# TÉCNICO LISBOA

# Parametric modelling of hulls for small crafts

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Thesis to obtain the Master of Science Degree in

## Naval Architecture and Ocean Engineering

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# ABSTRACT:

The goal of the work is to develop three parametric models of ship hulls. More specifically, the models developed are a planning hull of a motorboat, a displacement hull of a motorboat, and a displacement hull of a sailboat. The first part of the study dealt with an analysis of the characteristics that govern the construction of the shapes of these hull typologies. In addition, the "isocurves" that allow the 3D modelling of the three hulls were evaluated and analysed; thus, different types of curves and control points were found with which the end user can change the shape of the hull surface. Using the Rhinoceros 3D tool, the different methods of surface generation with the selected curves were studied and the most efficient was chosen, i.e., the one that can best represent such surfaces. Then the main parameters were found, such as angles, lengths and tangents, and their admissible values.

In the second part of the work, it was developed the code that allows the automatic creation of 3D models of ship hulls in the Rhinoceros 3D CAD system, using a visual parametric programming module, Grasshopper, software integrated in Rhinoceros 3D in the form of a plug-in. In addition to the generated surface models, the code also produces elements for the analysis of the hull characteristics such as simplified hydrostatics, the Lines Plane drawing, and the longitudinal variation curve of the cross-sectional areas (Sectional Area Curve).

Once the desired shape is obtained, the hulls got compared with existing vessel models to further validate the final surfaces' accuracy. Moreover, the code has been implemented with the addition of new calculations, such as the Lines Plan, the Offset Table, and the main dimensions of the object.

**Keywords**

Parametric 3D modelling, displacement hull, planning hull, sailing yacht, motor yacht, visual coding, Rhinoceros 3D, Grasshopper.

# RESUMO:

O objetivo do trabalho consiste em desenvolver três modelos paramétricos de cascos de embarcações. Mais especificamente, os modelos elaborados são de um casco planante de uma embarcação a motor, de um casco de deslocamento de uma embarcação a motor e de um casco deslocamento de um veleiro. A primeira parte do estudo tratou duma análise das caraterísticas que governam a construção das formas destas tipologias de cascos. Além, foram avaliadas e analisadas as "isocurvas" que permitem a modelação 3D dos três cascos; foram assim encontradas diferentes tipologias de curvas e de pontos de controlo com os quais o utilizador final pode alterar a forma da superfície do casco. Utilizando a ferramenta Rhinoceros 3D, foram estudados os diferentes métodos de geração de superfície com as curvas selecionadas e foi escolhido o mais eficiente, o seja, o que melhor consegue representar tais superfícies. Depois, foram encontrados os principais parâmetros, tais como ângulos, comprimentos e tangentes, e os seus valores admissíveis.

Na segunda parte do trabalho foi desenvolvido o código que permite a criação automática de modelos 3D de cascos de embarcações no sistema de CAD Rhinoceros 3D, usando um módulo de programação paramétrica visual, o Grasshopper, software integrado no Rhinoceros 3D sob a forma de um plug-in. Em complemento dos modelos de superfícies gerados, o código desenvolvido produz também elementos para a análise das características do casco tais como umas hidrostáticas simplificadas , o desenho do Plano Geométrico,  e ainda a curva de variação longitudinal das áreas da secção transversal (*Sectional Area Curve*).

Uma vez obtida a forma desejada, os cascos foram comparados com modelos de embarcações existentes para validar ainda mais a precisão das superfícies finais. Além disso, o código foi implementado com a adição de novos cálculos, tais como o Plano de Linhas, a Tabela de Compensação, e as principais dimensões do objecto.

**Palavras-chave:**

Modelação paramétrica 3D, casco planante, carena de deslocamento, veleiro, embarcação a motor, programação visual, Rhinoceros 3D, Grasshopper.

## Declaração

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e de Boas Práticas da Universidade de Lisboa.

## Declaration

I declare that this document is an original work of my own authorship, and it fulfils all the requirements of the Code of the University of Lisbon.

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# SYMBOLOGY

| | |
|---|---|
| $L_{OA}$ | Length Over All |
| $L_{WL}$ | Length Water Line |
| $B_{MAX}$ | Maximum beam of the hull |
| $B_{WL}$ | Beam at the water line |
| $T$ | Design draft |
| $D$ | Vertical distance from the deepest point of the keel to the sheer line |
| $FB$ | Freeboard, vertical distance between the sheer line and the water plane |
| $\nabla$ | Displacement in volume |
| $\Delta$ | Displacement |
| $LCB$ | Longitudinal position of the centre of buoyancy |
| $LCF$ | Longitudinal position of the centre of geometry of the waterplane area |
| $WL$ | Waterline |
| $CL$ | Centreline plane |
| $Cw$ | Waterplane area coefficient |
| $Cb$ | Prismatic coefficient |
| $Cp$ | Cross section coefficient |

# ACRONYMS

| | |
|---|---|
| **CAD** | Computer Aided Design |
| **CFD** | Computational Fluid Dynamics |
| **CL** | Centre Line |
| **CPC** | Central Plane Curve |
| **DWL** | Design Waterline |
| **FOB** | Flat Of Bottom curve |
| **FOS** | Flat Of Side curve |
| **GT** | Gross Ton |
| **LCF** | Longitudinal Centre of Flotation |
| **LNG** | Liquefied Natural Gas |
| **LPG** | Liquefied Petroleum Gas |
| **SAC** | Sectional Area Curve |
| **SQP** | Sequential Quadratic Programming |
| **VMS** | Curve of Vertical Moments of Sectional area |
| **LMS** | Curve of Lateral Moments of Sectional area |

# 1 INTRODUCTION

## 1.1 Background and Motivation

Shipbuilding is an old market that during the years proved to be open and highly competitive. Until the 1850s the business of ship construction was almost completely held by the Great Britain. The shipyards of this country kept the supremacy over the world until the World War II. In the 1950s the Japan start playing an important role over the global market. For some years Europe and Japan controlled 90% of the new constructions orderbook. The Japanese shipyards gradually managed to get a leadership position thanks to a rapid economic growth and to a well-coordinated state shipping and shipbuilding program. The dominance of this nation lasted three decades, until the 1990s. In these years South Korea focused on the implementation of new shipyards in number and size. Japan didn't manage to improve enough the technology of new production management methodologies. South Korea put its efforts on the construction of large tankers, ultra large containerships, LNG, LPG and so on. The world's demand was asking for bigger and bigger vessels, which brought the country to lead the global market. South Korea led the economy thanks to an industrial expansion strategy focused on the shipbuilding. In the early 2000s the cost of human resources got higher, and the raw materials began to run out. With insufficient quantities of domestic steel and rising prices of import market South Korea lost its supremacy, while keeping good competitiveness. A new world power took the leadership in 2010, China. With strong governmental investments, the lowest labour costs, and sophisticated technologies, nowadays China, continues to increase its productivity (Mickeviciene, 2011).
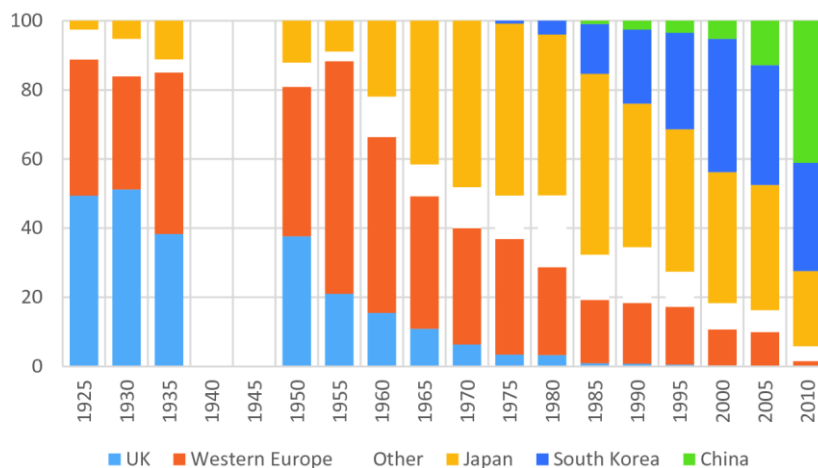


*Figure 1-1: Shipbuilding world trend (Tenoldl, 2018).*

In Figure 1-1 it can be seen that the shipbuilding world market has moved from Western Europe countries to Asia in the last century. Europe managed to keep a little slice of the business thanks to its strategic specialization as a niche player. The cruise ship market is still held by a few Europeans shipyards, even if some countries, such as S. Korea, started building this kind of vessels.
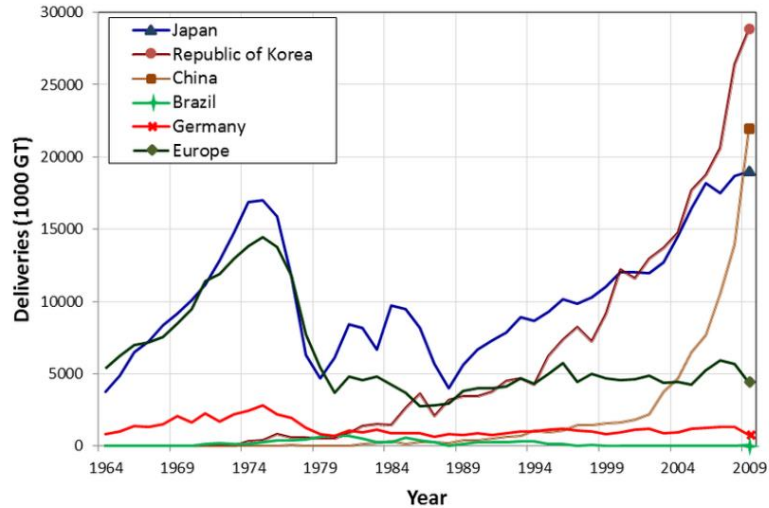
*Figure 1-2: World shipbuilding deliveries (Manoel and Weiss, 2018)*

In Figure 1-2 it is represented the big fall of western countries and Japan in front of the rise of China and S. Korea. In addition, there are some other countries that in the last decade started to push on the shipbuilding to improve their economy, among them is it possible to find Philippines, India, and Vietnam. In 2008, these countries, called the new players, took about 6% of new orders in the global market, in front of the 4.9% of the European countries.
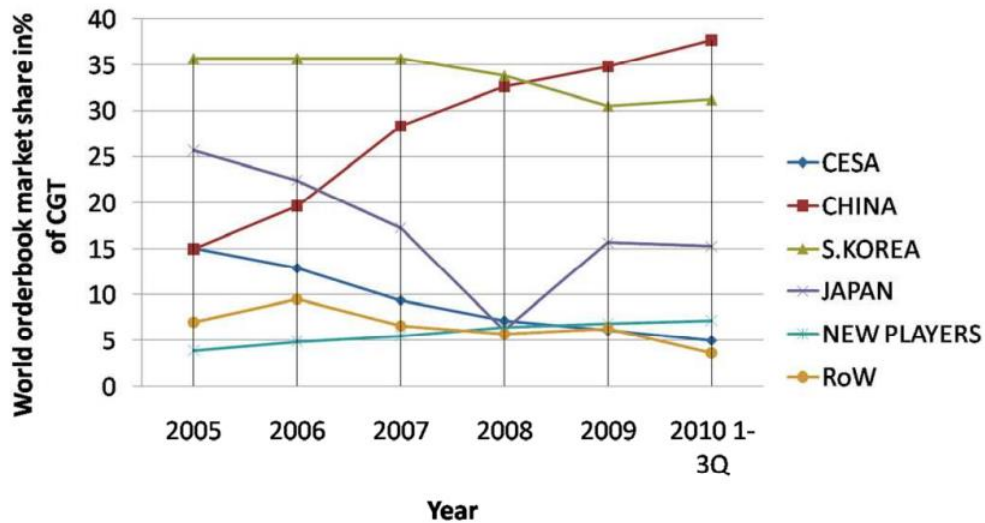


*Figure 1-3: World orderbook market (Mickeviciene, 2011)*

The shipbuilding market moved away from the European countries, but the leisure boats market is still strong and well settled in the east of the world. These boats are intended for recreation, pleasure, and tourism activity. Moreover, the market also includes many boats for other activities such as water sports, sailing, fishing and racing. A sector of the market includes the luxury yachts. Some of the strongest companies of the market are Brunswick (USA), Groupe Beneteau (France), Azimut Benetti (Italy), Sunseeker International Limited (UK), Ranger boats (USA), Tracker Boats (USA), Lund Boats (USA), Marine Product Corporation (USA), Bennington Marine LLC (USA), Hobie Cat Company (USA), Ferretti Group (Italy), Bavaria Yachtbau (Germany), Godfrey Pontoon Group (USA), Catalina Yachts (USA), and Mahindra Odyssea (India).

North America is the biggest market for recreational boats, and the market kept increasing from 2010 to 2020. Thanks to its developed infrastructures, extended coastline and rich population, more people participate in marine activities every year. The U.S. market is estimated at US$ 15.1 Billion in the 2021 (https://www.strategyr.com/market-report-leisure-boats-forecasts-global-industry-analysts-inc.asp).

The second biggest market is the European one. Italy, UK, France, and Germany are some of the biggest players in the recreational boats business. In these countries, it is expected a growth of the luxury yacht demand (https://www.persistencemarketresearch.com/market-research/recreational-boating-market.asp). The rise of the per capita income, the increase of the number of people, and the growing coastal and maritime tourism are the indicating factor of the future growth of this market. Moreover, it is expected to grow due to many advantages of these boats, like the low maintenance cost, the increase of marinas and deck areas along the coastal regions and more affordable engines. The rising economy of the western countries in the Asia Pacific Region is bringing people to the recreational boats market, which order crafts to Europe. China, the biggest western market is expected to reach a size of US$4.3 Billion in 2026 (https://www.strategyr.com/market-report-leisure-boats-forecasts-global-industry-analysts-inc.asp). The import demand from the developing nations to the European shipyards is growing day by day.
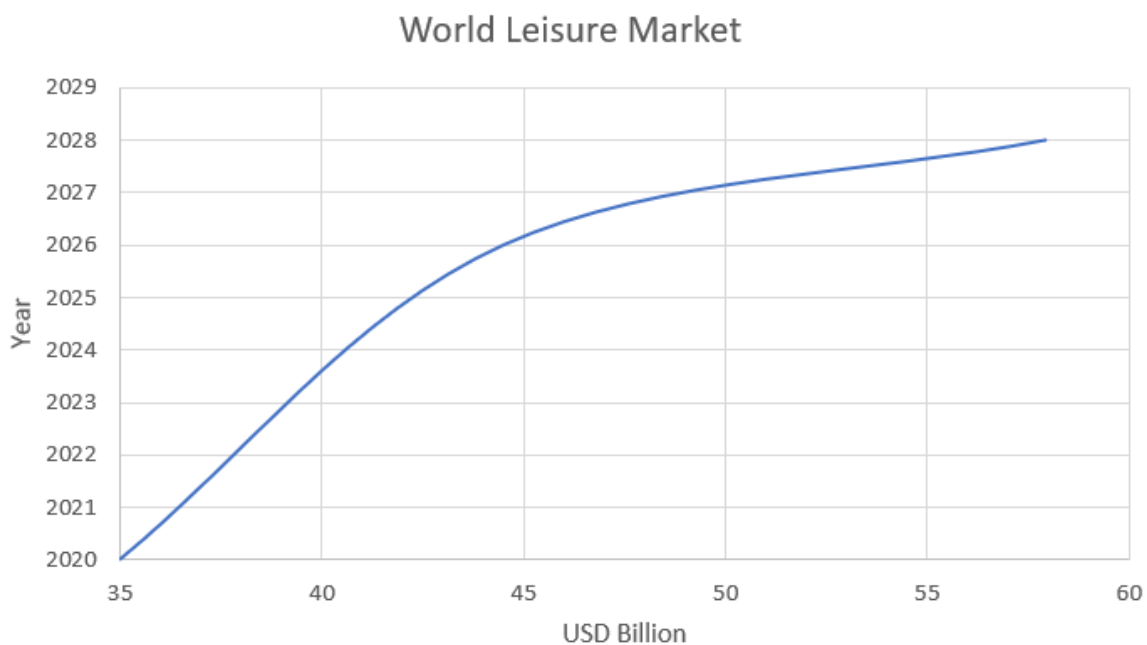


*Figure 1-4: Recreational boats market*

Engine powered boats are expected to be the future largest market and it is expected to reach a value of US$28.1 Billion in 2026. The global leisure boats market is estimated at US$ 35 Billion in the year 2020 and it is expected to reach the size of US$ 44.5 Billion in 2026 (https://www.strategyr.com/market-report-leisure-boats-forecasts-global-industry-analysts-inc.asp).

From the analysis carried out in the previous pages it is possible to deduct that the leisure boats of the European market will improve the economic power of the coastal states. This means that studies and research will be supported and encouraged by state and private companies. New technologies for building methods, less polluting engines and more efficient hull designs are the base for the growth of such a big market. This future prospect is an incentive for the work undertaken in the present thesis.

## 1.2 Objectives

The final objective of the work is the development of parametric procedures for the surface generation of different types of yacht hulls, namely a displacement hull of a sailing vessel, a displacement hull of a displacement motorboat and a planning hull of a motorboat. In order to avoid the additional complexity of developing a single script able to generate hulls with such different characteristics, it was decided to analyse each specific type of hull form and dedicate a discrete script to it.

The thesis is divided into different parts. First it is carried out the study of forms of the three typologies of hulls under consideration, the sailing yacht, the displacement motor yacht, and the planning motor yacht. The aim of the study is to identify the most common shape characteristics of the pleasure crafts on the market, their configurations and range of dimensions. For each kind of hull, first is created a number of curves, defined by sets of parameters. Next, these curves are used to generate the surfaces needed to model the hull. For each surface geometry it is adopted the generation algorithm that better fits the target shape.

The curves are the most important aspect of the 3D modelling procedure adopted. For this reason, in this stage the focus is applied to the description of these curves, with their dimensions and constraints. This study implied a first fought on the main parameters, such as angles and tangencies that could lead to a better modification control over the geometries. When enough information was collected it started the development of the 3D model with the use of Grasshopper (https://www.grasshopper3d.com/). Since for each hull different characteristics must be satisfied, the codes have been done with different methodologies for each single case.

After the hull shapes were considered satisfactory, some important calculations in naval architecture have been implemented, such as the main form coefficients, the metacentric heights, the drawing of the Lines Plan is produced and the Offset Table. The objective of these complimentary actions is to produce numeric and geometric data that can be used to evaluate the results produced. In this part of the work, it has been created the code for each yacht type, which is the final objective of the thesis. The possibility to generate a parametric hull without the need of coding or 3D modelling from zero every new project or every modification of an already existing one is a good save of time and money in the everyday life of a shipyard. Most of all in the first stages of the project in which the costumer asks for a preliminary project in a short period of time. The leisure boats are constructed in series, which is another good motivation to develop a grasshopper code that can help the designer to develop the shapes.

## 1.3 Structure of the Thesis

The organization of the thesis have been done dividing it into four chapters. Each chapter is divided into subchapters. The Chapter 1 is the introduction, in which it is carried on a study on the shipyards market. In this part of the work naval and leisure boats markets have been analysed. Moreover, in the introduction are discussed all the main goals and targets of the thesis. In this part it is given the main idea of the work. It is also explained why it is an important focus. In Chapter 2 it is analysed the state of art, in which concerns 3D parametric modelling of hulls. In Chapter 3 are analysed several hull forms of different sailing and motor yachts, covering displacement and planar hull types. After each analysis of hull form it is presented the methodology with which all the 3D models have been elaborated. It is explained step by step how to generate the yacht surfaces and it is made a comparison with an existing yacht to validate the precision of the 3D model done. Chapter 4 is the final chapter of the thesis. It contains the conclusions of the work and some ideas for future study on this subject.

# 2 LITERATURE REVIEW

## 2.1 Introduction

Hull form creation and fairing has been made by hand during many years. The Lines Plan drawing, and the Half Model were the main tools used by the designers to provide a valid representation of the ship and they could allow the engineers to undertake calculations and measurements to the full-size ship, such as displacement, coefficients, hydrodynamic estimation, and structural dimensioning. The Lines Plan and the Half Model have the objective to create the form of the hull and to give a representation of it. With the advance of the technology and the always increasing military and economic demand the traditional way have been overtaken by three-dimensional (3D) modelling, that become possible thanks to the computer.

The continuous development of the hardware and software allows nowadays the designers to develop a full model ship in 3D with the maximum accuracy (Bole, 1997). Onto the visual 3D models, it is possible, in a very reduced time, to carry out different calculations and verifications such as resistance and motion analysis. They can be evaluated hydrodynamic characteristic of a ship such as stability, resistance, and seakeeping, which are directly connected with the design of the hull shape (Bole,1997; Mancuso, 2004). Nonetheless the computer made achievable the optimization of the hydrodynamic properties of the hull. This process is very important to give a more precise and faster answer to the costumer request during the preliminary design project. The first stage of the project of a ship is a very important step to be competitive in the global market with which every company whether small or large must deal with. Furthermore, it brings to better results of the following calculations are based on the model (Sener, 2016).

The hull with all its appendages represents a difficult geometry to be modelled, so its fairing is a difficult task to carry out. In the years with the improving of the technologies this job is being solved constantly more efficiently, with improved final shapes and consistent saving of time. In addition to this, today it is possible to analyse the hull with various simulation methods, that permit to evaluate if the model corresponds to the required characteristics or passing through an optimization method, it is necessary to modify it. After the modification it is possible to run again the programs. This way it is carried on an iterative process until the goal is reached. One of these simulation methods, for instance, is the Computational Fluid Dynamics (Sener, 2016).

The first step of the project of a new hull is the shape design and all the following job is going to be depending on it, so to be able to execute a good first model the experts put a lot of effort in finding a way to facilitate this very important stage. In the recent years, the engineers investigated the possibility to elaborate the so-called Hull Equation, that should have been an algorithm that could grant the automatic hull shape of every kind of yacht. The hulls of all the kind of boats and ships are very different, for example we can just think about the distinct shapes of the rounded displacement sailboat hull and the edgy planning motorboat hull. Compute a common mathematical equation that includes all the possible shell shapes is until now a too hard challenge to bring off, because the geometry of the yacht shell depends on several parameters, which are commonly interrelated between them (Mancuso, 2004; Ingrassa et al, 2021). Up to few decades ago the creation of a formulation to shape a single kind of yacht form, for example a displacement hull was still very hard to obtain, for this reason most likely the main method to obtain a hull model design was by manual modification operated by the naval architect (Bole, 1997).

At the time being engineers work to create tools that can permit to form the shape of the hull surfaces. With the income of more and more sophisticated software that come in their help, they managed to pass from the construction of the yacht body made by templates, for instance squares, curves, splines, to full mathematical approaches. In these studies, the designers code sequence of instructions and formulas to

create a parametric hull generation that excludes the need of a skilled expert to develop the hull in the traditional way (Bole, 2019).

## 2.2    Parametric Modelling Typologies

During the last decades engineers studied different methods to develop a 3D parametric model, using different software and different approaches. Usually, the most used methodology is to study which are the curves that bring to the creation of the surfaces. Each hull present different characteristics that can be described by different constructing curves and different curve typologies. Each specific shape is controlled by its own parameters that the designer must identify. Depending on the parameters used to describe the model the parametric modelling typology take different denomination.

### 2.2.1    Modification of Hull Forms

One of the most common method to develop a hull in the ship building industry is to take an already existing hull form and change it. The hull to modify is selected with the closest characteristics as possible to the desired, so that it is easier to reach the requested dimensions and operation targets (Boiko, 2019). This kind of parametrization follows the same concept. In this method it is taken an already existing hull form and parametric features are applied to it. This way it is possible to obtain a new 3D model. The parametrization by transformation has very good points even if it is a less powerful mean than the full parametric generators. It is more generic, so it can be applied to all kind of hull forms. It can be used in many stages of the project of the ship and not only in the preliminary design. This kind of parametrization can be applied only to an area of the hull, in that case it is called local or partial parametrization. It also admits the use of more than one hull form that can be combined (Rodriguez and Fernandez-Jambrina, 2012). The designer creates a set of transformation functions, that are described by types of data like analytical data, surface data and distinct data, and applies it to the import model.

The best method to start a parametric transformation is to start from a distinct ship offset data. The offset data and the control points are directly used as parameters that directly act on the modification of the hull. The flexibility of moving on the three axes of the control points can represent an issue. With too much freedom there is the risk to change too much from the desired shape. In the most modern methods, the ship hull is divided into several sections identified by boxes. This way it is possible to have a good control using a small amount of control points as desired variables. The parameters that can be used are global parameters, such as ship dimensions and basic curves, and local parameters such as tangent and curvature (Hang et al, 2012).

### 2.2.2    Parametric Modelling

Parametric modelling is a method that allows to generate the hull from zero, using the main hull dimensions, some form coefficients, and several parameters. It is a very good mean to generate a preliminary design model in the first stage of the project. It let possible the designer to focus on the meaningful data that the ship is required to have and not on the geometric shape of the vessel. For example, some form parameters which with it is designed the ship can be the waterline coefficients, the centre of volume, the hydrostatic characteristics, the centre of buoyancy, etc. The most developed applications about global parametrization are FORAN hull form generator (https://www.marine.sener/subsystems) and FRIENDSHIP modeler (www.friendship-systems.com). The FRIENDSHIP modeler is a parametric design software based on the use of sections to obtain the hull form. The geometries created by this software are NURBS, which is very important because it facilitates the integration with many CAD programs. The parametric design sections are created by a set of longitudinal curves. This method is very valid because these curves are meaningful for the designer for example from them it is derived the sectional area.

In order to create the hull, FORAN uses parameters, which contain geometric, hydrostatic and hydrodynamic characteristics, and are connected to the formulation of the waterline. The software can elaborate a 3D

model with good flexibility. It has default values for every parameter, which makes the work easier when some information is missing. All the parameters of the waterline are controlled by a parametric draft function, which with it is possible to control its vertical distribution. Thanks to the draft functions the designer has complete control over the hydrostatic features (Rodriguez and Fernandez-Jambrina, 2012).

## 2.2.3 Geometric Parametrization

The geometric parametrization is a kind of parametrization in which the designer uses generic geometric dimensions to modify the shape of the hull. Some of the most common input parameters for example are the lengths, the angles, and the tangencies. In this methodology type the whole design is registered in a script, which has the parameters as input and the final shape with its main dimensions as output (Rodriguez and Fernandez-Jambrina, 2012).

It is presented a parametric model to generate a sailboat hull, hard chine or rounded. The curve types used are Rational Bezier curves of the second and third order (for rounded hull). The curves used to design the shape of the hull are transversal and longitudinal. The transversal curves are one fore section, one midship section and one aft section. The longitudinal curves are the sheer line the chine line and the deck line. The parameters used in this paper are the control points of these curves, which coordinates, and tangencies can be changed at user need. The section curves are composed of two rational Bezier curves of third or second order. The first one starts from the keel line and ends at the chine line and the second one starts from the chine and ends at the deck line. The Bezier curve formulations permit to keep the continuity of the joined curve in terms of curvature and tangency. Moreover, the Bezier curves are a very good mean because they permit the modification of the curve without moving the control points, but just changing the weights assigned to them. So, the user can first insert the values of the main dimensions and then adjust the hull shape with the angles and tangencies at the control points or acting on the weights of them (Ingrassa et al, 2021).

