Development of a hull generation method based on FORMDATA systematic series

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"*Experience serves not only to confirm theory, but differs from it without disturbing it, it leads to new truths which theory only has not been able to reach*."

D'Alembert

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I express my gratitude to my teacher and supervisor at Instituto Superior Técnico,

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Resumo

O desenho do casco é uma componente importante, exigente e demorada do projeto do navio. Melhorar o desenho do casco, tornando a tarefa mais fácil, através do desenvolvimento de ferramentas que possam ser utilizadas, na fase inicial do projeto do navio, para gerar rapidamente um ou vários cascos, pode ter um impacto significativo no processo de projeto. O objetivo principal deste trabalho consistiu no desenvolvimento de um método deste tipo. Com este objetivo, foi desenvolvido um método que foi testado usando o *software* MATLAB, para gerar um casco FORMDATA através de modelação baseada em parâmetros de casco (por exemplo, declives, número de seções, comprimento do corpo cilíndrico). A partir deste primeiro modelo, o programa permite gerar novos cascos através da alteração e modificação dos parâmetros, dando maior liberdade ao projetista para ensaiar diferentes alternativas de solução. O programa também fornece ao utilizador informação adicional, permitindo-lhe uma melhor compreensão das restrições e determinantes de cada casco gerado. Foram testadas várias soluções de casco. Os resultados obtidos mostraram um desempenho muito satisfatório do método e corresponderam aos objetivos iniciais, abrindo novas perspetivas sobre o uso de modelos FORMDATA no desenho de navios. A digitalização das coordenadas dos pontos constituintes das secções FORMDATA, que servem de base para o programa desenvolvido, são um produto intermédio do trabalho considerado de interesse para projetistas e investigadores.

Palavras chave: Hull generation, FORMDATA, systematic series, hull design, ship design, hull shape, hull form.

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Abstract

Hull design is an important, demanding, and time-consuming component of ship design. Improving hull design and making it an easier task, by developing tools that can be used in the preliminary steps of ship design to quickly generate one or several hulls, could have a significant impact on the ship design process. Developing the method for such a tool has been the primary objective of this project. A program was developed to test this method, using the MATLAB software, to create a FORMDATA hull through modelling based on hull parameters (e.g. slopes, number of sections, length of parallel middle body). Using this hull model, new hulls can then be generated by modifying some of the parameters, giving freedom to the designer to experiment with alternative solutions and allowing for a better hull development. The program also provides the designer with more information about the generated hull, leading him to a better understanding of the constraints and determinants of each generated hull. Several hull solutions were tested. The results showed a rather satisfactory performance of the method and met the initial objectives of the project, thus opening new perspectives on the use of FORMDATA models in hull design. A relevant intermediate result of the project is the digitalisation of coordinates of the FORMDATA series sections, previously only available in raster format, thus allowing for an easier future use of this data by hull designers or researchers.

Keywords: Hull generation, FORMDATA, systematic series, hull design, ship design, hull shape, hull form.

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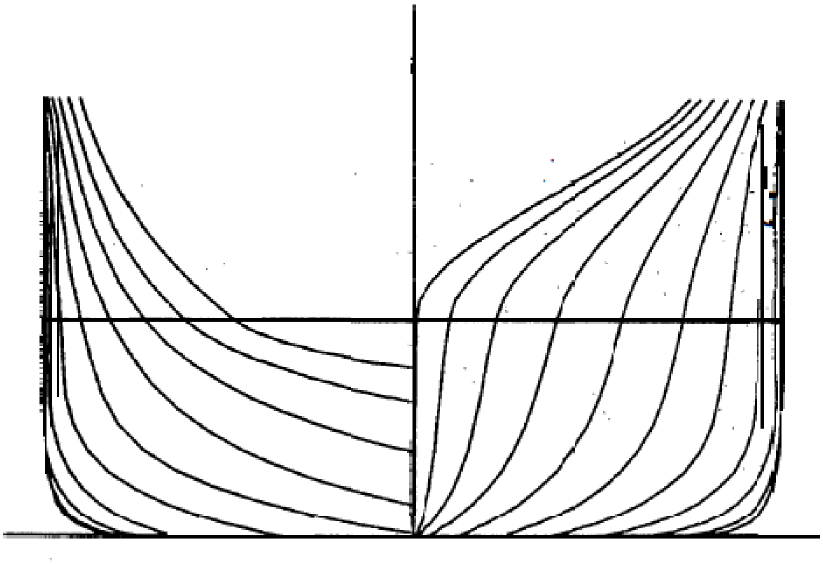

GLOSSARY

Lpp	Length between perpendiculars
L	Length of Ship
L_E	Length of Entrance
L_R	Length of Run
B	Breadth
D	Draught
T	Depth
C_B	Block Coefficient
C_M	Midship Coefficient
C_P	Prismatic Coefficient
CPE	Prismatic Coefficient of Entrance
CPR	Prismatic Coefficient of Run
F_N	Froude Number
A_M	Midship Section Area
CAD	Computer Aided Design
DWL	Design Waterline
SAC	Section Area Curve
FOB	Flat of Bottom
NURBS	Non-Uniform Rational B-Spline

1. Introduction

Ship design is a long and hard process involving several steps along the way that are repeated over and over again in a series of iterations in order to optimize the ship. The first step is the hull design, where the hull shape is developed. The hull shape is probably the most time-consuming step and the one that has the greater impact on the ship's performance. As such, this area has been the subject of several research and development studies. The hull shape is of upmost importance and complexity due to the complicated surfaces that are very difficult to represent mathematically and, as such, to properly define the form in a suitable manner for construction purposes.

When starting to design a new hull, there are four major methods to begin the process:

- Start from scratch.
- Use a parent hull.
- Use a systematic series.
- Use a parametric design method.

Of these four ways, the ideal one would be the fourth. A fully parametric design method where the hull shape is directly connected to parameters that the designer can easily change to quickly modify the hull shape. For example, the designer can study the evolution of the hull shape as he varies the block coefficient. This method allows the production of several similar hulls that may advance into the next design steps.

Before computers, this design process was made by hand. Therefore, there was no possibility of applying a parametric design method and most of the times a parent hull was used, usually coming from previously built ships. In parallel, several systematic series were created for research purposes, with the goal of studying the impact that small changes to the ship's characteristics would have on their performance. Designers took advantage of these series to start developing parent hulls when no previous design was available. All this information existed only in paper format. With the introduction of computers and CAD software in the 1950's and 1960's an evolution in the hull design occurred. In the beginning the CAD software could only work in two dimensions and only provided a speed-up on the design process. This meant that the ship was designed from lines that represented the final surface, and a great deal of interpretation and sensibility was required to understand the hull shape. With the introduction of 3D CAD, the possibility of developing the hull shape as a whole became a reality. A general shape was quickly made and then contour lines at specific places were obtained and used to modify this general shape. This freedom meant that a faster and more detailed design was possible. This process has been optimized over the years and most CAD programs allow to quickly jump from 2D to 3D design.

Unfortunately, most known CAD programs, such as AutoCad, Rhinoceros, OrcaFlex, AutoShip or ShipConstructor, do not support parametric design. Some steps are being made in order to bring some parametric methods into these programs, mostly by way of plugins, such as Grasshopper 3D. However, there is still a long way to go, especially when dealing with complicated surfaces, like the ones found in bows and sterns of the ships.

As the parametric design is not a real option for now, most of the hull shapes are still designed based on a parent hull. When using a parent hull, there is a need to scale the model. However, when scaling the model, some distortions may occur, especially in the bow and thruster area. Those areas will always require further specific work and development along the optimization process meaning that they are not the governing areas when obtaining the initial hull shape.

This initial hull shape needs only to comply with the initial parameters and have an adequate general form. As there are no strict restrictions on this shape, a tool to quickly develop these hulls is useful. The objective of this study is to transform the FORMDATA series into digital format and develop a hull shape generator tool. By transcribing the hull sections from FORMDATA, storing them in a library, and using the initial parameters, a hull shape can be generated through a series of interpolations.

This is meant to be an easy and fast process, allowing the designer to test several ideas in a short period of time. The solutions obtained for the ship are not optimal, but they are possible solutions that can further be refined along the optimization process in the design of the ship hull. The scope of this project is only the design of the hull shape, leaving compartments, machinery, costs, hydrodynamic and structural tests, and optimization outside.

The project thesis is organized as follows: Chapters 2 and 3 summarize the fundamentals of the development process of ship design and make an overview of the previous work done on the subject. Chapter 4 starts with a description of the methodology. Chapter 5 presents the results obtained by running the program and is followed by a discussion of these results in Chapter 6. The conclusions and an insight for future developments to this field of work are presented in Chapter 7 and 8.

2. Hull Form Design

In the past, hull form design was more an art than a science, relying heavily on empirical expertise of the naval architects that learned from experience the fundamentals of engineering. The design was done through heuristic methods, derived from knowledge obtained from a process of trial and error.

Today, ship design is a complex process that requires a good combination of different science fields, that work towards the creation of an optimised and sustainable design solution. The evolution of ship market requirements also adds to the complexity of ship design. To comply with the design requirements and constraints, the designer must consider the full lifecycle of the ship: concept/preliminary design, contractual and detail design, ship construction/fabrication process, ship operation and scrapping. Figure 1 represents schematically the lifecycle of a ship that includes the initial planning, the ordering requirements and the ship building followed by the operational life of the ship and ending in breaking and recycling after the end of useful life.

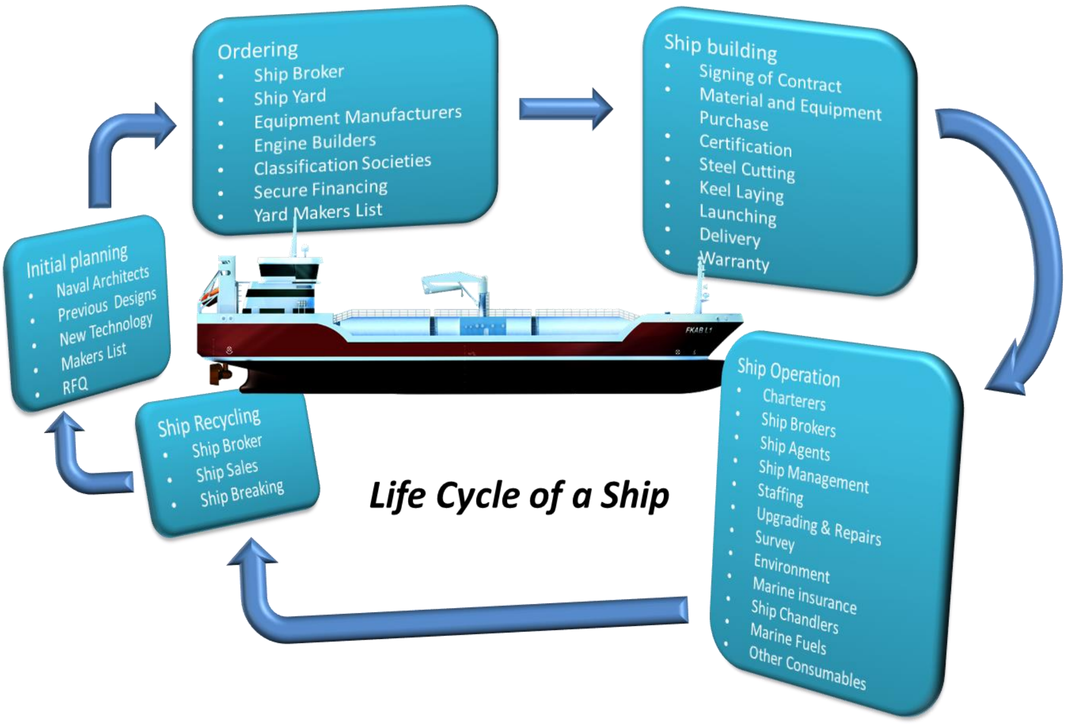

Figure 1 - Life cycle of a ship (http://www.shippipedia.com/life-cycle-of-a-ship/)

2.1. Ship Design Process

Ship design follows a sequential and cascading method of problem solving for many years now. This method is commonly known as the Design Spiral, where the designer follows a logical process of facing each crucial part of the project and evaluates the effect that any adjustments may have on the preceding and subsequent parts, thereby proceeding by successive iterations.

The Design Spiral method was first referenced by J. H. Evans, in 1959. Figure 2 shows the schematic development of a more modern design spiral used by Eyres & Bruce (2012). In this spiral, the design of a ship has three stages: concept design, preliminary design, and contract design. In each stage, an orderly succession of settings, calculations and analysis is followed: it starts with the objectives set for the vessel and follows with proportions, lines, hydrostatics, freeboard and subdivision, general arrangements, structure, and powering, and finishes with estimates of weight, capacities, stability, and cost. This illustration indicates that by using the given design objectives, the designer will work towards the optimal solution by adjusting and changing the interrelated parameters as he moves along the spiral.

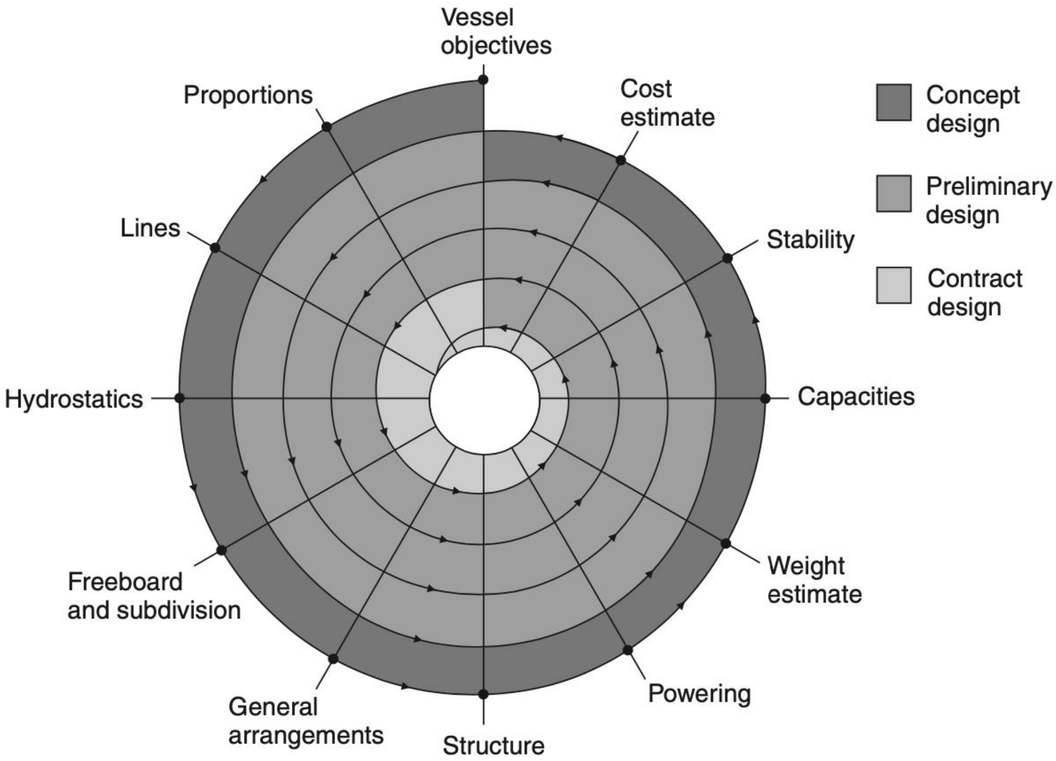

Figure 2 - Ship design spiral (Eyres & Bruce, 2012)

The three stages represented in Figure 2 can be described as follows:

i) Concept design: from the objectives set for the vessel, this stage provides sufficient information for a first techno-economic assessment of different project alternatives.

ii) Preliminary design: it analyses and processes the selected design derived from the concept stage, filling out the arrangements, structures and optimizing service performance.

iii) Contract design: the stage where the final arrangements and systems developed during the preliminary design after agreement of the owner are detailed, while satisfying the building contract conditions.

The design process is not complete at the end of this spiral. In fact, it only started and must be followed by the post-contract design, where confirmation is obtained that the ship will meet the operational requirements, including safety aspects from regulators. The design for production is the next step when the structure, outfit and systems are planned in detail to achieve a good cost and time effectiveness.

The ship design process is therefore long and complex. There are many steps along each part of the project and each new step is influenced by the previous step and influences the next step. Despite the advancements in project management, the process is very time-consuming, extensive and, ultimately, expensive.

The final design must comply, according to Molland (2008), with seven principal requirements that can be summarized as follows:

1. Adequate size and arrangement for the intended service, implying the ability to carry a specified amount of cargo and have adequate space for machinery, fuel, crew etc.
2. Floats at correct draught, which means that the sum of deadweight and lightship weight equals the buoyancy force.
3. Floats upright, which implies adequate stability.
4. Achieves correct speed, shows satisfactory estimates of resistance and propulsive power and suitable engines installation.
5. Is structurally safe/sound, implying structural design with the ability to withstand forces in the marine environment, usually under the requirements of a classification society.
6. Meets requirements for manoeuvring, course keeping and seakeeping; choice of suitable hull required.
7. Meets international standards of safety and reliability; needs to meet the requirements of IMO.

2.2. Hull Geometric Modelling

The hull is the core of the ship. It will determine the cargo layout, the ship's systems and most important, it will have a direct impact in the hydrodynamic behaviour. This shows the importance of defining the hull form and develop it correctly. The wider variety of options and studies a designer has access to, a better ship can be developed. This comes in line with Wilson et all (2010), where they are in the process of creating a computational tool to aid the ship design in the early stages in order to save developing time and make better decisions that will reduce costs along further down the development.

In fact, this topic has such a significant weight in the final shape and performance of the ship, that a consortium of fourteen European partners conducted a three-year long R&D study to improve the functional design of ship hull shapes, Maisonneuve et all (2003).

The main objective of hull form definition is to develop a geometric description, where all the relevant physical and geometrical characteristics, such as displacement or waterplane area, are met with an acceptable shape. There can be two ways to design a hull form for a new vessel: redesigning an existing hull shape or creating a new shape from scratch. It is common practice for the shipyards to use the data from previous projects to set up an initial hull which serves as a starting point for the new vessel. Creating a new hull is more common in the yacht design field where the entire hull shape is established practically from scratch. Yachts bare hull geometry is simpler and is also more conditioned by aesthetics, making this a more preferred work method for designers specialised in this field.

An advancement in the modelling approach will improve significantly both the design process and the results achieved. The modelling techniques can be classified in different ways and can be compared between them regarding flexibility, efficiency, and effectiveness.

3. Previous research on hull form design

Ship hull design and its representation through mathematical descriptions has a long tradition. Ancient and medieval ships can be represented by simple geometrical shapes such as circles, ellipses, parabolas, or sine curves which are simple to manufacture and represent.

According to Nowacki et al (1995), ship lines plan to develop and document empirical, free form hull shapes were introduced around 1700 together with draughting and lofting methods that used elastic splines as fairing tools. With remarkable results, this technique produced successful ship geometries that could be manufactured reliably. The Swedish naval constructor Chapman mentioned, in 1760, in his famous book “A Treatise on Ship-Building” the use of a family of parabolas for the development of the waterlines and other ship curves. This work was followed in the early 1790’s by the first recorded systematic tests on models, conducted by Marc Beaufoy and others. These models were geometrical shapes and had geometric or mathematical lines. From the 1830’s to 1870’s, these curves and streamlines around a Rankine stream were proposed and worked into the lines of ships by J. Scott Russel, James R. Napier, W. J. M. Rankine and others (Walker 2010).

John W. Nystrom expanded Chapman’s use of the parabolic trace and developed what he called the “Parabolic Shipbuilding Construction” in the 1860’s. He used parabolas of different orders, with fractional as well as integral exponents, to make up for both waterlines and sections. His method made possible the calculation of the complete set of offsets for a ship body plan, representing an underwater form with a numerical value of block coefficient (C_B) selected in advance. Nystrom was able to use reversed parabolas for hollow waterlines by calculating both the horizontal and vertical position of the center of buoyancy. This method also allowed him to draw a curve of displacement volume on a basis of draft.

3.1. Systematic hull forms – Model series

Later pioneering work by D. W. Taylor on mathematical ship lines, right after the turn of the century, used mathematical functions to describe empirical hull shapes. In his book “Calculations for Ship Forms”, in 1915, separate formulas are used for waterlines and sections. The curve families for fine sections are represented by 4th degree parabolas while for full sections he uses hyperbolas. The entrance and run, that extend from the bow and stern to the section of maximum area, are treated separately. To represent the sectional area curve and waterlines of the ship, he used an explicit polynomial of degree 5.

$$y(x) = tx + ax^2 + bx^3 + cx^4 + dx^5 \tag{1}$$

Taylor’s work does not mention a parallel middle body, although there can be a way around that. In fact, at the maximum area section, the hull can be divided, and any desired length can be added with this maximum-section shape. This method was suitable for practical and shipyard use. An example of a body plan using Taylor’s Method is shown in the Figure 3.

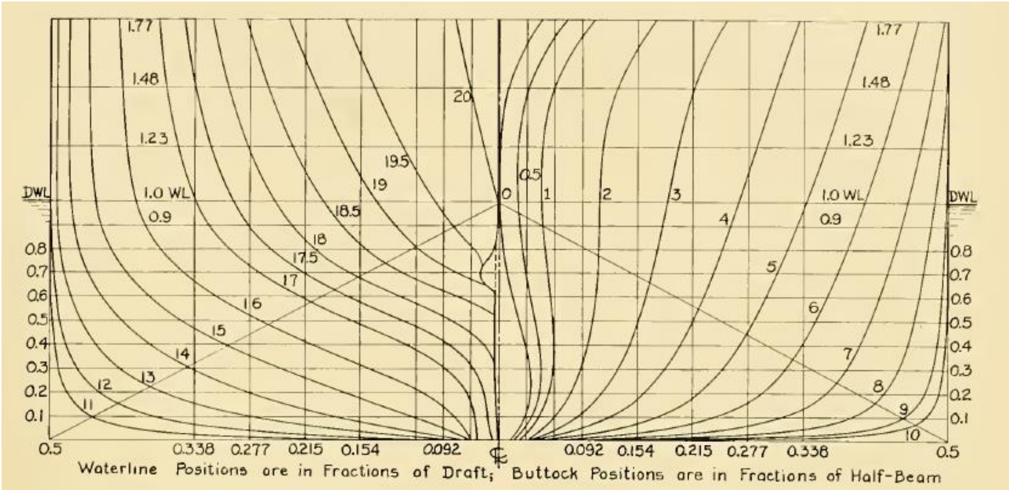

Figure 3 - Body plan of a ship with mathematical lines following the Taylor Method (Taylor 1915)

Other systematic series have been developed subsequently. From all the series available in the public domain, the FORMDATA series (Guldhammer, 1963) is the most complete and modern one despite having been created in the 1960's. There are more modern and better series, although not in the public domain, that are a result of hull form optimization with CFD tools and accumulated experience of ship model experiments.

Besides the Taylor Series, this work will explore in detail the Wageningen-Lap series (The Netherlands), the David Taylor Model Basin (DTMB) Standard Series 60 (USA) and the FORMDATA series (Denmark).

Some other systematic series that are explained in this work are:

- The Taylor-Gertler series (DTMB–USA, 1910–1954, for relatively sharp/fine hulls, C_P= 0.48 ~ 0.80);
- The BSRA series (NPL-U.K., early 1954, C_B = 0.55 ~ 0.85);
- The SSPA cargo ship series (Goeteborg-Sweden, early 1956, for cargo ships, C_B = 0.525 ~ 0.750);
- The NPL coasters series (U.K.-Dawson 1954–1959, C_B = 0.65, 0.70) for small, short-sea cargo ships (coasters);
- The SSPA coasters series (Sweden-Warholm/Lindgren 1953–1955, C_B = 0.60–0.70) for small short-sea cargo ships (coasters);
- The SRI series (Japan–Tsuchida et al. C_B = 0.77–0.84), for tankers and bulk carriers
- The NPL fishing vessels series (U.K.–Doust-O'Brien 1959, C_P = 0.60–0.70), for fishing ships/open-sea trawlers;
- The series of Stevens Inst. (USA, Roach, 1954, C_B = 0.458–0.560), for open sea tugboats;
- Various series of high-speed craft:
    - Royal Inst. of Technology (Sweden, Nordstrom, 1951);
    - Duisburg (W. Germany, Graff/Sturtzel, 1958);

- o DTMB Series 64 (USA, Yeh, 1965);
  - o NPL round bilge displacement series (UK, Bailey, 1976);
  - o MARIN high speed displacement hull series (Netherlands, Blok and Beukelmann, 1984);
  - o NSMB high speed displacement hull series (Netherlands, Oossanen, 1985);
  - o Laboratory of Ship and Marine Hydrodynamics—NTUA double chine series (Greece, NTUA-LSMH, Loukakis/Grigoropoulos).
- The series of fishing vessels of the towing tank of Potsdam, Berlin (medium and coastal fisheries) (Henschke 1964);
- The Ridgely–Nevitt trawler series (1963);
- The MARAD series (USA, Roseman, 1987 B *C* = 0.800–0.875, *L/B* = 4.5–6.5, *B/T* = 3.00 to 3.75), for bulky ships, tankers, and bulk-carriers.

The Wageningen-Lap Series (W. Lap), developed in 1954, assumes that the displacement and the prismatic coefficient C_P are pre-determined; then, based on the C_P and the specified speed (F_n number), the desired longitudinal position of the center of buoyancy is estimated. W. Lap estimates the category of the ship based on the given value of C_P, then proceeds to calculate the prismatic coefficient of entrance CPE and run CPR using Figure 4. With these two coefficients it is possible to use Figure 5 and Figure 6 to obtain the areas of sections 0 to 19 as percentages of the area of midship section.

