Parametric Modelling of Hull Forms for Merchant Ships

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Abstract

The objective of this paper is to create a fully parametric model that can create a wireframe model of merchant ships to be used in the concept design phase. The first step was to analyse the hull shapes of different types of merchant ships, focusing on bulk carriers, Ro-Ro, tankers and container ships. The objectives of this analysis were: identifying the most important curves to define hull's shape and the necessary parameters to define them. The curves were classified in two types: geometric curves and property variation curves. Eight geometric curves and three property variation curves were identified. The parametric model is implemented in a visual programming tool called Grasshopper, which is a Rhinoceros 3D plug-in. The model starts with input of eighty parameters, or less, depending on the complexity of the hull shape, which create points, then the geometric and property distribution curves, and finally the wireframe model. Curves are created with NURBS curves. After the parametric procedure is implemented, a validation of the parametric model is presented. This validation is carried out with five ships, with different characteristics. The validation procedure consist on a numerical validation, where the hydrostatic results are compared, and a graphical validation, where a body plan is created where the parametric and real sections were superimposed. The results show acceptable errors for hydrostatics and with the parametric sections showing acceptable shapes although in some cases they presented some difference in its areas.

Keywords: Parametric Modelling, Grasshopper, Hull Form, Ship Design

1. Introduction

Ship design is a very complex and iterative task where the aim is to create a new design or modify an existing one that meets a set of requirements defined by the ship owner, such as required cargo capacity, service speed, autonomy, etc. Traditionally this process is divided into 4 phases, of which the first two are known as basic design: concept design, preliminary design, contract design, detailed design.

Nowadays, ship design is a field under pressure due to the International Maritime Organisation (IMO) to make ships less polluting, aiming for new ships to meet the Energy Efficiency Design Index (EEDI) regulations in order to achieve a 40% reduction in greenhouse gases by 2030 and 50% by 2050. This objective puts pressure on ship owners and ship designers to create ships that are more environmentally friendly, so it is important that there are tools that allow the designer to explore various design options. To achieve this goal, Computer Aided Design (CAD) plays a very important role as it allows changes to be made to the shape of the hull. The most used techniques to modify the geometry of the hull shape are: parametric modelling and conventional modelling. These geometric modelling techniques are classified and analysed by Harries, Abt and Hochkirch in [1]. The classification split the geometric modelling techniques into three different types: fully parametric partial parametric and conventional. With the fully parametric modelling being the most efficient technique to be used in the basic design stage of ship design.

Conventional modelling has the advantage of being very flexible, but it is needed a very large know how and when the data necessary to represent the hull surface begins to increase any modifications are very time-consuming.

Partial parametric modelling allows you to make modifications to existing hull shapes by changing form parameters that describe the parts of hull geometry. It is widely used in optimization studies, as it allows creating a large number of different projects, quickly and easily. The main partial parametric approaches are: swinging and shifting, box deformation and morphing. Lackenby in 1950 [2] presented one of the first approaches to partial parametric modelling, more specifically a swinging and shifting technique. He came up with a way to make a systematic modification to the sectional area curve (SAC) and then move the sections longitudinally so that the new hull matches the new SAC. Usually the shifting techniques are made in the Cartesian plane as seen in [3–5]. Another shifting transformation technique is the use of radial displacements. An example is the use of radial basis functions (RBF). Harries and Uharek [6] used this type os partially parametric approach in combination with principal component analysis to reduce the time necessary to perform an hydrodynamic optimization of a catamaran. The box deformation method can also be called free-form deformation (FFD) consists of placing a B-spline control polygon, which surrounds the geometry and has an associated control volume. In 2015 Brizzolara et al. [7] presented a comparison between the FFD method and fully parametric approach. The results concluded that despite obtaining a similar reduction in wave resistance, 8.5% for the fully parametric approach and 8.4% for the FFD approach, the fully parametric approach manages to present a more realistic hull shape than the FFD method. Morphing or merging is the interpolation of two or more baselines, which need to be topologically identical to facilitate the computation of a new geometry. In [8, 9] the morphing technique combined with evolutionary algorithms is used to create hull shapes in a way that minimizes user input and can explore new designs efficiently and automated. This methodology was called Hybrid Evolutionary Algorithm and Morphing (HEAM).

