Parametric Generation of Yacht Hulls

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SUMMARY

There are currently no procedures for parametrically generating yacht hull forms. B-Splines functions provide the primary technique in most Computer Aided Hull Design packages for modelling the hull shape and they have not been used in a numerical hull generation procedure. This project investigates a parametric hull generation technique for yacht hull forms and defines the hull shape with B-spline functions.

Initially, the project looks at the techniques that have been developed in the past to generate hull forms and comments on the applicability of these techniques to yacht hulls and B-Spline functions. Then, by looking at the trends in the development of yacht design over the last century, the important parameters involved in the design of yacht hulls are found. The development of the yacht design is examined, to review how the process has changed and how numerical factors have become more import, creating a niche for a parametric hull generation procedure. A basic parametric yacht hull generation method is developed which provides the yacht designer with ability to quickly develop a yacht which can be analysed by other processes. Finally applications of the hull generation procedure are discussed, and illustrated with the development of a resistance optimisation process and a graphical interface.

1 INTRODUCTION

Since the computer became widely available, it has been used for a variety of engineering purposes. In naval architecture it can be used to design the shape of the hull. However, the medium in which the hull is designed has changed, the process of manually fairing the shape has not changed. A few methods have been developed that generate ships hull from numerical parameters. This project investigates the possibility in using a similar system in yacht design.

For centuries Naval Architecture was an art. But, once the ship attained commercial and military viability it was necessary to quantify the design in some manner, allowing it to be reproduced in the future. The Lines Plan and the Half Model, for centuries, provided an efficient method of accurately representing the ship, allowing measurements to be taken for the full size ship and calculations possible. Design remained the same until the computer became a practical possibility. This allowed the designer to model ships accurately in three dimensions, without the need of the skills required to make a half model and removing the two dimensional failings of the lines plan. Mathematical curve and surface generation techniques developed earlier this century, now found prominence as the reasonable amount of computation required for these methods was easily performed by the computer. Today the computer is a pre-requisite for the naval architect. It the design and performance of calculations which, before, could have taken hours, if not days, to perform.

Once generation techniques for designing hulls became possible, some naval architects thought about the process of design. They could see the large amounts of time required for modifying and fairing the shapes of vessels so that predefined goals, factors of design and coefficient could be met. With the power of the computer, however, would it not be possible to input the goals and the output to be a hull? Techniques were developed that created ships hulls, which allowed hulls to be rapidly created and more complex design properties such as resistance and motions could be analysed in a shorter time. Despite the development of these techniques, however, the main method of acquiring a fair hull is still by manual modification, performed by the naval architect.

The yacht design process is similar to that of ships, but in yachts, a greater variety of parameters and goals are required to complete a successful design. Since high profile events such as the America's Cup became big business and where national pride is at stake, excessively large amounts of money have been poured into the design of these small vessels. The most noticeable turning point was the event in 1983. A lot of money was spent on tank testing and computer modelling various prospective hulls for the Australian challenger. The result was a very successful vessel with the famous winged keel. Yacht design today owes much to the work that was performed for this one race.

One of the most useful tools that came out of this research was the Velocity Prediction Program (VPP). The VPP models the interaction of the sails and the hull and computes the effect. These programs allow the yacht designer to see, without the need for expensive tank testing, how the yacht will perform. It is based on research performed on commonly used sail plans and hull configurations. A velocity prediction program is one of the major parts of the much promoted International Measurement System (IMS) rating system. This system calculates the performance of a yacht and finds a handicap, a value that can be applied to a yacht's performance in a race, allowing it to compete on equal terms with other yachts racing. A good hull generation system would take account of the processes involved in the VPP and design a hull based on more important performance parameters rather than the basic geometric parameters.

The B-spline is a curve generating technique which is used in most hull design packages. This technique is very powerful as a wide range of different effects can be modelled. Industrial standards have be developed around B-spline functions, so that shapes defined by this process can be transferred to many different applications, which perform tasks such as hydrostatic calculations or numerically controlled machine cutting. Unfortunately, B-spline functions do not flow through a set of known points or have an easily modified function. Therefore, it is more difficult to use B-spline functions to perform any normal numerical task, such as forming a curve to bound a certain area. Due to this difficulty there are hardly any hull generating methods which use B-spline functions to define the shape of the hull. As B-splines are standard functions throughout most hull design programs, a hull created in a hull generating procedure using B-splines can be easily transferred to other CAD applications, allowing the hull to be modified further or to allow other design features to be added.

A set of parameters is required for a parametric hull generation method, these parameters hold values of certain properties which the generated hull must have. The choice of which parameters to use depends on the type of hull shape to be modelled. A hull generating method developed for the general merchant vessel does not have to be as flexible as one developed for the yacht hull, as most ships essentially have the same shape. The hull of the general merchant vessel has many straight regions, this is mainly due to economics, as a hull with straight sections can be constructed easier and can contain a greater cargo capacity. Alternatively, the yacht hull does not have any straight sections, as the hydrodynamics of the hull are important and yachts do not carry cargo. To select of a set of parameters to model a yacht hull is more difficult than for a ship, the yacht is almost exclusively made up of curves and a choice has to be made to how much of the shape is controlled by parameters and how much is controlled by the hull generation method.

A method to numerically generate yacht hulls would reduce design time. However, there are also more beneficial uses for this type of procedure. This investigation looks into some of the uses of the hull generation procedures to show that they can play a large part in the efficient design of marine vessels.

2 PROJECT OBJECTIVES

- To perform a critical review of current generation techniques used to create hulls, with a view to investigate if there is any method which would be applicable to yacht design.

- To identify the factors and parameters that are important in the design of a yacht and can be used in a parametric hull generation process.

- To research what requirements and mechanics a yacht generation method would need to have, to be used as a useful tool.

- To look at the applications of a parametric yacht hull generation process to justify how these procedures can be used to speed up design and allow other aspects of a yacht to be review in a shorter period.

- To identify and recommend areas of further study.

3 CRITICAL REVIEW

Most of the research into parametric hull generation was performed in the 1970's, when computer time and power was at a premium. But with the advent of powerful microcomputers, software could be developed which allowed more people access to design applications for a cheaper price. The result of this is that software developers have tended to depend on user interaction to create hulls. This could be one of the main reasons that over the last decade, less research has be undertaken in the area of parametric hull generation methods.

There are quite a few methods around for generating hulls. The publications examined here include Reed and Nowacki [1], Kyan [2], Jorde [3] and Vacanti [4]. This is by no means and exhaustive review of the subject, but, in the time given, it was thought to include all the major works on the subject directly relevant to the current project.

3.1 INTERACTIVE CREATION OF FAIR SHIP LINES

Reed and Nowacki [1] is an extension of previous work from many sources mentioned in the paper. The study itself is dedicated to looking at two areas:

(a) The introduction of Conformal Mapping functions to represent the underwater sections.

(b) To adapt the lines creation process to the medium of interactive design by computer graphics terminal.

There are many parametric inputs for this method. A break down of the parameters is as follows.

No of Parameters	What Parameters Affect
6	General Inputs affecting global size and shape
17	Section Area Curve inputs affecting size, shape, centroids and local effects
11	Waterline Curve inputs affecting size, shape, centroids and local effects. Keel inputs by a certain number of polynomial segments. Deck inputs by offsets and slope, sheer line is assumed to be parabolic.

The basic curve generation process is based on using polynomial influence functions. This is one of the standard tools found in this type of method. This process creates a polynomial curve by the superposition of other polynomial functions called influence functions. Each of the influence function is responsible for representing one of the constraints without affecting any of the others. These polynomials are computed once only and do not need to be resolved if the design constraints are changed.

Underwater sections are created by conformal mapping techniques. These techniques are well known. The Lewis Transformation is one of the most well known of these techniques. It uses only three free parameters, beam, draft and section area, to generate a section shape which can be used to perform many powerful calculations governing ship motions. By including more parameters in the mapping technique more features of the section shape can be controlled. Using this technique simplifies calculation of hydrostatic and hydrodynamic properties for the hull. The conformal mapping procedure used in this particular method extends the Lewis Transform so that it also includes x-moment and y-moment coefficients.

The solution of the influence functions is achieved by using a Newton-Raphson least squares technique, which is one of the methods which has the fastest convergence to a solution. The range of shapes that can be created depends on the number of coefficients used in the conformal mapping function. Tuck and von Kerezek [11] demonstrated, by using seven coefficients in the mapping and a Block coefficient of 0.7, close fits could be made of the Series 60 hull form. Fine high speed, transom stern, hull forms could also be created with the method.

The major drawback of using conformal mapping techniques is that the process only models the underwater section of the hull. Polynomials can be fitted to the section so that the upper sections can be formed. But the slope at the waterline created by the conformal mapping is infinite, an undesirable feature in bow and stern sections. To overcome this problem, the mapping process, which is based on a quadrant of a circle of unit radius between $-p/2 \le q \le 0$, is changed, so that the mapping process is carried out to a different value of θ producing a variable slope at the waterline.

This method was developed in 1974 when computer technology was still in its infancy. The method was developed to work on the University of Michigan's IBM 360 67 computer. By using a light pen and teletype, user interaction was possible on a graphics terminal.

This method of creating hull forms seems fairly useful especially from the ship design point of view. It allows the quick generation of lines with the added advantage that all the information about ship motions is included in the process. It is not mentioned how the accuracy of the motion characteristics is effected by sections which do not use the full quadrants in the mapping process. The influence functions provide a very useful method for modelling the constraints. The advantage of this system, as mentioned, is that the influence functions only have to be solved once. This feature must have been one of the most helpful aspects of the method for the computer system available at the time. The input parameters are varied and include many which describe local effects.

It is necessary to input offsets for deck and offsets are also required for the calculation of the keel polynomial. This means that a fairly detailed study must be made of the profile of the vessel before using this process. Parallel middle body is one of the parameters required in this method. It is not thought that this method would breakdown if the parallel middle body was removed to model a yacht, given that the influence functions are defined over the whole length of the hull. It is not mentioned how underwater part of a section is blended into the upper part of a section. This region of the hull, around the waterline, is important in a yacht as the flow of water must be considered in heeled conditions as well.

Conformal mapping techniques seem to be good idea, and would have been investigated had not the study been restricted to B-Spline functions only. The appeal of conformal mapping is that the sections produced are circular in nature, this is not dissimilar to the modern yacht.

3.2 DIRECT GENERATION OF FAIR SHIP HULL SURFACE FROM DESIGN PARAMETERS

The method used by Kyan [2], for generating ships hulls is similar to most other methods. Parameters are used as an input, to generate the shape of the hull. The parameters are:

- Primary Dimensions - Length, Beam, Draught and Depth.
- Block Coefficient and Longitudinal Centre of Buoyancy
- Sectional Area Curve
- Midship Section Coefficient
- Bow Profile
- Stern Profile
- Aft Control Section
- Shape Coefficient (A coefficient describing how similar the section is to ‘U’ or ‘V' shapes)
- Functions of Volume and Volume Moments

The main intention of this procedure is to generate hull forms with the same key design parameters, but with different varying vertical shapes. As this procedure is based on varying a similar shape it requires a basic hull form to start with and this is used to base the initial functions for volume and moments of volume. The hull form for this method has been taken from published sources of hull forms. The series 60 hull form is one which was followed closely in this study. The study is primarily concerned with obtaining for a hull form, the correct Block coefficient and longitudinal centre of buoyancy. The sections are defined in super elliptic equations and can be varied so that the desired Shape Coefficient is obtained. Super elliptic curves are also used to define the shape of the bow and stern profiles.

Surface equations based on power series are used to define the surface shape of the hull. Volumes and moments of volumes can be calculated from these equations. But higher order moment functions are required as part of the process. The higher order functions become increasingly difficult to obtain due to the complexity of ship hull shapes. Recurrence relationships are used to find the higher order functions necessary for the hull modification process.

This method is dependent on having a parent hull form to base initial calculations upon and the for the creation of initial functions. The method draws on the large amount of information that has been created over the years on certain hull forms. As computers have only be a fairly recent introduction to the shipping industry as a whole at the time of the work, it was necessary to research for hull forms which could be used as a basis, for ships to be designed around. In this way resistance and seakeeping behaviour could be known in detail about a certain hull. A naval architect could draw on this information to produce a similar hull which would perform well. Today as computer aided design and analysis is becoming more common, the basis hulls are or less importance, as hulls can be developed and analysed much quicker than ever before on computer based systems.

Given that this method was written at a time when computer systems were not as common as they are today, the method draws well on standard functions and equations used to modify hull forms from the basis shape. The method could probably be implemented easily today in modern spreadsheet computer packages.

This method has been specifically developed for the normal merchant ship shape. The modification process uses many features which are present in a ship hull and these features are not normally found in a yacht hull. For example, features such as “Flat of Side” are used to change the shape of the hull through the use of the moment functions of volume. The method uses two approaches for varying Block coefficient. One approach uses the standard system of changing the section area curve by modifying the length of the parallel middle body. The other draws on the use of the parent hull to change the value of the Block coefficient.

Yacht design has not benefited from the use of standard hulls in the past. Owners requiring a vessel normally have enough money to spend on a yacht for the designer to use care and attention to detail, to come up with a hull which performs well, with the theory and testing facilities available at the time. Although there has been much of research performed on certain hulls, notably those involved in the America's Cup, the information from these projects is generally kept confidential and it takes a long time for this research material to enter the public domain. Yacht naval architects generally design new vessels based on the information and the experience from a previous designs successes and/or failures.

As will be discussed later, the shapes of yachts are varied and the shapes can be based on the current racing trend or a pretty look. A ship hull has be developed for reasons different to those of a yacht. The economics is one of the most important factors in ship design. A completely new hull design is going to cost a ship owner a lot more money than one that has been developed from a tried and tested family of hulls. This is where this method would come in, to develop hulls quickly, keeping costs down. Yacht design would not benefit well from this type of development, the forefront of yacht design is based around testing new designs and discovering new shapes and techniques. Many of the large companies which build yachts for mass production have been previously using development similar to the shipbuilding industry. Such companies have enjoyed good success through the early stages of the growth of this leisure industry. Recently, as yacht design has become technical and scientific, these companies have started to look at their methods of hull development. New companies have started to produce yachts whose performance greatly exceed the old designs and the pioneering companies in this field have had to change their design strategy.

The direction followed by this method could be used successfully over a short period of time to develop a fleet yachts of different sizes, based on the same basis hull. For this method to be useful though, it would have to be able to adapt itself to new designs - a flexibility which this method does not pretend to be capable of. It would not, therefore, be a suitable approach to take for yacht hulls.

3.3 MATHEMATICS OF A BODY PLAN.

This recent method by Jorde [3], has been developed to demonstrate how body plans should depend on the main design parameters instead of using a parent hull or artificial input. It has been constructed so that it can be programmed into a spreadsheet. The example given uses Microsoft Excel 5.0. Fortunately, a copy of the original calculation as well as the paper was made available to the author. Given that the method has been developed for a standard spreadsheet, it goes to proving that large computing power is not necessarily required to use a hull generating technique.

The method is fairly simple in that the curves used are cubic polynomials of the form:

$$Y = A + Bx + Cx^2 + Dx^3$$

This basic function is used to generate every curve used in the process. The method can be looked at in three parts: creation of section area; forming of the longitudinal curves, i.e. deck line, waterline; creation of the sections.

The section area curve is created using various lengths, including length of parallel middle body. Section area curve is modelled using a cubic curve at the bow and at the stern of the vessel and joining the two curves by a straight line dependent on the parallel middle body. By setting the slope of these two curves at the bow and the stern and by modifying the lengths, the shape of the section area curve can be changed. The waterline is created in a similar fashion.

The deck line and a knuckle line are created by specifying the distance of these lines above the waterline. The keel line is formed by inputting the offsets of the keel at various sections.

Now with all the longitudinal geometric lines formed, the section area coefficient is formed for each section. The parameters for each section are then given to a function which creates the sections. The sections are again created in two parts:, an underwater part, and an above-water part. The lower part of the sectional shape is created with a polynomial function with constants k, q, p. k is a constant dependent on the rise of floor. q is a constant that controls the order of the function, while p is a scalar of one of the components. These functions take the parameters of draught and waterline beam. p and q are found through integration of the sectional area. Rise of floor is controlled by having a global value of the slope and applying it to all the sections.

Once the sections have been created, the curve of section area coefficient, p and q are analysed. How these curves are analysed is not mentioned and the p and q lines are not shown in the example spreadsheet. Above waterline sectional shape is created by attaching a third order polynomial with the same slope as found in the lower part at the waterline. Also a knuckle line is found below the deck line.

This method shows how a hull can be created by using fairly simple mathematical techniques. The spreadsheet example is given and it became clear that a good knowledge of the formulation of the method is required in order to make full use of it. It is fairly difficult to go into the spreadsheet without knowing what all of the parameters are. There are many parameters which govern local effects and the keel line must be formed by supplying offsets. The method also demonstrates how easy it is to add other effects to the hull, for instance, the addition of a knuckle line.

The major problem with a system based on using standard polynomial functions of explicit form is that, although the mathematics involved appear to be simpler, the range of hulls that can be created is smaller than when using parametric polynomials. This make the method less versatile than others. The method that is obtained when the formulation process is followed is dependent on the type of hull to be generated. A method based on one type of hull cannot be used to create another type of hull. This paper has tried more to demonstrate how easy it is to create a preliminary hull design based on mathematical formulation. It is thought that the idea behind this project is that a new method should be created for each different hull form. This is a fairly appealing concept, but the example method was somewhat restrictive in the degree of hull form variation, which would suggest that if larger modifications were required many method would have to be developed.

The spreadsheet example is fairly difficult to use as the input parameters are placed well apart around the spreadsheet. The spreadsheet is protected so that an investigation into the details of this method cannot be made. The paper only shows the basic theory involved in creating a method. Additional information would be required on how to construct a method to ensure that the formed hull was fair.

This method is very effective, but should only be used to create a preliminary hull. A good amount of preliminary work should be performed on the hull to make sure that it is good and fair. To create a yacht with this method would be fairly easy. Although there is still the problem of a second order discontinuity in the section shape at amidships, where the two section area functions are joined.

One of the problems found with explicit polynomial functions is that, when developing a procedure which creates a function to fulfil a range of criteria, is that the more boundary conditions that are applied to the function, the less fair the curve produced by the function becomes. Generally, the curve produced by the function will be completely useless for any hull. This is one feature of using parametric B-splines for the yacht project, as they generally keep a good shape even when applied with many boundary conditions. This is one of the reasons why the B-spline technique has been chosen for the current study.

3.4 PROLINES 6.23

This commercial system [4], does not use a true parametric generation process, but it seems to bridge the gap between a full parametric design method and the normal interactive B-spline surface design computer application. Prolines uses a basic generating technique to create the B-spline surface used for design. This makes the design process quicker as all one has to do is modify the hull, which is of the correct size, so that the coefficients such as block and prismatic coefficient match your goals. The application, on the user selecting "New" displays figure 3.1.

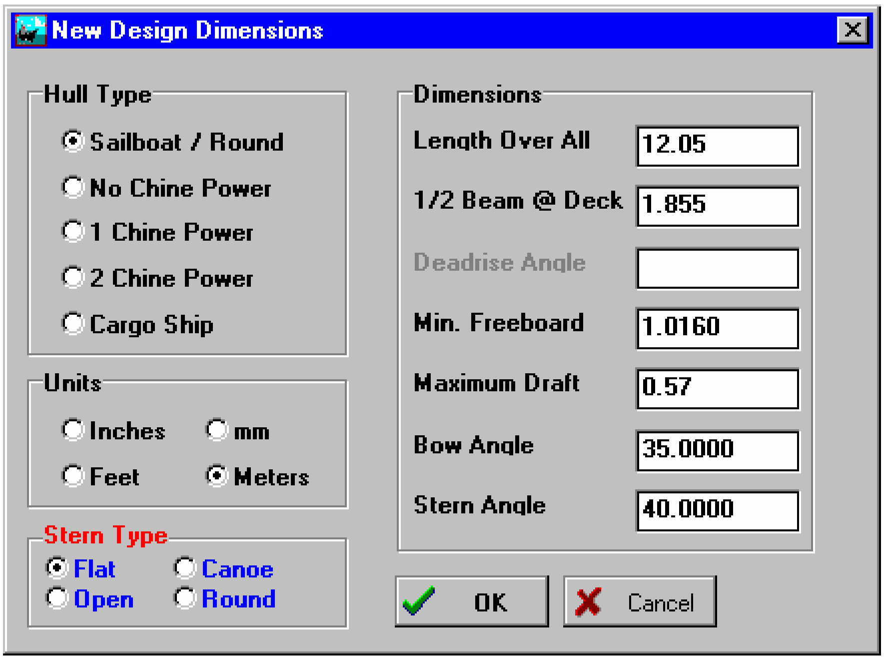

Figure 3.1, The hull creation dialogue box.

It can be seen that there are three basic types of vessel that can be created: sail, powered vessel or a cargo ship. The powered vessel has three chine variations. The figure 3.1 currently shows Length overall, Half Beam and Draft corresponding to the example yacht designed in Larsson and Eliasson [6]. Figure 3.2 shows the surface produced by the process.

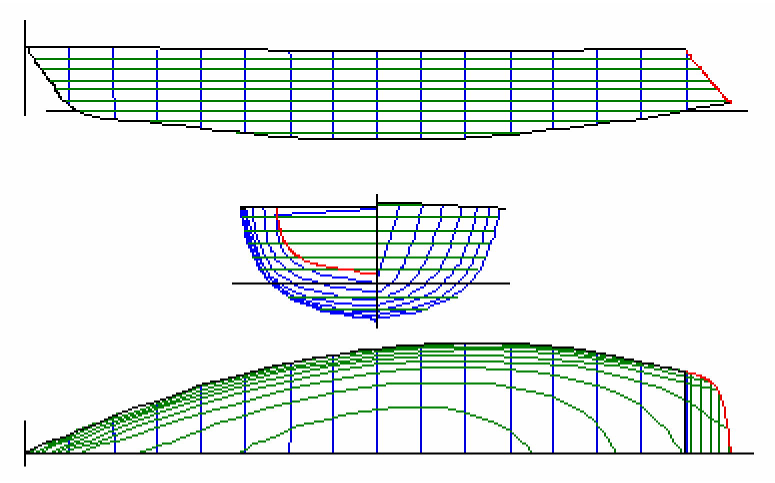

Figure 3.2, The initial hull produced by the options set in figure 3.1

The application produces a B-spline surface of quadratic order with five-by-five control points net. The method that the program uses for designing hull is by having a basis hull and scaling it by the input parameters. Then modification is made to get the desired hull by manually moving the control vertices. This procedure for creating a hull is fairly useful. However, it is really only useful for vessels which do not have hulls with special effects. The cargo ship in this example has a bulbous bow which would be very difficult to modify and retain a fair hull. This limitation can be overcome if more longitudinal control vertices are added to the net, but this point was not raised by the authors.

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4 B-SPLINE FUNCTIONS

Defining a curve in space using standard mathematical functions such as explicit polynomials can be difficult when these curves are to be used for design purposes. Design is a process of looking at an existing problem to obtain a solution. In many cases, design is a spiral process where many iterations may be used to design and evaluate the potential solutions. This is true for ship design as well. During the design of a vessel the shape of the ship may change many times. In modern ship CAD applications the surface of the hull must be defined by some mathematical method. Explicit functions have a limited flexibility rendering them unsuitable for developing ships hull surfaces. However, the invention of parametric piecewise functions such as B-Splines, has allowed rapid advance in using CAD for ships and other curved objects, such as cars and shoes.

Curve fitting techniques, such as Cubic splines, can be used do define the shape of curved objects. However, these techniques are unsuitable for *ab initio* design. Numerical specification of the direction and magnitude of tangents, used in many of these curve fitting techniques do not provide the intuitive ‘feel’ required for *ab initio* design. An obvious relationship between the numbers and the shape of the curve produced by these techniques does not always exist.

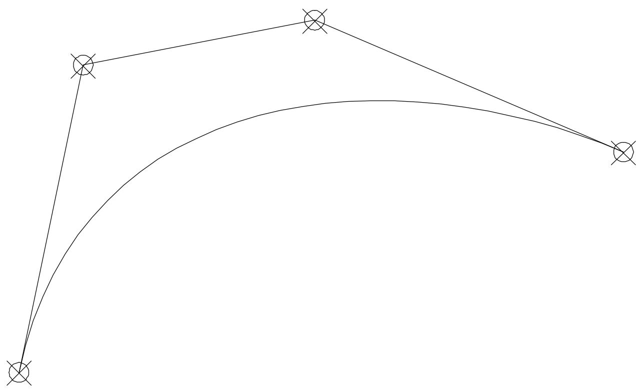


Figure 4.1, A B-spline and control polygon.

Alternative methods of curve generation, suitable for *ab initio* design were developed. The B-spline basis was first suggested in 1946 by Scoenberg and practical recursive algorithm was developed independently by Cox (1971 and de Boor (1972). A B-spline curve is generated from a defining control polygon, Figure 4.1. B-spline functions exhibit the property of local modification, which is very useful in iterative design. When a single vertex of the B-spline control polygon is modified, the shape of the B-spline curve is only changed over a small area local to the control vertex. This effect is extremely useful, as it allows small regions of a object to be modified, without the whole object changing. However, many more hull generation techniques may have been developed if this property had not been discovered. More technical details about B-spline functions can be found in Rogers and Adams [13].

B-splines, today, have developed into powerful functions with associated buzzwords. NURB function surface is one feature which many modern CAD applications support and can be used to develop objects, of almost any shape. B-spline functions allow objects and shapes to be shared between CAD applications, as a relatively small amount of data can be used to store a complex shape.

A hull generation procedure, using B-splines, would have advantages over techniques using other curve functions, as a B-spline hull definition can be directly exported to other applications. However, the major advantage that explicit functions over parametric functions such as B-spline functions, is that explicit functions can easily integrated. Unfortunately, there are no techniques for integrating B-spline functions directly and so the current hull generation technique uses Simpson’s rule for approximate integration.

5 THE DEVELOPMENT OF THE YACHT

Figure 5.1, The Open 60, PRB.

Yacht: *Light vessel for racing or pleasure.*

A parametric hull generation procedure requires numerical parameters to define the shape of the yacht. To make a choice as to which parameters to select, it is necessary to review the development of the yacht, so that design trends and the reasons for the current shape of the yacht hull can be identified.

The yacht has been around for many centuries. The first yachts were not the light vessels found today, but the large luxury barges the Emperors of China entertained their guests upon. This concept was developed over the years, mostly by the noble and the rich to be a small private vessel that could be used for pleasure. The original yachts were powered vessels, used for special occasions or extra homes. The word 'yacht' is of Dutch origin and is a shortened form of the earlier *jacht schip*. A Dutch-Latin dictionary published in 1599 described a *jacht schip* and a *jacht* (or *joghte*) as a swift light vessel of war, commerce or pleasure.

It was not until the end of the 19th century that the design of the sailing yacht came close to the form it is seen in today. The industrial revolution had created many affluent people who had money to spend on their leisure. Yachting was one popular pastime for the wealthy. Since then the sailing yacht hull has developed through many shapes. To understand why the sailing yacht can be seen in such diverse forms today it is necessary to look at the origin of the design of these small vessels.

At the start of this century, two types of yacht owners could be found. There was the fairly wealthy owner who spent weekends and holidays on his reasonably small vessel of around 6 to 7 metres in length. These vessels would probably have been designed by a naval architect with experience mostly of fishing vessels and their related construction techniques. The other yacht owner would be the extremely wealthy type, people like heads of state and large business owners. Examples of these vessels are the J-Class and Pre J-Class racing yachts. These vessels were around 30 to 40 metres in size with correspondingly large sail areas. These vessels were almost always used for racing and required finances in large scale to fund good performance over a racing season. The naval architects who designed these vessels were just starting to appreciate the different factors involved in the design of large sailing vessels.

The working sailing vessels at this time were either the large square rigged ships or “fore and aft” rigged fishing boats. Working vessels were built on tradition and a “trial and error” basis - science only played a small part in the design. The racing yachts used the fore and aft sailing rig and much testing was required to develop these rigs into efficient propulsion systems. Initial designs were based on supplying the most amount of sail possible. This and the fact that yachts of the time had very large length to beam ratios, resulted in uncomfortable sailing angles of up to 75°. When the yacht was developed scientifically the initial design of the yachts changed. This metamorphosis is demonstrated well in yachts that have raced in the America’s Cup competitions.

Figure 5.2, A ‘J’ class racing yacht.

The initial design of the hull of large racing yachts was similar to fishing vessels. The long deep keel was a feature found on all vessels. As yacht design developed, it was found that vessels performed better when wetted surface area was reduced. Reducing keel size was one of the ways the surface area could be minimised and has given rise to the exceptionally small keels found on some racing yachts today. As the size of the keel reduced, the shape of the hull became less of a 'V' shape and more of a 'U' shape. This 'U' shape was found to have a major advantage as flat sections create a certain amount of hydrodynamic lift raising the vessel out of the water, reducing the wetted surface area. The weight of the original heavy wooden yachts could be reduced by using modern materials such as glass fibre reinforced plastics. The sail area was reduced, as less power was needed due to the lighter weight.

The major advances in design can be seen to come from the major racing events such as the America's Cup. Sponsors found originally that by throwing more money into the design than the other competitors, their yachts would win races. Research establishments were gladly funded by syndicates, and would design and test prospective competitors. Much study was performed in the test tank and wind tunnel, testing various designs. Although most of the designs were supposed to be secret, the discoveries filtered out to the rest of yacht design, resulting in the designs found today.

Rating rules have also played a large part in the design of yachts. The rules restrict the dimensions of a yacht so that it is able to compete on level terms with other yachts in a race. The job of the yacht designer is to design a vessel which can beat others while still complying with the rule. This type of designing, called "rule cheating", can be applied in to ways. Either by designing a better vessel on physical principles, or by modifying a yacht hull, sometimes in what can be considered a nonsensical manner to leave the rating unchanged. The now defunct IOR (International Offshore Rule) is one example where rule cheating was common. The rule measured certain dimensions at various point along the vessel. It, therefore, did not necessarily consider the areas between the measured points, giving an area which could be changed without affecting the rating of the yacht.

The effect of rating rules is to restrict development. Rating rules were originally designed to measure performance and seaworthiness. However, in the case of IOR, yachts became less seaworthy. The Fastnet Race disaster in 1979 led to an examination which analyse why so many yachts were disabled or lost. It was found that the restrictions of the IOR rule produced inherently unsafe vessels. The IMS (International Measurement System) rule, which was developed to supersede the IOR rule, uses full analysis of a yacht's performance to judge it with other vessels. The IMS rule uses a velocity prediction program (VPP) to analyse performance and this uses many empirical formulae. Rule cheating could be used here as well by analysing the formulae used in the VPP.

Besides racing, designs based around operability have also been developed. The "Colin Archer" type vessel is regarded as one the most seaworthy small vessels. Colin Archer was a Norwegian naval architect of Scottish origin. He designed the polar ice ship *Fram* and also developed sailing vessels for the Norwegian life boat service. These lifeboats were heavily constructed in wood to deal with the weather conditions common to the North Sea. They are called "Double Enders" as they have a sharp stern similar to the bow. They have long deep keels. The vessel is gaff rigged with a "Swedish Pole Mast", which was basically a very large diameter mast that allowed the rigging to be smaller. A sharp stern has found to be very effective in following seas, reducing "pooping", a phenomenon where the waves break dangerously over the stern of the vessel. These types of vessels have been known to sail all over the world and are very forgiving, i.e. they generally behave well when sailed in bad conditions with a crew who sail the vessel very hard. One example of this is a voyage made by Earling Tambs [12], an author who sailed extensively in the South Pacific in his first vessel, the Colin Archer designed pilot vessel *Teddy*. After wrecking the *Teddy* off the north coast of New Zealand he took the Redningskiote or Lifeboat, *Sandefiord*, across the Atlantic from Norway to America. In a storm, Mr Tambs refused to reduce sail and the 14 meter vessel pitch-poled (a longitudinal capsize) in the middle of the Atlantic twice, removing the mizzen mast and a crew member was lost. However, the heavy construction of the vessel allowed it to sail on to its destination. It would be very difficult to find a modern light vessel that would be able to undertake this amount of punishment at sea and be able to continue sailing.

It is interesting to note that even in the late 19th century Colin Archer and another naval architect John Scott Russell, designer of the Great Eastern, had developed techniques for controlling the shape or lines of a vessel. Based on observations, Colin Archer constructed a simple formulation based on a circle, which linked the variation of section area over the length of a vessel to the wave making characteristics of a hull. It simply stated that the section area should vary at the same rate that the volume of water is removed from the path of a vessel. John Scott Russell developed a similar method at the same time but this was based on the shape of the waterlines. There was great discussion over which of these methods was better or true. However, they have both been discredited modern naval architects. It does show, nevertheless, that even one hundred years ago hull generation techniques were being developed.

In summary the design of a yacht is based on many factors. If these were categorised then the design of a yacht could be based on the following.

- The age of the vessel.
- Function of the vessel, for example, offshore racing, local racing *round the buoys*, weekend sail boats, long distance cruising yachts.
- The style preference of the owner/designer.
- Developments due to coastal layout and, or local weather conditions.

A quick glance at a yacht will show the basis that the vessel was designed around. A light hull of round bilge with ‘U’ shaped sections would have been developed from a racing background. While a yacht used for long distance cruising would be best with a long deep keel and modest to high displacement.