Another study uses the following curves of form: deck line, sheer line, waterline, profile, one section area curve. For the construction of the sheer line, it is used a B-spline, which parameters are $FB_{stern}$, $FB_{mid}$ and $FB_{bow}$. The shape of the sheer can be set straight concave or convex. The deck line is a quadratic B-spline with one control point at mid length which modify the $B_{max}$ parameter and one control point at the transom which determines the beam at transom parameter. The waterline is constructed with a fore control point to modify the entrance angle that is an important value for the control of the resistance of the ship. After the control point next to the bow, it is set one middle control point with two degrees of freedom x and y, which identifies the $B_{wl}$ and the $L_{cf}$ parameters. The last control point of the waterline is the aft control point with an y coordinate floating value, it is used to adjust the waterplane area. Other parameters that affect this control points are the $C_{wp}$ and the $L_{wl}$. The Profile can be described by three different zones: the bow, the keel, and the transom. The bow has five parameters: the angle at the deck, the tangent at the deck, the angle at the waterline, the upper and lower tangencies in correspondence of the waterline. The keel has seven control points, which are modified by the following parameters: $L_{oa}$, $L_{wl}$, $T_c$ and Forward Overhang. The transom is composed of a straight line parallel to the Y vector at the deck with the beam at the transom as parameter and one straight line moving on the centreline plane (XZ) with the transom angle set has parameter. It is constructed a section area curve with which are connected the $L_{wl}$, the LCB and the $C_p$ parameters. Varying the parameters connected to the section area it is possible to modify the midship section area, change the underwater volume, move the longitudinal centre of stability, and adjust the coefficients curve. The use of sections is adopted to keep the longitudinal curvature under control. The midship cross-section curve is constructed with the help of 4 diagonals, all lying on the defined YZ plane. The diagonal one (D1) passes through the intersection point between the waterplane and the hull and a point on the centreline plane $B_{wl}/4$ far from the waterplane. Diagonal four (D4) passes through the intersection point between the waterplane and the centreline plane with an inclination of 10 degrees. Diagonal two and three in the middle of D1 and D4 have an inclination of 45 degree (D2), passing through the intersection point between waterplane and

centreline plane and 54.2 degree (D3) passing at a distance of $B_{wl}/8$ from the waterplane. On the diagonals can move the control points which parameters are $C_m$, FB, $B_{wl}$, $B_{max}$ and D. The curve used to generate the section is a cubic B-spline. The same method is used to generate a section at the transom. (Bole, 1997)

It is given a working example of the program design method. It is used a script to perform the construction of the 3D model of the hull. It is created the forward body of a big merchant ship. This zone of the hull contains the bulb. The first curve constructed is the profile curve. After the creation of the curve, tangent conditions are given to each point of the line. The next step is to produce three section curves with a tangency pattern. The curves lie each one on a distinct YZ plane with centre in a point moving on the XX axis with a X coordinate floating value. The surface is constructed with a patch function between sections, profile, and a new curve that the designer uses to indicate the tangency condition at the fore border. This code can be applied to any similar offset table. Moreover, the tangency values make up parameters for a new user. The X and Z values of the profile curve points constitute part of the parameters (Rodriguez and Fernandez-Jambrina, 2012).

The traditional way to model a hull is by the employ of waterlines and sections. The third group of curves that can be used by the designer are the buttocks. These curves permit to check the simultaneous fairing of waterlines and sections, so that it is possible to have control over the geometric characteristics of the yacht. The possibility to modify tangency and curvature have an important role to reach the hydrostatic and hydrodynamic targets. In the present study the main curves used to construct the hull are the keel line and the waterline. The parameters directly connected to the shape of the keel curve are the forward angle traced on the centreline plane between the waterplane and the keel line, $L_{wl}$ and the $T_c$ (Draft). The parameters used to shape the waterline are $B_{max}$, LCF and $L_{wl}$. Moreover, to have a better control on the hull the following parameters have been added: prismatic coefficient, $C_0 = \frac{Lwl}{\sqrt[3]{\nabla}}$ which is used to influence habitability and resistance, $C_1 = \frac{Awl}{Lwl*Bmax}$ that is used to control the fulness of the ends of the yacht (connected to the shape of the waterline) and $C_2 = \frac{As}{Bmax*Tc}$ which determines the cross section geometry, the closer it is the ratio the squared it is the section (Mancuso, 2005).

In (Sener, 2016) it is presented a fully parametric model for a frigate with two different bow types, a conventional one and one designed with a sonar dome (that will not be discussed). The name of the design tool is CAESES, which generates geometries in terms of form parameters and fairness criteria. First of all, it is carried out a study of parent hulls in order to see which dimensions and constraints the geometries have to undertake. It identifies the main dimensions and ratios of the initial hull form. The values it decides to elaborate are the ones of $L_{oa}$, $L_{wl}$, $B_{max}$, D, $B_{wl}$, $L_{wl}/B_{wl}$, $L_{wl}/\nabla^{1/3}$ and $LCB/L_{wl}$. The curves used in the study are the F-spline. The F-spline is a curve that is possible to generate giving a starting point, an ending point, and the tangent angles at these two points. The parameters used are of two typologies: global parameters and local parameters. The global parameters are the ones that modify the general shape of the hull, for example $L_{wl}$ or $B_{wl}$, and the local parameters are used to vary a specific curve or surface of the vessel, for example the value of the tangent at the bow. The curves used for the creation of the shell are the deck curve, the design waterline, the central profile curve, the flat bottom (fob), and a set of sections. With the use of these basic curves and design sections four surfaces have been created. The parameters that control the basic curves are $L_{oa}/2$, $L_{wl}/2$, D, T, Xendfob/2, Xfwdbase/2, $B_{max}$, $B_{wl}$, $B_{fob}$, $Z_{transom}$, $T_{transom}$, $X_{aftbase}$, $B_{transom}$, BtransomWL, Entrance Angle Curve Section Fullness Curve. The parameters used to modify one section curve at any x position are: Cross Section Area (obtained with the formula $A_x = (FOB * T) + (Bwlx - FOB) * T * SectionFullness_x$), $Bmax_x$, $Bwl_x$, Deck Tangency Curve, Waterline Tangency Curve, Keel Tangency Curve and T. Other additional parameters were added to calculate the form coefficients.

The processes that bring to the generation of design curves start with the mathematical description of them. The definition of a curve is given by a set of data elements of the curve. The process can lead to different

results according to the curve properties and generation procedure chosen. In the following study are used B-spline curves generated by the fairness optimization process. Sets of form parameters are taken as constraints, such as distance constraints, end constraints, area constraints and many other types. The end constraints are imposed to the start and end points of a curve, and they are tangent and curvature. The area constraints are imposed to the area under a curve. All the planar curves are described by the following form parameters: Position (X, Y, Z), Tangent angle, Curvature, Area, Centroid, Fairness. The curves used in the tool are the design waterline, the flat of side curve, the centreline plane curve, the flat of the bottom curve and the deck line. It is designed also the section area curve using an F-spline curve. The form parameters describing the F-spline are the three coordinates (X, Y, Z), angle, volume, and centroid (longitudinal centre of buoyancy). An important parameter used to modify the bow profile shape and the entrance angle is Δα. This differential form parameter influences the resistance of the ship. Once the longitudinal basic curves are generated using fairness-optimized parametric curve, it is time for the transversal section to be created. After the cross sections are defined it is possible to generate a set of surfaces that approximate the design sections. This kind of construction of the final shape brings to a complex input data set because many form parameters are used for different parametric basic curves and many parameters are correlated in between each other (Hang et al, 2012).

The parametric design, which provide quick generation and variation of the forms of the hull, can be accompanied by a hydrodynamic optimization process in order to obtain the best shape as possible. The line typology chosen to elaborate the hull is the planar curve represented by the NURBS curve. Each construction line is provided with features, the ones for the cross-section line are:

Section Line :

$$Q(t) = \begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = \frac{\sum_{i=0}^{n} w_i N_{i,k}(t) d_i}{\sum_{i=0}^{n} w_i N_{i,k}(t)} \tag{1}$$

Half of sectional area S :

$$S = \int_{t_E}^{t_B} x(t) dy(t) = \int_{t_E}^{t_B} x(t) y'(t) dt \tag{2}$$

Sectional area A :

$$A = 2S \tag{3}$$

Lateral moments of sectional area :

$$XcS = \int_{t_E}^{t_B} \frac{1}{2} x(t) ds = \int_{t_E}^{t_B} \frac{1}{2} x(t) x(t) y'(t) dt \tag{4}$$

Vertical moments of sectional area :

$$(T-Yc)S = \int_{t_E}^{t_B} y(t) ds = \int_{t_E}^{t_B} y(t) x(t) y'(t) dt = \int_{t_E}^{t_B} x(t) y(t) y'(t) dt \tag{5}$$

Where (Xc, Yc) is the centroid of area S.

By utilizing the NURBS surface, the hull form can be expressed $as$[4,5]

$$S(u,w) = \frac{\sum_{i=0}^{n} \sum_{i=0}^{n} B_{i,p}(u) B_{j,q}(w) W_{i,j} V_{i,j}}{\sum_{i=0}^{n} \sum_{i=0}^{n} B_{i,p}(u) B_{j,q}(w) W_{i,j}} \tag{6}$$

Where $V_{i,j}$ (i=0,…n; j=0,…m) from a bidirectional control net, $B_{i,p}(u)$ and $B_{j,q}(w)$ are the non-uniform rational B-spline basic functions defined on the knot vectors U = $\{u_0, \ldots, u_{n+p+1}\}$, W = $\{w_0, \ldots, w_{m+q+1}\}$, $W_{i,j}$ are the weights.

In the common practice the parameters can be obtained by manually position the vertexes of the NURBS curve. The modelling of the curve can be seen as part of an optimization problem. The process that brings to the fairing of the hull starts from the parametric fairness criterion of the planar curve.

Objective function:

$$E = \int_{t_A}^{t_B} \left[ \left(\frac{d^2x}{dt^2}\right)^2 + \left(\frac{d^2y}{dt^2}\right)^2 \right] dt \qquad (7)$$

The vertex of the NURBS curve are treated as free variables. In order to solve the optimization problem, it is used Sequential Quadratic Programming (SQP), which is an iterative method for constrained nonlinear optimization.

The design of the hull starts from the specification of the form parameters. Once completed the first step it is done the parametric design of the set of longitudinal curves concerning the hull. The third step of the design concerns the parametric modelling of the sections which forms the body plan. Finally, it is generated the hull form. The form parameters used in the method are principal dimensions and coefficients. The curves used for the design are subdivided into three distinct categories, which are longitude basic curves, longitude integral curves and longitude differential curves.

The longitude curves consist in four curves: Central Plane Curve (CPC), Design Waterline (DWL), Flat Of Side curve (FOS) and Flat Of Bottom curve (FOB).

The longitude integral curves are: Sectional Area Curve (SAC), Curve of Vertical Moments of Sectional area (VMS) and Curve of Lateral Moments of Sectional area (LMS).

The longitude differential curves are constituted of the following: curve of slope at beginning of the section line, curve of slope at end of the section line, curve of curvature at beginning of the section line, curve of curvature at end of the section line. The longitude curves are the ones that contain the necessary information to generate the hull form. Each curve is modeled with its own parameters.

The hull form fairing process is subdivided into five distinct steps. First of all, CPC and a certain number of sections are designed. Afterwards the NURBS algorithm is used to generate the control vertexes of transverse curves. Once created the control vertexes they are used to generate the longitude curves, which equation is the following:

$$E = \int_{t_A}^{t_B} \left[ \left(\frac{d^2x}{dt^2}\right)^2 + \left(\frac{d^2y}{dt^2}\right)^2 + \left(\frac{d^2z}{dt^2}\right)^2 \right] dt \qquad (8)$$

Control polygons are got from the longitude curves. Finally, using Eq. (6) it is possible to apply the interpolate algorithm of NURBS (Zhang et al, 2008).

The successful design of a yacht depends on a big number of factors, the generation of a hull which satisfy all the restrictions and constraints can take up to some days to be developed. Once accomplished, scientific methods are available to check resistance, seakeeping, rig forces, maneuverability etc. The task of making changes to a certain design in order to improve its performance is one of the more complicated and it can take a lot of time, since the systematic shape variation are very time consuming. The formulation of the design is the difficult part of the job, since the steps of the mathematic resolution can be done with common tools. A joint project has been undertaken between the Technical University of Berlin, Carpe Diem Yacht Design and FRIENDSHIP-System, which case study is the problem formulation of a 30 m$^2$ inshore racing yacht. the first step taken is the acquisition of information. When setting up a model, understand which is the problem, is the key to the issue. First, the real world must be specified, that means everything important for the design and operation of the yacht. The information is collected mainly from previous designs,

measurement rules, reports, and specifications. For the project under discussion the initial data was made available from:

- The original measurement formula including modifications.
- One very early Lines Plan.
- Two different 3D CAD-models of already built hulls.
- The designer of the two previous designs
- A potential producer of a small series of this type of yacht.

From this data it is possible to create and implement a first parametric model. The authors decided to develop multiple nested optimizations of uniform B-spline curves. The definition of B-spline curves is as follows:

$$\vec{Q}(t) \ = \ \sum_{i=0}^{m-1} \vec{V_i} N_{ik}(t) \tag{9}$$

Where m is the number of vertices, k the order of curve, $\vec{V_i}$ are the vertices of the defining polygon and $N_{ik}$ are the base polynomials representing the influence of a vertex within a certain range of the curve. FRIENDSHIP-modeler is used to generate a B-spline curve, with the use of the information which optimizes the shape of the curve. The vertices are controlled by a numerical algorithm that manage to arrange them in such a way that the specified properties are met, and the curve is kept fair. In order to measure the fairness, it is applied the integral of the second derivatives of the B-spline:

$$E_2 \ = \ \int_0^1 \left( \frac{dx^2}{d^2t} + \frac{dy^2}{d^2t} + \frac{dz^2}{d^2t} \right) dt \tag{10}$$

In order to give an example of how further parameters can be supplemented to refine the shape it is chosen the longitudinal descriptor for the shape of deck. The description of the plan view of the deck, the sheer line, flare at deck and deadrise along the centerplate curve for a conventional round bilge hull shapes should be sufficient. From this set of curves, it is possible to create sections, which are then interpolated in order to obtain the hull surface.

There are different kinds of constraints defined in the study, implicit constraints, and the explicit constraints. The explicit constraints have to be investigated afterwards, they mainly consist of derived properties.

The implicit constraints can be set within the geometric generation process, which means directly at the stage of producing the geometry. The constraints that can be formulated implicitly are:

- The feasible domain of design parameters of a parametric description, such as draft, beam, sail area, displacement etc.
- The parameter ratios can be set up to fulfil sets of constraints relative to each other, e.g. beam vs length ratio, etc.
- Constant parameter values, the knowledge obtained from previous designs result in parameters which are kept constant, for example the freeboard is usually set at a specific location as low as allowed by the rule.

The determination of the constraints is a matter of the formulation of the design description, for this reason the definition of the constraints is not unique. It can happen that constraints that are first identified as implicit can be converted into explicit during the disinvolvement of the implementation. Explicit constraints are investigated after the geometry has been produced. For example, the girth length at a specific section must not be greater than a certain value. Since the girth length results from sectional properties like beam at deck, tangents, draft and curvature constraints, the function of the grith length is a function of design parameters.

$$G(x = M_S \ = \ \int_0^1 (\vec{Q}(u, v) \cap M_S) ds \tag{11}$$

Ms denoting the measurement section, and $\vec{Q}$ (u,v) the 3D representation of the hull surface.

The rule to measure the yacht under study contains a number of design constraints which are listed in the following table:

*Table 2-1: Measurement constraints of the 30m² yacht.*

| Lower bound | parameter | Upper bound | Type |
|---|---|---|---|
| 1.4 | $L_{max}/L_{WL}$ | 1.6 | Explicit |
| 1.0t | displacement | | Explicit |
| 1.75 m | $B_{max}$ | | Implicit |
| 0.36 m | Freeboard | 0.4 m | Implicit |
| | $L_{max}/B_{max}$ | 4.5 | Implicit |
| | $overhang_{bow}/overhang_{total}$ | 0.6 | Explicit |
| | $overhang_{stern}/overhang_{total}$ | 0.6 | Explicit |
| 0.9 | $B_{WL}/B_{max}$ | | explicit |

For the first shape it has been chosen the better rated design already available, which has been modelled parametrically. The first impressions of the magnitude and relation of wave and frictional resistance come from the use of CFD, which confirmed the selected approach. The first step is the implementation of the design characteristics, then it is chosen to minimize the wetted surface. After it comes the optimization for total resistance for the upper range of speed and at the end free variables are selected in order to redistribute the displacement. Very effective design parameters are the following: the position of the maximum draft and beam, the transom beam, deadrise in the bow region and the radius of the centerplane curve at its maximum draft position. Each run is performed with about 10 free variables (Hochkirch, 2002).

The parametric modelling is a technique which with it is possible to generate a hull form using a set of parameters that are preserved during the creation of the geometry. Moreover, the parametric generation guarantee that the design algorithm creates a hull that is constrained by the design parameters without any need of further interactions with the code.

One single script is usually able to reproduce only a certain typology of hull. In the current method it is created an algorithm able to produce planning hulls. CFD is used in order to optimize the final object. A 3D approach to boundary curve definition needs a great number of parameters, only in order to define the curves, for this reason the method uses a 2D approach. The study utilize constrained B-spline fitting of points obtained from 2D curves to define the 3D boundary lines.

The parametrization is based on the distance from the data points to the B-spline. Afterwards a net of stations (B-spline curve), that matches the 3D boundaries is generated, finally a set of lofting surfaces is produced to obtain the hull form.

A single chine un-stepped hull can be modelled by decomposing the surface into boundaries or control curves that will be constrained by the design parameters. In the case study the chine, which is the more significant curve of the planning hull, the enclosed area and centroid are included into the parameters. The curves used as parameters are the keel line or the center line (CL), the chine line and the sheer line.

The parameters chosen for the development of the model are related to further aspects of the ship design. The set of curves has been simplified by considering the transom of the hull as a vertical one and imposing that the aftermost point of all the lines has a zero abscissa. The maximum dimensions of lengths and breadth of the hull are $L_S$ and $2*B_X$.

The method divides the station curves into two different groups, the ones below the chine line and the ones above it. They are elaborated parameters that control the convexity/concavity of these curves. The parameters control the maximum deviation of every station piece from a straight segment.

The study creates B-spline surfaces that represent a ship hull based on the constraints listed below.

Table 2-2: Parameters of the method

| Name | Description | Location |
|---|---|---|
| **Length** | | |
| $L_S$ | Length of the sheer line | Center, sheer |
| $L_0$ | Abscissa where the forefoot is tangent to the keel line | Center |
| $L_X$ | Abscissa of the sheer's maximum breadth | Sheer (plan) |
| $L_C$ | Length of the chine | Center, chine |
| $X_C$ | Abscissa of the centroid of $A_C$ | Chine (plan) |
| $X_{C1}$ | Abscissa of an intermediate point of the chine | Chine (profile) |
| **Width** | | |
| $B_S$ | Sheer's half-breadth at the transom | Sheer (plan) |
| $B_X$ | Ordinate of the sheer's maximum half-breadth | Sheer (plan) |
| $B_C$ | Chine's half-breadth at the transom | Chine (plan) |
| $S_P$ | Width of the spray rail at the transom | 3D |
| **Height** | | |
| $H_S$ | Height of the foremost point of the sheer | Center,sheer (profile) |
| $H_C$ | Height of the foremost point of the chine | Center, chine (profile) |
| $R$ | Rocker at the transom | Center |
| $H_S$ | Sheer's height at the transom | Sheer (profile) |
| $H_C$ | Chine's height at the transom | Chine (profile) |
| $Z_{C1}$ | Height of $X_{C1}$, normally the draft of the ship | Chine (profile) |
| **Angles** | | |
| $\alpha_K$ | Angle at the stern | Center |
| $\alpha_S$ | Angle at the foremost point of the sheer in plan view | Sheer (plan) |
| $\beta'_s$ | Angle at the transom of the sheer in lateral view | Sheer (profile) |
| $\alpha'_S$ | Angle at the foremost point of the sheer in lateral view | Sheer (profile) |
| $\alpha_c$ | Angle at the foremost point of the chine in plan view | Chine (plan) |
| $\beta c$ | Angle at the transom point of the chine in plan view | Chine (plan) |
| $\alpha'_c$ | Chine's angle at the foremost point in profile view | Chine (profile) |
| $\beta'_c$ | Chine's angle at the transom point in profile view | Chine (profile) |
| **Areas** | | |
| $2*A_c$ | Enclosed area between the chine and the X-axis in plan view | Chine (plan) |

The B-spline curves are the ones that better suits the loftman's splines, this is the reason why they are the most used in the ship designs.

Usually, in the planning hulls, the keel line has no appendages and runs in a straight line from the transom, then it curves up and it arrives at the stern with a certain angle. The curve constraints are the tangent angles at the end points of the curve. The shape of the forefoot van be altered in order to vary the dead-rise angle of the forefoot sections. The method uses distinct curves pieces, which increases the flexibility of the model because the curves can be converted into a single B-spline by considering different points on both lines.

The sheer line runs from transom to stern. Usually, the design methodologies develop the curve with a maximum when the breadth at the transom is lower than the maximum breadth, or the maximum breadth is constant afterwards. The B-spline is generated using four control points. The tangent angle at the transom is not imposed. The sheer line and the inner volume distribution above the water are connected through the angle $\alpha_S$. More in detail the angle and the volume at the fore part are directly proportional. Considering the sheer line in the lateral view, it starts from transom and end at stern, in correspondence with its projection with the plan view. In the planning hulls it does not have minimum or maximum. It starts at a given height hs at transom with a given angle $\beta'_s$ and it arrives at the stern with a given height Hs and a given angle $\alpha'_s$. The line used is a second degree B-spline with three control points.

In the planning yachts the chine line is the one that gives the planning characteristics to the hull, for this reason this is the most important curve of the design. The chine in the plan view elaborated runs from transom to stern, starting at a certain point with a certain angle $\beta c$ and ending at a certain point with a certain angle $\alpha_c$. The method imposes a confined area (Ac) and a longitudinal position of the center of enclosed area (Xc). The area of the closed B-spline is computed with Greens' theorems, the area is enclosed by the curve and the X-axis. The shape of the chine in the plan view is strictly connected with the planning behavior of the hull. Taking into consideration the profile view the line starts from transom with a given angle $\beta'_c$ and arrives at the center line with a certain angle $\alpha'_c$.

The next step is the creation of the 3D curves. The method used to generate the 3D definition of the ship's main curves is based on the orthographic projections. It is adopted a way that take into consideration the effect of the distance of the data points from the B-spline, which is a parametrization based on a minimum distance. The process is iterative. Ones completed this operation it is possible to create the stations, which are the curves used to generate the surface. All the stations are divided into two segments, one going from keel line to chine line and one going from chine line to sheer line. A set of stations is defined. All the lines below and above the chine are created using a second degree B-spline with three control points.

The last step of the study is the generation of B-spline surfaces based on the stations previously defined. It is created one surface between the chine line and the center line and a second one between the chine line and the sheer line (Perez-Arribas, 2014).

# 3 METHODOLOGY

## 3.1 Introduction

In the following the geometric reference system adopted will be set with the zero at the intersection point between the Daft, which is the depth taken at the aftermost point of the deck and the horizontal plane, parallel to the waterplane, passing through the lowest point of the keel.
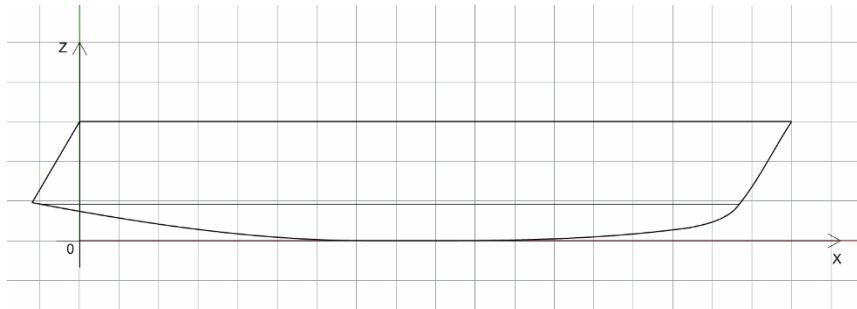


*Figure 3-1: Reference system, XZ axis*

Figure 3-1 shows the XZ base plane, that corresponds to the centreline plane of the yacht. The keel line, the sheer line and one line of the transom lie on this plane.
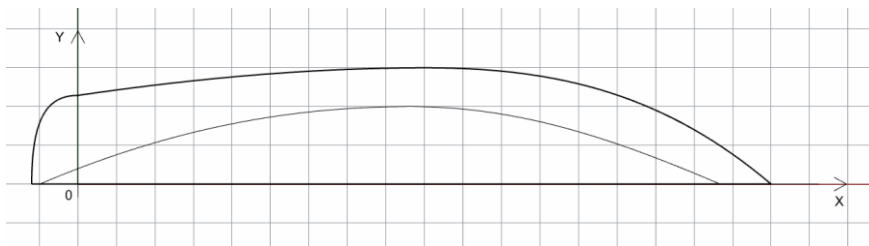


*Figure 3-2: Reference system, YX axis*

In Figure 3-2 it is represented the base plane XY, that is the plane parallel to the waterplane, passing through the lowest point of the hull.



*Figure 3-3: Reference system, YZ axis*

The vertical plane YZ of the reference system adopted, contains the Daft of the yacht and the aftermost point of the sheer line. An important plane, that will be used many times for the analysis and construction of the yacht is the vertical plane passing through the most forward point of the deck. This YZ plane contains the Dfrw, which is the depth measured at the most forward point of the hull.

## 3.2   Generic methodology
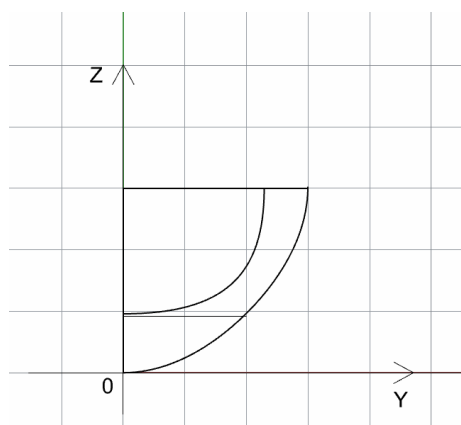
The program used to generate the final shapes is Grasshopper, a visual programming software integrated in Rhinoceros 3D (McNeel, 2016) in the form of a plug-in. It is possible to generate a code by defining a cause-effect system, led by using parameters as inputs, the surfaces of the hull as main core, generating an excel file with the main dimensions, the graphic section area curve, the Lines Plan, and the Offset Table as output.

The process of the surface development starts from the creation of the control points. Those points are next used to create the main control space curves, that finally are used to generate the surfaces which compose the hull. The control points are connected to parameters that define their position in the 3D space, the number of variables with which a point can be provided goes from one to three.

Part of the parameters used to control the model are linear dimensions that can modify the main geometries of the hull, such as the length of the deck, the maximum beam, and the draft. Other parameters define the distance in between key points and hull references. The last typology of parameters connected to the control points are the angular parameters which are linked to the points through trigonometrical formulas.

The points are mostly connected with F-Spline curves. The F-spline is a curve that is possible to generate giving a starting point, an ending point, and the tangent angles at these two points. This kind of curve permit to add parameters that give the control onto the tangent at the start and the end point.

All the models are generated using these three kinds of parameters, linear dimensions, angles, and tangents. The code of the sailing yacht hull presents one different kind of parameter, which is the waterplane area coefficient. Once completed the curves it is possible to start the study of the surfaces, the hull is composed of a different number of lines which assume different shapes depending on the design target. It is very important that the chosen surfaces have a good accuracy for each one of the hull form possibilities. The final surface is the mean used to reach the following goals of the work.

The code is implemented with calculations that permit to reproduce all the output already mentioned. The creation of these kind of features goes forward points and lines, it is at this point that more complex Grasshopper's (Payne, 2014) commands come to help to elaborate the requested calculations. For example, it is not possible to elaborate any of the output without having acquired a good understanding of the data trees.

The Offset Table is generated using two parameters, one for the number of columns and one for the number of rows. In this part of the script, it is used the ''Expression'' command, which is a box in which it is possible to write a relevant variety of functions. The creation of the Offset Table requested the matrix's knowledges.

The creation of the section area curve request skills onto the brep manipulation and a good usability with the treatment of lists of data and their elaboration.

Before being able to reproduce the Lines Plan it is undertaken a study regarding the geometric surfaces, their representation ways, and their modification in the 3D space.

The table containing the main dimensions of the hull is created thanks to the mathematical operation tools supplied by Grasshopper.