In fully parametric modelling, the hull form is defined by form parameters. These parameters can describe three types of geometry properties: positional (length, breadth, draught, etc.), differential (tangent at a specified point, etc.), and integral (area, volume, etc.). This is a powerful modelling technique as it allows changes to be made both in the initial design phase and in the optimization phase. Harry and Abt in 1998 [10] present a modelling process for a bare hull. The process was divided in three consecutive steps, the first is to parametric design of basic curves, then define design sections derived from the basic curves, and lastly generate the surface. There are 12 basic B-splines curves. The parametrization of these curves is made by 13 form parameters. Zhang et al. [11] presented a method based in Harries work to optimize the hull's hydrodynamics. With the emergence of fully parametric approaches, hydrodynamic optimization has become a time consuming process as they are done in different languages, which creates a bottleneck in the hull shape development, as stated in [12]. Because of these difficulties the authors of the paper presented a Computer Aided Engineering (CAE) software called FRIENDSHIP-Framework, now called CAESES. Over the years the CAESES platform was used to develop parametric procedures. In 2016 Sanches [13] presented an fully parametric modeller for merchant ships. The hull geometry was defined by 9 geometric curves and seven property distributions curves. In 2022 Feng et al. [14, 15] develop a parametric procedure applied to container ships. The hull shape was developed with a total of 37 parameters. Bole in [16] proposed a method to combine form parameter design and conventional modelling. This concept is called IntelliHull and is implemented in PolyCad.

With the development of commercial software capable of creating parametric definitions, there has been the introduction of new parametric modellers. Ginnis et al. [17] presented a parametric procedure implemented in CATIA software. The parametric modeller uses 30 parameters. Katsoullis, Wang and Kaklis [18] developed a T-splines based parametric modeller called TshipPM to generate complex ship forms. In 2021 Ingrassia et al. [19] presented a design tool that is able to guide the designer in creating an hull form mostly based on shape coefficients and non-dimensional ratios. This tool is developed in Visual Basic for Application (VBA) for Excel. The visual programming tool Grasshooper, a Rhinoceros 3D plug-in is also used to develop parametric methods. In 2020 Pérez-Arribas and Calderon-Sanchez [20] developed a parametric methodology for Small Waterplane Area Twin Hull (SWATH). In the next year Romanelli [21] developed a parametric modeller to small crafts. This parametric modeller is capable of developed a planning hulls and displacement hulls. Earlier this year Zhou et al. [22] created a software that uses parametric modelling process, that uses NURBS to define the hull geometry.

The objective of this work is to develop a fully parametric procedure to produce wireframe models that represent the hull shapes of merchant ships to be used in the basic design. This parametric procedure must be able to reproduce the most used forms of merchant ships with the input of parameters that describe it. It must also be able to create connections between the curves that define geometric and properties characteristics of ships, with the ability to make changes in the input parameters without losing feasible shapes of the hull. This is an important objective as it makes the optimization procedure faster and easier, which is very important given the need to reduce greenhouse gas emissions.

2. Implementation

The parametric hull generation method is implemented in Grasshopper a visual programming tool available as a plug-in of Rhinoceros 3D CAD software. With the information gathered from the study of the most common shapes of merchant ships, the curves were divided into two types: geometric curves that represent in a simplified way the shape of the hull, and property variation curves that control properties such as the area and angles of a cross section. The curves are created with Non-Uniform Rational B-Spline (NURBS).

2.1. Main Hull Particulars

The hull main particulars are all the dimensions and coefficients that have impact in every aspect of the hull from the location of control points for each geometric curve to hull hydrostatics. The considered dimensions and coefficients were: length between perpendiculars ($\mathrm{L_{pp}}$), breadth (B), depth (D), draught (T), longitudinal centre of buoyancy (LCB), block coefficient ($\mathrm{C_B}$), midship section coefficient ($\mathrm{C_M}$), waterline coefficient ($\mathrm{C_{WP}}$), length of cylindrical mid body ($\mathrm{L_C}$). An important parameter that is not used as an input is the ship's displacement (∇), The information of this parameter is taken from the block coefficient by the following formula.

2.2. Geometric Curves

By analysing the shape of the ship, it was possible to identify eight geometric curves that defined it. These curves are: bow and stern contour, midship section, flat of bottom (FOB), flat of side (FOS), transom, design waterline (DWL) and deck waterline.

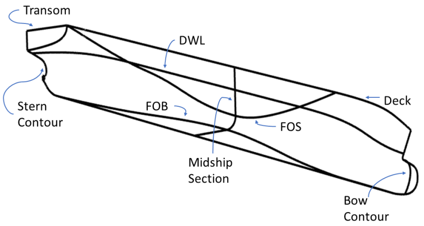


Figure 1: Bow Without Bulb Parameters

2.2.1 Bow Contour

As identified in the previous chapter, the bow contour was divided into two different configurations: bow without and with bulb. In the model it is necessary to specify what type of bow the ship has,because the number of input parameters depends on the chosen bow configuration.

To define a bow without bulb five parameters are needed, the distance between the forward perpendicular and the first and last point (X_fp and X_Deck), the vertical coordinate of the point located at the forward perpendicular (Z_fp) and two angles (α_{deck_ent}, α_{deck_run}) and the length of stem straight section (L_Stem).

