requirements, not only in terms of physical performance but also overall appearance. The parametric design module provides shape modifiers that affect the three key regions of a yacht hull, each constructed using either cubic or quadratic Bezier curves. Each shape modifier is formulated while integrating critical quality criteria (e.g. hull fairness) and independent parameter modifications. An objective function is then introduced for fair and smooth modifications of the hull feature curves. The GDM generates a user-defined number of space-filling hull forms that satisfy the given design constraints. Among these, the customer selects the most suitable, and it is then used to perform additional attribute- or interactive-based modelling. The attributes are mathematical models of design parameters with coefficients obtained using a machine-learning process. Using the interactive module, a space-shrinking technique is applied, which narrows the design space at each interaction based on selected attributes. The new space is fed back into the GDM to generate a new set of designs for the next interaction. This generative and interactive process continues until the customer chooses the final desired shape. ModiYacht's user interface was created using C++ with the Parasolid 3D modelling kernel and OpenGL.

In the future, we plan to extend ModiYacht's capability for different types of ship hulls. More importantly, we plan to integrate computational design tools, such as that of Belibassakis et al. (2013), to enable design analyses. We also intend to use machine learning approaches (e.g. generative adversarial networks) to upgrade ModiYacht's capabilities to achieve smoother design modifications. Enhancing the capacity of ModiYacht for optimising the compartment arrangements and overall structural integrity is also in our plans. So, the yacht is not only customer-centred based on its outer form but also optimal for its internal layout and compartment arrangements.

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