# 4 Displacement Hull for Sailing Yachts

The sailing yachts use as main propulsion system the sails that exploit the power of the wind to move the hull trough the water. In a displacement hull, the lift is obtained entirely from the buoyancy and does not change with the speed.

## 4.1 Analysis of Form Characteristics

In this section, the more important lines of the sailing yacht hull are identified. The curves studied are the ones that make possible the construction of the 3D model surface representing the shell shape of the vessel. Using existing Lines Plan drawings and different images of real yachts it has been possible to obtain the characteristic shapes, the constraints, and the main dimensions.

The curves can be classified into two different groups, those that run in the longitudinal (X) direction, such as the sheer line, the deck line, the bow line, and the keel line; and those that run in the transverse (Y) direction, the transom line, and the cross section. These curves are analysed in the following.

Sheer Line

The sheer line is a longitudinal curve extended form bow to transom. It is a 2D line located on the centreline plane. It is part of the deck and is this line that determines longitudinal curvature of it. The sheer line in the sailing yacht can assume different forms. In the new designs, the sheer line is usually straight, without any curvature. It can be parallel to the water plane, or it can be rising from stern to bow with the highest point at the most forward point of the hull.

When this form curve is inclined, it has an angle with the ZZ axis with origin at the aft point of the sheer line that lies in the range of about 88° to 90°. The length of the sheer line can be equal to the length over all or a percentage of it, in which case its value varies from 100% to 90%.
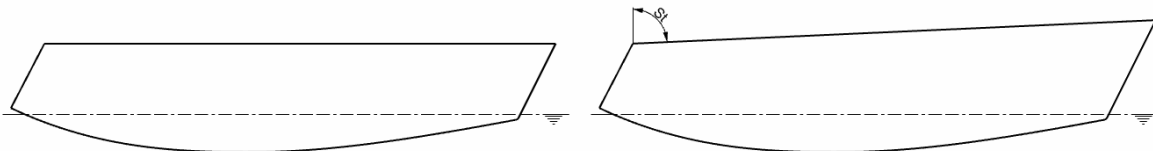


*Figure 4-1: Sailing yacht, straight sheer line*

In the past years when composite materials were not available on the market and the shipyards of sailing yachts were used to make use of wood for the construction of the vessels the sheer line was designed differently.

The common practice was to develop this curve with a curvature. In this case it was adopted a concave shape for the sheer line design. The lowest point of the curve can find its position at the transom, or it can be located along the length of the ship. Nowadays there are still some shipyards that work with this kind of design.
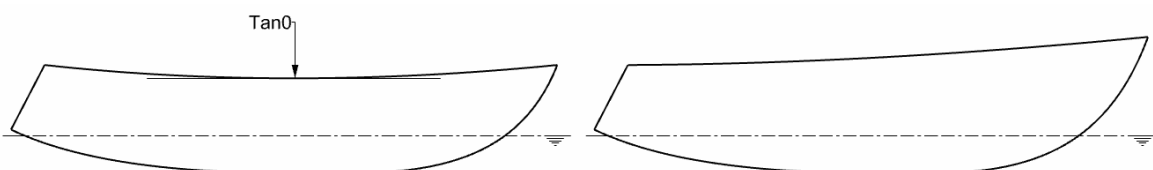


*Figure 4-2: Sailing boat, rounded sheer line*

In Figure 4-2 it is possible to notice that the sheer line of the image on the left present a point along the length of the ship with a tangent value equal to zero. The angles before and after the point, included between the tangent and the hull go from 1° and 3°. The location of the lower point of the line can reach a distance from Lpp/2 equal to the 34% of Loa.

Deck Line

The deck line is the top external curve of the shape of the hull. It starts at the centreline plane at the most forward point of the hull, and it ends at the most external point of the transom. It can be a 2D curve or a 3D one, depending on the modelling choice.

The angle of entrance at the bow, that is defined as the angle formed between the centreline of the vessel and the tangent to the deck line at the most forward point of the hull, can have a range from 15° to 25°. This angle can be different along the bow line length, it is studied in 2 distinct points, at the top point of the bow line and at the intersection point between the hull and the forward perpendicular, where it forms the angle with the tangent with the design waterline.

The angle at the waterline in front of the one at the deck can increase until the 37% or it can decrease until the 30% of it.
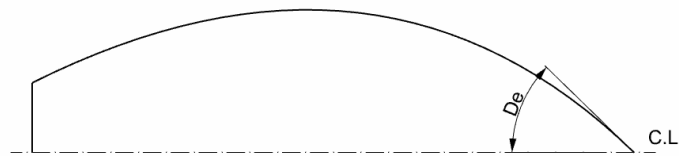


*Figure 4-3: Sailing yacht, angle of entrance at the bow*

The maximum beam can be forward the Lpp/2, which is a very rare case, or before it with a maximum value up to 14% of Loa. The angle of run, which is included between the hull and the YZ plane passing through the aftermost point of the line, goes from 63° to 81°.
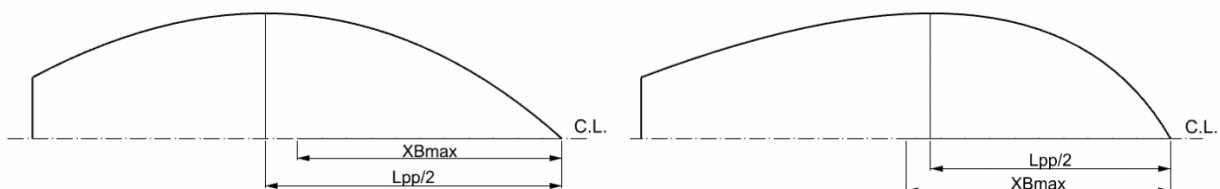


*Figure 4-4: Sailing yacht, maximum beam position*

The maximum beam of the sailing yachts can reach a value equal to the 16% of the Loa.

The deck line, following the sheer line behaviour, can be parallel to the waterplane or it can be inclined going up from transom to bow. It can have a curvature, or it can be straight. In the wooden vessels it usually has a concavity.
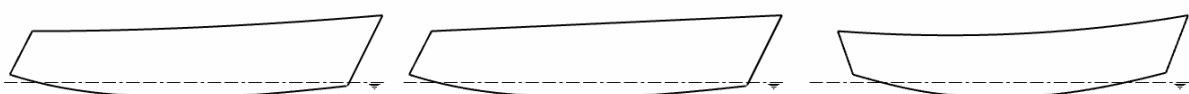


*Figure 4-5: Sailing yacht, deck line with curvature, straight and concave*

<u>Bow Contour</u>

The bow line is a very important component for the design because the resistance of the ship depends on it. It is a 2D curve that lies on the centreline plane. It can have a null inclination, so that this element of the hull is parallel to the Z vector, or it can assume an inclination going from 0° to 45°. The angle considered is taken between the bow contour and a YZ plane with origin at the most forward point of the hull. This form curve can be all straight or partially rounded. In the second case usually, it is designed to have an upper straight segment and a lower rounded one. The upper segment relates to the sheer line and the lower one is connected with the keel line.
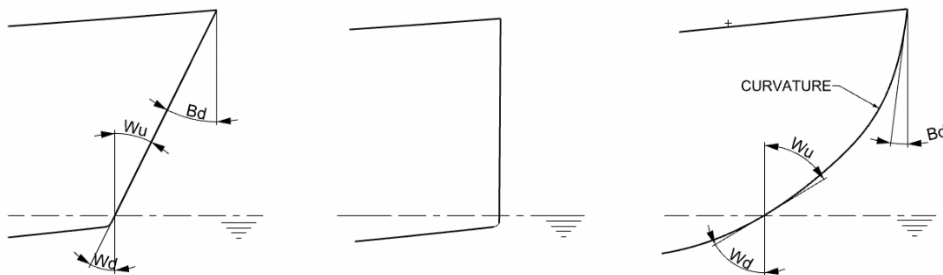


*Figure 4-6 : Sailing boat, possible Inclinations of the bow line*

The intersection point between the bow line and the waterline has two angles, one defined as the up-waterline angle (Wu) and the other defined as the down waterline angle (Wd). The first one is included between the plane perpendicular to the waterplane, passing through the intersection point, and the dry part of the hull. The second one is included between the same plane and the part of the hull under the waterline. Wu has a range going from 17° to 74° and Wd has a range going from 11° to 67°.

In the wooden boats the line can be completely rounded.

<u>Keel Line</u>

The keel line is the lowest curve of the hull. It is a 2D curve that lies on the centreline plane. It starts from the lowest point of the transom, and it ends at the bow line connection. The keel line can be all rounded and present one point with tangent equal to zero. This point can be located before or after the Lpp/2, in the first case it has a maximum distance from it equal to 4% of Loa, in the second case 9% of Loa. the angles before this point can go from 1° to 4°, the ones after have the same range between 1° and 4°.

Otherwise, the keel line can be partially straight and parallel to the waterplane, the straight segment length depends on the Loa of the yacht, so it can be studied as a percentage of it.
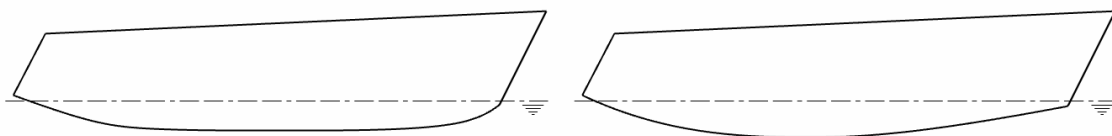


*Figure 4-7 : Sailing boat, all rounded keel line and partially straight*

The angle between the tangent at the most forward point and the XY plane passing through the point goes from 11° and 70°. The angle included between the YZ plane passing through the aftermost point and the tangent to the hull at the point has a range between 63° and 89°.

Transom line

 The transom is the surface forming the stern of the yacht. This surface is made up of three curves, two straight lines and one rounded. The two straight lines (CH and CF) are 2D, line CH lies on the central plane and moves along it, and line CF is perpendicular to it and lies on the XY plane. The rounded curve (FH) is a 3D geometry and connects the other two lines.
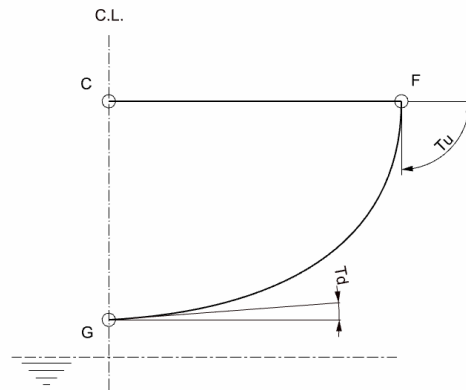


*Figure 4-8: Sailing boat, transom lines and angles*

The rounded curve of the transom is studied through two angles. The top angle (Tu) is included between the curve and the plane parallel to the waterplane, passing through the connection point between deck and transom, it goes from 72° to 131°. The low angle (Td) is included between the transom curve and the plane parallel to the waterplane and passing through the intersection point between keel and transom, its range goes from 0° to 13°. The range of the transom beam, corresponding to CF line, goes from 4% of Loa to 17% of Loa. The length of the CG curve goes from 4% of Loa to 11% of Loa.

In the sailing yachts the transom can be designed parallel to the ZZ axis or inclined up to 45° (image b). The angle describing the longitudinal inclination (Tb) is taken between the XY plane with origin in point C and line CH. In the wooden boats the transom can be inclined with an angle up to 105° (image c).
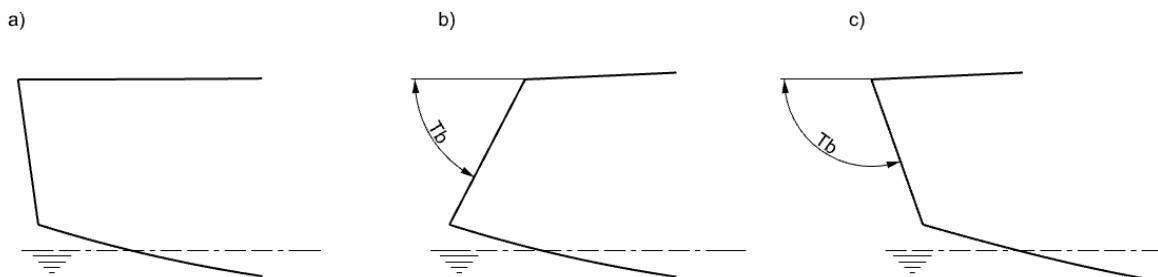


*Figure 4-9: Sailing boat, different inclination of the transom*

Looking at the transom from the top view it is possible to study this form curve curvature by the angles at the connection point with the deck line (TopD) and with the sheer line (TopS). TopD goes from 20° to 90° and TopS goes from 0° and 6°.

## 4.2   Modelling Methodology

To develop the hull of the sailing boat, first off all it is created the sheer line. This is an interpolated curve that is built up with three points placed in the centreline plane, the first one is positioned on the ZZ axis, the

second one is in the halfway of the deck length and the third one finds its position at the most forward point of the yacht.
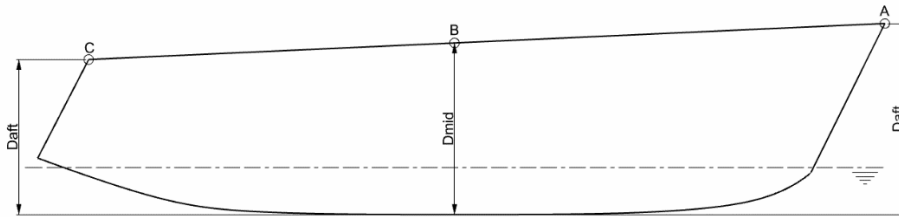


*Figure 4-10: Sailing boat, sheer line parameters*

The parameters used to control the sheer line are the deck length (Ld) and three Depths, that are the lengths relative to the distance in between the XY base plane and the central point Dmid, the aft point Daft and the forward point Dfrw of the line. This way it is possible to control the curvature of the sheer and model it straight, rounded, parallel to the water plane or inclined.

After the creation of the sheer line the second main curve created is the deck line, which is composed of two joined interpolated curves and three control points.

The first segment is AE, where point A is the most forward point of the hull, point E is the point corresponding to the maximum beam of the yacht, which parameter Bmax controls the horizontal distance between E and the centreline. Moreover, another parameter is connected to this segment, which is the angle of entrance of the deck line. The angle De is included in between the centreline plane and the tangent at the most forward deck line point.

The second segment (EF) starts in point E and ends in point F, which is controlled by parameter Th, the horizontal distance between the centreline and the aftermost point of the deck line. As well as the first segment AE, also EF has one angular parameter to guarantee a better control over the shape of the curve. The angle in object (Dr) is the angle of run, that is included between the base plane YZ and the tangent at the aftermost point of the deck line.
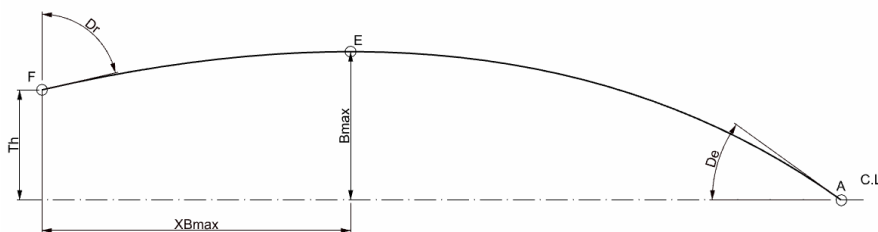


*Figure 4-11 : Sailing boat, deck line parameters*

Consequently, to the deck line it is possible to construct the transom shape, that is made up of two lines and one curve. It is created a new point H that is located down the deck, it lies on the centreline plane, and it can move on the XX axis from Daft backway. The parameter that controls this motion is Tl. It is possible to set the vertical distance of point H from the lowest point of the hull with the parameter Tv. The first line created is CG.

*Figure 4-12: Side view of transom form curves shape.*

The second line CF is the connection between the two already existing points F, aft point of the deck line, and C, aft point of the sheer line. This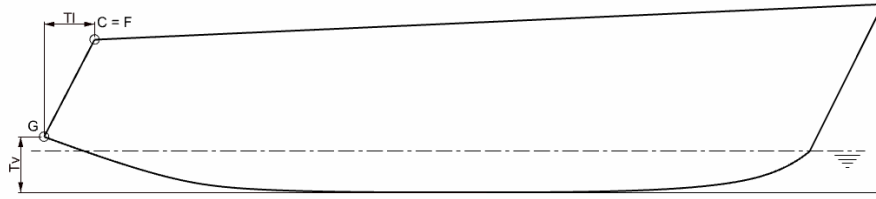 is a 2D horizontal line which length is possible to be modified by the parameter Th. GF is the rounded curve built to close the transom surface. This is a 3D form curve very important for the transom shape. To have a good control over the shape of this line two parameters are connected to it. At point F parameter Tu can be used to modify the angle included between the line FG and the XZ plane passing through F. At the lower point of the transom the angle taken in between the plane XY passing through G and the transom contour is controlled by parameter Td.
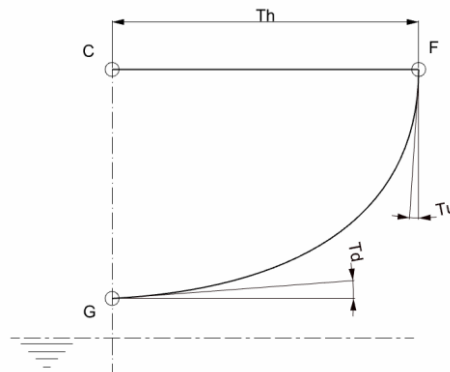


*Figure 4-13 : Sailing boat, back and side view of transom lines and parameters*

Once completed the modelling of the transom it is possible to start the creation of the profile curve, for this application two distinct curves have been used, the bow contour, and the keel line. The bow contour is a 2D interpolated curve built with two control points. The most forward point of the hull, point A, is the only one already existing and discussed.
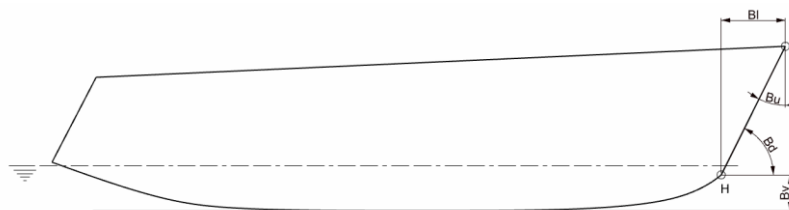


*Figure 4-14: Bow contour parameters*

The lower point H with the angular parameters, permit the user to set the desired shape to the bow line. Bl is useful to modify the longitudinal distance measured between the Dfrw and the end point of the bow line. Bv can be used to set the vertical distance between H and the lowest point of the hull. Bu is the angle included between the plane YZ passing through the most forward point of the yacht and the bow contour. Bd is the angle taken in between the plane XY passing through H and the bow line. These two parameters help the user to set the curvature of the bow contour.

22

The second segment to define the profile of the sailing yacht is the keel line. This is a 2D curve that runs from stern to bow. The extremes of the segment are point G, already built in the transom, and point H, discussed in the construction of the bow. Point H has two parameters, Tl already explained in the transom methodology and Tv, which is the vertical distance from the lowest point of the hull to the aftermost point of the yacht surface.
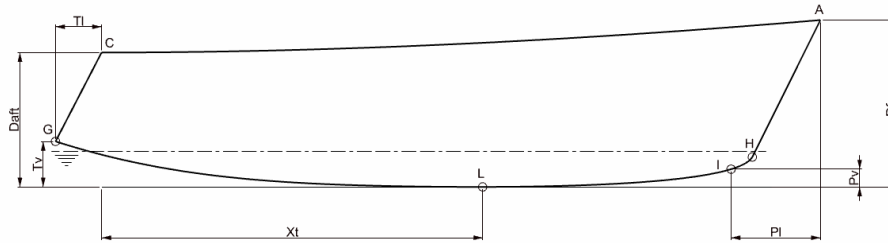


*Figure 4-15: Keel line linear parameters*

The keel curve is built with three distinct segments, that joined together constitute the keel itself. Starting from the stern the first segment goes from G to the lowest point of the hull L. The parameter Xt controls the longitudinal distance from Daft to point L. The middle segment is LI. The sailing yacht new designs are mostly characterized by a bow line almost perpendicular to the waterplane. For these reason in between the bow contour and the keel line there is need of a fillet segment, that in the case study is represented by IH. I is the starting point of the third segment (IH) and the end point of the middle segment LI, that starts at the lowest point of the hull.
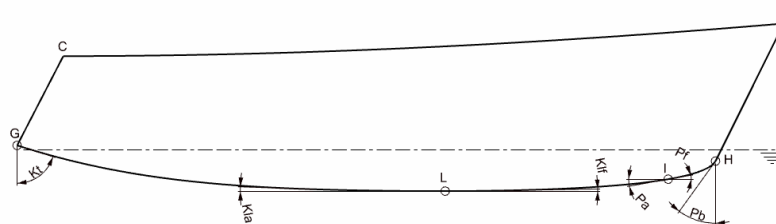


*Figure 4-16: Keel line angular parameters*

All the control points are provided of one or two parameters to have a good shape control over the three segments constituting the keel line. Kt is the angle included between the YZ plane passing through G and the tangent at the keel line. Point L has two parameters Kla and Klf, both are described as the angle taken in between the base plane XY and the keel line, Kla is the aft angle and Klf is the forward angle. At point I it is used the same parameters construction. Pa and Pf are the aft and the forward angles taken between the hull and the plane XY passing through I. The last parameter of the keel line is Pb which is the angle included between the form curve and the vertical plane YZ passing through point H.

Once obtained the profile curve it became possible to elaborate the waterline. This is a 2D form curve, that lies on the waterplane. The draft (T) is a parameter of the form curve, which controls the vertical distance from the lowest point of the hull and the waterplane. The intersection points (O and M) between the profile curve and the waterplane are the start and the end point of the waterline. The third control point N runs along the curve OM. N is the point corresponding to the maximum beam of the waterline, represented in Figure 4-17, to which is connected the parameter Bwl. In this point the hull is tangent to the XZ plane passing through N. XBwl is the parameter that controls the longitudinal position of the point. Two other parameters are added to the form curve, the angle of run (Rwl), and the entrance angle (Ewl). Both the angles are included between the centreline and the hull.
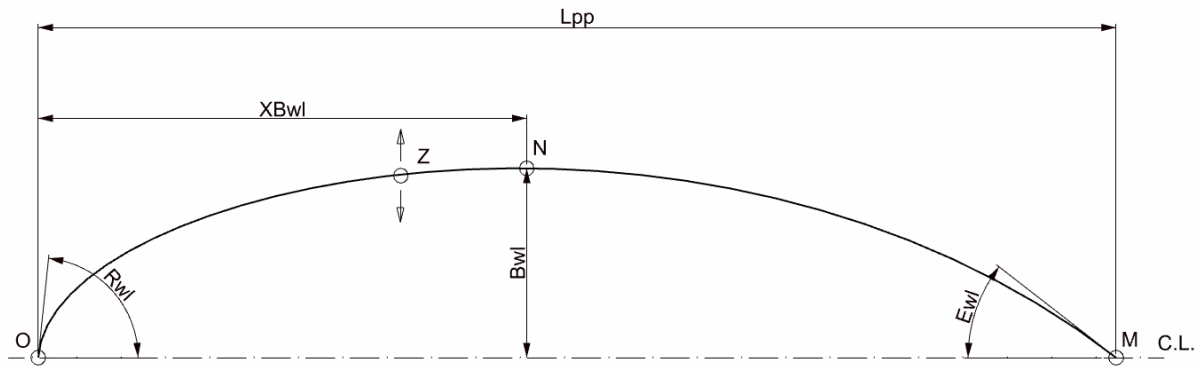
*Figure 4-17 : Sailing boat, waterline curve parameters*

The curve elaborated with these parameters was not enough precise, so it has been added another parameter, Cw. The user can set the value of the waterplane area coefficient in order to change the shape of the segment ON. Cw is connected to point Z, which lies on the aft segment of the waterline, in between point N and O. Through an iterative process the point moves along the YY axis until the coefficient's condition is not verified.
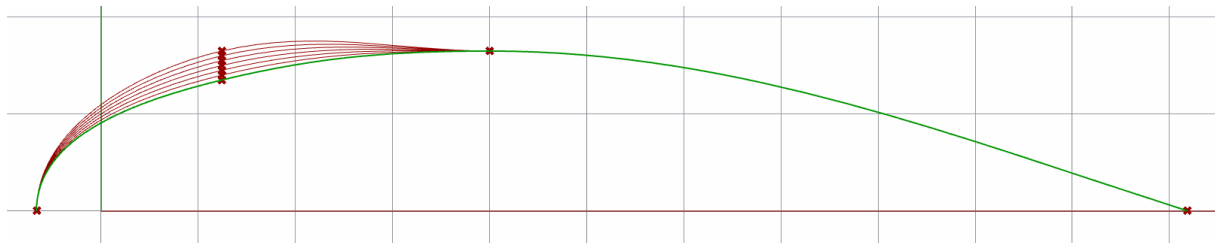


*Figure 4-18: Iterative process applied on Z point to reach the target Cw*

The X coordinate of point Z is set to be the length measured between Daft and XBwl divided per 2.5. The green line in Figure 4-18 is the final curve, created once the iteration process produces an acceptable value. The red lines, up the green one, are all the attempts of the code to reach the target Cw.

The last line that has been created to be able to design the hull surface is the cross section.

The transversal section is an interpolated curve that passes through three points, all of them identified by the intersection between the hull and a YZ plane, more specifically the control points are at the deck line at the waterline and at the keel line. The longitudinal position (Xc) of the cutting plane is a parameter of the cross section. Xc is the distance between Daft and the transversal section, taken on the XX axis.

*Figure 4-19 : Sailing boat, cross section parameters*

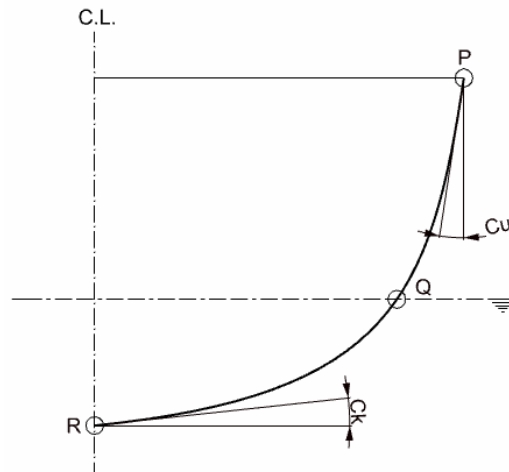Cu and Ck are two parameters to control the shape of the form curve. Cu is the angle included between the plane XZ passing through point P and the hull. Ck is the angle taken in between the XY plane passing through R and the hull. The setting of the cross section depends also to other parameters that have been already explained, such as T, Bwl and Bmax.

In Table 4-1 are listed all the parameters that is possible to use to create the desired shape.

