IMPROVED SAILBOAT DESIGN PROCESS AND TOOLS USING SYSTEMS ENGINEERING APPROACH

Matthew Robert Zanella

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Alan J. Brown, Chair
Stefano Brizzolara
W. Nathan Alexander

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ACADEMIC ABSTRACT

This research provides a detailed and systematic update of the traditional sailboat design process, with specific attention being paid to the tools used for evaluation purposes, and in doing so creates an improved and optimized design process for sailboats. More specifically, this report seeks to modify a systems-engineering approach to the ship design process, in order to properly incorporate modern sailboat evaluation techniques as well as elements of traditional sailboat design while providing analysis of a case study from Virginia Polytechnic Institute and State University's ocean vehicle design class. In considering all intricacies of sailboat design and with applications and gradual improvement in quality of design through the use of multi-objective optimization methods, a new sailboat design process evolves, which initially considers a wide variety of design options and alternatives. Specific attention is paid in this process to the evolution of the ordering and analysis of each segment of the subprocesses, reducing design risk through the use of industry standard assessment procedures and ensuring consistent interaction with the customer. In doing so, an improved and effective design process is established, to be used by future sailboat design teams at Virginia Polytechnic Institute and State University.

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GENERAL ABSTRACT

Boats and marine vehicles of different types have long been a mainstay in the growth and development of this country's military, economic and transportation infrastructure. Whether being used for fishing purposes in the Pacific Northwest or moving oil and gas to different cities along the eastern seaboard, marine transportation plays a critical role in day to day life. Long before the invention of gasoline powered engines, most boats were powered by wind which was harnessed by the use of sails. In the 1800's sailboats were used extensively for fishing, delivering mail and a number of other important activities. Nowadays, the use of sailboats is more geared towards recreational endeavors including racing or simply cruising local waterways. It is the responsibility of the sailboat designer to deliver options and products commensurate with the prospective owner's preferences. As such, it is important for the designer to develop a process or system which incorporates useful tools which can successfully evaluate design alternatives. In doing so, useful information will be produced by which the owner and designer can collaboratively make decisions. Unlike a military or commercial ship, the owner of a sailboat is most likely the main operator and shares a personal connection with the boat. This study modifies a systems-engineering approach to the ship design process, in order to properly incorporate modern sailboat evaluation techniques as well as elements of traditional sailboat design. In doing so, the operation provides a process and tool benchmark for future sailboat design teams at Virginia Polytechnic Institute and State University.

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1 Introduction

1.1 Objective

The objective of this research is to provide a thorough update of the traditional sailboat design process, with specific attention being paid to the tools used for evaluation purposes, and in doing so, to create an improved and optimized design process for sailboats. The case study used for this particular analysis is from Virginia Polytechnic Institute and State University's ocean vehicle design class. Each year, teams are assigned a certain marine vehicle to design based on the provided requirements. These vehicles can range from recreational to military or commercial. In this case, the prospective owner, Professor Alan Brown, provided a team with a list of requirements for the development of a historical sailboat. This report seeks to modify a systems-engineering approach to the ship design process, in order to properly incorporate modern sailboat evaluation techniques as well as elements of traditional sailboat design. In doing so, an improved and effective design process is established, to be used by future sailboat design teams at Virginia Polytechnic Institute and State University (VT).

1.2 Manuscript Format

This thesis is presented in the VT manuscript format, including expanded drafts for two co-authored papers detailing work, led and contributed to by the author, in fulfillment of the thesis requirement. The two manuscripts presented in this thesis were prepared in collaboration with my academic co-author and derived from research performed at VT. The author of this thesis is the lead author of both papers.

It is the intent of the authors to submit sections of the manuscripts for publication through two symposiums of particular interest in the future. The first is the Herreshoff Marine Museum's Classic Yacht Symposium. Usually held on an annual basis, the museum was closed temporarily in 2020 for safety and health reasons associated with the COVID-19 pandemic. The second convention of interest is the Chesapeake Sailing Yacht Symposium, which is held every three years, and is due to be held in 2022.

This thesis also will be used as a reference source for sailboat design teams in VT's ocean vehicle design course. As such, the thesis includes additional material consistent with an instruction manual at some points, rather than a pure manuscript formatted set of papers. Prior to official submission for publishing, each paper will be refined and shortened to emphasize portions of the study which are of particular interest to attendees of the symposium rather than VT students.