6 CHOICE OF PARAMETERS

6.1 HULL TYPES

Yacht hulls come in many shapes, forms and flavours. An effective parametric hull generation method should be able to deals with these shapes. It goes without saying that the success of such a method depends on its ability to model the hull. The shape of yacht hulls are so various that a method developed to model all types of hulls would find it difficult to complete the task well. It is the profile of the yacht that has changed the most and it is this shape that presents the most difficult problem in modelling all yacht hulls, as the waterplane shape has hardly changed. In Figure 6.1 a selection of photographs show how variable the shape profile can be.

Figure 6.1, Yacht Profiles

By necessity parametric hull generation system will be mostly based on numbers. If it were possible to develop a method that could create any hull, then it is likely that there would be some parameters that are used on certain types of hulls and for others. If a new type of hull were developed, new parameters may have to be included in the method for the system to accommodate the new hull. Such a universal system would be difficult to develop as it would have to allow for the use of dynamic parameters, i.e. those parameters which could be added, changed or removed from the method. Most generation methods concentrate on one type of hull. A yacht generation method should to the same and allow it to specialise and model that type of hull well. To select a yacht type to model, it is necessary then to look at which types of hull could benefit from the parametric design.

Numerically, the best type of hulls that would benefit from the use of a parametric generation method is those involved in racing. The racing hull from the beginning is involved with numbers. These may include size, performance and rating under a rule. To be a good racing yacht designer, a good understanding of how hull factors can affect performance is necessary. In this type of design today, the Velocity Prediction Program (VPP) is becoming the designer’s most important tool. This utility analyses the performance of a yacht and returns the results as numbers. The designer must be able to analyse the results to see how the hull can be optimised. Naval architecture in this respect has lost its art to science. This type of hull, therefore, would benefit the most from a hull generation method as a computer is much faster at making modifications.

Traditional yacht design is still an art. There has been some resurgence in traditional style yachts, as the design of light cruiser/racer yachts developed over the past decade has reached a stage where all yachts look very similar. The traditional hulls have much more variation in the different shapes that can be found. The key problem encountered in modelling a traditional style yacht is the variation of the profile. The most efficient way a tradition profile could be modelled is by having one input to the program similar to the approach taken by Jorde [3]. This approach is not necessarily good, as it can take many hours to design the correct shape. The best that this method can cope with is a number of offsets to implement the shape and these will not capture the true shape.

The hull of a traditional yacht is very different to the modern shape. The keel is normally part of the hull and is faired into the hull, introducing high curvature, whereas on a modern yacht the keel is basically an appendage which is bolted on to the bottom of the vessel. The integral keel of traditional yachts gives rise to ‘Y’ shape sections. A computerised generation method would find it difficult to deal with these types of hulls and is more likely to produce many unsuitable hulls.

Moreover, designing traditional yachts is much harder as in the past the curves have been judged by eye instead of numerical analysis. A parametric hull generation would be unable design the traditional hull form as it would be unable to compete and should not be allowed to compete with the skills of the traditional yacht naval architect. This said, new yacht designs such as the Truly Classic range designed by André Hoek have traditional styling above the waterline, while, below, modern theories are used to produce yachts that not only look impressive but have respectable performance too.

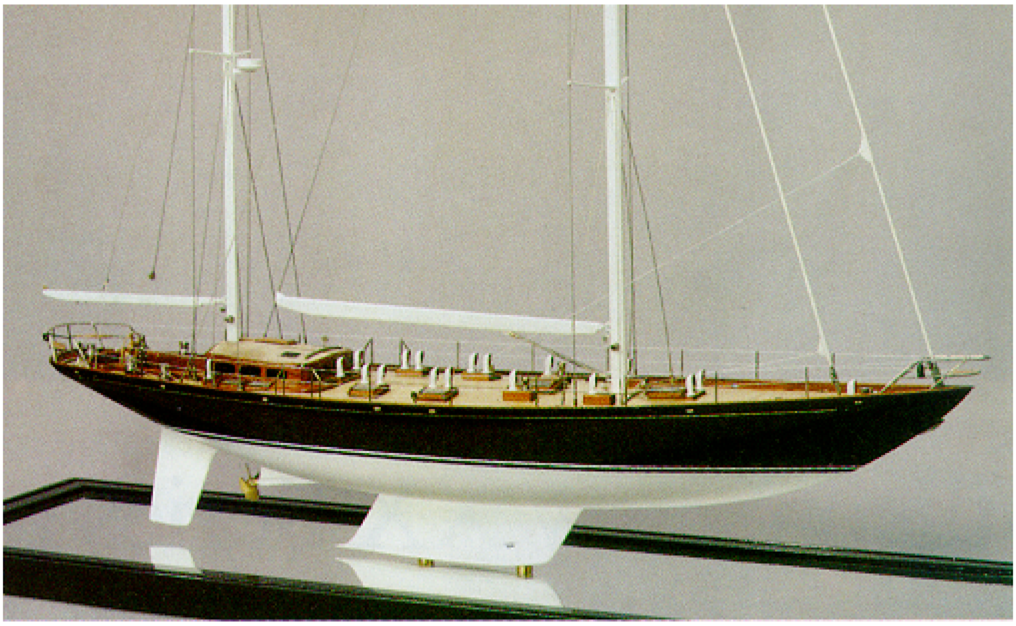


Figure 6.2, Truly Classic 75 by André Hoek.

The modern fast cruiser/racing hull has benefited the most from computer technology. Computers are used to design the hull, assess sailing performance and evaluate structural aspects, so that these yachts can win races. Hulls of the modern yacht are mostly similar and have become easy to design. There are no areas where tight curvature is found. It would be of more benefit to “Yacht Design”, if methods used for designing modern yachts are evaluated rather than to develop a method that was able to generate a yacht with traditional styling.

6.2 CHOOSING THE PARAMETERS

The parameters used to define the shape of the hull can be divided into two sets. There are the global parameters which can be used to define any marine vessel, and these include parameters such as waterline length (L_{WL}) and block coefficient (C_B). In the other set there are the other parameters which are defined as local. These affect the shape over small areas and are normally a function of the type of yacht being designed. An example of this would be any parameters defining the shape of the stern post. Some yachts do not have a stern post so these parameters would be useless to use on a yacht of such type.

(a) Overall Dimensions

To start with ,the basic dimensions of the vessel should be selected, i.e. the lengths in x, y and z. To any vessel there is more that one of these length dimension in any of the three axes.

The basic dimensions include:

- Length overall (L_{OA}).
- Waterline length (L_{WL} or D_{WL}).
- Maximum beam (B_{MAX}).
- Waterline beam (B_{WL}).
- Depth (D).
- Draught (T_C).
- Freeboard, at different points.

(b) Form Coefficients

Once the basic size of the yacht hull has been selected, coefficients need to be selected which describe the effectiveness of the hull. A coefficient should have a value which lies between 1 and 0. These non-dimensional coefficients are very useful, as, when the vessel is scaled, the coefficients do not change, keeping the volume and areas scaled in with the size of the vessel. The form coefficients are important and also play an important role in calculating resistance through the Delft Yacht Series [5].

The basic form coefficients which are available are:

- Block coefficient (C_B).
- Prismatic coefficient (C_P).
- Midship section coefficient (C_M).
- Waterplane coefficient (C_{WP}).
- Vertical prismatic coefficient (C_{VP}) .

(c) Centroids

The hull has many area and volumes. The centroids of these areas and volumes need to be specified because the correct balance of the yacht depends on it. The quantities are normally linear dimensions measured from a reference point to the centroid. Under a scaling transformation these parameters would have to be changed *pro rata* to stop the centroid from moving relative to the shape of the hull. If the positions of the centroids were specified in a non-dimensional forms then under a scaling transformation the position of the centroid relative to the hull would not change. One way of achieving this is to specify the positions of the centroids as percentages of the given waterline length.

The centroids available are:

- Longitudinal centre of buoyancy (LCB), as a percentage of L_{WL}.

- Longitudinal centre of flotation or longitudinal centroid of the waterplane (LCF), as a percentage of L_{WL}.
- Vertical centre of buoyancy (VCB), as a percentage of the hull draught T_C.
- Centre of Lateral Resistance (CLR), as a percentage of L_{WL}.

(d) Local Parameters

The generation method will create the shape of the profile, waterline and sheerline. To create these curves it is necessary to use parameters to specify local effects. These parameters will be mentioned in more detain in Chapter 8, as they are required to set up the algorithm which creates these curves. These are:

- Bow profile - angle at deck.
- Bow profile - deck tangent.
- Bow profile - angle at WL.
- Bow profile - tangent above WL.
- Bow profile - tangent below WL, (adjusts forefoot depth).
- Transom angle.
- Aft Extreme - above WL.

It was felt that there were too many parameters defining the shape of the bow profile. In later methods, the number of bow profile parameters was reduced to two; one varies the curvature in the bow by adjusting the angle of the tangents; The other parameter was the original bow profile - tangent below WL.

6.3 REQUIREMENTS FOR MORE DETAILED ANALYSIS

The Velocity Prediction Program has been mentioned previously as a tool that can analyse a yachts performance. Beside needing information about the hull, this program requires information about the devices attached to the hull. If the parametric hull generation process was taken a step further so that it was included as part of a VPP then the following parameters could be used to describe the other appendages found on a yacht.

Keel:

- Aspect ratio.
- Taper ratio.
- Depth of keel (T_K).
- Position of keel of the keel on the yacht.
- Sweep angle.

Rudder:

- Aspect ratio.
- Taper ratio.
- Depth of rudder.
- Position of rudder on yacht.

Sail Plan:

- Mast height.
- Sail area and factors corresponding to sail size.
- Centres of effort (CE) and Area.
- Position of mast on yacht.

- The “Lead” (the distance between CE and CLR, as percentage of L_{WL}).

These parameters would give all the information that the VPP needs to know about the yacht. As the VPP attempts to model the performance of the yacht at sea, it also requires parameters to describe the operational environment. These would be:

- Wind speed (affecting power generated by sails).
- Wave height (affecting resistance in waves).
- Wave frequency (also affecting resistance in waves).

7 METHOD 1

7.1 INTRODUCTION

It was now necessary to put all the concepts together to develop the hull generation technique. Initially, the method was developed similarly, to the approach taken by Jorde [3]. The basic approach of this system is to create the vessel by considering the various beams, draughts, depths and areas of sections along the length of the vessel, by using the curves of form. By varying the curves of form, the correct goals and targets specified by the parameters can be met. Most curves of form will be produced, where permitted, with cubic or fourth order B-spline functions. Once the curves of form are created, the hull sections can be generated to give a full hull definition.

7.2 CURVES OF FORM

The curves of form model the shape of certain properties of the hull, such as the draught. The draught at any point along the hull can be found by inspecting the draught form curve. Each of the curves of form have to be defined fully before they can be used. The curves of form used in this method are:

- Deck and Sheerline profile.
- Waterline.
- Profile.
- Section area curve.

(a) The Deck and Sheerline

This curve is the most complex shape to produce, it is one of the major curves which effect the look of a yacht. The curve is not coplanar and it is, therefore, more difficult to control its formation. The deck and sheerline are essentially the same space curve, however, if the curve was developed with only one curve technique, the shape formed may not be pleasing to the eye. Techniques generating the deck and the sheerline were considered ,separately, in the event that, if technique generating the sheerline produce an unsuitable curve it could easily be replaced.

On yachts today, there are a variety of sheerline shapes, the basic shapes are straight sheer, normal sheer and inverse sheer as shown in Figure 7.1.

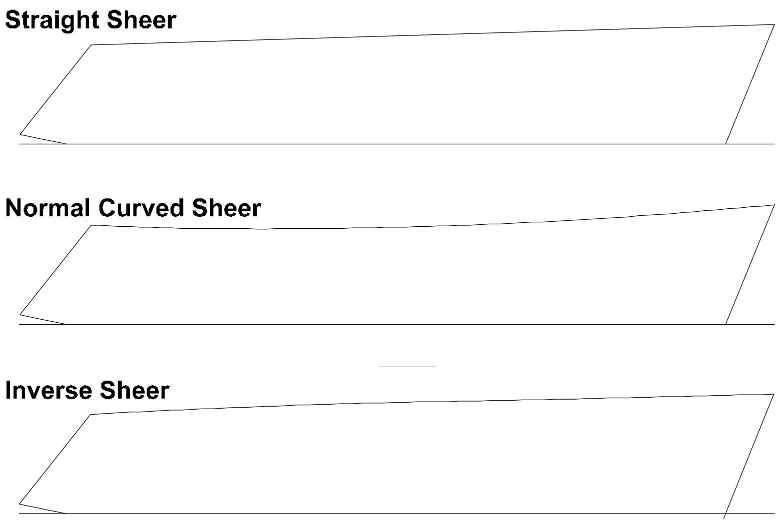


Figure 7.1, Types of Sheer.

A method must be selected that allows all these types of sheer to be produce so that whatever shape is in fashion can be modelled. There are a variety of methods that can be used to produce the sheerline. The following curve techniques were considered.

- A cubic spline.
- A B-spline Fit.
- Standard Sheer.
- Circular sheer.
- Straight sheer.

These techniques were tried and the differences between each technique were not large enough to be illustrated within a diagram. However, there are some functions which are better than others for describing the Sheerline.

Standard Sheer is used mostly in ship design, it cannot form a straight line and the sheer that is produced by this method is not classed as suitable for a yacht.

The cubic spline and the B-spline fit techniques seem to produce the best shaped curves, but minimum freeboard or the lowest point of the sheerline cannot be directly specified with the B-spline fit technique.

The circular technique produced a good sheerline shape, but was unable to produce straight sheer. The shape of circular sheer is fixed and more "interesting" sheer profiles cannot be produced with this technique.

The B-spline fit was chosen to create the sheer profile, because B-spline functions are used exclusively throughout the rest of the method and the specification of a minimum freeboard height was not considered a limitation. The freeboard can be specified at the bow, stern and amidships as in Figure 7.2 and a good shape is produced.

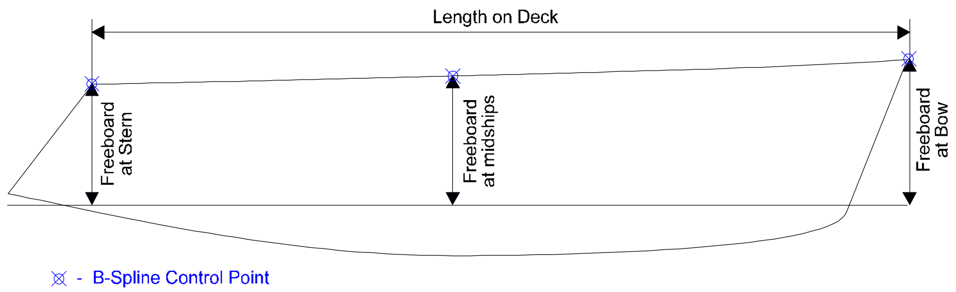


Figure 7.2, Parameters affecting the shape of the Sheerline.

The deckline is the sheerline curve, but viewed in plan. This curve is formed with a normal B-Spline. The maximum beam (B_{MAX}) and the beam at the transom ($B_{TRANSOM}$) are parameters used specified to the shape of the curve. The point of maximum beam along the length is free.

The B-spline control polygon producing the deckline is shown in Figure 7.3. A quadratic B-spline function is used to create this curve, as to the number of vertices in the control polygon is only 3. The control point at mid length is varied by an iterative process, until maximum point of the curve is equal to the maximum beam specified. The point of maximum beam along the length of the hull is free and a more natural shape is produced as a result .

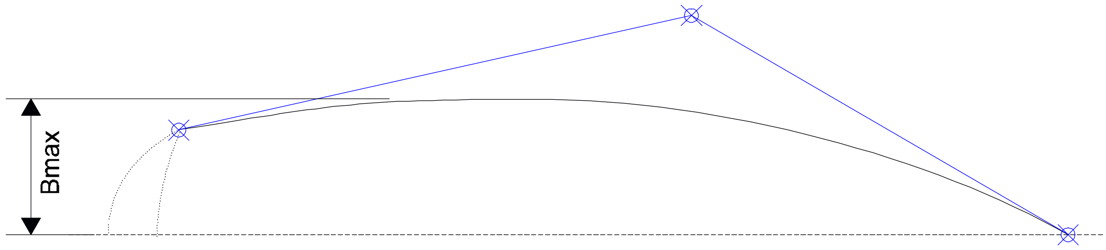


Figure 7.3, The Deck Line and B-Spline control polygon.

(b) The Waterplane

The waterplane is an important shape in any marine vessel. It is a key factor which influences the resistance of the vessel, that a good waterline shape is vital in most ships.

The maximum point of width on the waterline is controlled by the waterline beam (B_{WL}). To define the curve with a maximum beam as specified, a process similar to that used to create deck line was employed. The entrance angle of the waterplane can have an important role in the resistance of the yacht. Advice is given in [7] about what the waterplane entrance angle should be, based on the speed to length Ratio, Table 8.4.

$V / \sqrt{L}$	Entrance Angle Degrees
0.5	30
0.6	26
0.7	22
0.8	18
0.9	14
1.0	10
2.0	10

Table 8.4, Entrance angle based on Speed-Length ratio.

It is possible to specify the area and centre of area of the waterplane shape. The area is specified with the waterplane area coefficient C_{WP} and the centre of area, a quantity important in longitudinal stability, is specified with the longitudinal centre of flotation (LCF). The parameters used to specify the shape of the waterplane are shown in Figure 7.5

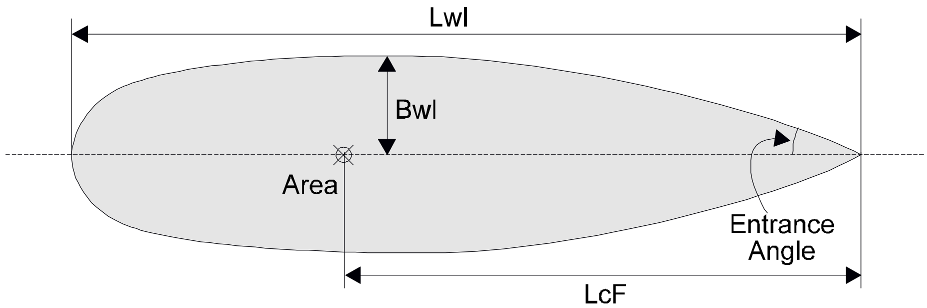


Figure 7.5, Parameters affecting the shape of the waterplane.

With all these parameters, the shape of the waterline curve can be produced. The main difficulty is producing the correct shape. The control polygon of cubic B-spline function chosen to create the waterplane shape is shown in Figure 7.6, each adjustments are made to the control polygon by iterative processes.

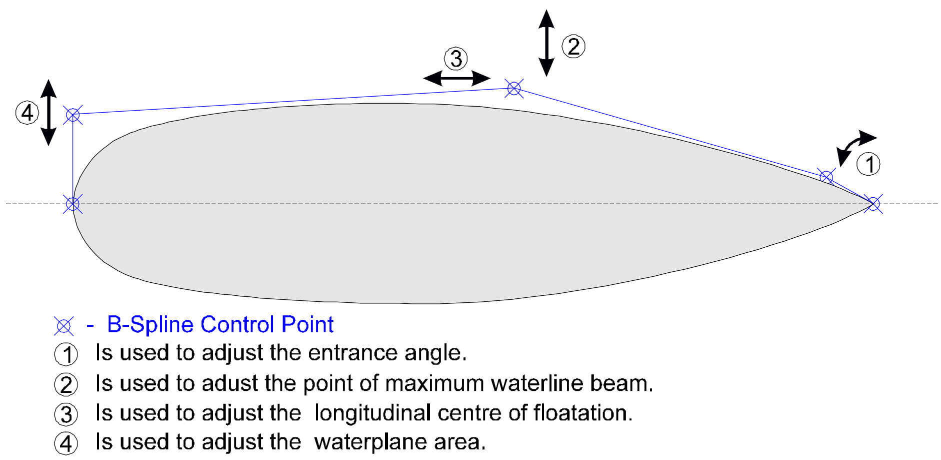


Figure 7.6, The Waterplane B-Spline control polygon.

(c) The Profile

The shape of the profile is one that defines the style of the yacht. The profile with the shape of the sheerline can make the yacht look fast or slow. The profile has the most number of parameters defining the shape. Figure 7.7 shows the basic parameters required to create the profile.

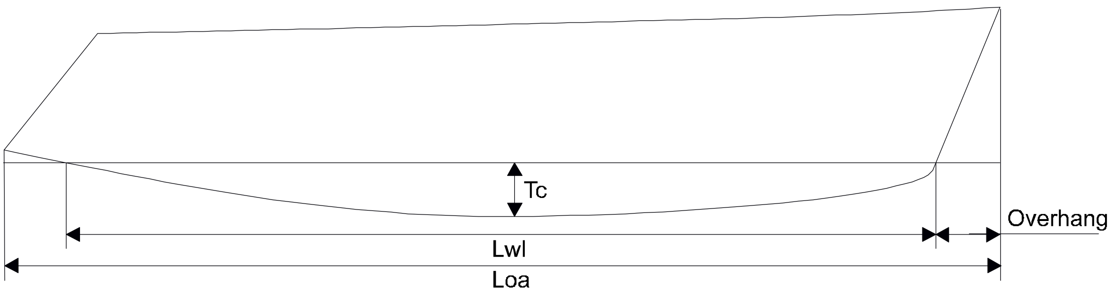
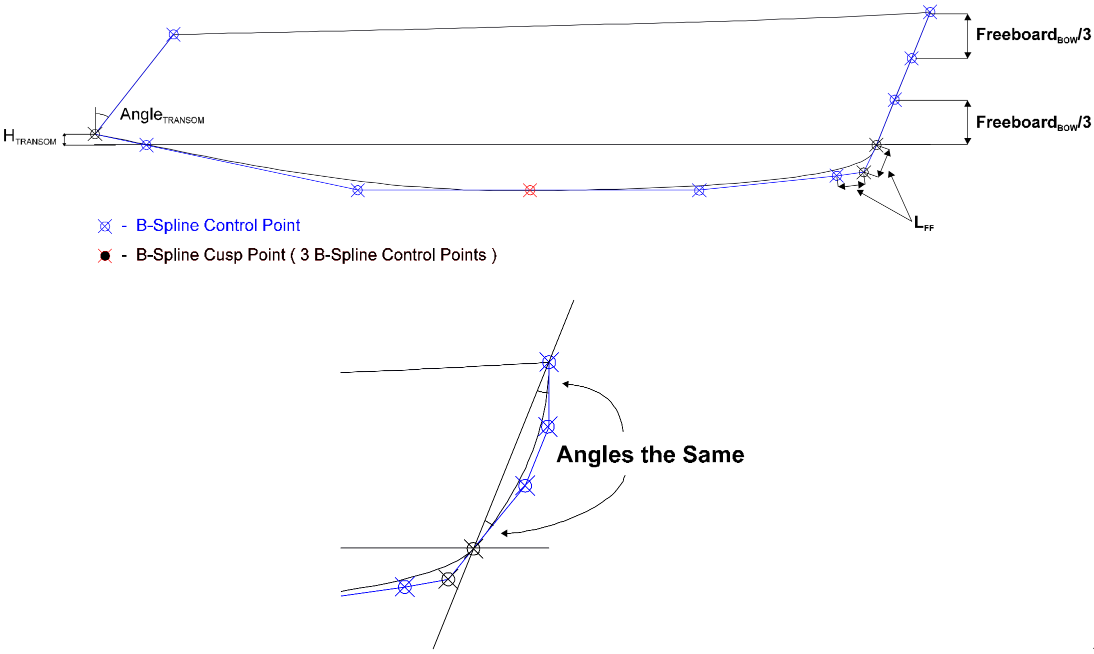


Figure 7.7, Profile Parameters.

The profile requires many local parameters to produce the shape. These parameters are used to define the angle of the bow and if there is any curvature in the bow. The depth of the forefoot needs to be controlled, as well as aspects of the transom.
Figure 7.8 shows the control polygon of the 4th order B-spline curve used to define the profile shape. This shape does not use any iterative processes, as all of the parameters directly modify parts of the control polygon.

To begin with, the definition of the bow profile was made with five parameters, each controlling the various features, where the profile joins at the deck and at the where the profile intersects with the waterline. Later, The number parameters controlling the bow was reduced to two; the angle of the curvature in bow profile and forefoot depth, because this made specification of the profile easier to understand.



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igure 7.8, The B-Spline control polygon defining the profile shape.

(d) The Section Area Curve

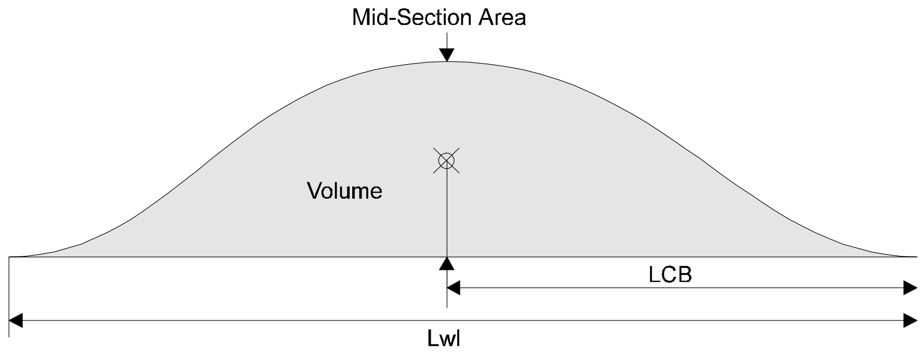


Figure 7.9, Parameter affecting the shape of the Section Area Curve.

The section area curve is one of the forms that are used is most hull generation techniques. Figure 7.9 shows the main parameters which are used to define the shape of this curve. Most section area curves defined for generation methods incorporate a section of parallel middle body. This can be helpful as it allows the curvature between the bow and stern area to be separated and the section area curve can be solved in two parts. However, parallel middle body is undesirable for yachts and the section area curve normally does not contain a straight line segment. Most techniques used in other hull generating procedures require a parallel section, because it breaks up the solution of the section area curve, making it easier to solve. In these techniques, if the length of parallel section was set to zero, a discontinuity would be created in the section area curve, as a result, these techniques cannot be used for yacht hulls as a continuous section area curve is required.

A direct mathematical section area curve was investigated for the current study to see if it would have any advantages over a B-spline method. The curve was developed in a similar way to the section area curve developed by Jorde [3], but without a parallel section. It was found that at least a fifth order polynomial function was required to produce a section area curve which featured no discontinuities. The shape produced by the derived function, however, is utterly useless for a section area curve as it apt to oscillate between positive and negative.

A quadratic B-spline function was chosen to model the shape of the section area curve, as the curve produced by a third order B-spline function was closer to the shape of a yacht section area curve than a fourth order B-spline curve. Figure 7.10 shows the control polygon adopted in this study to define the sectional area curve. By using iterative processes, modification of the B-spline curve could be performed to achieve the specified goals. Modification ① is used to make the maximum point of the curve coincide with maximum sectional area defined by the input parameters. The modification is made by moving control points A and B, vertically together. Modification ② is used to change the immersed volume. The modification is made by moving control points A and B, horizontally, closer together or farther apart. Modification ③ is used to modify the longitudinal centre of buoyancy. The modification is made by moving control points, A and B, both forward or both aft, together. These modifications, ①,② and ③, are made by the computer program to reach the specified goals. Modification ④ was originally set by parameters. But in later methods (as can be seen later) these end tangent vectors are used to correct the shape of the sectional area coefficient curve.

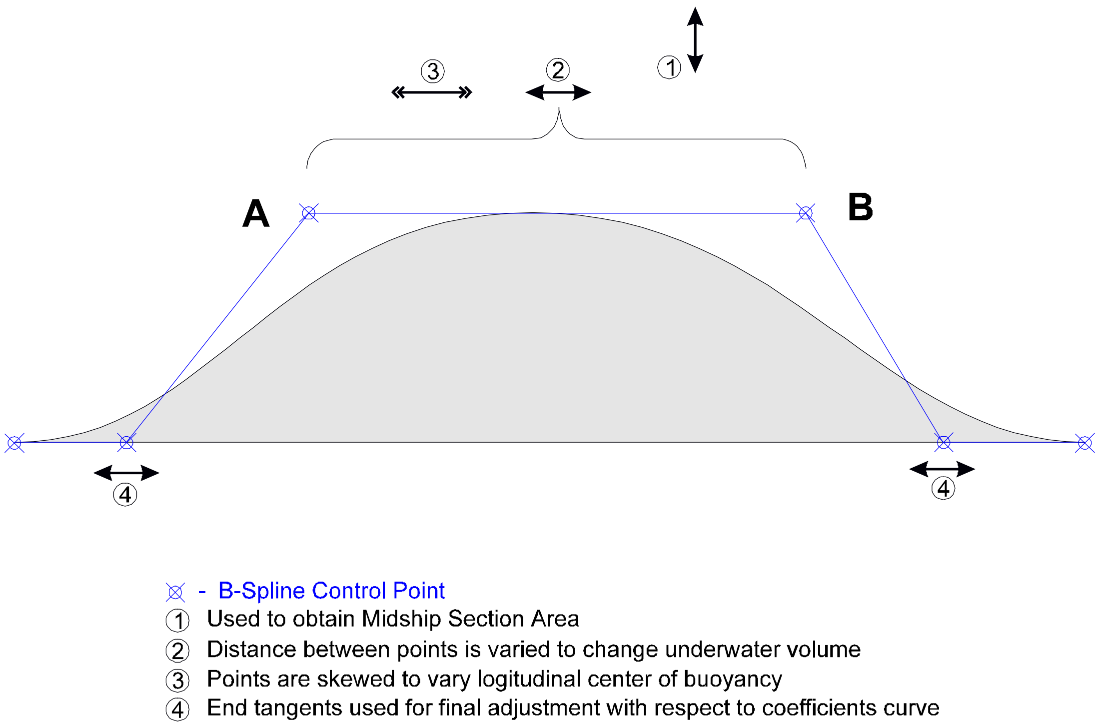


Figure 7.10, The B-Spline control polygon defining the shape of the Section Area Curve.

7.3 THE SECTIONS AND DIAGONALS

The shape of a hull can be modelled with a B-Spline surface. But when the control points of B-Spline surface are modified, an area local to the control point is also changed, this phenomenon is called the property of local modification. This effect is undesirable in a hull generation technique, as a shape controlled by one process can be modified by another unconnected local process, destroying the integrity and flow of the iteration procedure. For this hull generation method, transverse sections will be used instead of a full surface. Relying on transverse sections only, can result in the longitudinal curvature effects being ignored. To keep longitudinal curvature under control, diagonals are employed. The diagonals are primarily used to fit new sections into the hull.. The diagonals secondary function is to keep the longitudinal shape of the hull under control, so that heeled waterplanes remain fair.

Diagonals are curves, similar to waterlines, created by planar cuts though the hull, but diagonals are not generally horizontal or vertical cuts. Diagonals are, generally, used to judge the fairness of the hull. These lines become more important for a yacht hull, as a yacht heels when it is sailed. Diagonals can be used to represent the shape of the waterplane in heeled conditions. Diagonals are normally shown on lines plans, but there does seem to be any standard location for diagonals on a hull, it is up to the designer. For the best results, diagonals should be drawn so that intersection with the hull takes place, Normally. This can be difficult to ensure, as the angle between a plane through the hull and the hull surface will change along the length of the vessel. An iterative hull generation procedure would find it difficult to maintain diagonals normal to the surface of the hull, as the angle of the diagonals would have to change every time the hull was modified. In design, a naval architect will generally select angles for diagonals, which are either close to being normal with the hull at amidships or for ease of draughting, angles which are found on a set of triangles or set-squares.

In the current study, the angles chosen for the diagonals, are set so that the diagonals are close to being normal to the hull and also easily defined. Figure 7.11 shows the layout of the diagonals.

In more detail:

- Diagonal (1) has an angle of 45º and it intersects with the centreline of the waterplane. This seem to be the only diagonal which has a standard angle and intersection point throughout yacht design.

- Diagonal (3) is set, so that it intersects the hull centre plane at a point a quarter of the maximum waterline beam above the waterplane. It also intersects with the maximum waterline beam on the waterplane. This diagonal has a angle of 63.4º.

- Diagonal (2) is an intermediate between diagonals (1) and (3). It intersects the centre plane at an eighth of the waterline beam above the waterplane and it has an angle which is the average of the angle of diagonals (1) and (3), i.e. 54.2º.

- Diagonal (4) is used to stop a Cusp forming at the keel, allowing half sections to be generated instead of full sections. The angle of Diagonal (4) is set to 10º so that it has a greater weighting at sections found amidships and a much smaller weighting effect at sections found towards the ends of the hull.

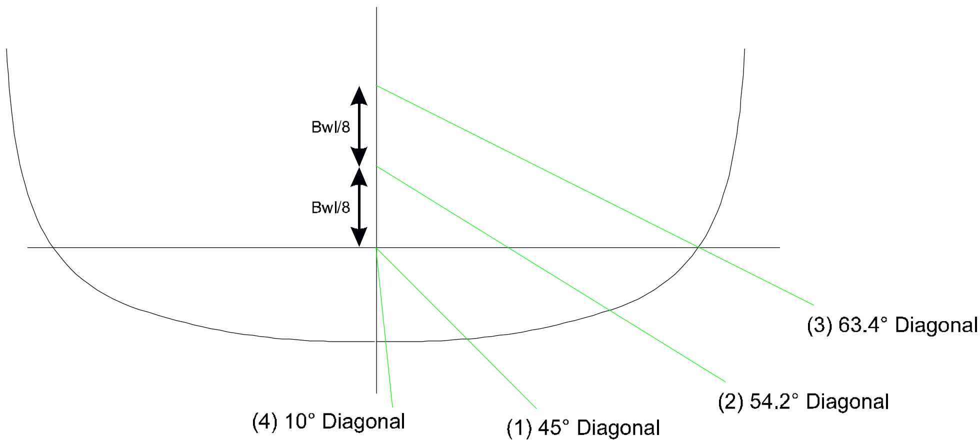


Figure 7.11, The layout of the diagonals.