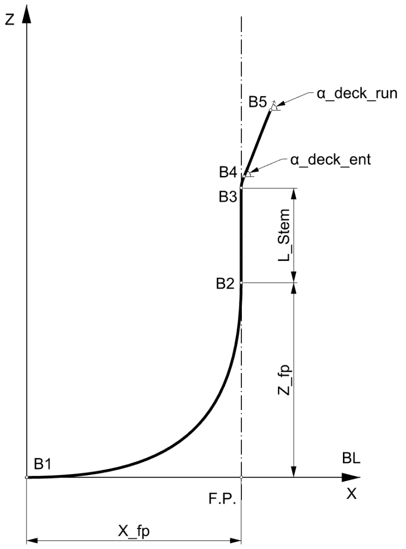


Figure 2: Bow Without Bulb Parameters

Nowadays, most merchant ships have a bulbous bow due to several benefits such as reducing the ship's and wave resistance, consequently they also have an impact in the ship's economy because less power is needed to make the ship move at a certain speed. Bulbs can be divided into two types, depending on their shape: integrated or added bulbs. In order to create the longitudinal contour it was necessary seven parameters. Two parameters was used to define the tip of the bulb (X_TipBulb and Z_TipBulb), bulb height (H_Bulb), the lateral parameter of Kracht (C_ABL), and the height of the first point (Z_fp) and tangent angles at initial and end point of the contour (α_{fp}, α_BulbUpper).

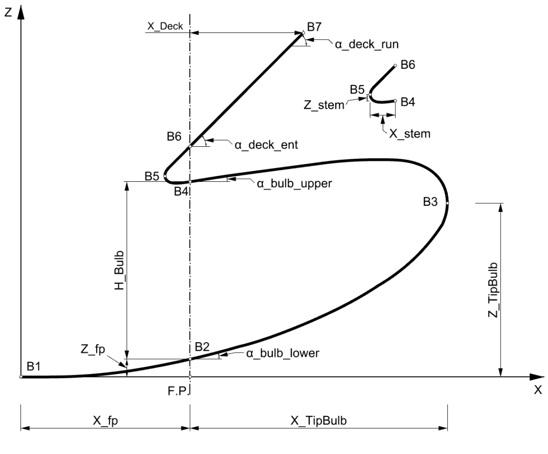


Figure 3: Integrated Bulb Parameters

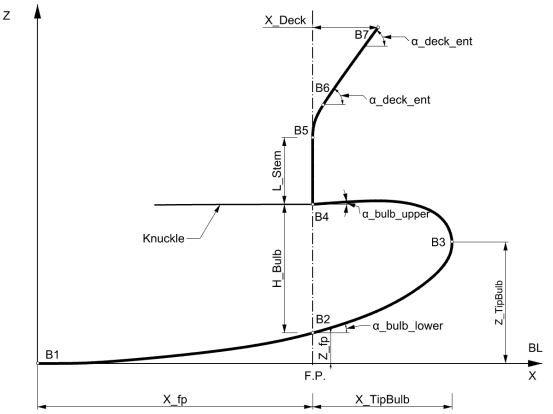


Figure 4: Addition Bulb Parameters

The cross section of the bulb is defined by the maximum breadth point defined by two parameters (B_Bulb, Z_CG), the entrance and run angles (α_Bulb_t_l, α_Bulb_t_u) and the cross-section parameter of Kracht (C_ABT).

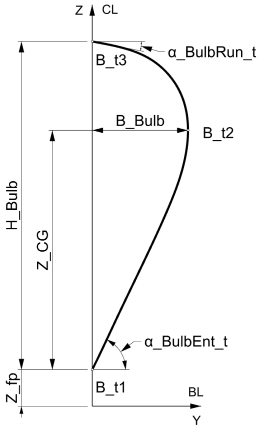


Figure 5: Bulb Transversal Section Parameters

2.2.2 Stern Contour

The stern contour is defined by the position and the height of the transom panel (X_Transom, H_Transom), the angle it makes with z axis (α_Transom_d), the angle of the longitudinal contour with the lower point of the straight segment (α_Transom_b), the propeller clearance point (X_Clearance, Z_Clearance) and the end point (X_SternEnd). When there is an stern bulb, the parameters used to define a bulb less stern are not sufficient. It was necessary to have information about the x and z coordinates of the propeller boss (X_Boss, Z_Boss), the radius of the boss (R_Boss) and the angles of entrance and run in the propeller boss (α_Boss_ent, α_Boss_run).