*Table 4-1: Hull Parameters*

| CURVE | PARAMETERS | DEFINITION | RESTRICTIONS [m] |
|---|---|---|---|
| Sheer Line | Daft | Vertical distance between the aftermost point of the sheer line and the lowest point of the underwater body. | 0 ≤ Daft ≤ 5 |
| | Dmid | Vertical distance between the middle point of the sheer line and the lowest point of the underwater body. | 0 ≤ Dmid ≤ 5 |
| | Dfwr | Vertical distance between the most forward point of the sheer line and the lowest point of the underwater body. | 0 ≤ Dfwr ≤ 5 |
| | Ld | Longitudinal distance measured from Daft to Dfrw. | 0 < Ld < 24 |
| | Xs | Longitudinal distance between Daft and Dmid | 0 < Xs < 24 |
| Transom | Tl | Longitudinal distance between the aftermost point of the sheer line and the lowest point of the transom line. | -3 ≤ Tl ≤ 3 |
| | Tv | Vertical distance measured between the lowest point of the hull and the lower point of the transom. | 0 ≤ Tv ≤ 5 |
| | Th | Horizontal distance between aftermost point of the deck line and centreline plane. | 0 ≤ Th ≤ 4 |
| | Td | Angle included between the hull and the XZ plane with centre at the most external point of the transom. | 0° ≤ Td ≤ 45° |
| | Tb | Angle taken in between the hull and the XY plane passing through the lower point of the transom. | 0° ≤ Tb ≤ 45° |

| Deck | XBmax | Longitudinal distance between aftermost point of the hull and maximum beam point. | $0 \leq XBmax \leq 24$ |
| --- | --- | --- | --- |
| | Bmax | Horizontal distance between the centreline plane and Bmax. | $0 \leq Bmax \leq 12$ |
| | Dr | Angle included between the hull and the YZ base plane. | $0° \leq Dr \leq 120°$ |
| | De | Angle taken in between the centreline plane and the hull at the most forward point of the deck. | $0° \leq De \leq 45°$ |
| Keel | Xt | Longitudinal distance from Daft and the lowest point of the hull. | $0 \leq Xt \leq 24$ |
| | Kt | Angle taken in between the YZ plane passing through lower transom point and the hull. | $0° \leq Kt \leq 90°$ |
| | Kla | Angle taken in between the XY plane and the aft part of the hull at the lowest point of the keel | $0° \leq Kla \leq 45°$ |
| | Klf | Angle taken in between the XY plane and the forward part of the hull at the lowest point of the keel. | $0° \leq Klf \leq 45°$ |
| | Pl | Longitudinal distance between Dfrw and the aft point of the fillet segment of the keel line. | $0 < Pl < 5$ |
| | Pv | Vertical distance between XY plane and the aft point of the fillet segment of the keel line | $0 < Pv < 5$ |
| | Pa | Angle included between the XY plane passing through the aft point of the fillet segment and the aft part of the hull | $0° \leq Pa \leq 30°$ |
| | Pf | Angle included between the XY plane passing through the aft point of the fillet segment and the forward part of the hull. | $0° \leq Pf \leq 30°$ |
| | Kb | Angle taken in between the vertical plane passing through the bow lower point and the keel line. | $0° \leq Kb \leq 45°$ |
| Bow | Bu | Angle included between the vertical plane passing through the most forward point of the hull and the bow line. | $0° \leq Bu \leq 45°$ |
| | Bd | Angle taken in between the ZY plane passing through the lower point of the bow contour and the bow line. | $0° \leq Bd \leq 45°$ |
| | Bv | Vertical distance taken in between the lower point of the bow and the lowest point of the keel. | $0 \leq Bv \leq 2$ |
| | Bl | Longitudinal distance taken in between the lower point of the bow and the Dfrw. | $0 \leq Bl \leq 3$ |
| Waterline | Bwl | Horizontal distance between centrreline plane and control point Bwl. | $0 \leq Bwl \leq 8$ |
| | XBwl | Longitudinal distance between aftermost point of the hull and XBwl control point. | $0 \leq XBwl \leq Loa$ |
| | T | Vertical distance between the waterline and the lowest point of the hull. | $0 \leq T \leq 2$ |
| | Ewl | Angle included between the waterline and the centreline plane. | $0° \leq Bd \leq 90°$ |
| | Rwl | Angle included between the waterline and the YZ base plane. | $0° \leq Bd \leq 90°$ |
| | Cw | Waterplane area coefficient | $0 < Cw < 1$ |

| Cross-section | XC | Longitudinal distance measured between Daft and cross-section. | 0 < XC < 24 |
|---|---|---|---|
| | Cu | Angle included between the XZ plane passing through the top point of the cross-section and the hull. | 0° ≤ Cu ≤ 45° |
| | Ck | Angle taken in between the XY base plane and the hull, at the cross-section. | 0° ≤ Ck ≤ 45° |

Once obtained all the main curves (deck line, design waterline, keel line, bow contour line and transom), they have been used to generate the required hull surfaces. The transom surface has been created separately and then joined together with the other surface, producing the total final shape.
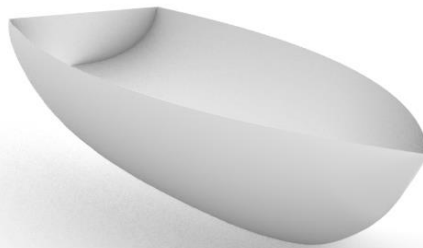


*Figure 4-20 : Hull surface*

As a complement of the modelling work, the code was implemented with some hydrostatic calculations and the production of drawings that are used to assist in the study of the quality assessment and of the analysis of the final characteristics of the hull produced.

Regarding the hydrostatic characteristics, are computed the displacement volume, the longitudinal position of the centre of buoyancy, the waterplane area and the longitudinal position of the geometric centre of it. Moreover, it is elaborated a set of form coefficients that includes block coefficient, prismatic coefficient, waterplane are coefficient and midship section coefficient. The longitudinal and transversal inertias and the respective metacentric radius are also calculated in the script.

Regarding the graphic results of the script, the Sectional Area Curve and the Lines Plan are produced as output. The generation of the Lines Plan is a very important step. It is composed by the three views of the hull: front, top and side. With this 2D representation it is possible to have a better understanding of the shape of the vessel. It is also possible to obtain the coordinates of the intersection points that are used to produce the Offset Table.

The generation of the Lines Plan started with the division of the ship into the longitudinal, vertical, and horizontal way. Longitudinally it has been divided with twenty planes, vertically it has been divided using five planes and horizontally it has been divided by six planes plus the middle plane. The choice of the number of sections is up to the user. From each intersection between the hull and the planes one specific curve has been obtained. The curves, that appear in the side view, comes from the intersection with the XZ planes (the buttocks) and the projection to the centreline plane. The curves obtained from the intersection with the XY planes (the waterlines) have been projected to the XY plane with origin in (0,0,0), which can be observed by the top view. The result is shown in Figure 4-21.
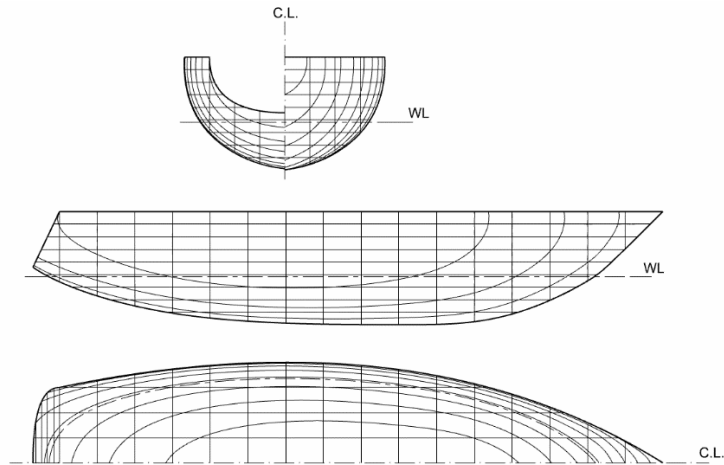
*Figure 4-21 : Sailing yacht displacement hull lines plan.*

In the lines plan, according to the most common representation, it is drawn the waterline.

The representation of the front view is a bit more complex than the side and top views. In order to have a better understand of the drawing the sections are divided into two distinct groups. The sections included between the aftermost point of the hull and the maximum beam of the yacht make part of the first group and the sections comprised between the maximum beam of the vessel and the most forward point of the hull represent the second group. Now, it is taken a YZ plane with centre in the aftermost point of the yacht, it is split by the centreline plane into right side and left side. Finally, it is now possible to project the first group of sections on the left side and the second group on the right side. This organization makes possible the representation of all the sections in one single view with more clearness and order.

|  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WL1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| WL2 | 0.00 | 0.71 | 0.74 | 0.77 | 0.81 | 0.85 | 0.89 | 0.91 | 0.91 | 0.86 | 0.76 | 0.65 | 0.56 | 0.46 | 0.36 | 0.26 | 0.15 | 0.03 | 0.00 | 0.00 |
| WL3 | 0.00 | 1.21 | 1.23 | 1.25 | 1.28 | 1.31 | 1.33 | 1.35 | 1.35 | 1.34 | 1.31 | 1.26 | 1.14 | 0.97 | 0.79 | 0.61 | 0.44 | 0.26 | 0.06 | 0.00 |
| WL4 | 0.00 | 1.28 | 1.31 | 1.34 | 1.37 | 1.40 | 1.42 | 1.44 | 1.44 | 1.44 | 1.42 | 1.39 | 1.34 | 1.27 | 1.16 | 1.02 | 0.84 | 0.61 | 0.35 | 0.05 |
| WL5 | 0.00 | 1.35 | 1.38 | 1.41 | 1.44 | 1.47 | 1.49 | 1.51 | 1.52 | 1.52 | 1.51 | 1.49 | 1.46 | 1.41 | 1.34 | 1.23 | 1.08 | 0.88 | 0.62 | 0.30 |

*Figure 4-22: Displacement sailboat, offset table*

In Figure 4-22 It is represented the Offset Table of the sailing yacht. The script allows to change the number of sections produced in the Table (parameter Ot).
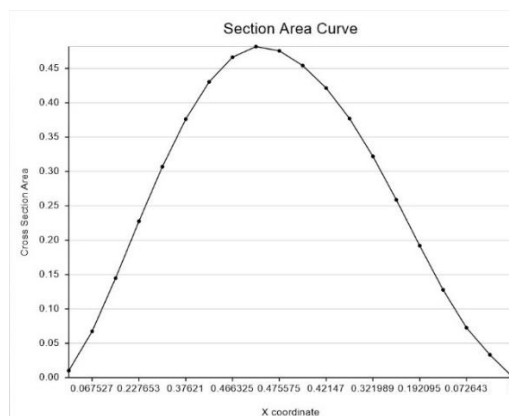


*Figure 4-23: Displacement sailboat, section area curve*

Figure 4-23 shows the X coordinate and the cross-section area of the sailing yacht. Parameter Sac permits the user to set the number of cutting planes, so he can decide the definition of the graph.

## 4.3 Validation

Once completed the coding of the script, it starts the work of validation of the output. It is now possible to choose a real sailing yacht hull and make a comparison with the model elaborated. This is an important step to verify the accuracy of the obtained model, the kind of forms that can be reproduced and also to identify regions requiring further improvements.

The Lines Plan used to undertake the validation is the Figaro Solo of 1989 and 1992, designed by Groupe Finot and Jean Berret, constructed in the shipyard Bénéteau.
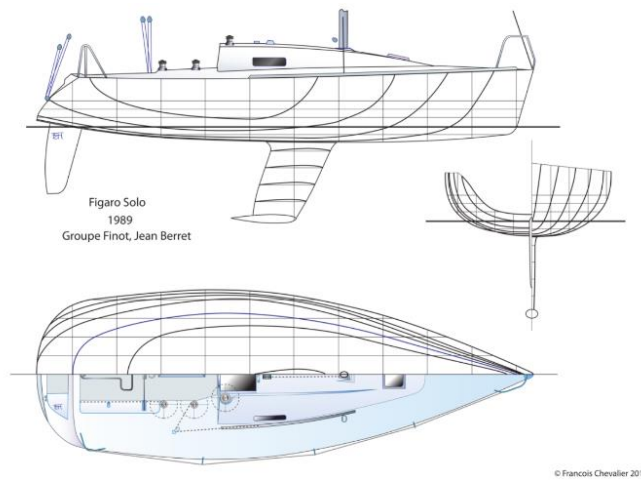


*Figure 4-24: Lines Plan Figaro Solo. Image taken from http://chevaliertaglang.blogspot.com/2017/01/the-figaro-single-handed-jubilee-1966.html*

The Lines Plan in Figure 4-24 has been analysed using the software Rhinoceros 3D. All the parameters requested by the model have been collected and inserted as input into the code.
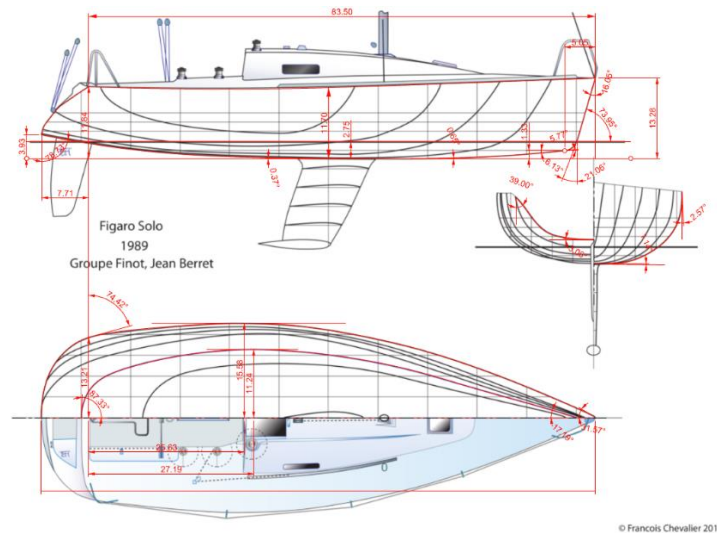


*Figure 4-25: Figaro Solo analysis of main parameters*

The linear dimensions of Figure 4-25 are expressed in decimetres, they are transformed in meters to be input of the code, as well as the angles that are transformed from degrees in radians. Table 4-2 shows all the parameters of the racing sailing yacht Figaro Solo that have been collected from the Lines Plan and inserted in the Grasshopper code.

Table 4-2: Figaro Solo input parameters

| LINE | PARAMETER | DISTANCE [m] | ANGLE [rad] |
|---|---|---|---|
| SHEER | Ld | 8.35 | |
| | Daft | 1.18 | |
| | Xs | 3.95 | |
| | Dmid | 1.17 | |
| | Dfrw | 1.32 | |
| BOW | Bl | 0.5 | |
| | Bv | 0.13 | |
| | Bu | | 0.28 |
| | Bd | | 1.29 |
| DECK | XBmax | 2.56 | |
| | Bmax | 1.55 | |
| | Dr | | 1.30 |
| | De | | 0.39 |
| TRANSOM | Th | 1.32 | |
| | Tb | | 0.05 |
| | Td | | 0.68 |
| | Tv | 0.39 | |
| | Tl | 0.77 | |
| KEEL | Kt | | 1.36 |
| | Kla | | 0.01 |
| | Klf | | 0.01 |
| | Xt | 3.95 | |
| | Pa | | 0.11 |
| | Pv | 0.13 | |
| | Pl | 0.5 | |
| | Pf | | 0.10 |
| | Kb | | 0.37 |
| WL | XBwl | 2.7 | |
| | Bwl | 1.12 | |
| | Ewl | | 0.31 |
| | Rwl | | 1.55 |
| | T | 0.27 | |
| | Cw | 0.66 | |
| CS | XC | 2.56 | |
| | Cu | | -0.04 |
| | Ck | | 0.02 |

In Figure 4-26 the violet lines are the representation of the main curves created by the code. As it is possible to see the script can reproduce a good copy of the form curves of the original Figaro Solo construction lines.
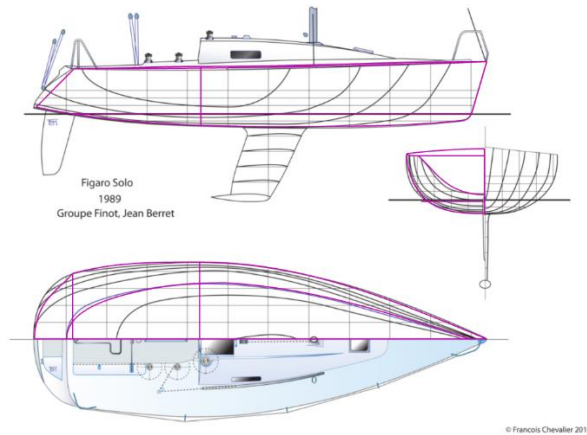
*Figure 4-26: comparison between grasshopper form curves and Figaro Solo lines plan.*

The code is not able to perform a perfect reproduction of all the main lines, the transom is the curve with the less precision, the code doesn't manage to perfectly reproduce the curve in neither one of the three views of the Lines Plan.

The deck line is well shaped, as much as the keel line and the bow line, which is a perfect copy of the Figaro Solo bow contour. The cross section has a good precision from keel to waterline, but in the upper segment of the curve it does not manage to follow the target line.
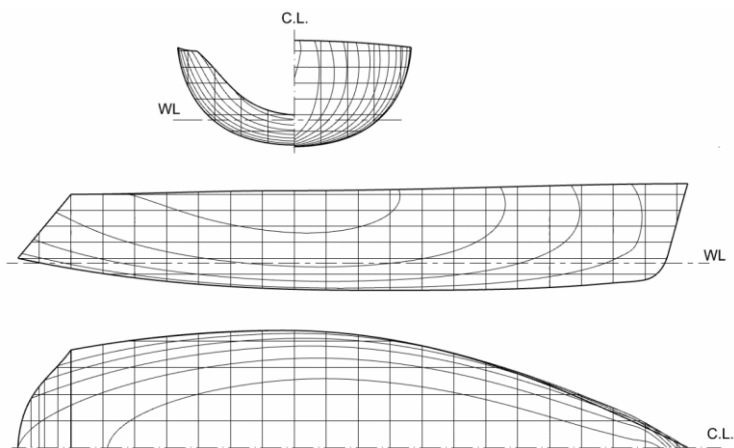


*Figure 4-27: Grasshopper lines plan using the parameters of Figaro Solo.*

The Lines Plan represented in Figure 4-27 is one of the most important output of the code, the thicker lines of the draw have been modified with Rhinoceros 3D to give more clearness to the draw. The surface is divided with 21 stations, 6 buttocks and 5 waterlines.

*Table 4-3: Grasshopper Offsets, using the parameters of Figaro Solo*

|     | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|-----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| WL1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| WL2 | 0.00 | 0.00 | 0.46 | 0.73 | 0.94 | 1.11 | 1.25 | 1.36 | 1.43 | 1.44 | 1.34 | 1.22 | 1.09 | 0.94 | 0.77 | 0.60 | 0.43 | 0.26 | 0.09 | 0.00 |
| WL3 | 0.89 | 1.17 | 1.37 | 1.53 | 1.65 | 1.74 | 1.79 | 1.82 | 1.84 | 1.83 | 1.75 | 1.63 | 1.49 | 1.32 | 1.12 | 0.91 | 0.68 | 0.45 | 0.21 | 0.00 |
| WL4 | 0.00 | 1.41 | 1.58 | 1.72 | 1.83 | 1.91 | 1.97 | 2.01 | 2.04 | 2.04 | 1.96 | 1.84 | 1.69 | 1.51 | 1.30 | 1.07 | 0.83 | 0.57 | 0.30 | 0.03 |
| WL5 | 0.00 | 1.66 | 1.80 | 1.92 | 2.01 | 2.07 | 2.12 | 2.15 | 2.16 | 2.14 | 2.06 | 1.95 | 1.80 | 1.63 | 1.42 | 1.19 | 0.94 | 0.67 | 0.39 | 0.09 |

The Offsets Table is an output of the Grasshopper code. This is the starting point of the study of the sailing yacht resistance. The number of columns and rows is defined by two division coefficients, one concerning the stations spacing and one related to the waterlines spacing. The two values divide one the length (Os) of the yacht and the other the depth (Od).
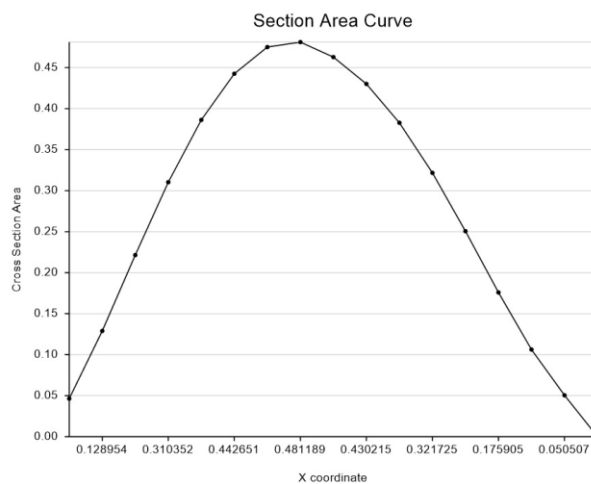
*Figure 4-28: Grasshopper cross area curve using the parameters of Figaro Solo.*

In Figure 4-28 it is represented the graph concerning the section area curve of the surface created by the Grasshopper's code. Grasshopper does not have a strong graph function, so it doesn't manage to produce the axis, to do so it is necessary the use of a Plug-in called ''Climatestudio''. On the longitudinal axis there are the values regarding the spacing of the yacht waterline length, which is divided by a coefficient equal to 0.6, which is a parameter that can be modified at user need.

*Table 4-4: Main dimensions.*

| | | |
|---|---|---|
| Loa | 12.6 | [m] |
| Lwl | 11.42 | [m] |
| DraftBow | 1.80 | [m] |
| B | 4.4 | [m] |
| Bwl | 3.03 | [m] |
| Freeboard | 0.53 | [m] |
| Immersion | 0.45 | [m] |
| Cb | 0.39 | [-] |
| Cwp | 0.69 | [-] |
| Cm | 0.69 | [-] |
| Cp | 0.57 | [-] |
| Lcf | 5.04 | [m] |
| Lcb | 5.30 | [m] |
| Inertia Tr | 12.72 | [m^4] |
| Inertia L | 169.38 | [m^4] |
| Metacentric Transversal Radius | 0.49 | [m] |
| Metacentric Longitudinal Radius | 6.56 | [m] |
| cross section area | 0.96 | [m^2] |
| waterplane area | 12.01 | [m^2] |

The last output of the code is the table of the main dimensions. Grasshopper is not provided with a good function that permit the generation of a file excel above which it is possible to write all the measures and coefficients. To create the excel table it is added a Plug-in called ''LunchBox''.

# 5 Displacement Hull for Motor Yachts

## 5.1 Analysis of Form Characteristics

The displacement motor yachts present a smooth rounded hull, that do not have any big angular changing from keel to deck as we will see in the planning ones. The motor yacht displacement hulls find many similarities with the sailing yachts studied in the previous chapter.

For this reason, the analysis follows the same procedure used in the sailing vessel displacement hulls. The main useful curves for the creation of the final shape have been identified.

The curves defined are sheer line, deck line, waterline, bow line, keel line, transom line and cross section.

Sheer Line

This curve presents two main different kinds of behaviour. It can be straight, or concave. In the first case it can be parallel to the waterplane, or it can be inclined with a positive angular coefficient.

When the form curve is concave it can have a point with tangent parallel to the waterplane (Tan0), in this configuration from transom it goes down and then rise again at the bow. The most forward point of the sheer can have the same Z coordinate of the aftermost point of the line (c), or it can have a higher value (d). The delta between the Z coordinates of the two points is identified with Sd. Usually, the point of 0 tangent is before the Lpp/2.
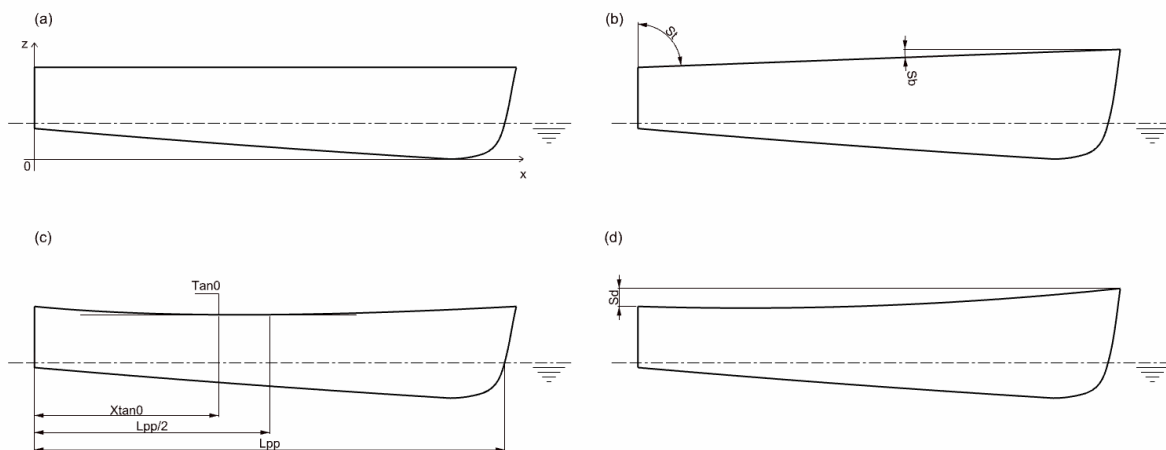


*Figure 5-1: General behaviours of the sheer line*

The angle (St) taken between the YZ base plane, and the sheer line can vary between 82° and 94°. The tangent position is measured with the difference between Lpp/2 and the tangent point, on the XX axis (Lpp/2-XTan0), and it is studied as percentage of the Loa. The maximum value found is 34% of Loa.

At the point Tan0 the tangent forms two angles with the hull, the aft angle has a maximum value of 4° and the forward angle of 3°. The angle (Sb) formed between the sheer line and the XY plane with origin at the extreme bow can reach 15°.

Deck Line

The deck line presents itself like a smooth rounded curve that starts from the bow with an entrance angle that goes from 32° to 63°. It has an increasing Y value until it reaches the maximum beam and then it starts to decrease.
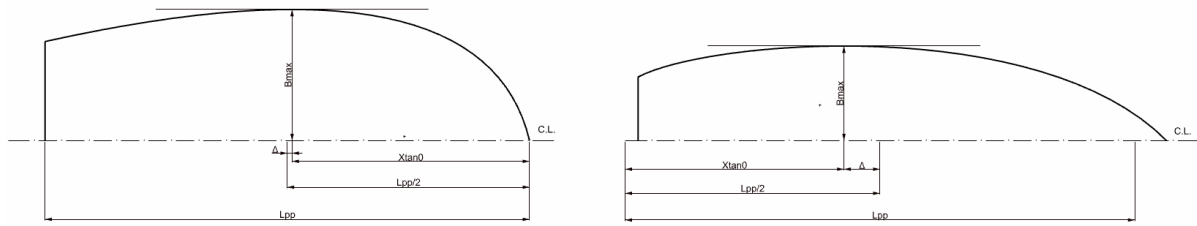
*Figure 5-2: Deck line parameters*

The maximum beam can be before or after the middle length point. The distance from the Lpp/2 in the first case can reach 9% of Loa and in the second case it can reach the value of 10% of Loa. The deck line finds its end at the connection with the transom line. In some cases, when the design surface is without transom, the end of the form curve is directly connected to the profile (Figure 5-3 image on the left). The angle of run is taken between the YZ base plane and the deck line at the transom connection point, its values go from 79° to 87°.
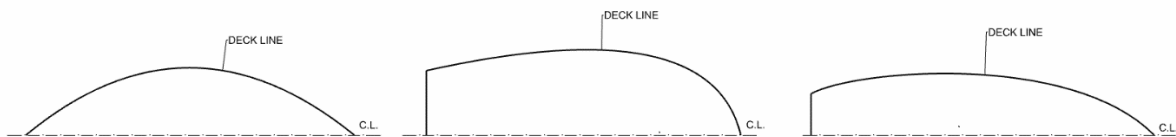


*Figure 5-3: Deck line possible settings*

All the cases studied presented this rounded kind of behaviour. So, it has been decided to define the constrains of the two angles included in between the plane parallel to the XZ base plane with centre at the maximum beam and the deck line. The angle before the point of tangency goes from 1° to 3° and the angle after goes form 1° to 4°.
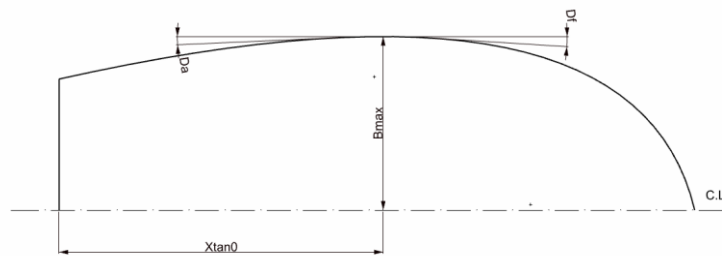


*Figure 5-4: Da, Df parameters included between Tan0 and deck line*

Waterline

This is one of the most important lines of the design. The waterline form follows the deck line shape, but it has its own parameters and values, completely separated from the deck curve.
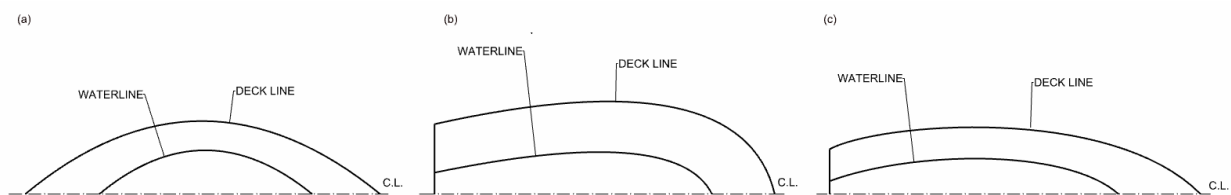


*Figure 5-5: Waterline shape*

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The waterline can have a different entrance angle (Ew) from the deck line, which values go from 19° to 30° with a maximum variation in front of the entrance angle at the deck of the 64% in some cases. The maximum waterline beam can be located in the same place of the deck maximum beam, but it can also be back or in front of it. The position of the point of maximum beam is measured looking at its distance from the Lpp/2, following the methodology adopted in the deck line analysis. Bwl can be set, aft or forward the Lpp/2 depending on the design target.
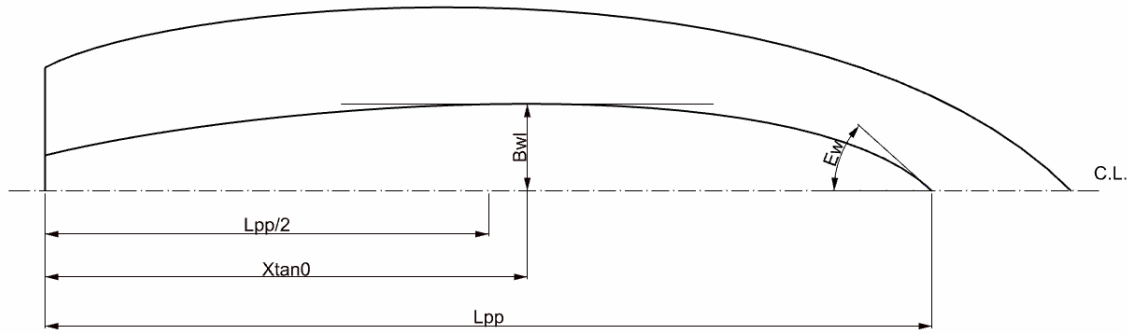


*Figure 5-6: Waterline maximum beam located forward the Lpp/2*

In Figure 5-6 it is represented a waterline with the maximum beam placed in front of the Lpp/2.