Section shape is modelled with a cubic B-Spline curve. Data taken from points on the various curves of form, is used to specify the properties of a certain section. This data provides parameters to section generation procedure, for example, the draught dimension of a section. The end vertices of the B-Spline section control polygon can be placed easily, using the given parameters which describe section freeboard, section beam at the deck and section draught. Generally, B-Splines do not travel through known points, unless some procedure has been used to fit a curve or if there are discontinuities present. Therefore, the correct section area coefficient and waterline beam cannot be simply formed by placing vertices. It is necessary to use a iterative process to vary points on the section control polygon until the specified goals for section area and waterline beam are reached. Figure 7.12 shows the parameters that are passed to the process generating section shape.

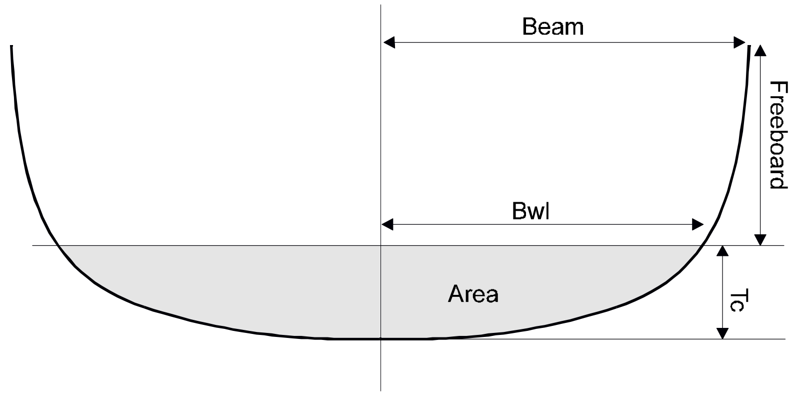


Figure 7.12, Parameters controlling section shape.

The position of the diagonals allow a simple mechanism to be developed, which controls the shape of sections. The vertices on a section control polygon can be modified more efficiently, when attached to diagonals. Sections can be then be modified by “sliding” vertices along the diagonals. Figure 7.13 shows the mechanism and control polygon that is used to control the shape of sections.

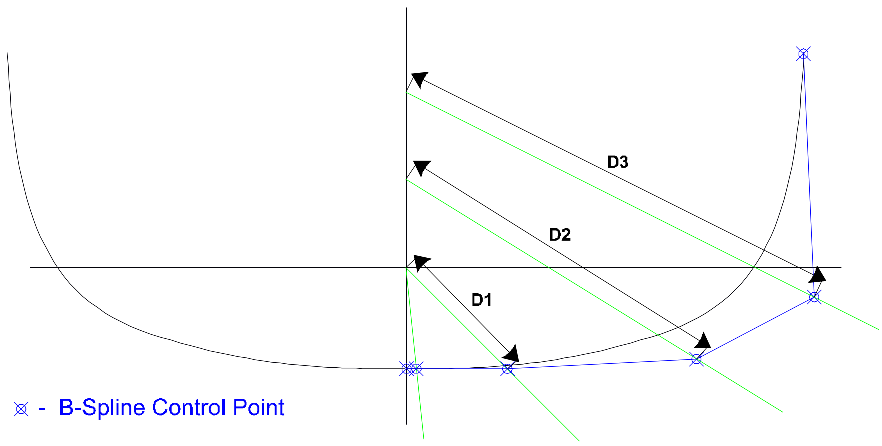


Figure 7.13, The mechanism controlling section shape.

Complications occur because there are only two parameters, section area and waterline beam, which are used specify the shape of the curve between the edge of the deck and the keel. It can be seen in Figure 7.13, that D3 can be used to control the waterline beam of a section. The position of the control vertex on diagonal (4) is controlled by the draught of the section. Leaving D1 and D2 to control the amount of section area and the overall shape of the section. However, by making assumptions about the shape of the section, based on the value of section area coefficient, a function can be designed to link D1 and D2 together. Assuming that a section area coefficient of 0.5 will create a approximately triangular shaped section and a section area coefficient of 1.0 will create a rectangular section etc., the angle of the control polygon segment, between diagonals (1) and (2) can be predicted. Using co-ordinate geometry, functions can be developed, to allow D1 to be found from D2 using the angle of the control polygon segment between D1 and D2, and vice versa.

Attaching the section control polygon to the diagonals makes the longitudinal fairing shape easier. By using diagonals fitted through the vertices of each section control polygon, the longitudinal shape of the hull is kept fair, processing is reduced, as the process does not have to consider the actual section shape, to develop the diagonals. Figure 7.14 shows how the diagonals are fitted through the section control polygons.

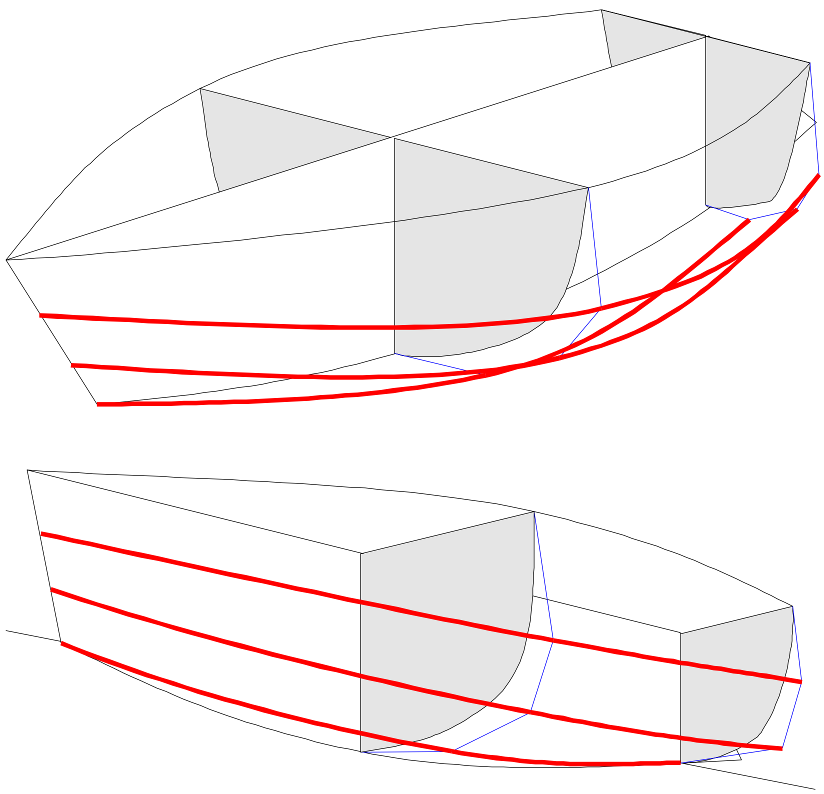


Figure 7.14, The initial arrangement of the diagonals.

During the process of generating the hull, it is not desirable to create each section from the basic parameters supplied by the curves of form only, as a “family” of sections will not be created. Three initial stations can be created, from basic parameters, to allow diagonals to be fitted to the section control polygons. When further sections are created, the initial shape of the control polygon can be obtained from the location of the diagonals at that length of the hull, Figure 7.15. The section now, has only to be modified by small amount, from the initial shape, to reach the goals specified in the section parameters.

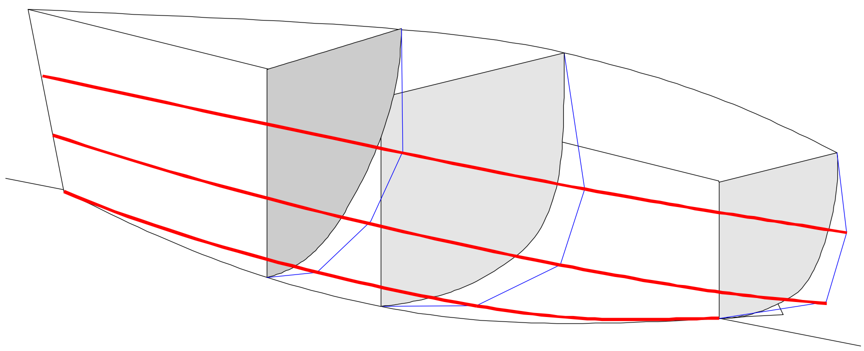


Figure 7.15, The insertion of a new section

7.4 Method 1

Now the basic form definition curves have been defined, the data has to be connected together to enable a hull to be generated.

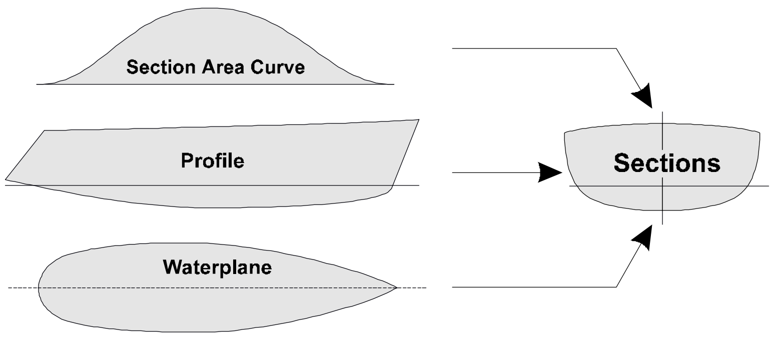


Figure 7.16, Method 1.

An interesting problem now arises. What is the correct shape for these form curves to take? This problem is not mentioned in any of the other methods looked at in the review. The waterline and profile shapes are fairly standard shapes. The profile is set by the values of the parameters. The waterline is set by the parameters and should be roughly symmetrical about the midsection. However, the section area curve is a shape which although easily defined, can be wrong. To acquire the correct shape, the vertices of the control polygon must be placed in the correct place. The difficulty is to find the correct shape that the section area curve should be.

In the method developed by Jorde [3], the Section Area curve is created by maintaining a fair Cross Section Area Coefficient (C_X) Curve. By taking this criterion and using it for the current method, the correct the shape of the Section Area curve can be obtained. The tangents at the bow and stern of this curve (See (d) of Section 8.2) can now be used to modify the section area curve to obtain the correct shape. By considering the difference, measured by $\Delta C_{X(BOW)}$ and $\Delta C_{X(STERN)}$ in Figure 7.17, between the true C_X curve formed from the Curves of Form at all stations and a C_X curve constructed from a B-Spline function fitted through the values of C_X at stations 1, 10, and 19, analysis can be made on how to change the bow and stern tangents of the section area curve so that two C_X curves can match up.

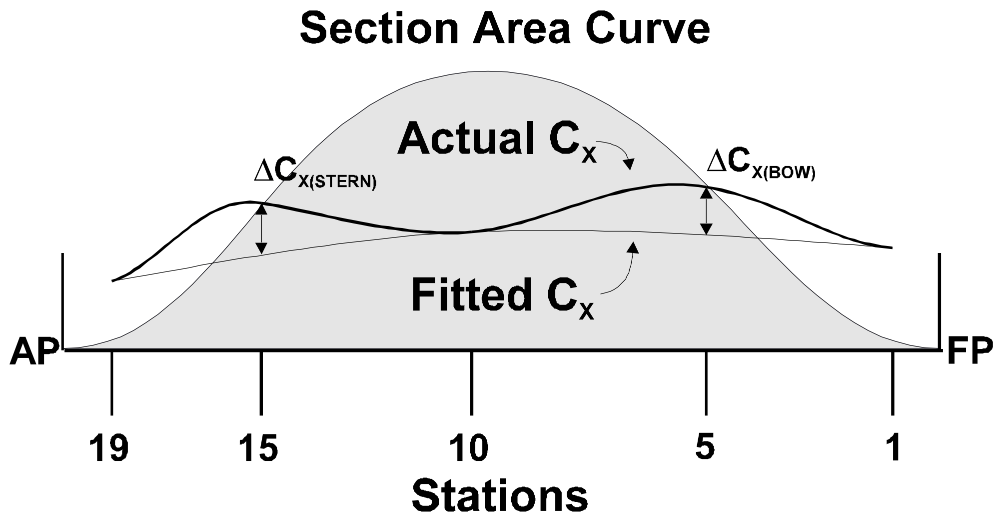


Figure 7.17, Actual and Fitted C_X curves.

A completely fair C_X curve cannot always be produced by this process, as the differences between the actual C_X curve and fitted C_X curve are only measured at stations 5 and 15. To analyse in more detail, the differences between these two curves would require more processing time. However, a more comprehensive analysis is unlikely to increase the fairness of the hull.

The next stage in the method is to create the stations. Twenty one stations are used because at the bow and stern more stations better define the shape and it is easier to work with stations of uniform spacing. The stations are numbered from 0 to 20 with Station 0 forming the Forward Perpendicular (FP). The stations are created from initial values taken from the diagonals. The first step is to set the initial shape of the diagonals. For this, at least three known points are required. The diagonals are fitted through point on the bow profile, points on the midship section (Station 10) and point on the aft perpendicular (Station 20). The diagonals at the bow are attached to the stem profile by setting the values of the diagonals to zero when they reach the stem. The midship section is created using the parameters C_M and B_{WL} and the method as detailed in 8.3. The aft perpendicular is created by analysing the conditions at this station. Diagonals (1) and (4) are zero as they lie on the waterline which has no beam at this point. The control vertex of diagonal (2) is set to lie on the waterline so that the curvature is maintained across the station centreline. The control vertex of diagonal (3) is set to lie directly below the deckline so that this segment of the control polygon is parallel to the section centreline. This creates a sectional shape which is fixed throughout all hulls.

An extra parameter could be used to modify the position of the control vertex on diagonal (3), but it is thought that the current arrangement of the control polygon at station shall not affect the overall results of the method.

There are now three known points for each diagonal. A quadratic B-Spline function can now be fitted through these points to give the other stations information about what shape to take. The result produced is shown in Figure 7.14. Stations 5 and 15 are modified from their basic shape defined by the diagonals. Then the diagonals are fitted to the three original points and new points found on station 5 and 15. A fourth order B-Spline function is now fitted though five points. Next stations 3, 7, 13 and 17 are modified after using the same process and 5 and 15. Now each diagonal is defined by nine points. A quadratic least squares fit is now made through these points to remove some of the effects of having fixed the shape of the curve. The body plan of the hull can now be created using, directly, the Curves of Form curves and the diagonals.

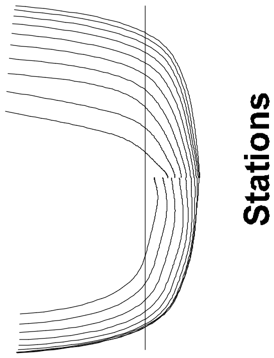
7.5 TESTING

The process detailed here was constructed into a program and the following five figures show the results of this process. It was necessary to choose a set of parameters which were close to a designed yacht. A matched set of parameters would allow a real hull to be analysed. Parameters chosen arbitrarily, cannot be relied upon to produce a real hull. A range of hulls must be created by the method, so the hulls produced must be analysed over a range of different parameter specification. Resistance is important and the Delft Series [5] supplies a method for calculating the value of these factors. The Delft Series is a set of functions based on a fit of data from test experiments. These functions use many of the parameters used for the current method as an input. The most important variables in these functions are block coefficient, C_P and longitudinal centre of buoyancy, LCB. These quantities seem to affect resistance the most, full analysis of these parameters with respect to resistance performance is given in Larson and Eliasson [6]. The resistance functions of the Delft Series are only valid for a certain range of C_P and LCB. This range corresponds to the region in which most popular sizes of hulls exist. The method will be tested at the limits of this range to see if hulls can be produced. Table 8.18 shows the valid range of the Delft Series with respect to C_P and LCB is:

Low	Parameter	High
0.52	C_P	0.6
50%	LCB (% of LWL from Bow)	55%

Table 8.18

7.6 METHOD 1 - RESULTS



Output From Hull Generation Method	
Method	N° 1.
Parameter Basis	YD-40 Hull
Parameters	
Loa	12.050 m
Lwl	10.020 m
Bmax	3.710 m
Bwl	3.170 m
Beam at Transom	2.000 m
Tc	0.570 m
Forward Overhang	0.900 m
Freeboard at Bow	1.500 m
Freeboard at Centre	1.350 m
Freeboard at Aft	1.300 m
Cp	**0.570** -
Cm	**0.752** -
Cwp	0.730 -
LCF	55.000 % of Lwl
LCB	**53.000** % of Lwl
Bow Profile - Deck Angle	0.000 °
Bow Profile - Deck Tangent	0.500 m
Bow Profile - Waterline Angle	0.000 °
Bow Profile - Upper WL Tangent	0.500 m
Bow Profile - Lower WL Tangent	0.200 m
Transom Angle	-30.000 °
Transom Fixed Point	0.200 m on WL

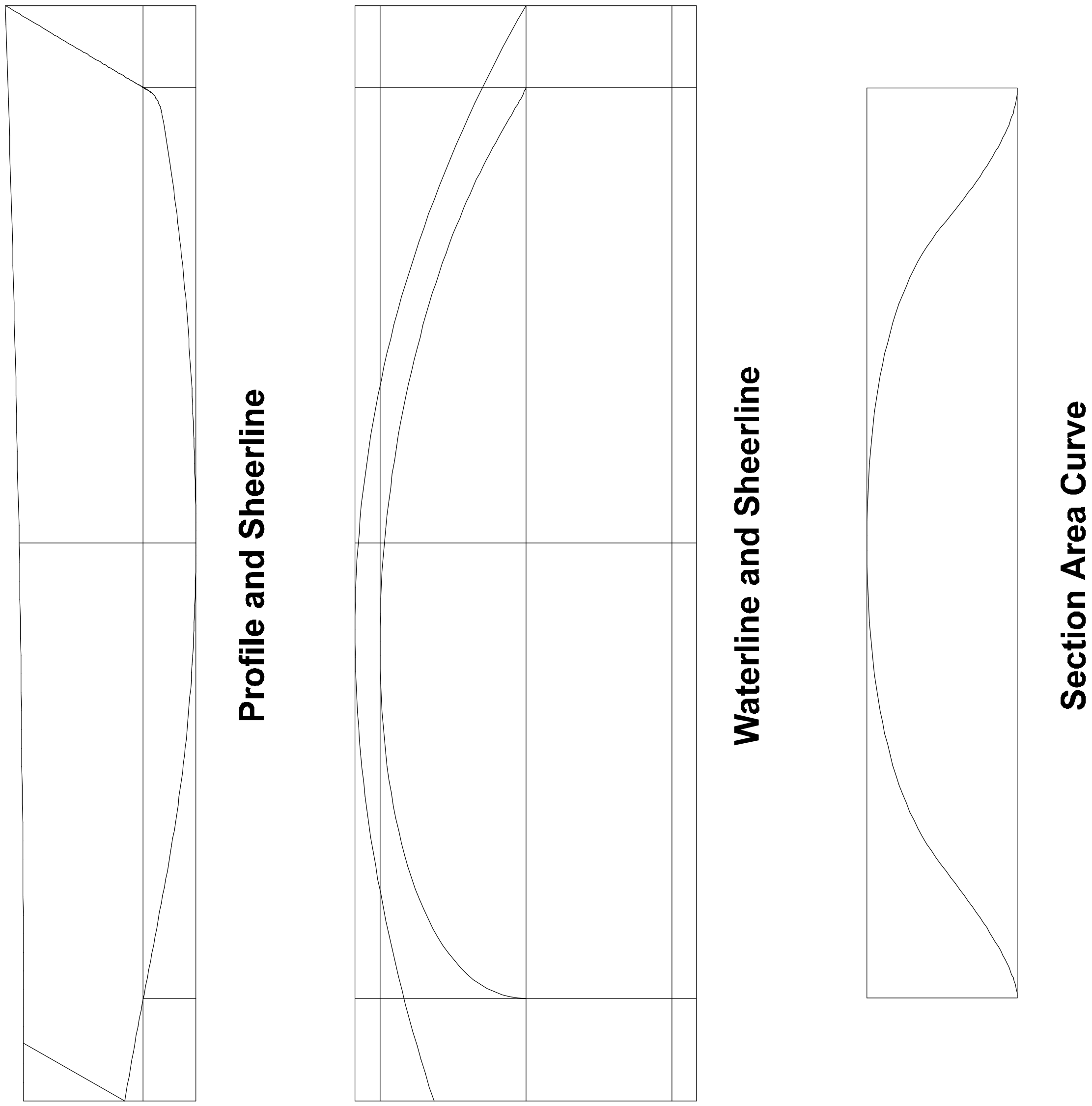
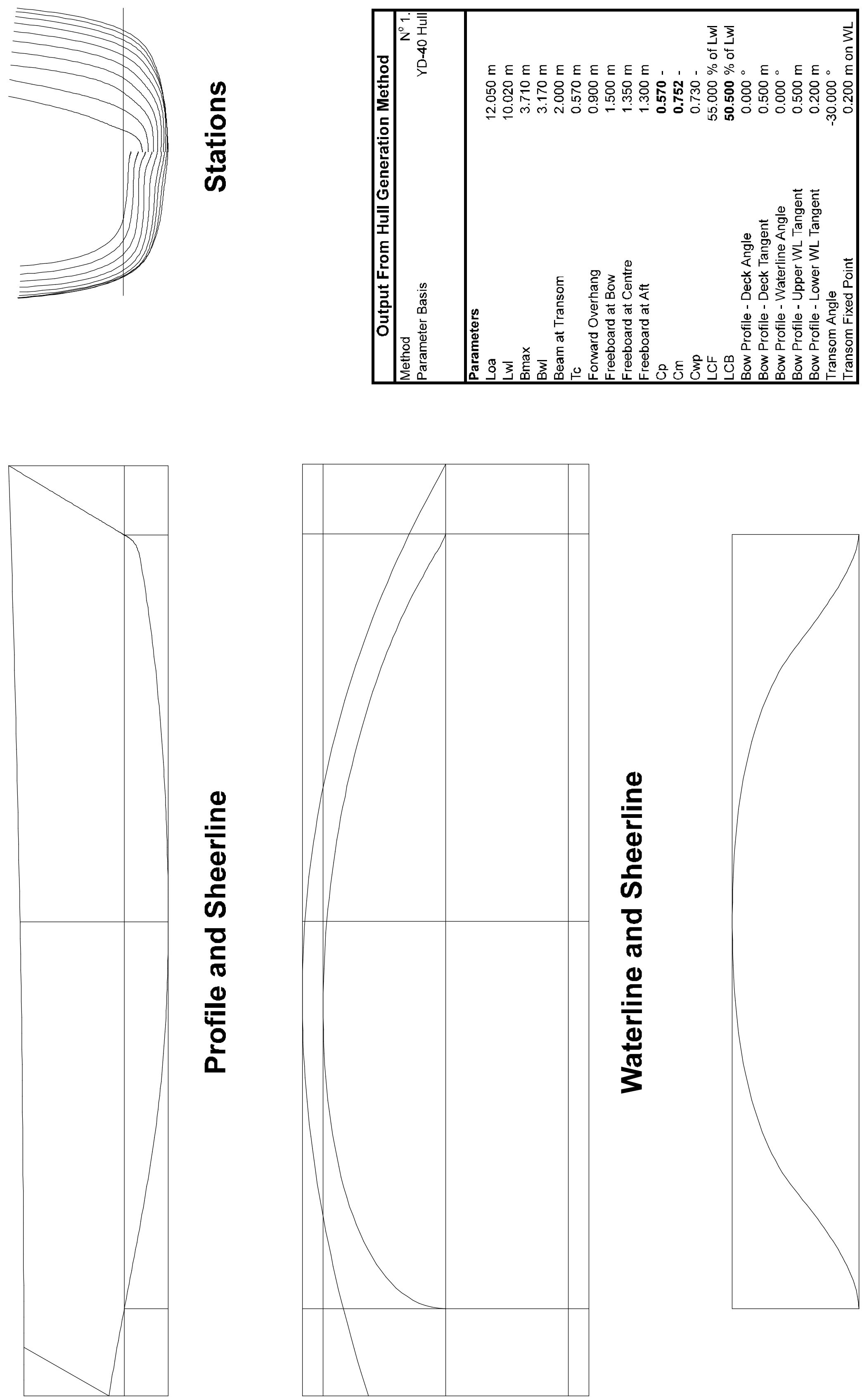
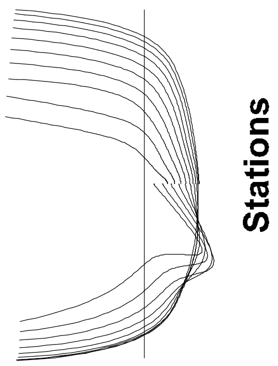


Figure 7.19, Method 1 - C_P = 0.57, LCB = 53%

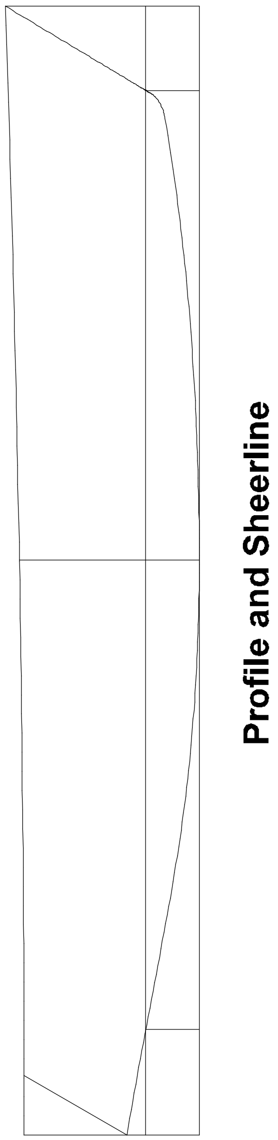


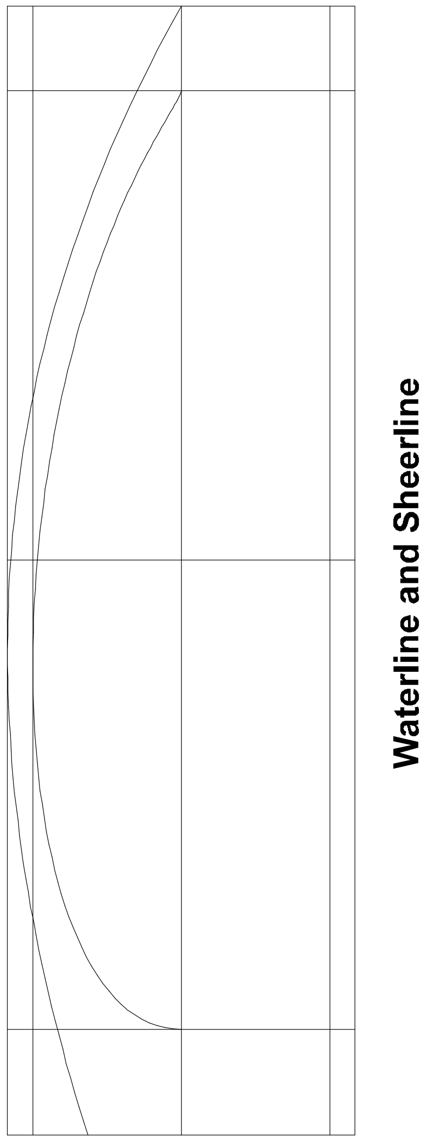
Output From Hull Generation Method		
Method		N° 1.
Parameter Basis		YD-40 Hull
Parameters		
Loa	12.050	m
Lwl	10.020	m
Bmax	3.710	m
Bwl	3.170	m
Beam at Transom	2.000	m
Tc	0.570	m
Forward Overhang	0.900	m
Freeboard at Bow	1.500	m
Freeboard at Centre	1.350	m
Freeboard at Aft	1.300	m
Cp	**0.570**	-
Cm	**0.752**	-
Cwp	0.730	-
LCF	55.000	% of Lwl
LCB	**50.500**	% of Lwl
Bow Profile - Deck Angle	0.000	°
Bow Profile - Deck Tangent	0.500	m
Bow Profile - Waterline Angle	0.000	°
Bow Profile - Upper WL Tangent	0.500	m
Bow Profile - Lower WL Tangent	0.200	m
Transom Angle	-30.000	°
Transom Fixed Point	0.200	m on WL

Figure 7.20, Method 1- $C_P = 0.57$, LCB = 50.5%



Output From Hull Generation Method	
Method	Nº 1.
Parameter Basis	YD-40 Hull
Parameters	
Loa	12.050 m
Lwl	10.020 m
Bmax	3.710 m
Bwl	3.170 m
Beam at Transom	2.000 m
Tc	0.570 m
Forward Overhang	0.900 m
Freeboard at Bow	1.500 m
Freeboard at Centre	1.350 m
Freeboard at Aft	1.300 m
Cp	**0.570** -
Cm	**0.752** -
Cwp	0.730 -
LCF	55.000 % of Lwl
LCB	**54.000** % of Lwl
Bow Profile - Deck Angle	0.000 °
Bow Profile - Deck Tangent	0.500 m
Bow Profile - Waterline Angle	0.000 °
Bow Profile - Upper WL Tangent	0.500 m
Bow Profile - Lower WL Tangent	0.200 m
Transom Angle	-30.000 °
Transom Fixed Point	0.200 m on WL





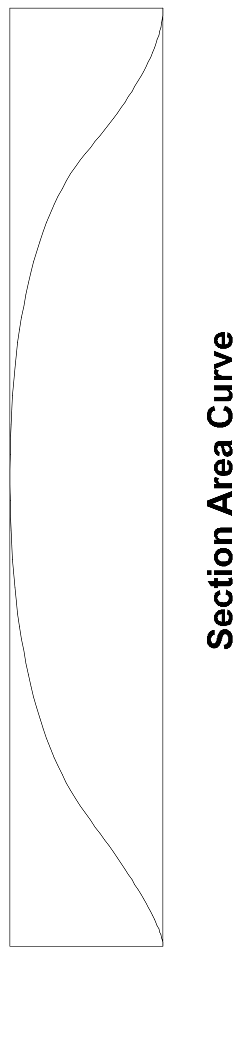
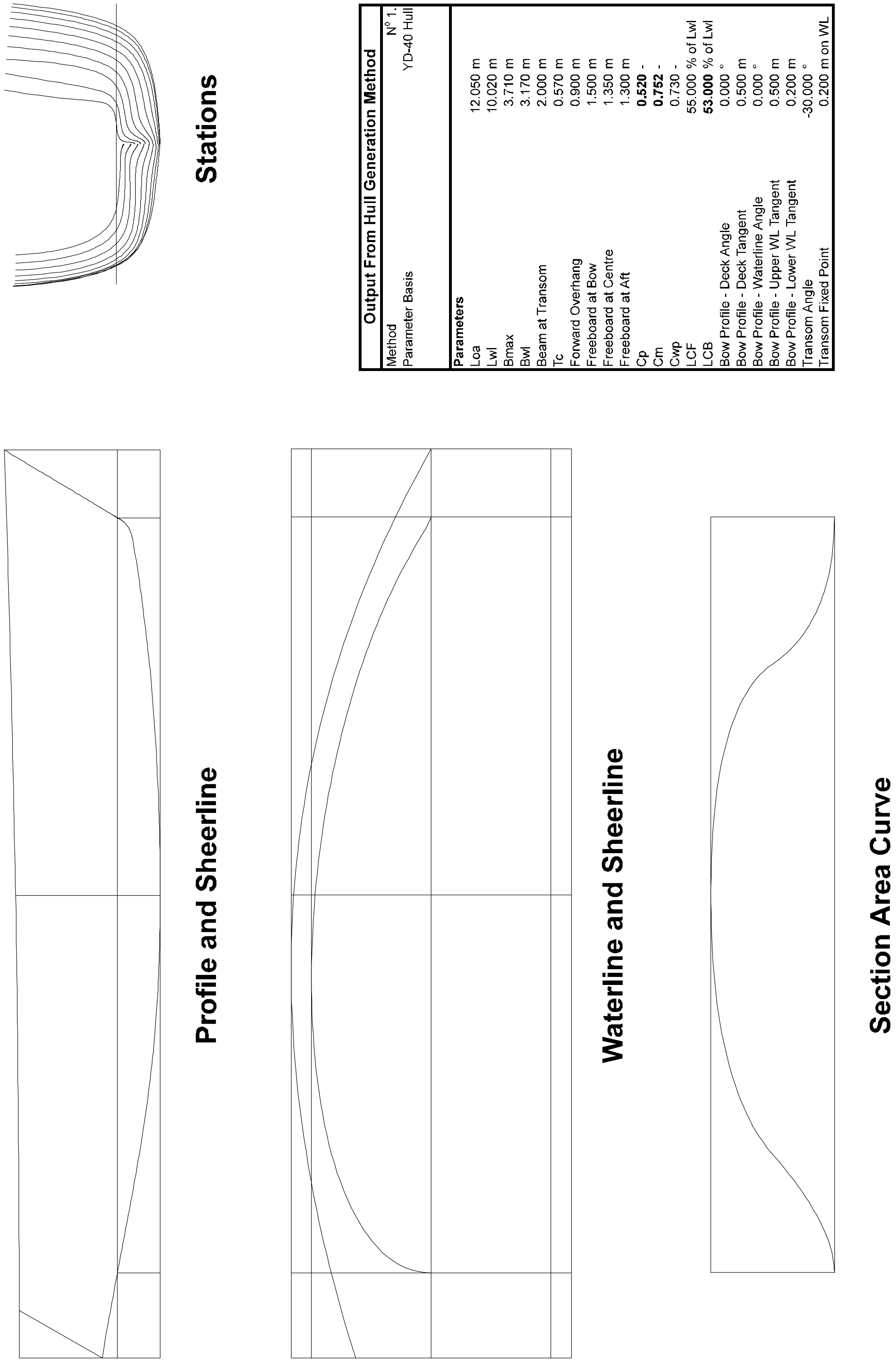


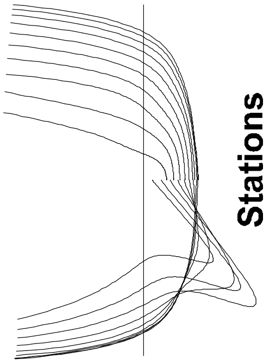
Figure 7.21, Method 1 - C_P = 0.57, LCB = 54%.