The following manuscripts have been prepared for submission and publishing:

- Improved Concept Exploration Process and Tools for Sailboat Design Using Systems Engineering Approach
    - Co-Authored with Alan J. Brown
- Improved Concept Development Process and Tools for Sailboat Design
    - Co-Authored with Alan J. Brown

2 Improved Concept Exploration Process and Tools for Sailboat Design Using Systems Engineering Approach (Paper #1)

2.1 Introduction

Design involves the creation, "of a product, making choices and documenting those choices in an organized way to support the eventual procurement of material and creation of instructions for production workers to produce a final product that meets customer needs" (Brown, 2018). The "product" referred to, in this case, is a sailboat. However, there is not one all-encompassing methodology for designing sailboats, and few if any of the existing methodologies benefit from a modern systems-engineering approach. Existing sailboat design methods and processes differ greatly based on the characteristics required and the designer. This study focuses on adapting a combination of two previously established design processes, one a systems-engineering ship design process and the other a traditional sailboat design process, to develop an improved design process for a sailboat in the size range of twenty to fifty feet.

The two design processes combined in this research include Virginia Tech's (VT) naval ship design process and a sailboat design spiral method presented in *Principles of Yacht Design.* The first process uses a systems-engineering approach to produce a capable naval ship, while the other aims to design a sailing yacht using a more pragmatic, iterative procedure. These processes are inherently very different.

By following the particulars of the naval ship design process and considering the design process proposed in *Principles of Yacht Design*, an improved sailboat design process is generated. This paper specifically focuses on the concept exploration phase of the design process. It starts with a broad design space which is gradually reduced throughout the process to find an improved baseline concept design. Working from this baseline concept design, the concept may be further developed using a design spiral approach. This further concept development process is discussed in detail in a second paper, "Improved Sailboat Concept Development Process and Tools for Sailboat Design."

2.1.1 Sailboat Design Historical Context

In the latter half of the nineteenth century, approximately two hundred different types of small boats propelled by sail were used in North America. Each type of craft was, "developed to work in its home waters and weather conditions and to meet the physical requirements of its employment." Limited in available monetary and raw material resources, workboats were created using a trial and error process over a long period in order to meet the requirements of their use. However, over the past century or so, wind propelled workboats, similar to the boat shown in Figure 1, have been almost entirely phased out of use. They were not phased out, "because they were impractical, slow, or leewardly, or because they were not strong, lasting, or seaworthy" (Chapelle, 1977). The majority of these sailboats no longer exist, due primarily to the rise of low-cost gasoline engines in workboats.

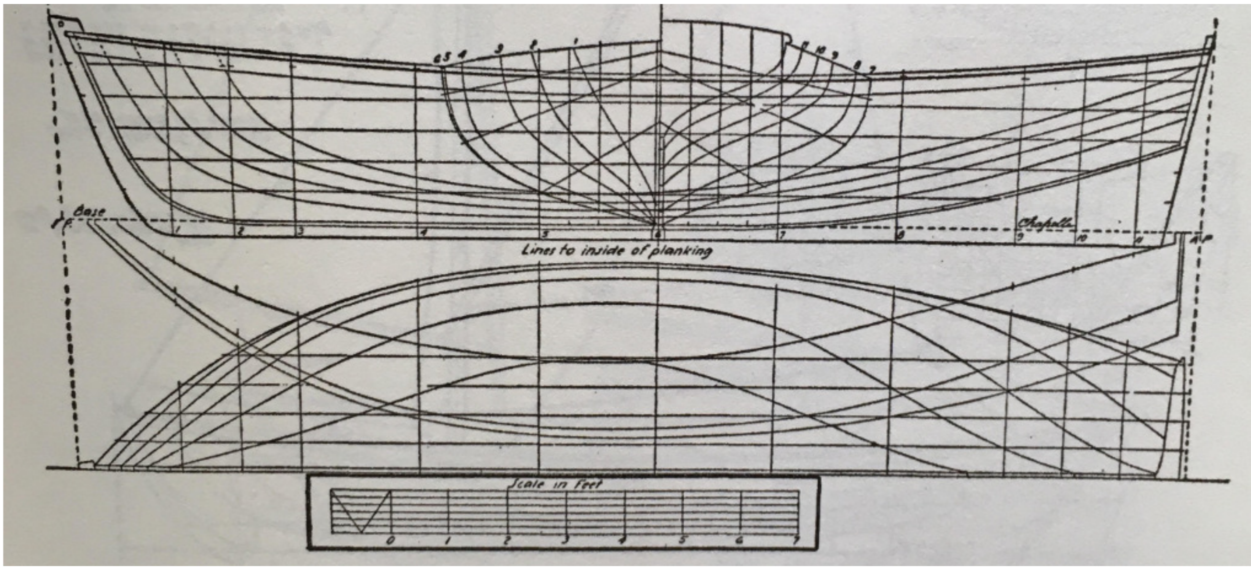


Figure 1 - Yawl-boat. Popular workboat choice in 1800's (Chapelle, 1977)