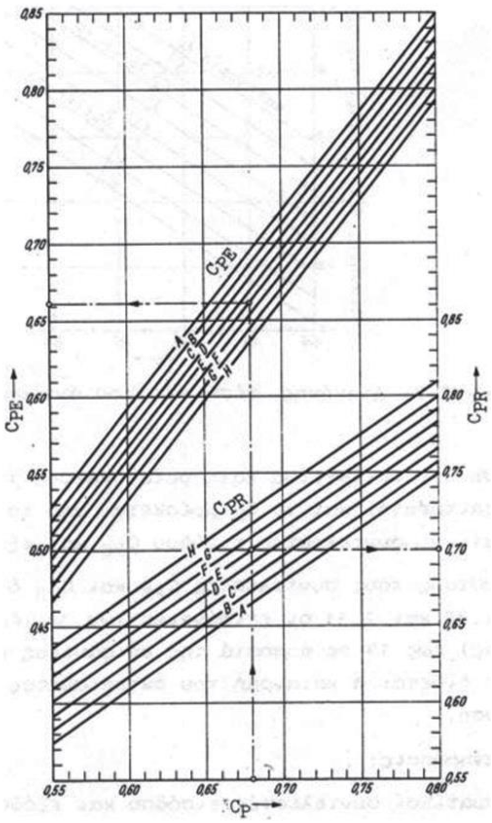

Figure 4 – Prismatic coefficient of entrance C_{PE} and run C_{PR} according to Lap A. J. W. (1954)

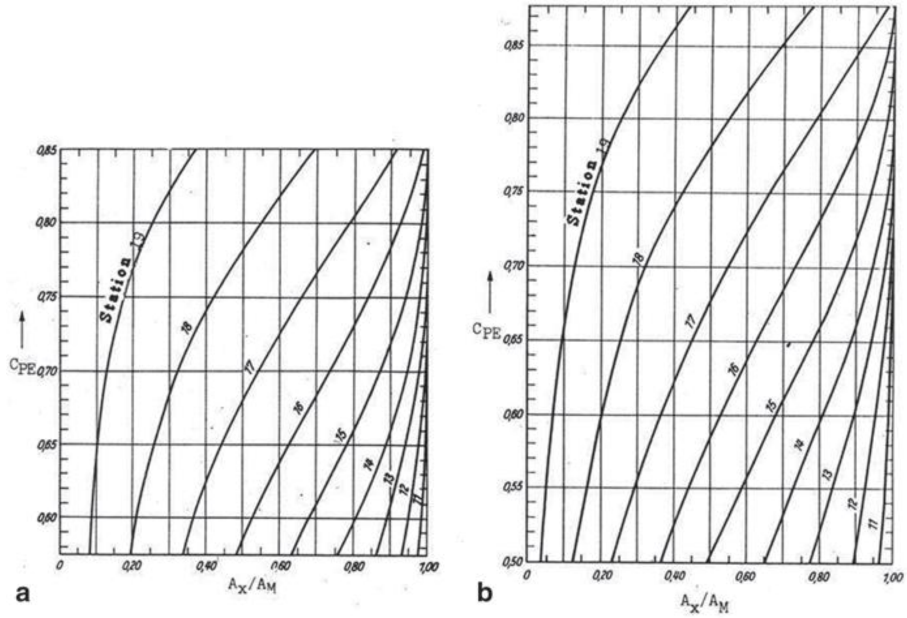

Figure 5 - Percentage distribution of sectional areas of fore-body according to W. Lap. A) For single-screw ships. B) For twin-screw ships Lap A. J. W. (1954)

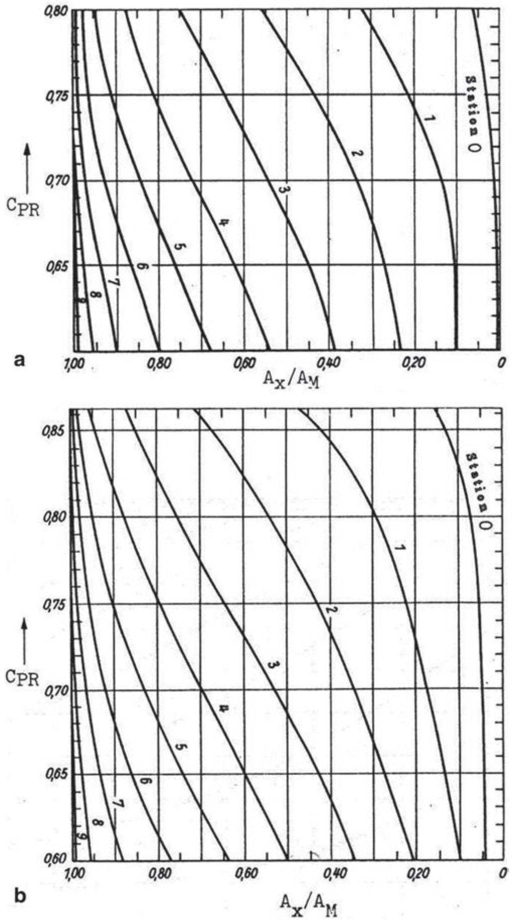

Figure 6 - Percentage distribution of sectional areas of aft-body according to W. Lap. A) For single-screw ships. B) For twin-screw ships Lap A. J. W. (1954)

The Series 60 Hull Form was developed a few years later. This method, developed by Todd et al. (1957), follows a procedure like the one followed for the Wageningen series of W. Lap with the following changes:

1. The prismatic coefficients of entrance C_{PE} and run C_{PR} are selected as functions of LCB and C_B from Figure 7;
2. The length of entrance L_E of the parallel body L_P (thus: L_R=L-L_P-L_E) and the curvature radius of midship section are selected from Figures 8 and 9;
3. For the selected prismatic coefficients C_{PE} and C_{PR}, the sectional areas, as percentages of A_M, are selected from Figures 10 (fore-body) and 11 (aft-body). Attention is drawn to the method of measuring the sections according to US convention (section 0 is at the forward perpendicular, section 20 is at the aft perpendicular).

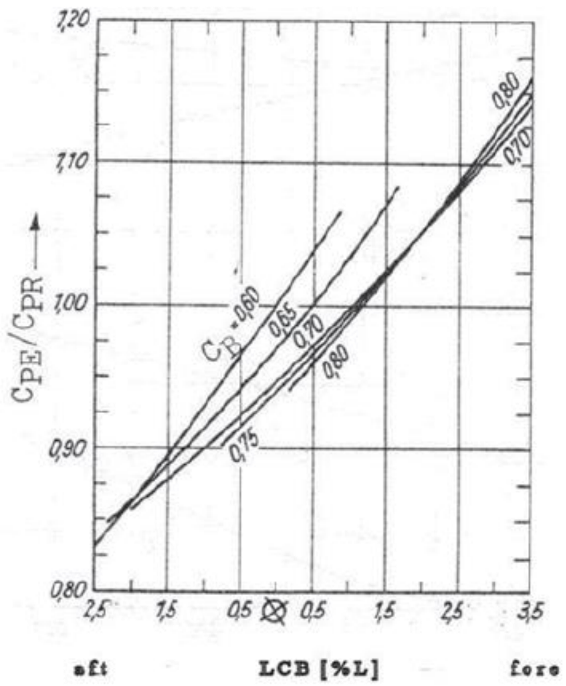

Figure 7 – Prismatic coefficient of entrance and run as a function of LCB/Lpp and C_B from Series 60 (Todd et al., 1957)

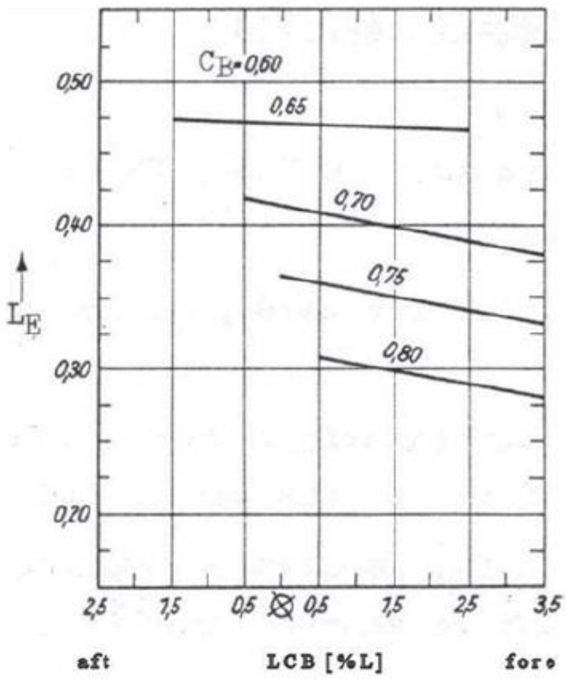

Figure 8 - Length of entrance as a function of LCP/Lpp and C_B from Series 60 (Todd et al., 1957)

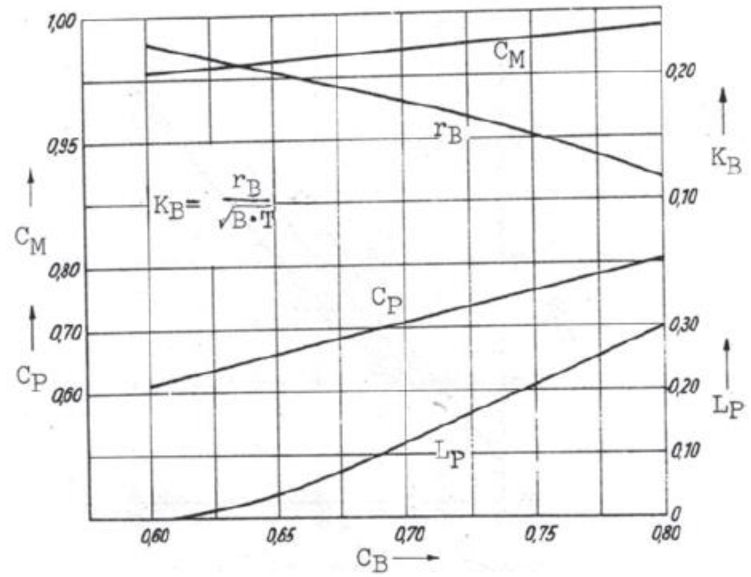

Figure 9 - Curvature Radius of midship section as a function of L_P, C_P, C_M, K_B and C_B from Series 60 (Todd et al., 1957)

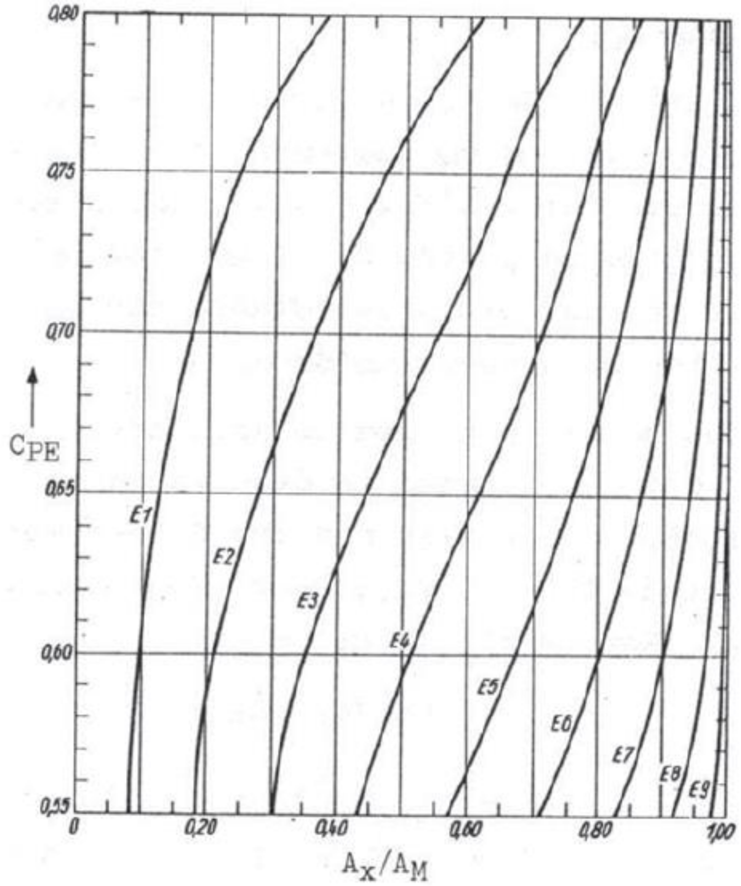

Figure 10 - Distribution of areas of fore-body sections as a function of C_{PE} from Series 60 (Todd et al., 1957)

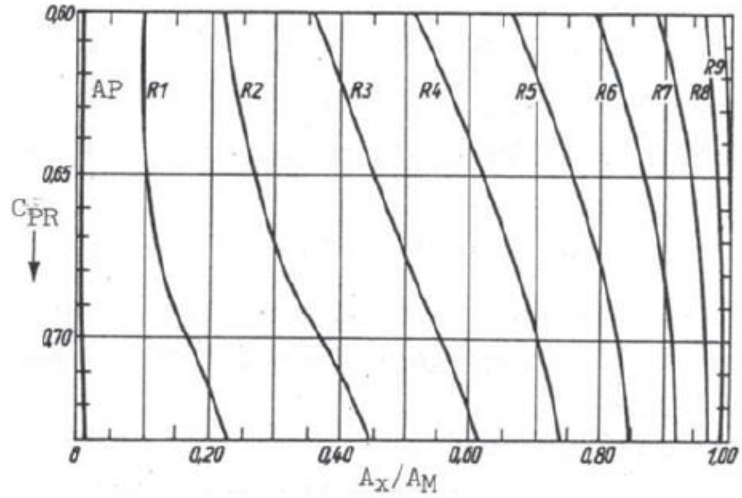

Figure 11 - Distribution of areas of aft-body sections as a function of C_{PR} from Series 60 (Todd et al., 1957)

The systematic FORMDATA of the Technical University of Denmark (DTU), Lyngby (Copenhagen, Denmark) is still considered today as the most complete of the public domain series and responds well to the hull form requirements of modern merchant ships. This series has been developed based on the systematic analysis of the geometric data of a high number of existing ships in the 1960's and of earlier systematic series, also considering their calm water hydrodynamics (resistance).

The FORMDATA series provides data both for the determination of the hydrostatic/stability characteristics of the ship during the preliminary design stage and for the required propulsive power as can be seen in Guldhammer and Harvald (1974).

Contrasting with the previously elaborated series of W. Lap and Series 60, the FORMDATA systematic series provides, in a systematic way, "*the ordinates of sections (offsets) in dimensionless percentages of the beam and of the reference draft*" (Papanikolaou, 2014). The ship sections form is given in proper scale instead of needing to be developed based on determined sectional areas. This greatly reduces the effort for the drafting of the ship lines.

Relevant characteristics of FORMDATA systematic series are:

1. It refers to ships with vertical sides at the midship section. The recommended midship section coefficients (CM = 0.74 ~ 0.995) are shown and are arranged according to the numbers 1 to 6 (Figure 12);

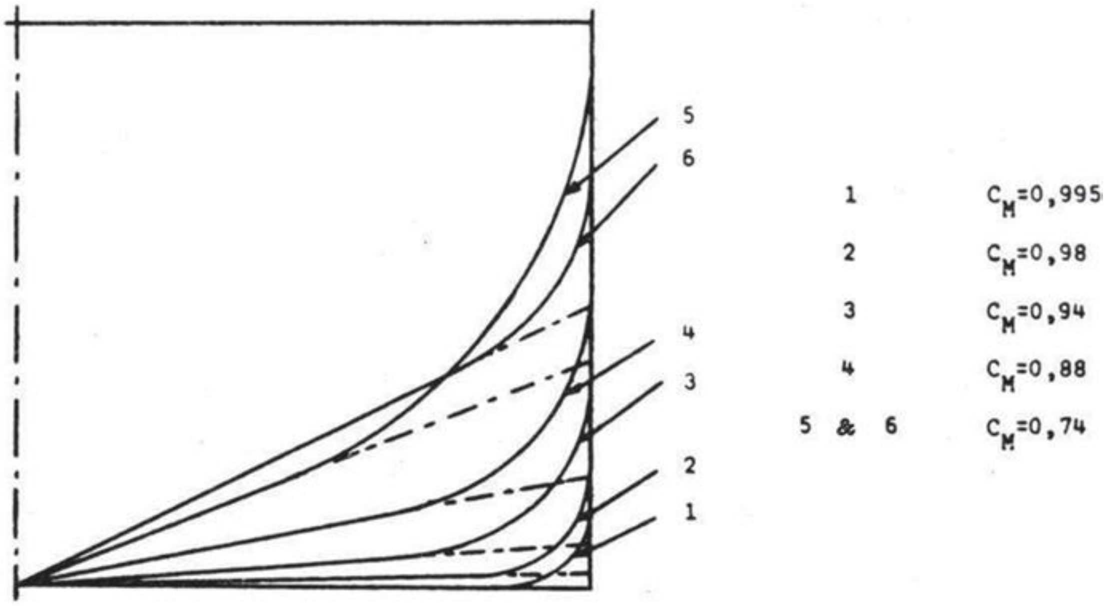

Figure 12 - Corresponding code number of midship section coefficient C_M (Guldhammer, 1963)

2. Three basic section forms are contemplated: sections of strong U character (full lines of U shape), V type sections (shape V) and N type sections (normal sections, without pronounced character);

3. The U, V and N sections are combined with two sets of stern A (aft) and Bow F (forward) sections;

4. The configuration of the bow and stern is in principle possible as can be seen in Figure 13. Also, various types of bulbous bow (symbol B), transom stern (symbol C1), or conventional cruiser stern (symbol T) are offered in Figure 14;

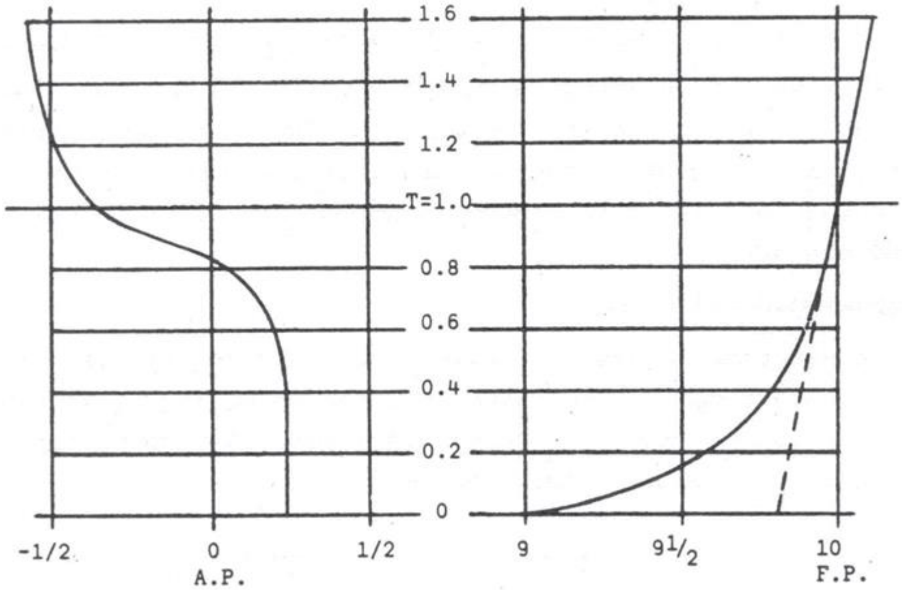

Figure 13 - Left: Profile of conventional cruiser stern associated to U, N, V sectional forms. Right: Profile of conventional bow associated to U, N, V forms (Guldhammer, 1963)

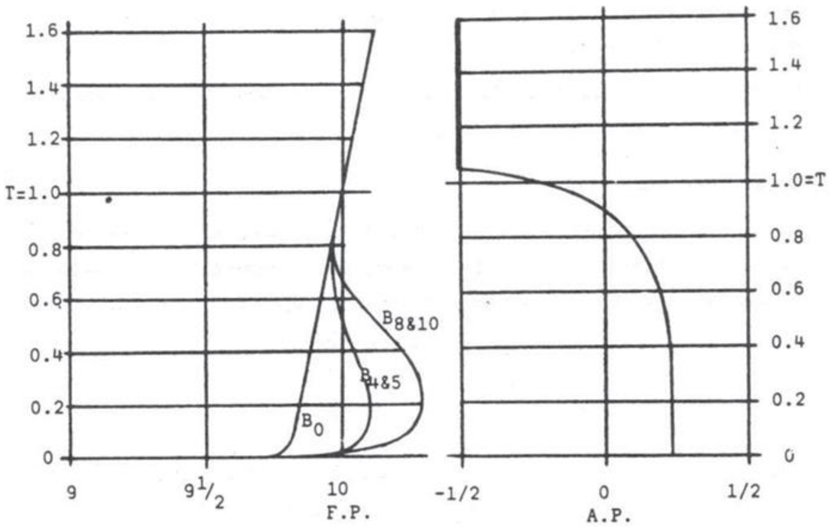

Figure 14 - Left: Profile of bow forms B (bulbous bow). Right: Profile of stern forms C (transom stern) (Guldhammer, 1963)

5. Every set of the given curves is encoded by a combination of symbols and numbers, with three characters and sometimes with one index (e.g. U2 F, T_B2A);

6. The hull is divided in 10 sections plus one additional section between section 0 and 1 and one additional section between section 9 and 10.

The application procedure for this series can described as follows:

1. Select the aft and fore-body block coefficients based on the known C_B and LCB (positive means abaft of midship)

$$C_{BF} = C_B\left(1.003 - 3.5\frac{LCB}{L_{PP}}\right) \quad (2)$$

$$C_{BA} = C_B(0.997 + 3.5\frac{LCB}{L_{PP}}) \quad (3)$$

Based on the coefficients CBF and CBA, it is possible to select a combination of the fore and aft-body sections. Figures 15 and 16 show the feasible fore-body forms in the first row and in the second row the corresponding values of CBF while in the first column the possible aft-body forms are listed with the corresponding coefficients of C_{BA}.

2. Typical set of curves of the FORMDATA series for various combinations of C_M, C_B, type of sections and the bow/stern, are given in the following figures. The complete set of FORMDATA curves is given in Guldhammer (1963).

3. Limits of the series application:

$$C_B = 0.50 \sim 0.850$$
$$C_M = 0.74 \sim 0.995$$
$$C_{WP} = 0.50 \sim 0.95$$

SECTIONS SERIES		B_0 1F	B_5 1F	B_{10} 1F	B_0 2F	B_4 2F	B_8 2F	B_0 3F	B_4 3F	B_8 3F
	C_{BF} C_{BA}	*0.70 – 0.90*	*0.70 – 0.90*	*0.70 – 0.90*	*0.50 – 0.75*	*0.50 – 0.75*	*0.50 – 0.75*	*0.50 – 0.70*	*0.50 – 0.70*	*0.50 – 0.70*
T1A	*0.70 – 0.85*	0.70 – 0.85 (-4.50)–(+3.52)	0.70 – 0.85 (-4.50)–(+3.52)	0.70 – 0.85 (-4.50)–(+3.52)						
U1A	*0.70 – 0.80*	0.70 – 0.85 (-4.50)–(+2.38)	0.70 – 0.85 (-4.50)–(+2.38)	0.70 – 0.85 (-4.50)–(+2.38)					C_B / X_B (%L_{BP})	
U2A	*0.55 – 0.75*				0.53 – 0.75 (-4.50)–(+5.10)	0.53 – 0.75 (-4.50)–(+5.10)	0.53 – 0.75 (-4.50)–(+5.10)			
N2A	*0.55 – 0.75*				0.53 – 0.75 (-4.50)–(+5.10)	0.53 – 0.75 (-4.50)–(+5.10)	0.53 – 0.75 (-4.50)–(+5.10)			
V2A	*0.60 – 0.70*				0.55 – 0.73 (-3.38)–(+4.92)	0.55 – 0.73 (-3.38)–(+4.92)	0.55 – 0.73 (-3.38)–(+4.92)			
U3A	*0.50 – 0.70*							0.50 – 0.70 (-4.64)–(+4.92)	0.50 – 0.70 (-4.64)–(+4.92)	0.50 – 0.70 (-4.64)–(+4.92)
N3A	*0.50 – 0.70*							0.50 – 0.70 (-4.64)–(+4.92)	0.50 – 0.70 (-4.64)–(+4.92)	0.50 – 0.70 (-4.64)–(+4.92)
V3A	*0.50 – 0.70*							0.50 – 0.70 (-4.64)–(+4.92)	0.50 – 0.70 (-4.64)–(+4.92)	0.50 – 0.70 (-4.64)–(+4.92)

Table 1 - Combinations of cruiser stern and bulbous bow of the FORMDATA series according to Guldhammer (1963)

SECTIONS SERIES		U1F	U2F	N2F	V2F	U3F	N3F	V3F	N4F
	C_{BF} C_{BA}	0.70 – 0.80	0.55 – 0.65	0.55 – 0.75	0.55 – 0.65	0.50 – 0.70	0.50 – 0.70	0.50 – 0.70	0.45 – 0.65
T1A	0.70 – 0.85	0.70 – 0.83 (-2.20)–(+3.52)							
U1A	0.70 – 0.80	0.70 – 0.80 (-2.20)–(+2.36)						C_B / X_B (%L_{BP})	
U2A	0.55 – 0.75		0.55 – 0.70 (-2.25)–(+4.80)						
N2A	0.55 – 0.75			0.55 – 0.75 (-4.50)–(+4.80)					
V2A	0.60 – 0.70				0.58 – 0.68 (-1.08)–(+3.68)				
U3A	0.50 – 0.70					0.50 – 0.70 (-4.64)–(+4.92)			
N3A	0.50 – 0.70						0.50 – 0.70 (-4.64)–(+4.92)		
V3A	0.50 – 0.70							0.50 – 0.70 (-4.64)–(+4.92)	
N4A	0.45 – 0.65								0.50 – 0.65 (-4.82)–(+5.10)

Table 2 - Combinations of cruiser stern and non-bulbous bow of the FORMDATA series according to Guldhammer (1963)

After completing all the steps described before it is possible to get the lines plan for the aft or fore body for the type of ship selected. Figure 17 shows an example where the lines for each section represent a certain value for C_{BA}. In case the value obtained is different, some interpolation is necessary to produce the corrected line.

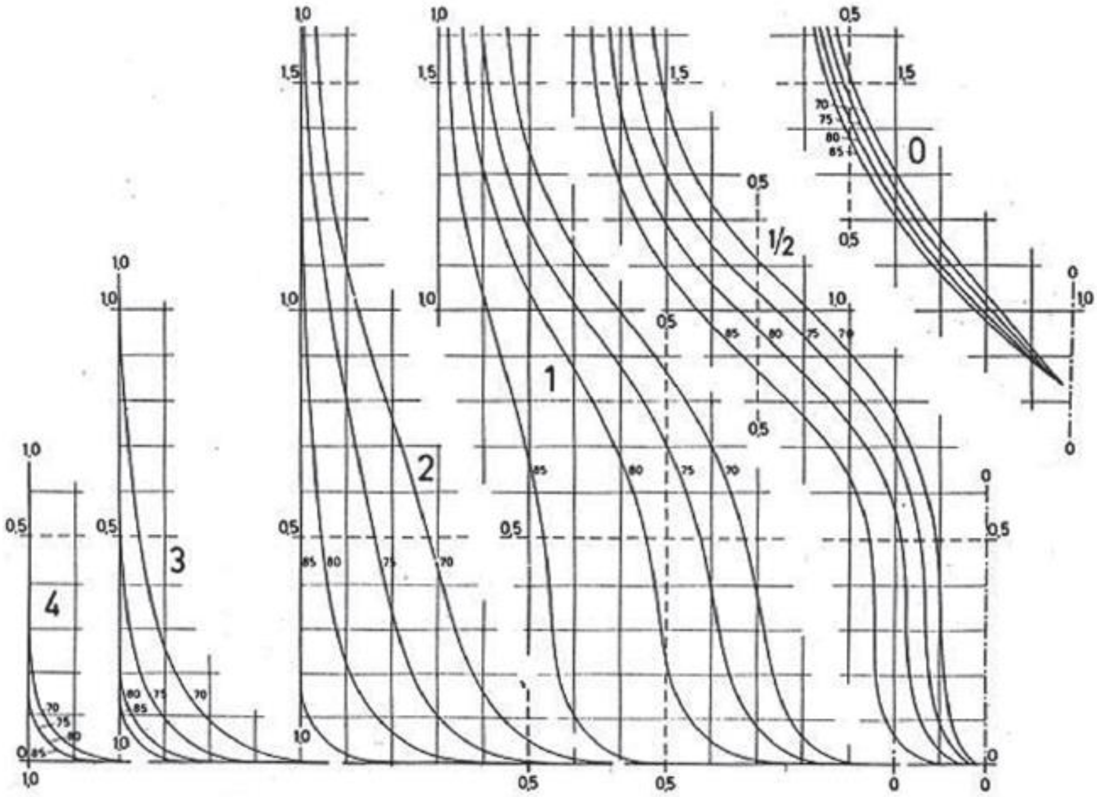

Figure 15 - Dimensionless sections T1A-FORMDATA for stern section of U type, series of tankers (T: tanker), cruiser CM = 0,995 and CBA = 0.70–0.75–0.80–0.85 (Guldhammer, 1963)

3.2. Fully parametric design

In the fully parametric design method, the shape is created using a small data set, only capturing the essence of the intended shapes and their possible variations. This method creates the hull geometry based on relationships established by form parameters. These parameters are core entities that reflect and influence the functional characteristics of the geometry, and can be grouped in the following classes:

- **Positional:** Length, beam, draft, etc.;
- **Differential:** Tangents, curvature information, slopes, etc.;
- **Integral:** Areas, volumes, high order moments, etc.