Output From Hull Generation Method

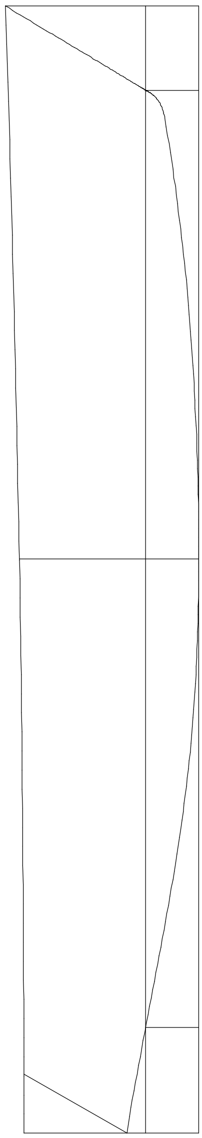
Method		Nº 1.
Parameter Basis		YD-40 Hull
Parameters		
Loa	12.050	m
Lwl	10.020	m
Bmax	3.710	m
Bwl	3.170	m
Beam at Transom	2.000	m
Tc	0.570	m
Forward Overhang	0.900	m
Freeboard at Bow	1.500	m
Freeboard at Centre	1.350	m
Freeboard at Aft	1.300	m
Cp	**0.520**	-
Cm	**0.752**	-
Cwp	0.730	-
LCF	55.000	% of Lwl
LCB	**53.000**	% of Lwl
Bow Profile - Deck Angle	0.000	°
Bow Profile - Deck Tangent	0.500	m
Bow Profile - Waterline Angle	0.000	°
Bow Profile - Upper WL Tangent	0.500	m
Bow Profile - Lower WL Tangent	0.200	m
Transom Angle	-30.000	°
Transom Fixed Point	0.200	m on WL

Figure 7.22, Method 1 - C_P = 0.52, LCB = 53%.

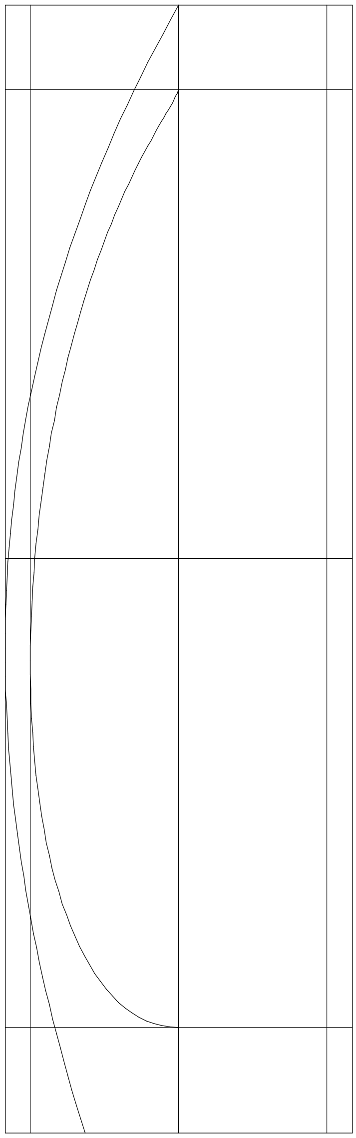


Stations

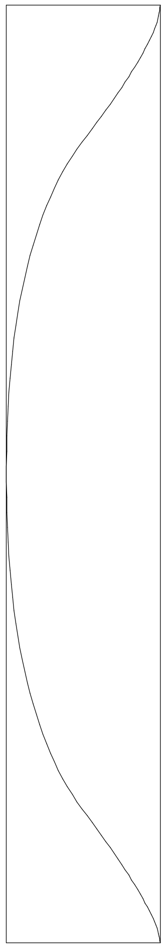
Output From Hull Generation Method	
Method	Nº 1.
Parameter Basis	YD-40 Hull
Parameters	
Loa	12.050 m
Lwl	10.020 m
Bmax	3.710 m
Bwl	3.170 m
Beam at Transom	2.000 m
Tc	0.570 m
Forward Overhang	0.900 m
Freeboard at Bow	1.500 m
Freeboard at Centre	1.350 m
Freeboard at Aft	1.300 m
Cp	**0.600** -
Cm	**0.752** -
Cwp	0.730 -
LCF	55.000 % of Lwl
LCB	**53.000** % of Lwl
Bow Profile - Deck Angle	0.000 °
Bow Profile - Deck Tangent	0.500 m
Bow Profile - Waterline Angle	0.000 °
Bow Profile - Upper WL Tangent	0.500 m
Bow Profile - Lower WL Tangent	0.200 m
Transom Angle	-30.000 °
Transom Fixed Point	0.200 m on WL



Profile and Sheerline



Waterline and Sheerline



Section Area Curve

Figure 7.23, Method 1 - $C_P = 0.60$, LCB = 0.53%.

7.7 DISCUSSION OF RESULTS

The first method has many problems. It is able to produce a hull, however, the hulls produced can not be used as yacht hulls. The most noticeable feature in these results is the shape of the stations produced. The stations produced follow a "family" of curves, this shows that the method for producing stations with assistance from the diagonals works. However, the section shape produced is wrong, the curvature in the lower bilge area of the sections present some interesting results. The reason why stations are produced with this shape is through the use of the section area curve.

The process developing the Section Area curve has no feedback from the stations about the shape responds to area assigned area. The procedure that develops the section area curve is a blind process, all does is produce a B-spline curve which has represents the correct volume and LCB. The result is that sections are often assigned areas which result in section areas coefficients greater than 1.0. This phenomenon is illustrated in Figures 7.23 and 7.21. The opposite situation can presented in Figure 7.22. Low values of section area have been supplied to sections and the waterline beam goals have also be met. The method produces sections at the bow with very large hollows.

The unsuitability of the section area curve is exhibited in all of the five examples produced by this method. Figure 7.22 gives good example of this failing. The section area curve produced, at the bow of the yacht has a very steep gradient. The section area curve procedure can produce more extreme examples of this effect, however, final process constructing the sections is unable to finish the task due to the extreme section shapes involved.

The procedure developed to produce the section area may not create a curve in many cases. In this situation the program with either produce an mathematical error or the procedure will produce an infinite loop. These situations cannot be predicted or be recovered from. The iteration process analysing the shape of the C_X curve is the only process that adjusts the segments of the control polygon defining the section area curve. As the iteration process has no knowledge of the limits for the length of these segments, it can specify unsuitable values. The result is that the section area curve can sometimes have end segments of negative length resulting in a curve longer than the waterline or the section area curve can acquire “loops” if the end segments are too long.

Modifying the shape of every section may not be the best way of producing a hull. The stations produced, as a result of evaluation at every possible point, have a very fixed shape. The arrangement developed so that the diagonals are able to modify section shape is not efficient at producing sections that are position well away from amidships. At the bow, the waterline beam becomes much less that maximum waterline beam, the result of this is that diagonal (3), which is used to change the waterline beam, is in the wrong position. At amidships diagonal (3) is close to the waterline, however, at the bow the height of this diagonal above the waterline is about half the freeboard. The vertex on diagonal(3) is too far away from the waterline to adjust the waterline beam of a section correctly. Fairer hull may be produced if less sections were used during generation process. The remaining sections could be produced from the diagonals at the end of the process.

It can be seen from Figure 7.22 that the functions adjusting section shape, based on these parameters only, do not have enough information to produce suitable sections. It is necessary to consider the effects of curvature to stop unsuitable hull being produced.

The shortcomings of this method were analysed to produce method 2.

8 METHOD 2

8.1 INTRODUCTION

It was necessary to analyse the shortcomings of Method 1 to rectify the process which caused the problems outlined at the end of the last chapter.

The section area curve appears to have a simple shape, however, the exact curve is required. In method 1, the magnitude of the section area curve cannot be limited to stop the area of a certain section becoming too large. To solve this problem it was necessary to find a new way to produce the section area curve. Various methods for producing a section area curve were examined, such as direct mathematical approaches, however, these refused to produce the required results. The study, therefore, had to take a step back and examine the method of generation the section area coefficient curve.

8.1 The Process

Considering method 1, it can be seen that the primary goal was to fair the curve of section area coefficients, the C_X curve, by modifying the section area curve. If the C_X curve could be specified, correctly, by some procedure, then the condition where large section areas were produced would not occur. To do this, a close examination of the C_X curve is necessary, to identify key characteristics.

It is known that at the midship section, the C_X curve goes through a point defined by the midship section coefficient C_M. Unfortunately, the ends of the C_X curve become undefined, as beam and draught at these sections are zero. By making assumptions, it is possible to assign a dummy a value for C_X at these points.

The underwater sections near the bow of a modern yacht can generally be said to be "V" shaped, with two relatively flat sides, converge to a point at the lowest point. Moving towards the bow end, the sides of these sections become flatter, resulting in more triangular sections. The C_X of these section should be close to 0.5.

Figure 8.1, Triangular sections at the bow.

At the stern, the sections are generally referred to as being "U" shaped. The shape of the section at the bottom is flat and almost horizontal. Moving towards the aft end of the yacht hull, the bilge shape of sections becomes flatter. The underwater shape of the sections close to the Aft perpendicular will be approximately triangular. The value for C_X found at these sections will again be close to 0.5.

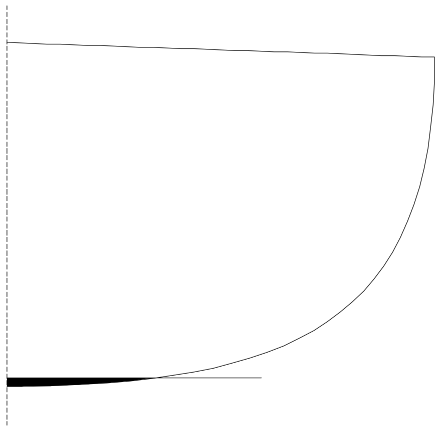


Figure 8.2, Approximately triangular sections at the stern.

Next, points are required to vary the shape of the C_X curve, for example, points placed on the curve at stations 5 and 15 meet this modification well. These points are move to the correct values for Volume and LCB to be obtained.

Using this procedure, however, it is still possible to for the C_X curve to produce section area coefficients of greater than 1. To stop this occurring the value of midship section coefficient (C_M) was selected to be the maximum magnitude the C_X curve. To limit the C_X curve to C_M or less, it is necessary to have one of the other form curves as a variable. The profile was selected to be the variable curve, as it is not as important as the waterline from the resistance point of view. More specifically, points at stations 5 and 15 on the profile curve allowed the rocker shape of the hull to be varied.

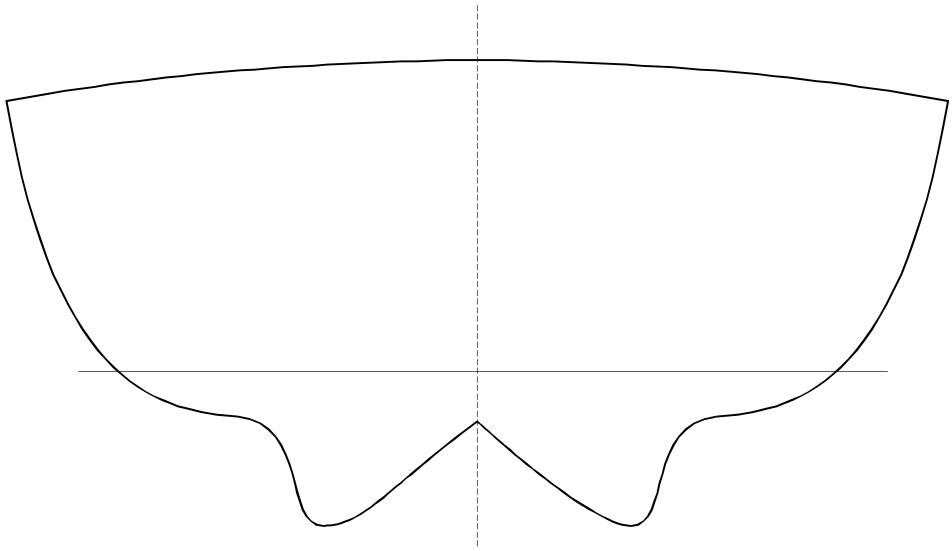


Figure 8.3, Method 1 could produce sections where the lowest point did not coincide with the centreline.

Another consideration examined by method 2, is the shape of the sections. In method 1, it was possible for the lowest point of a section to not coincide with the centreline, Figure 8.3. By analysing the curvature of the sections, this feature can be detected, so that the method can make a correction to the C_X curve.

Various techniques for analysing the section shape were investigated. Initial, it was thought that an effective technique would be produced by inspecting the second derivative of the B-spline function, however, this did not always produce the required result and increased the time required, to generate a hull, significantly.

A more direct approach to the problem was necessary. By inspecting the layout of the section control polygon, a technique could be developed to allow the shape of section to controlled further.

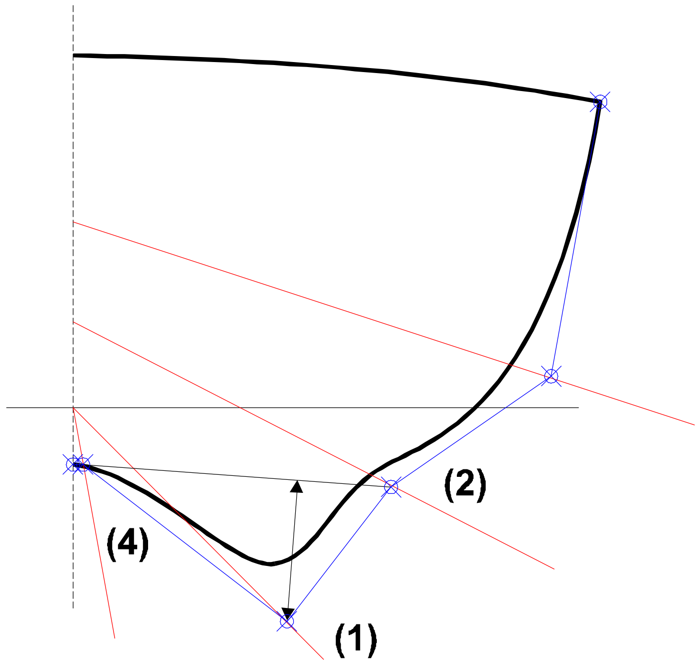


Figure 8.4, The distance used to detect unsuitable sections.

The height of the triangle formed by control vertices on diagonals (1), (2) and (4), Figure 8.4, could be used, as measure of the current bilge shape of a section. By inspecting this value at stations 5 and 15, the process can adjust the shape of the C_X curve to reduce any unwanted effects.

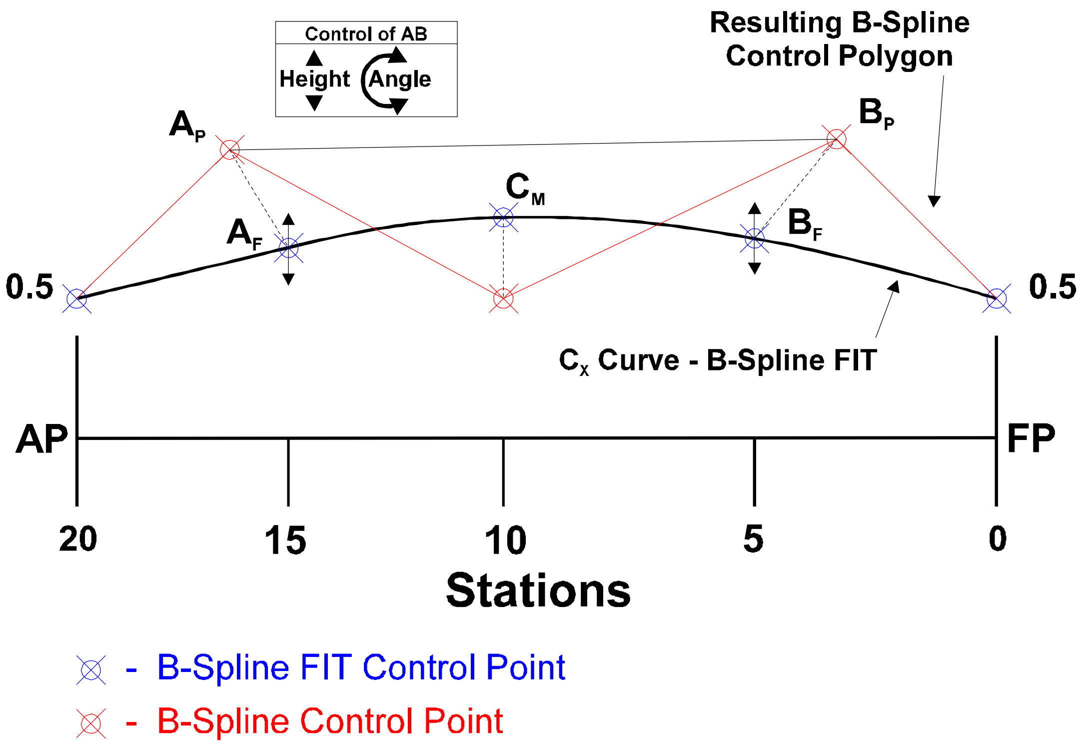


Figure 8.5, The mechanism used to generate the C_X curve.

To implement the analysis of the C_X curve, it was necessary to use some process. Figure 8.5 shows the control polygon used to define the C_X curve. Points A_F and B_F are used to change the volume and LCB of the hull. The iteration process can position these points anywhere, with the possibility that the curve produced may have values of C_X which are higher than one. The analysis procedure changes the shape of the profile curve so that line A_PB_P has an average height of C_M. The result of this is that the line A_PB_P will generally go through the point C_M.

As can be seen from Method 1, aft sections that have a high amount of curvature, producing bulbous effects, Figure 7.23, generally produce bow sections with low amounts of curvature. By modifying the profile shape, the aft sections of the profile have an increased draught and bow section have a reduced draught, the curvature of the sections will be changed.

The procedure analysing curvature detects the effects of this process as a change in the gradient of line A_PB_P. A target angle for line A_PB_P is set by the curvature analysis procedure. When the angle of A_PB_P reaches the Target Angle, the curvature of stations 5 and 15 is analysed again to see if it is suitable. It the curvature is not suitable then the target angle is adjusted by interpolation.

A flow chart for Method 2 is shown in Figure 8.6

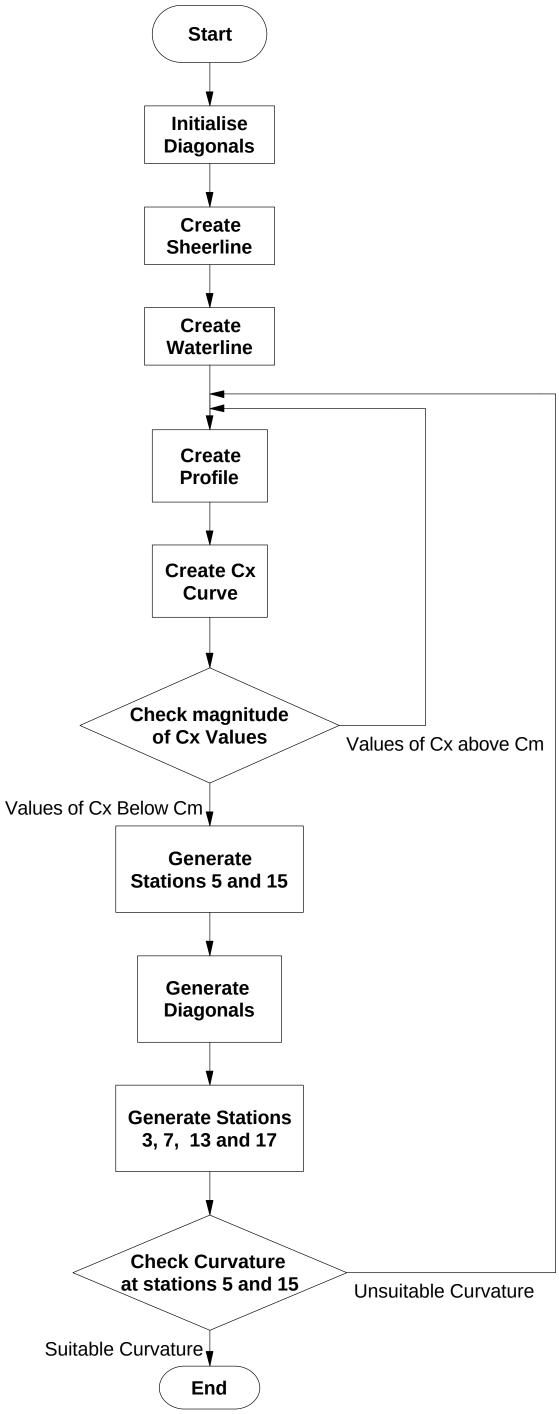
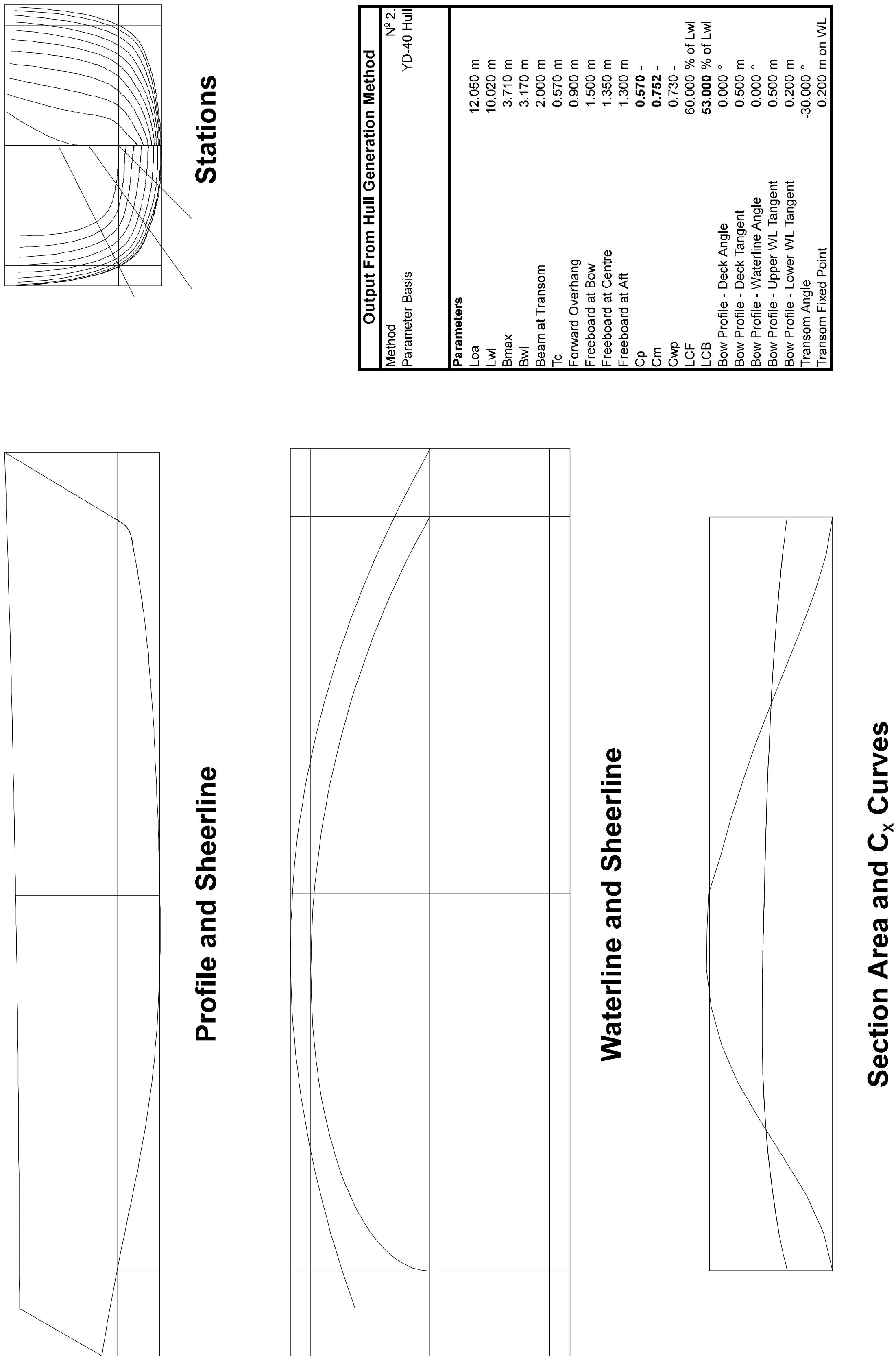


Figure 8.6, A flow chart of method 2.

8.3 RESULTS



Output From Hull Generation Method		
Method		Nº 2.
Parameter Basis		YD-40 Hull
Parameters		
Loa	12.050	m
Lwl	10.020	m
Bmax	3.710	m
Bwl	3.170	m
Beam at Transom	2.000	m
Tc	0.570	m
Forward Overhang	0.900	m
Freeboard at Bow	1.500	m
Freeboard at Centre	1.350	m
Freeboard at Aft	1.300	m
Cp	**0.570**	-
Cm	**0.752**	-
Cwp	0.730	-
LCF	60.000	% of Lwl
LCB	**53.000**	% of Lwl
Bow Profile - Deck Angle	0.000	°
Bow Profile - Deck Tangent	0.500	m
Bow Profile - Waterline Angle	0.000	°
Bow Profile - Upper WL Tangent	0.500	m
Bow Profile - Lower WL Tangent	0.200	m
Transom Angle	-30.000	°
Transom Fixed Point	0.200	m on WL

Figure 8.7, Method 2 - C_P = 0.57, LCB = 53%.

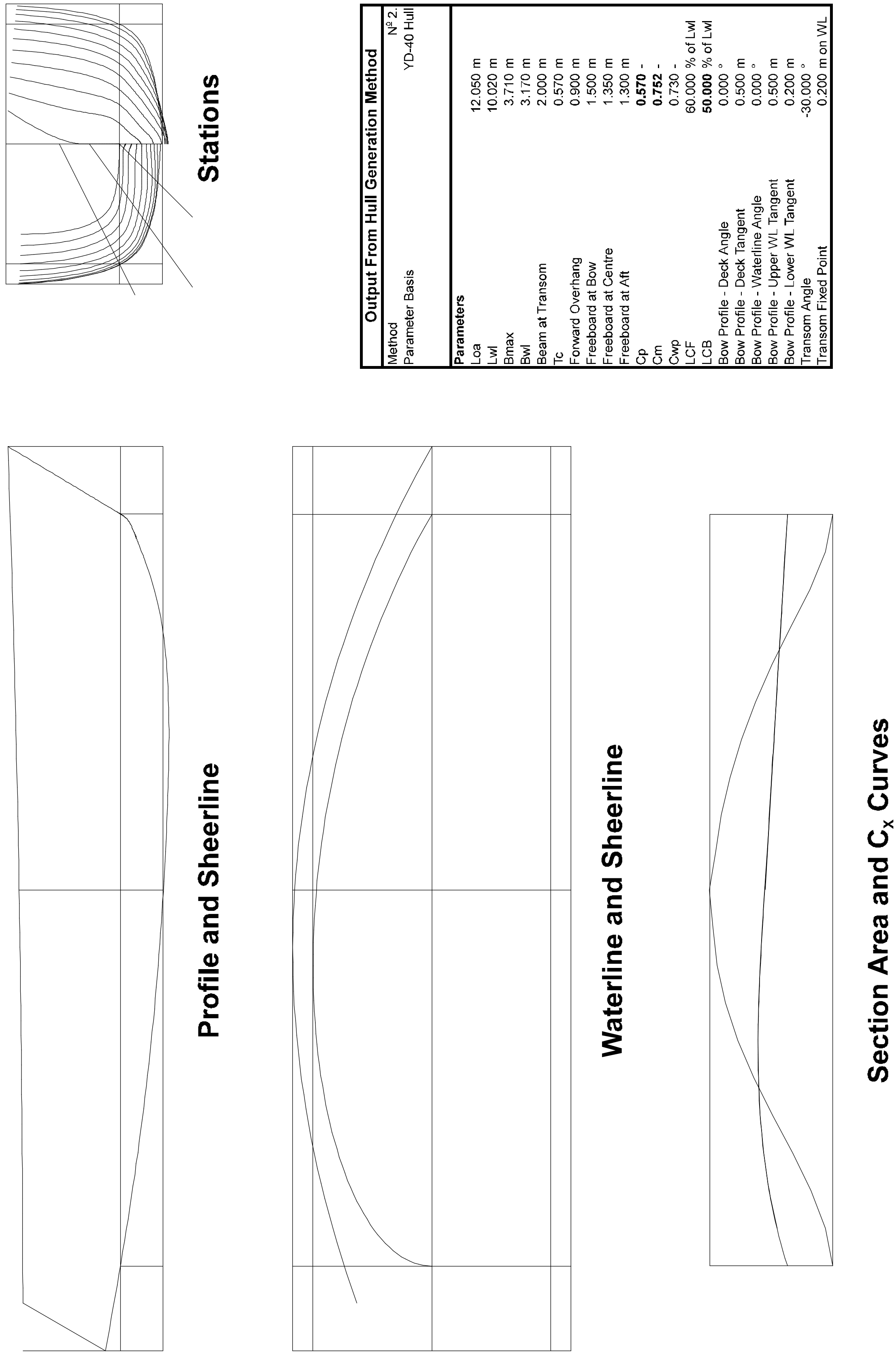
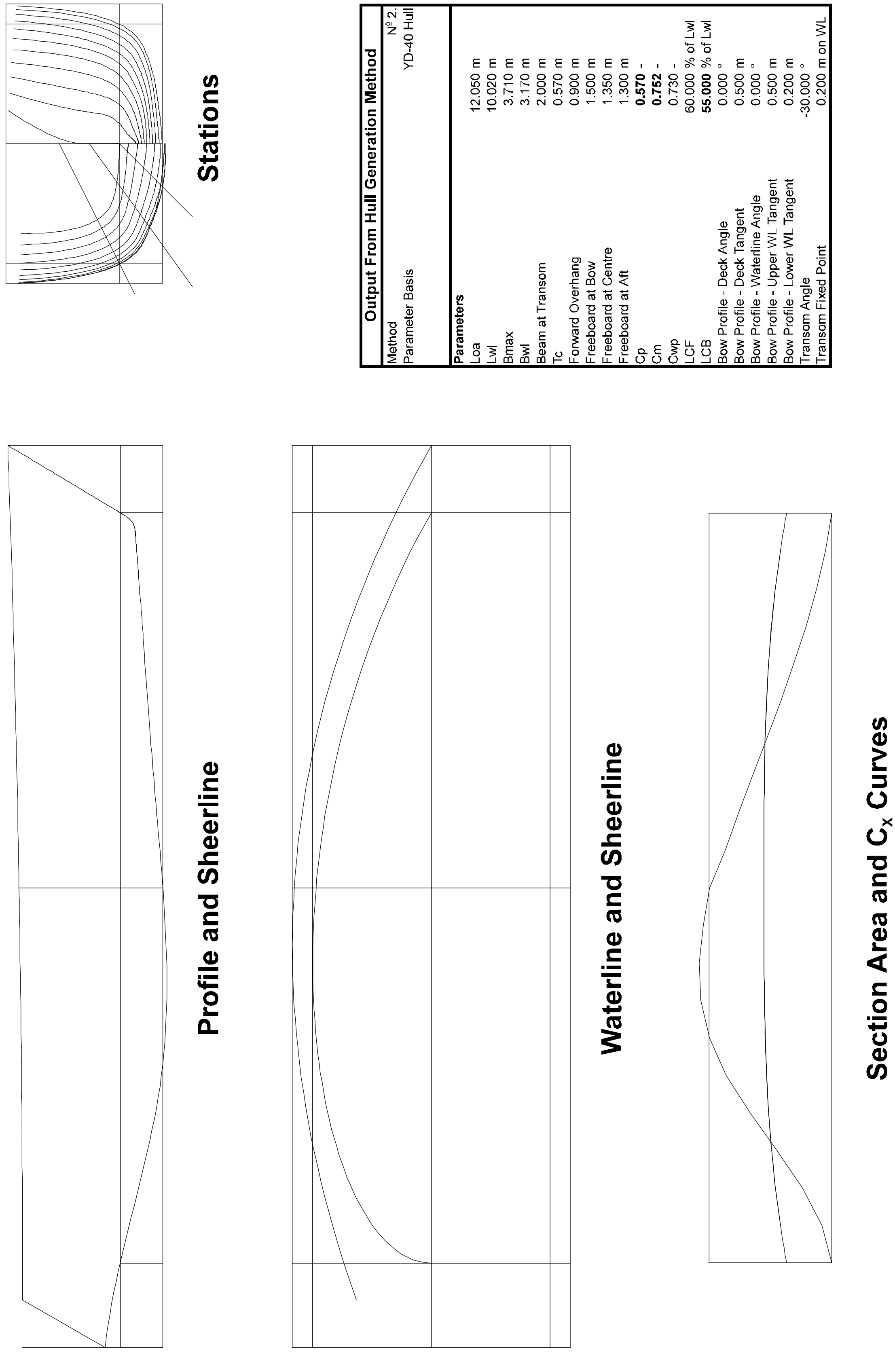
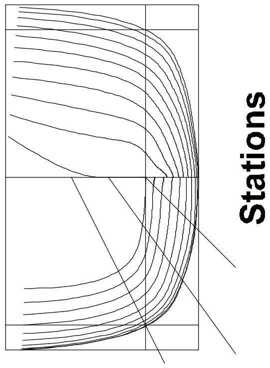


Figure 8.8, Method 2 - CP = 0.57, LCB = 50%



Output From Hull Generation Method		
Method	Nº 2.	
Parameter Basis	YD-40 Hull	
Parameters		
Loa	12.050	m
Lwl	10.020	m
Bmax	3.710	m
Bwl	3.170	m
Beam at Transom	2.000	m
Tc	0.570	m
Forward Overhang	0.900	m
Freeboard at Bow	1.500	m
Freeboard at Centre	1.350	m
Freeboard at Aft	1.300	m
Cp	**0.570**	-
Cm	**0.752**	-
Cwp	0.730	-
LCF	60.000	% of Lwl
LCB	**55.000**	% of Lwl
Bow Profile - Deck Angle	0.000	°
Bow Profile - Deck Tangent	0.500	m
Bow Profile - Waterline Angle	0.000	°
Bow Profile - Upper WL Tangent	0.500	m
Bow Profile - Lower WL Tangent	0.200	m
Transom Angle	-30.000	°
Transom Fixed Point	0.200	m on WL

Figure 8.9, Method 2 - C_P = 0.57, LCB = 55%.