Present day yacht standardization produces designs which do not possess the same advantages or unique characteristics as those older boats which were built with a specific operating environment in mind. Furthermore, yachting standards in, "construction, finish, rig, and fittings" are quickly becoming very expensive for most small-boat sailors. Mass production of small boats seeks to address the cost issue, but this has led to an, "even narrower standardization in hull and rig and more misfits for local conditions and individual needs" (Chapelle, 1977). Moreover, mass production does not fully address lower cost, as expenses due to distribution and advertising often surpass the manufacturing cost. (Chapelle, 1977)

The early 1800's proved to be a time of experimentation with sailboat rigs in America and is demonstrated by the sail plans appearing in many drawings of naval ships. In fact, the wide variety of sail and rig options seen in the country at that time offered many choices for commercial small boats. Rigging and sailing arrangements continued to evolve in local markets as the desire for faster small craft and more weatherly rigs were driven by competition. (Chapelle, 1977) The most common types of rig configurations seen during this time, which are still found today, include yawls, schooners, ketches, and sloops. The yawl has two masts with the mizzen (aft) mast shorter and aft of the rudder post, while the ketch arrangement is similar, but with the mizzen forward of the rudder. A schooner has two or more masts with a shorter foremast, as shown in Figure 2. A sloop has a single mast which carries a jib (triangular sail usually hoisted from a bowsprit to the top of a mast). The cutter rig design includes one mast with several working headsails. (Yacht Invest, n.d.)

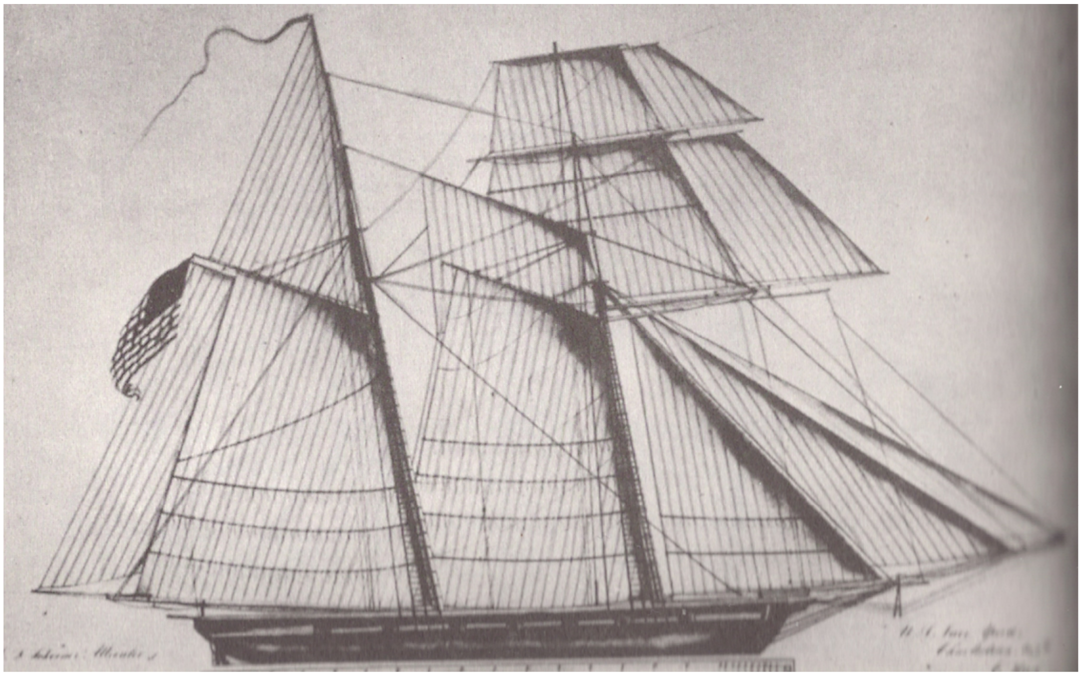


Figure 2- USS Alligator Sail Plan (Chapelle, 1949)

The case study for this paper specifies a Sharpie design. Sharpies are a unique type of workboat that enjoyed a time of popularity consistent with other small sailboats in the late 1800's. An example of a popular Sharpie hull is provided in Figure 3. While the exact origins of the sharpie are unknown, it has been established that flat-bottomed craft of many types and sizes existed prior to recorded history. Here, flat-bottomed includes single curvature (longitudinally) bottoms and sides which are flat transversely. Flat or single-curvature boats are much simpler and less costly to build. From across the Atlantic in Europe and the British Isles, flat-bottomed craft came to America on the decks of ships and were reproduced in the colonies in the forms of skiffs and scows varying in type and size. These early boats were limited by the availability of planking stock and were normally less than twenty feet. In New England, European settlers learned to make log canoes from Native Americans. Log canoes were used to lighter goods from ships at anchor outside of the shallow harbor in New Haven. The New Haven canoes ranged from twenty-eight feet to thirty-five feet in length, three to 3.5 feet wide, and three to four inches in draft. By the mid-nineteenth century, the oyster fisheries dictated a need for a longer, modified flat-bottom craft design. Through demand, flatiron skiffs quickly evolved into a longer, proportionately narrower and better-performing craft. These boats came to be known as "sharpies" due to their long, fine, and sharp bows. (Parker, 1994)