Bow Contour

Usually, the bow contour is a straight line, but in some cases, it can be curved, or it can be straight near the deck, and it can present a curvature in proximity of the connection with the keel. The angle (Bu) between the plane perpendicular to the waterline with origin at the highest point of the bow contour varies from 0° to 25°.

The upper external angle (Bwu) between the form curve and the waterline goes from 40° to 73°. The lower internal angle (Bwd) taken between the bow line and the waterline goes from 37° to 70°.
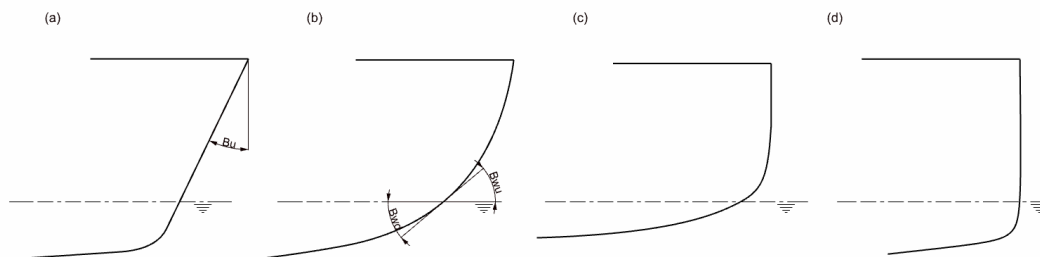


*Figure 5-7: Bow contour different curvatures*

Keel Line

This is one of the most complex curves to develop, because it presents the most vary configuration of shapes. All the analysed keels have a central straight segment. The final part of the line is a segment connected to the bow contour, that is always rounded.
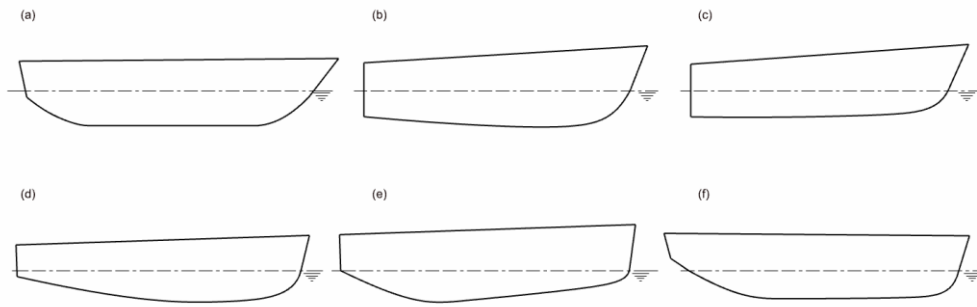
*Figure 5-8: Keel configurations*

The angle (Pb) formed at the connection point between the keel line and the bow contour between the YZ plane passing through the point and the keel curve goes from 38° to 70°.

The part of the keel that is linked with the transom can be straight or rounded, the angle (Kt) included between this segment and the YZ plane with centre at the lower point of the transom, goes from 62°to 89°.
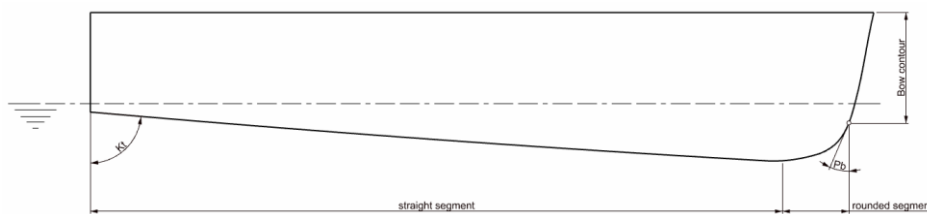


*Figure 5-9: Keel line, angle at the connection with the bow contour and at the transom*

The keel central segment can be parallel to the XY plane, or it can have an inclination. The form curve presents the possibility to have a Tan0 point along its length. It has been studied the distance between the point and the Lpp/2 and the angles before and after the intersection point. The length of the segment has a maximum extension of 30% of Loa.

The angle (Ksa) at the start of the straight segment has a range that goes from 0° to 3° and the values of the angle (Ksf) after the segment go from 0°to 2°.
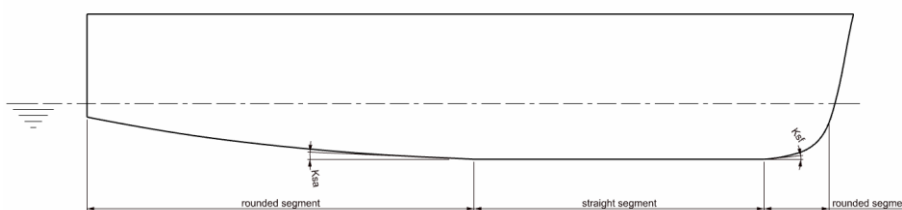


*Figure 5-10: Keel line with rounded segment at the transom connection*

Transom Line

The last curve in analysis is the transom line. The transom in the displacement motor yachts can be composed of straight or rounded segments. The curvature that can be observed from the top view, the concavity bow way of the rounded cases has been studied through two angles. The external one (Td) has been taken between a plane parallel to the centreline plane and the transom line. The other (Ti) has been taken between the centreline plane at the aft point of the ship and the transom curve. The values of the first angle vary from 60° to 90° and the values of the second one goes from 90° to 86°.
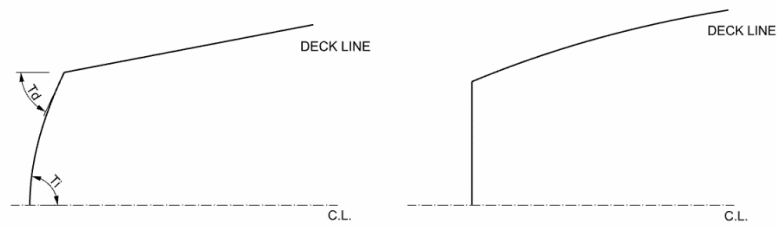
*Figure 5-11: Transom shape top view*

From the top view of Figure 5-11 it is possible to notice the two transom shapes, the one on the right presents a curvature and the one on the left is designed with a straight line.

The surface of the transom can be parallel to the YZ plane, or it can be inclined in direction of the bow with an angle (Tb) that can reach 23°. The angle in object is included between the vertical line of the transom and the plane YZ with centre at the aft point of the hull.
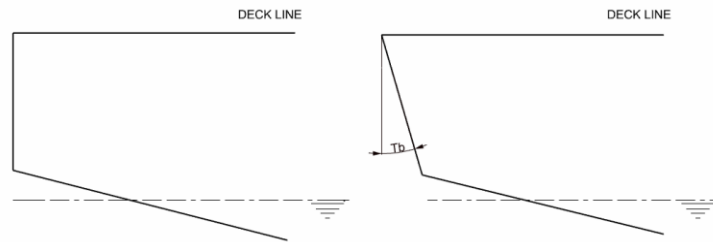


*Figure 5-12: Transom shape side view*

Figure 5-12 represent a side view of two possible transom designs. In the left one geometry is perpendicular to the deck. In the right image it is reported an inclined transom.
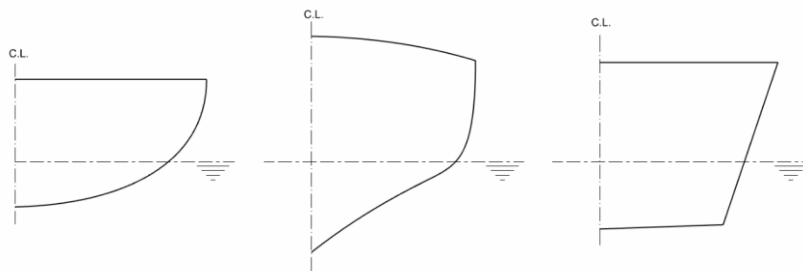


*Figure 5-13: Transom shape back view*

In Figure 5-13 are represented two different rounded shapes and one shape designed with straight lines, which is more common in the planning motor yacht hulls.

## 5.2   Modelling Methodology

The displacement motor yacht hull is a kind of form which, as the speed changes, more the less maintains the same hull volume.

Some design characteristics of this kind of vessel are like the sailing yacht displacement hulls. For this reason, some steps of the following parametric model adopt the same methodology of the one described in chapter 4.2. The sheer line of a displacement motor yacht can be straight or concave, parallel to the waterplane or inclined, so its configurations are the same of a sailing yacht displacement hull. The design of this line is the same of the one previously described. In chapter 3.2.2 the parameters used to control this curve are Daft,

Dmid, Dfwr, Ld and Xs, so it is in the script of the displacement motor yacht hull. The deck line follows the same modelling methodology used for the sailing yacht, as for the sheer line it happens for the deck line, it is possible to observe the construction of this form curves in the previous chapter. In the design of the motor yacht are used the following parameters to modify the shape of the deck line, XBd, Bd and Bt. The last curve that follows the same modelling methodology of the previous model is the cross-section. The remaining form curves, bow line, keel line, waterline, and transom line must accomplish different hydrostatic and hydrodynamic characteristics from a sailing yacht, so their shape needs to present different properties.

The bow line must be able to be straight or rounded. To permit these two different settings the curve has been designed with one interpolated line, with control over the angles at the upper point and at the lower one. The upper point (A) is the already existing connection point between deck line and sheer line. The lower point (H) X coordinate can be set choosing its distance from Dfrw, this parameter is called Hl. It is possible to impose the vertical position of H setting, with the parameter Hv, the distance from the lowest point of the hull.
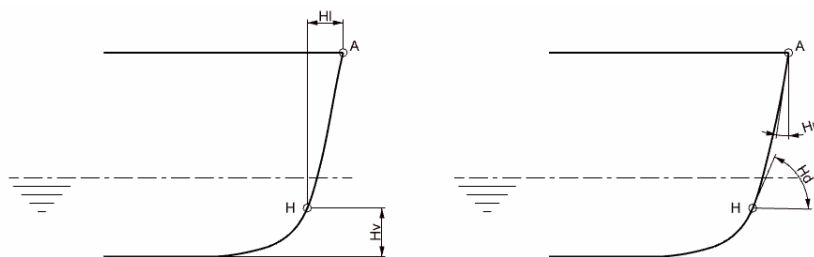


*Figure 5-14: linear and angular parameters concerning the bow contour.*

The curve created with these two points have two more parameters to control its shape. One is the angle (Hu) included between the bow contour and the YZ plane with centre at the upper point, the other is the angle (Hd) included between the bow line and the XY passing through point H.

The last point of the bow line is the first point of the keel line, but before starting this form curve it is necessary to elaborate the transom and its three curves.

Once modelled the bow contour it is defined the transom shape. The first line created is the line CF which is modelled using three control points, to permit the curve to be able to assume a concave shape. It is used the NURBS curve. The start point is the aftermost point of the sheer line. The end point is the aftermost point of the deck, which constructions have already been explained in the sailing boat chapter. In the design of the motor yacht this line is provided with a new parameter, Tb. After this modification the end point can be modelled using two parameters, one to set the longitudinal distance from the Daft, Td and the other is used to control the horizontal distance from the centreline plane, which is the beam of the transom, Th. The point C' is constructed with the same X,Z coordinates of C, with exception of the Y value that is equal to Th/2.
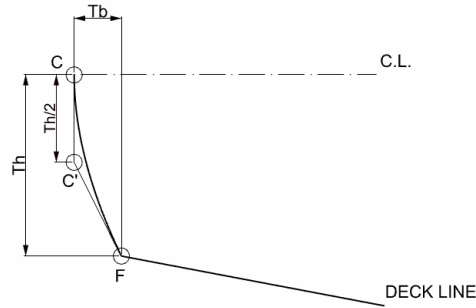
*Figure 5-15: Transom line CF parameters*

The second line starts from point C of the sheer line and ends at a new point G, that lies on the centreline plane. The parameters of G are longitudinally, the distance from Daft and vertically, the distance from the lowest point of the hull.
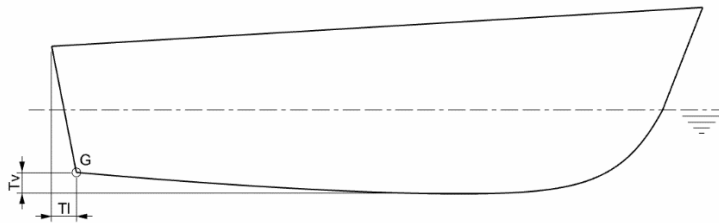


*Figure 5-16: Transom contour parameters*

The third line of the transom is the one connecting point F with point G. The 3D form curve in object is designed with the same modelling methodology of the one of the sailing yacht, its parameters are Tu for the control over the tangent at point F and Td for the control over the tangent at point H.
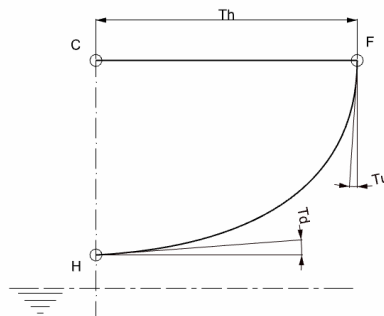


*Figure 5-17: transom parameters*

After the transom it has been possible to create the keel line. It is a 2D curve that lies on the longitudinal centreline plane. The first and the last points of the keel line are the lower point of the bow line H and the lower point of the transom G. Two new points are created, point I corresponding to the lowest point of the hull and point L corresponding to the end of the straight segment of the keel line. The two points can be set with the same Z coordinate, to produce a central straight segment parallel to the waterplane. It is possible to modify the angle between the XY plane with centre at the respective point and the tangent at L and I with two angular parameters, Ksa (for L) and Ksf (for I).
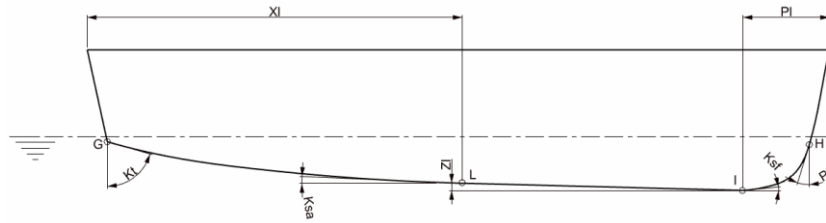
*Table 5-1: Parameters of the keel form curve.*

Kt and Pb are the parameters, corresponding to the angles at G and H, which are included between the YZ plane passing through the point and the tangent to the keel line at the respective point. Xl is the parameter that allows the user to set the longitudinal distance of point L from Daft, by the other side Pl is the parameter with which it is possible to rule the distance from Dfrw to point I. The last parameter of point L, Zl, controls its vertical distance from the lowest point of the hull.

Once obtained the profile it became possible to elaborate the waterline. This is a 2D form curve, that lies on the waterplane. The draft (T), which is the vertical distance from the lowest point of the hull and the waterplane, is a parameter of the form curve. The intersection points (O and M) between the profile curve and the waterplane are the start and the end point of the waterline. The third control point N finds its position in between O and M. N is the point corresponding to the maximum beam of the waterline, represented in Figure 5-18, to which is connected the parameter Bwl. In this point the hull is tangent to the XZ plane passing through N. Two other parameters are added to the form curve, the angle of run (Rwl), and the entrance angle (Ewl). Both the angles are included between the centreline and the tangent to the hull.
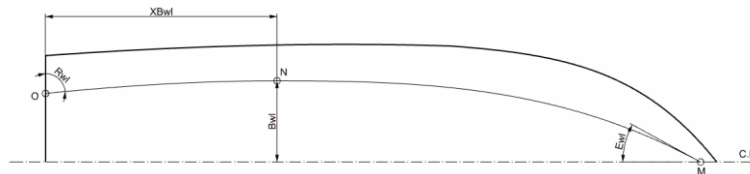


*Figure 5-18 : Sailing boat, waterline curve parameters*

The last line that has been created to be able to design the hull surface is the cross section.

The transversal section is an interpolated curve that passes through three points, all of them identified by the intersection between the hull and a YZ plane, more specifically the control points are at the deck line at the waterline and at the keel line. The longitudinal position of the cutting plane (Xc) is a parameter of the cross section. Xc is the distance between Daft and the transversal section, taken on the XX axis.
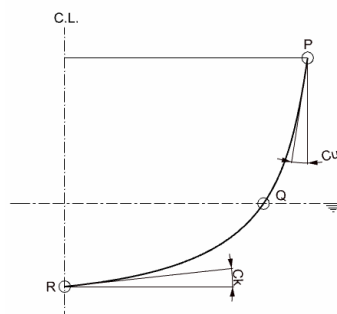


*Figure 5-19 : Sailing boat, cross section parameters*

Cu and Ck are two parameters to control the shape of the form curve. Cu is the angle included between the plane XZ passing through point P and the hull. Ck is the angle taken in between the XY plane passing through R and the hull.

The setting of the cross section depends also to other parameters that have been already explained, such as T, Bwl and Bmax.

*Table 5-2: Parameters of displacement hull for motorboat*

| CURVE | PARAMETERS | DEFINITION | RESTRICTIONS [m] |
|---|---|---|---|
| Sheer Line | Daft | Vertical distance between the aftermost point of the sheer line and the lowest point of the underwater body. | 0 ≤ Daft ≤ 5 |
| | Dmid | Vertical distance between the middle point of the sheer line and the lowest point of the underwater body. | 0 ≤ Dmid ≤ 5 |
| | Dfwr | Vertical distance between the most forward point of the sheer line and the lowest point of the underwater body. | 0 ≤ Dfwr ≤ 5 |
| | Ld | Longitudinal distance measured from Daft to Dfrw. | 0 < Ld < 24 |
| | Xs | Longitudinal distance between Daft and Dmid | 0 < Xs < 24 |
| Transom | Tl | Longitudinal distance between Daft and the lowest point of the transom line. | -3 ≤ Tl ≤ 3 |
| | Tv | Vertical distance measured on the YZ plane between lowest point of the hull and lower point of the transom. | 0 ≤ Tv ≤ 5 |
| | Th | Horizontal distance between transom deck connection point and centreline plane. | 0 ≤ Th ≤ 4 |
| | Tu | Angle included between the hull and the XZ plane at the most external point of the transom. | 0° ≤ Tu ≤ 45° |
| | Td | Angle taken in between the hull and the XY plane passing through the lower point of the transom. | 0° ≤ Td ≤ 45° |
| | Tb | Longitudinal distance between Daft and aftermost deck point | 0 < Tb < 1 |
| Deck | XBmax | Longitudinal distance between aftermost point of the hull and maximum beam. | 0 ≤ XBmax ≤ 24 |
| | Bmax | Horizontal distance between the centreline plane and Bmax. | 0 ≤ Bmax ≤ 12 |
| | Dr | Angle included between the tangent at the aftermost point of the hull and the YZ base plane | 0° ≤ Dr ≤ 120° |
| | De | Angle taken in between the centreline plane and the hull tangent at the most forward point of the deck. | 0° ≤ De ≤ 45° |
| Keel | Xl | Longitudinal distance from Daft and point L. | 0 ≤ Xl ≤ 24 |
| | Kt | Angle taken in between the vertical base plane and the hull, at the transom connection point. | 0° ≤ Kt ≤ 90° |
| | Ksa | Angle taken in between the XY plane and the aft part of the hull at point L. | 0° ≤ Ksa ≤ 45° |

| | | | |
|---|---|---|---|
| | Ksf | Angle taken in between the XY plane and the forward part of the hull at the lowest point of the keel. | 0° ≤ Ksf ≤ 45° |
| | Pl | Longitudinal distance between Dfrw and the lowest point of the keel line. | 0 < Pl < 5 |
| | Zl | Vertical distance between point I (lowest hull point) and point L. | 0 < Zl < 5 |
| | Pb | Angle taken in between the vertical plane passing through the bow lower point and the keel line. | 0° ≤ Pb ≤ 45° |
| Bow | Hu | Angle included between the vertical plane passing through the most forward point of the hull and the bow line. | 0° ≤ Bu ≤ 45° |
| | Hd | Angle taken in between the XY plane passing through the lower point of the bow contour and the bow line. | 0° ≤ Bd ≤ 90° |
| | Bv | Vertical distance taken in between the lower point of the bow and the lowest point of the keel. | 0 ≤ Bv ≤ 2 |
| | Bl | Longitudinal distance taken in between the lower point of the bow and the Dfrw. | 0 ≤ Bl ≤ 3 |
| Waterline | Bwl | Horizontal distance between centreline plane and control point Bwl. | 0 ≤ Bwl ≤ 8 |
| | XBwl | Longitudinal distance between aftermost point of the hull and XBwl control point. | 0 ≤ XBwl ≤ 24 |
| | T | Vertical distance between the waterline and the lowest point of the hull. | 0 ≤ T ≤ 2 |
| | Ewl | Angle included between the waterline and the centreline plane. | 0° ≤ Bd ≤ 90° |
| | Rwl | Angle included between the waterline and the YZ base plane. | 0° ≤ Bd ≤ 90° |
| Cross-section | XC | Longitudinal distance measured between Daft and cross-section. | 0 < XC < 24 |
| | Cu | Angle included between the XZ plane passing through the top point of the cross-section and the hull. | 0° ≤ Cu ≤ 45° |
| | Ck | Angle taken in between the XY base plane and the hull. | 0° ≤ Ck ≤ 45° |

The final shape has been created joining two surfaces the transom surface and the hull surface. The transom surface is the one contained by the transom lines and the hull surface is the one that goes from keel to deck and from the rounded transom curve to the bow line.
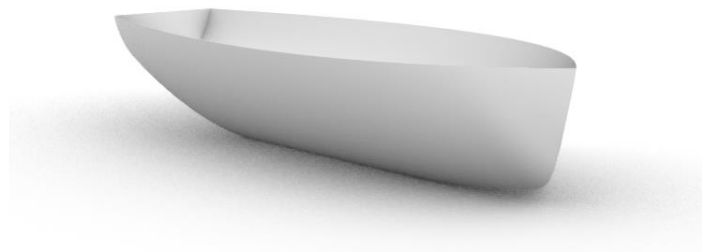


*Figure 5-20: Displacement motorboat, parametric surface*

All the calculations applied to the surface in chapter 3.2.2 have been applied to this case study. It has been used the same script to obtain the coefficients, the main dimensions, the section area curve, and the Offset Table.
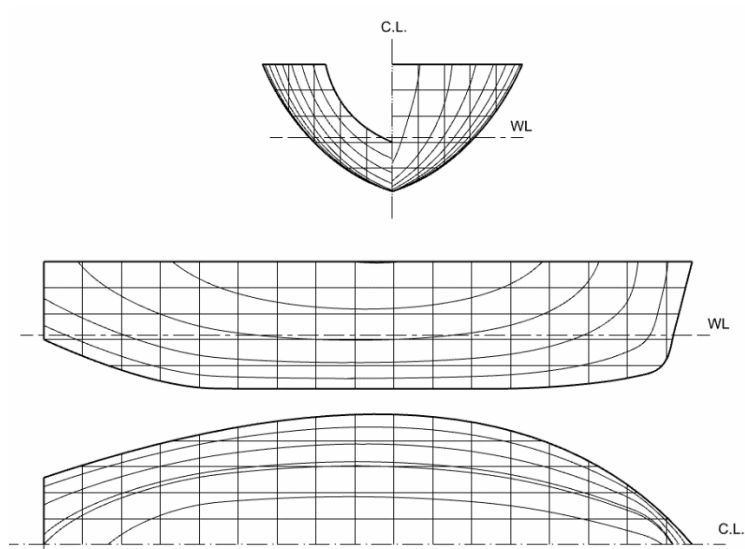


*Figure 5-21: Displacement motor yacht, lines plane*

Figure 5-21 shows the output of the code as the Lines Plan of the displacement motor yacht. The specific surface is a representative one, generic parameters have been used to generate it.
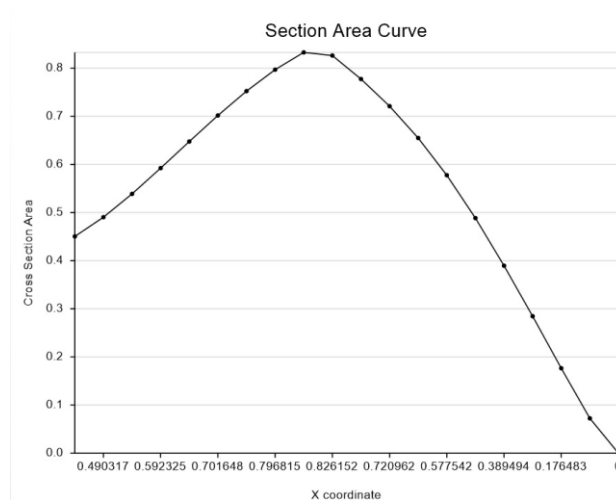


*Figure 5-22: Displacement motorboat, section area curve*

The graph shown in Figure 5-22Figure 1-1 is the representation of the section area curve, such as the code of the sailing yacht the input of the displacement motor yacht is provided with a parameter with which is possible to set the number of sections to apply to the underwater volume.

## 5.3   Validation

The code of the displacement motor yacht hull is now complete, it can reproduce the hull surface with its main curves and the Lines Plan. Moreover, it can create the Offset Table and the main dimensions and coefficients table on excel.