Output From Hull Generation Method		
Method	Nº 2.	
Parameter Basis	YD-40 Hull	
Parameters		
Loa	12.050	m
Lwl	10.020	m
Bmax	3.710	m
Bwl	3.170	m
Beam at Transom	2.000	m
Tc	0.570	m
Forward Overhang	0.900	m
Freeboard at Bow	1.500	m
Freeboard at Centre	1.350	m
Freeboard at Aft	1.300	m
Cp	**0.560**	-
Cm	**0.752**	-
Cwp	0.730	-
LCF	60.000	% of Lwl
LCB	**53.000**	% of Lwl
Bow Profile - Deck Angle	0.000	°
Bow Profile - Deck Tangent	0.500	m
Bow Profile - Waterline Angle	0.000	°
Bow Profile - Upper WL Tangent	0.500	m
Bow Profile - Lower WL Tangent	0.200	m
Transom Angle	-30.000	°
Transom Fixed Point	0.200	m on WL

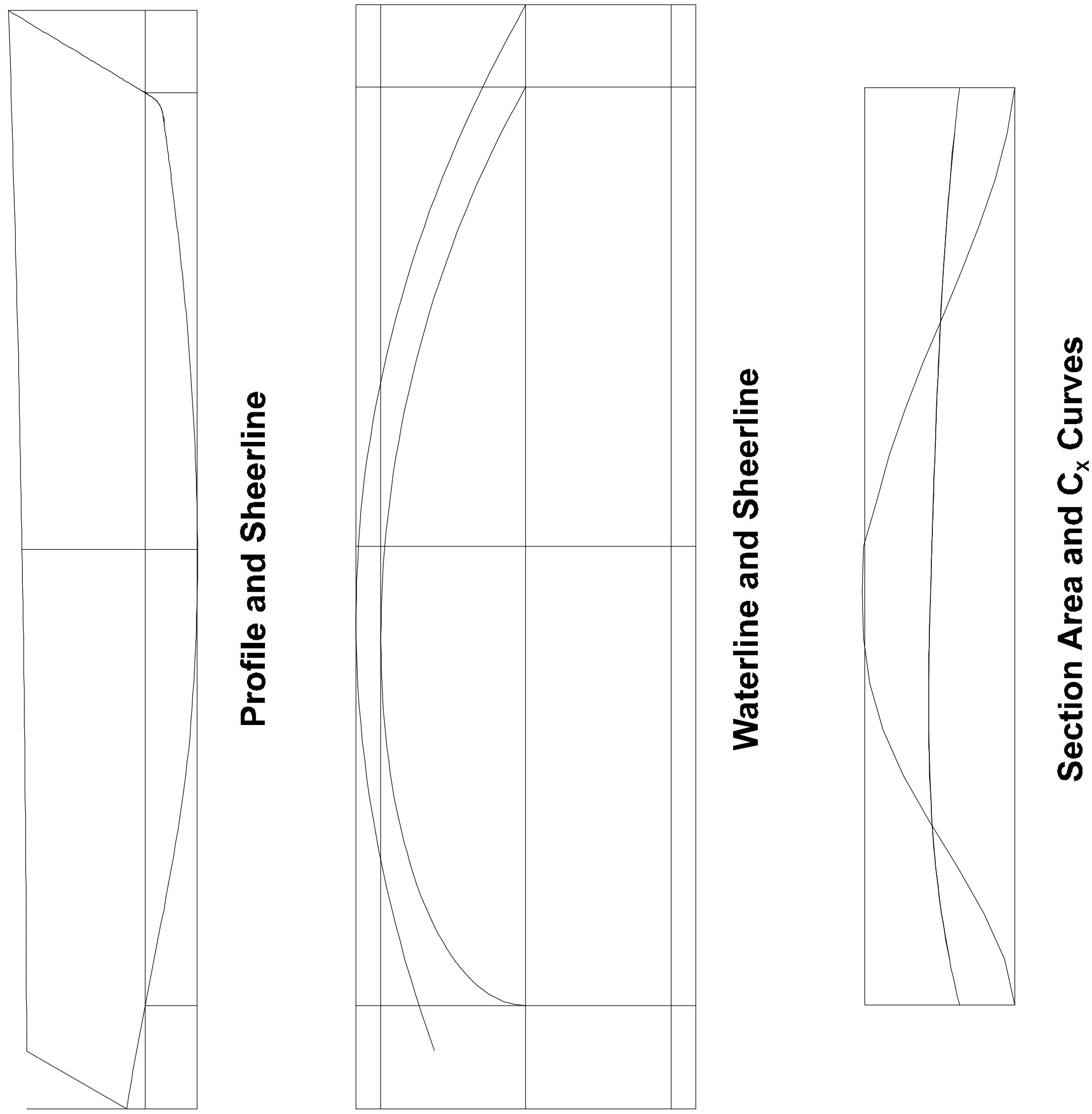


Figure 8.10, Method 2 - C_P = 0.54, LCB = 53%.

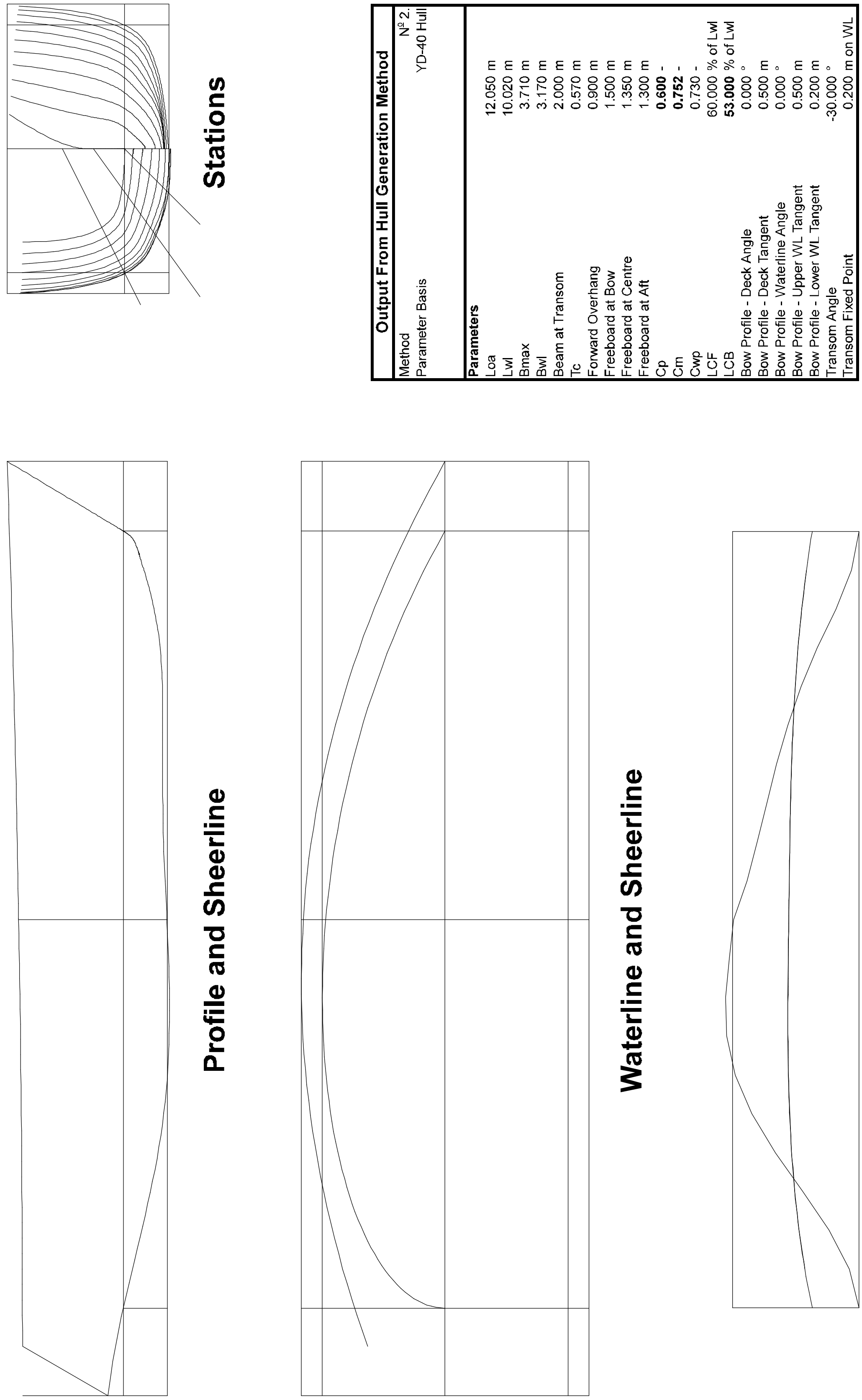


Figure 8.11, Method 2 - C_P = 0.60, LCB = 53%.

8.4 DISCUSSION OF RESULTS

Method 2 produces section with better shape that method 1. An interesting factor to note is that since the method now analyses the shape of certain stations, the shape of the stations almost stays the same throughout the range of values investigated.

The side effect of this methods ability to evaluate section shape, is that the Rocker profile is modified to correct section shape. In cases where unreasonable sets of parameters have been specified, the maximum draught of the hull is ignored, producing a profile shape which is unsuitable for a yacht, illustrated in Figures 8.8 and 8.10. In these figures the LCB was specified at the limits values for the Delft series, 50% and 55% of L_{WL}. The method is increased the draught of the profile to allow this parametric goal to be met.

The method finds difficulty in obtaining hulls with prismatic coefficients of below 0.56, for the YD-40 basis hull. If the specified prismatic coefficient is less than 0.56 the method goes into an infinite loop and fails to produce any hull.

Further analysis of the sections produced by this method shows that, at the bow, the waterline beam is larger than what should be expected on a yacht hull. The waterline curve suffers from similar problems as the section area curve, i.e. it is difficult to obtain the correct shape. Different ways of producing a better waterline curves were considered. Unfortunately, none of the techniques tested produced a waterline shape that was more suitable than the one currently being used.

The amount of time taken to produce a hull greatly increased, due to the increased number of iterative procedures. The time required to produce a hull is on average around ten to fifteen minutes. This may be much longer than a professional designer would take to produce a fair hull in a modern computer package.

A more appropriate technique for changing the shape of the C_X curve was, later, brought to the attention of the author. By using a quadratic B-spline function to define C_X, An iterative procedure would not be required to place the C_X through C_M, as the point C_M would always lie on A_PB_P. The use of this technique would have greatly reduced the amount of time that was required to run the process.

9 METHOD 3

9.1 INTRODUCTION

The increased complexity and the analysis of curvature in method 2, did not produce hulls with a suitable enough range of parameters. These methods were developed in a similar way to the approach taken by Jorde [3]. The approach take by Jorde to produce a hull generation technique does not work well with B-Spline functions or yacht hulls. B-Spline functions generate unsuitable shapes as more shape constraints and/or goals are applied.

The system of connected sections and diagonals, developed for the current hull generation procedure, could restrict the ability of method 1 and 2 to produce a hull. The connected sections and diagonals form a structure which is similar to a surface. Therefore, section area and waterline curve are already produced, by the surface. Previous methods may have failed, because the section area and waterline curves produced by the surface, cannot take the same shape as produced by the curves of form. By modifying the surface, defined by the diagonals and sections, the section area and waterline curves would always produce the correct shape.

9. 2 THE PROCESS

Method 3 was developed to use the surface defined by the sections and diagonals. However, the curves of form are still required. The profile and sheerline are necessary to define the edges of surface. It is also, still necessary to use a generated waterline curve, although only in the initial stages of the method. This allows the waterline beam at amidships, Station 10, to be found, as this is rarely the maximum waterline beam.

To create the initial shape of the diagonals, the Bow Profile, Station 10 and the aft perpendicular are used, allowing all sections along the hull to be generated. The section area coefficient (C_X) for each section can be calculated to allow the volume and longitudinal centre of buoyancy to be found.

An iterative process now begins. This adjusts the section area coefficient for stations 5 and 15, until the goals specified for volume and longitudinal centre of buoyancy. All the sections in the hull are linked to stations 5 and 15, through the diagonal. Every time stations 5 and 15 are modified, the diagonals and all the sections have to be reproduced to allow the volume and longitudinal centre of buoyancy to be calculated.

The goals affecting the shape of the waterline are only used to create the initial shape of this curve. This reduced the complexity of the method, to allow a hull to be produced with a reasonably suitable shape. The complete process is outlined in Figure 9.1.

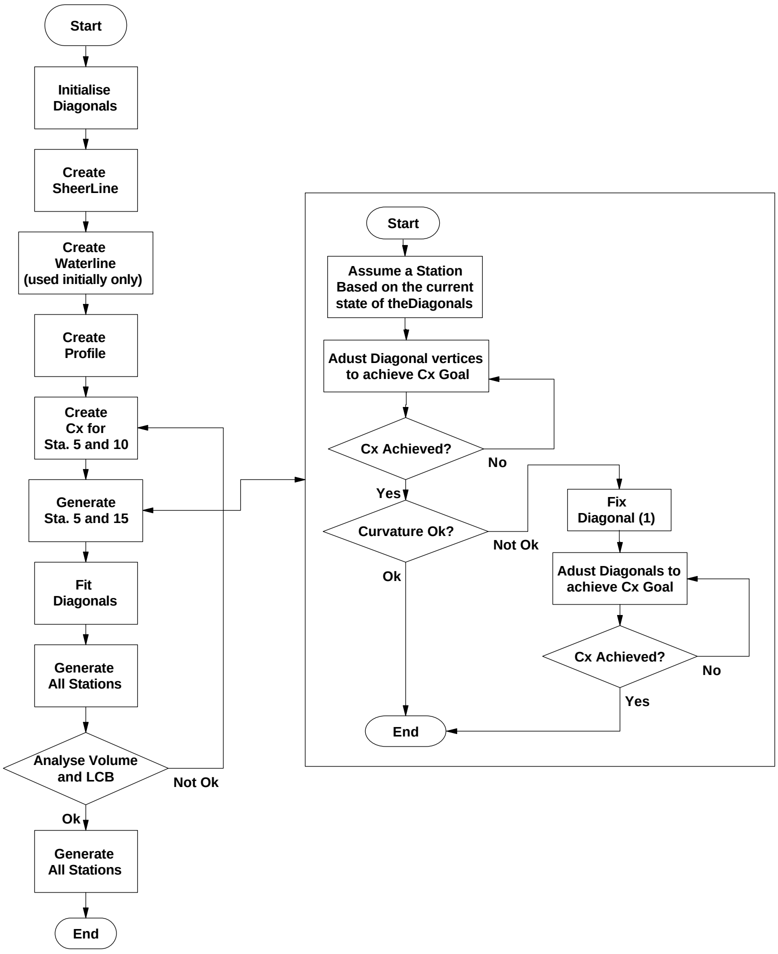


Figure 9.1, The flow of Method 3.

As method in previous methods, the shape of the sections is important. In Method 2 the shape of stations was analysed, in the last process, i.e. after all the other goals were satisfied. This may have been one of the factors that increased the amount of time that was required to produce a hull. In the new development of the method, the analysis of the section shape take place as they are created. Analysing the shape at this level allows the global iteration process concerning the hull to be unaffected by the process looking at individual sections.

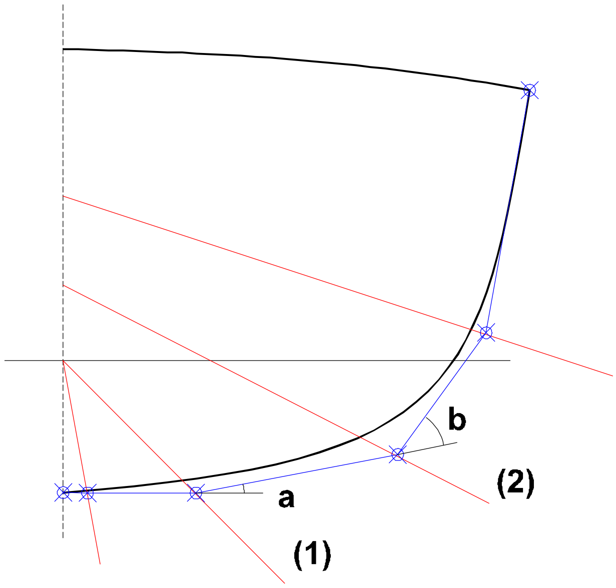
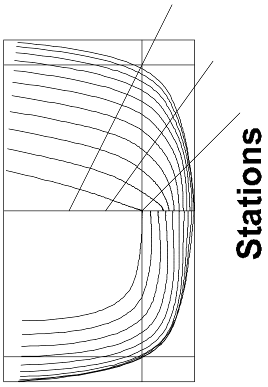


Figure 9.2, The angles used to detect the shape of the section.

The process used to generate sections, analyses the shape of a section by inspecting the control polygon at angles a and b, shown in Figure 9.2. An iterative process changes the angle of the segment between diagonals (1) and (2) until the difference between a and b is within a defined tolerance. This modification and the modification performed to generate the correct section area, produces sections with a distributed shape. Inspecting the shape of a section in this manner does not always make the lowest point coincide with the centreline, however, the effects produced by methods 1 and 2 are greatly reduced by distributing the shape more efficiently.

Once a section has been created with this method, the control polygon further reviewed. The process inspects the position of the control vertex on diagonal (1). If the vertex is found to be in a position below the maximum draught of the section, it is modified, so the vertex lies fixed, on the maximum draught. The process of governing the area of the section is restarted and the area is corrected with the position of the vertex on diagonal (1) fixed.

9.3 RESULTS



Output From Hull Generation Method	
Method	Nº 3.
Parameter Basis	YD-40 Hull
Parameters	
Loa	12.050 m
Lwl	10.020 m
Bmax	3.710 m
Bwl	3.170 m
Beam at Transom	2.000 m
Tc	0.570 m
Forward Overhang	0.900 m
Freeboard at Bow	1.500 m
Freeboard at Centre	1.350 m
Freeboard at Aft	1.300 m
Cp	**0.570** -
Cm	**0.752** -
Cwp	Not Used -
LCF	Not Used % of Lwl
LCB	**53.000** % of Lwl
Bow Profile - Deck Angle	0.000 °
Bow Profile - Deck Tangent	0.500 m
Bow Profile - Waterline Angle	0.000 °
Bow Profile - Upper WL Tangent	0.500 m
Bow Profile - Lower WL Tangent	0.200 m
Transom Angle	-30.000 °
Transom Fixed Point	0.200 m on WL

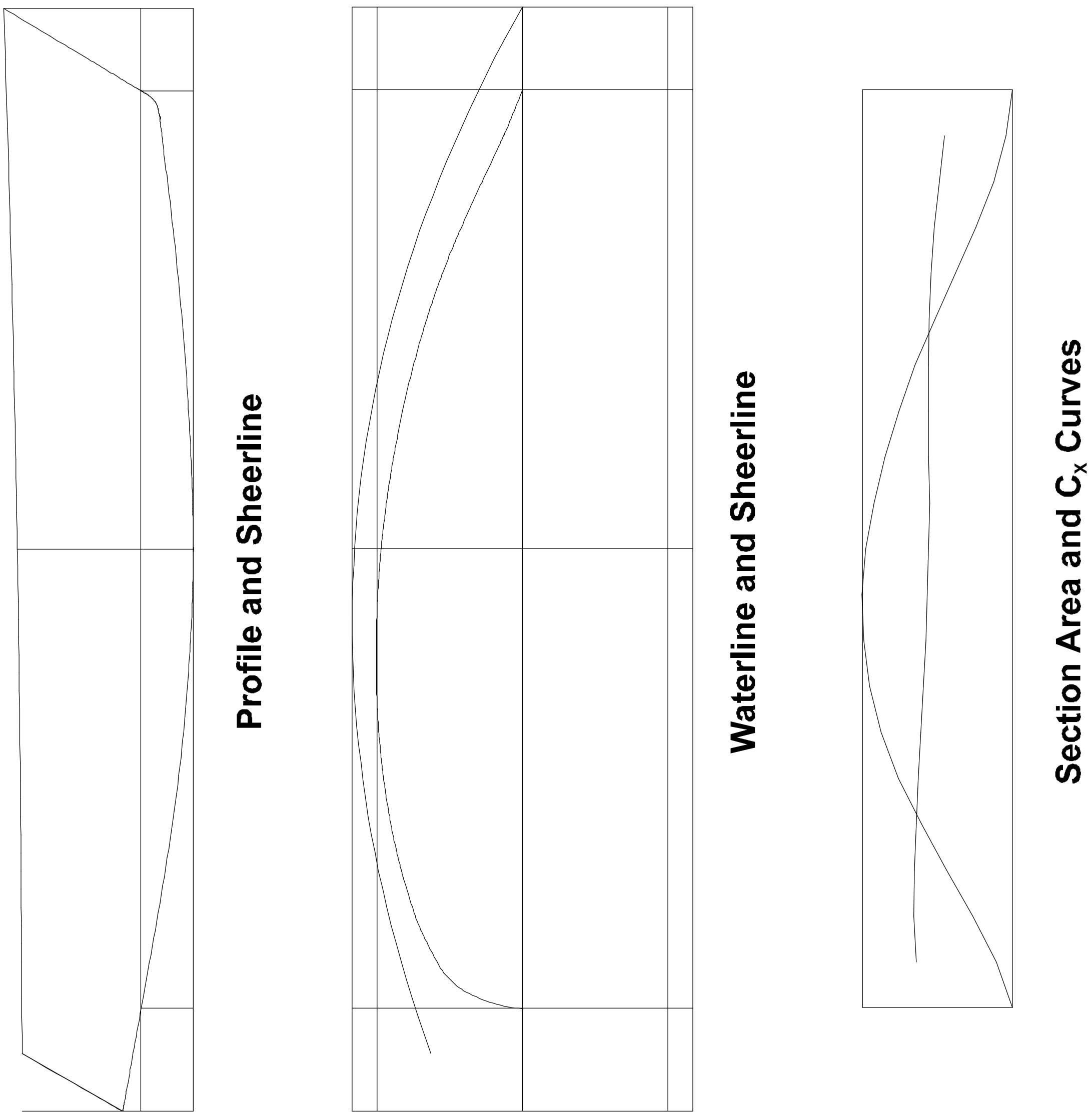
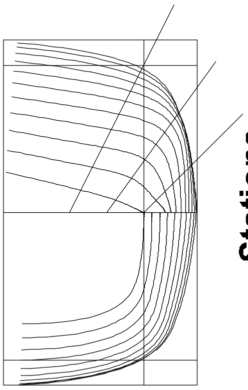
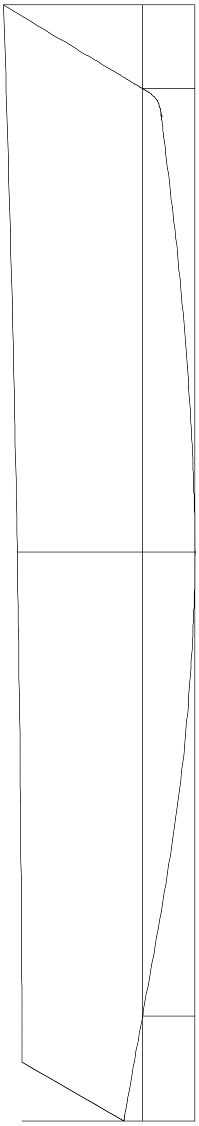


Figure 9.3, Method 3 - C_P = 0.57, LCB = 53%.

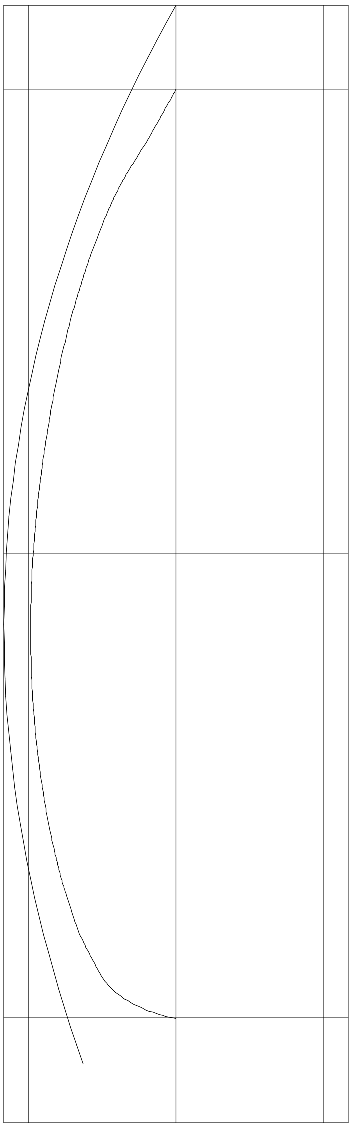


Stations

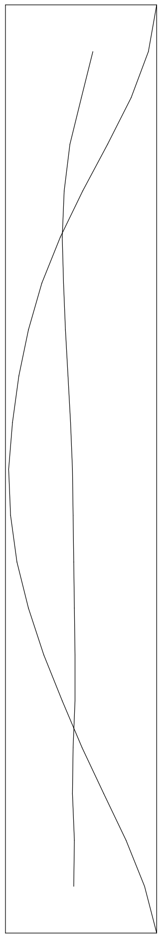
Output From Hull Generation Method		
Method		N° 3.
Parameter Basis		YD-40 Hull
Parameters		
Loa	12.050	m
Lwl	10.020	m
Bmax	3.710	m
Bwl	3.170	m
Beam at Transom	2.000	m
Tc	0.570	m
Forward Overhang	0.900	m
Freeboard at Bow	1.500	m
Freeboard at Centre	1.350	m
Freeboard at Aft	1.300	m
Cp	**0.570**	-
Cm	**0.752**	-
Cwp	Not Used	-
LCF	Not Used	% of Lwl
LCB	**50.000**	% of Lwl
Bow Profile - Deck Angle	0.000	°
Bow Profile - Deck Tangent	0.500	m
Bow Profile - Waterline Angle	0.000	°
Bow Profile - Upper WL Tangent	0.500	m
Bow Profile - Lower WL Tangent	0.200	m
Transom Angle	-30.000	°
Transom Fixed Point	0.200	m on WL



Profile and Sheerline

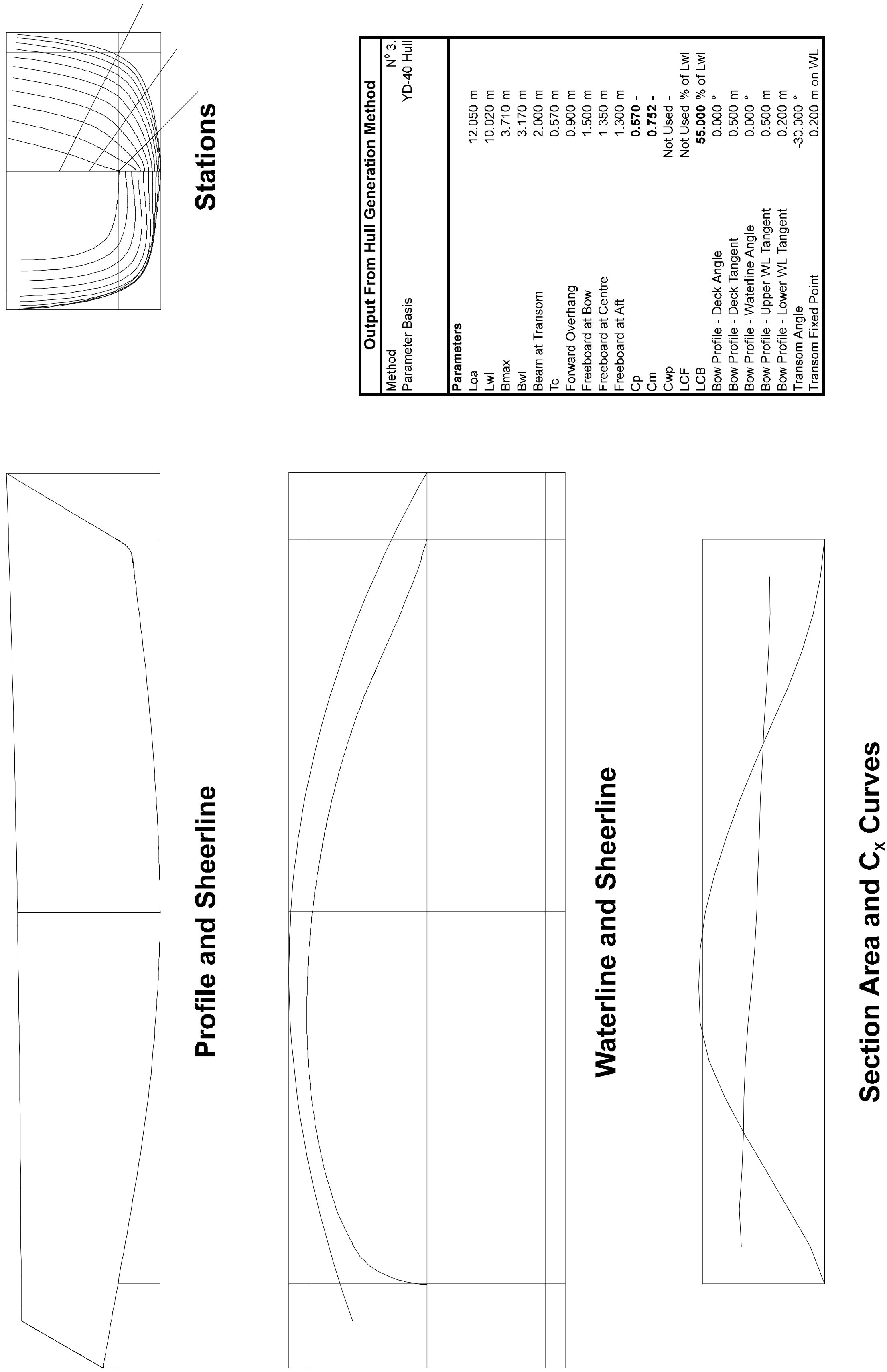


Waterline and Sheerline



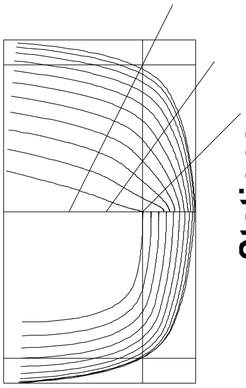
Section Area and C_x Curves

Figure 9.4, Method 3 - C_P = 0.57, LCB = 50%.