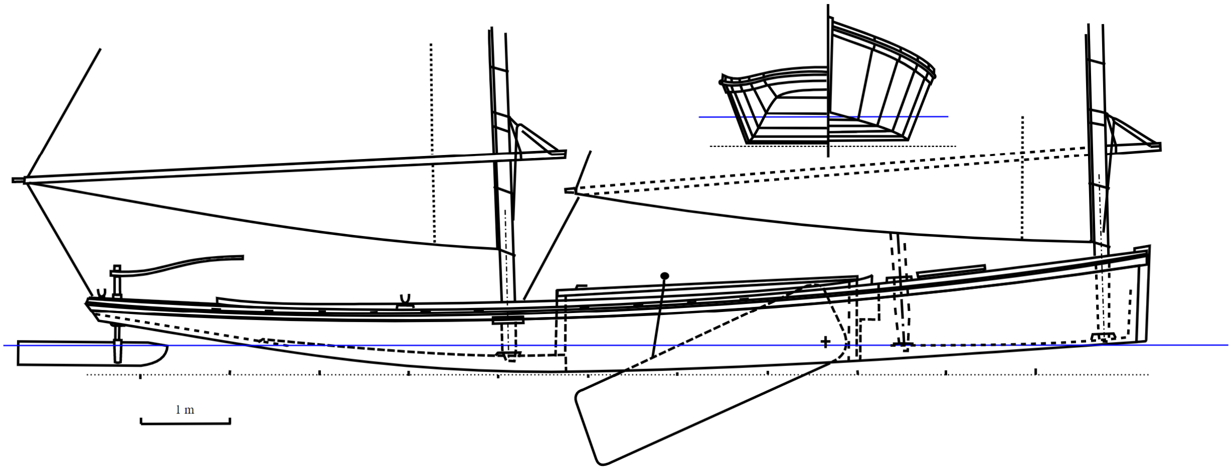


Figure 3- 35' New Haven Sharpie (Parker, 1994)

No certain description of early sharpies exists, but it is assumed they were twenty to thirty feet long, narrow, open, flat-bottomed skiffs with a square, raked transom and a centerboard. These boats carried one to two freestanding pole masts stepped through thwarts and used “leg-o’-mutton sails”, shown in Figure 4. These leg-o’-mutton sails were of simple triangular design and consisted of a long spar mounted horizontally on the mast, running in a fore and aft direction. The setup uses a spar mounted high instead of a boom to allow the helmsman more visibility and is similar to a “spritsail” but uses triangular sails as opposed to square (Routh, 2020). Sharpies used for gathering oysters were defined by their high, tucked sterns, while the oysters were loaded into the deepest part of the hull bottom located just aft of midships. This design characteristic enabled the sharpies to be heavily loaded in the aft portion of the boat, without immersing stern or stem, and while also preserving the lowest possible center of gravity. Sharpies designed for racing and cruising differed from these sharpies in their lower sterns, as well as the amount of curvature distributed in the longitudinal contour of the boat. On these boats, the lowest part of the hull body was located further forward, resulting in a flatter run and lower displacement potential. (Parker, 1994)

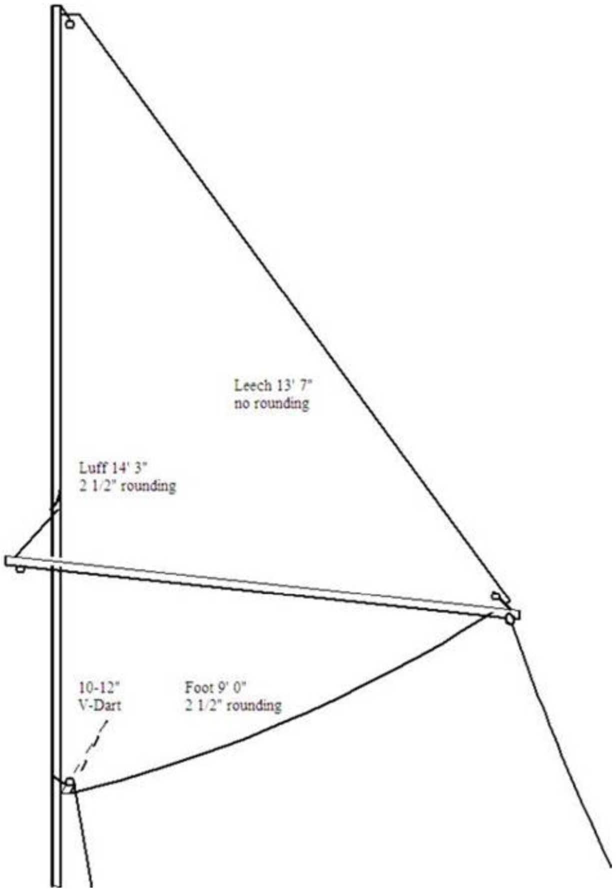


Figure 4- Leg-o'-mutton Sail (Gray, 2009)