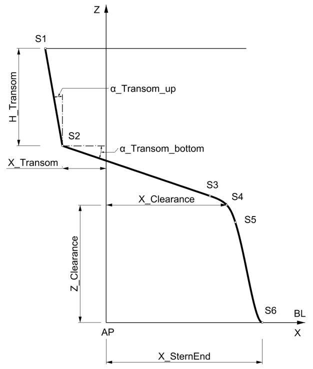


Figure 6: Stern Contour Without Bulb Parameters

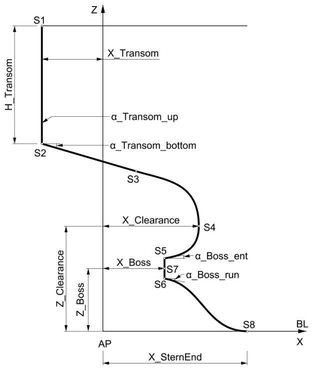


Figure 7: Stern Contour With Bulb Parameters

2.2.3 Flat of Side (FOS)

To define the FOS it is necessary the position of the first point (X_FOS, H_Aft_FOS), the length of FOS (L_FOS), the intersection points between FOS and design waterline (DWL), the angle at the start and end point of the FOS and at the intersection points (α_Aft_FoS, α_Fwd_FoS, α_Aft_wtl_FoS, α_Fwd_wtl_FoS).

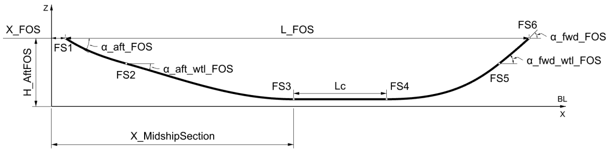


Figure 8: FOS Parameters

In some ships the FOS curve begins at the transom panel (X_FOS = X_Transom). When this happens the first point of the FOS is the maximum breadth point of transom and creates a linear segment.

2.2.4 Midship Section

The midship section is located at the beginning of the cylindrical mid body (X_MidshipSection). To define the midship section it is necessary a minimum of four points with a maximum of seven points, this number depends on the complexity of midship section. The bilge is developed with a NURBS curve.

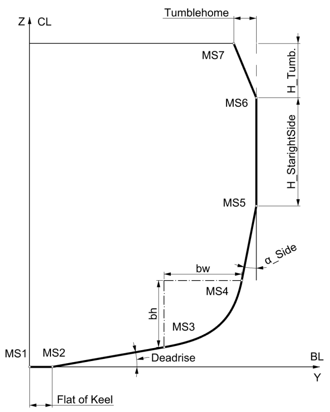


Figure 9: Midship Section Parameters

In figure 9 all the parameters used to define a complex midship section are presented, but in most merchant ships the midship section is very simple, as it is composed of a bottom line, a curve and a lateral line. This causes many of the parameters presented above to be equal to zero, e.g. deadrise, tumblehome, etc. with the exception of the bilge parameters.

2.2.5 Transom

The transom panel is defined with seven parameters. The number of curves used to describe the transom changes depending on the shape of the transom (Normal or U shape). If it is a U shape it needs four curves (one is a NURBS and three are lines), if it is normal shape it only needs two curves (one NURBS and one line). If the transom presents a normal shape the parameters Transom_bw and Transom_bh became equal to zero.

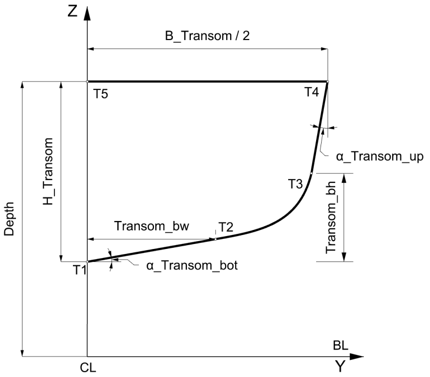


Figure 10: Transom Parameters

2.2.6 Flat of Bottom (FOB)

The FOB coincides with the lowest waterline (z=0). This curve is composed of two curves, one at the aft body and one at the fore body, and one or two linear segments, one is the line that connects the start point (X_FOB) to the end of the FOB and if there is a cylindrical body there is another line. The parameters used to define the FOB curve were: the longitudinal position of the first point (X_FOB), the length of FOB (L_FOB), length of cylindrical body (L_c), midship section position (X_MidshipSection) and the entrance and run angles (α_aft_FoB, α_run_FoB)