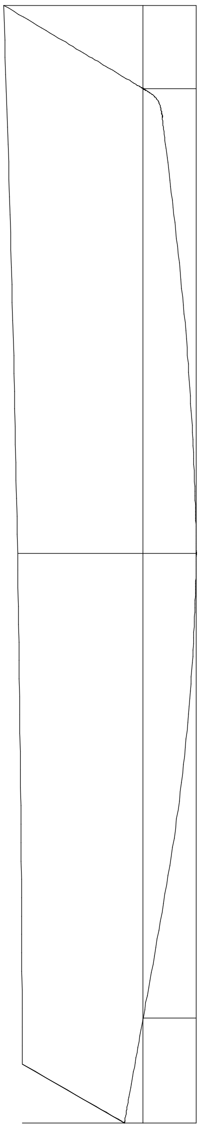


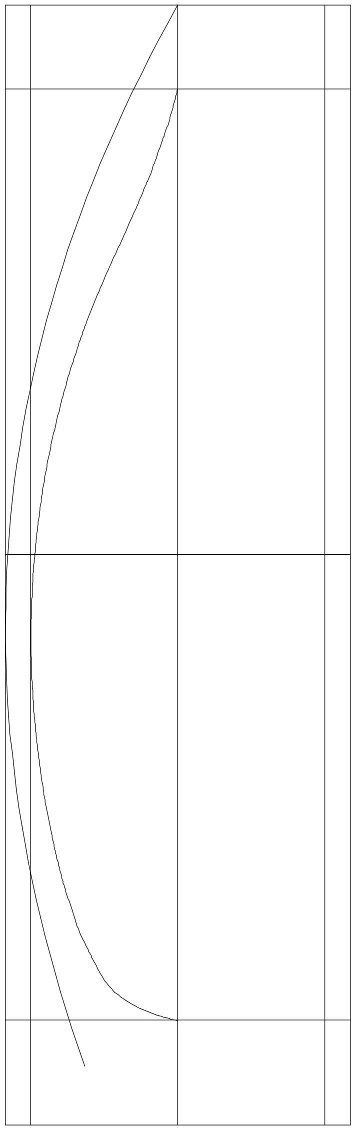
Output From Hull Generation Method	
Method	N° 3.
Parameter Basis	YD-40 Hull
Parameters	
Loa	12.050 m
Lwl	10.020 m
Bmax	3.710 m
Bwl	3.170 m
Beam at Transom	2.000 m
Tc	0.570 m
Forward Overhang	0.900 m
Freeboard at Bow	1.500 m
Freeboard at Centre	1.350 m
Freeboard at Aft	1.300 m
Cp	**0.570** -
Cm	**0.752** -
Cwp	Not Used -
LCF	Not Used % of Lwl
LCB	**55.000** % of Lwl
Bow Profile - Deck Angle	0.000 °
Bow Profile - Deck Tangent	0.500 m
Bow Profile - Waterline Angle	0.000 °
Bow Profile - Upper WL Tangent	0.500 m
Bow Profile - Lower WL Tangent	0.200 m
Transom Angle	-30.000 °
Transom Fixed Point	0.200 m on WL

Figure 9.5, Method 3 - C_P = 0.57, LCB = 55%.



Output From Hull Generation Method		
Method		N° 3.
Parameter Basis		YD-40 Hull
Parameters		
Loa	12.050	m
Lwl	10.020	m
Bmax	3.710	m
Bwl	3.170	m
Beam at Transom	2.000	m
Tc	0.570	m
Forward Overhang	0.900	m
Freeboard at Bow	1.500	m
Freeboard at Centre	1.350	m
Freeboard at Aft	1.300	m
Cp	**0.520**	-
Cm	**0.752**	-
Cwp	Not Used	-
LCF	Not Used	% of Lwl
LCB	**53.000**	% of Lwl
Bow Profile - Deck Angle	0.000	°
Bow Profile - Deck Tangent	0.500	m
Bow Profile - Waterline Angle	0.000	°
Bow Profile - Upper WL Tangent	0.500	m
Bow Profile - Lower WL Tangent	0.200	m
Transom Angle	-30.000	°
Transom Fixed Point	0.200	m on WL





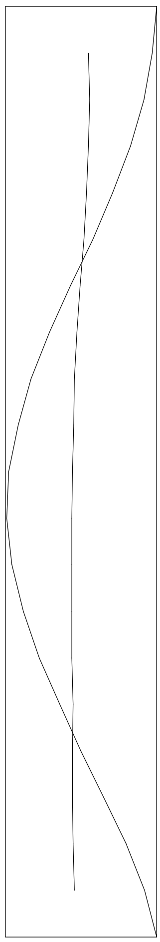
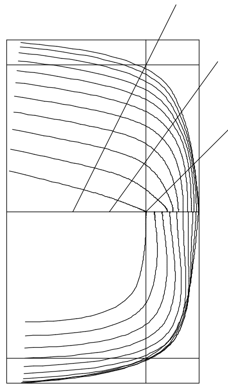
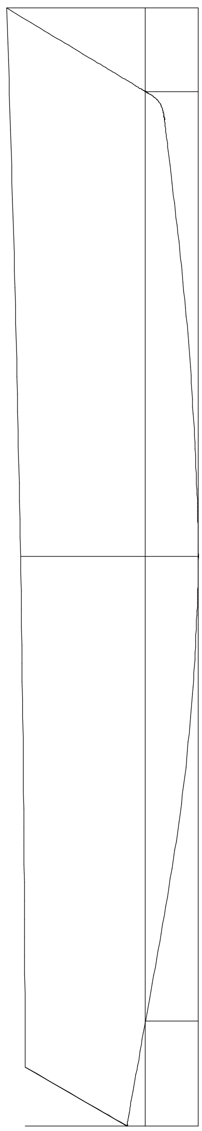


Figure 9.6, Method 3 - C_P = 0.52, LCB = 53%.

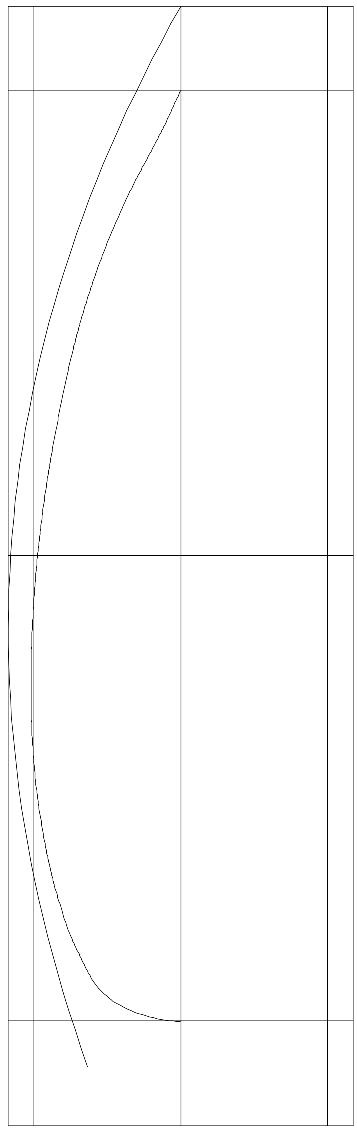


Stations

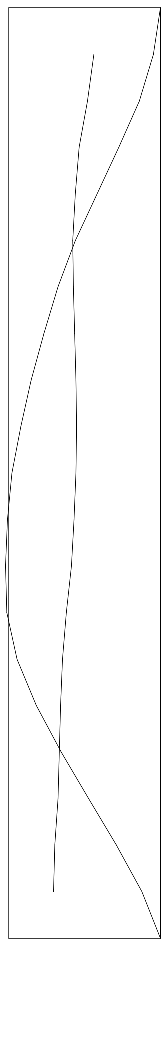
Output From Hull Generation Method		
Method		N° 3.
Parameter Basis		YD-40 Hull
Parameters		
Loa	12.050	m
Lwl	10.020	m
Bmax	3.710	m
Bwl	3.170	m
Beam at Transom	2.000	m
Tc	0.570	m
Forward Overhang	0.900	m
Freeboard at Bow	1.500	m
Freeboard at Centre	1.350	m
Freeboard at Aft	1.300	m
Cp	**0.600**	-
Cm	**0.752**	-
Cwp	Not Used	-
LCF	Not Used	% of Lwl
LCB	**53.000**	% of Lwl
Bow Profile - Deck Angle	0.000	°
Bow Profile - Deck Tangent	0.500	m
Bow Profile - Waterline Angle	0.000	°
Bow Profile - Upper WL Tangent	0.500	m
Bow Profile - Lower WL Tangent	0.200	m
Transom Angle	-30.000	°
Transom Fixed Point	0.200	m on WL



Profile and Sheerline



Waterline and Sheerline



Section Area and C_x Curves

Figure 9.7, Method 3 - C_P = 0.60, LCB = 53%.

9.4 DISCUSSION OF RESULTS

The results of Method 3 proved to be very good and is the quickest of the three developed so far. The previous five figures show the various hulls that have been generated by this process. This method produced hulls to a suitable standard within the region that the Delft Series is valid. This method is also able to produce a solution hull, with parameters set at values which not be found for a yacht hull.

Considering the previous figures, Figure 9.3 shows a hull generated with the prismatic coefficient and longitudinal centre of buoyancy similar to the YD-40. The bow sections produced are suitable to be used on a yacht hull. The aft sections have specified with section coefficients which are too high, producing a shape which go below the maximum draught of the section. The previous method tried to eliminate the effect of high values of C_X by modifying the shape of the Rocker profile. However, this modification attempt failed, producing an unsuitable profile shape. A better approach may be, to allow the profile shape to specified at stations 5 and 15 by parameters.

The shape of the section area coefficient curve in all figures is good and there are no abrupt changes in the shape to suggest inconsistencies in the sectional area curve. In Figures 9.4, 9.5 and 9.7 the parameters are set to the limits of the Delft Series and unsuitable hulls are produced. To produce more suitable hulls with the values of prismatic coefficient and longitudinal centre of buoyancy used in the figure, it is conceivable that the major dimensions would hull would have to be modified.

In Figure 9.4 the stations at the bow quarter, have bunched close together, at around mid draught. This effect shows up well on the C_X curve, where the section of the curve at the bow has a definite change in gradient.

In Figure 9.6, quite a fair hull has been produced. This figure demonstrates that, although most of the stations have a fair shape, stations produced by the method at the bow can have small fluctuations in shape, due to position of the diagonals. This effect is not so pronounced on hulls produced with values of C_P and LCB close to the optimum values associated with the YD-40 hull.

This method has demonstrated that a fair hull can be produced quickly. It can produce hulls over a reasonable range of parameters, especially values of C_P and LCB within the range associated with the Delft series. This method produces a hull which can be used in preliminary design and will be developed further so that the complete hull is produced.

10 FURTHER DEVELOPMENT

Now that a process has been developed, which can produce a hull quickly and efficiently. The method can now be developed further, so the procedure develops something which can be used for design purposes.

10.1 WATERPLANE SHAPE

Method 3 does not obtain the goals used to specify the shape of the waterplane. The process generates a good hull, given a suitable set of parameters and the shape of the waterplane is indirectly controlled by parameters such as longitudinal centre of buoyancy and some hull dimensions. It is thought that if the method 3 was developed, further, so that the waterplane shape was restricted with parameters, the hull would become less fair. It would also increase the time required to produce a hull by three or four times. There does not seem to be any disadvantage to losing the ability to create the correct waterplane, as long as an efficient waterplane is produced.

10.2 FURTHER TESTING

Testing, so far, has been concerned with making sure that the method can produce a yacht hull over a predefined range of prismatic coefficient and longitudinal centre of buoyancy, corresponding to the Delft series. Further testing was necessary, to see if a range hulls could be generated with different main dimensions.

This testing demonstrated the ability of the method to develop hulls with different geometric ratios. Two hull forms were considered, the first, had a high beam to length ratio, producing a slender hull. The second hull form, had a low beam to length ratio and high draught to waterline beam ratio. The second hull form is one which has ratios, which would be commonly found on the current Open 50 and Open 60 class racing yachts, Figure 5.1.

First the slender hull was tested. The slender hulls tested were, generally, very wall sided. This initial caused some problems to the procedure analysing section curvature.

The curvature in a section is analysed by considering the layout of the B-Spline control polygon. Angles between certain segments of the polygon are evaluated, to review the uniformity of the curvature in the section. The angle of each polygon segment is obtained by considering the gradient of the segment. By using an inverse tangent function, the angle of segment can be found. Generally, the inverse tangent function has a range of -90° to 90°. This range of angle only takes account of the gradient of the segment and not the direction. During the construction of a hull with wall sided sections, using method 3, the direction certain polygon segments became close to vertical (90°). As the iteration process varied the shape of the section, the angle of these segments would increase beyond the vertical, to obtain angles of more than 90°. In this situation, the inverse tangent function converts the gradient on segment into a negative angle. The iteration procedure was unable to cope with the rapid change in the sign of the angle and a section of unsuitable shape was produced. To overcome this problem, an inverse tangent function was developed, to produce a range of -180° to 180°.

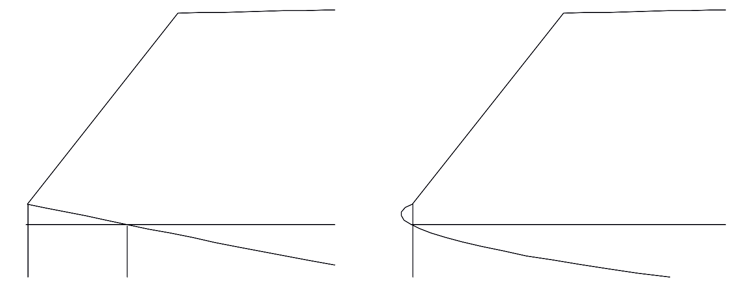


Figure 10.1, Various transoms produced with the original profile mechanism.

During the testing of the second hull form, a problem which existed in both hull of both form was discovered. Both hull types tend to have very small and in most cases no stern overhang, as a result, the aft perpendicular is the transom. The current process used to define the profile does not allow these types of hulls to be formed well. In the previous methods, the aft profile is constructed by allowing the curve to go through a specified point on the waterline, at the aft perpendicular, to a point on the bottom of the transom, some distance above the waterline. In a yacht with no transom is possible to create a bad profile shape. Figure 10.1 shows the transom of the YD-40 hull and the transom produced, when the overhang of the same yacht is reduced to zero. A loop is produced, with the size dependant on the order of the B-Spline function producing the curve.

To remove this unwanted feature, the position of the extreme end of the transom, above the waterline, was allowed to be found by the profile generating process. An iterative procedure was developed to vary the position of the this point on the transom, until the profile intersects with the waterline at the aft perpendicular. This solved two problems; first, a yacht with no stern overhang could be produced and second, the aft profile or "Run" of the yacht was now more hydrodynamically sympathetic.

The Open 50 and 60 class yachts are designed, primarily, for downwind sailing. Optimising the hull for this sailing direction produces very flat, beamy, aft sections, which allow the yacht to plane at speed, causing a reduction in resistance. The flat sections are used over most of the stern of the yacht and the beam at the transom is almost the same as the maximum beam, Figure 10.2.

Figure 10.2, An Open 60 with the wide stern characteristics.

A large transom beam created problems. The fixed section shape of Station 20, at the aft perpendicular, created an initial hull with large, deep, aft sections. The main hull generation procedure attempted to obtain the correct prismatic coefficient and longitudinal centre of buoyancy for the hull, producing aft sections with section area coefficients higher that one. The fixed nature of Station 20 was changed so that the angle of flare, at the deck edge, could be modified to reflect the real shape of hull and to allow sections, with shallower draught, to be generated.

10.3 THE TRANSOM

None of the methods so far have generated the full shape of the transom, however, the profile contains a segment which specifies angle of the transom. The shape of the transom is similar to the sections. By using this assumption, the transom can be formed in a similar fashion to the sections, by using the diagonals to specify the vertices of the transom control polygon. The diagonals are currently, only defined between the bow profile and Station 20, as the B-Spline fit procedure does not allow these curves to be extrapolated. By using a least squares regression technique, a curve of quadratic order can be fitted, to diagonals between Station 10 and 20. The shape of the diagonals can then be projected to the aft, to the region of the transom. Assuming that the transom is a plane, the intersection points between the extrapolated projected diagonals and the transom can be found. The points can then be used to form the vertices of the control polygon, Figure 10.3

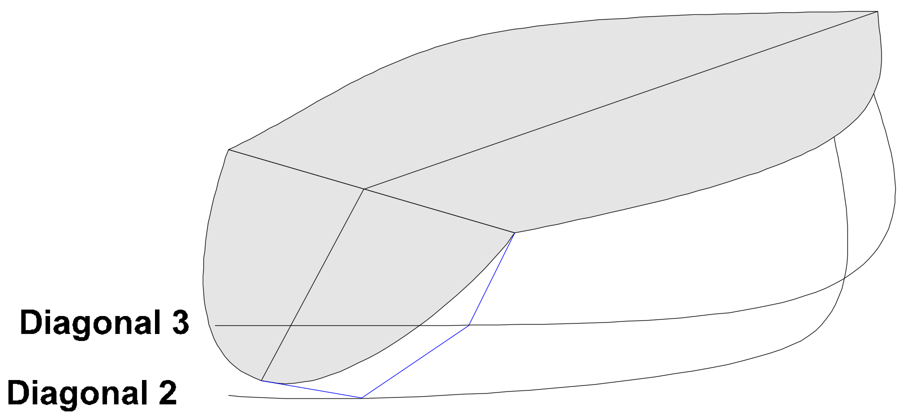


Figure 10.3 - Intersection of Diagonals with Transom

In some cases, diagonal (2) will not be able to form part of the transom, when the intersection of diagonal (2) with the transom plane, is below the transom. In this situation, the process detects this condition and places the vertex controlled by diagonal (2) at the bottom of the transom. This is also the position that the vertices of diagonals (1) and (3) are placed.

Under the specification of certain parameters it is possible to get unusually shaped transoms. This should not be regarded as a failure, as in these conditions, it is likely that the transom has been projected from a hull that was specified with unsuitable parameters.

10.4 OUTPUT

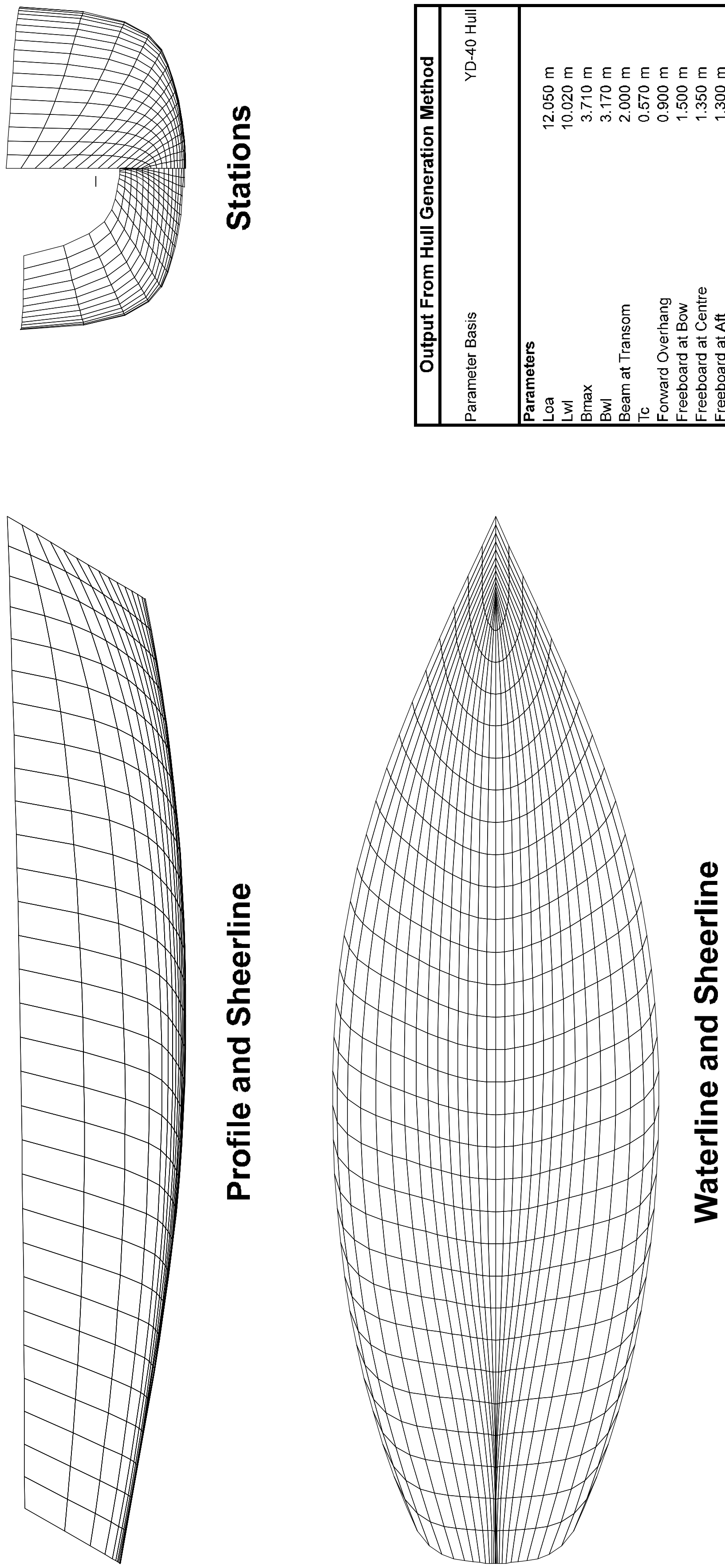
The hull generation procedure must produce an output for it to be deemed useful. There are a wide variety of methods and formats that this output could take. The most useful format would a surface. If the hull was defined with a surface it could transported to many other ship design applications to allow further modification.

A investigation was made into turning the sections created by method 3, into a surface. If a B-Spline surface was used to define the hull, other CAD applications could have access the surface. There are a variety of ways that a B-Spline surface can be formed from the generated sections.

The first method attempted was similar to the B-Spline fit process used for curve fitting. The B-Spline fit process used for curves, uses matrices to construct the control polygon from the specified fit vertices. The procedure was extended, to allow surfaces to be fitted to a set of points. Unfortunately, the standard procedure used to numerically invert matrices is unable to handle the size and amount of numbers that can be involved during the fitting process for a surface definition.

A second procedure was investigated. This used the concept that the system used to create the yacht hull is almost a surface. B-Spline sections are formed from B-Spline diagonals, two B-Spline processes, one after the other, similar to the technique employed in B-Spline surface. The positions of the vertices in the diagonal control polygons must be close to the vertices of the control polygon net for the B-Spline surface. All that has to be found, are the remaining points for the surface control net, the points that define the sheerline and the profile. Initially, this process failed. However, a similar procedure developed by Jensen and Baatrup [10], was discovered. This develops ship body plans into a B-Spline surfaces by using B-splines fitted through sections and B-splines fitted through waterlines. As this successful procedure followed a similar process to the sections and diagonals of the current hull generating method, the surface procedure was debugged, as it was found to contain many errors and, once clear, produced a B-Spline surface, Figure 10.4. The surface, as yet, has not been analysed, to see if the result produced is accurate to the original sections and profile.

Once the surface is found to be accurate, the method can be developed further, into a hull pre-processor for a main stream CAD package such as AutoSHIP or as part of an in-house CAD package. In further development, the hull generation method may be developed to be surface based procedure or using Jensen and Baatrup [10], the yacht sections may be transformed into a B-Spline surface.



Output From Hull Generation Method	
Parameter Basis	YD-40 Hull
Parameters	
Loa	12.050 m
Lwl	10.020 m
Bmax	3.710 m
Bwl	3.170 m
Beam at Transom	2.000 m
Tc	0.570 m
Forward Overhang	0.900 m
Freeboard at Bow	1.500 m
Freeboard at Centre	1.350 m
Freeboard at Aft	1.300 m
Cp	**0.570** -
Cm	**0.752** -
Cwp	0.730 -
LCF	55.000 % of Lwl
LCB	**53.000** % of Lwl
Bow Profile - Deck Angle	0.000 °
Bow Profile - Deck Tangent	0.500 m
Bow Profile - Waterline Angle	0.000 °
Bow Profile - Upper WL Tangent	0.500 m
Bow Profile - Lower WL Tangent	0.200 m
Transom Angle	-30.000 °
Transom Fixed Point	0.200 m on WL

Figure 10.4, A surface produced during the last development of the method.

11 IMPLEMENTATION

11.1 PROGRAMMING LANGUAGES AND STYLES

To be able to use a numerical method, such as B-spline techniques it is essential to use a computer. At the initial stage of this project, the programs were written using Turbo Pascal 7.0 with Objects. This is an MS-DOS™ based programming environment where a program can be written, edited and run all within the same application. Programming at the low DOS level means that a system can be simpler. Using more complex operating systems such as Microsoft Windows™ could add problems which would not be connected with the hull generation method itself. Later in the study, the program will be ported to a Microsoft Windows based system. Using Borland Delphi, with is compatible with Turbo Pascal, a "user friendly" interface can be made to this complex process.

Today, Programming languages and systems have progressed to the extents that complex programs can be written in very short amounts of time. There are now a bewildering variety of programming tools some of which provide an integrated development environment in which writing, editing, compiling, debugging and execution can all be performed at the touch of a few buttons.

Borland Turbo Pascal has good mathematical functions and the graphics library supplied with this language also allows the display of curves and geometry on the screen so that the results of a calculation can be quickly analysed.

Turbo Pascal also supports object-oriented programming, OOP. An object oriented programming approach allows a problem to be broken up into smaller pieces, where an object forms one of these pieces. An object groups all the information and code relating to a problem or item together so that the situation can be solved in easier stages. All the main program has to do is interact or "talk" to the object. Turbo Pascal also uses one of the fastest compilers that can be found in compilable high end languages with the possible exception of C.

11.2 THE APPROACH

A modular approach to programming has been followed, which means that the system is made up of separate modules or parts. Each module performs it's own iteration operation on the hull. This allows every module to have a similar format or layout to achieve the iteration goal, and the program can be debugged and modified in an easier manner during the development process. The modular approach also gives flexibility so that various operations can be changed, removed or added as necessary. The modules can be called by, or call other modules, as part of the process. As mentioned in section 7.1, Turbo Pascal 7.0 supports OOP, which for the majority of the hull generation procedure this type of programming is not necessary, but it can be used for the many ancillary systems necessary in any program, such as data storage and retrieval.

Each module follows a similar format. The main procedure of a module initialises iteration information, such as the intended goal to be reached and the accuracy or tolerance at which the goal should be reached. The main procedure passes the initial start values, iteration information and a modification function to the iteration process.

The modification function resides within the module. The function takes the form of Y=F(X). The value of X, is the initial start value of the iteration process and the X value is modified by the iteration procedure until the goal is obtained. The modification procedure uses the value of X to modify the shape of the hull. Then a calculation procedure is called to find the value corresponding to the eventual goal to return as Y. Each module can control up to two effects, generally a volume or area and the centroid of that volume or area.

11.3 THE ITERATION PROCEDURE

The design of the process of attaining the goals is very important. Previous hull generation systems have used the Newton-Raphson technique to obtain solutions. The Newton-Raphson is considered one of the most efficient techniques for obtaining, numerically, a solution to a function. To use the Newton-Raphson technique with any success one requires a mathematical function which can be differentiated. A differential function for a B-Spline function can be obtained, but it is much more complex to calculate than the original B-spline function. So, to attain goals in the current hull generation method an engineering approach was taken, by using simple standard linear interpolation, iteration technique.

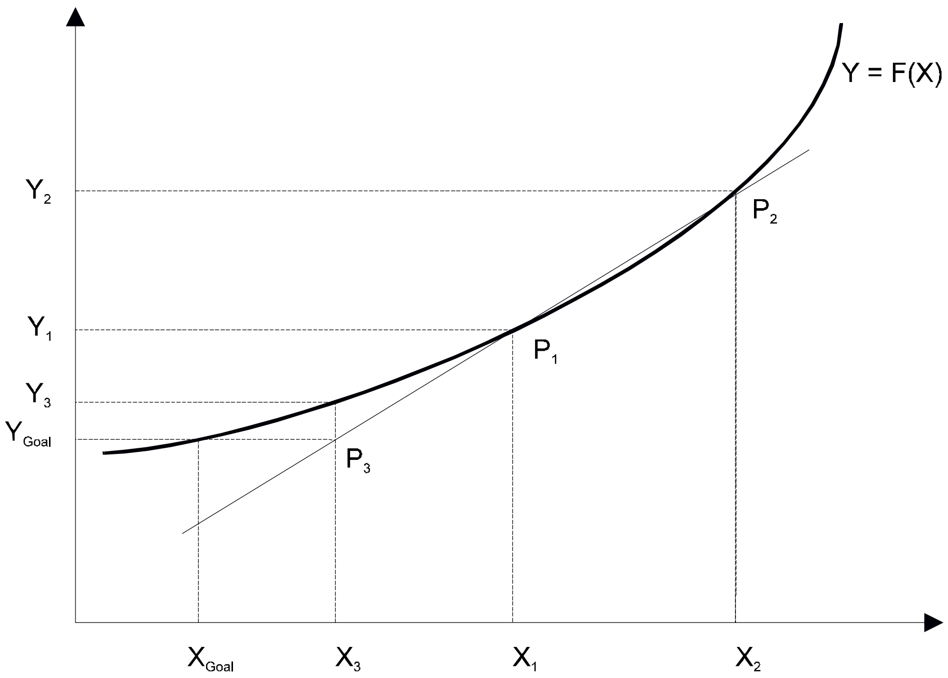


Figure 11.1, The structure used in linear interpolation.

Considering Figure 11.1, the value of X_1 is sent to the iteration procedure when it is initially called. X_1 is a variable which can be used to vary, for example, the prismatic coefficient C_P. The iteration process calls the modification function with X_1 as a parameter. The modification function takes the form of $Y_n=F(X_n)$. The result of the modification function, Y_1, in this case will be the returned value of C_P. Next, as part of the initialisation process, the iteration procedure increases X_1 by 5% to obtain a value X_2. X_2 is passed to the modification function which returns a C_P in Y_2. Now a line can be placed through the points P_1 and P_2 with co-ordinates (X_1, Y_1) and (X_2, Y_2). The line can be extended so that the required prismatic coefficient, Y_{GOAL}, can be used to find the value X_3. X_3 is now passed to the modification function. If Y_3 is close enough to Y_{GOAL}, then the required C_P has be found and the value X_3 can be used to create the hull. If the value of Y_3 is not close enough to Y_{GOAL}, then a line is drawn though P_2 and P_3 and the process is repeated. The linear interpolation technique may fail if applied to a curve with complex shape, however, it thought that most of the curves iterated in the hull generation procedure are fairly simple.

The iteration procedure is illustrated in Figure 11.2.

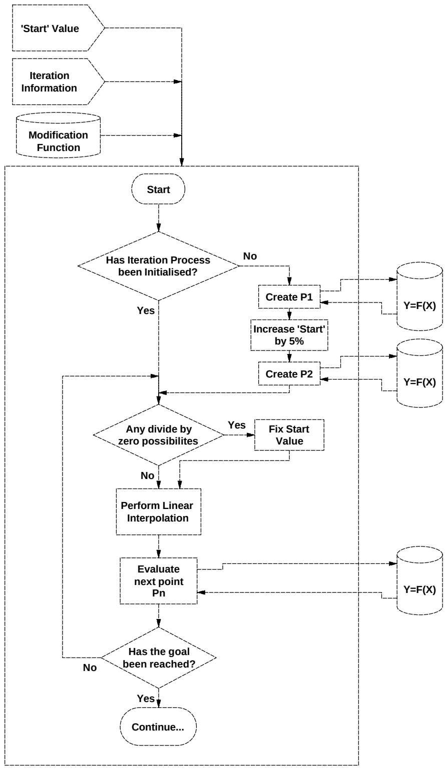


Figure 11.2, The iteration procedure.

11.4 USING THE PROGRAM

It is historically common for many calculation programs to use "command line" operation because of the wide use of the UNIX operating system. One of the reason for the popularity of UNIX is the fact that it supports that management required for a large number of computer terminals and files. The UNIX system, however, is text based, it does not support have any graphics system of its own. Thus, a command line is used to run and perform operations. This means that a program or calculation procedure will be started by typing the command into the operating system. The operating system will load the program, the program will open it's input file, perform the calculation and return its output in another file.

One of the essential ingredients of implementing the hull generation technique is the use of graphics. Using graphics not only allows the curves to be displayed, but the progress of the iteration can be displayed to show the evolution of hulls. It is useful, for example, in the cases where the iterations do not produce simple-value convergence.

Above all else, the use of graphics enables the system to be interactive. Modern day computer users are thoroughly spoilt with fancy displays and fast execution to the extent that is essential for the system to be interactive, with an attractive easy to use and powerful user interface.

The Figures 11.3 to 11.8 show views of the application that was used to develop the hull generation technique. The application was initially developed from simple showing curves on the screen, to a full graphical user interface as more functions were added. The figures show a hull developed with Method 2.