By the end of the nineteenth century, deep keel cutters had become the most commonly used yacht design. Nonetheless, Long Island boatbuilder Thomas Clapham felt strongly that the small draft sharpie design was superior to the deep keel cutter. Clapham repeatedly defended this stance, stating, “I am at present building a sharpie, on experimental lines, and if the captain of any cutter or deep keel yacht is anxious to prove a shaky theory I will be most happy to give him a turn to windward and home in any kind of weather and the rougher it is, the more sanguine I am of demonstrating that 15” is better than 15’ in the way of draft” (Parker, 1994). Supporters of the deep keel and heavily ballasted hulls used in England during this time period argued, “It would be opposed to the lessons of practice should such small bodies and rigs on a (given) length be accepted as equal in general ability of yachts of more power” (Chapelle, 1977). In short time, sharpies were banned from racing any sailboats other than sharpies, as they were simply too fast. As sharpie critics continued to argue that the sharpie design did not exhibit comparable seaworthiness characteristics to the deep keel cutters, Clapham cited a maritime rescue in 1879 to support his position; “Reported that a sharpie went out from Branford, Connecticut to the reef off that harbor and rescued the crew of a schooner wrecked there when neither smack nor tug could be found in New Haven to venture out.” In 1881, he went on to say, “There is not the slightest difficulty in producing an uncapsizable light draft yacht that will equal or surpass the cutter in seaworthiness and speed yet be absolutely unsinkable. Why, then, should we turn to England and borrow a loggy, slow and unhandy model when at our own water’s edge, we have something better at far less cost”

(Parker, 1994)? This question posed by Clapham will be revisited in the sequel to this paper, "Improvement of Concept Development Process and Tools", as the performance of Sharpie designs are analyzed and compared.

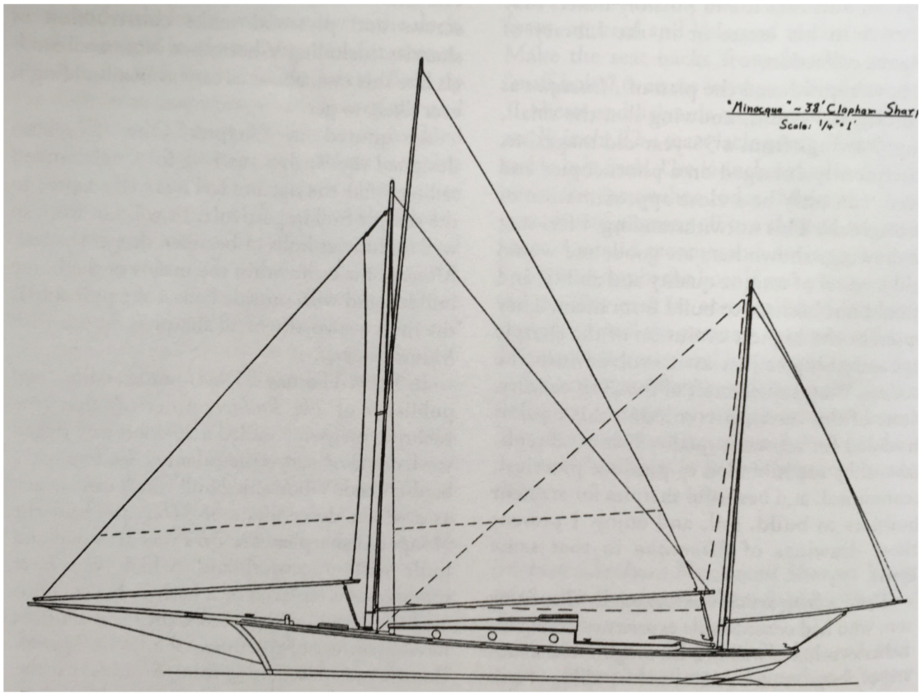


Figure 5- Clapham's 38' Nonpareil Sharpie (Parker, 1994)

This significant affinity for English "plank-on-edge" type cutter sailboats is often referred to as the American "cutter craze." Essentially, yachtsmen had become split between a preference of deep-keeled, heavily ballasted hulls and shoal-bodied centerboard hulls. The shoal-bodied centerboard hulls, much like the boat shown in Figure 5, were generally faster, but isolated accidents frequently resulted in their condemnation as unsafe. Even though most of these accidents were the result of errors in judgment, it remained that shoal-bodied hulls were almost never self-righting, contrary to the self-righting abilities of deep-keeled hulls. The late Howard Chapelle, America's foremost authority on small-craft design and history, through his research surmises, "The speed of the sharpies has ample testimony, and some of the large boats were found to have sailed at remarkable rates: one sharpie covered eleven nautical miles in thirty-four minutes [over nineteen knots!], and another averaged sixteen knots for three consecutive hours. These high speeds were obviously with started sheets and with the hull in a planing attitude" (Parker, 1994).