The ship's geometry is described using longitudinal curves, called basic curves, like the sectional area curve and the design waterline. The modelling of these basic curves is done by using the form parameters that should, ideally, contain all the information needed to produce the hull shape.

New hull forms can be created by modifying the initial model parameters values, updating the relationships of the parameters, and creating curves and surfaces with acceptable fairness. The parameters can be changed manually or through equations that include other parameters intended to give a final hull closer to perfection.

It is possible to distinguish three consecutive steps in the process of creating a new bare hull, as can be seen in Figure 16:

1. Parametric design of longitudinal curves (SAC, DWL, Slopes, etc.).
2. Parametric modelling of sections derived from the basic curves.
3. Generation of surfaces using the curves obtained in steps 1 and 2.

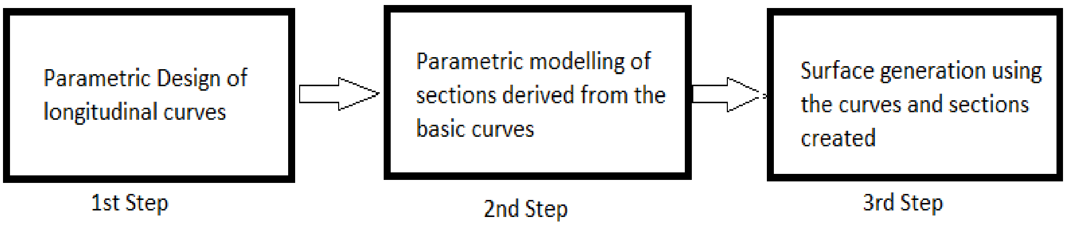

Figure 16 - Hull Design Process steps

The development of the ship hull lines plan through a fully parametric method is very interesting as it allows more freedom when developing the lines plan. Ideally, a merge of the two methods would be beneficial as it would create a hull with a solid base but with the freedom to change any parameter at the choice of the designer. With that in mind, a research in the field of fully parametric design was also made to better understand and possibly merge the two together.

The expression “mathematical representation of ship forms” involves a procedure which is often very complex, as developed by Williams (1964) who set out a practical procedure for mathematically delineating ships and applied it to the hull of a tanker. However, the method was not entirely applicable for a full-scale use due to computing difficulties. The main mathematical calculations were applied to the ship’s waterlines. The entrance and run were treated separately, dividing the entire waterline from fore to aft into two separate equations. Also, special expressions were used near fore stem and stern. The mathematical forms used for the calculations were: polynomials, exponential functions and trigonometrical functions, or a combination of them.

Watson and Gilfillan (1976) reviewed the methods in ship design and analysed their evolution considering the relationships between dimensions, coefficients and approximate formulae. They discovered that one of the most fundamental changes was in the starting point of designing a new ship. With the introduction of computers, ship owners were able to use their operating experience from existing ships to have a rational approach when taking the first step of designing a new ship: defining the initial parameters.

For choosing the appropriate main dimensions, ships can be divided in three main categories:

1. The deadweight carrier: distinguished by the fact that its main dimensions are given by the formula:

$$\Delta = C_b LBT * 1.025 * (1 + s) = W_D + W_L \quad (4)$$

where,

- L = Length BPP in meters
- B = Breadth mld. In meters
- T = Load draught in meters
- C_b = Moulded block coefficient at draught T on Length BPP
- Δ = Full displacement in tonnes
- s = Shell, stern and appendages displacement expressed as a fraction of the moulded displacement
- W_D = full deadweight in tonnes
- W_L = lightship weight in tonnes

2. The capacity carrier: The dimensions are determined by the equations:

$$V_h = C_{bD} LBD^1 = \frac{(V_r - V_u)}{(1 - S)} + V_m \quad (5)$$

where,

- D_1 = Capacity depth in meters;
- D_1 = D+ c_m + s_m;
- D = Depth moulded in meters;
- c_m = Mean camber in meters = 2/3c for parabolic camber;
- s_m = Mean sheer in meters = 1/6 (s_f+s_a) for parabolic sheer;
- C_{bD} = Block coefficient at the moulded depth;
- V_h = Total volume in m_3 of the ship below the upper deck, and between perpendiculars;
- V_r = Total cargo capacity required, in m_3;
- V_u = Cargo capacity available above the upper deck, in m_3;
- S = Deduction for structure in cargo space expressed as a proportion of the moulded volume of these spaces;
- V_m = Volume required for machinery, tanks, etc. within the volume V_h.

3. The linear dimension ship: where the linear dimensions of the ship are distinguished by the fact that they are primarily fixed by considerations besides the deadweight and/or volume.

The form-parameter method of ship design using a piecewise polynomial development was proposed by Arthur L. Fuller (1978). Fuller created a program where the user would be able to get a representation of an early stage design of the ship's body by using a very minimum input of length, beam, draft, prismatic coefficient and midship section coefficient, LCB, LCF and deck at edge definition. His program, HULGEN, was specifically developed for the early stage design where many optional hulls could be developed rapidly, determining whether the hull form could be developed from the gross dimensions and form coefficients available. HULGEN provides the capability to produce a station at any point from the tip of the bow to the aft perpendicular. These cuts are generated by the following three polynomials, from top to bottom:

- One third order polynomial from the main deck at edge to the load waterline.
- One fourth order polynomial from the load waterline to the flat of bottom specially developed for fine sections and by a bilge radius for full stations.
- One polynomial connecting the flat of bottom to the keel.

It is important to note that in his program, the result is not a wire frame body plan, but one where every point on the surface is defined and can be computed with the appropriate station waterline intersection. Also, this program was created by and for the U.S. Navy type hulls, so there may be some differences or missing parameters when comparing to a merchant ship.

HULGEN produces a body plan based on the following curves:

- Section area;
- Flat of bottom;
- Load waterline;
- Main deck at edge;
- Profile;
- Deadrise slope;
- Load waterline slope;
- Main deck at edge slope.

Using the curves described above, it is possible to obtain a result like the one shown in Figure 17 where it is possible to observe that the program produces a body plan with a good set of lines for a preliminary design.

When developing a ship form from an initial set of parameters, the first curve, and probably one of the most important, is the section area curve. In fact, the section area curve has a high significance since it impacts on the final hull form, as studied by McNaull (1980). McNaull set out to generate a new ship using a parent hull by varying the SAC parameters:

- Prismatic coefficient;
- Longitudinal center of buoyancy;
- Length of parallel middle body;
- Slopes at entrance or run.

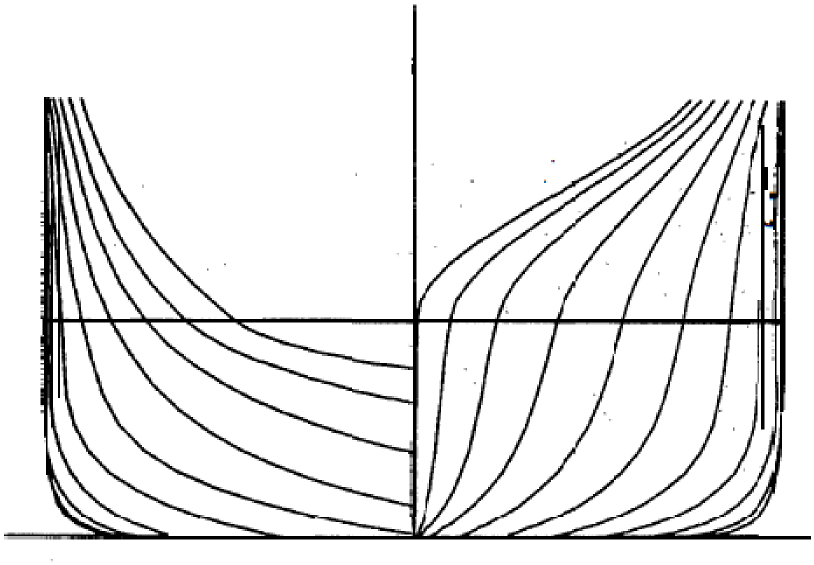

Figure 17 - Body Plan from HullGen, (Fuller 1978)

These new ship lines can be derived through a single parent hull (lines distortion approach), a series of parent hulls (standard series approach) or geometrical hull form parameters (form parameter approach). The lines distortion method has the advantage of the hull lines being given by a known parent hull with good stability, resistance and seakeeping and the possibility of selecting each one of these qualities as a starting point for the new ship. These lines can be distorted using a systematic approach developed by Lackenby (1950) or through transformation functions of Söding and Rabien (1977) that distort section area curves, bilge radius, etc.

In the standard series approach, the hull form is obtained by interpolating the design of that ship series. The series can be created from one or more parent ships, or from ships derived from the line's distortion method. Some of the most known standard series are the Taylor series, Series 60, Japanese, British, FORMADATA Series, etc. (McNaull 1980).

In contrast to these methods, the form parameter approach does not require parent hulls. In this method, the lines are created mathematically according to specified parameters that define the significant curves of the new hull form. Of the three methods, this last one is the method that allows the greatest range of form variation but also the one that requires the most experience and knowledge from the designer. McNaull (1980) focused on the first method and calculated the section area curve variation through the following parameters:

- Draft.
- Design waterline.
- Midships location.
- Forward and aft perpendicular.
- Maximum area or area of midship section.
- Length of forebody and aft body.
- Longitudinal center of buoyance.
- Abscissa of centroids of fore and aft body.
- Underwater volume of fore and aft body.
- Angle of entrance and run.

Figure 18 shows a schematic representation of the SAC and the parameters involved in its creation as given by McNaull (1980).

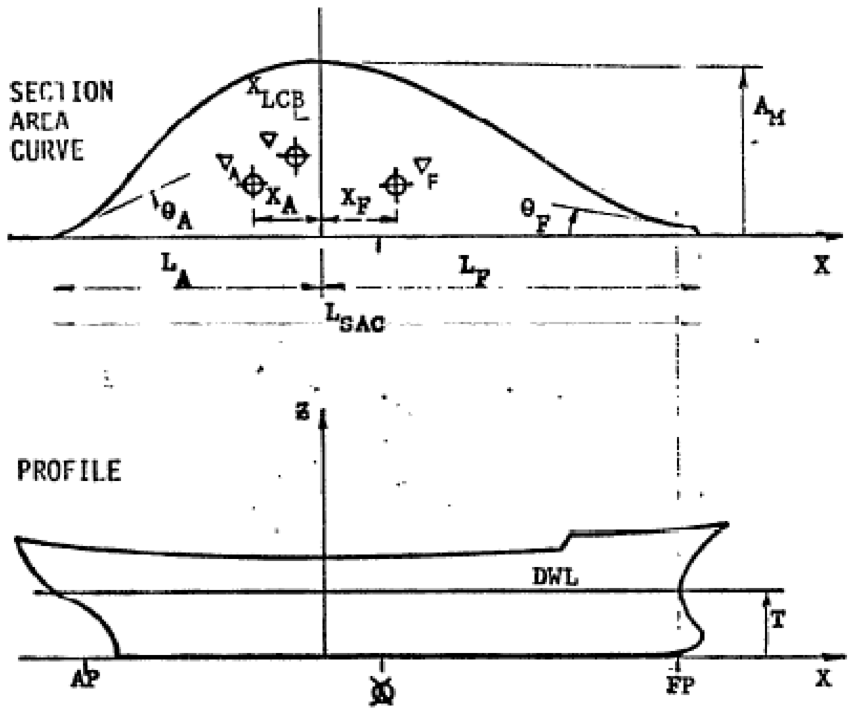

Figure 18 – SAC and profile according to McNaull (1980)

In their endeavour of finding an easy process of designing a hull form, Abt et al. (2001) studied a parametric modelling approach to the design of ship hull forms. Their method allows the creation and variation of ship hull quickly and efficiently. The complexity of their method could vary from a global expression like “a post pan max container carrier with draft restriction” to a complicated mathematical detail like the variation of the weight of a control point from a given section. They divided the process into three topology levels:

- Topology of Appearance.
- Topology of Design.
- Topology of Representation.

They used CFD programs to evaluate the ships performance and, according to their reliable ranking from Harries and Schulze (1997), used them in the optimization process. Their modelling requirements for the mathematical representation, inside the respective three topology levels can be seen in Figure 19.

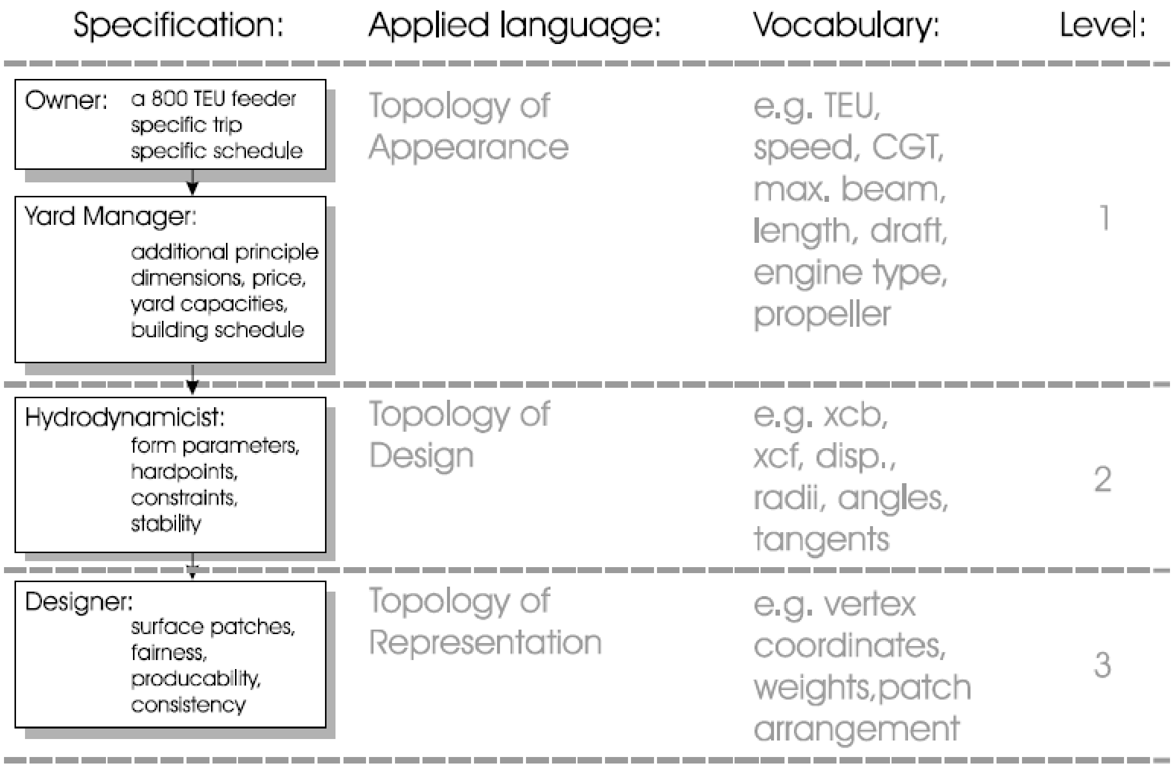

Figure 19 - Topology levels, Abt et al. (2001)

On the third topology level, representation, they started to think of the hull as a series of surface patches. These patches make up the general appearance of the hull, such as flat areas, knuckle lines, curved regions, while avoiding gaps and overlaps.

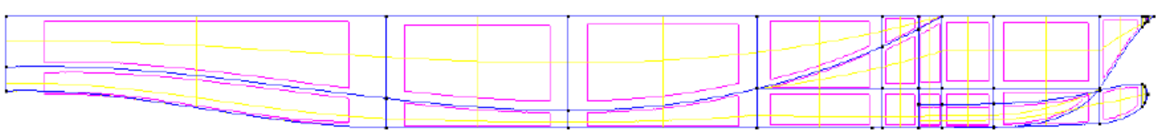

Figure 20 - Surface patches example from Abt et al. (2001)

On top of this method they applied a parametric curve generation developed by Harries and Abt (1998) and used it to generate and optimize bare hulls by Harries (1998). The method consists on a parametric curve generation process where the vertices of all B-Splines curves are computed from a geometric optimization, applying fairness criteria and capturing global shape characteristics. Hull properties, such as the shape of the deck for example, are represented as curves created from form parameters.

Parametric curves represent the properties of the sectional shape of the ship at any longitudinal position. Once these basic curves are created, a numerical algorithm is applied to create a set of sections at selected locations and a skinning is performed to create a surface definition from the skeleton of design sections (Woodward, 1988). A suitable arrangement of design sections is determined automatically from an analysis of the basic curves. The geometric modelling system developed by the authors came to be known as the FRIENDSHIP modeller.

Pérez et al. (2008) also studied a parametric solution to generate simple hull lines using B-Splines and NURBS. Their study focused on sailing ship hulls and round bilge hulls, allowing the generation of hull lines that meet hydrodynamic coefficients imposed by the designer. Their method allows a more flexible design than using a normal affine transformation of a parent hull. They subdivide computer-aided ship hull design (CASHD) into shape representation and shape design and focused on the latter which deals with the initial modelling of a new hull form.

The base of their proposed method is the sectional area curve and the load waterplane area and their influence on the hull form result. These two curves are described through polynomials with constraints.

4. Development of the hull design tool

In this chapter, a detailed explanation of the methodology used to develop hull shapes based on the FORMDATA series is presented.

The tool used to support and test the creation of the hull shapes was MATLAB, which "is a programming platform designed specifically for engineers and scientists. The heart of MATLAB is the MATLAB language, a matrix-based language allowing the most natural expression of computational mathematics." (See https://www.mathworks.com/discovery/what-is-matlab.html)

The developing process is divided into three parts: initial parameters, FORMDATA series hull form and new hull shape. Each part has its own purpose, and an in-depth analysis is given in the following subchapters. The program developed to test this methodology is also divided into three modules as shown in Figure 21.

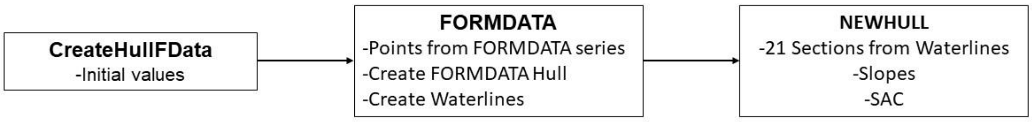

Figure 21 - Hull design program modules

Base data on hull shapes for different types of hulls was obtained from FORMDATA, by determining the coordinates of points directly on the figures containing the hull sections. Since FORMDATA is only available on paper or raster format, extracting the coordinates was a lengthy procedure and involved accuracy issues (more on this aspect in Chapter 6). All FORMDATA sections available at https://docplayer.net/29017058-FORMDATA-series-characteristics-of-the-FORMDATA-series.html were processed to obtain the coordinates and the data was compiled by the author in one digital file, in FORMDATA.

The hull is defined length wise with its 0 at the stern perpendicular, as can be seen in Figure 22. The vertical zero is also placed at the stern perpendicular at the maximum depth of the hull. The division between stern and bow is made at half the length.

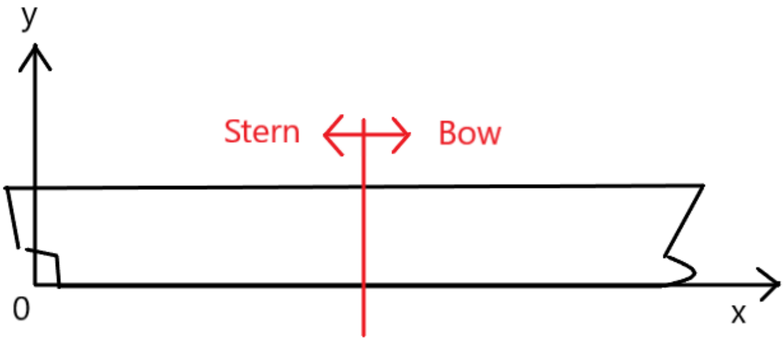

Figure 22 - Location of the axis on the hull

4.1. Initial hull parameters

The initial parameters of the hull shape design are the first thing to define and specify. The basic properties defined are length between perpendiculars (L_{pp}), breadth (B), draught (T), draft (D), block coefficient (C_b) and longitudinal center of buoyancy (L_{cb}) as can be seen in Table 3. It is important to note that the L_{cb} has its zero at half the L_{pp}, being positive if it is forward or negative if behind, as shown in Figure 23.

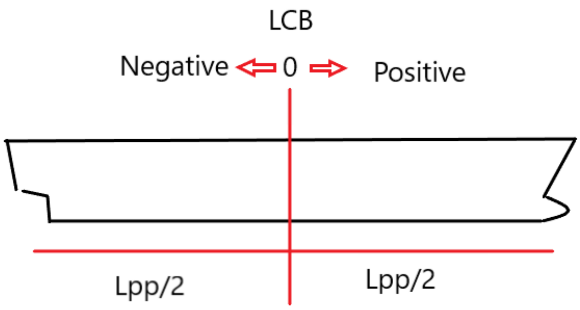

Figure 23 - LCB location

Length between perpendiculars	L_{pp}
Beam	B
Draught	D
Depth	T
Block Coefficient	C_b
Longitudinal Center of Buoyancy	L_{CB}

Table 3 - Initial hull parameters

4.2. FORMDATA hull shape

To develop a FORMDATA hull shape using the initial parameters given, first two calculation are needed: the aft block coefficient and the fore block coefficients, or C_{ba} and C_{bf} respectively. These coefficients are defined by the formulas shown next

$$C_{ba} = C_b * (0.997 + 3.5 * \frac{L_{CB}}{L_{pp}}) \tag{6}$$

$$C_{bf} = C_b * (1.003 - 3.5 * \frac{L_{CB}}{L_{pp}}) \tag{7}$$

Once both these coefficients are defined it is necessary to convert the FORMDATA section figures into points. With the aid of the CAD program *Rhinoceros*, the figures were imported, and points were drawn over the figure and then their position was obtained as can be seen in Figure 24. The points that were chosen are marked in red in the figure and they were placed along the section lines with an even spacing of 0.1 in the y-axis. The criteria to choose this spacing was to keep a constant variance along one of the axes. It is also important to notice that the last point has a y-coordinate of 1.62 instead of 1.6 as the lines end above it. The example shown in Figure 24 is from FORMDATA - Figure B.13 and represents the stern sections of a tanker with a block coefficient of 0,995.

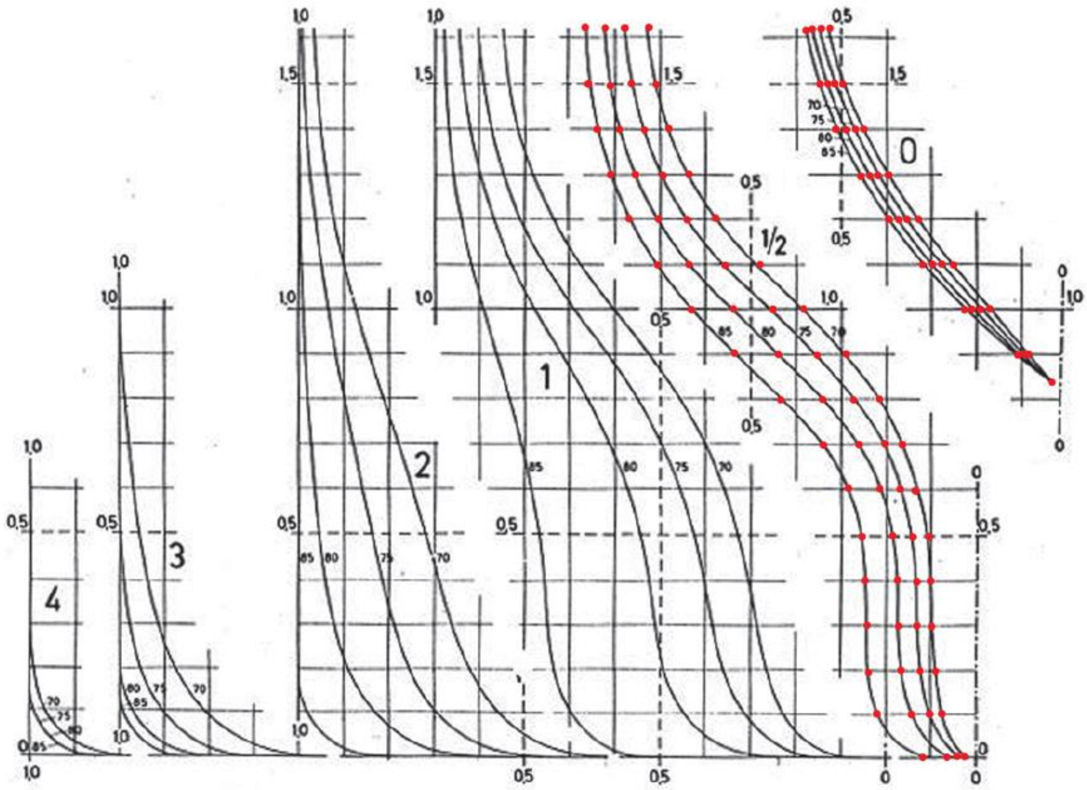

Figure 24 – Example of the points (in red) obtained from FORMDATA (Guldhammer, 1963) used in the FORMDATAHULL module

Still looking at Figure 24, the points obtained for the section 0 were:

- Points Y = [0.84 0.9 1 1.1 1.2 1.3 1.4 1.5 1.62];
- Points X (Cba = 0,7) = [0.02 0.076 0.16 0.25 0.32 0.39 0.44 0.48 0.52];
- Points X (Cba = 0,75) = [0.02 0.087 0.18 0.27 0.35 0.41 0.46 0.5 0.54];
- Points X (Cba = 0,8) = [0.02 0.1 0.2 0.29 0.37 0.43 0.48 0.52 0.55];
- Points X (Cba = 0,85) = [0.02 0.1 0.21 0.31 0.39 0.45 0.5 0.54 0.57].

The same method was applied for all sections for all types of sterns and bows resulting in a large list of points. All these points were gathered in a matrix for each section and each type of hull. The bulbous sections were divided into two sections: Section 10A and Section 10B. Section B is the bulbous part and section A is the rest of the section.

These sets of points were arranged by type of hull. First was by stern (T type, U type, V type or C type) for the sections between [0,5] then by types of bow (U type, N type, V type, Bulb 4% of A_M, Bulb 5% of A_M, Bulb 8% of A_M and Bulb 10% of A_M).

Once the pretended type of chosen stern or bow is identified, another condition is necessary to align the correct set of points to its corresponding section, which is the C_b. Only the U type stern for non-tanker ships has two Cb possibilities: 0,98 or 0,995. A list of the Cb possibilities according to type of hull is shown in Table 4 and Table 5.