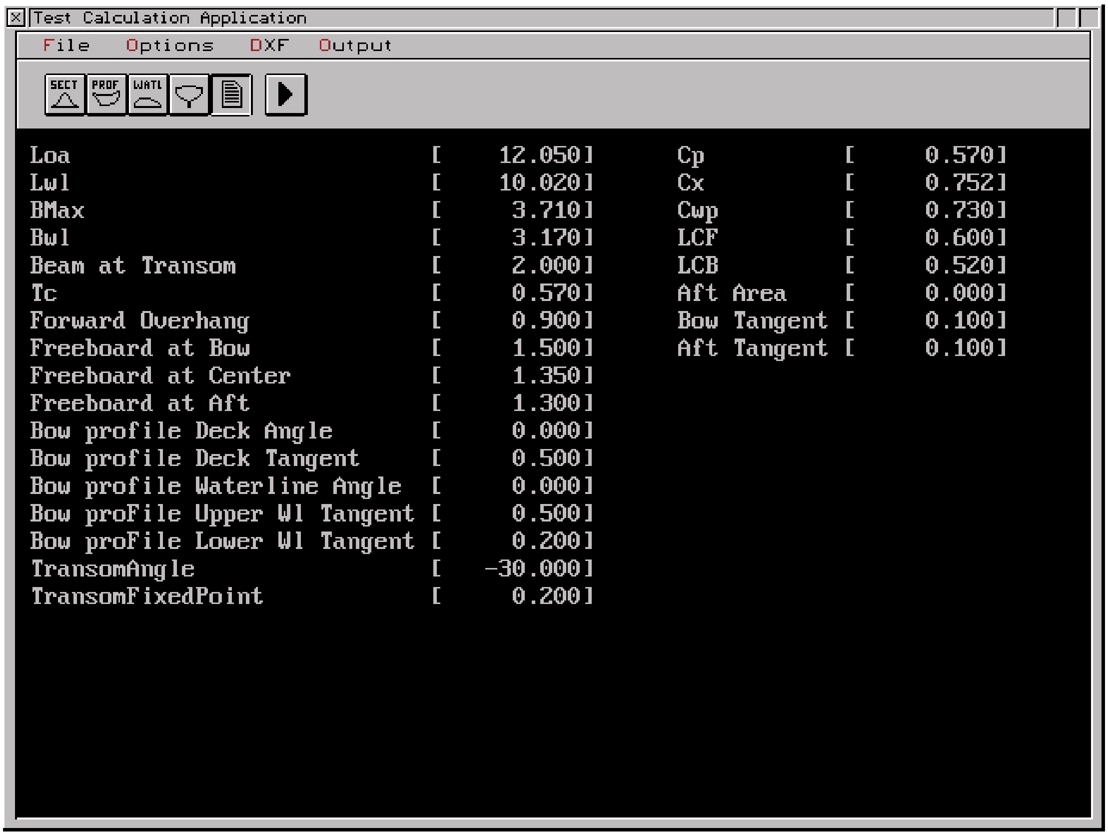


Figure 11.3, The application, showing the page used to specify parameters

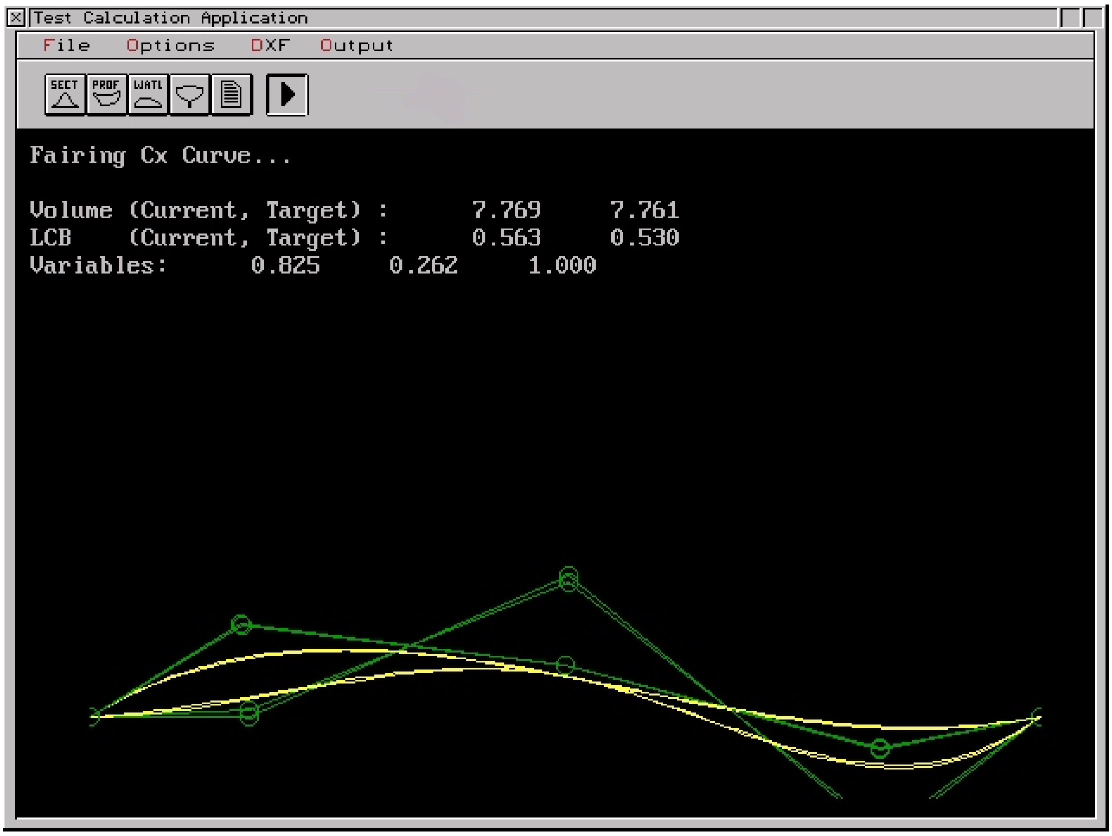


Figure 11.4, The application showing the progress of a calculation

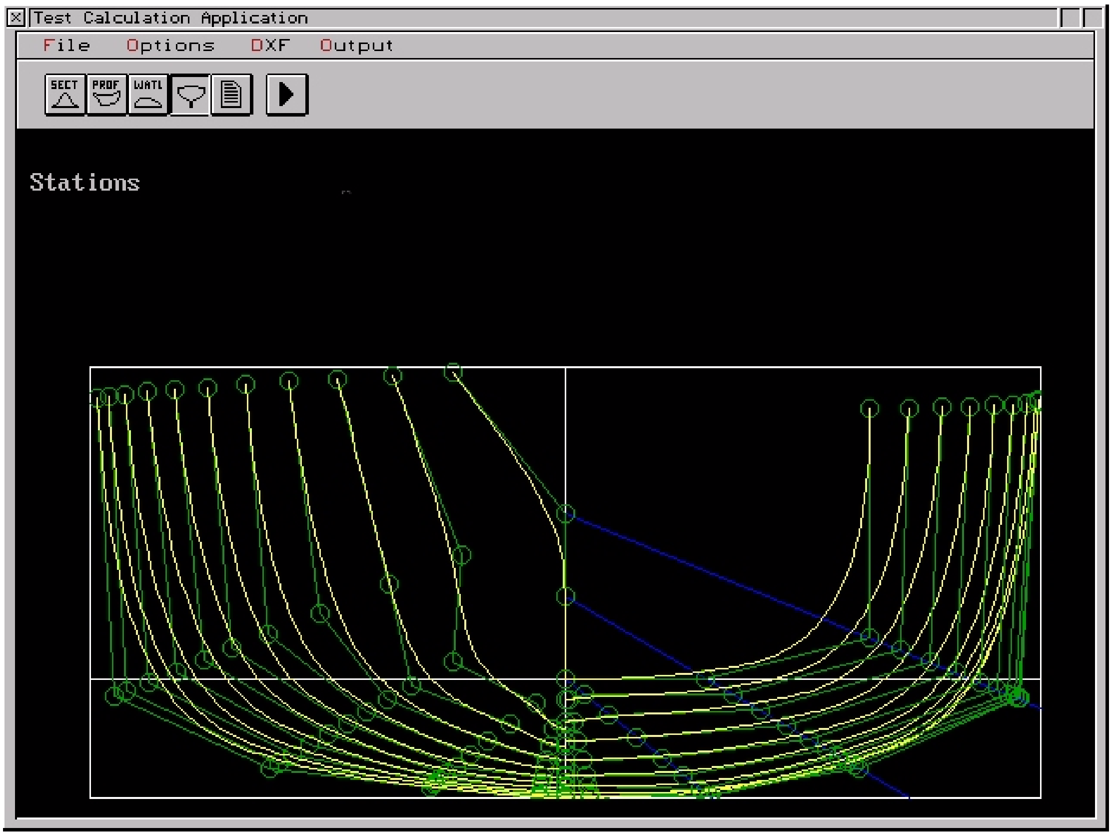


Figure 11.5, The display of the stations produced by the application.

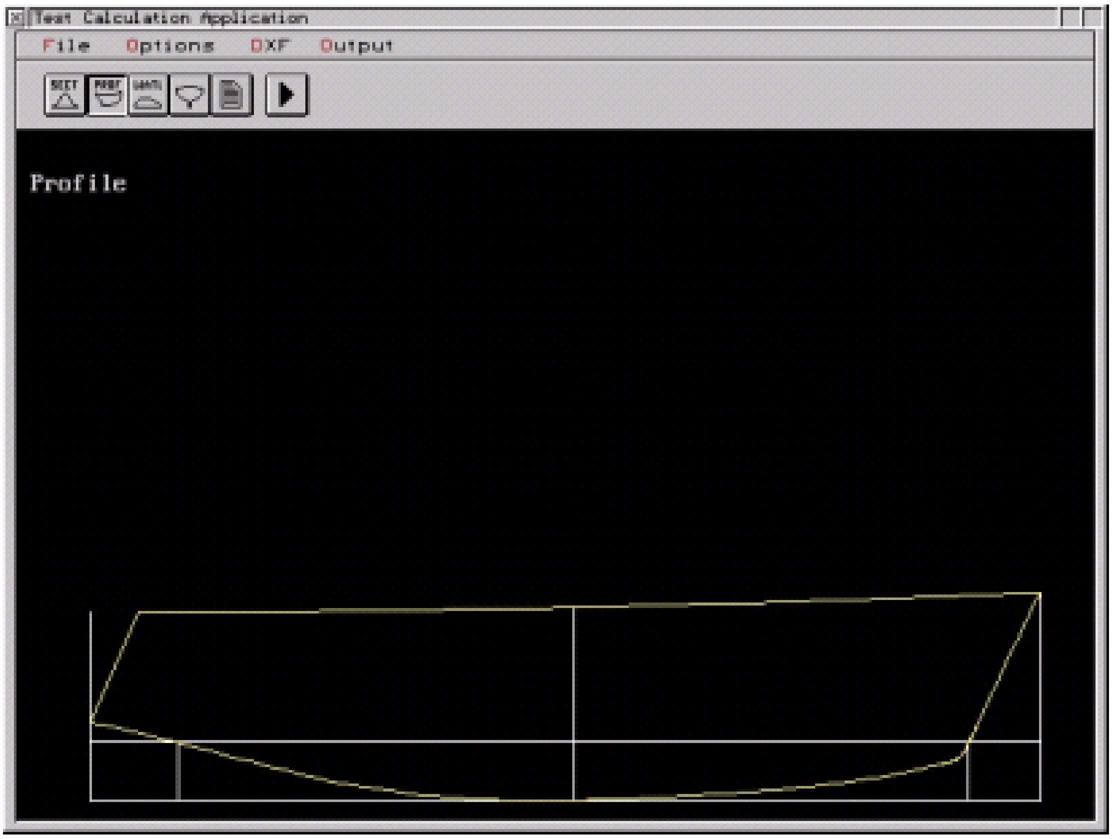


Figure 11.6, The application displaying the profile of the hull

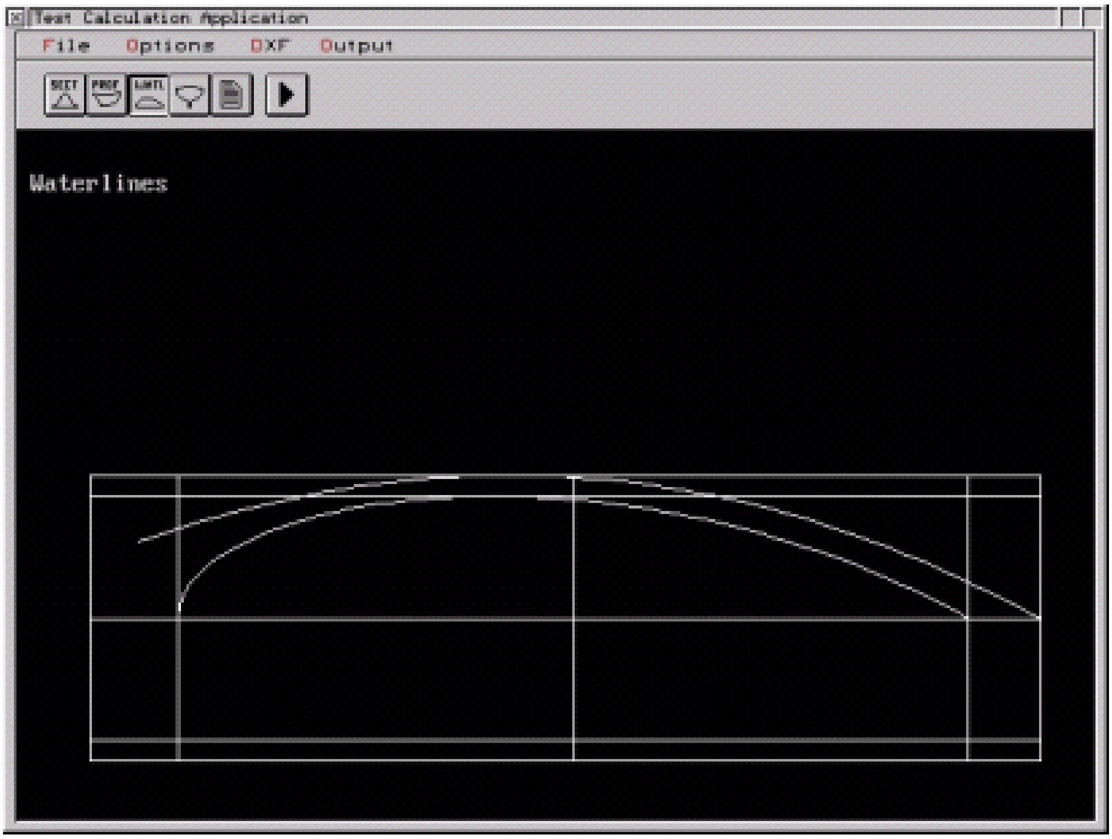


Figure 11.7, The plan view of the hull displayed by the application.

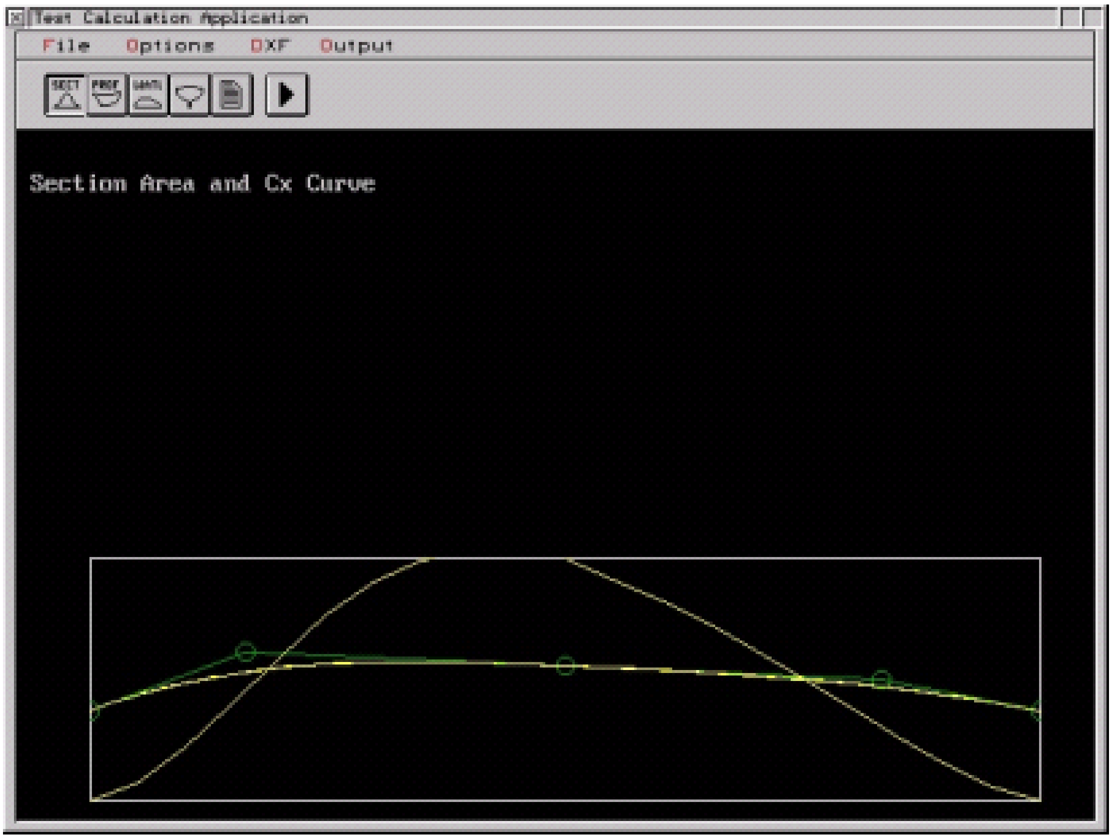


Figure 11.8, The section area and C_X curves produced by the application.

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12 APPLICATIONS OF HULL GENERATION PROCEDURES

A powerful system has been developed, which creates yacht hulls. The uses of such a system should now be considered. As mentioned in section 10.3, it possible to develop the method further, so that a hull can be modified further, by another program to add other features, such as superstructure, different transoms or detailed interior plans. It also allows the hull definition to be used for construction purposes by using Computer Aided Manufacturing and this technology has become standard throughout the marine industry. However, by developed the method further, analysis can performed on important aspects of the hull, increasing the sophistication of the generation process.

12.1 HULL OPTIMISATION

The method generates a hull rapidly, which opens up opportunities for it to be part of a much larger process. There are already systems being developed, which can change a hulls shape, to optimise or analyse more important characteristics than the general hull specification parameters. An American company, New Wave Systems [8][9], is developing a commercial ship design software suite, the Nautilus System, which contains hull variation and evaluation procedures. The hull variation process used in the Nautilus System appears to be a general system, which can change the shape of any existing hull form to achieve goals similar to those used in the current study. The evaluation process developed by Hollister [9], for the Nautilus system, is a Geosim Coefficient Resistance Evaluation process. However, the resistance evaluation system is dependent on access to a resistance database to analyses certain types of hull form.

Other more interesting evaluation techniques are being investigated by New Wave Systems. Five types of evaluation routines are current being developed.

1. **Geosim Coefficient Resistance Evaluation** - These techniques break the overall resistance of the vessel into their component parts, such as viscous resistance (C_V), residual resistance (C_R), and appendage resistance. Residual resistances are often determined from a regression analysis of tank test data.

2. **Planing Hull Resistance Evaluation** - This type of resistance evaluation uses the same force breakdown techniques as the Geosim approach, but adds moments of forces about the centre of gravity of the boat. This defines a steady state free body diagram of the boat that can be solved for the resistance and trim of the boat.

3. **Sailboat Velocity Prediction (VPP)** -This type of resistance prediction is also based on a Geosim approach, but adds sail and hull lift and drag forces. A search technique is used to determine the velocity and heel angle of the boat for each wind speed and wind angle.

   Note that for certain racing sailboats, the hull variation process is further complicated by the need to meet the shape constraints of any applicable rule, such as the America's Cup rule.

4. **Computational Fluid Dynamics Methods (CFD)** - These techniques typically use a polyhedron mesh generated from the shape of the hull to perform a full 3D analysis of the resistance of the hull.

5. **Finite Analysis Methods (FEM)** - These techniques use a polyhedron mesh generated from the shape of the hull to perform a 3D structural finite element analysis of the hull shell.

The evaluation processes are being developed around very import fields in marine design and it shows how a hull variation procedure can be used as part of a much complex numerical analysis system using CFD or FEM. Topics, such as CFD and FEM, are too complex to discuss at this level and as this project follows a yachting theme, velocity prediction will be discussed further.

12.2 VELOCITY PREDICTION AND HULL VARIATION

The Velocity Prediction Program (VPP) is becoming one of the most important tools in yacht design. Even the recently developed IMS rating system uses a VPP to evaluate a yachts performance. It is also common for large, successful yacht designers to develop their own VPP analysis software. The yacht hull generation procedure, when generating hull in conjunction with a VPP, would greatly reduce the time required to develop a hull with optimised performance.

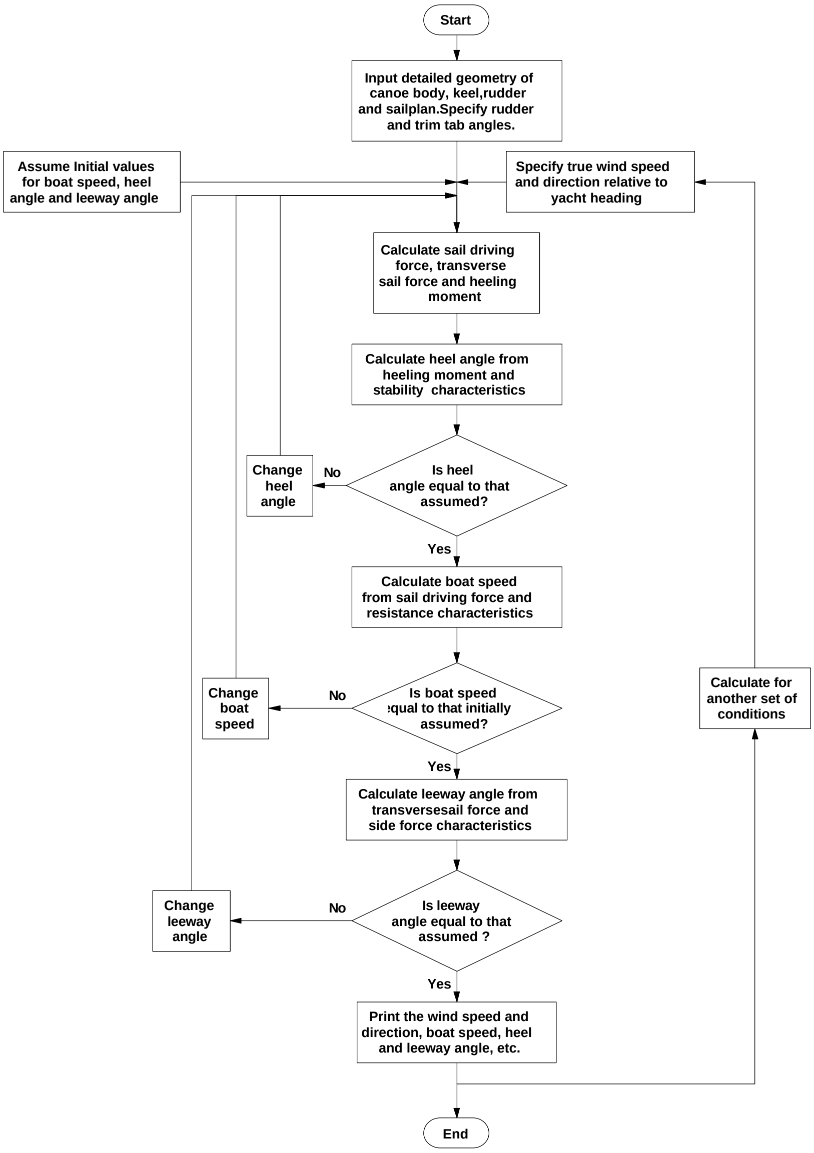

Figure 12.1 - The Basic VPP procedure.

A VPP, Figure 12.1, follows a fairly simple process, balancing the forces and moment affecting a yacht, when under sail. The process is iterative and is similar to the hull generation system. In this process, the goal is to minimise the difference between assumed and calculated angles. A good velocity prediction program will consider all the systems found of a yacht, to determine the performance. A VPP has to consider effects generated by the hull and appendages. Effects are generated by:

1. The Hull
2. Keel(s)
3. Rudder(s)
4. Sails
5. Trim Tabs
6. Propeller

Operational environmental factors are considered and these are:

- Wind Speed
- Wind Direction
- Wave Frequency
- Wave Direction
- Wave Length

To analyse all these systems, a complex set of functions required. The functions found in VPPs are, generally, based on experimental results. Functions, developed through the regression analysis of experimental data, are used so that the results of tests can be interpolated to other hull and sail configurations. This is common practice and it is easy to forget that the data will only be truly valid over the range studied in experiments.

Velocity prediction programs use theories from three areas of study, Resistance, Aerodynamics and Foil hydrodynamics. The theory used for foil hydrodynamics is fairly standard and well known, as much experimentation has be made on families of foil shapes, such as the NACA series. The procedures used to calculate resistance and aerodynamic effects are not as well known. Most techniques are recent work. The resistance of the yacht hull has been investigated, more recently, to allow VPPs to have more accurate methods of prediction hull resistance. Today, the resistance of hulls that are not important enough to be tank tested, can be analysed, through the use of regression functions.

The University of Delft has developed the Delft Series [5], for use within the Delft VPP. This resistance method uses data calculated from 39 test hulls, to construct resistance extrapolators for residuary resistance, induced resistance and heeled resistance. Calculation of frictional resistance is made by using Froude's method. The Delft Series has limitations, any hulls that are not within certain boundaries and similar to the original test hull may not give reliable results. Therefore, if a hull generation procedure was used as part of a VPP optimisation process, step would have to be take to stop a hull moving outside of the valid range of the resistance data, otherwise, the hull produced would not be correctly optimised.

Aerodynamics in a VPP are calculated through a similar procedure as resistance. Using the various lift and drag coefficients developed for the IMS system by C. L. Poor in 1986, the forces developed by the sails can be estimated. The sail functions take account of many complex effects, including interaction effects between sails.

The VPP is highly dependent on experimental data. If a VPP was used in conjunction with a hull optimisation technique, the validity of the analysis functions used in the VPP may be compromised as the hull is changed. A better VPP could be developed in the future, Computational Fluid Dynamics procedures could be used instead of regression functions based on experimental data. This is likely to make the VPP more accurate and allow valid calculations to be made on hulls of all shapes.

A hull generation method can be easily adapted to become part of a VPP. The main difficulty is to decide which hull features the VPP should control. The VPP cannot control all features on a yacht, as the system would be to complex and would always produce the same yacht solution. A study of a simple VPP was considered to extend this hull generation study, however, to develop a system which could vary more than the hull would require a detailed study of sail characteristics. A full study of VPPs in relation to hull generation and optimisation would require an investigation greater that the current study.

The functions used in a VPP governing the hull, were analysed to see if the performance of the hull could be optimised at a lower level. The hull only has control over resistance characteristics, so a smaller study of a resistance optimising procedure is explained in appendix 16.3.

12.3 THE IMPACT OF HULL GENERATION PROCEDURES

The hull generation procedure developed has shown how easy it is to develop a computer based procedure to rapidly produce hulls. It can now take a matter of seconds to develop a hull, which before may have taken hours. Although the hull produced cannot always be used directly, it shows how the computer can greatly reduce the amount of time required to produce a hull.

The introduction of a system which can produce hulls quickly has a impact on the types of people using a design system. Using a hull generation procedure, less design skill is required to produce a hull. The operator of such system does not need to know how to produce a hull or even what is involved in producing a hull. But it is important that the operator should have studied the theory to allow the result from the computer to be checked.

The hulls produced by this method will be part of the same family. This means that, generally, they will all look the same. Much design today is already at this stage, a look at the car industry show similar cars have become. This is probably the result of making a car more economical, by considering aerodynamic effects and wind tunnel testing vehicles. Unfortunately, the result produced is less variety in the style of cars available today. This trend in design has been recognised and now some manufactures are starting to design cars with “character”. A design trend similar to the car industry has been followed in yachts, resulting in mass production yachts with standard “Off the shelf" styling. A parametric hull generation procedure will produce "Off the shelf" styling, which would reduce the variety in yacht hulls.

The hull generation procedure would be only be effective in optimising the design of racing yachts. Designers and owners search for even the smallest amounts of extra performance and a hull generation technique assist in the process. Hull generation procedures have been successfully developed for ship design, here economy is a priority, however, there may not be as much scope for a generation system to be used in yacht design. Generally, an owner will not purchase a yacht unless the look of the yacht is pleasing, even if it performs well.

13 DISCUSSION

13.1 REVIEW OF THE FINAL METHOD

It has been demonstrated that a good hull can be produced with a parametric hull generation technique using B-Spline functions. A yacht hull can be created with the method in a matter of a minutes. The hulls produced by the method are, in most cases, fair. However, most hulls will require further by using another program or by "tweaking" some of the numeric parameters. Under most circumstances a shape is produced, however, a good hull will be only produced if sensible sets of parameters are used.

It was predicted that, it would be straight forward and fairly easy to develop a hull with a parametric process. However, skill is required to select parameter, which generate a good hull and it can be seen, in many of the results, that by modifying parameters, good hulls are not always produced. There does not seem to be a clear reason for this, however, possible reasons for these effects could be either (a), there is a range of numeric parameters for which fair yachts hulls fall within or (b), there is a range of numeric parameters, within which, the procedure will only produce a fair hull. It is difficult to test these hypotheses with the current method, as in yacht design, generally, these problems do not transpire and the current procedure has not been tested enough to disprove (b).

To develop a good hull, knowledge about how the different parameters affect a hull is required. Most naval architects will be aware of the parameters that are used in the method, as they are common throughout the design of all marine vessels. However, it can be shown that it becomes difficult to generate good hull without a real grasp of the effects of each numeric parameter. An interesting application of a hull generative method would be teach prospective naval architects about the numerical values that are used in the design and shape of marine vessels.

The hull generation technique is heavily reliant on the function linking the control vertices of a section together, to control the shape of a section. This function is a very small part of the method, yet, it is the only part of the keeping sections "yacht" shaped.

The effects of this function should be investigated in greater detail, to find out if further development would produce a method, which would allow a greater flexibility in the type of yacht hulls produced and to see if the imperfections in the hull produced, with the current method, can be removed. The quality of the function controlling the section shape has a major influence on whether a good hull is produced. By improving this function the hull generation method may become a more powerful design tool.

Despite these small shortcomings, good hulls can be produced and in most cases the hull can be developed further, into a yacht. The generation technique produced in this study will be developed further, to produced an application which provides more functionality that the system developed to date.

14 CONCLUSION

The final development of the hull generation technique provides a quick and efficient way of designing a yacht hull, which can be used directly or developed further to the taste of the designer. The following conclusions can be drawn about a computer method designed to generate yacht hulls with B-Splines:

- It is possible to develop a method that generate yacht hulls with B-Splines.
- Computer based generation procedures do not always provide enough flexibility in the amount of the shape of a hull can be varied
- B-Splines do not provide the best method for producing curve which have flow through points and bound areas. Characteristics that are required for a hull generation technique.
- B-Splines do provide the best method for transporting the hull definition to other applications and programs.
- A compromise has to be found to the number of parameters to optimise, to ensure a hull with the correct proportions is generated and to ensure that hull is suitable to be used as a safe marine vehicle.
- There seem to be many more applications for hull generation techniques than originally predicted, however, many of these applications are not considered to be as important in yacht design as they are in commercial ship design.

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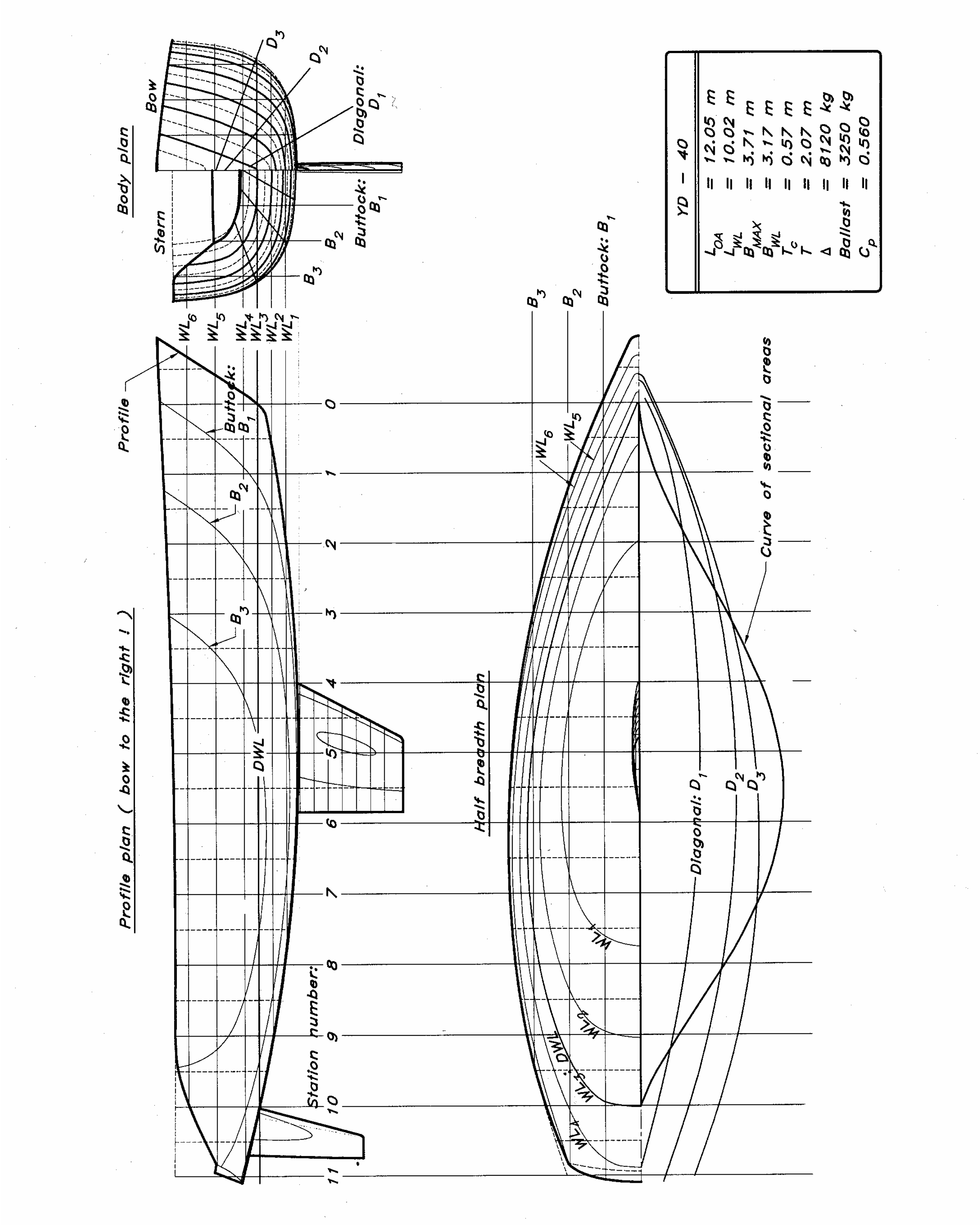
16 APPENDICES

APPENDIX 1 PARTICULARS OF THE YD-40.