Over the past hundred years, there have been few new developments to the sharpie for various reasons. As the onshore oyster industry declined in the Long Island Sound, oysters began being collected farther offshore and steam powered ships were used for this purpose. In the Chesapeake Bay area, V-bottomed boats found more favor. The use of gasoline power effectively ended the age of sail for non-recreational purposes. Two world wars slowed the development of new boat types. Lastly, fiberglass almost completely replaced wood in construction, which encouraged different hull shapes. The flat sections and chines of the sharpie do not lend themselves to fiberglass construction. Modern day flat-bottomed boats have survived in the form of workboats, and plywood skiffs, which are generally engine powered. As a result, the boats are beamier, heavier, and rarely display the beauty and efficiency of sharpies. (Parker, 1994)

Although the sharpie design was continually disparaged for its lack of seaworthiness and seakeeping, Clapham and others maintained that these boats could easily be made "uncapsizable and unsinkable, great seakeepers, with dry decks" (Parker, 1994). However, no modern conclusive study has taken place to determine this matter in an unbiased fashion.

For this paper, it is beneficial to provide further historical context on two specific types of sharpies, which are used as representative designs in the case study for this process for comparison purposes. The "Egret" was developed by Commodore Ralph Munroe in the 1870's, and was brought to Biscayne Bay, Florida in 1876, introducing the sharpie to the southeast portion of the country (Chapelle, 1977). An "Egret" Sharpie design customized for the waters of Florida is provided for reference in Figure 6.

Figure 6- Sharpie Built in 1885 for Florida Waters (Parker, 1994)

The Egret is widely accepted as the most seaworthy of all sharpies. The Egret is characterized by its double-ended shape. Her narrow bottom is slightly deeper, and topsides higher and more flaring than the average sharpie (Parker, 1994). Munroe described the Egret as a, "sharpie-lifeboat… very strongly but lightly constructed. She drew eight inches, and had only fifty to seventy-five bricks, laid under her floor, for ballast. She was fitted with all appurtenances needed to keep the sea in almost any weather, and if necessary, to be put on the beach without harm" (Parker, 1994). The Egret distinguished herself in a variety of ways including transporting the mail from Palm Beach to Miami in all seasons. Although the original lines for Munroe's Egret do not exist, *Woodenboat Magazine* generated an interpretation of the original based on older photographs and descriptions. In addition, Reuel Parker, who authored *The Sharpie Book* provided his own interpretation of old Egret photographs, which is presented in Figure 7.

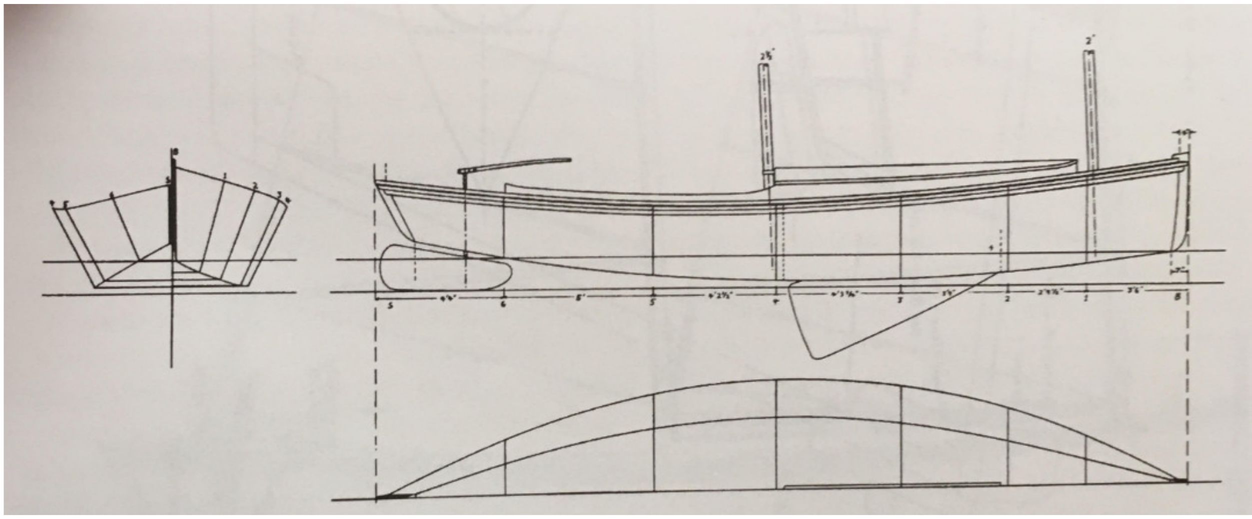


Figure 7 - Parker's Interpretation of Munroe's Egret (Parker, 1994)