In the following it will be carried out the validation work, in which it is chosen a real hull that will be compared with the model.
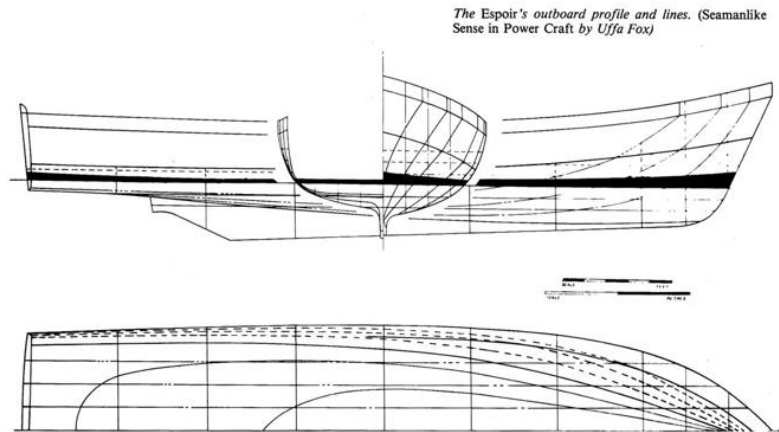


*Figure 5-23: Espoir motor yacht lines plan, designed by Uffa Fox. Image taken from https://www.pinterest.it/nicola5761/boat-plans/*

The motor yacht chosen for the validation of the code is the Espoir outboard designed by Uffa Fox. In the form study it has been done an approximation at the bow line, since at the top of it there is an angle that the code is not able to reproduce.
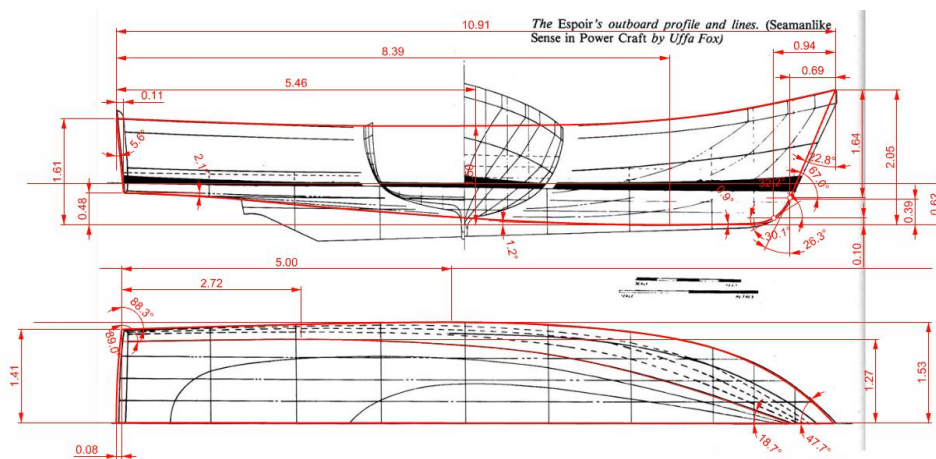


*Figure 5-24: Espoir's lines plan form study top and side view*
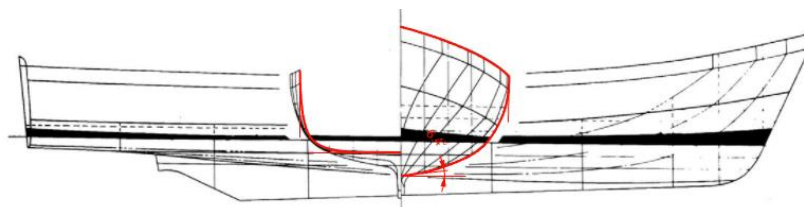


*Figure 5-25: Espoir's lines plan form study front view*

Once obtained all the measures of the displacement motor yacht, the angles have been changed from degrees to radians and then all the values have been inserted into the Grasshopper code.

*Table 5-3: Displacement motor yacht Grasshopper input parameters*

| LINE | PARAMETER | DISTANCE [m] | ANGLE [rad] |
|---|---|---|---|
| SHEER | Ld | 10.9 | |
| | Daft | 1.61 | |
| | Xs | 5.46 | |
| | Dmid | 1.5 | |
| | Dfrw | 2.05 | |
| BOW | Bl | 0.69 | |
| | Bv | 1.64 | |
| | Bu | | 0.40 |
| | Bd | | 1.17 |
| DECK | XBmax | 5 | |
| | Bmax | 1.53 | |
| | Dr | | 1.54 |
| | De | | 0.44 |
| TRANSOM | Th | 1.41 | |
| | Td | | 0.00 |
| | Tu | | 0.00 |
| | Tv | 0.48 | |
| | Tl | 0.11 | |
| KEEL | Kt | | 0.04 |
| | Ksa | | 0.02 |
| | Ksf | | 0.02 |
| | Xl | 8.39 | |
| | Zl | 0.1 | |
| | Pl | 0.69 | |
| | Pb | | 0.46 |
| WL | XBwl | 2.72 | |
| | Bwl | 1.27 | |
| | Ewl | | 0.33 |
| | Rwl | | 1.55 |
| | T | 0.33 | |
| CS | Ck | | 0.00 |
| | Cu | | 0.11 |
| | Xc | 5 | |

Once all the values have been inserted into the code it is possible to start to extract the main lines of the model. The violet lines, which are the once created by Grasshopper, have been put onto the target lines plan. All the appendices are not taken into consideration in the study.
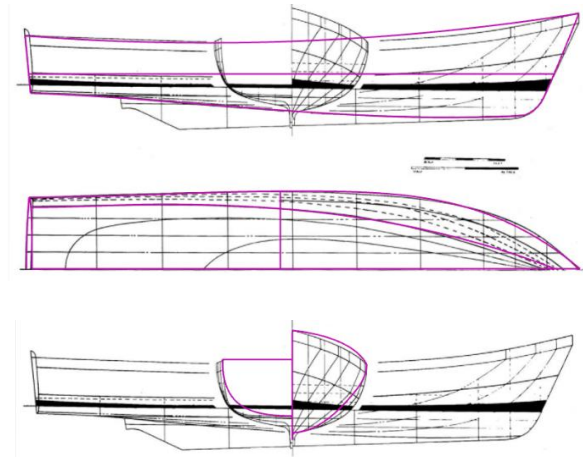
Figure 5-26: Main lines created by the Grasshopper code using the values of the Espoir.

As is it possible to see in Figure 5-26 not all the lines correspond to the target curves. The deck line, the keel line and the waterline have a good precision, but the transom line and the cross-section area, because of their complex shape, are two difficult geometries to elaborate. The real curves are more rounded than the Grasshopper output.

These two lines need further investigation to reach the target. The deck line is a 3D curve, so its shape can be analysed from the three views, the top one shows a curvature very close to the Espoir's one, in the side one the trajectory appears higher than the desired one, which can be noticed also form the front view.
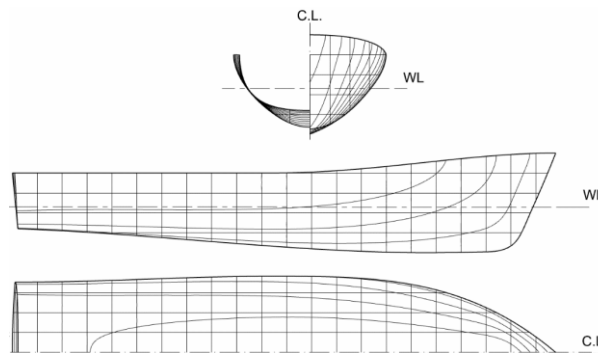


Figure 5-27: Lines plan generated by the Grasshopper code using the Espoir values.

The Lines Plan shown in Figure 5-27 is created with the same code of the displacement sailing yacht. It is provided with three parameters which control the spacing of the sections. Pv is the parameter which with is possible to modify the stations, Pw is the one which with is possible to set the number of waterlines and Pb changes the number of buttocks.

Table 5-4: Offset Table generated by the Grasshopper code using the Espoir values.

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WL1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.30 | 0.44 | 0.51 | 0.54 | 0.49 | 0.43 | 0.38 | 0.32 | 0.25 | 0.18 | 0.11 | 0.05 | 0.00 | 0.00 |
| WL2 | 0.00 | 0.88 | 0.90 | 0.93 | 0.95 | 0.97 | 0.98 | 0.98 | 0.97 | 0.94 | 0.87 | 0.81 | 0.73 | 0.64 | 0.54 | 0.42 | 0.30 | 0.16 | 0.03 | 0.00 |
| WL3 | 0.00 | 1.25 | 1.26 | 1.28 | 1.29 | 1.30 | 1.29 | 1.28 | 1.25 | 1.21 | 1.16 | 1.10 | 1.02 | 0.92 | 0.81 | 0.67 | 0.51 | 0.33 | 0.12 | 0.00 |
| WL4 | 0.00 | 1.37 | 1.39 | 1.40 | 1.42 | 1.43 | 1.44 | 1.44 | 1.44 | 1.42 | 1.39 | 1.34 | 1.28 | 1.20 | 1.10 | 0.96 | 0.78 | 0.56 | 0.29 | 0.00 |
| WL5 | 0.00 | 1.41 | 1.42 | 1.44 | 1.46 | 1.48 | 1.50 | 1.51 | 1.52 | 1.52 | 1.51 | 1.49 | 1.46 | 1.41 | 1.32 | 1.19 | 1.01 | 0.78 | 0.47 | 0.08 |

In Table 5-4 it is shown the Offset Table of the Espoir displacement motor yacht hull. The number of waterlines and stations can be set with two parameters Ow and Os. The parameters are division factors, which control the number of planes that divide the length over all and the depth of the hull.
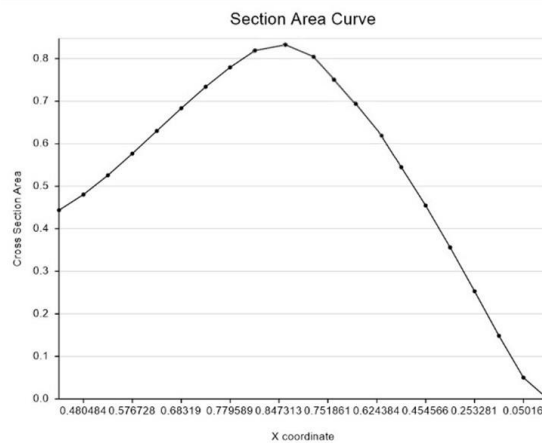
*Figure 5-28: Cross section area curve created by Grasshopper code using Espoir values*

Figure 5-28 represents the section area curve of the Espoir motor yacht, from this graph it is possible to see the behaviour of the underwater volume of the hull. The last output of the code, which concerns the main dimensions of the vessel, is shown in the table below. Moreover, the table provides some important hydrostatic calculations, which are used in the first steps of the preliminary project of the yacht.

*Table 5-5: Main dimensions obtained by the grasshopper code using the Espoir values*

| | | |
|---|---|---|
| Loa | 10.9 | [m] |
| Lwl | 10.3 | [m] |
| DraftBow | 1.59 | [m] |
| B | 3.06 | [m] |
| Bwl | 4.58 | [m] |
| Freeboard | 0.74 | [m] |
| Draft | 0.73 | [m] |
| Cb | 0.32 | [-] |
| Cwp | 0.38 | [-] |
| Cm | 0.39 | [-] |
| Cp | 0.81 | [-] |
| Lcf | 4.25 | [m] |
| Lcb | 4.64 | [m] |
| Inertia Tr | 6.25 | [m^4] |
| Inertia L | 116.45 | [m^4] |
| Metacentric Transversal Radius | 0.13 | [m] |
| Metacentric Longitudinal Radius | 2.50 | [m] |
| cross section area | 1.34 | [m^2] |
| waterplane area | 18.00 | [m^2] |

# 6  Planning Hull of Motor Yachts

## 6.1  Analysis of Form Characteristics

The planning hulls are the fastest of the three different typologies studied. Thanks to their shape when they gain enough speed part of the hull raises above the water. From this moment they are in the planning regime. The hulls characterized by this property are V-shaped and have squared forms with evident angles, plane regions and convex planes.

The lines needed to develop this kind of shapes are the following: sheer line, deck line, bow line, keel line, transom line and the chine line. This typology of hull has the most various shape possibilities. The planning hulls are characterized by a new line that didn't appear before, the chine line. The shell of these kind of yachts cannot be created with one single surface because of the hard change of angle that takes place at this new design component. The different geometry that is possible to give with this line permits the planning yachts to reach hydrodynamic values not achievable by the displacement ones.

Sheer Line

This curve is more complex than the other ones previously analysed. It can be straight and parallel to the XY plane, or it can be straight and present an inclination in which the aftermost point is the lowest one. To study this kind of behaviour it has been taken the angle at the transom included between the sheer line and the perpendicular to the waterline (St). The angle can vary from 88° 90°.
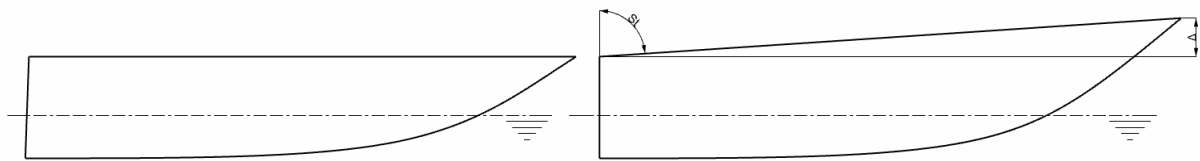


*Figure 6-1: Straight sheer line, parallel and inclined*

In other cases, the form curve can be concave with the lowest point at the transom, or it can have a point along its length with tangent equal to zero, in which case this point is the lowest point of the sheer line. To be able to describe this kind of shape it has been adopted a new angle, Sb, that is the angle included between the form curve and the perpendicular with the waterline at the most forward point of the hull. The range of Sb for the concave sheer line yachts goes form 90° to 95°; and the range of St goes from 90° to 92°
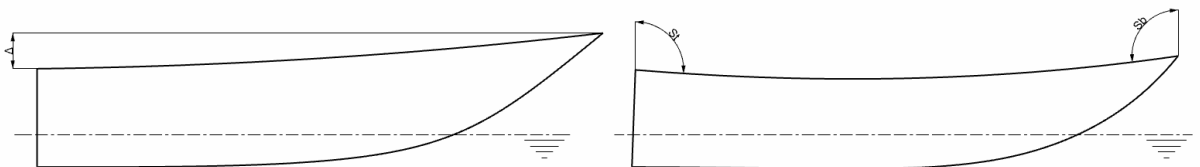


*Figure 6-2: Concave sheer line, lowest point at the stern and along the length*

In many design models, this curve can be convex. In the motor yachts where this kind of design is adopted the upper point of the curve can be the connection point between deck and bow, or they can have a tangent equal to zero along the length of the sheer line, in this case this is the upper point of the curve. For this design methodology the study showed up 90°<St<83° and 90°<Sb<94°.
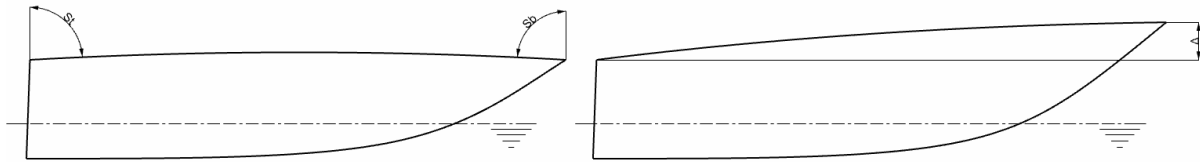
*Figure 6-3: Convex sheer line, Upper point along the length and at the bow*

There is one more possible configuration of the sheer line. The last shape that it can assume is the one in which it is concave near the stern, and it turns convex going to the bow. The form curve presents a change of curvature along its length.
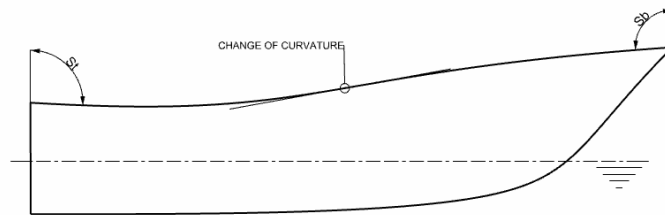


*Figure 6-4: Sheer line shape, change of curvature*

It is possible to say that the angle St moves from a minimum of 83° to a maximum of 92° and the angle Sb goes from a minimum value of 84° to a maximum of 94°.

In addition to these values, they have been studied also the ranges of the angle before (Tbk) and after (Tak) the zero-point tangent along the length of the sheer line. The values of Tbk go from 0° to 1.5° and the ones of Tak go from 0° to 4.5°.
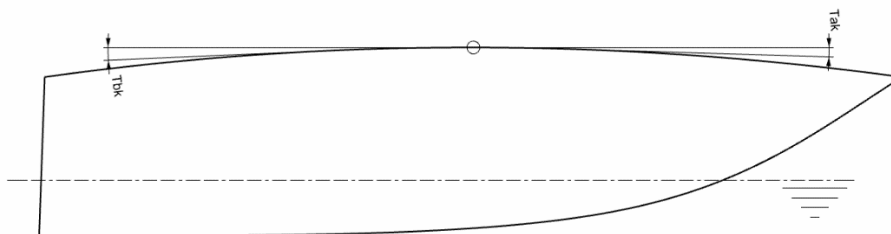


*Figure 6-5: Sheer line angles*

The undermark point in Figure 6-5 is the zero-tangent point, it can be placed at the Loa/2 of the sheer line, it can be set before Loa/2, of a maximum of 25% of Loa, or after it of the 22% of Loa.

Deck Line

The deck line can be completely rounded, in which situation usually the maximum beam is situated between the Lpp/2 and the bow.
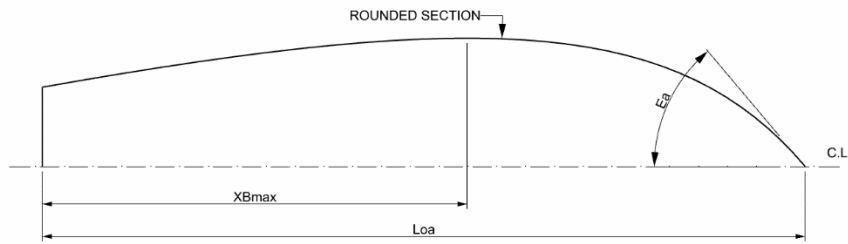
*Figure 6-6: Planning motorboat, rounded deck*

Sometimes the deck line is designed to have a rounded segment at the bow followed by a straight section that runs from the maximum beam point to the transom connection.
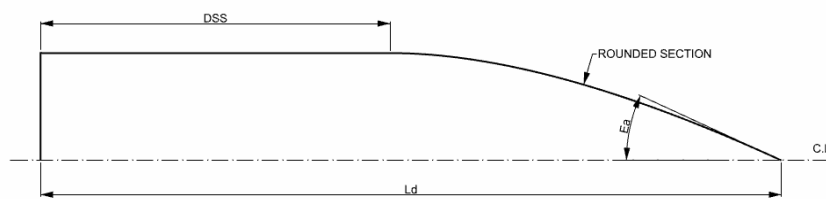


*Figure 6-7: Planning motorboat, rounded and straight deck contour*

The straight section, along its length, can maintain the same y coordinate or it can have a decreasing y coordinate, so it can be parallel to the XZ plane, or it can be inclined with a certain angle.
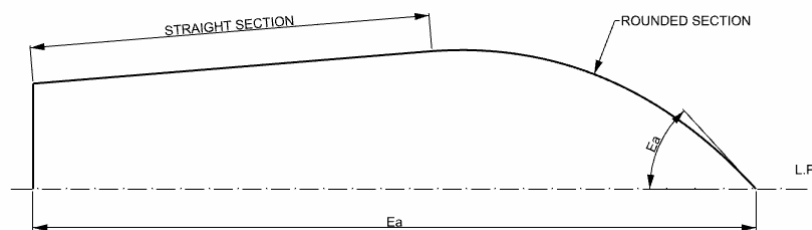


*Figure 6-8: Planning motorboat, rounded and straight inclined deck contour*

To describe all the possible shapes, that the deck line can assume it has been decided to take various parameters under consideration.

The angle at the stern, Ds, is taken as the angle included between the form curve and the YZ base plane, goes from 72° to 90°. The straight section DSS, can reach a maximum extension of 55% of the Loa. The angle before the point with tangent equal to zero, Dbs, which is included between the parallel to the longitudinal plane and the form curve, goes from 0° to 7°. The angle after the tangent point, Das, taken the same way of the one before, has a range going from 0° to 6°. The entrance angle, Ea, can vary from 32° to 72°. When it has been possible it has been studied also the correspondent entrance angle at the waterline, which can go from the 22% up to the 72% of Ea. The maximum beam has a range going from 13% to 26% of Loa. It can be set before of Loa/2 of a maximum of 15% or it can be after the middle ship length overall of a maximum of 5% of Loa.
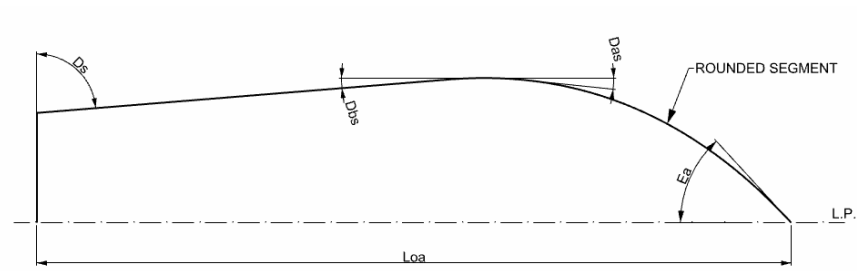
*Figure 6-9: Deck line parameters*

## Chine Line

The chine line is a curve characteristic of the planning yachts. It is a 3D form curve. It divides the hull surface, in the longitudinal way, into two different regions. The curve can start from the transom line and end or at the bow line, or before it, depending on the design choice. It can vary its curvature along its length, for example it can be in the first part (close to the transom) straight and rounded in the second part (close to the bow).
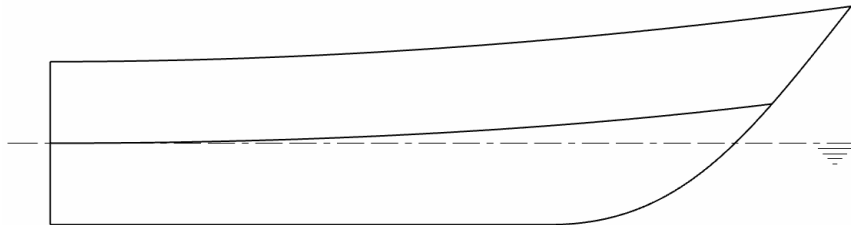


*Figure 6-10: Planning motorboat, chine line*

The chine divides the hull surface into two distinct surface regions. These two areas of the hull can be both straight, or both concaves.
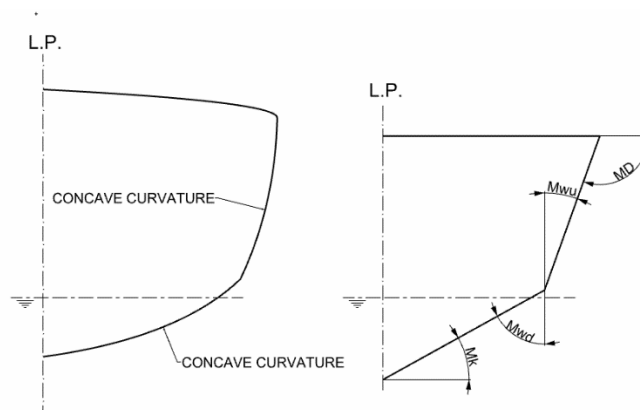


*Figure 6-11: Hull sections, straight and concave*

Moreover, they can be both convex or one concave and the other convex, depending on the requested construction characteristics of the hull.
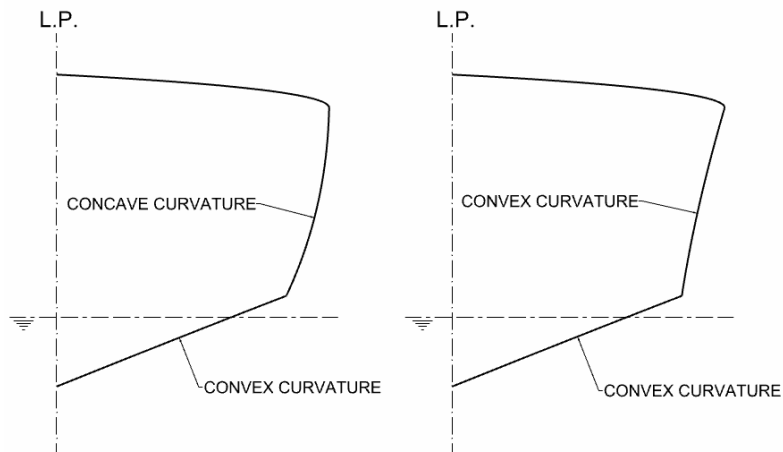
*Figure 6-12: Planning motorboat different hull curvatures*

Two angles for each surface are needed to study their shape, taking into consideration the cross section at the maximum beam. For the upper surface they are considered MD, the angle included between the hull and the plane parallel to the centreline plane passing through the point corresponding to Bmax, and Mwu, the angle between the hull and the XZ plane passing through the point at the chine line. For the lower surface other two angles are needed. Mwd is the angle between the plane taken for Mwu and the lower hull surface. Mk is the angle included between the yacht shell and the XY base plane.
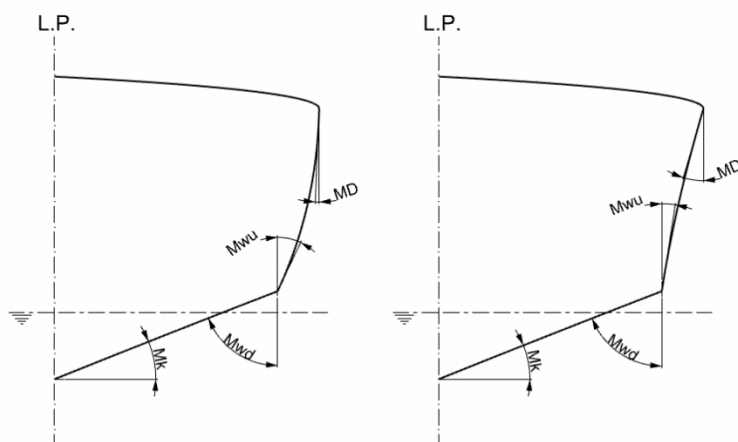


*Figure 6-13: Planning motorboat, section curve parameters*

Bow Line

This curve can be designed straight or rounded; The first angle studied is the one controlled by the tangent at the connection point between the bow contour and the deck line, Btp, included between the form curve and the perpendicular to the waterline. It goes from 5° to 62°. The other two angles studied to describe this design curve are the ones at the intersection point between the bow contour and the waterline. One is included between the waterline and the upper part of the bow line, Iwu, which values go from 17° to 74°, the other is taken between the waterline and the lower part of the bow line, Iwd, which range is from 15° to 63°.
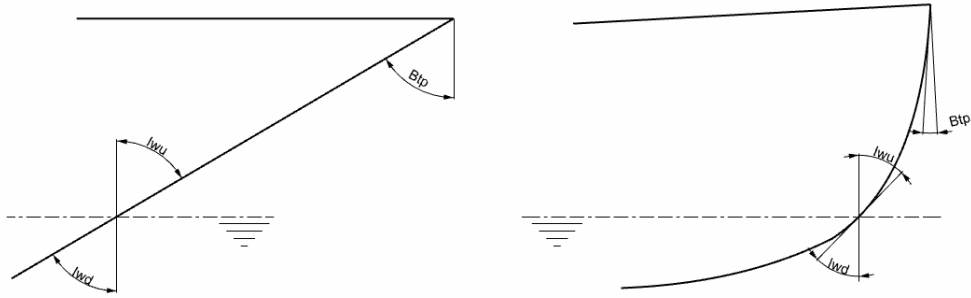
*Figure 6-14: Planning motorboat, straight and rounded bow contour.*

The curve can be concave from start to end or it can start convex and turn concave at a certain point before the intersection with the waterline.
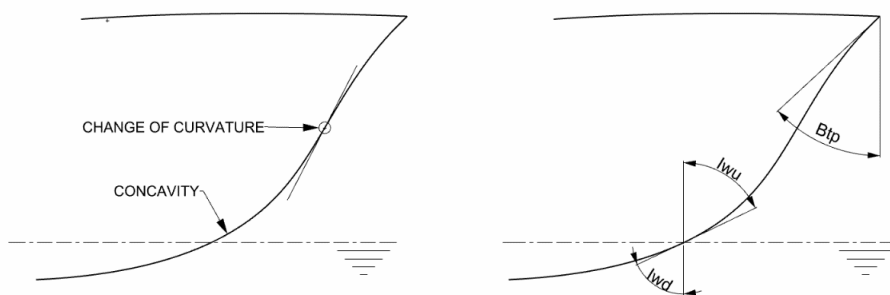


*Figure 6-15: Planning motorboat, convex to concave bow contour.*

Otherwise, this line can have a straight first segment and a rounded second one. In this case the change of form is before the waterline.
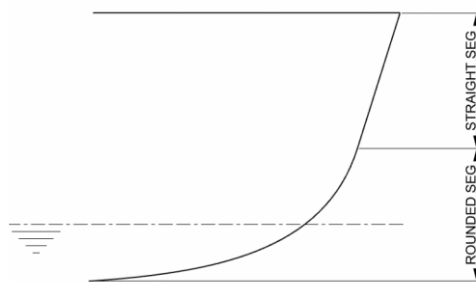


*Figure 6-16: Planning motorboat, straight to rounded bow contour.*

Keel Line

The keel line in most of the design studies is constructed to be almost completely straight from transom to bow, but at the point of connection with the bow line it is always rounded. the straight part of the curve can be parallel to the XY plane, or it can assume different inclinations. Its length can reach a maximum value of 63% of Loa.
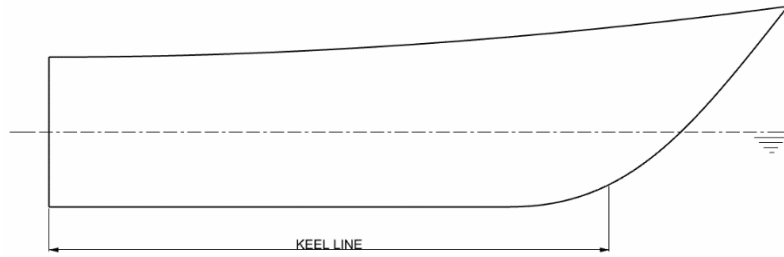
*Figure 6-17: Planning motorboat, keel line parallel to waterplane.*

The keel line can have a segment with a decreasing Z coordinate from transom to bow. The last inclination that it can assume is the one with the transom point as the lowest point of the hull.
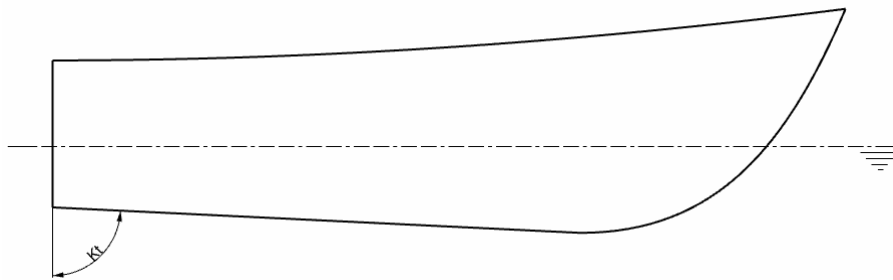


*Figure 6-18: Planning motorboat, front inclined keel line.*

To study the inclination of the form curve it has been taken the angle at the stern, Kt, at the point where the keel line relates to the transom line. The angle is included between the form curve in object and the perpendicular to the waterline. Its range goes from 87° to 95°.