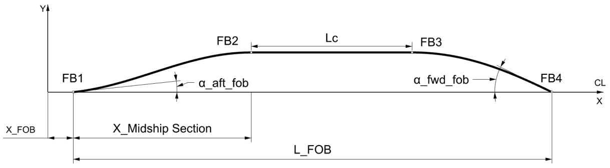


Figure 11: FOB Parameters

2.2.7 Design Waterline (DWL)

This DWL curve is composed by three different parts: aft part, mid part and forward part. The aft part can be defined by one NURBS curve or one line and one NURBS curve, the second option happen when there is an intersection with the transom panel. A parameter was created to define the longitudinal position of the first point of the stern curve called X_DWL, with its end point being the first point of intersection between FOS and DWL. The mid part is related with the parallel mid body because this line is the connection between the two points related with the intersection between the DWL and FOS. The forward part is defined by a NURBS curve starting at the end point of the middle part and ending at the forward perpendicular. To complete the definition of the DWL curve, it was necessary to create two more parameters related to the entrance and run angle (α_Aft_DWL, α_Fwd_DWL). The area under the DWL curve is an important aspect as it is related to the water plane coefficient. Because of this, two more parameters were created that individually control the area under the DWL forward and aft curve (t_fullness_aft, t_fullness_fwd)

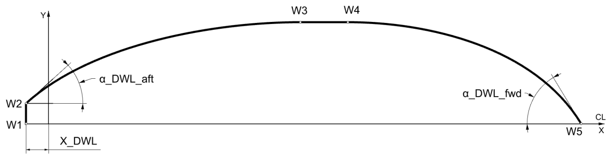


Figure 12: DWL Parameters

2.2.8 Deck Waterline

The deck waterline curve can be divided into three segments, the aft, middle and forward curve. The aft curve can sometimes blend in with the middle part as it is related to the transom, and in cases where the transom width is equal to the ship's breadth, the aft curve becomes a line. If this is not the case, it is important to study the range of values for the entrance angle of the aft curve, for that a parameter called α_Deck_aft was created. The mid curve of the deck waterline is always a line in direct relation to the FOS curve. The parameter Lc is responsible for defining the length of the line. The forward curve is created between the furthest point of the FOS and the end point of the deck waterline that coincides with the highest point of the bow contour.

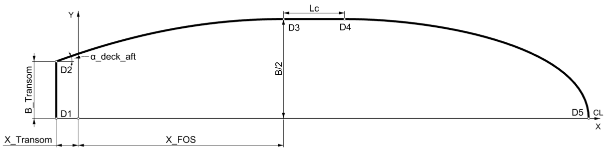


Figure 13: Deck Waterline Parameters

2.3. Property Variation Curves

The property variation curves described the variation of the geometric properties along the ship, either longitudinally or vertically. Three property variation curves were identified, namely: sectional area curve (SAC), angles variation of sections and waterlines.

2.3.1 Sectional Area Curve (SAC)

The SAC curve gives an area relative to a specific longitudinal position, and allows to change the distribution of underwater volume of the ship. A parameter with great influence on underwater volume distribution is the longitudinal centre of buoyancy (LCB). This curve is created with three NURBS curves and with one line that represents the length of parallel mid body. The parameter A_TransUW is different than zero when the design waterline intersects with the transom panel but if the transom is above the water then the parameter is zero. When A_TransUW $\neq 0$ its value is calculated by dividing the transom in two (a part underwater and part above water) and the area of the submerged part is calculated. The parameters A_MS and A_Bulb_T are related to the parameters of the midship section curve and bulb cross-section curve, respectively. The numerical value for A_Bulb_T is related to the cross section parameter (C_ABT). When A_Bulb_T is equal to zero it means that there is no bulbous bow and the end point of the SAC is located at the forward perpendicular.

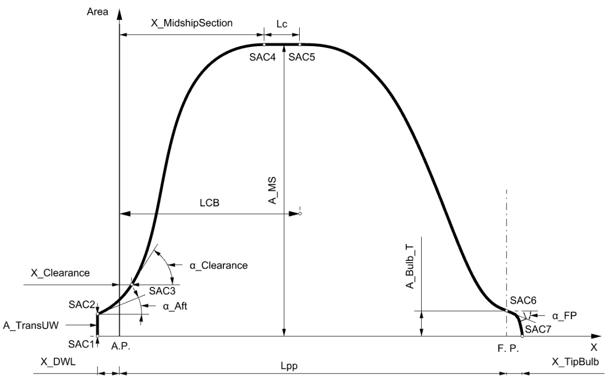


Figure 14: SAC Parameters

2.3.2 Longitudinal Variation of Section Angles

This curve shows how the section angles evolve longitudinally, the angles are measured at 3 points: at the section exit, at the DWL and on deck. These three angles are shown in figure 15.