T type	C_b=0.98 C_b=0.995
U type	C_b=0.98
V type	C_b=0.98
C type	C_b=0.98

Table 4 - Stern type possible C_b

U type	C_b=0.98
N type	C_b=0.98
V type	C_b=0.98
Bulb 4% of A_M	C_b=0.98
Bulb 5% of A_M	C_b=0.98 C_b=0.995
Bulb 8% of A_M	C_b=0.98
Bulb 10% of A_M	C_b=0.98 C_b=0.995

Table 5 - Bow type possible C_b

However, the whole series was not available to the author. From Table 1 and Table 2, the only bows and sterns available are T1A, U1A, U2A, N2A, V2A, U2F, V2F, N2F, $B_4$2F, $B_5$2F, $B_8$2F, B_{10}2F

Once the corrected C_b is identified it is possible to proceed to assemble the sets of points depending on the C_{ba}, for sterns, or the C_{bf}, for bows. As can be seen in Figure 24, there are four different lines for each value of C_{ba}. This implies the existence of multiple scenarios, 7 scenarios for this section 0, which are:

$$\begin{cases} Cba \ \le 0{,}7 \\ 0{,}7 \ < Cba \ < 0{,}75 \\ Cba = 0{,}75 \\ 0{,}75 \ < Cba \ < 0{,}8 \\ Cba = 0{,}8 \\ 0{,}8 < Cba \ < 0{,}85 \\ 0{,}85 \ \le Cba \end{cases}$$

If the value of C_{ba} is equal to 0,7/0,75/0,8/0,85 the points used are the ones shown before. However, in most of the cases this will not happen. To account for that possibility, if the value falls between two of those values, the program will do a linear interpolation between both sets of points also considering the value of C_{ba}. The formula is shown below using x_A for one line and x_B for other line interpolating between the C_{ba} values of 0.7 and 0.75.

$$Section\ 0\ x\ vale = x_A + (x_B - x_A) * (C_{ba} - 0.7)/(0.75 - 0.7) \quad (8)$$

Once the set of points is defined, it will be stored in two matrixes, one for the X values and another for the Y values, called Sec0x and Sec0y respectively. The name of the matrix comes from:

$$\begin{cases} Sec \ \rightarrow Section \\ 0 \ \rightarrow Number\ of\ Section \\ X \ \rightarrow X\ or\ Y\ values \end{cases}$$

All sections are calculated using this method. However, depending on the type of stern or bow, the number of sections differs. This process is explained in an easier way in the chart shown in Figure 25, where a flow chart of the selection process can be seen.

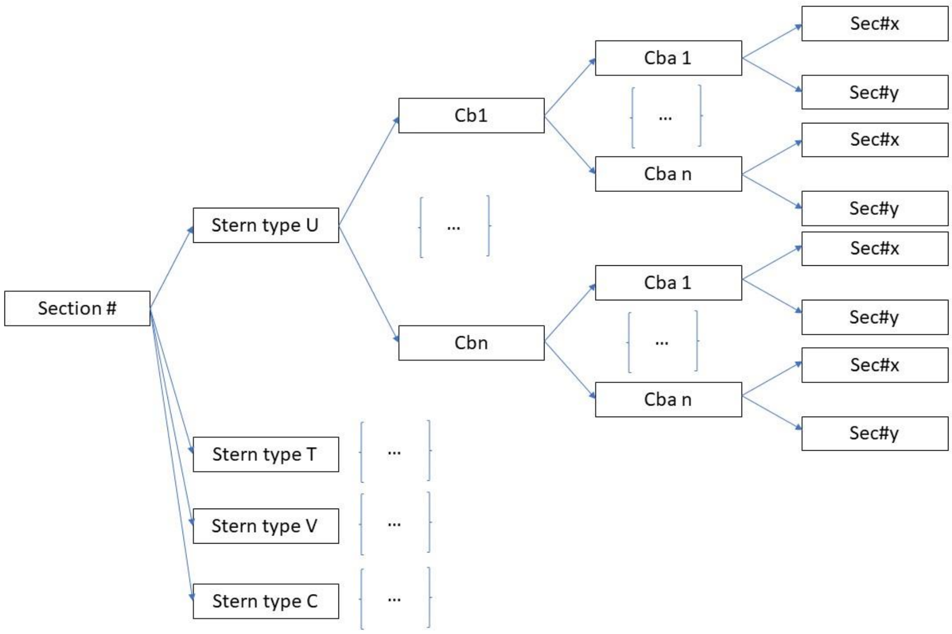

Figure 25 - Flow chart of the process to obtain the section points for stern section

Once the coordinates for all the points are set, it is time to refine the sections. Each section is fitted with a new type of curve to represent the shape of the section. This is done to improve the shape as can be seen by comparing Figure 26 and Figure 27.

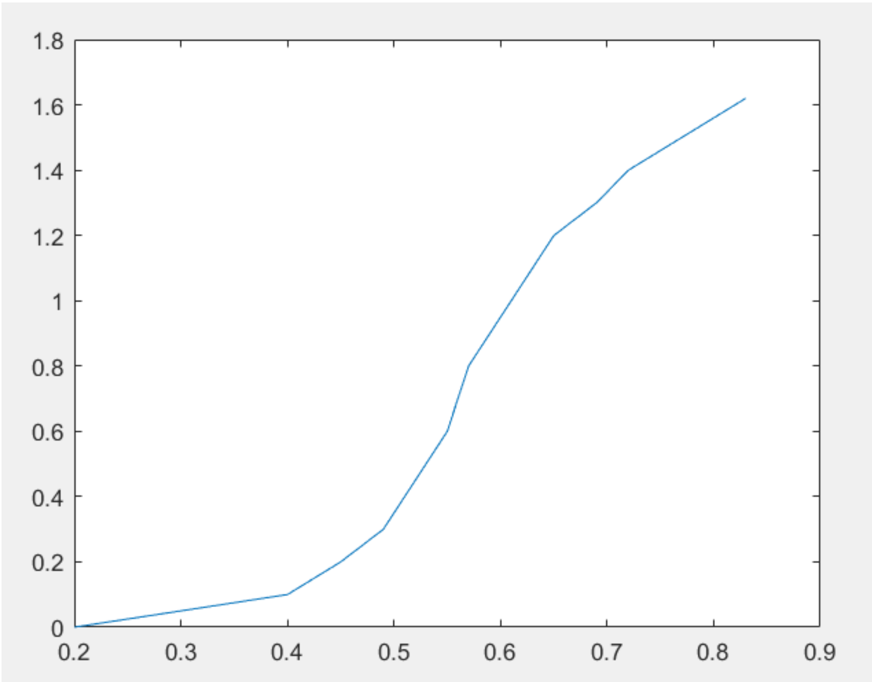

Figure 26 – Example of an original section using the points obtained from FORMDATA series

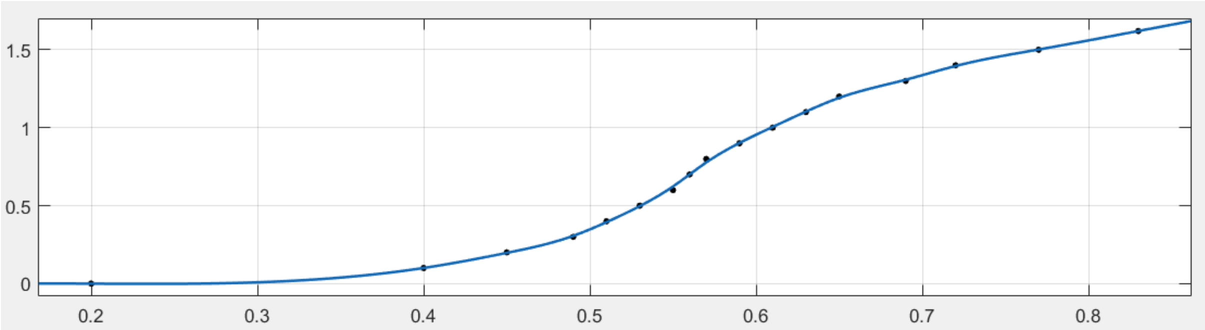

Figure 27 - Example of a smoothing spline applied to the points obtained

As can be seen by comparing both figures, the first curve is much rougher than the second one. The first one is built by connecting each point with a straight line, which creates the dents along the line. The second curve is a spline that tries to match the slope before each point with the slope after each point, while trying to have the smallest length possible. It is important to note, that the first curve ensures that every point belongs to the curve while the second one is not obligated to do so. The points in a spline act like nodes, all with their own weight that dictate the behaviour of the curve. The curve does not necessarily pass through the points but near them, which can lead to small errors, but it can also forgive some small errors.

As there are a huge variety of different interpolating curves and methods, a toolbox was chosen, which contains 6 types of interpolation methods. They are:

- Smoothing spline.
- Cubic Spline.
- Exponential.
- Fourier.
- Gauss.
- Polynomial.

Each method has its vantages and disadvantages. An overview on each method is given with some illustrations to better visualize each curve behaviour and aspect.

- ### Smoothing Spline

The smoothing spline, as can be seen above in Figure 27, is a function estimate, f(x), obtained from a set of high amplitude observations y_i (e.g. noise) of the target $f(x_i)$. The goodness of the fit is balanced by using a derivative based measure of the smoothness of the fit. The most common example is the cubic smoothing spline but there are many others.

This type of spline interpolation allows the spline to withstand small point deviations and provides a better trajectory along the curve.

- Cubic Spline

Cubic spline interpolation is used very often to avoid the Runge's phenomenon. This phenomenon is an oscillating problem at an interval edge that occurs when using polynomial interpolation with high degree polynomials over a set of equidistance interpolation points. This phenomenon is similar to the Gibb's phenomenon in Fourier series approximations, described ahead.

This cubic spline method provides an interpolating polynomial that is smoother and with smaller errors than other interpolating polynomials such as Newton's or Lagrange's polynomial. An example can be observed in Figure 28 below.

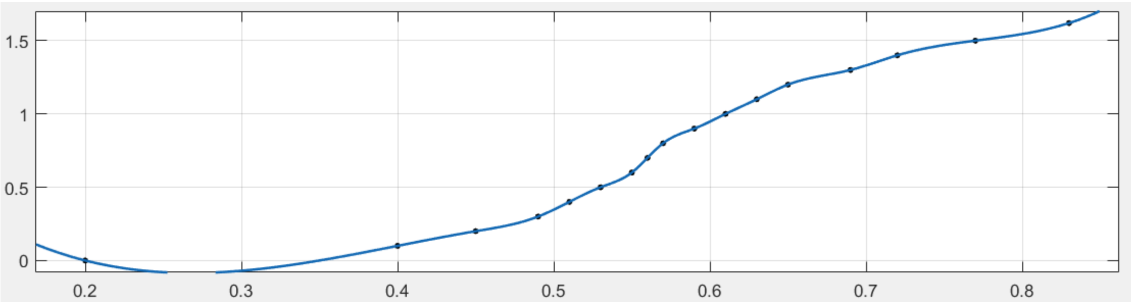

Figure 28 - Cubic spline interpolation example

- Exponential

This spline interpolation method allows the avoidance of the inflection points, given by cubic polynomial splines and smoothing splines, and consists on an interpolating function composed of piecewise exponentials that join smoothly at each node. An example of the result can be seen in Figure 29. This method, as can be seen, does not produce a good fit to the points that make up the section and, therefore, is not a suitable method.

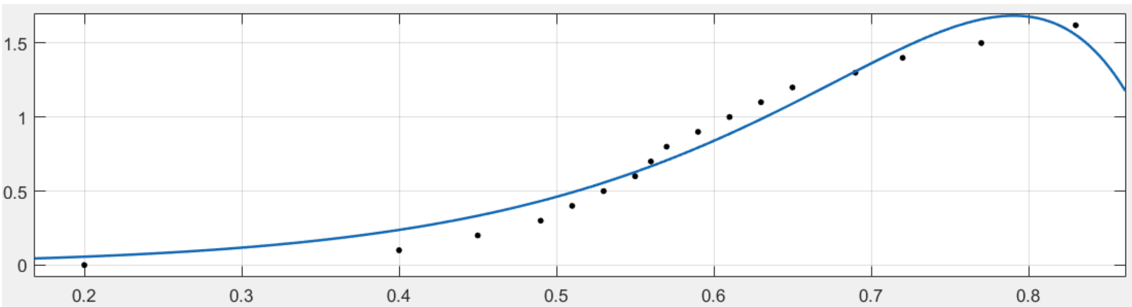

Figure 29 - Exponential interpolation example

- Fourier

Fourier interpolation method is based on the Fourier transform which consist in the decomposition of a general function by means of trigonometric functions. This interpolation function has to be a sum of sines and cosines of a given period, which makes it suitable to interpolate periodic functions. As can be seen in Figure 30 the spline created by the Fourier method follows the shape of the section but has a big error margin when compared to other methods.

The Gibb's phenomenon described before is related to the manner in which the Fourier series of a piecewise periodic function behaves at a jump discontinuity, seen by big oscillations near the jump.

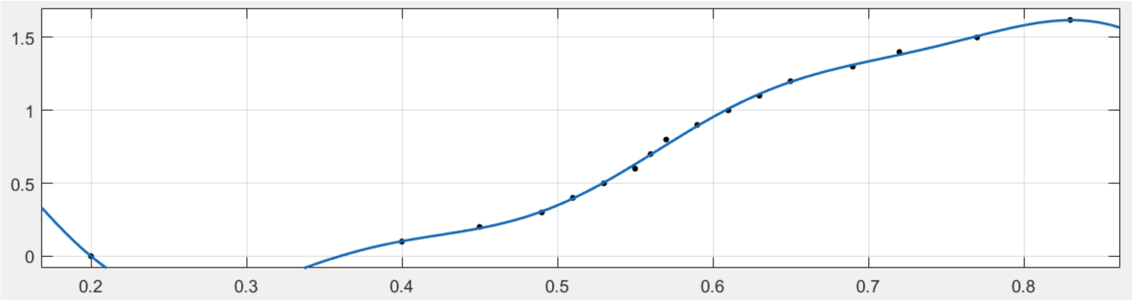

Figure 30 - Fourier interpolation example

- Gauss

The Gauss interpolation method is based on the Gaussian process to interpolate a given set of data. This process is a non-linear tool and a stochastic process, meaning that every combination of the random variables has a multivariable normal distribution.

This method can be used to fit a spline that passes exactly through the data points but also for regression. In this case, some margin is given to each spline to let them better fit to the points and with that a better flow along the section. An example can be seen in Figure 31 where a Gauss interpolation is fitted to the same section as in the other cases.

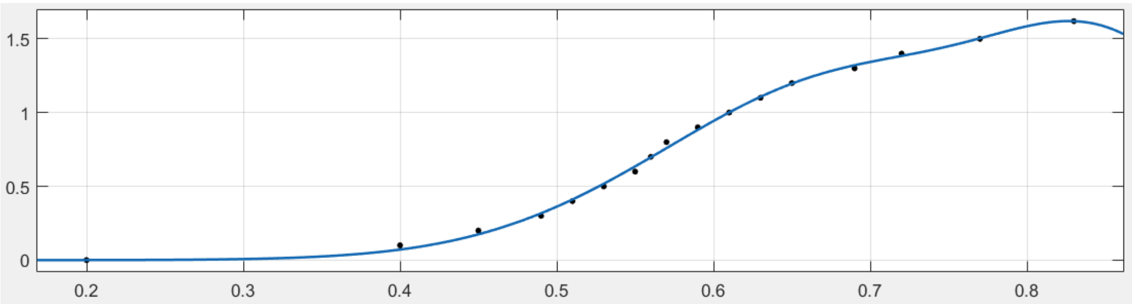

Figure 31 - Gaussian interpolation example

- Polynomial

The polynomial interpolation method is a very interesting method, due to the simplicity to work with equations that come from the interpolation. The objective of this method is to interpolate a given data set by finding the polynomial of lowest degree possible that respects the boundary conditions.

This allows the fitting of very large sets of data and to control its shape by constructing the curve, along the data set, using several polynomials. This resulting curve is easy to evaluate due to the mathematical simplicity of polynomials.

There are flaws however. It is not practical to apply these curves to some data sets that require a high order polynomial, which respects the boundary conditions, because the higher the order the higher the curve “freedom” and loss of shape control. If the governing equation is of a high degree, the curve in absence of any constraints is free to deviate from the intended path.

In Figure 32, a polynomial interpolation is applied to the same set of points presented in Figure 26. It is possible to note the inflection between the first and second point, which is not desired, and that the curve does not pass through all points.

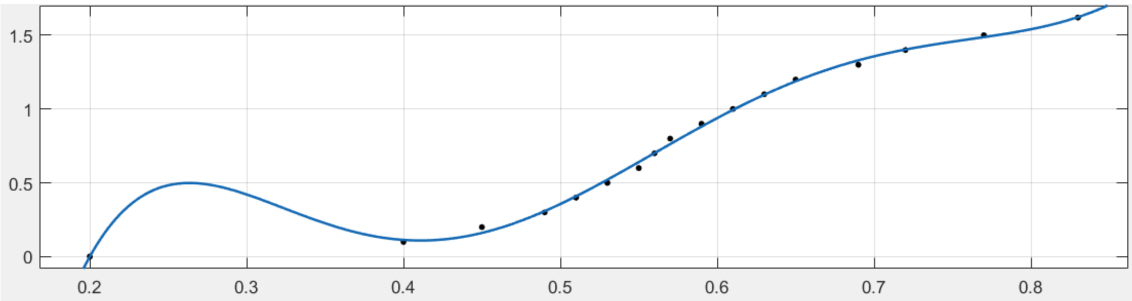

Figure 32 - Polynomial interpolation example

Looking at the figures above, it is possible to see that the smoothing spline is the best option to represent the sections. Using this spline, it is possible to extract as many points as possible from it, easier than the ones extracted from the FORMDATA series pages. We can take the new points and store them in new matrixes for these “improved” sections. By applying this spline to all data sets, the FORMDATA series replication is done. Further development can be made and is described in the next chapter.

4.3. Further development

Using the sections obtained from the FORMDATA series an improvement to these sections can be made and more information can be obtained from the basic sections obtained.

Each type of stern and bow has its own number of sections and they are not always the same. A table of the sections for each type of stern and bow is presented below:

Stern T	○ Section 0; ○ Section ½; ○ Section 1; ○ Section 2; ○ Section 3; ○ Section 4.
Stern U	○ Section 0; ○ Section ½; ○ Section 1; ○ Section 2; ○ Section 3; ○ Section 4.

Stern N	○ Section 0; ○ Section ½; ○ Section 1; ○ Section 2; ○ Section 3; ○ Section 4.
Stern V	○ Section 0; ○ Section ½; ○ Section 1; ○ Section 2; ○ Section 3; ○ Section 4; ○ Section 5.
Stern C	○ Section 0; ○ Section ½; ○ Section 1; ○ Section 2; ○ Section 3; ○ Section 4.
Bow U	○ Section 6; ○ Section 7; ○ Section 8; ○ Section 9; ○ Section 9 ½; ○ Section 10.
Bow V	○ Section 6; ○ Section 7; ○ Section 8; ○ Section 9; ○ Section 9 ½; ○ Section 10.
Bow N	○ Section 6; ○ Section 7; ○ Section 8; ○ Section 9; ○ Section 9 ½; ○ Section 10.
Bow 4% of A_M	○ Section 6; ○ Section 7; ○ Section 8; ○ Section 9; ○ Section 9 ½; ○ Section 10 A; ○ Section 10 B.

Bow 5% of A_M	○ Section 7; ○ Section 8; ○ Section 9; ○ Section 9 ½; ○ Section 10 A; ○ Section 10 B.
Bow 8% of A_M	○ Section 6; ○ Section 7; ○ Section 8; ○ Section 9; ○ Section 9 ½; ○ Section 10 A; ○ Section 10 B.
Bow 10% of A_M	○ Section 7; ○ Section 8; ○ Section 9; ○ Section 9 ½; ○ Section 10 A; ○ Section 10 B.

Table 6 - Stern and bow available sections

Taking this into account, the possible hull shapes that can be obtained by combining the several bows and sterns are shown in Figure 33.

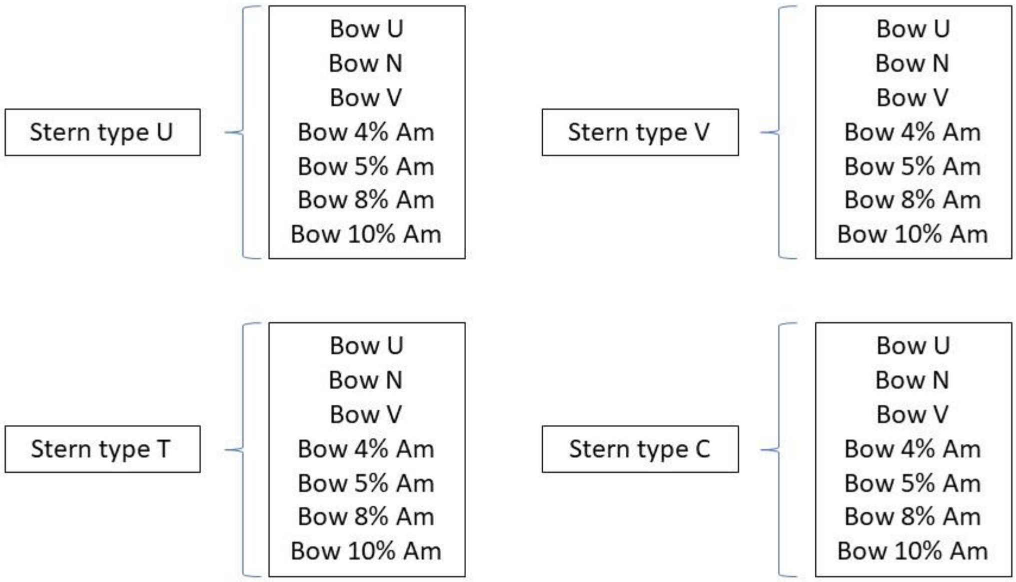

Figure 33 - Possible hull configurations

By combining all the improved sections obtained from the FORMDATA series and intercepting with horizontal planes it is possible to obtain points to design the waterlines. To obtain the waterlines the sections were intercepted 17 times, from 0 to 1.6 spaced by 0.1 as can be seen in Figure 34.

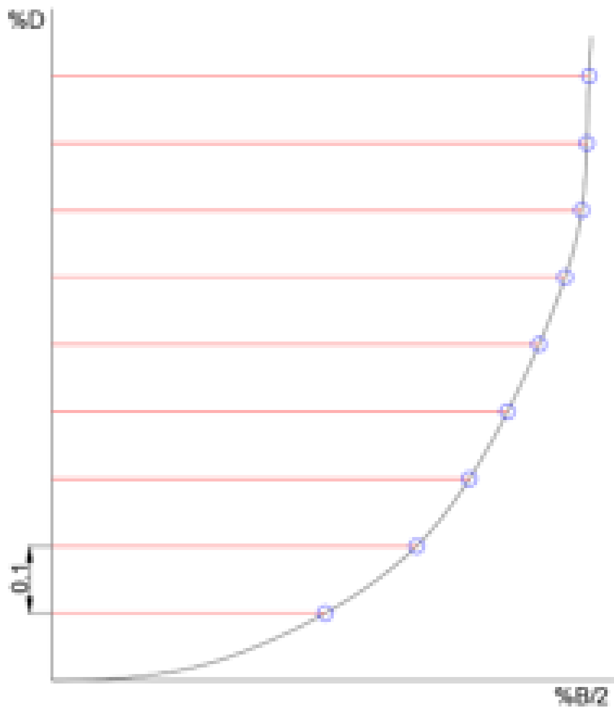

Figure 34 - Waterlines definition example

The method was to group the longitudinal (along x-axis) coordinates of each section with the horizontal plane intersection yy values, as described in Figure 34. By collecting the pairs of points from the same horizontal plane intersection with all sections, a waterline can be drawn. An example can be seen in **Error! Reference source not found.**. A spline can be created that crosses all points obtained and with that the waterline is complete. The spline chosen and its alternatives follow the same process and explanation as the one made for the section lines.

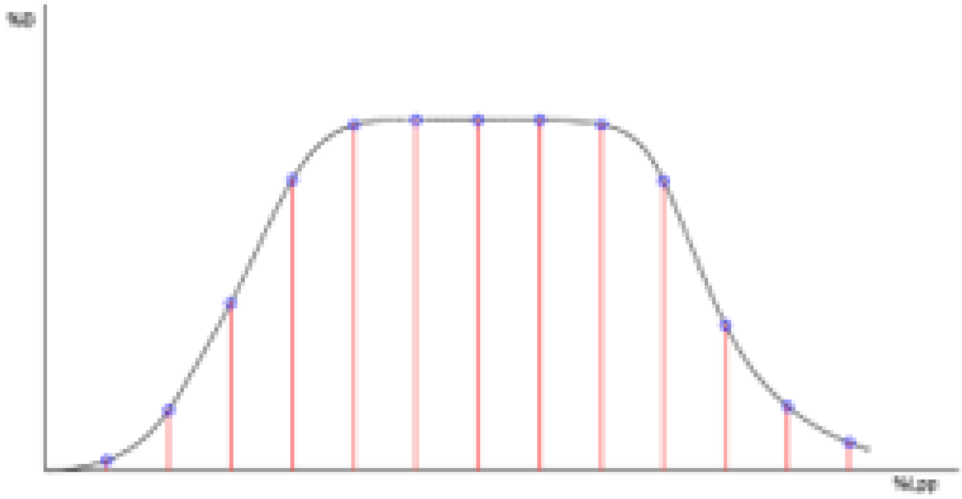

Figure 35 - Waterline example

It is important to notice that not all hull configurations have the same number of sections, and therefore the waterlines will be different. Each waterline obtained, eleven in total by default, will represent the FORMDATA waterlines ranging from 0 to 1, or from the bottom to the draught.

One last horizontal intersection is designed, the deck at edge curve. The deck curve is created in the exact same way as the waterlines but this time at the value of 1.62. The deck is created, also with a shape preserving spline, by pairing the X values described above with the waterlines. The value of 1.62 comes from the FORMDATA study and it does not represent the true deck height. As to be possible to apply to all types of ships, with a variety of sizes, the FORMDATA series end at a height of 1.62 and when applied to a defined vessel, the section should be "cut" at the correct value. In this study the value of 1.62 was followed and kept.

With all waterlines defined and known a great number of possibilities opens up. In the process of better define the ships' hull and better understand the shape it is taking the next step chosen is to redraw the sections.

As mentioned before, the FORMDATA sections divide the hull in 12 sections, at the most, with 10 sections equally spaced along the full length of the hull and two sections between the first and last pairs of sections. For example, if we are talking about a 300 m vessel the frame spacing will be 30 m. This may be insignificant when looking at the middle of hull but when looking at the bow or stern is to great a distance between sections. This probably happens due to the amount of information that would be required to collect, store, and reproduce, making it impractical to have that many sections. With this present, there are 3 options available to further develop the hull:

1. Raise the number of sections to reduce the section spacing.
2. Re-arrange the location of the sections, so that the areas of greater interest are better defined.
3. A combination of points 1 and 2.

Of course, the option chosen will depend on the designer and what stage of the design process he is, or even what information he is after. If we think that the bow and stern, who have very optimized shapes that often result in complex shapes, the designer can leave those shapes to a later stage and does not require more information than the one provided by the initial stage FORMADATA.

However, he could be after a more defined hull right from the start of the design process. If that is the case, he can choose from the options above.