The second boat referred to in this paper is the North Carolina Sharpie, which is shown in Figure 8. Dozens of bays and sounds protected by long strips of barrier islands from the Atlantic Ocean, help to define the maritime landscape of this area of the country. The majority of this water is, "tidal estuary, rich with shellfish in very shallow water, often little more than three feet deep" (Parker, 1994). Given the parameters of the navigable waterways, the sharpie proved to be an extremely effective design for working the surrounding oyster grounds in the 1890's. The North Carolina Sharpies were larger than many of the other original sharpie designs and increased further in size when dredging replaced tonging as the primary oyster-harvesting method. Although not as fast as some of the other sharpie designs, the boat's increased beam allowed for greater initial stability and the ability to carry more sail. She retained the fine lines and low freeboard that most sharpies share while possessing a very raked transom. The North Carolina Sharpie was a very able craft under unfavorable conditions and often worked in, "fierce gales that swept the Carolina Sounds in the fall and spring" (Parker, 1994).

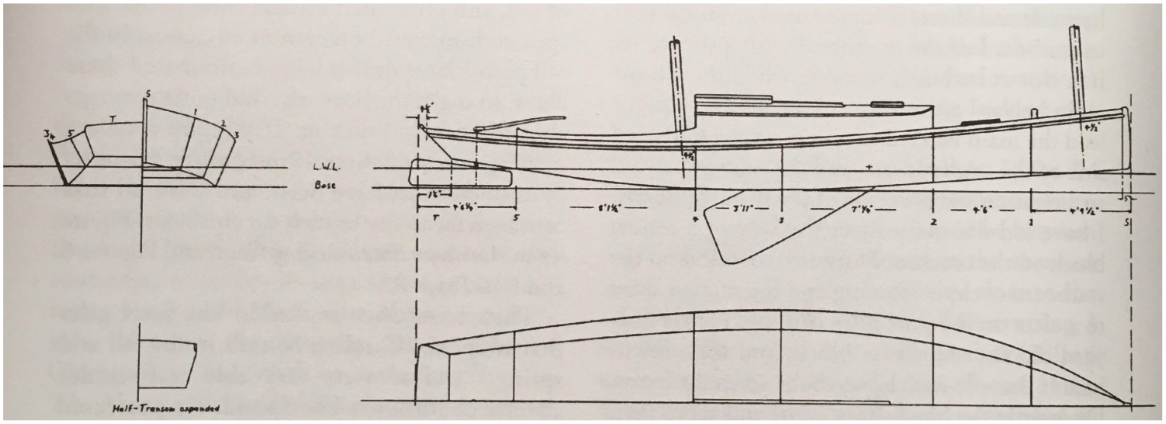


Figure 8 - 33' North Carolina Sharpie (Parker, 1994)

2.1.2 Modern Sailboat Design

In modern sailboat design as practiced by most current designers, the “trial and error” process of yesteryear has evolved to a “design spiral” operation. *Principles of Yacht Design* describes industry standard design practices and outlines the design spiral method, as illustrated in Figure 9. In the design spiral, “the designer runs through all the design steps and then returns to the starting point, whereupon a new ‘time-around’ begins. After several turns, the process may have produced the desired result” (Larsson & Eliasson, 2000).

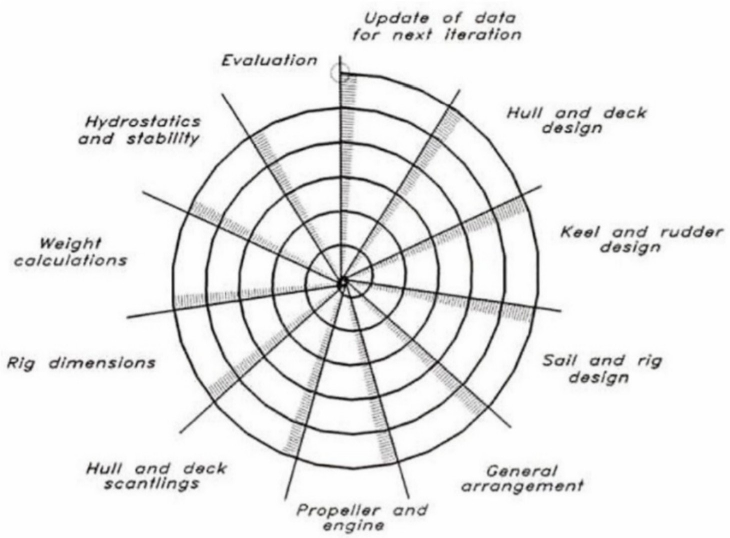


Figure 9- Design Spiral (Larsson & Eliasson, 2000)

Eleven separate segments of the design spiral are identified and represent distinct operations by the designer. Not all operations need to be completed in each iteration, and the tools used may vary from turn to turn. As a matter of principle, more and more segments are included, with increasingly more high-fidelity tools used as the process converges to the final solution (Larsson & Eliasson, 2007).