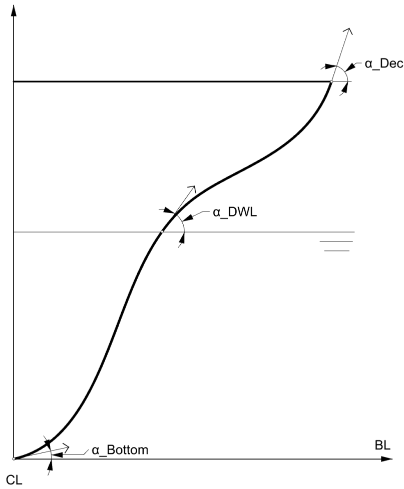


Figure 15: Angles of sections

Three curves are needed to define all the angles necessary to build a cross section at a given longitudinal position. In order to be able to create the curves, it is first necessary to define the domain for each of the three curves. For the curve that defines the entry angle of the sections (α_Bottom) the domain was as follows: [X_Transom $\leq$ X $\leq$ X_Clearance] $\bigcup$ [X_Clearance < X $\leq$ X_FOB_Aft] $\bigcup$ [X_FOB_Aft < X < X_FOB_Fwd] $\bigcup$ [X_FOB_Fwd $\leq$ X $\leq$ X_Lpp]. For the curve that defines the run angle of the part of the underwater section (α_DWL) the domain was as follows: [X_Transom $\leq$ X $\leq$ X_Clearance] $\bigcup$ [X_Clearance < X $\leq$ X_DWL_Aft] $\bigcup$ [X_DWL_Aft < X < X_DWL_Fwd] $\bigcup$ [X_DWL_Fwd $\leq$ X $\leq$ X_Lpp]. Finally, the domain of the angle variation curve of the section on the deck waterline is: [X_Transom $\leq$ X $\leq$ X_Clearance] $\bigcup$ [X_Clearance < X $\leq$ X_FOS_Aft]

$\bigcup$ [X_FOS_Aft < X < X_FOS_Fwd] $\bigcup$ [X_FOS_Fwd ≤ X ≤ X_Deck]. There are two assumptions made, one is that between the FOB length the angle is always 0 degree and the other is that the angle in the FOS region is always 90 degree. If there is a stern bulb or a bulbous bow, two separate curves are created to define the entry and exit angles of the sections. The domain for the stern bulb is as follows: [X_Boss < X < X_Clearance]. For the bulbous bow the domain is as follows: [X_Lpp < X < X_BulbTip]. With the domain and distribution defined for the three curves, it is possible in each domain to extract information from one hundred points to create a curve in Rhino associated with that domain.

2.3.3 Vertical Variation of Waterlines Angles

For the waterlines, two curves were created to represent the vertical variation of angles. The water lines were divided into two regions: aft and forward regions. The forward region has two domains as follow: [0 < Z < T] $\bigcup$ [T < Z < D]. The aft region when there is a stern bulb has 4 domains as follow: [0 < Z < $Z\_Boss - R\_Boss$] $\bigcup$ [$Z\_Boss - R\_Boss$ ≤ Z ≤ $Z\_Boss + R\_Boss$] $\bigcup$ [$Z\_Boss + R\_Boss$ < Z ≤ $D - H\_Transom$] $\bigcup$ [$D - H\_Transom$ < Z < D]. It is assumed that for the domain [$Z\_Boss - R\_Boss$ ≤ Z ≤ $Z\_Boss + R\_Boss$] the angle is always 0 degree. When there isn't a presence of a stern bulb only two domains are necessary, namely: [0 < Z < $D - H\_Transom$] $\bigcup$ [$D - H\_Transom$ ≤ Z < D].

2.4. Wireframe Model

A wireframe of a ship is made up of: sections, waterlines and buttocks. These curves result from the intersection of the YZ, XY and XZ planes, respectively, with the geometric curves that define the basic shape of the ship.