Another important angle to define the keel line is the angle Ka, which is the one at the connection point with the bow. Its values go from 15° to 63°.

The angle Ks after the straight segment, included between the plane XY passing through the point at the end of the straight part and the start of the rounded segment of the keel contour has a range going from 1° to 4°.
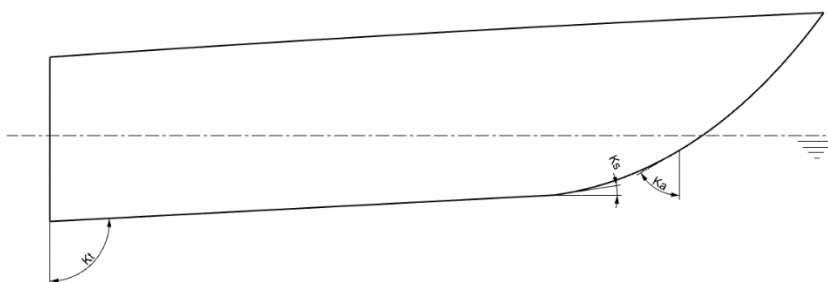


*Figure 6-19: Planning motorboat, back inclined keel.*

In few planning motor yacht models the keel is design to have a full rounded shape.
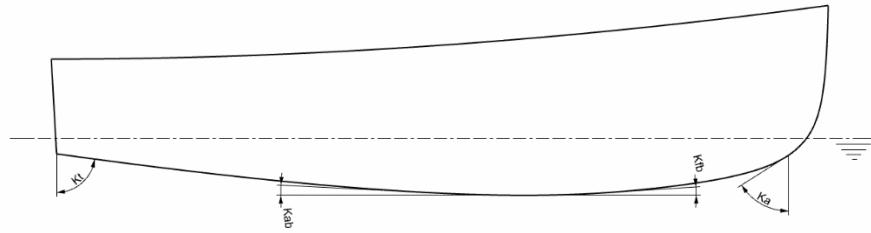
*Figure 6-20: Planning motorboat, rounded keel.*

When the keel curve is all rounded it has a point with tangent equal to zero along the length of the curve. In the study it has been found this point being always before the Loa/2 with a maximum distance from it of 19% of Loa.

The angle Kab formed between the parallel to the water plane and the keel line before the point can be maximum of 1° and the angle Kfb included between the parallel to the waterplane and the keel line after the point can reach a value of 2°.

Transom Line

The transom can be designed with different shapes. It can be a plane panel, or it can have a curvature in which condition the lateral extremes of the surface are rounded bow way. In both typologies it can be vertical or it can have an inclination, that means that it is not perpendicular to the waterplane.
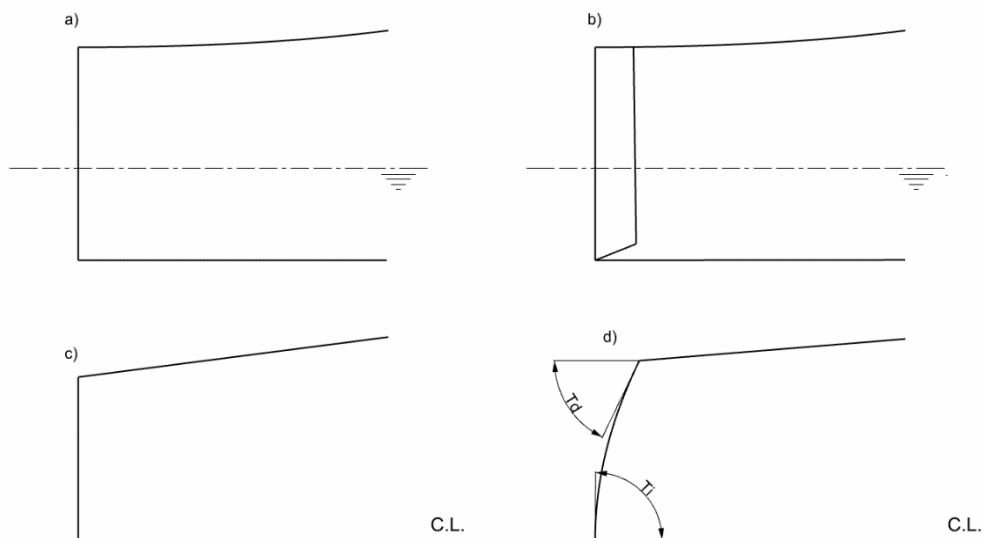


*Figure 6-21: Planning motorboat, straight and rounded transom.*

Figure 6-21 represents the side view (image a and b) and top view (image c and d) of two different transom configurations.

Moreover, this component of the yacht can be inclined forward, or it can be perpendicular to the water plane. In case of bow way inclination, the point with the smallest X coordinate is the intersection between keel and transom and it can have an angle Ta going from 90° to 104°.
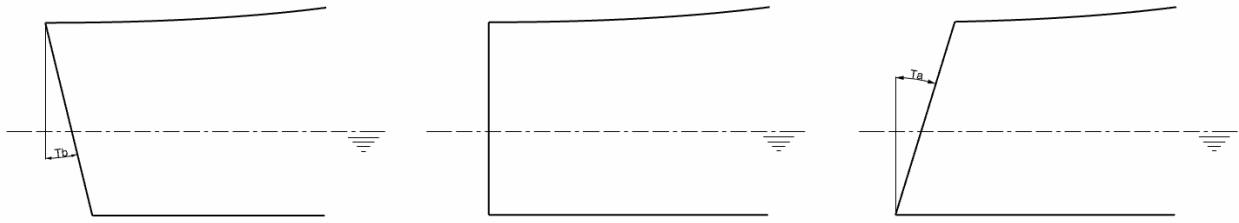
*Figure 6-22: Planning motorboat, forward and backward inclined transom.*

In the case of the back way inclination the point with the smallest X coordinate is the one at the deck intersection and it can have an angle Tb going from 90° to 105°.

In the outboard engine motorboats, the transom presents a modification so that it is possible to install the propulsion system.
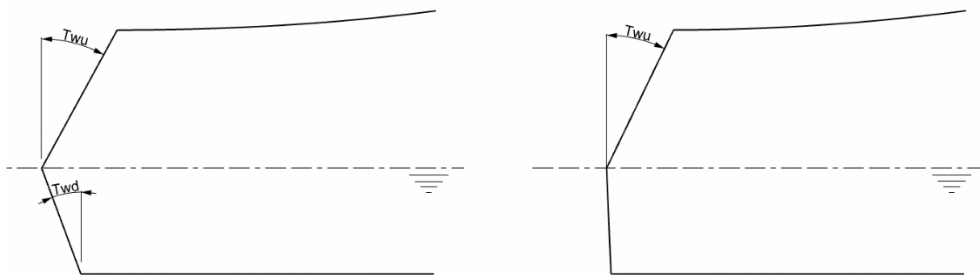


*Figure 6-23: Planning motorboat, two inclinations transom.*

In some cases, the transom is built with a first segment connected with the keel, that can be perpendicular to the waterplane or inclined with an angle Twd that can reach 12° and a second inclined segment, that runs up to the deck. The inclination angle Twu of the second segment goes from 19° to 50°.
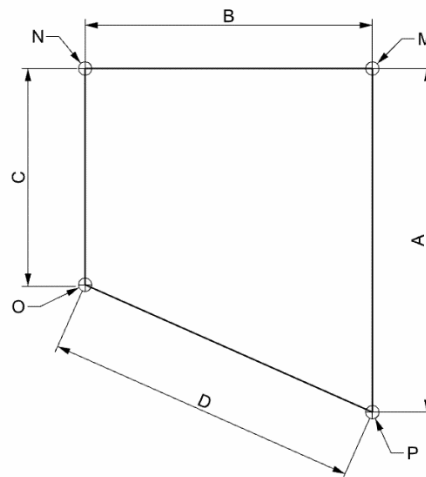


*Figure 6-24: Linear parameters*

Line A represents the maximum height of the transom, it goes from point P to point M. Its length can reach a maximum value equal to 20% of Loa. Line B is the one that describes the maximum beam of the transom. It is extended from point M to point N and it can have a length equal to 20% of Loa. Line C and D are the external curves of the hull surface. Line C goes from point N to point O and line D goes from point O to point P. The length of the upper line (C) and the lower one (D) can assume values up to 17% of Loa.
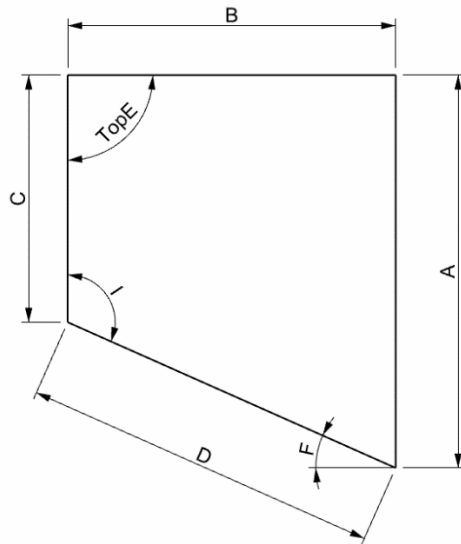
*Figure 6-25: Transom angle parameters*

The angle TopE is included between the top line B, that has been found to be always horizontal, and the external vertical line C, that can assume different inclinations. the values of this angle go from 80° to 125°. The angle I is included between line C and line D, in the middle of them is enclosed the chine line, point O is its transversal section. This angle can vary between 109° and 120°.
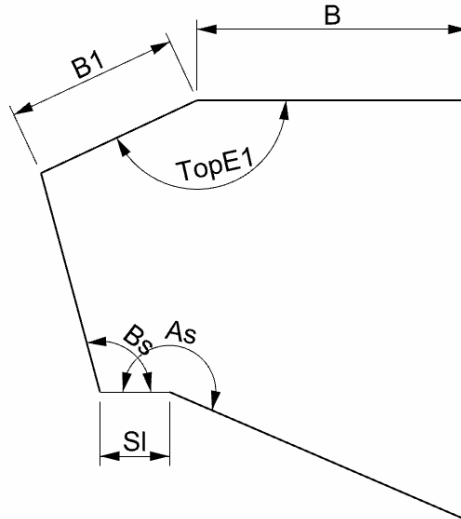


*Figure 6-26: Transom parameters and step parameters*

The fastest planning motor yacht have a surface with the step. This kind of design element is a strip of hull parallel to the waterplane, its width Sl can vary from 1% to 4% of the length overall. Its length is equal to the length of the chine. The angle Bs is the angle between the step and the upper surface, the range of values of this measure goes from 57° to 105°. The angle As, which is the angle included between the step and the lower part of the hull, can vary between 191° and 231°. The top line of the transom can be designed as two distinct segments, like it is shown in Figure 6-26. In this specific configuration, segment B can have values between

7% and 19% of Loa, segment B1 length can vary between 5% and 8% of Loa and the angle included between the two lines can go from 175° to 130°.

## 6.2 Modelling Methodology

The last parametric model developed in the thesis is the planning motor yacht hull, these kind of pleasure crafts are characterized by a volume change corresponding to the velocity change. More in detail as the velocity increases the hull gets out of the water decreasing the displacement and the waterplane area. This kind of yacht does not have a design waterline for the reason already explained, so this form curve will not be used for the generation of the hull. A new form curve is introduced to achieve the creation of the final surface, the chine line.

As it happened between displacement motor yacht and displacement sailing yacht, also between displacement motor yacht and planning motor yacht there are some similarities. Since some parts of the two hulls behave in the same way it has been possible to use the script of some displacement form curves to code the planning yacht parametric hull. Thanks to the analysis undertaken in the forms study it is decided to use the same code for the sheer line, the deck line, the bow line, and some steps of the transom.
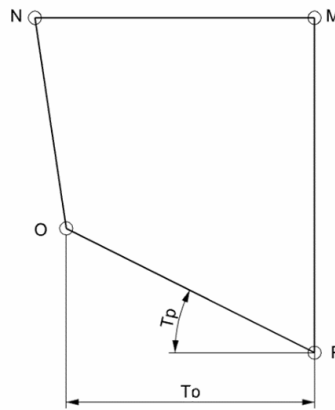


*Figure 6-27: Transom shape*

The transom is composed of four lines. PM and MN are constructed starting from the same points of the displacement hull, but they are connected with straight lines and not interpolated curves. Point O is a new point, that lies on the vertical base plane YZ. The parameters to control it are the distance from the centreline plane (To) and the angle (Tp) included between the segment OP and the XY plane.

The keel line has been created after the transom, this form curve is composed of three points, the lower point of the transom, the lower point of the bow and the point corresponding to the end of the straight segment of the keel. The parameters to control the shape of the form curve are the tangent at the bow connection point, the tangent at the transom point, the length of the straight segment and the tangent at the straight segment point end.
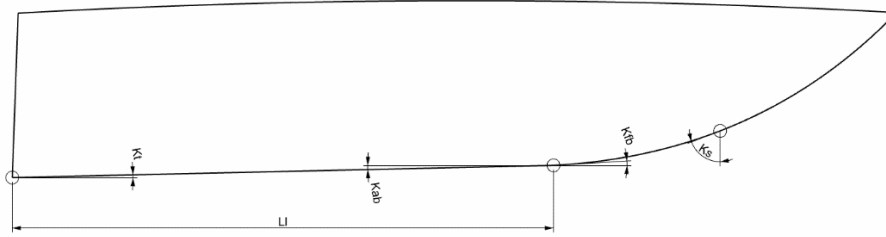
*Figure 6-28: Keel line parameters*

The next form curve created for the modelling of the planning yacht is the cross-section. This form curve is composed of two interpolated curves. The upper one goes from the deck line to the chine line and the lower one goes from the chine line to the keel line. The two segments compose the 2D form curve, that lies on a moving YZ plane. The points come from the intersection between the plane and the three main curves. The parameter Xc controls the longitudinal position of the cross-section. There are other four parameters connected to this form curve, each one of them controls one angle.
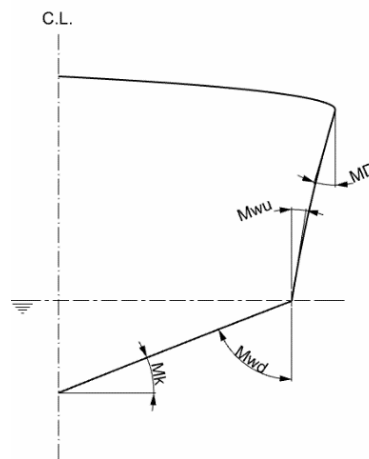


*Figure 6-29: Cross section parameters*

The last form curve modelled for the creation of the surface is the chine line. This is a 3D Interpolated curve that runs from transom to bow. Three control points permit the shaping of this form curve. The first point lies on the transom external curve. It is generated with the possibility to move along its length. The parameter that controls the position of the aftermost point of the chine line is Za, from which it is possible to set the Z coordinate along the transom curve. The second point is located on the cross section, it is created to be able to move along the form curve. The parameter that controls the Z coordinate along the line is Zs. The third point of the chine line is the point at the bow connection. The point is constricted to move on the bow contour. It is possible to set its vertical position on the curve using the parameter Zb. The chine line created has other two parameters to permit a better control over its shape. The first one (Ct) relates to the tangent at the transom point and the second one (Cbb) is connected to the tangent at the bow point.

*Table 6-1: Planning motorboat, parameters*

| CURVE | PARAMETERS | DEFINITION | RESTRICTIONS [m] |
|---|---|---|---|
| Sheer Line | Daft | Vertical distance between the aftermost point of the sheer line and the lowest point of the underwater body. | 0 ≤ Daft ≤ 5 |

| | | | |
|---|---|---|---|
| | Dmid | Vertical distance between the middle point of the sheer line and the lowest point of the underwater body. | 0 ≤ Dmid ≤ 5 |
| | Dfwr | Vertical distance between the most forward point of the sheer line and the lowest point of the underwater body. | 0 ≤ Dfwr ≤ 5 |
| | Ld | Longitudinal distance measured from Daft to Dfrw. | 0 < Ld < 24 |
| | Xs | Longitudinal distance between Daft and Dmid | 0 < Xs < 24 |
| Transom | Tl | Longitudinal distance between the aftermost point of the sheer line and the lowest point of the transom line, taken on the central plane. | -3 ≤ Tl ≤ 3 |
| | Tv | Vertical distance measured on the YZ plane between lowest point of the hull and lower point of the transom. | 0 ≤ Tv ≤ 5 |
| | Th | Horizontal distance between transom deck connection point and centreline plane. | 0 ≤ Th ≤ 4 |
| | Tu | Angle included between the hull and the XZ plane at the most external point of the transom. | 0° ≤ Tu ≤ 45° |
| | Tp | Angle taken in between the hull and the XY plane passing through the lower point of the transom. | 0° ≤ Td ≤ 45° |
| | Tb | Distance between Daft and aftermost deck point | 0 < Tb < 1 |
| | To | Distance between point O and centreline plane | 0 < Tp < 4 |
| Deck | XBmax | Longitudinal distance between aftermost point of the hull and maximum beam. | 0 ≤ XBmax ≤ 24 |
| | Bmax | Horizontal distance between the centreline plane and Bmax. | 0 ≤ Bmax ≤ 12 |
| | Dr | Angle included between the hull and the YZ base plane. | 0° ≤ Dr ≤ 120° |
| | De | Angle taken in between the centreline plane at the most forward point of the deck and the hull. | 0° ≤ De ≤ 45° |
| Keel | Ll | Longitudinal distance between Daft and point L. | 0 ≤ Xl ≤ 24 |
| | Kt | Angle taken in between the vertical base plane and the hull, at the transom connection point. | 0° ≤ Kt ≤ 90° |
| | Kab | Angle taken in between the XY plane and the aft part of the hull at point L. | 0° ≤ Kab ≤ 45° |
| | Kfb | Angle taken in between the XY plane and the forward part of the hull at the lowest point of the keel. | 0° ≤ Kfb ≤ 45° |
| | Ks | Angle taken in between the vertical plane passing through the bow lower point and the keel line. | 0° ≤ Ks ≤ 45° |
| Bow | Bv | Vertical distance taken in between the lower point of the bow and the lowest point of the keel. | 0 ≤ Bv ≤ 2 |
| | Bu | Angle included between the vertical plane passing through the most forward point of the hull and the bow line. | 0° ≤ Bu ≤ 45° |
| | Bd | Angle taken in between the ZY plane passing through the lower point of the bow contour and the bow line. | 0° ≤ Bd ≤ 45° |

| | | | |
|---|---|---|---|
| | Bl | Longitudinal distance taken in between the lower point of the bow and the Dfrw. | 0 ≤ Bl ≤ 3 |
| Chine line | Za | Vertical distance between lowest point of the hull and chine start point | 0 < Za < 4 |
| | Zs | Vertical distance between lowest point of the hull and chine cross section intersection point | 0 < Za < 4 |
| | Zb | Vertical distance between lowest point of the hull and chine end point | 0 < Za < 4 |
| | Ct | Angle included between the chine line at the most forward point and the centreline plane | 0° ≤ Ck ≤ 45° |
| | Cbb | Angle included between the chine line and the XZ plane passing through the end point of the curve | 0° ≤ Cbb ≤ 45° |
| Cross-section | Mk | Angle taken in between the XY base plane and the hull, at the cross-section. | 0° ≤ Ck ≤ 45° |
| | XC | Longitudinal distance measured between Daft and cross-section. | 0 < XC < 24 |
| | MD | Angle included between the XZ plane passing through the top point of the cross-section and the hull. | 0° ≤ Cu ≤ 45° |
| | Mwu | Upper angle included between hull and XZ plane passing through point O. | 0° ≤ Mwu ≤ 45° |
| | Mwd | Lower angle included between hull and XZ plane passing through point O. | 0° ≤ Mwd ≤ 45° |

With the last form curve modelled it has been possible to generate the surfaces that compose the hull. The surface methodology is different from the ones used before. The surface created concerns half model that has been mirrored. It is created one surface for the transom (B) and four surfaces for the hull, the forward bottom one (E) is generated in between cross-section, chine line and profile, the aft bottom one (C) is in between transom line, cross section, keel line and chine line, the side forward one (D) is between bow line, cross section, deck line and chine line and the aft side one (A) is between the transom the cross section the deck line and the chine line.
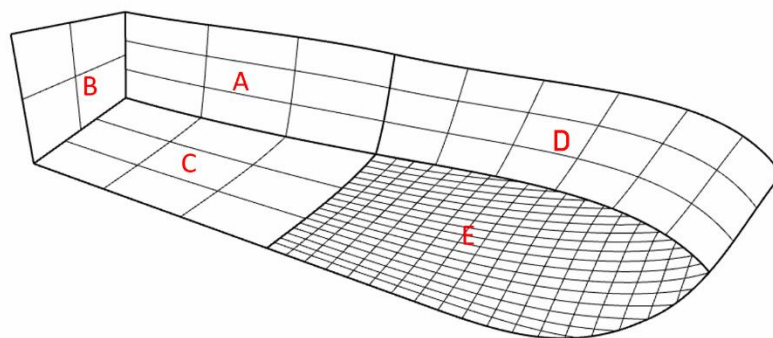


*Figure 6-30: Representation of the surfaces of the hull*

As well as the other models, the script regarding the forward calculations have been applied to the hull surface. This way it has been possible to obtain the main dimensions, the section area curve, the Lines Plan, and the Offset Table.
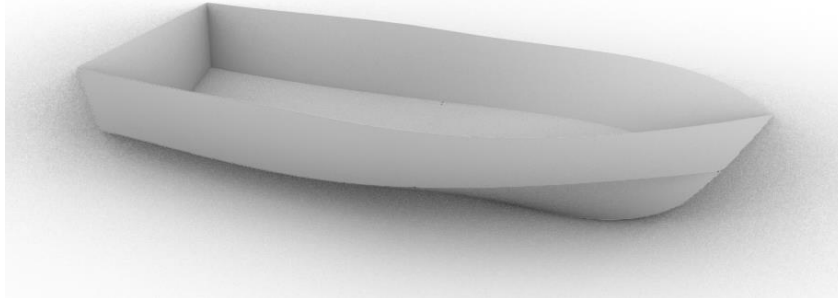


*Figure 6-31: Surface output Grasshopper code of the planning hull*

## 6.3    Validation

Once completed the code of the planning motor yacht hull it started the validation work. From the web site https://www.pinterest.ca/pin/469148486178890560/ it has been chosen the model below. It is an outboard motorboat, which hull present one chine running from transom to bow.
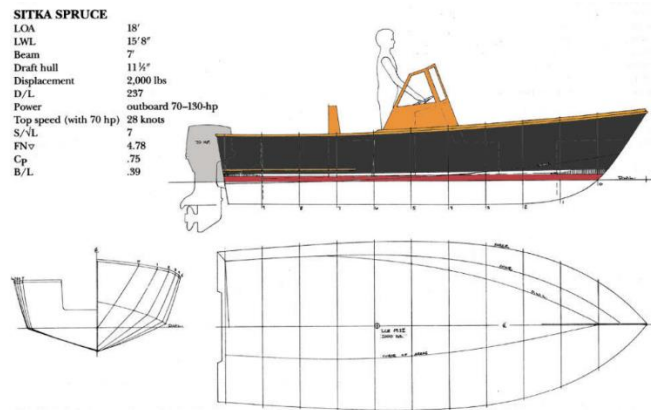


*Figure 6-32: Lines plan of the Sitka Spruce motorboat. Image taken from https://www.pinterest.ca/pin/469148486178890560/*

Using Rhinoceros 3D on the Lines Plan of the Sitka Spruce all the main curves needed to build the surface have been highlighted with a thick red line. The drawing has been quoted so that all the Grasshopper input parameters have been extracted from the image.
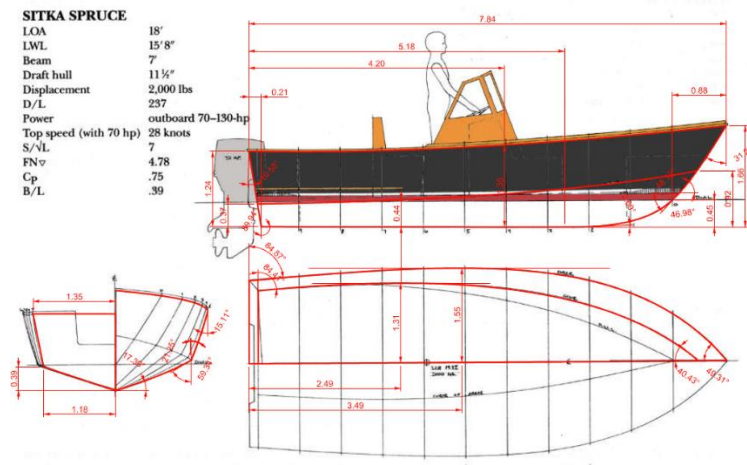
*Figure 6-33: Quotes taken with Rhinoceros onto the Sitka Spruce motorboat Lines Plan.*

Once completed the process of data extrapolation shown in Figure 6-33 all the values have been inserted in the Grasshopper code. The script works in radians, so the angles have been changed from degrees to radians.