The first option is the simpler one where the length of the hull is divided in as many sections as are needed, all equally spaced. This option trades localized information for calculation simplicity and processing required.

The second option requires information, or past experiences, to pinpoint where each section will better define the hull and provide better information.

The third option is the completer and more complex one. Commonly the hull is divided in 21 sections. These sections can be equally spaced or the spacing can vary. For example, for the first and last 25% of the hull length the spacing is a section every 5%, and for the middle 50% the spacing will be one section each 10%. This results in 16 sections, which demonstrates that usually the spacing is even less than the one used in the example, and even smaller than the one used in the basic form of FORMDATA.

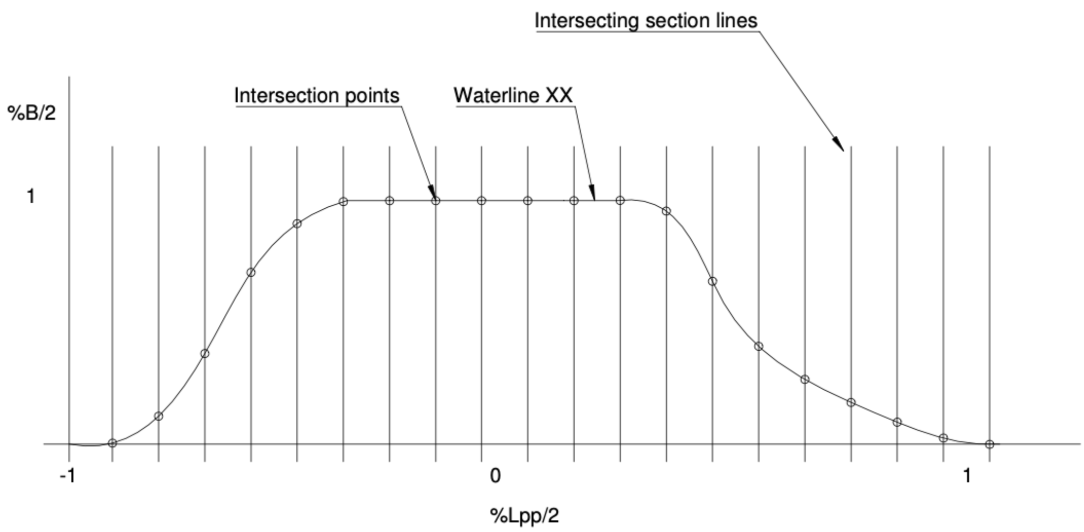

Figure 36 - Waterline being intersected by vertical planes

For this case, the hull was divided in 21 equally spaced sections. As such, picking the waterlines obtained previously and intersecting them with vertical planes at each section location, the sections points were obtained. This process can be seen in Figure 36 shown above.

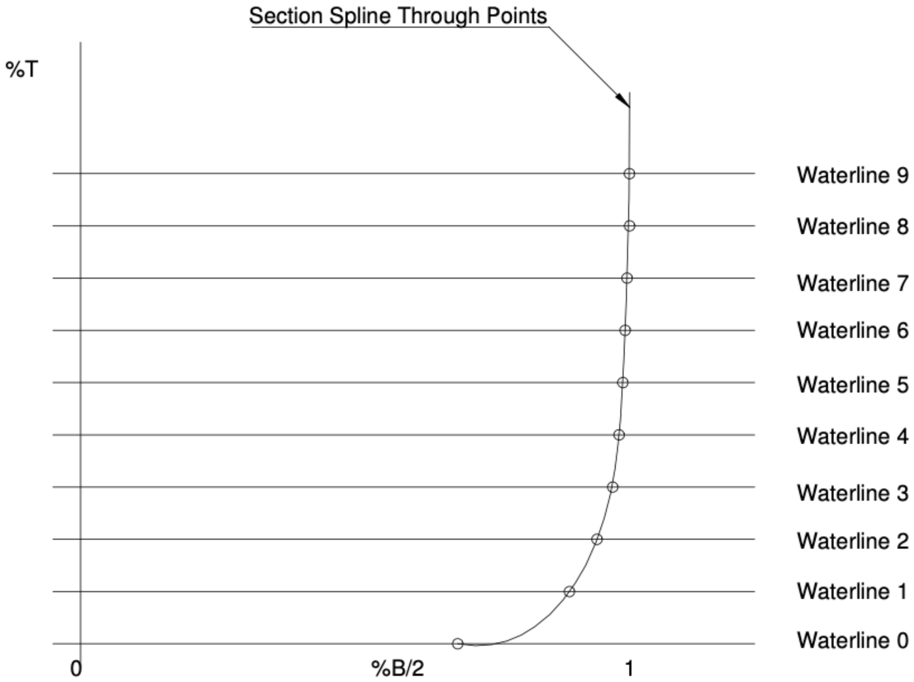

Figure 37 - Waterline points from a vertical plane being intersected by a spline

Just like the process used to obtain the "improved" FORMDATA sections, a shape preserving spline was applied to the 11 points obtained at each intersection plane. With this the designer obtains the new sections, as shown in Figure 37, and can now move to further develop those sections.

These new sections will be divided into two parts: below waterline and above waterline. They are improved separately and then joined together at the waterline. This method allows the designer to focus on the "wetted" part of the hull, which requires more attention, separately without having to pay much attention to the part above the waterline.

1. Sections below the waterline

The sections below the waterline are the ones that require the most attention and work because they will dictate the hydrodynamic behaviour of the hull. Although, to reach "perfection", a great deal of interactions and different programs are used to develop them, there are some parameters the user can control to make the sections more optimized. An easy way to control the shape of the hull is by using slopes. By enforcing slopes at any given point, the user has some control over the general shape of the section, or at least before and after the slope application point.

As such, these sections are divided into two zones: the flat of bottom and waterline.

- ### Flat of bottom

The flat of bottom part refers to the bottom portion of the section, where the slope controls the angle that the section leaves the horizontal part and starts rising up. This is the first thing that can indicate a general shape of the hull. For example, a U shape hull, probably, has a bigger flat of bottom slope than a V shape hull.

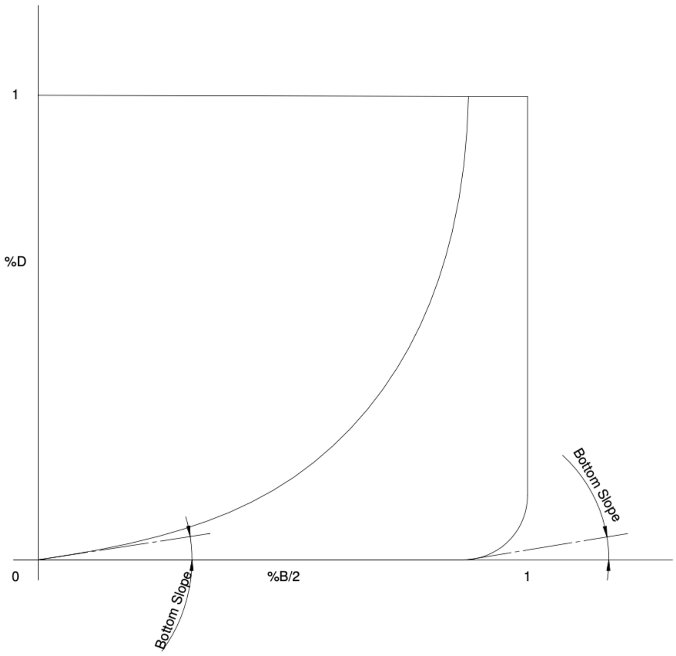

Figure 38 - General Section with Bottom Slope

- Waterline

This part refers to the slope that the section makes when reaching the waterline. These slopes influence how the section will transition between the below and above waterline parts. Usually, above the waterline is only a smooth continuation of the shape developed below the waterline.

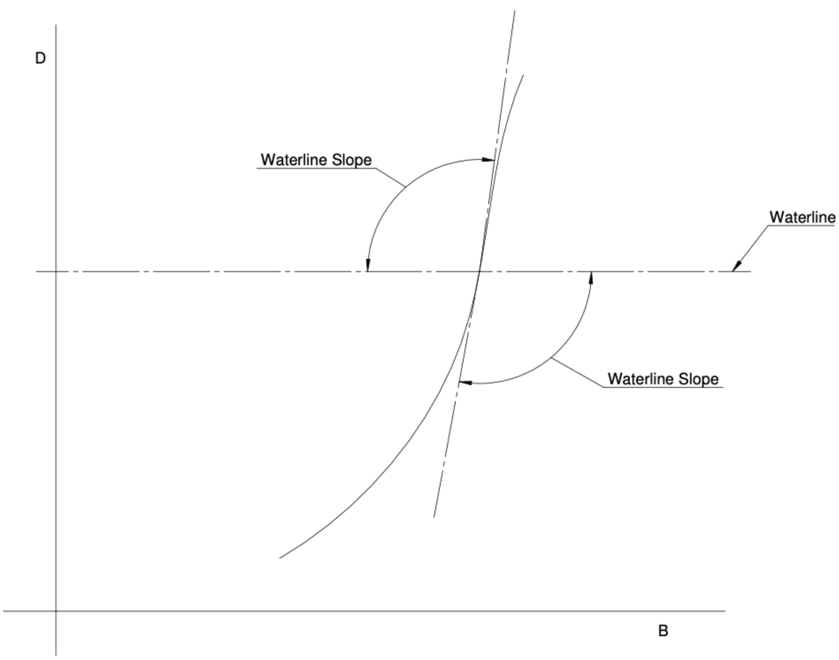

Figure 39 - Waterline Slope

2. Sections above the waterline

These sections do not carry much weight for cargo carrying ships as they usually only continue the shape developed below the waterline. As these sections do not influence the hydrodynamic quality of the hull, they usually do not have much relevance in this part of the design process. Further down the design spiral, a study to see the interaction between the hull and the wind, true or apparent, can be proven quite useful.

This section also has two areas of focus: the waterline area and the deck area. The waterline area will enforce and ensure that a smooth continuum of the section shape is achieved, and the deck slope will enforce the shape in which the section will finish at the deck.

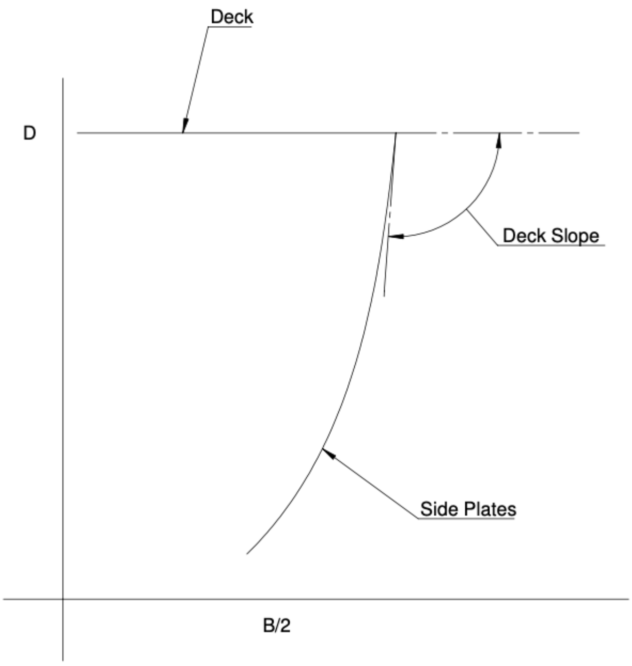

Figure 40 - Deck Slope

With this, all possible adjustments are complete, and a final representation of the designer's intention can be represented. Of course, this does not mean that it will only take one attempt to get the hull shape. However, this fast method will not only aid the designer in the hull shape definition but also provide visual aid to continue the design process or repeat this first part with new or improved information.

With all of this explained and shown, some results were compiled and are shown in the next chapter where the inputs and design intentions for each case study are shown as well as the produced results.

5. Results

In this chapter, three case studies will be presented, and the results derived from the design process explained before will be shown. There will be a total of four results that reflect the most common hull shapes nowadays. The hull for each case will try to mimic an existing hull if there is enough information available to the author.

The case studies are:

- U shape hull – Tanker ship.
- T-transom hull – Container ship.
- V shape hull – Ro-Ro ship.
- N shape hull – Bulk carrier ship

5.1. Case 1: U shape hull

This case studies mimics a tanker ship. Tanker ships are known for having high block coefficients and a fuller aspect. The input given can be found in Table 7.

Lpp	320.0	m
B	44.0	m
D	21.0	m
T	14.6	m
CB	0.7	-
CM	0.98	-
LCB	-5	m
BowTypeU	1	-
SternU	1	-

Table 7 - Case 1 input parameters

Once these parameters are set, the program can run through the process described in the previous chapter and produce the following results.

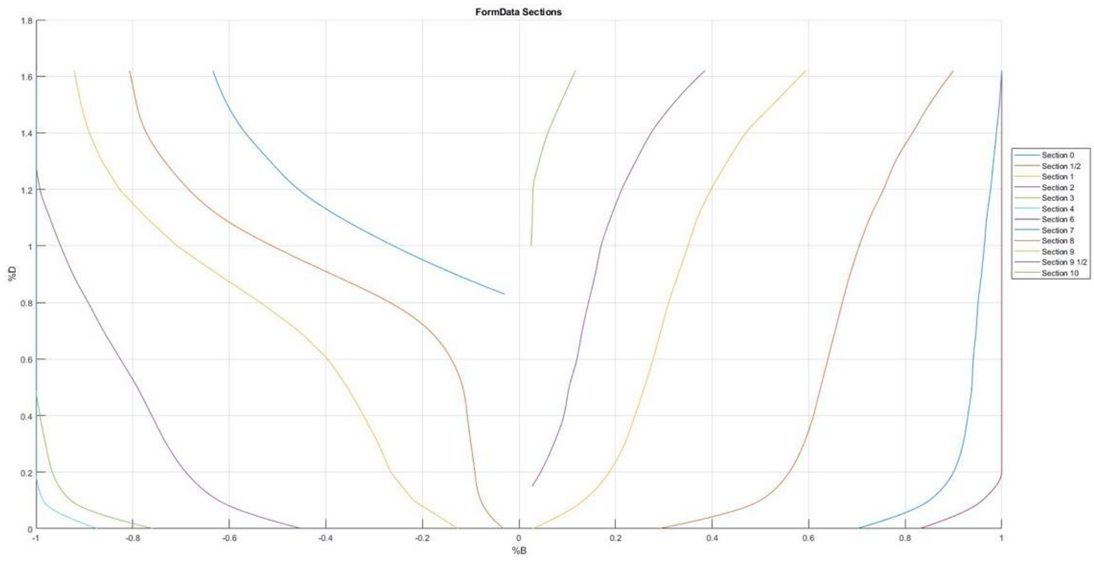

Figure 41 - Case 1 results: FORMDATA sections

The first result is the FORMDATA sections, shown in Figure 41, obtained from the FORMDATA Sections compendium. This result is the simpler one as it is the base for the all the results that follow. Next are the waterlines that are shown in Figure 42.

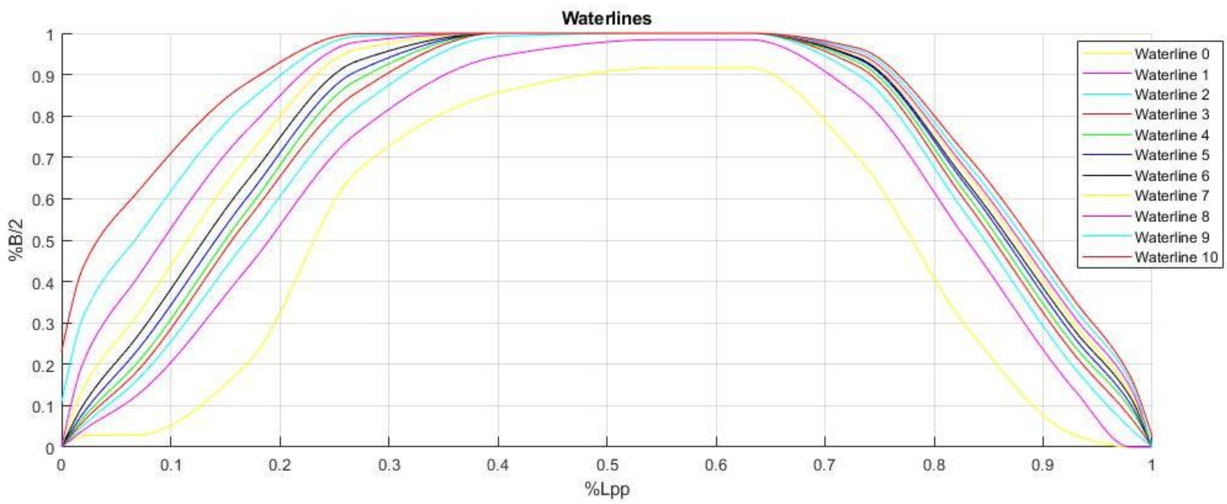

Figure 42 - Case 1 results: Waterlines

From this previous result, we can isolate the first and last waterline to show the next two results: Deck at edge curve and the Flat of bottom, Figure 43 and Figure 44 respectively.

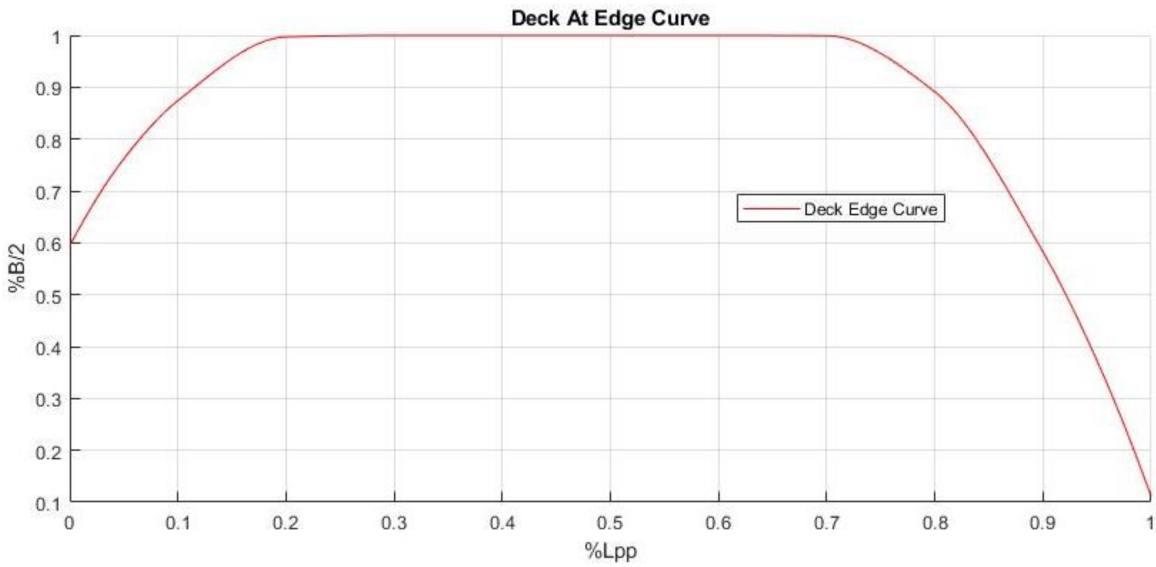

Figure 43 - Case 1 results: Deck at edge curve

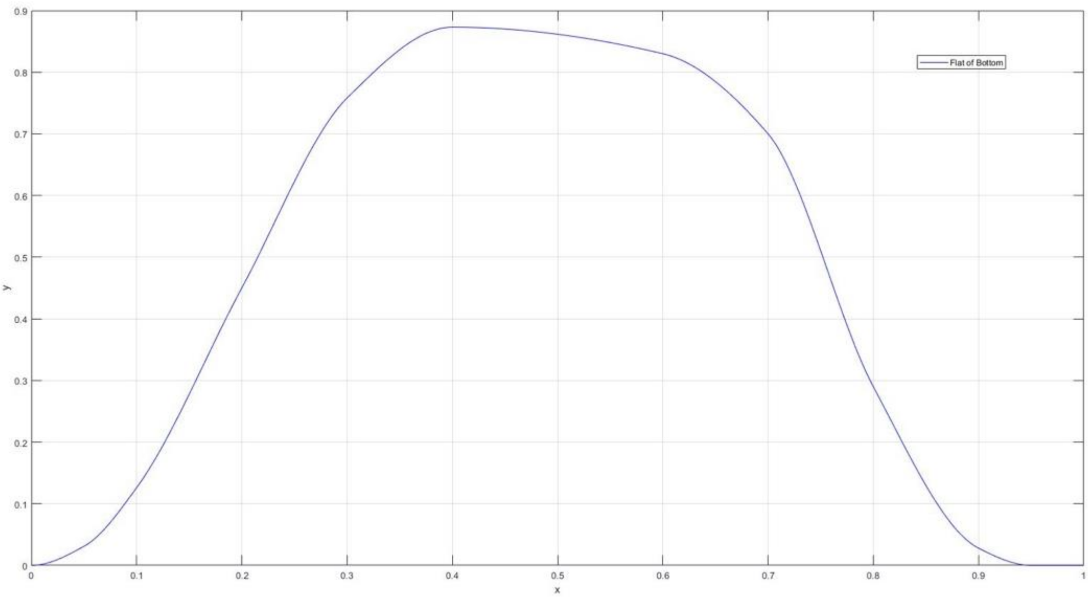

Figure 44 - Case 1 results: Flat of bottom

The next result is the slope curves shown in Figure 45. These will influence the final set of results, the 21 set of final sections.

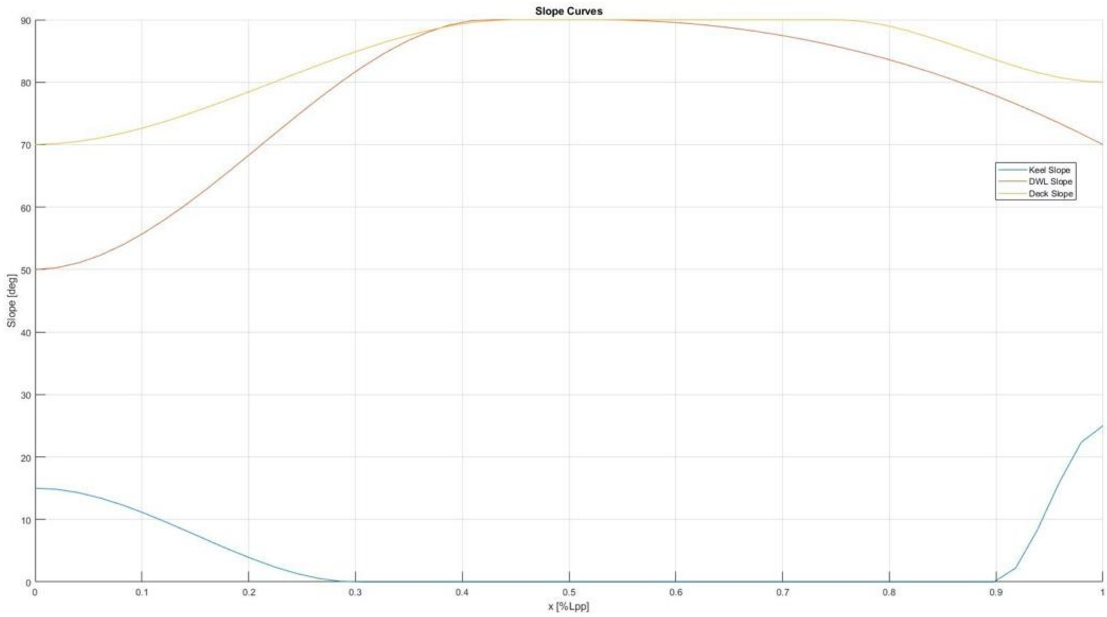

Figure 45 - Case 1 results: Slope curves

The next set of results comes as a pair. These are the sections below the waterline, Figure 46, and the section above the waterline, Figure 47.

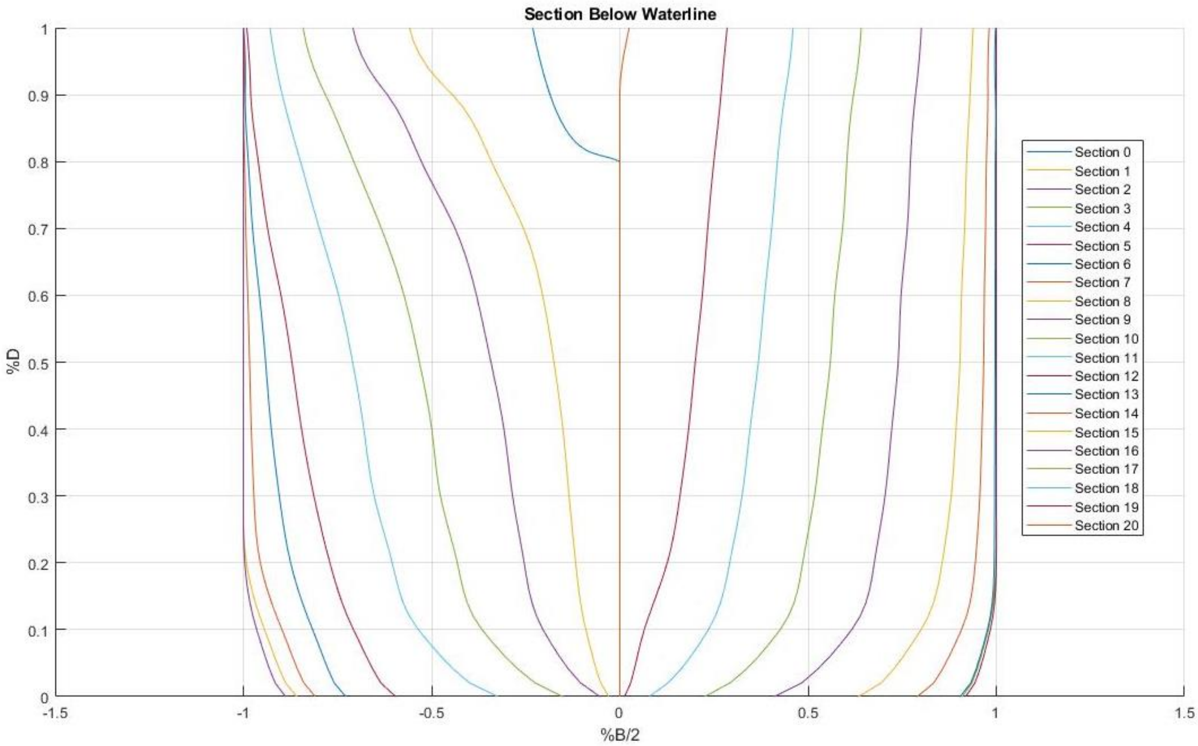

Figure 46 - Case 1 results: Section below the waterline

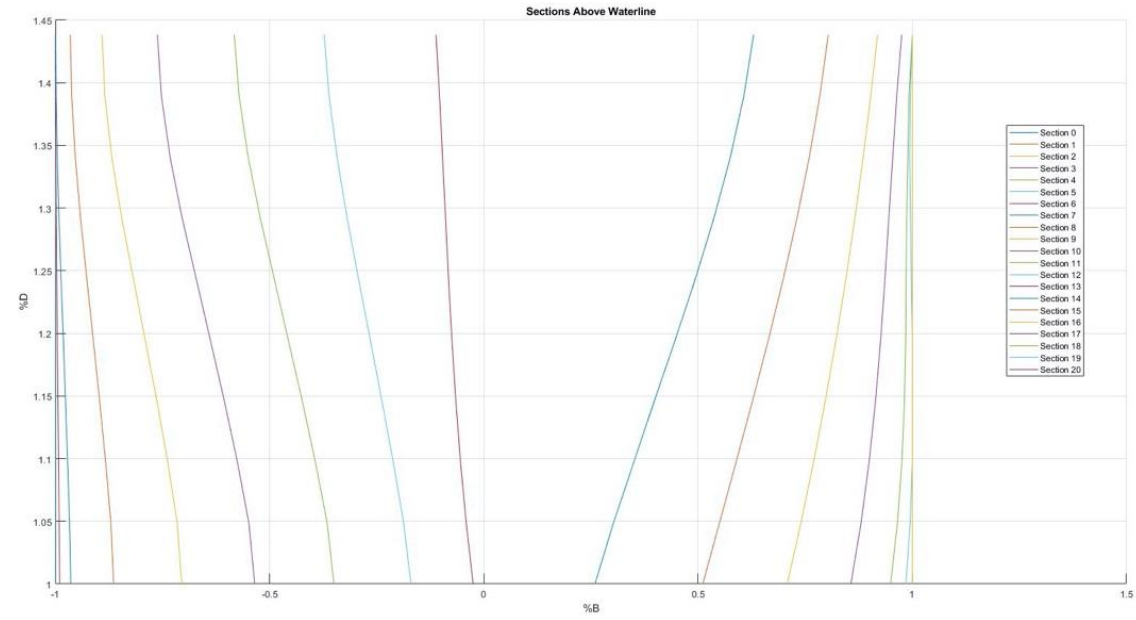

Figure 47 - Case 1 results: Sections above the waterline

After the sections under the waterline are done and using them, we can obtain the section area curve shown in Figure 48.