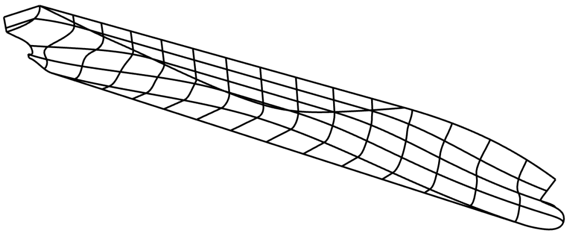


Figure 16: Example of a ship wireframe model

To create a section it is necessary to discover its crossing points in a longitudinal position. This longitudinal position must be between the limits of the ship's hull, if this limit is not respected, it is not possible to create the section. To find these crossing points, an intersection is made between a YZ plane, the geometric curves and two auxiliary waterlines. These auxiliary curves are created at the height of the propeller clearance (z = Z_Clearance) and the height of the propeller boss (z = Z_Boss). The shape of these curves depends on whether the section is U or V shaped. Because of this it is possible to define the entrance and run angle for each curve. The point information is stored in a list. This list is then divided into two, one with the points under water and the other with the points above the water. The division is done by comparing the Z value of each crossing point with the draft value. When this division is done it is possible to create the section also dividing it in the part below and above the DWL. In addition to the crossing points, the angles represented in the figure 15 are also necessary. When the section is created the underwater area is compared to the area designated in the SAC for the same longitudinal position. If there is an error greater than 3%, the curve is adjusted until the condition no longer exists. The process described above is for creating a section but the model is also prepared to give a specific number of sections. The method is the same only that waypoint information is stored in a data tree, with the tree having n branches where n is the number of desired sections. The process for obtaining one or a certain number of waterlines is the same as the process for sections, with the difference that instead of intersecting the geometric curves with a YZ plane, it intersects with an XY plane, and the angles used come from the vertical variation of angles curves. From the three curves presented in the wireframe model the buttocks are the least important, as they have no real importance in the hydrodynamics or other properties of the ship, with the longitudinal contour and FOS being the only relevant buttocks, because of this only this two curves are presented in the wireframe.

3. Validation

To validate the parametric model, a graphical and numerical validation was chosen. The graphical validation was performed by creating a body plan with five sections in the aft and forward body, where the parametric sections were superimposed on the real sections. If the ship has a stern bulb, one section is added to the body plan and if there is a bulbous bow, two sections are added. Numerical validation was performed by obtaining some hydrostatic properties of the parametric model and comparing them with the real values. The hydrostatic characteristics compared were: displacement (∇), Cb, Cm, Cwp, prismatic coefficient (Cp), LCB, buoyancy centre ordinate (KB), transverse metacentric radius (BMt), transverse metacentric height (KMt) and transverse moment of inertia (Ixx). The ship's displacement results from the measurement of the area under the SAC curve with the area information of forty sections. The error used to compare the results between model and real ship was the relative error (equation 1).The validation was carried out for five ships with a bulk carrier, oil tanker and Ro-Ro, two container ships and each one of them presenting differences in characteristics between them.

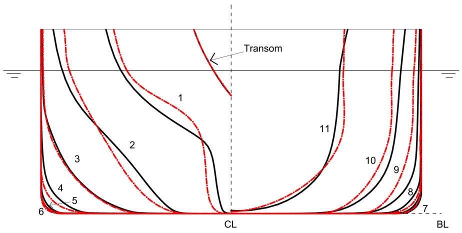
$$RelativeError = \left| \frac{Model - Real}{Real} \right| * 100 \qquad (1)$$

The numerical validation (Table 1) show good results for hydrostatics, with most results being between zero and four percent. Usually the biggest error presented was related to the KB, being around seven and eight percent. The ship with the best hydrostatic results was the bulk carrier, which exhibits errors between zero and two percent with only two hydrodynamic characteristics passing very slightly over two percent. The errors related to the ship equilibrium are usually larger by one or two percent, this is more visible on ships where there are some differences between the area of the parametric and real sections.

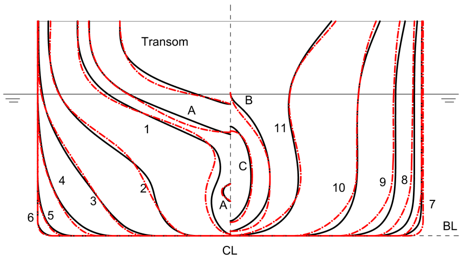
Table 1: Hydrostatic Results

Hydrostatics	Relative Error Results				
	VLCC	JBC	Ro-Ro	KCS	Colombo
Displacement, t	0,11%	0,00%	1,54%	1,04%	1,85%
Cb, [-]	0,16%	1,81%	1,52%	0,15%	1,84%
Cm, [-]	0,10%	0,00%	0,93%	0,41%	0,24%
Cwp, [-]	0,89%	1,21%	2,51%	1,10%	0,39%
Cp, [-]	0,50%	1,40%	0,58%	2,62%	1,61%
LCB, [m]	0,52%	0,16%	0,56%	0,40%	1,45%
KB, [m]	3,31%	2,13%	8,53%	7,72%	7,00%
Ixx	3,67%	2,19%	3,29%	2,75%	1,27%
BMt, [m]	1,38%	0,25%	1,80%	1,72%	0,58%
KMt, [m]	2,29%	0,88%	5,21%	4,09%	2,12%