*Table 6-2: Parameters used in the Grasshopper code to elaborate the planning motorboat form curves*

| LINE | PARAMETER | DISTANCE [m] | ANGLE [rad] |
|---|---|---|---|
| SHEER | Ld | 7.84 | |
| | Daft | 1.24 | |
| | Xd | 4.2 | |
| | Dmid | 1.35 | |
| | Dfrw | 1.66 | |
| BOW | Bl | 0.88 | |
| | Bv | 0.45 | |
| | Bu | | 0.55 |
| | Bd | | 0.84 |
| DECK | XB | 3.49 | |
| | Bd | 1.55 | |
| | Dr | | 1.48 |
| | De | | 0.86 |
| TRANSOM | Th | 1.35 | |
| | Tp | 1.1 | |
| | Tb | 0.74 | |
| | Tv | 0 | |
| | Tl | 0.21 | |
| KEEL | Kt | | 1.57 |
| | Kab | | 0.00 |
| | Kfb | | 0.05 |
| | Ll | 5.18 | |
| | Ks | | 0.82 |
| CS | Xcs | 3.49 | |
| | MD | | 0.26 |

| | | | |
|---|---|---|---|
| | Mk | | 0.30 |
| | Mwu | | 0.37 |
| | Mwd | | 1.04 |
| CHINE | Bc | 1.31 | |
| | XBc | 2.5 | |
| | Zs | 0.44 | |
| | Ct | | 0.71 |
| | Cbb | | 1.47 |
| | Za | 0.37 | |
| | Zb | 0.92 | |

Completed the data fulfilling operation it is possible to run the code to obtain the output curves of the planning motorboat hull. The script produced the violet lines, which have been superimposed on the drawing of the Sitka Spruce, so that it is possible to compare the model created by Grasshopper and the target model.
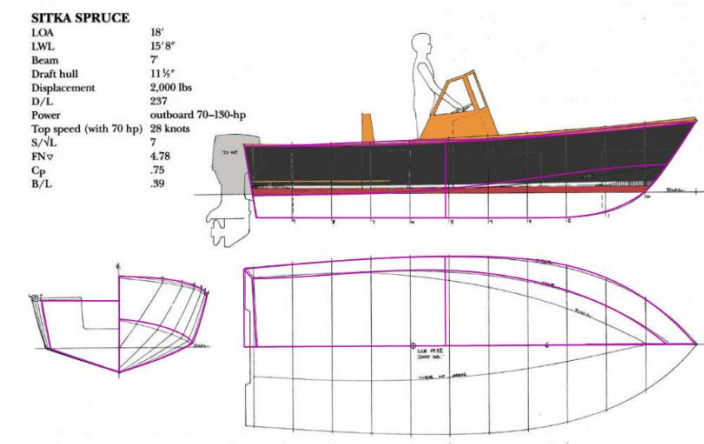


*Figure 6-34: Construction lines created by Grasshopper code compared with the Sitka Spruce Lines Plan.*

As it is possible to notice from Figure 6-34 the deck line, the keel line, the bow line, and the transom line follow the target lines of the chosen model. The chine line trajectory is the one that presents the bigger error, since from the cross-section to the bow contour it does not follow the trajectory of the target chine line.
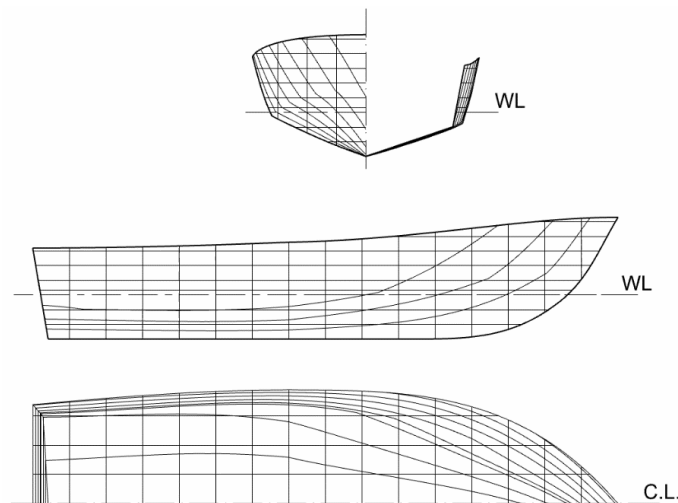


*Figure 6-35: Planning motor yacht, line plan produced by grasshopper.*

The Lines Plan generated by the Grasshopper code has three parameters, each one of them controls the number of planes that divide the surface, so the number of waterlines (Pw), stations (Ps) and buttocks (Pb). The Lines Plan of Figure 6-35 is produced with the standard number of sections.

*Table 6-3: Offset table of the model produced by Grasshopper's code.*

|     | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|-----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| WL1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| WL2 | 0.00 | 0.71 | 0.74 | 0.77 | 0.81 | 0.85 | 0.89 | 0.91 | 0.91 | 0.86 | 0.76 | 0.65 | 0.56 | 0.46 | 0.36 | 0.26 | 0.15 | 0.03 | 0.00 | 0.00 |
| WL3 | 0.00 | 1.21 | 1.23 | 1.25 | 1.28 | 1.31 | 1.33 | 1.35 | 1.35 | 1.34 | 1.31 | 1.26 | 1.14 | 0.97 | 0.79 | 0.61 | 0.44 | 0.26 | 0.06 | 0.00 |
| WL4 | 0.00 | 1.28 | 1.31 | 1.34 | 1.37 | 1.40 | 1.42 | 1.44 | 1.44 | 1.44 | 1.42 | 1.39 | 1.34 | 1.27 | 1.16 | 1.02 | 0.84 | 0.61 | 0.35 | 0.05 |
| WL5 | 0.00 | 1.35 | 1.38 | 1.41 | 1.44 | 1.47 | 1.49 | 1.51 | 1.52 | 1.52 | 1.51 | 1.49 | 1.46 | 1.41 | 1.34 | 1.23 | 1.08 | 0.88 | 0.62 | 0.30 |

In addition to the Lines Plan the code produces the Offset Table which is a very important element to start further studies.
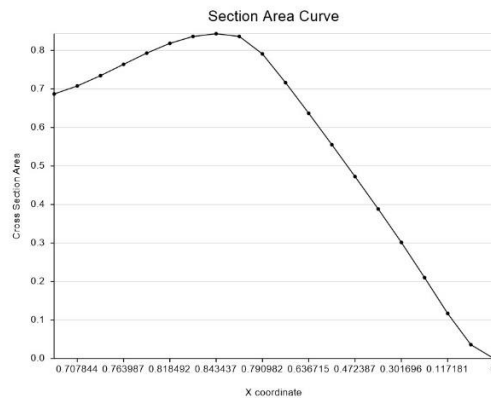


*Figure 6-36: Cross section area curve generated by the planning motor yacht grasshopper code*

The graph represented in Figure 6-36 Is the cross-section area curve. On the X axis there are the X coordinates of the yacht waterline length and on the Y axis there are the values of the cross-section areas at each spacing length. Thanks to this Graph it is possible to check the underwater volume of the planning motor yacht hull.

*Table 6-4: Mian dimensions of the planning yacht generated by grasshopper*

| Loa | 8.00 | [m] |
|-----|------|-----|
| Lwl | 7.18 | [m] |
| DraftBow | 1.35 | [m] |
| B | 3.10 | [m] |
| Bwl | 5.44 | [m] |
| Freeboard | 0.49 | [m] |
| Immersion | 0.62 | [m] |
| Cb | 0.43 | [-] |
| Cwp | 0.39 | [-] |
| Cm | 0.63 | [-] |
| Cp | 0.69 | [-] |
| Lcf | 3.08 | [m] |
| Lcb | 2.91 | [m] |
| Inertia Tr | 7.50 | [m^4] |

| | | |
|---|---|---|
| Inertia L | 45.46 | [m^4] |
| Metacentric Transversal Radius | 0.18 | [m] |
| Metacentric Longitudinal Radius | 1.06 | [m] |
| cross section area | 2.12 | [m^2] |
| waterplane area | 15.04 | [m^2] |

The last output that the code produces is the table of the main dimensions and the most important coefficients of the hull surface. With these four outputs it is possible to start the further calculations, such as hydrostatic, outfitting, chosen of the engine and so on.

# 7 CONCLUSIONS AND FUTURE WORK

## 7.1 Conclusions

In this Thesis were developed methodologies for the automatic generation of surface models of leisure craft hulls, using a software tool for visual parametric geometric modelling, Grasshopper. First were studied the typical forms of three types of leisure boat hulls, one sailing yacht displacement hull, one motor yacht displacement hull, and one motor yacht planning hull. Various hull forms of existing hulls described by Lines Plan drawings or by images have been collected and, using Rhinoceros 3D, analysed in their characteristic forms. Then, the main curves that characterize each hull form have been identified, and for each curve, the parameters necessary to control its shape and to define its characteristics of form have been found.

The sailing yacht displacement hull and the motor yacht displacement hull have similar geometries. The main differences of the two yachts occur in the transom line shape, in the waterline and in the keel line. The planning motor yacht is the one that presents the greatest variety of forms, so the analysis of this kind of hull was the most complex of them all

Using Rhinoceros 3D, the main dimensions and the relevant geometric parameters have been obtained from the drawings and figures collected. The parameters identified have been compiled in a table as well as the range of variation of their values. Once completed the part of analysis and obtained the modelling knowledge, it started the implementation part of the work. Scripts were coded in Grasshopper for the automatic parametric generation of 3D surface models of each of the types of hulls selected.

The parameters used in the Grasshopper scripts are mostly geometric magnitudes such as linear dimensions and angular values. In the case of sailing yacht displacement hull's, the waterplane area coefficient is adopted as parameter to provide a better control over the aft part of the design waterline. Once created the main curves, it has been undertaken an analysis to find the most suitable surface generation method in Rhinoceros 3D, taking into consideration the input data available and the boundary conditions.

After the conclusion of the modelling scripts, it was carried out a validation procedure to verify if the code produced was really able to reproduce the shape of existing hull forms.

In the case of the hull of a sailing vessel, six lines were used to create two surfaces to represent the hull and the transom. The surface generation method considered most suitable was the curve network surface. In the validation, as overall, the main curves produced presented a good accuracy. The only line which the code is not able to reproduce accurately is the transom line.

Regarding the displacement hull for motor yachts, the lines and the surfaces used are the same of the sailing yacht ones. The final output of the design waterline, the bow contour and the keel line were considered suitable. The deck line, although well shaped from the top view, appears to have a bit different trajectory, in the side view, then the target one. The transom rounded curve and the cross-section curve could be improved since they don't manage to perfectly reproduce the motor yacht curvature chosen for the validation.

The lines used to create the planning hull are the deck line the, the transom line, the profile, the chine and the cross section. The generation methods used to create the surfaces are patch (surface defined bu the four edges) and curve network. The hull is modelled with five surfaces, one for the transom and the other four for the bottom and side shell using the profile, the cross section and the deck lines. The chine line is well shaped from transom to cross section, but the forward part of this curve loses precision as it appears in the side view.

The codes of the displacement sailing yacht hull and the displacement motor yacht hull can perform most of the shapes on the market with a reasonable precision. The code of the planning motor yacht hull is the one that needs to be improved the most, it is far from reproducing the large number of geometries that this type

of hulls can assume. The restrictions are given by the chine which has a lot of different design possibilities. The script produces well shaped hulls with a single chine running from stern to bow. The code simplifies the work of the preliminary project with an important spare of time, and it gives the elements to start the design project.

## 7.2   Future Work

Regarding future work, in general, more hull form coefficients should be introduced as parameters for a better control of the resulting hull form.

The study of the planning crafts' forms does not involve all the possible shapes: the investigation, indeed, could pursuit other ways, as it demonstrates the analysis of the two chines' hulls, which can be deepened, or the "step" design shaping. The code created for the planning motor yacht hulls cannot yet produce shapes with two chines and is not able to perform complex geometries such as the step, and so it deserves further investigation. Moreover, the script can just model vessels with the chine starting at the transom and ending at the bow, and this constitutes a limitation, since there are some motorboat hulls characterized by having this line ending at a point before the bow contour.

The search of hulls should be extended to identify other variations of the hull shape. Planning hulls of sailing vessels should also be analysed and modelled.

Since some motor yachts are designed with the bulb it would be interesting to apply further efforts on the developing on a code able to reproduce it.

Regarding the validation, more complete sources of reference hulls are needed, for which the main hull form coefficients are known or able to be computed. Having this information available, it will be possible to quantify the discrepancies between the target values of displacement, Cb, Cp, Cwl and the actual values resulting from the produced models.
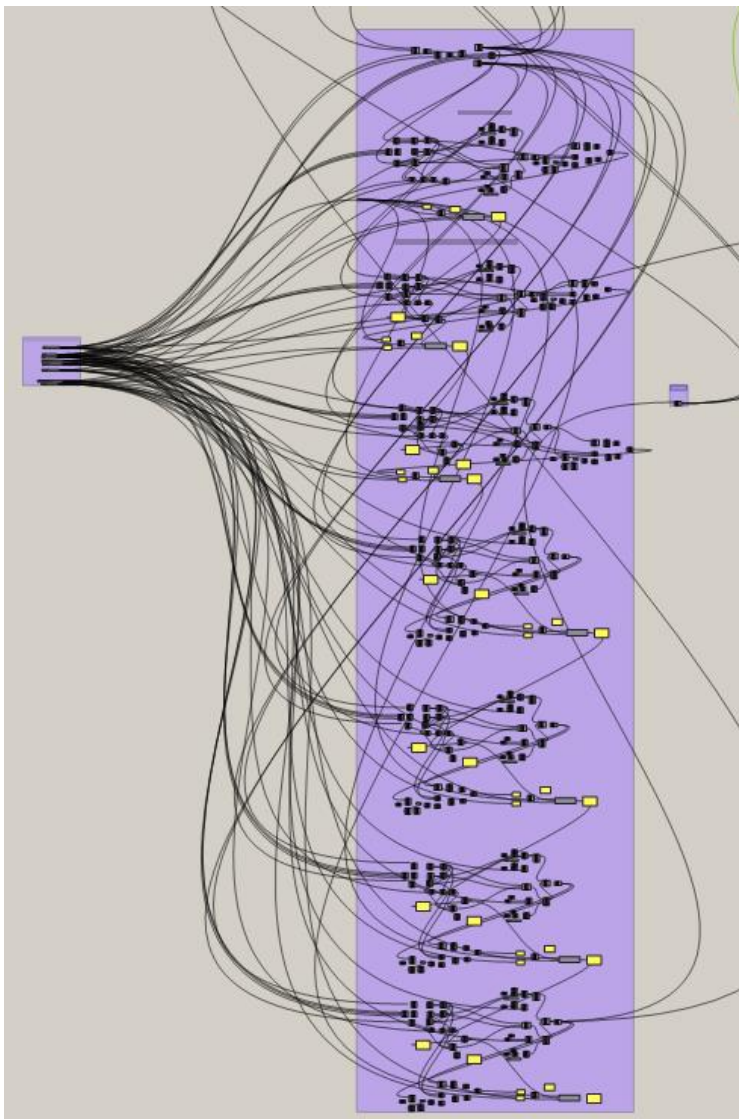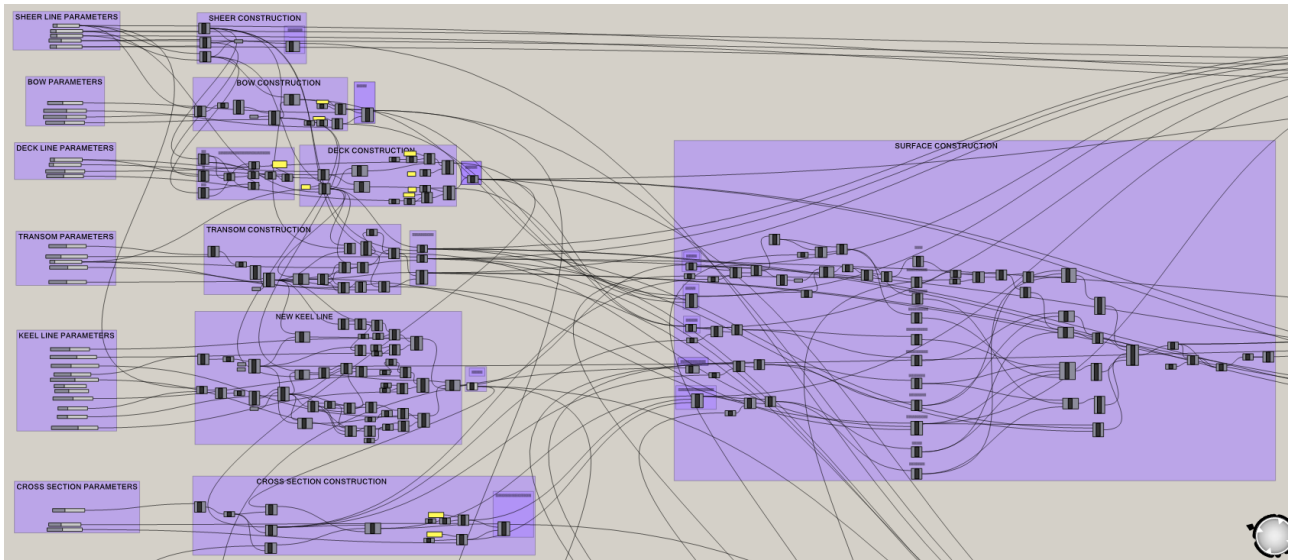
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# ANNEX A – Sailing yacht hull Grasshopper code and Grasshopper commands description



**GRASSHOPPER COMMANDS DESCRIPTION**

| | |
|---|---|
| **Number Slider (Ld)** | Numeric slider for single values |
| **Construction point (Pt)** | Construct a point from $\{xyz\}$ coordinates |
| **Deconstruct point (pDecon)** | Deconstruct a point into its component parts |
| **Point (Pt)** | Contains a collection of three-dimensional points |
| **Point Cylindrical (Pt)** | Create a point from cylindrical $\{angle, radius, elevation\}$ coordinates |
| **Line (Ln)** | Create a line between two points |
| **Interpolate (t) (IntCrv(t))** | Create an interpolated curve through a set of points with tangents |
| **Nurbs Curve (Nurbs)** | Construct a nurbs curve from control points |
| **Join Curves (Join)** | Join as many curves as possible |
| **Shatter** | Shatter a curve into segments |
| **Flip Curve (Flip)** | Flip a curve using an optional guide curve |
| **Curve/Plane (PCX)** | Solve intersection events for a curve |
| **Curve Proximity (CrvProx)** | Find the pair of closest points between two curves |
| **XZ Plane (XZ)** | World XZ plane |
| **XY Plane (XY)** | World XY plane |
| **YZ Plane (YZ)** | World YZ plane |
| **Plane 3Pt (Pl 3Pt)** | Create a plane through three points |
| **Flip Plane (PFlip)** | Flip or swap the axes of a plane |
| **Number (Num)** | Contains a collection of floating-point numbers |
| **Unit X (X)** | Unit vector parallel to the world $\{x\}$ axis |
| **Unit Y (Y)** | Unit vector parallel to the world $\{y\}$ axis |
| **Unit Z (Z)** | Unit vector parallel to the world $\{z\}$ axis |
| **Vector 2Pt (Vec2Pt)** | Create a vector between points |
| **Rotate (VRot)** | Rotate a vector around an axis |
| **Reverse (Rev)** | Reverse a vector (multiply by -1) |
| **List Item (Item)** | Retrieve a specific item from a list |
| **Merge** | Merge a bunch of data streams |
| **Entwine** | Flatten and combine a collection of data streams |
| **List Item (Item)** | Retrieve a specific item from a list |
| **List Length (Lng)** | Measure the length of a list |
| **Partition List (Partition)** | Partition a list into sub-lists |
| **Null Item (Null)** | Test a data item for null or Invalidity |
| **Pick'n'Choose (P'n'C)** | Pick and choose from a set of input data |
| **Edge Surface ( EdgeSrf)** | Create a surface from two, three or four edge curves |
| **Patch** | Create a patch surface |
| **Network Surface (NetSurf)** | Create a surface from curve networks |
| **Brep/Plane (Sec)** | Solve intersection events for a Brep and a plane (otherwise known as a section) |
| **Area** | Solve area properies for breps, meshes and planar closed curves |
| **Mirror** | Mirror an object |
| **Project** | Project a curve onto a Brep |
| **Brep Join (Join)** | Join a number of Breps together |
| **Cap Holes (Cap)** | Cap all planar holes in a Brep |
| **Bounding Box (BBox)** | Solve oriented geometry bounding boxes |
| **Box Corners** | Extract all 8 corners of a box |
| **Contour** | Create a set of Brep or Mesh contours |
| **Expression** | Evaluate an expression |
| **Construct Matrix (Matrix)** | Construct a matrix from initial values |
| **Scale NU** | Scale an object with non-uniform factors |

# ANNEX B – Displacement motor yacht hull Grasshopper code
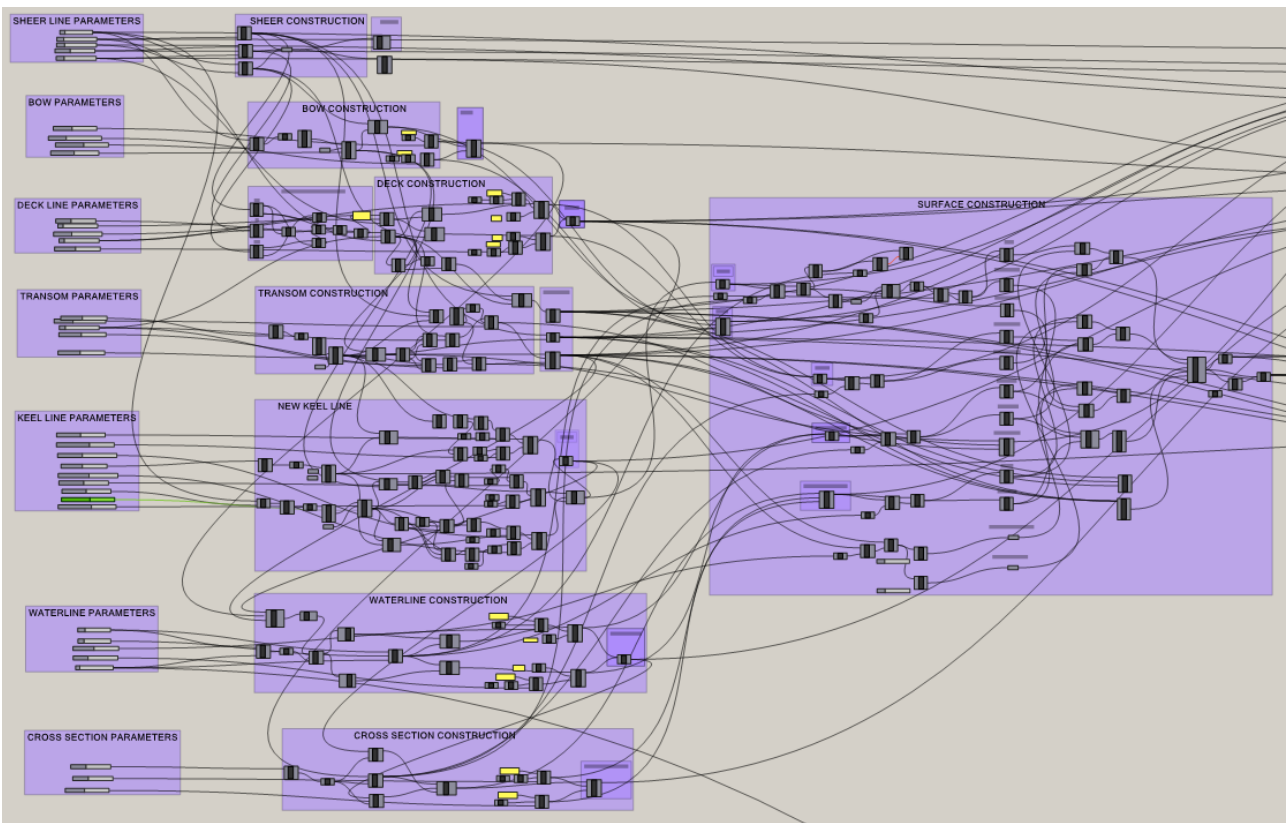
# ANNEX C – Planning motor yacht hull Grasshopper code
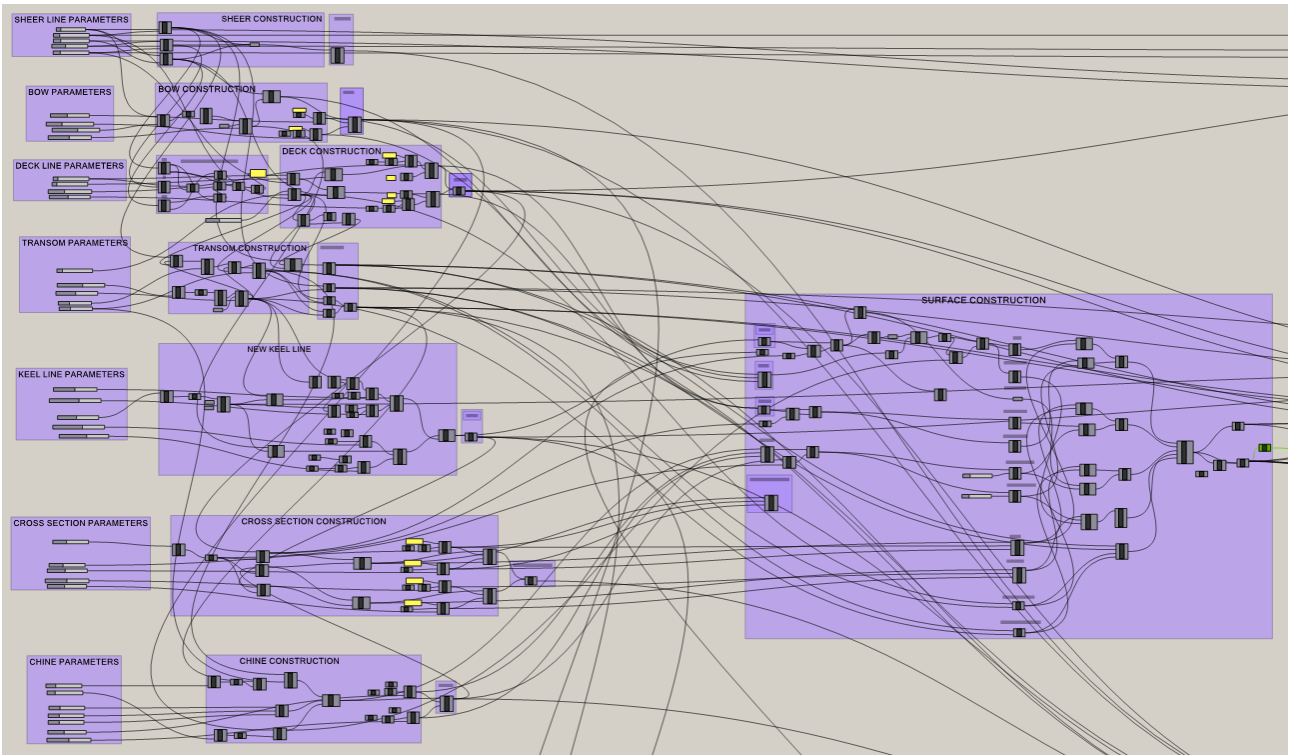
# ANNEX D – Lines Plane, Offset Table, Section Area Curve Grasshopper code



LINES PLAN

OFFSET TABLE