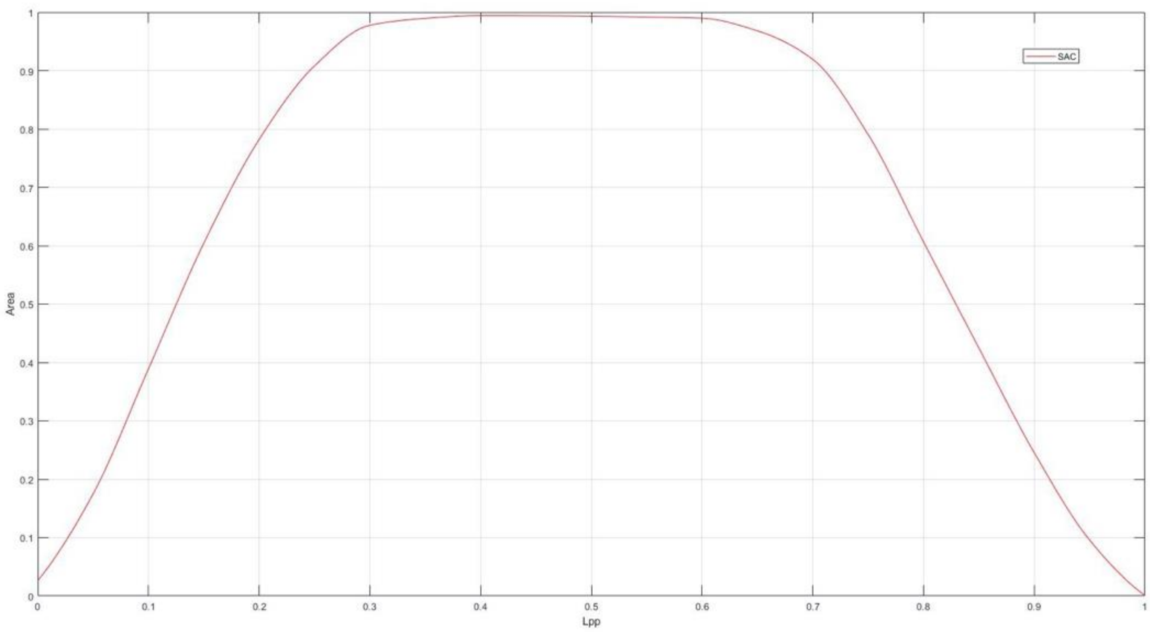

Figure 48 - Case 1 results: Section area curve

The last result provided is the combination of the sections both under and above the waterline. This is shown in Figure 49 where the full sections are displayed.

An in depth look into these results and analysis is done the next chapter.

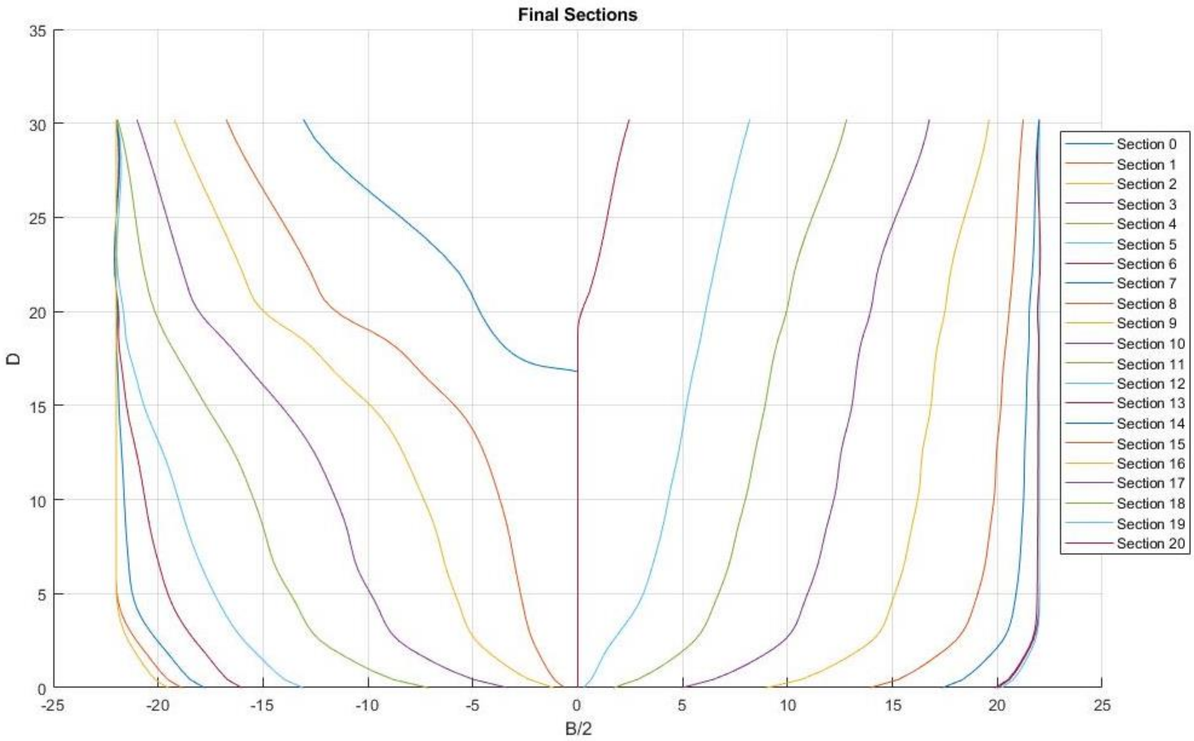

Figure 49 - Case 1 results: Final sections

5.2. Case 2: T-transom hull

This case studies mimics a container ship. Nowadays, over 80% of non-bulk cargo is shipped by container ships. Container ships now rival crude oil tankers and bulk carriers as the largest commercial vessels.

There are some key characteristics in the design of container ships. The hull is built around a strong keel. Into this frame numerous tanks are set. The holds are closed by hatch covers, onto which more containers can be placed upon. Due to the necessity of storing box shaped containers inside and on top of the deck, the side of the ships is vertical almost all around the ship. This provides a very squared shape to the ship, ideal to transport a great number of containers. The input given can be found in Table 7.

Lpp	286.0	m
B	40.0	m
D	24.2	m
T	13.75	m
CB	0.63	-
CM	0.98	-
LCB	-10	m
SternC	1	-
SternCSlopeA	1	-
Bow8Bulb	1	-

Table 8 - Case 2 input parameters

Once these parameters are set, the program can run through the process described in the previous chapter and produce the following results.

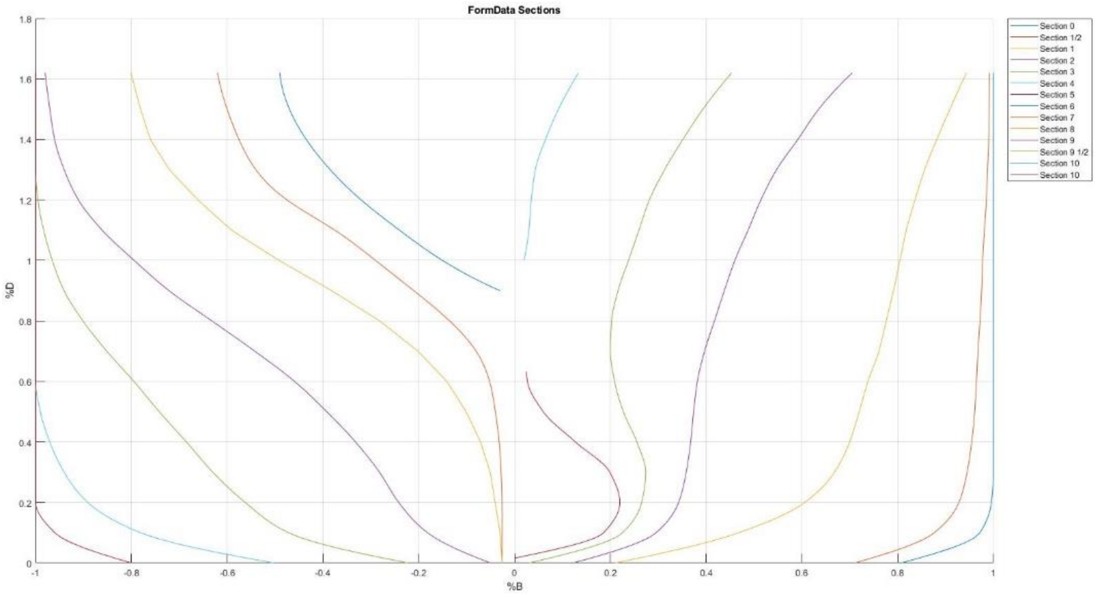

Figure 50 - Case 2 results: FORMDATA sections

The first result is the FORMDATA sections, shown in Figure 50, derived from the FORMDATA Sections compendium. This result is the simpler one as it is the base for the all the results that follow. Next are the waterlines that are shown in Figure 51.

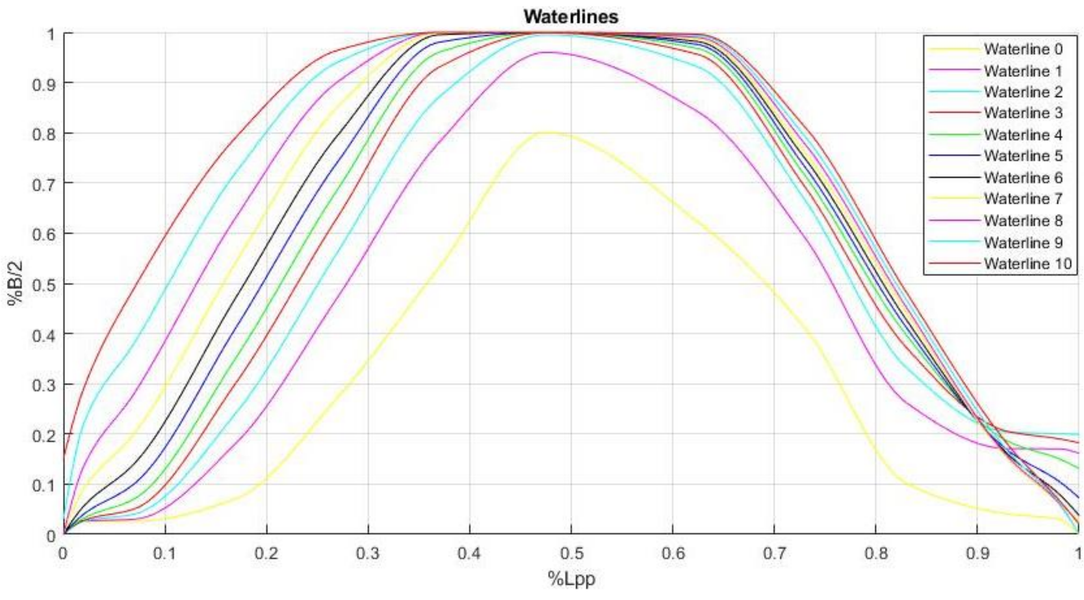

Figure 51 - Case 2 results: Waterlines

From this previous result, we can isolate the first and last waterline to show the next two results: Deck at edge curve and the Flat of bottom, Figure 52 and Figure 53 respectively.

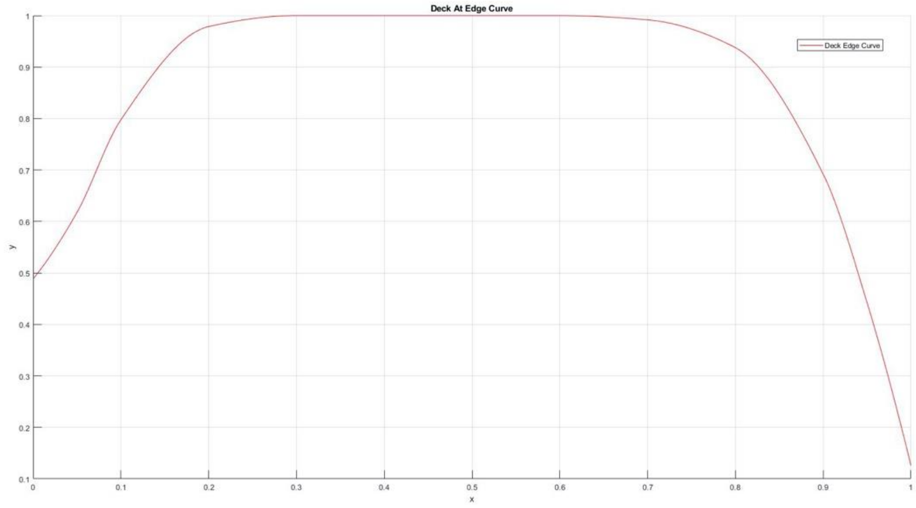

Figure 52 - Case 2 results: Deck at edge curve

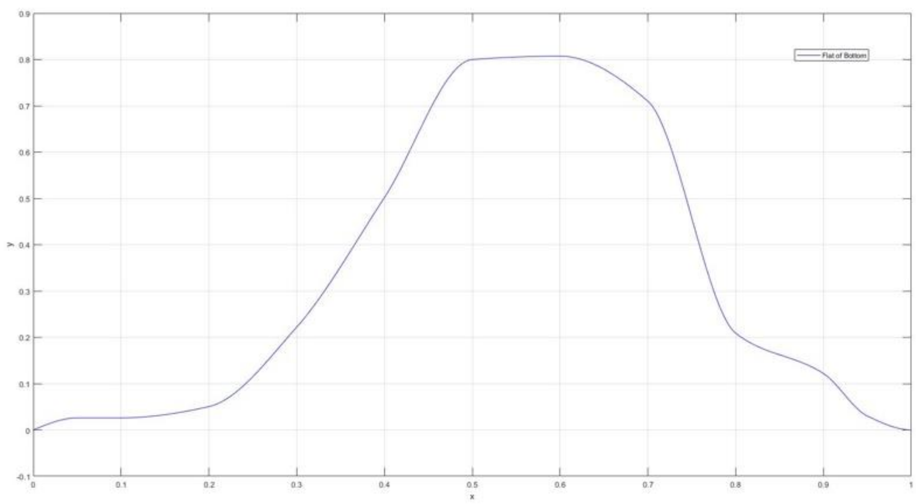

Figure 53 - Case 2 results: Flat of bottom

The next result is the slope curves shown in Figure 54. These will influence the final set of results, the 21 set of final sections.

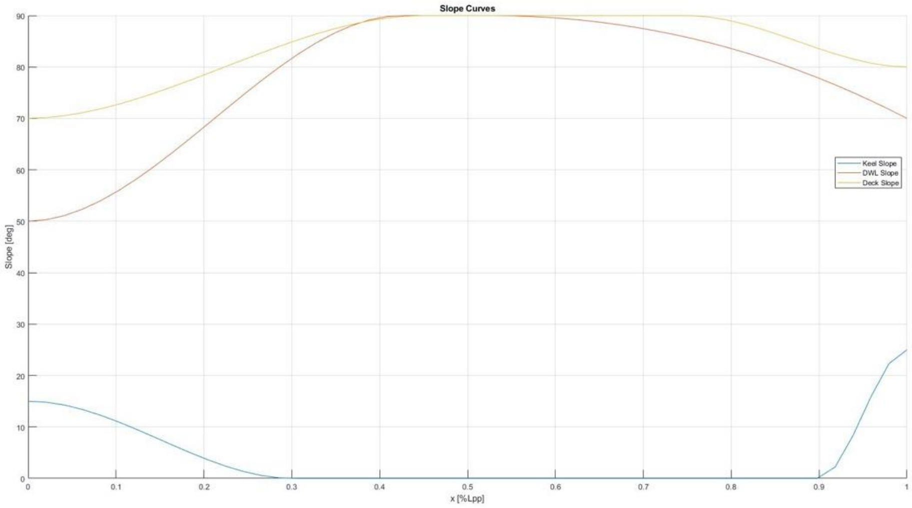

Figure 54 - Case 2 results: Slope curves

The next set of results comes as a pair. These are the sections below the waterline, Figure 55, and the section above the waterline, Figure 56.

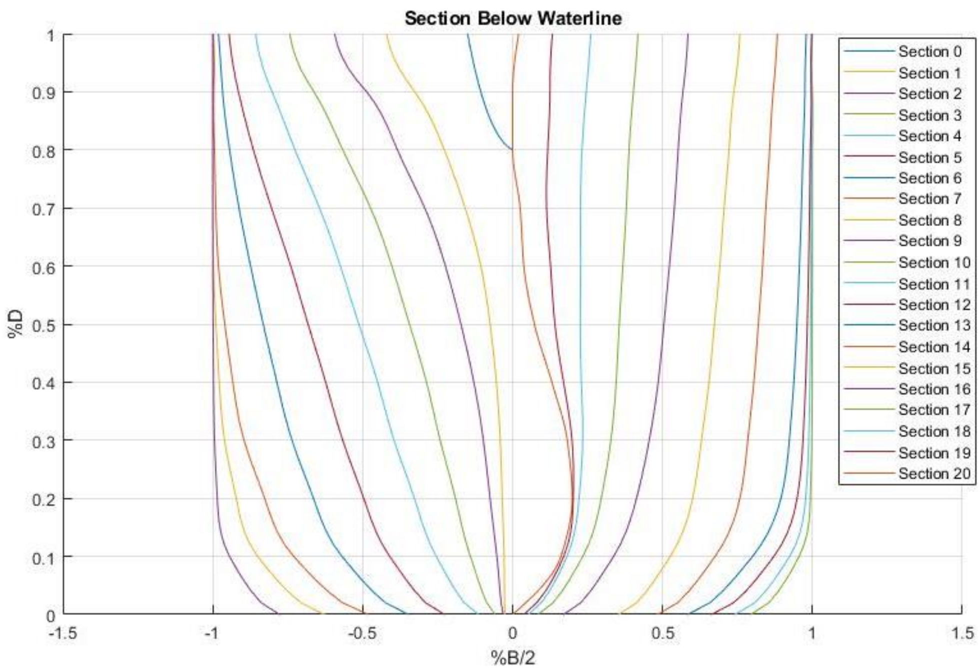

Figure 55 - Case 2 results: Section below the waterline

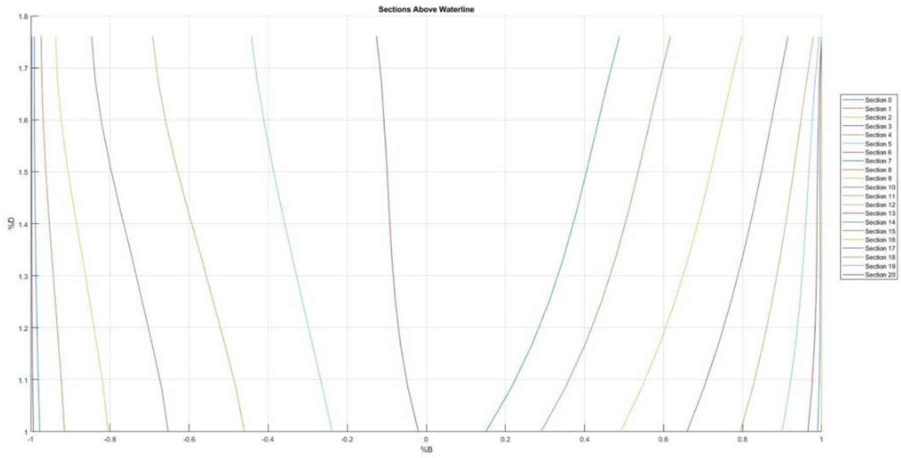

Figure 56 - Case 2 results: Sections above the waterline

After the sections under the waterline are done and using them, we can obtain the section area curve shown in Figure 57.

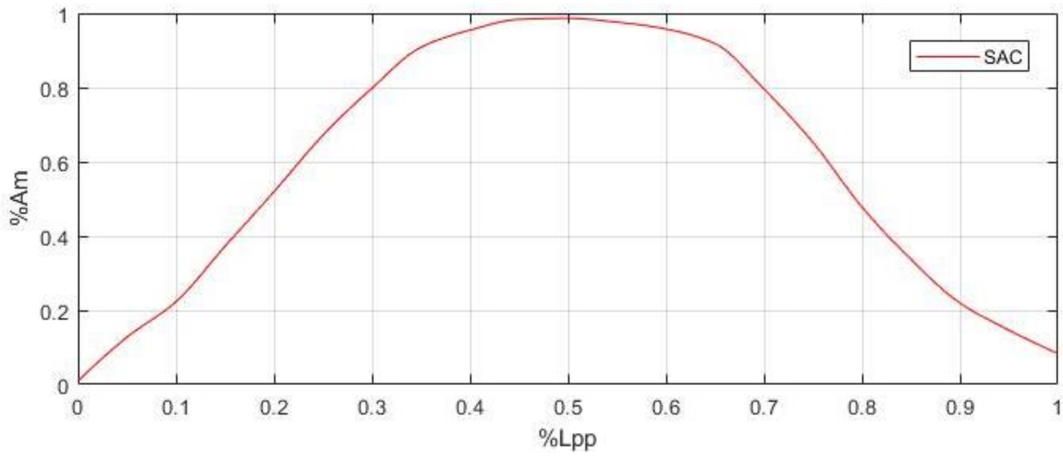

Figure 57 - Case 2 results: Section area curve

The last result provided is the combination of the sections both under and above the waterline. This is shown in Figure 58 where the full sections are displayed.

A more in depth look into these results and further analysis will be done in the next chapter.

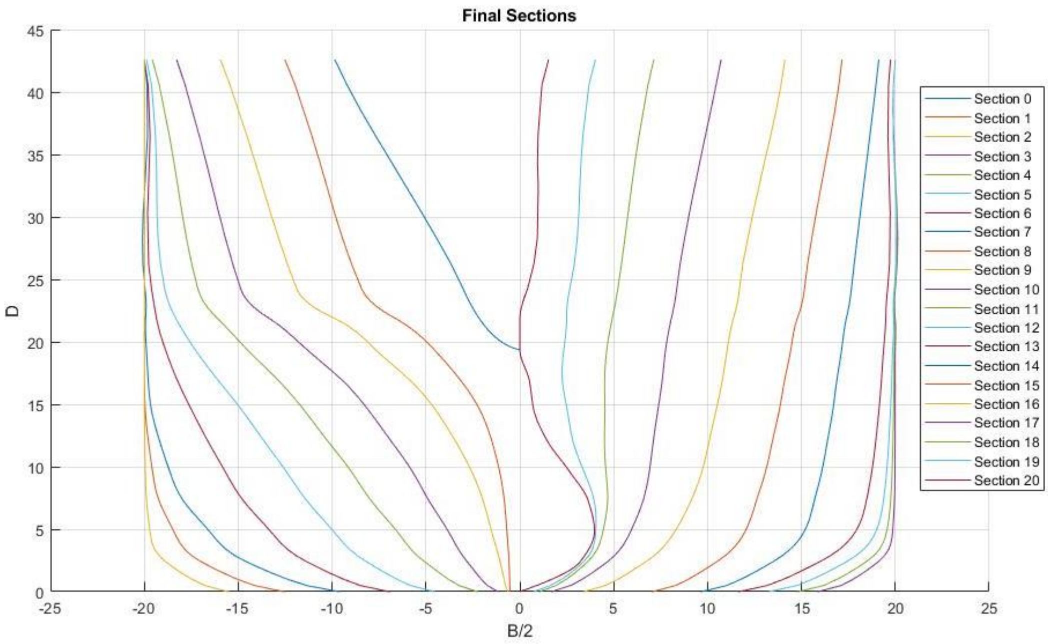

Figure 58 - Case 2 results: Final sections

5.3. Case 3: V shape hull

This case studies tries to replicate a passenger and car ferry. This ships usually have low depths and draughts when comparing to their beam. This example also has a deployable ramp at the bow. The input given can be found in Table 7.

Lpp	43.50	m
B	9.0	m
D	2.70	m
T	1.80	m
CB	0.7	-
CM	0.98	-
LCB	-5	m
BowTypeV	1	-
SternV	1	-

Table 9 - Case 3 input parameters

Once these parameters are set, the program can run through the process described in the previous chapter and produce the following results.

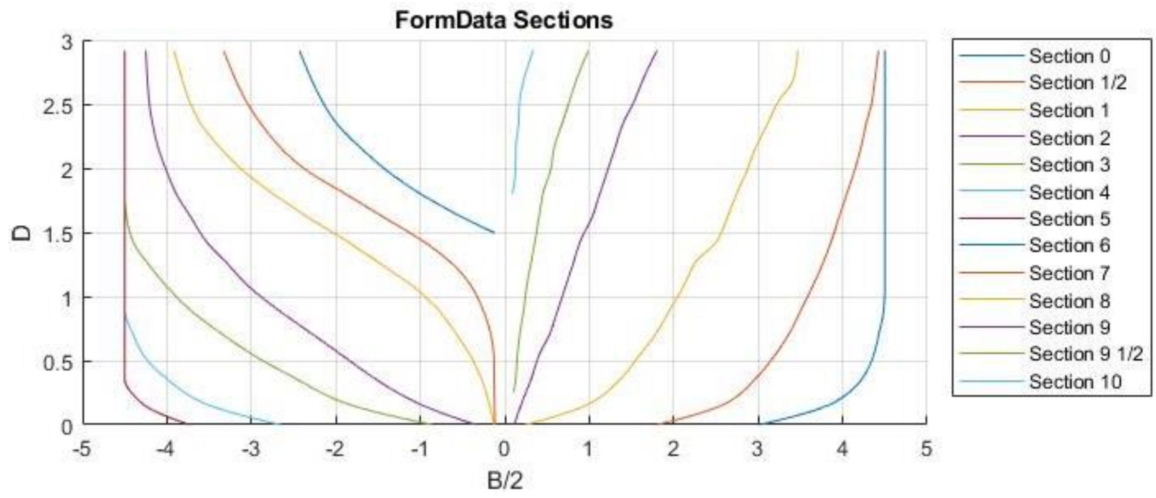

Figure 59 - Case 3 results: FORMDATA sections

The first result is the FORMDATA sections, shown in Figure 50, derived from the FORMDATA Sections compendium. This result is the simpler one as it is the base for the all the results that follow. Next are the waterlines that are shown in Figure 51.