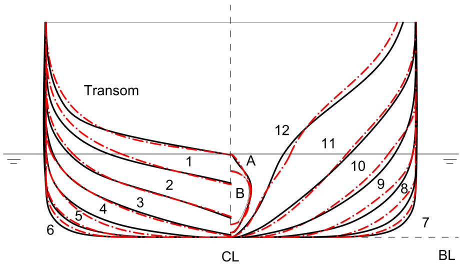
The graphical results (Figure 17) showed that the parametric sections presented good shape despite some differences in areas, being more noticeable in the sections closer to midship. This indicates that the SAC parametrization has some limitations, as it is not capable of reproducing precise areas in the regions closest to the beginning and end of the cylindrical mid body. The ships with the best results were the KCS (Figure 17(d)) and the Ro-Ro (Figure 17(c)), with the worst result being the tanker. The tanker (Figure 17(a)) presents the worst result because in addition of the problem with the SAC parametrization, also presents a noticeable variation in the y coordinates of the points located at the DWL. This happens because the parametrized DWL in this case is not able to reproduce with quality the real DWL curve, despite presenting good results for coefficient C_{WP}.



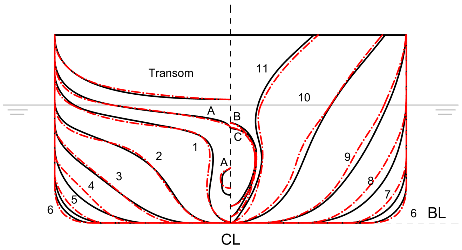
(a) Tanker - VLCC



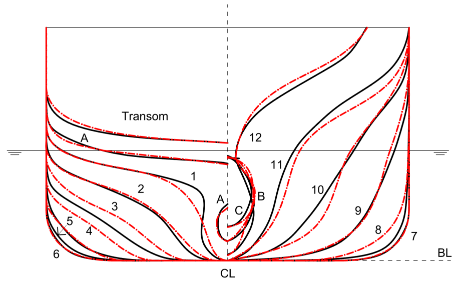
(b) Bulk Carrier - JBC



(c) Ro-Ro



(d) Containter - KCS



(e) Container - VLCC Colombo

Figure 17: Comparative body plan of the real hull (black continuos line) and the parametric hull (red dash dot line)

4. Conclusions and Future Work

4.1. Conclusions

In this thesis a wireframe procedure was developed, as it can provide all the curve information that is needed in the initial phases of the ship design. The curves were classified in two types: geometric curves and property variation curves. Eight geometric curves were identified: bow and stern contours, midship section, FOB, FOS, transom, DWL and deck waterline. Three property distribution curves were identified: SAC, longitudinal variation of section angles and vertical variation of waterline angles.

The procedure was implemented in a visual programming tool called Grasshopper, a plug-in of Rhinoceros 3D. The procedure starts with the input of eighty parameters, or less, depending on the complexity of the hull shape. With this data a number of points are created, then the geometric and property variation curves, and finally the wireframe model. The final wireframe model produced can be detailed up to fifty sections and up to twenty waterlines.

The numerical validation was the comparison of some hydrostatics properties values and present acceptable results. The graphical validation was made by creating a body plan where the parametric sections were superimposed over the real sections, with the results showing acceptable shapes but with some differences between the areas of the sections. Although, the cross sections produced may present some local discrepancies with the area from SAC, they present feasible shapes and lead to good hydrostatics results. Therefore, it was considered that the parametric procedure developed is capable of being used in the concept design phase, with the objective of this thesis being fulfilled.

The major achievements of this work, was the development of a fully parametric procedure, that is able to create a hull shape with the input of parameters. In addition, it has flexibility to do local shape adjustments allowing the designer the freedom to easily explore different shape features.

4.2. Future Work

The present parametric model have some limitations in aspects that are important for merchant ships shapes and the usability of the model. At the moment the parametric procedure is able to create a knuckle only when there is an addition bulb, but the merchant ships can have more knuckles in other regions, for example when the transom panel presents a V shape section. In the future it would be interesting the possibility to create a knuckle at any desired location. Another limitation of the model is the capability to only reproduce stern contour with a single propeller. Another future work can be to develop parameters to reproduce ships with a twin-propeller. There are two more types of bulb that are being used in certain types of ships instead of the traditional bulbs that the parametric model is able to create. These types are the X-bow and the axe-bow and it would be interesting if the model was able to create them. As identified in the validation of the parametric procedure, the parametrization of the SAC curve has some limitations, so in a later version of this parametric method it would be interesting to create more parameters that would create a more accurate SAC. For the parametric model to be used in more advanced stages of the ship design procedure, it is necessary to developed a quality surface model. To fulfil this objective, it is advisable to create parameters related to the surface to ensure that has good fairness. To improve the usability of the model, it would be advantageous to develop a user interface that allows configuring and changing the input parameters in the Rhinoceros 3D software instead of having to look for the parameter slider in Grasshopper which can be a complex task if the person using the parametric model is not familiar with the location of it.

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