APPENDIX 2 CALCULATION OF AREA AND CENTROIDS OF B-SPLINE CURVES.

In other methods, the use of explicit mathematical functions allows areas and centroids to be found easily through the use of integration. Method using this characteristic can find the shape of the curve by a reverse process of analysis. This can reduce the size of a method and in most situations a mathematically “elegant” process is developed. Finding the curve properties for B-Splines is more difficult, due to the complexity of the function. It was suggested that, if a process could be found for directly integrating B-Spline functions, then, a direct procedure for finding the shape of the B-spline curves, similar to the other methods could be used.

B-Spline functions are constructed from two parts, the Basis Functions and the control polygon. The Basis functions are normally found by the numerical analysis of the knot vector set. The numerical procedure for creating a B-Spline curve can be analysed so that Basis functions can be obtained. These functions are simple and can be easily integrated. Thus area under the basis functions can be found. The control polygon imparts a weighting factor on the B-Spline function, an area can be found for the B-Spline curve by multiplying the area found from the basis functions by the control polygon co-ordinates.

There are some interesting problems associated with this procedure. A number of equations are required to produce each Basic function, because the Basis functions are piecewise. A large number of piecewise functions is required for a B-Spline defined with many more points. However, the basis functions are mostly similar and are only non-zero for four sections of the control polygon of a cubic B-Spline. It may be possible to use a set of similar piecewise equations on most of the Basis functions to find the area of each. However, it is not directly clear what “area” is found by this procedure, as the function is parametric and it may not be a quantity that is of any use.

A procedure for finding the area of a B-Spline curve, for the general case would be intensive as it would have to put many small equations together to find the area of each Basis Function. The parametric nature of the B-Spline function makes it more difficult include boundary features when calculating, for example, the area of a section below the waterline. This complexity may make a mathematical procedure for finding the area of B-Spline curve practically impossible. Finally, A well defined B-Spline curve has control polygon with many vertices. An attempt to find the shape of a station, for example, by the analysis of the area and moments, such as used in other methods, would require more information to place correctly, the vertices of the control polygon. This procedure would have to result to an iterative process to find the position of these points and no advantage gained over a hull generation method using Simpson’s rule to find the area of B-spline curves.

APPENDIX 3 A RESISTANCE OPTIMISATION PROCESS

In most mobile marine vessels resistance is an important factor. As parametric hull generation methods can produce hulls quickly, there is scope for these types of procedure to include resistance optimisation. Functions developed to analyse resistance, generally, depend on experimental resistance data. The Delft series is one such procedure and can be used to find many components of resistance for a modern type of yacht hull.

Resistance is important in all vessels, however, in a yacht it has a higher priority. Although the wind is a free power source, there is no control over availability. Therefore, the sails and the hull have to be designed and constructed in a fashion to reduce the amount of energy lost. Without this, journey times can greatly increase. The Velocity Prediction Program is a tool which assists in this optimisation process. The VPP is, currently, unable to change the shape of the hull to optimise the performance, however, with the addition of a parametric hull generation procedure, this may be possible.

There are many components which contribute to the resistance of a yacht and the Delft series [5] is one technique which can be used to calculate these components. The functions used to calculate the resistance components of a yacht are:

- **Frictional resistance** - By using Froude's extrapolator, the energy lost due to the friction generated between the water and the hull surface can be calculated. The Froude extrapolator is also used to calculate frictional resistance caused by the appendages such as the keel and rudder.

- **Residuary Resistance** - This is a function which Delft series uses to model, through the use of experimental data, the energy loss in wave generation and from viscous pressures.

- **Induced Resistance** - This function is used in the Delft series to model, through the use of experimental data, the energy loss due to the induced drag associated with lift, which is generated by the hull and appendage foils.

- **Heeled Resistance** - This function is used in the Delft series to model, through the use of experimental data, the energy lost when the yacht is heeled.

- **Wave Resistance** - This function models how the resistance is affected when the yacht travels in waves.

These components all act to slow the yacht. By minimising the effect of each the hull can be made more efficient.

To optimise all these resistance components a Velocity Prediction Program would have to be constructed, as the effects of the sails have to be considered. A simpler resistance optimisation procedure can be developed if only the upright resistance is considered. Upright resistance is the largest resistance component, resulting in approximately 60% to 80% of the total resistance. Upright resistance is found from frictional and residuary resistance function.

A large section of the Hull Design chapter in Larsson and Eliasson [6] details which effects must be considered, when minimising resistance. For a hull of fixed geometric dimensions the resistance is governed by three key factors.

1) Optimum Prismatic Coefficient.

2) Optimum Longitudinal Centre of Buoyancy.

3) Optimum Gyradius.

Gyradius is a measure of the rotational inertia of a body and is controlled by the distribution of weight. Gyradius controls how well a yacht performs in waves, influencing average velocity. In a yacht, gyradius is controlled by the position of ballast, masts, auxiliary engine and outfit. The gyradius cannot be adjusted by a parametric hull generation system. Optimum values of Prismatic Coefficient and Longitudinal centre of Buoyancy can be adjusted by a parameter hull generation system, as these are some of the main parameters. Graphs of optimum values of these parameters are obtained from [6] and are shown in figure 16.2 and 16.3

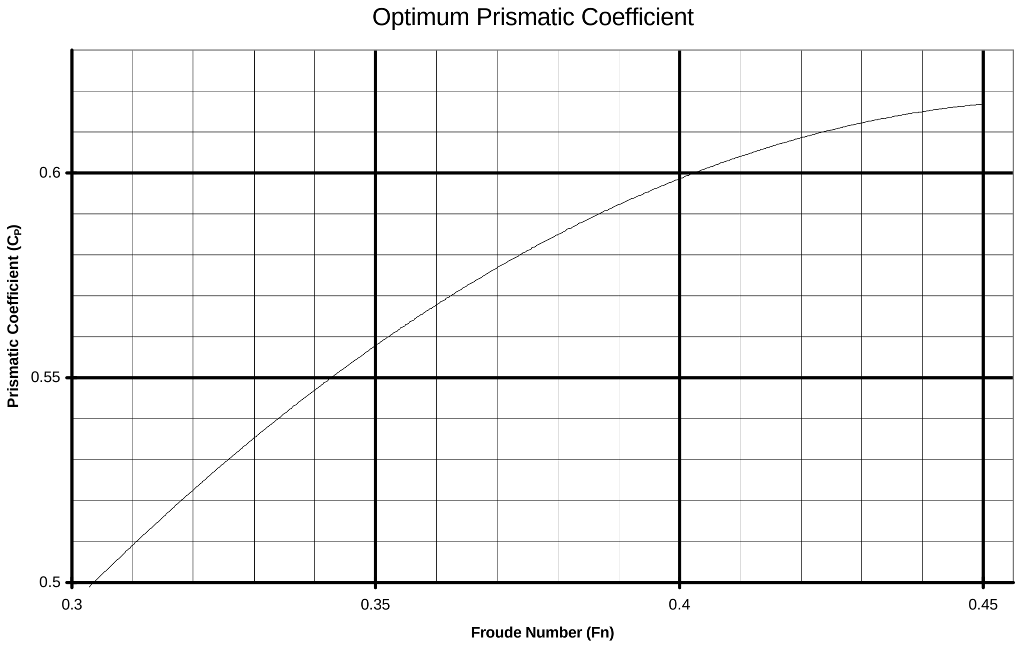


Figure 16.2, Optimum Prismatic Coefficient.

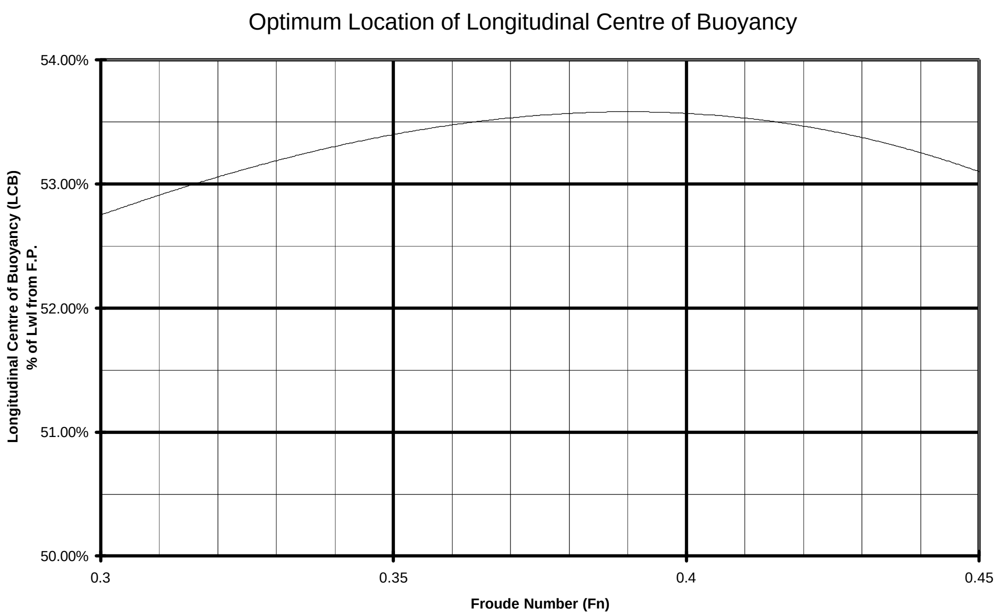


Figure 16.3, Optimum Position of LCB.

Both Figures 16.2 and 16.3 plot optimum values against Froude number. A decision must be made to which speed the yacht will have optimum performance. Larsson and Eliasson state that, normally, hulls are designed to have optimum performance for upwind sailing. The losses involved in upwind sailing are high as the yacht system has do travel against the flow of water, wind and waves. For upwind sailing, Larsson and Eliasson suggest that, the Froude number should be around 0.35.

To develop a resistance optimisation procedure it is necessary to include a database of information to allow the resistance to be optimised. Functions can developed from Figures 16.2 and 16.3 could be used to optimise the resistance, however, these may not contain enough information about the range of hulls and sailing velocities that could be considered. An example of the other affects that may be studied can be found the in yachts which competed in the last round the world Vendee Globe yacht race. The race is sailed mostly downwind, as the race is run from west to east. The Open 50 and 60 class yachts sailing in the race, were developed to have optimal performance downwind. To study these vessels the selected Froude number would not be that same as for upwind sailing.

A better method to optimise a hulls resistance characteristics can be develop by considering the upright resistance functions from the Delft series. By varying the values of prismatic coefficient C_P and longitudinal centre of buoyancy LCB, and calculating the resultant resistance, optimum values for C_P and LCB can be found. It is necessary to vary these factors by keeping other parameters constant. For this optimisation procedure, the displacement was kept constant by allowing the midship section coefficient C_M to vary.

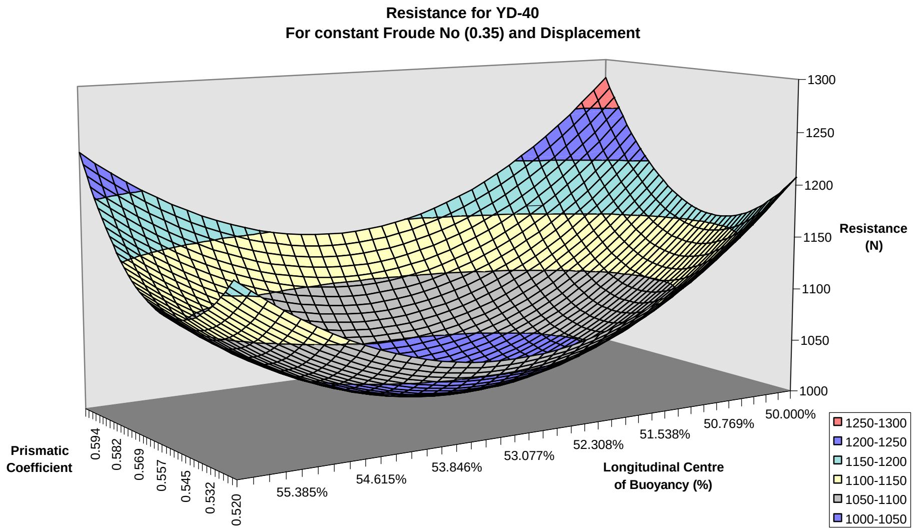


Figure 16.4, How resistance varies with C_P and LCB for a YD-40 (Fn=0.35).

Figure 16.4 shows the variation in resistance of the YD-40 hull with respect to C_P and LCB at a Froude number of 0.35. It can be seen that at this Froude number there is a minimum value of resistance.

The optimum values of prismatic coefficient and longitudinal centre of buoyancy can be found by using multivariable regression, over the data points found from the resistance calculations. The point of optimum resistance can be found from the resulting surface. However, this method would require the calculation of many resistance data points, which would take time and finding the minimum point would be more difficult. An easier method was chosen. By assuming that the effects of prismatic coefficient and longitudinal centre of buoyancy are independent, a single variable regression technique could be used. Two quadratic least squares fit were constructed through resistance data points dependent on prismatic coefficient and longitudinal centre of buoyancy. The quadratic regression functions can be easily differentiated to find the minimum point corresponding to optimum values of C_P and LCB. Results from the process agreed well with the optimum values of C_P and LCB developed for the YD-40 in [6].

The resistance optimisation procedure was developed further to be part of the desktop interface, YachtLINES, which was developed to demonstrate a graphical user to the hull generation method. The interface to the resistance optimisation process is shown in Figure 16.5.

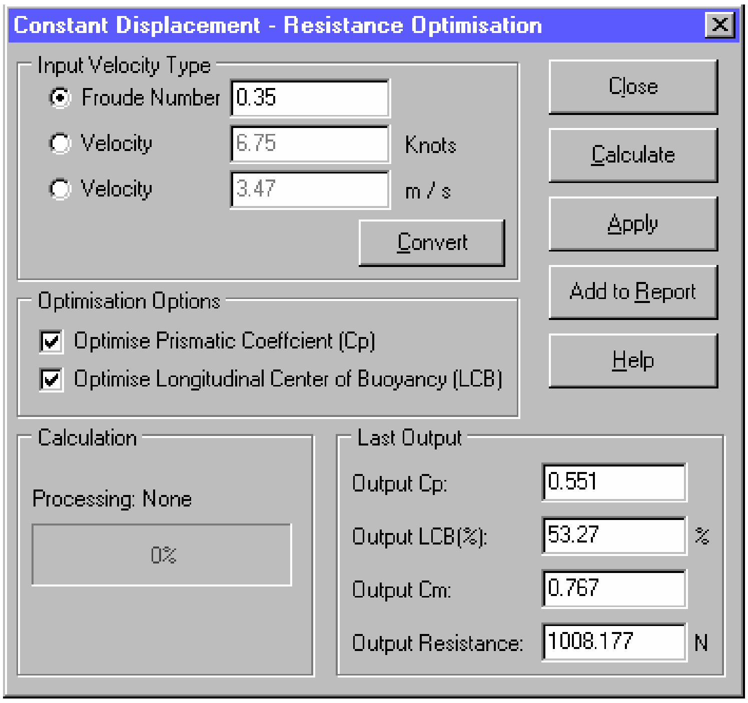


Figure 16.5, Resistance Optimisation Interface to YachtLINES

This interface creates an easy method to changes the velocity at which the hull is optimised. It also allows the user to specify which parameters are optimised and shows the progress of the procedure. Finally, all the information obtained from the hull, about resistance, is displayed.

APPENDIX 4 YachtLINES: A DESKTOP INTERFACE.

The parametric hull generation method developed, so far, has been implemented from within the basic DOS operating system. This operating system was developed to be simple. It does not supply full support for devices such as mice neither does it support high graphical screen resolutions. These shortcomings mean that a program has to supply its own software device drivers for every computer hardware system, to allow t every computer user to use the application in the same way. To supply device drivers for every computer system is difficult, as there are so many manufactures making equipment.

The Microsoft Windows operation system removes these headaches from the program. The operating system has support for most computers and supplies an interface to a program so that it can access all hardware functions, such as mouse operations. This type of operating system has given rise to visual program compilers such as Visual Basic and Borland Delphi. These systems allow a programmer to draw an application on the screen. The compiler does all of the work connecting the program to all different systems within the Windows operating. As a result, application programming for Window, with these compilers, is very simple and allows the programmer to concentrate on giving the application a fully functional user friendly interface.

The method has previously been programmed in Borland Pascal. Borland Delphi is a programming language that has been developed especially for the Microsoft Windows operating system and it is fully compatible with Borland Pascal. This allows the parametric hull generation system to brought directly from DOS to Windows.

Creating a user friendly interface within Windows allows the following functions to be performed easier.

- Loading and saving files.
- Viewing the hull, three dimensionally.
- Editing of Parameters.
- Easy addition of extra functions, such as a resistance optimisation process.

The interface was developed initially to support a Velocity Prediction Program with a full hull optimisation process. However, when the theory regarding the velocity prediction system was found to be fairly complex and based fully on experimental data, it was decided to make a less ambitious program. The primary aims of the program were to provide a graphical interface, to allow the parameters to easily edited and to allow the resulting hull to be viewed directly. The interface consists of four primary parts, each is contained in a separate window:

- **Generator** - This contains all the parameters allowing them to be edited easily. It also provides feedback from the hull generation procedure about the state of the generation procedure and if any warning or errors have occurred.

- **Yacht Lines** - This provides the primary means of viewing the hull. It is a view port which displays three the standard views of the hull in a layout similar to a lines plant. When parameters are edited, construction lines depicting the boundaries of the hull are displayed within the view port. After the hull generation procedure has been run the stations and hull outlines curves are displayed.

- **3D Viewer** - This displays only one hull containing the same lines as displayed in Yacht Lines and it allows the hull to be rotated around in three dimensions.

- **Report** - This is a text viewer in which a document can be created containing information such as input parameters, resistance information and hydrostatics.

Besides the parts necessary for parametrically generating the hull other functions included: a resistance optimisation procedure, hydrostatic calculations and a file export function to allow the hull to be used in other programs.

It was possible to develop a system which would have allowed the parameters to be edited interactively. A system such as this would re-generate the hull every time a parameter was changed. This would give the user more information about how the parameters affect a hull. However, this feature would have slowed down the hull generation process, as time taken to create a hull would have caused an inconvenient pause within program. The following figures 16.5 to 16.8 show the full application, YachtLINES, in use.

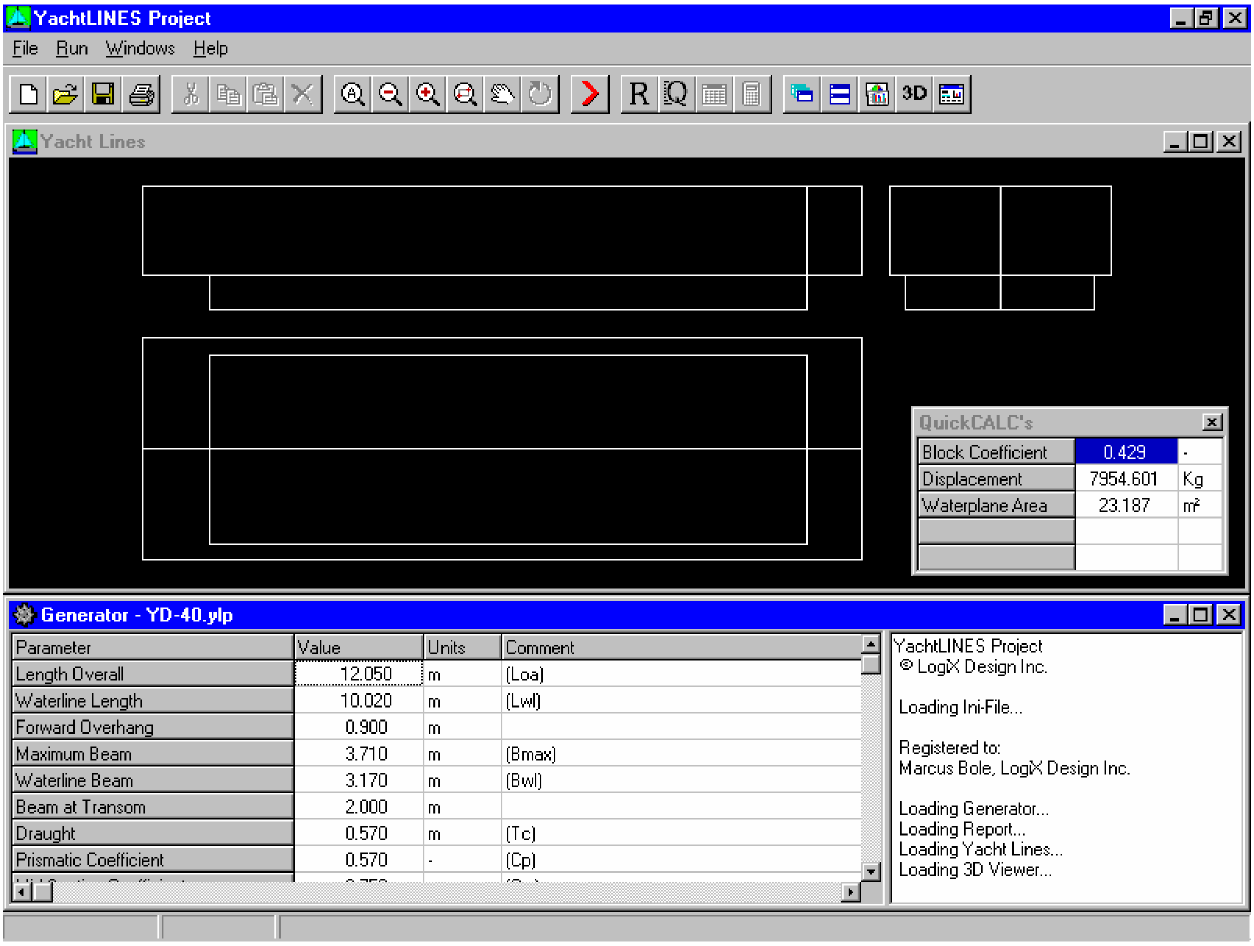


Figure 16.5, The display after the YD-40 parameters have been entered. The display shows the construction lines which outline the region within which the hull exists. The hull generation procedure can now be started.

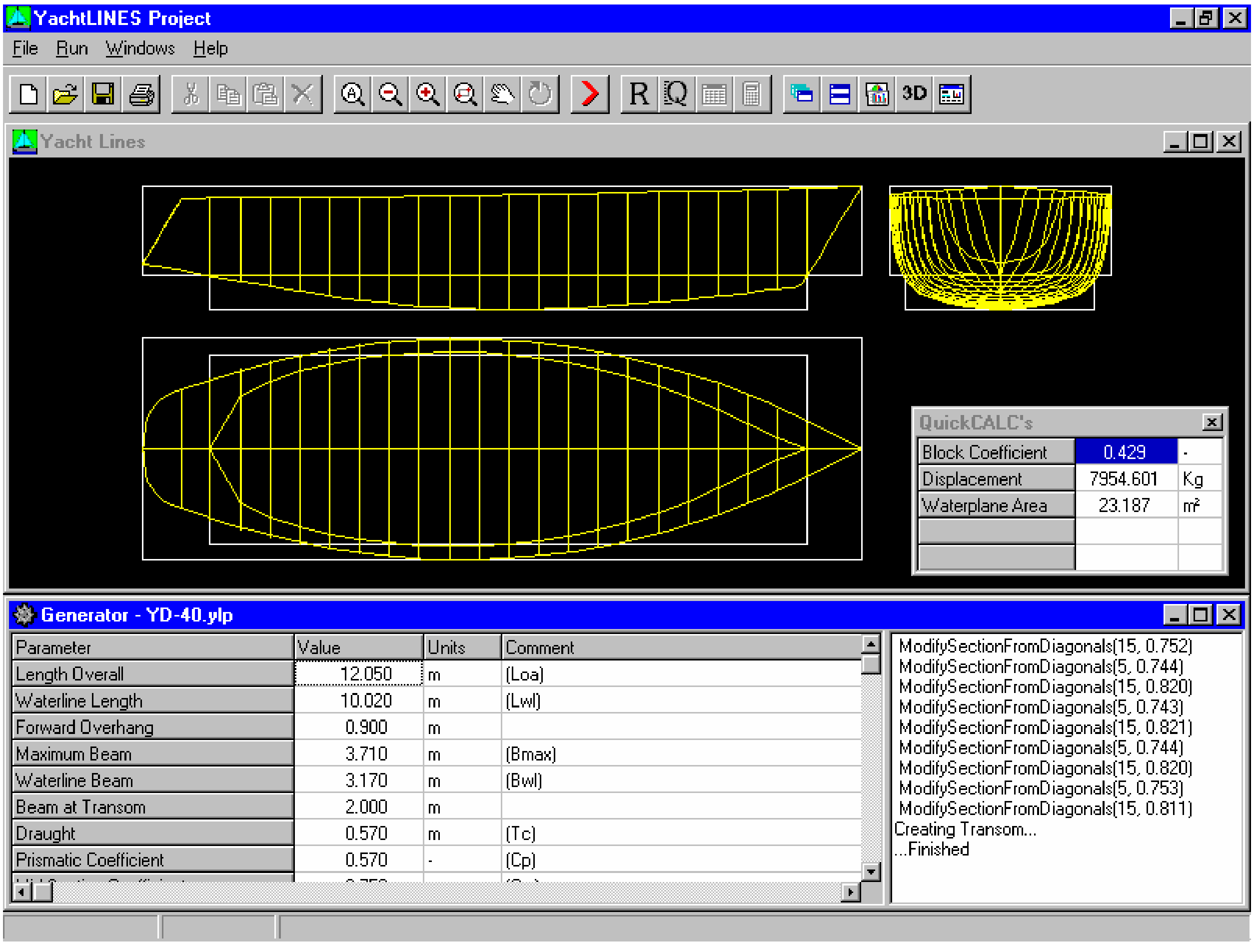


Figure 16.6, The display after the hull generation procedure has been run. The stations and hull outlines are shown in the Yacht Lines view port. Bottom right is the feedback given from the hull generation procedure.

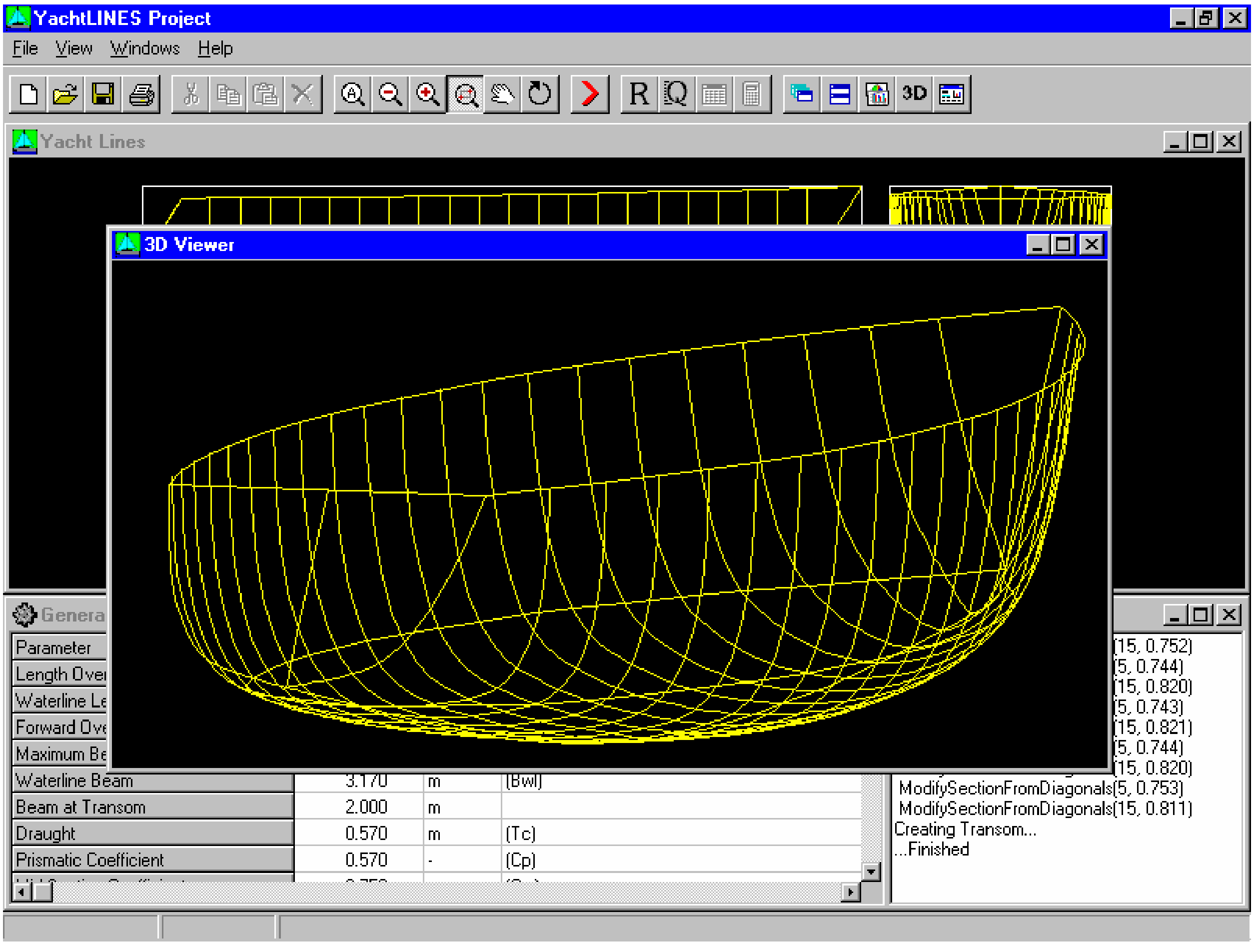


Figure 16.7, The 3D Viewer shows the hull in three dimension allowing the user to gain a better idea of the shape of the yacht hull.

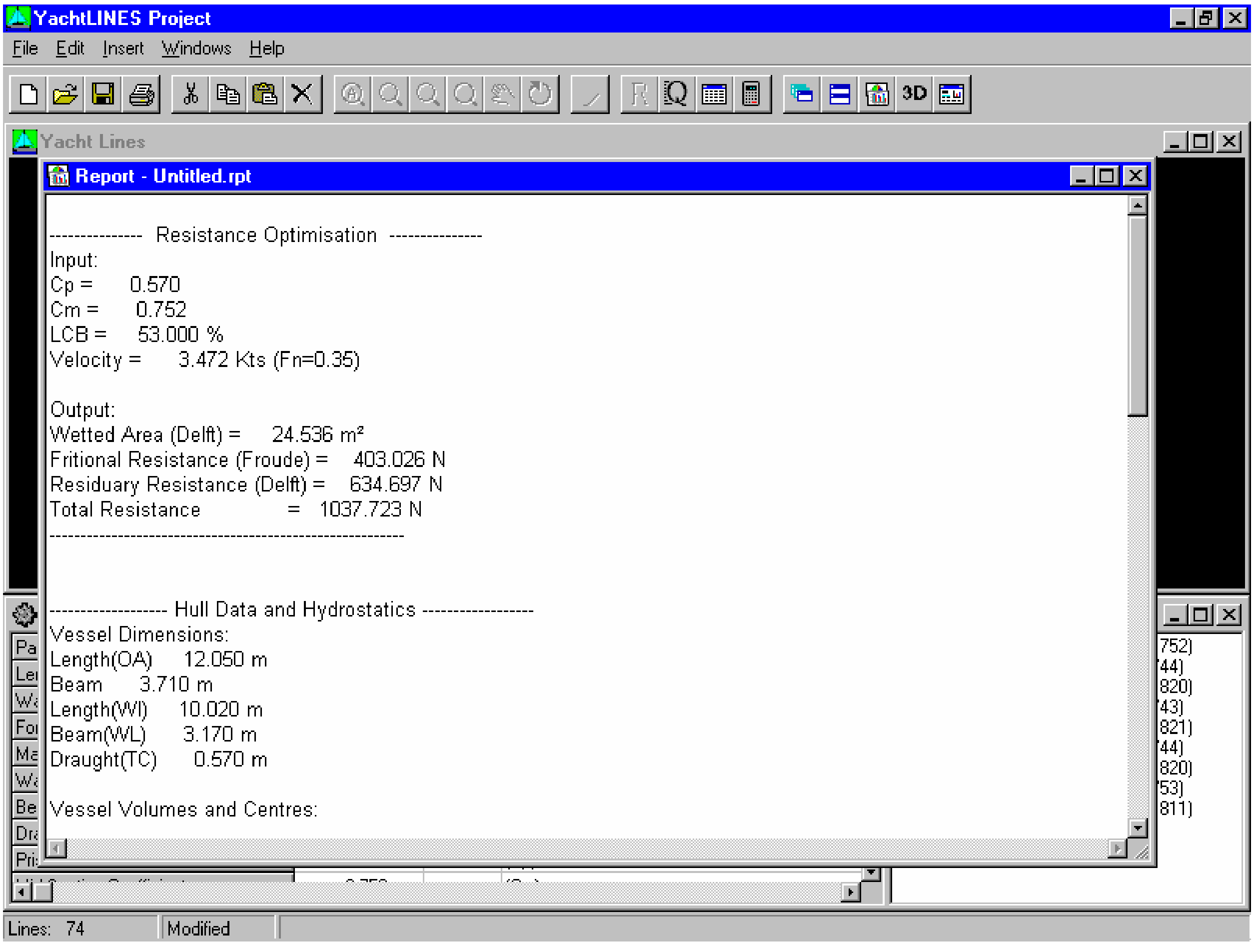


Figure 16.8, The Report window allows a record of the hull to be kept, containing information such as input parameters, resistance information and hydrostatics