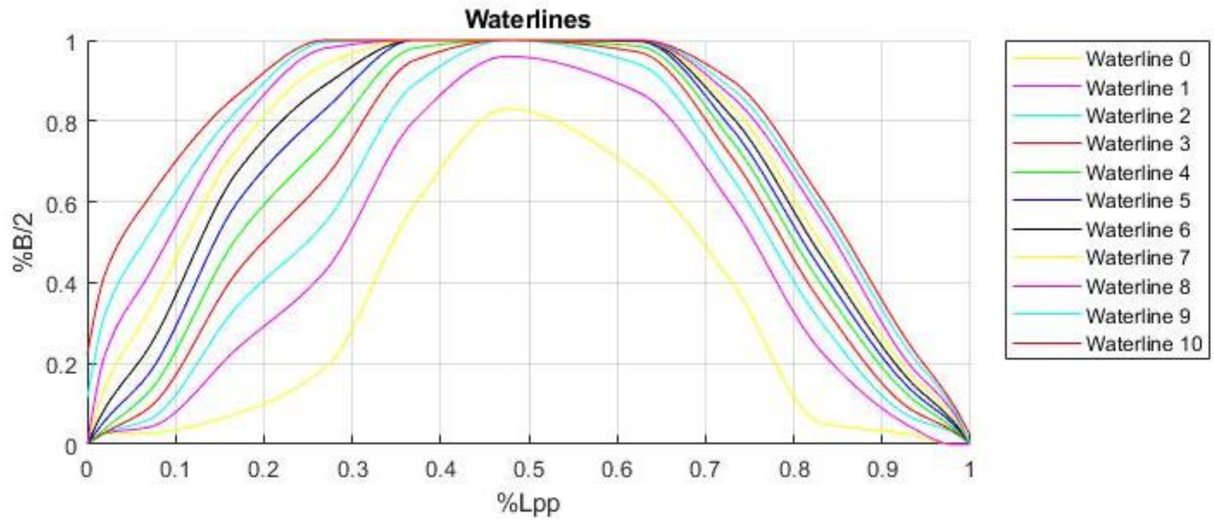

Figure 60 - Case 3 results: Waterlines

From this previous result, we can isolate the first and last waterline to show the next two results: Deck at edge curve and the Flat of bottom, Figure 52 and Figure 53 respectively.

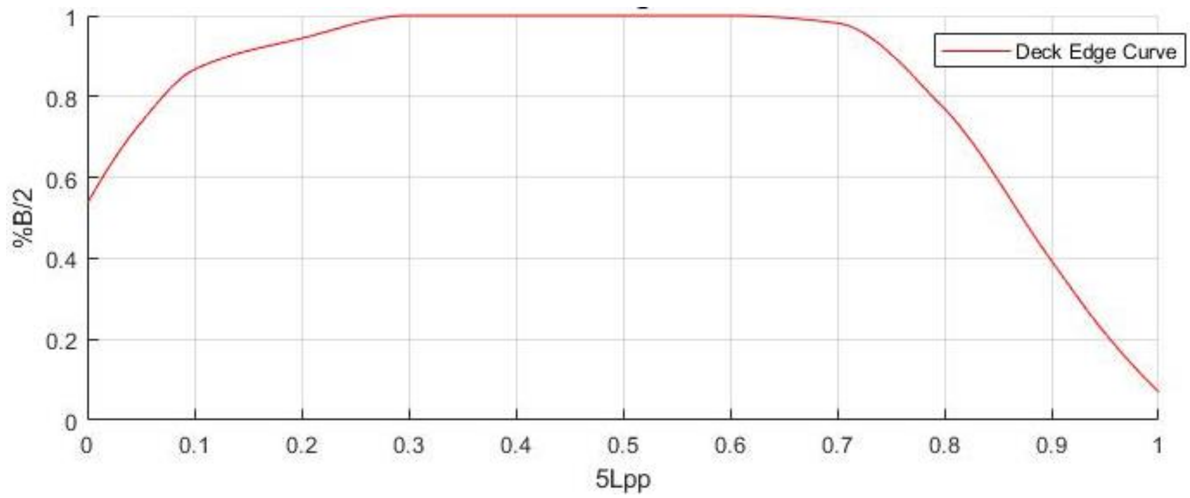

Figure 61 - Case 3 results: Deck at edge curve

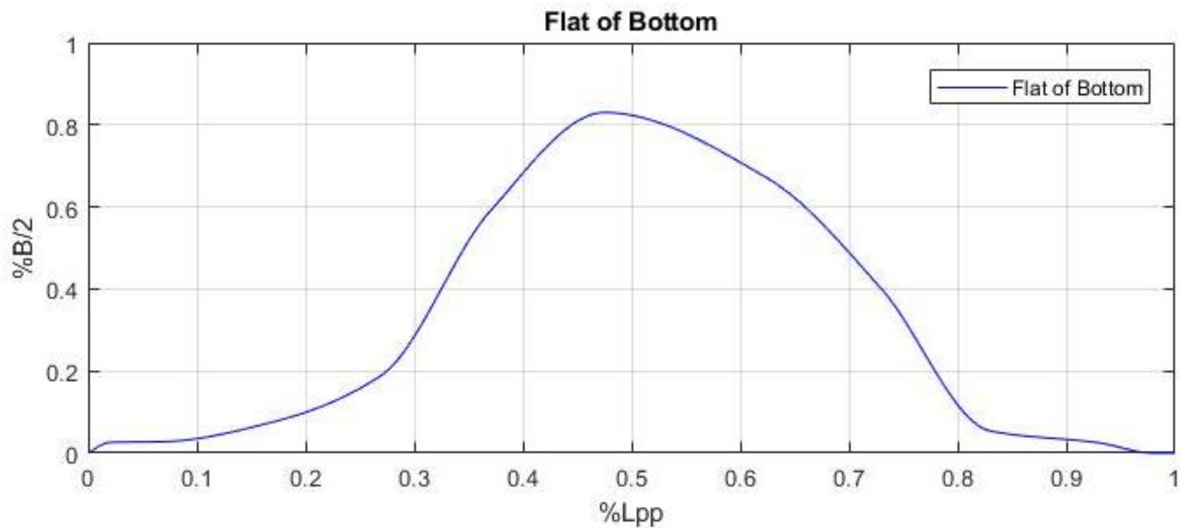

Figure 62 - Case 3 results: Flat of bottom

The next result is the slope curves shown in Figure 54. These will influence the final set of results, the 21 set of final sections.

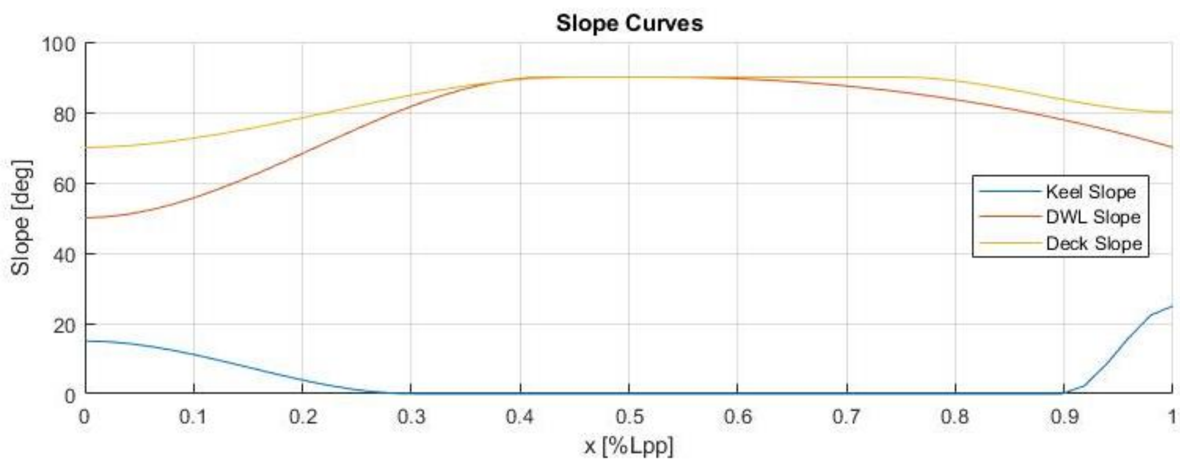

Figure 63 - Case 3 results: Slope curves

The next set of results comes as a pair. These are the sections below the waterline, Figure 55, and the section above the waterline, Figure 56.

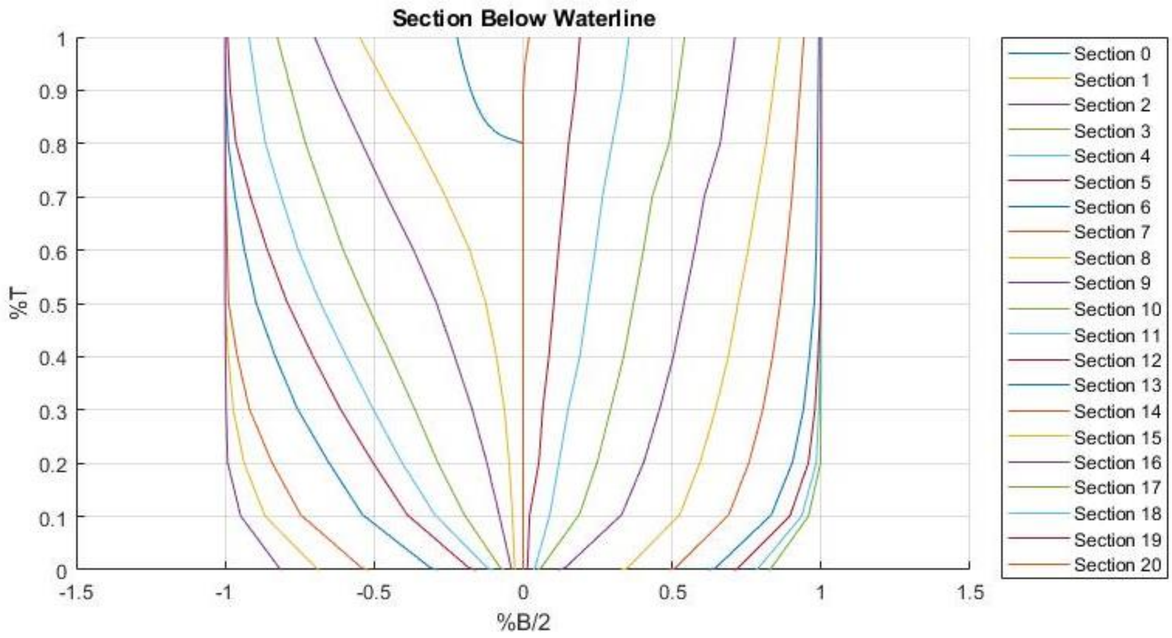

Figure 64 - Case 3 results: Section below the waterline

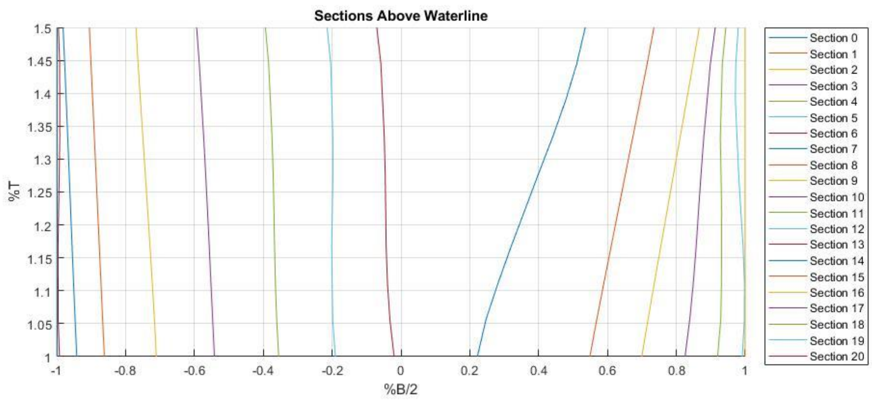

Figure 65 - Case 3 results: Sections above the waterline

After the sections under the waterline are done and using them, we can obtain the section area curve shown in Figure 57.

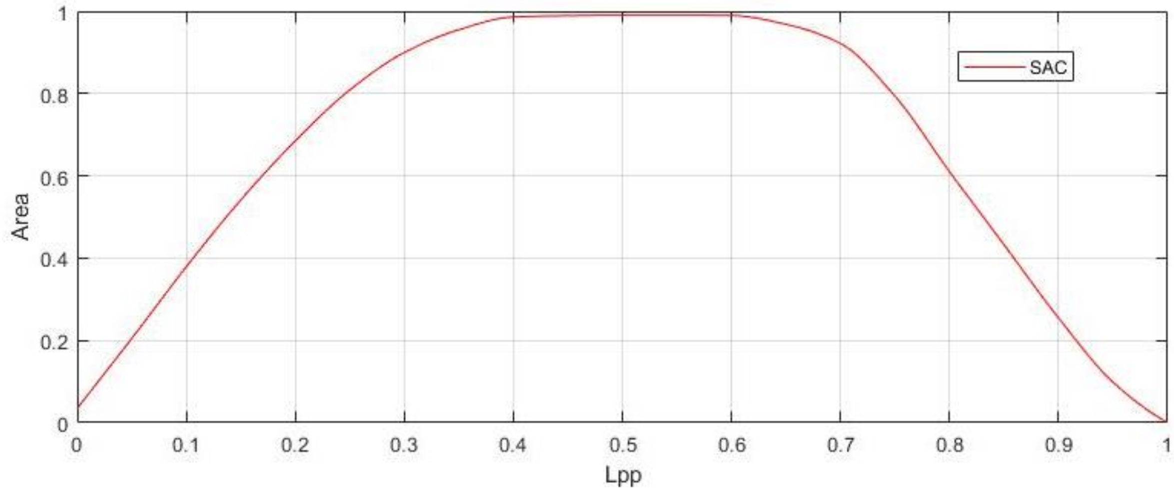

Figure 66 - Case 3 results: Section area curve

The last result provided is the combination of the sections both under and above the waterline. This is shown in Figure 58 where the full sections are displayed.

A more in depth look into these results and further analysis will be done in the next chapter.

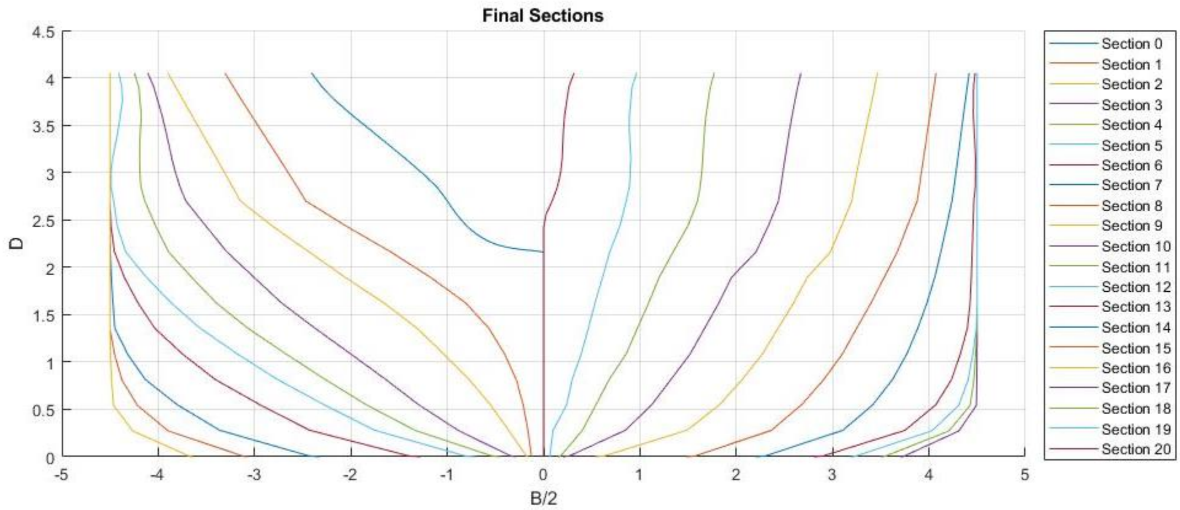

Figure 67 - Case 3 results: Final sections

With this last result, the study cases are complete, and a detailed analysis is given in the next chapter.

5.4. Case 4: N shape hull

This case studies tries to replicate a handy size bulk carrier. This type of ship and its size was chosen due to being a popular type of ship. There are hundreds of handy size bulk carriers usually with restricted dimensions by port regulations, however their small size allows the ships to load/offload in more shallow waters.

This is something that this project aims to aid and accelerate. Taking that into account, a N-shaped hull with general dimensions was chosen for this fourth and last case study. The input given can be found in Table 10.

Lpp	173.0	m
B	29.8	m
D	16.1	m
T	10.6	m
CB	0.83	-
CM	0.98	-
LCB	0.8	m
Bow4Bulb	1	-
SternN	1	-

Table 10 - Case 4 input parameters

Once these parameters are set, the program can run through the process described in the previous chapter and produce the following results.

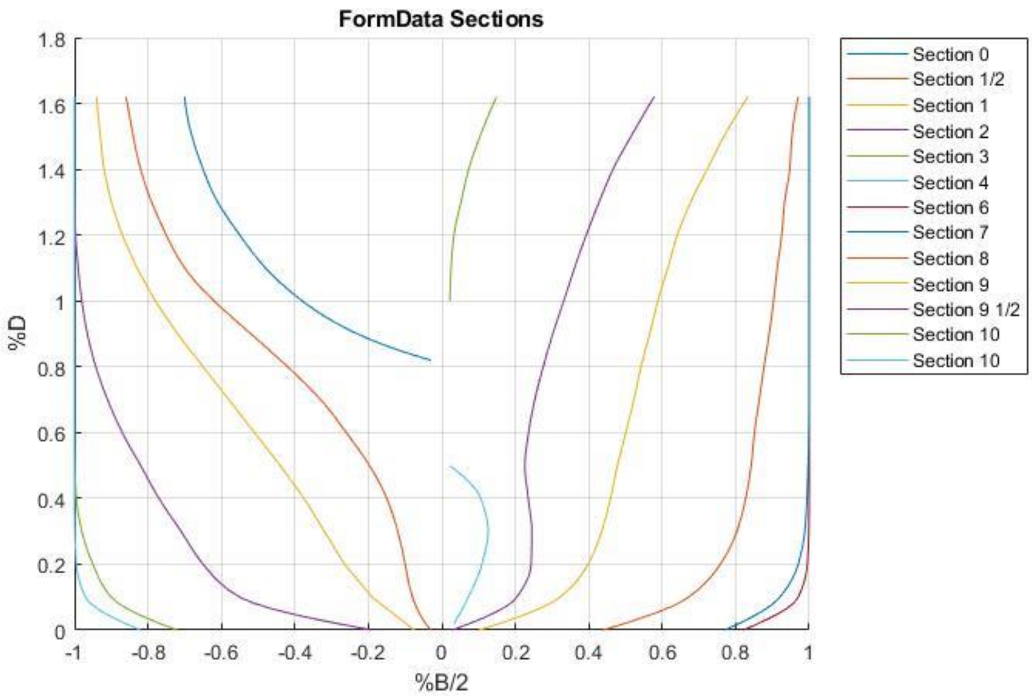

Figure 68 - Case 4 results: FORMDATA sections

The first result is the FORMDATA sections, shown in Figure 68, derived from the FORMDATA Sections compendium. This result is the simpler one as it is the base for the all the results that follow. Next are the waterlines that are shown in Figure 69.

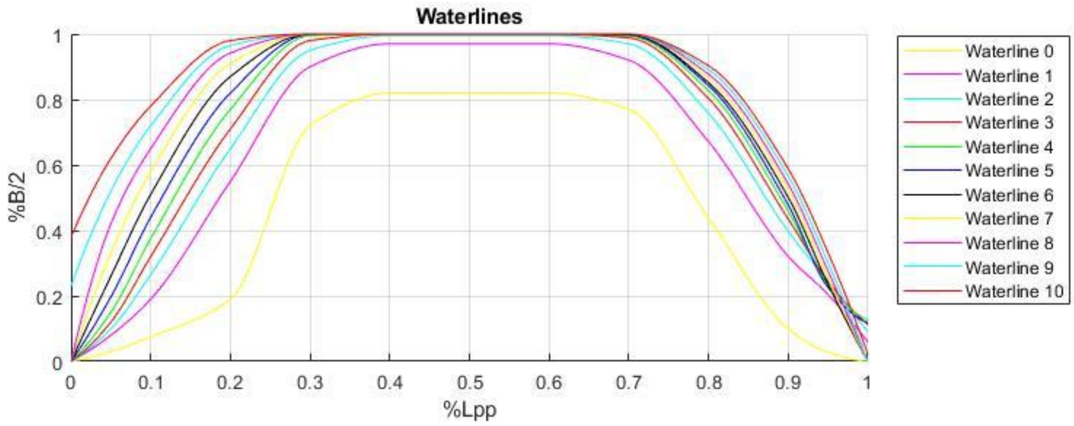

Figure 69 - Case 4 results: Waterlines

From this previous result, we can isolate the first and last waterline to show the next two results: Deck at edge curve and the Flat of bottom, Figure 70 and Figure 71 respectively.

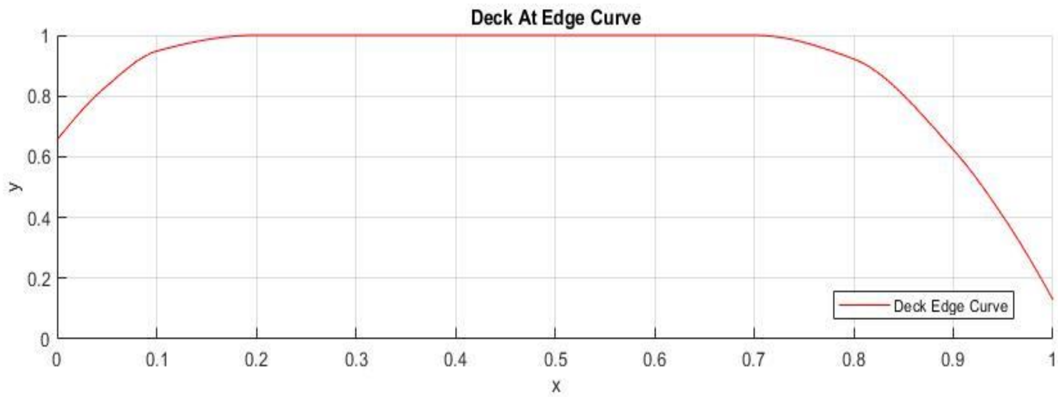

Figure 70 - Case 4 results: Deck at edge curve

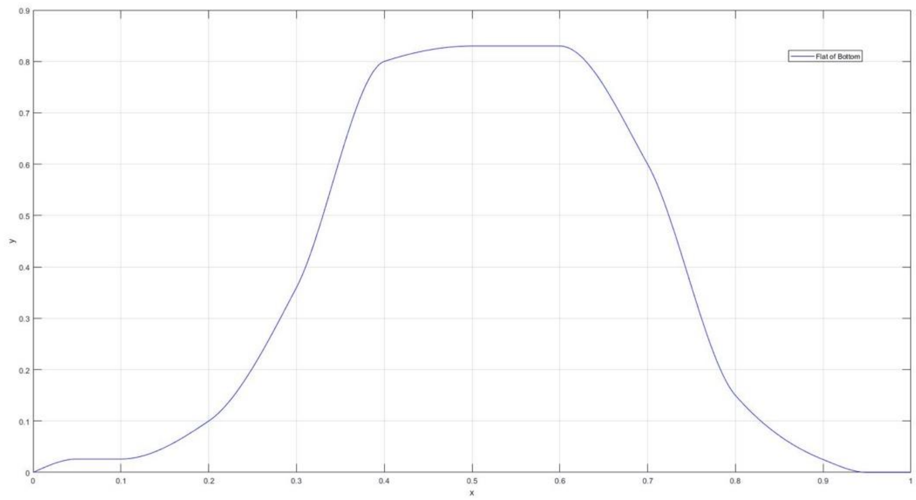

Figure 71 - Case 4 results: Flat of bottom

The next result is the slope curves shown in Figure 72. These will influence the final set of results, the 21 set of final sections.

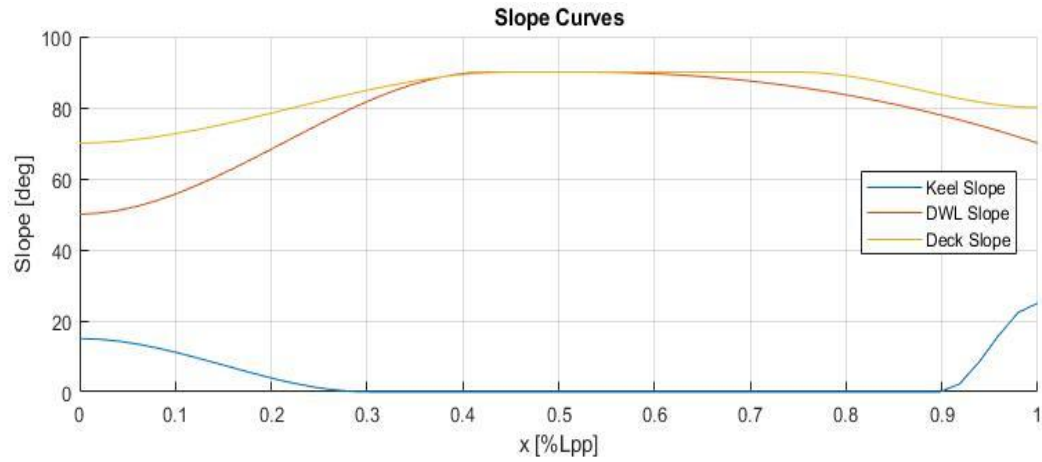

Figure 72 - Case 4 results: Slope curves

The next set of results comes as a pair. These are the sections below the waterline, Figure 73, and the section above the waterline, Figure 74.

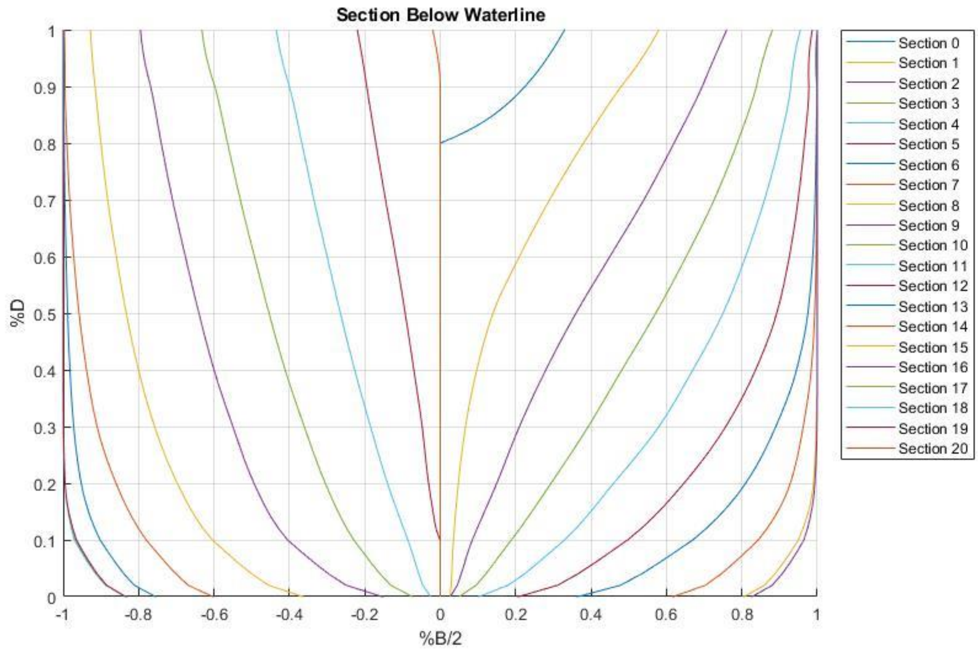

Figure 73 - Case 4 results: Section below the waterline

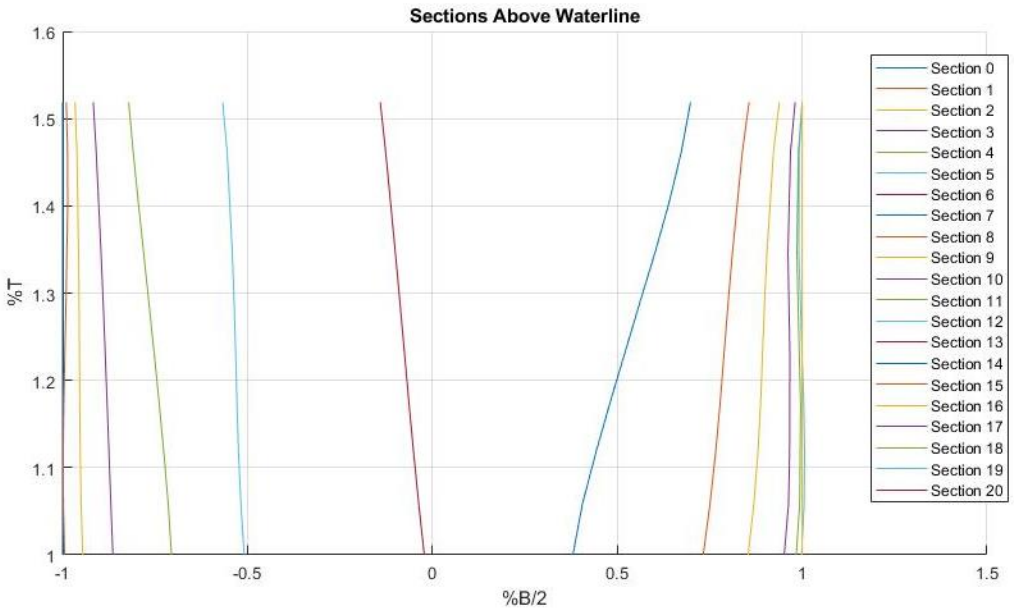

Figure 74 - Case 4 results: Sections above the waterline

After the sections under the waterline are done and using them, we can obtain the section area curve shown in Figure 75.

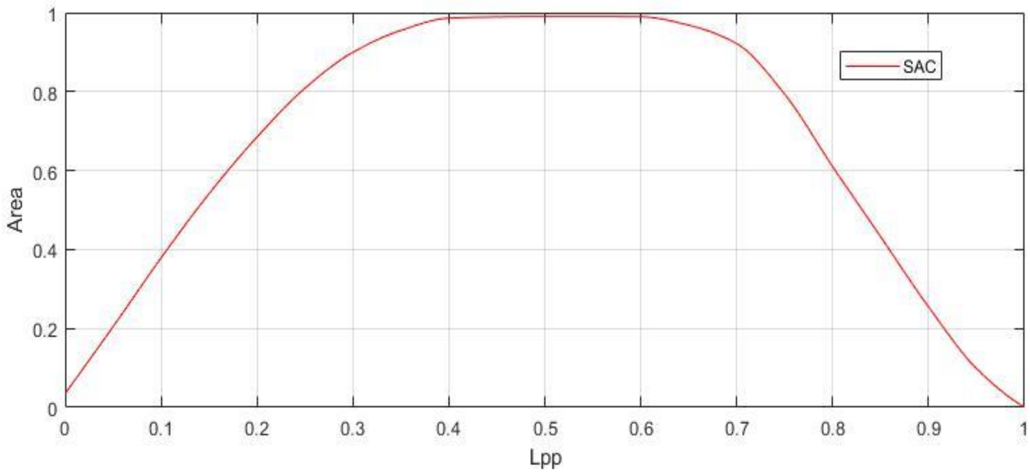

Figure 75 - Case 4 results: Section area curve

The last result provided is the combination of the sections both under and above the waterline. This is shown in Figure 76 where the full sections are displayed.

A more in depth look into these results and further analysis will be done in the next chapter.

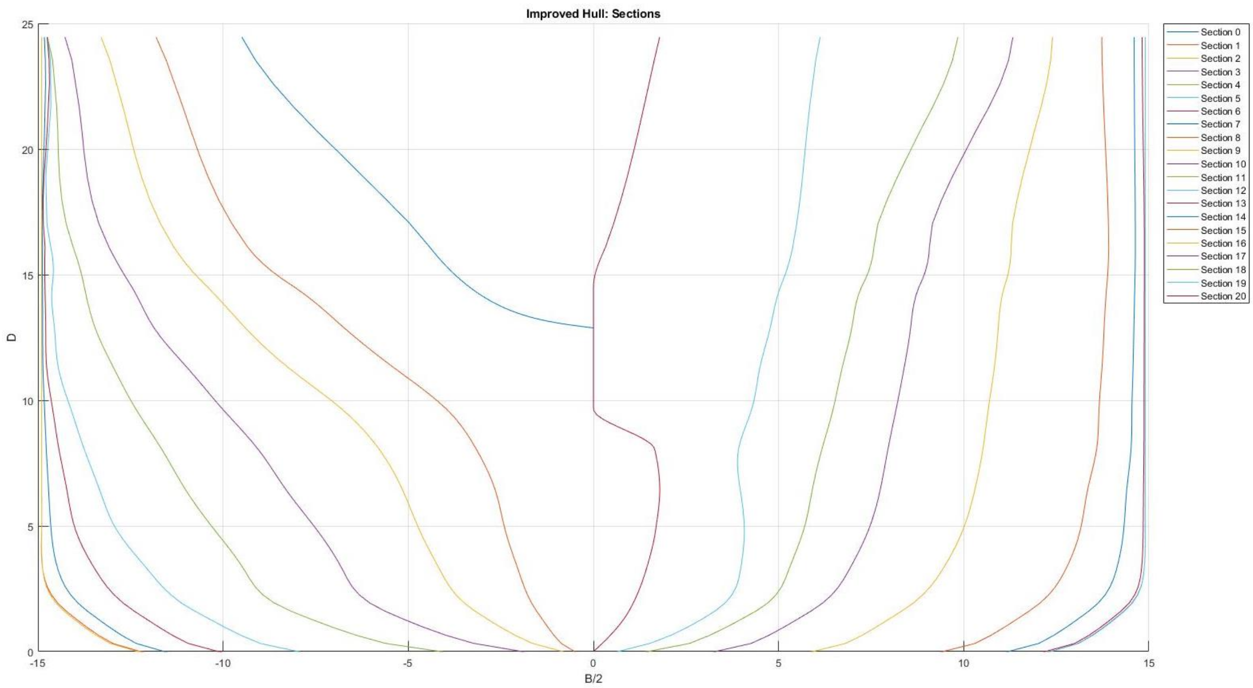

Figure 76 - Case 4 results: Final sections

With this last result, the study cases are complete, and a detailed analysis is given in the next chapter.

6. Result analysis

In this chapter a detailed analysis of the results is carried out. The results are influenced by the initial accuracy of the FORMADATA points. These points can have some errors attached to them.

For example, the compendium obtained by the author can have already suffered multiple copies and can have slight deformations. There can also exist errors from reading the table sections in the compendium. The tables have a low resolution, and a slightly incorrect value can be chosen, especially when several lines cross one another. This will generate an error which can propagate and increase throughout the development of the hull.

As there are also a huge set of point coordinates, there is also the possibility of some errors while transcribing the information into the program that was used to carry out the hull development method test.

It is important to note that the results will be judged by their visual aspect and by resemblance to the ship they try to mimic. In the end, a quick note will be given into whether or not the results are suitable for a first interaction hull in the design spiral.

6.1. Case 1: U Shaped Hull

In this case a U shape hull was designed with an intent to be a tanker. These types of hulls have high C_bs which means fuller sections.

6.1.1. FORMDATA sections

The first result, the FORMDATA sections, present sections typical in a tanker ship. There are some edges and vertices along the lines, but that maybe due to small errors and from the number of points that were used to design them. There is however an improvement that could be made. The bottom part of the section is very rectilinear and should be rounder and "fluid". This could be improved by adding more points to the initial part of the section. This however would greatly increase the number of data required.

6.1.2. Waterlines

Next comes the waterlines. Here it is possible to see that the parallel middle body extends from 0.4% to 0.6% of L_{pp}. This result is directly linked to the previous one, meaning that any mistake or imperfection on the FORMDATA sections will directly appear here. This result is also harder to analyse in terms of global hull shape as all waterlines represented are on top of each other. The better analysis is the general shape which corresponds quite well with a real tanker.

6.1.3. Deck at edge curve

The deck at edge curve shows a "fat" hull, going outwards really fast and staying at the full breadth until 0.73% of L_{pp}. This again shows that the hull is intended for maximum cargo space inside.

When we compare the result obtain with a real tanker, we can observe that the deck curve resembles a real ship and, as such, we can consider it a good enough result.

6.1.4. Flat of bottom

The flat of bottom curve represented is shows the flat part of the bottom of the hull. This curve is a good approximation, but it shows the need to make some improvements. For example, the beginning part and the end part, outside of the parallel middle body, could show a curvier development instead of a more abrupt shape. This is also exaggerated by the software when plotting and some leniency has to be given.

6.1.5. Slope curves

The slope curves show the slope at the keel, waterline, and deck. They show that the major development of the sections is made below the waterline. It is also possible to see that the bottom starts its flat part before the side become vertical. The bottom line, which represents the bottom slope has small degree value as it represents how the section line leaves the keel or the flat of bottom part. Then, both top lines represent the waterline and deck slope. Usually, the waterline slope has inferior or equal values than the deck slopes. Meaning that above the waterline the hull still develops further or continues the same that it is at the waterline.

6.1.6. Sections below the waterlines

The sections below the waterline represent a hull with a high C_b, typical of a tanker ship. In Figure 46, we can see that the bilge area is not very smooth, which implies that the addition of the slopes to the sections might not have been much useful.

When comparing the section lines to real tanker ships it is possible to see that when this compendium was created, tanker ships did not usually have bulbous bows.

6.1.7. Sections above the waterline

The sections above the waterline don't provide much new information, just that the hull develops predominantly vertically above the waterline.

6.1.8. Section Area Curve

The section area curve is an important result, not only for further calculations that are necessary for the development process but give a general idea of the hull shape, below waterline, at each section as a hole. With this, the designer can see if the area of each section is somewhat correct and it is only a matter of deforming the section or if the section needs to increase or decrease.

It is possible to see that the initial value is very small but bigger than zero, due to the existence of a stern panel. This can also be seen at the deck edge curve, where it starts with a value higher than zero but ends at zero at the bow. The centroid of the area below the curve should be located near the center as it represents the buoyancy longitudinal coordinate and is very important when calculating the hull dynamics.

6.1.9. Final Sections

In this result we can see that the final sections are presented in their real values. This not only shows the final sections of the ship hull, but it also allows the designer to better identify areas that need improvement as small errors will be multiplied by the breadth or draft. This will result in a magnified version of the results shown before and also will allow for a better perspective as the axis don't have the sane boundaries anymore.

Looking at Figure 49, we can see that the bilge area needs further development as well as an insertion of a bulbous will be necessary. At this stage, the bulbous is not critical as it usually requires a detailed analysis to ensure the best hydrodynamic behaviour is achieved.

6.1.10. Final Remarks

Looking at the results for a tanker ship, the outcome is quite satisfactory. The time it took for producing these results, from inserting initial data to results output, was less than 5 minutes. This means that several hills can be made with ease and quite fast.

A calculation of the error between the FORMDATA Cb and the final Cb, as well as the CM, can be seen in Table 11.

	Initial	New Hull	Error
CB	0.7	0.71	1.3%
CM	0.98	0.9948	1.5%

Table 11 - Case 1: Cb and CM error

The hull shape is accurate to some extent and can provide a good starting point for the design process.

This compendium does not provide tankers with a bulbous bow. So, if the designer wishes to project a tanker with a bulb, he should choose a different bow for this ship.

6.2. Case 2: T Transom Hull

In this case a T transom hull was designed with an intent to be a container carrier. These types of hulls have larger deck in order to provide maximum space to place containers on top of the deck.

6.2.1. FORMDATA Sections

The first result, the FORMDATA sections, present the sections straight from the compendium. This configuration is trickier than the previous one and the results can have a bigger deviation from what is desired.

We can see that the sections start to open as they rise towards the waterline. It is possible to notice that some section lines are a bit wobbly. This may require some tampering and adjustment in the FORMDATA points coordinates. An initial look at the result could show that the sections could have a more predominant turn towards the breadth of the ship that it is displayed but they show a fast aperture towards maximum breadth and vertical sides as it is to be expected.

This configuration shows a bulb, that is little bit out of shape. However, there are a small number of sections that show the bulb, so a good comprehension of the general shape is hard. The bulb however will be a specific study carried out along the design spiral.

6.2.2. Waterlines

Next comes the waterlines. Here it is possible to see that the parallel middle body extends from 0.5 % to 0.6 % of L_{pp} which is smaller than expected. This result is directly linked to the previous one, meaning that any mistake or imperfection on the FORMDATA sections will directly appear here. This result is also harder to analyse in terms of global hull shape as all waterlines represented are on top of each other.

There is a step on the fore part of the hull, shown in the waterlines results, explained by the existence of the bulb that enlarges the bottom part of the hull right before the bub itself. A critical analysis of the hull shape finds that the bottom waterlines develop a bit strangely in the beginning and in the end. Also, these transitions could be smoother.

6.2.3. Deck at Edge Curve

The deck at edge curve shows a large deck area, going outwards really fast and staying at the full breadth until 0.7% of L_{pp}. This again shows that the hull is intended for maximum inside cargo area.

Nowadays, the hull shape is made so that the vertical side reach the stern. This implies that result is outdated and would need further development or transformation.

6.2.4. Flat of Bottom

The flat of bottom curve represented is shows the flat part of the bottom of the hull. This curve is a medium approximation, and it shows the need to make some improvements. For example, the beginning part and the end part, outside of the parallel middle body, could show a curvier development instead of a more abrupt shape. This is also exaggerated by the software when plotting and some leniency has to be given. However, the curve smoothness needs to be improved to better represent a real ship.

6.2.5. Slope Curves

The slope curves show the slope at the keel, waterline, and deck. They show that the major development of the sections is made below the waterline. It is also possible to see that the bottom starts its flat part before the side become vertical. The bottom line, which represents the bottom slope has small degree value as it represents how the section line leaves the keel or the flat of bottom part. Then, both top lines represent the waterline and deck slope. Usually, the waterline slope has inferior or equal values than the deck slopes. Meaning that above the waterline the hull still develops further or continues the same that it is at the waterline.

6.2.6. Sections below the waterline

The sections below the waterline represent a hull with an average C_b, typical of a container ship. In Figure 55, we can see that the bilge area is again not very smooth, and that the bulb area might be too big and that some work might need to be done in that area.

When comparing the section lines to real container ships it is possible to see that when this compendium was created, these ships did not usually have flat sides extending all the way to the stern.

6.2.7. Sections above the waterline

The sections above the waterline do not provide much new information, just that the hull develops predominantly vertically above the waterline.

6.2.8. Section Area Curve

The section area curve is an important result, not only for further calculations that are necessary for the development process but give a general idea of the hull shape, below waterline, at each section as a hole. With this, the designer can see if the area of each section is somewhat correct and it is only a matter of deforming the section or if the section needs to increase or decrease.

It is possible to see that the initial value is very small but bigger than zero, due to the existence of a stern panel. This can also be seen at the deck edge curve, where it starts with a value higher than zero but ends at zero at the bow. The centroid of the area below the curve should be located near the center as it represents the buoyancy longitudinal coordinate and is very important when calculating the hull dynamics.

It is possible to notice that the section area at the end, 100% of L_{pp} is bigger than 0 due to the existence of the hull.

6.2.9. Final Sections

In this result we can see that the final sections are presented in their real values. This not only shows the final sections of the ship hull, but it also allows the designer to better identify areas that need improvement as small errors will be multiplied by the breadth or draft. This will result in a magnified version of the results shown before and also will allow for a better perspective as the axis don't have the same scale anymore.

Looking at Figure 58, we can see that the bulb area needs further development as well as the transition from below to above the waterline. At this stage, the bulbous is not critical as it usually requires a detailed analysis to ensure the best hydrodynamic behaviour is achieved.

6.2.10. Final Remarks

Looking into these results as a hole, the results are somewhat satisfactory. While it is true that the general design on the hull shape has evolved to a bigger deck and wider hull at the stern, the results still provide a good base to start working on.

A calculation of the error between the FORMDATA Cb and the final Cb, as well as the CM, can be seen in Table 12Table 11.

	Initial	New Hull	Error
CB	0.63	0.60	5.2%
CM	0.98	0.987	0.7%

Table 12 - Case 1: Cb and CM error

The visual representation of the results may sometimes mislead the designer as they are affected by the plot function and the number of points used to plot each line. Most times, the dents or the vertices are due to small number of points to define the curve.

6.3. Case 3: V Shaped Hull

In this case a V shaped hull was designed with an intent to be a ferry. These types of hulls have a goal of maximize deck space.

6.3.1. FORMDATA Sections

The first result, the FORMDATA sections, present the sections straight from the compendium.

We can see that the hull grows quickly in the beginning of the length of the hull and decreases quickly as well. The sections that do not reach full breadth show a V shape, making the hull look like a knife.

6.3.2. Waterlines

Next comes the waterlines. Here it is possible to see that the parallel middle body extends from 0.4% to 0.6% of L_{pp} with some higher waterlines extending this part to 0.3% to 0.7%. This result is directly linked to the previous one, meaning that any mistake or imperfection on the FORMDATA sections will directly appear here. This result is also harder to analyse in terms of global hull shape as all waterlines represented are on top of each other.

6.3.3. Deck at Edge Curve

The deck at edge curve shows a large deck area, going outwards really fast and staying at the full breadth until 0.7% of L_{pp}. This again shows that the hull is intended for maximum inside cargo space.

The resulting shape is quite trustworthy with the only changeable part being the bow part. In more modern ships, the deck curve would stay at full breadth longer and make a more rounded bow than shown I the results.

6.3.4. Flat of Bottom

The flat of bottom curve represented is shows the flat part of the bottom of the hull.

This curve shows that some improvements have to be made to the bottom of the hull. The curve should represent a higher rise in the beginning and also a higher fall at the end. The length of the parallel middle body in the bottom section is too short, while it usually is the shortest among all waterlines, it should be longer. In this result, virtually no parallel body is shown.

6.3.5. Slope Curves

The slope curves show the slope at the keel, waterline, and deck. They show that the major development of the sections is made below the waterline. It is also possible to see that the bottom starts its flat part before the side become vertical. The bottom line, which represents the bottom slope has small degree value as it represents how the section line leaves the keel or the flat of bottom part. Then, both top lines represent the waterline and deck slope. Usually, the waterline slope has inferior or equal values than the deck slopes. Meaning that above the waterline the hull still develops further or continues the same that it is at the waterline.

6.3.6. Sections below the waterline

The sections below the waterline represent a hull with an elevated C_b, typical of a VLCC ship. In Figure 64, we can see that the bilge area is again not very smooth and that some work might need to be done in that area.

When comparing the section lines to real VLCC ships it is possible to see that when this compendium was created, these ships did not used to be so “full”. The VLCC concept was created around 1963 and the hull shape has evolved until what it is today.

6.3.7. Sections above the waterline

The sections above the waterline do not provide much new information, just that the hull develops predominantly vertically above the waterline. This result is to be expected and will be mainly defined by the freeboard calculations in a later step of the design process.

6.3.8. Section Area Curve

The section area curve is an important result, not only for further calculations that are necessary for the development process but give a general idea of the hull shape, below waterline, at each section as a hole. With this, the designer can see if the area of each section is somewhat correct and it is only a matter of deforming the section or if the section needs to increase or decrease.

It is possible to see that the initial value is very small but bigger than zero. The centroid of the area below the curve should be located near the center as it represents the buoyancy longitudinal coordinate and is very important when calculating the hull dynamics.

It is possible to notice that the section area at the end, 100% of L_{pp} is 0 due to the inexistence of the bulb. A detailed analysis can see that the first part of the curve is very linear and is usually curvier. This, however, represents an acceptable result.

6.3.9. Final Sections

In this result we can see that the final sections are presented in their real values. This not only shows the final sections of the ship hull, but it also allows the designer to better identify areas that need improvement as small errors will be multiplied by the breadth or draft. This will result in a magnified version of the results shown before and also will allow for a better perspective as the axis do not have the same scale anymore.

6.3.10. Final Remarks

Looking into these results as a hole, the results are satisfactory. While it is true that the general design on the hull shape has evolved to a bigger length of parallel middle body, the results still provide a good base to start working on. With these results the designer can start the design spiral with a good base and advance into optimization of the hull shape.

A calculation of the error between the FORMDATA C_b and the final C_b, as well as the C_M, can be seen in Table 13.

	Initial	New Hull	Error
CB	0.7	0.67	4.6%
CM	0.98	0.9891	0.9%

Table 13 - Case 1: Cb and CM error

The visual representation of the results may sometimes mislead the designer as they are affected by the plot function and the number of points used to plot each line. Most times, the dents or the vertices are due to small number of points to define the curve.

6.4. Case 4: N Shaped Hull

In this case a N shape hull was designed with an intent to be a bulk carrier. These types of hulls have average C_bs which means normal sections and flattened bulbs with high elevation.

6.4.1. FORMDATA sections

The first result, the FORMDATA sections, present sections typical in a bulk carrier. There are some edges and vertices along the lines, but that maybe due to small errors and from the number of points that were used to design them. There is however an improvement that could be made. The lines could have a rounder shape with a more fluid shape. This could be improved by adding more points to the initial part of the section. This however would greatly increase the number of data required.

6.4.2. Waterlines

Next comes the waterlines. Here it is possible to see that the parallel middle body extends from 0.4% to 0.6% of L_{pp}. This result is directly linked to the previous one, meaning that any mistake or imperfection on the FORMDATA sections will directly appear here. This result is also harder to analyse in terms of global hull shape as all waterlines represented are on top of each other. The better analysis is the general shape which corresponds quite well with a real vessel.

6.4.3. Deck at edge curve

The deck at edge curve shows a normal hull, going outwards really fast and staying at the full breadth until 0.73% of L_{pp}.

When we compare the result obtain with a real vessel, we can observe that the deck curve resembles a real ship and, as such, we can consider it a good enough result.

6.4.4. Flat of bottom

The flat of bottom curve represented is shows the flat part of the bottom of the hull. This curve is a good approximation, but it shows the need to make some improvements. For example, the beginning part and the end part, outside of the parallel middle body, could show a curvier development instead of a more abrupt shape. This is also exaggerated by the software when plotting and some leniency has to be given. Despite the errors that can be found, this is a good tool to know which areas will need further development and special attention throughout the development process.

6.4.5. Slope curves

The slope curves show the slope at the keel, waterline and deck. They show that the major development of the sections is made below the waterline. It is also possible to see that the bottom starts its flat part before the side become vertical. The bottom line, which represents the bottom slope has small degree value as it represents how the section line leaves the keel or the flat of bottom part. Then, both top lines represent the waterline and deck slope. Usually, the waterline slope has inferior or equal values than the deck slopes. Meaning that above the waterline the hull still develops further or continues the same that it is at the waterline.

6.4.6. Sections below the waterlines

The sections below the waterline represent a hull with a high C_b, typical of a bulk carrier ship. In Figure 73, we can see that the bilge area is not very smooth, which implies that the addition of the slopes to the sections might not have been utilized at their full potential.

6.4.7. Sections above the waterline

The sections above the waterline do not provide much new information, just that the hull develops predominantly vertically above the waterline.

6.4.8. Section Area Curve

The section area curve is an important result, not only for further calculations that are necessary for the development process but give a general idea of the hull shape, below waterline, at each section as a hole. With this, the designer can see if the area of each section is somewhat correct and it is only a matter of deforming the section or if the section needs to increase or decrease.

It is possible to see that the initial value is very small but bigger than zero, due to the existence of a stern panel. This can also be seen at the deck edge curve, where it starts with a value higher than zero but ends at zero at the bow. The centroid of the area below the curve should be located near the center as it represents the buoyancy longitudinal coordinate and is very important when calculating the hull dynamics.

6.4.9. Final Sections

In this result we can see that the final sections are presented in their real values. This not only shows the final sections of the ship hull, but it also allows the designer to better identify areas that need improvement as small errors will be multiplied by the breadth or draft. This will result in a magnified version of the results shown before and also will allow for a better perspective as the axis do not have the same boundaries anymore.

Looking at Figure 76, we can see that the bilge area needs further development. At this stage, the bulbous is not critical as it usually requires a detailed analysis to ensure the best hydrodynamic behavior is achieved.

6.4.10. Final Remarks

Looking at these results, the outcome is quite satisfactory. The time it took for producing these results, from inserting initial data to results output, was less than 5 minutes. This means that several hulls can be made with ease and quite fast.

A calculation of the error between the FORMDATA C_b and the final C_b, as well as the C_M, can be seen in Table 14Table 11.

	Initial	New Hull	Error
CB	0.68	0.72	6.3%
CM	0.98	0.99896	1.0%

Table 14 - Case 1: Cb and CM error

The hull shape is accurate to some extent and can provide a good starting point for the design process.

7. Conclusion & Future Developments

The designing of a hull is a very time consuming and laborious process and is an evolving process as new design or optimization methods are developed.

The goal of this project was to facilitate this process by speeding up the first step: designing a model hull to start working on. This first hull is not an optimized hull, rather a possible hull that meets the initial thoughts of the designer. The ability to quickly change the parameters or type of hull is very interesting and allows the designer to produce, test or study different types of hulls.

This project aims to produce two sets of hulls for the type selected. One hull purely taken from the FORMDATA series and another new one that derives from the previous hull which can be more customized.

After finishing this project, it is possible to conclude that the initial goals were met. The results appear to be good. The process was rather difficult, and it required an in-depth study of the hull development and its requisites. The author believes that the program can be useful to create several different hulls, quickly by changing the initial parameters. These different hulls can then be used in an optimization process to be refined.

The program has some limitations. Some come from the FORMDATA series that were chosen as the base others come the code written inside it. Some improvements could be made in the code to make it faster or to further improve the calculations.

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ANNEX

Annex A – FORMDATA series