The first iteration begins with owner’s requirements provided by the customer, and the designer starting with a number of assumptions regarding the main dimensions of the hull based on experience and/or data from other yachts (Larsson & Eliasson, 2000).

While the first iteration may involve only a few operations, the second step might begin the design of the hull, appendages, and sail plan. An approximate layout of the exterior and interior design may be done, in order to generate an initial weight estimate. The initial weight estimate is essential for stability calculations, but as the weight is likely to be incorrect, several turns around the design spiral may be required to satisfy reasonable requirements. Once reasonable weight and stability values have been established, the next iteration may include detailed hull scantling calculations, as well as rig sizing, and auxiliary propulsion determination. (Larsson & Eliasson, Principles of Yacht Design, 2007)

Within the segments identified by the design spiral, internal iterations may be necessary. For example, the hydrostatics and stability segment may require finding the proper sinkage and trim when the hull heels at large angles. If these iterations are completed manually, iterations may take a substantial amount of time to be completed. (Larsson & Eliasson, 2007)

Unlike Clapham and other boatbuilders of his time, modern yacht design can enlist the assistance of several new tools to evaluate the performance and characteristics of a design. Through use of these tools, rather than relying strictly on experience, more accurate iterations for certain segments can be completed in a shorter amount of time, with respect to the overall design spiral (Larsson & Eliasson, 2007).

The most revolutionary tool that plays a significant role in modern yacht design is computer aided design (CAD), which is a powerful program that allows for the generation of hull lines. In modern CAD programs, hull surfaces are represented mathematically by non-uniform rational b-splines (NURBS) patches. In this case, once two coordinates of a point are given, the third coordinate is computed. For example, if the designer inputs the distance from the bow, X, as well as the distance above the waterline, Z, the CAD program should compute the local beam, Y, at the specified location. (Larsson & Eliasson, 2007)

In addition to aiding in the production of new hulls and/or duplicating existing hulls, CAD programs also have the capability of rotating the hull to show its perspective on the screen. This capability is a major advantage over the manual approach, in which only three (3) standard views are available. As an example, the sheer line may look significantly different in perspective when compared to the side view because the sheer line is also influenced by the beam distribution along the hull. While a hull may look satisfactory in a side view, it may appear quite differently in reality.

Additionally, CAD modules can include hydrostatics and stability programs. These programs are able to calculate stability at small and large heel angles, weight per unit sinkage and moment per degree of trim, saving a considerable amount of time versus completing this manually. (Larsson & Eliasson, 2007).

Another tool that has become important for the modern yacht designer is the Velocity Prediction Program (VPP). This is a computer program which predicts speed, heel, leeway, and other quantities for a boat based on wind speed and direction. By methodically altering the program input, while also specifying the hullform, the designer can optimize the design with respect to different qualities. *Principles of Yacht Design* provides a basic flowchart for a VPP, including many of the requisite formulae, which are mostly based on information generated from empirical data.

Model testing is a technique which allows for the population of more exact information for a particular design. However, this approach is cost prohibitive for many designers. Model testing is usually completed only in connection with large projects such as the America's Cup. (Larsson & Eliasson, 2007)

Depending on method, level of fidelity and design stage, computational fluid dynamics (CFD) can provide a quicker and less expensive alternative to model testing. CFD is used to carry out numerical flow calculations and is an increasingly popular tool used for professional yacht design. The popularity of this tool is due to the rapid development of computers. This method provides an additional advantage over model-testing, in that detailed information can be obtained on the flow everywhere around the hull. Velocity vectors, pressure distributions, and streamlines are standard CFD outputs, and can be examined for additional information. Whereas, finding this data via model testing would be exceptionally expensive.

2.1.3 Virginia Tech Ship Design Process

A systems-engineering-based ship design process has evolved at VT over the last twenty years. It was developed primarily for naval ships, which must carry out combat missions in addition to satisfying various other machinery, electrical and propulsion requirements. As such, the VT process includes a number of steps that are not found in the design spiral process shown in *Principles of Yacht Design.* The VT ship concept design process consists of two main phases, concept exploration followed by concept development.

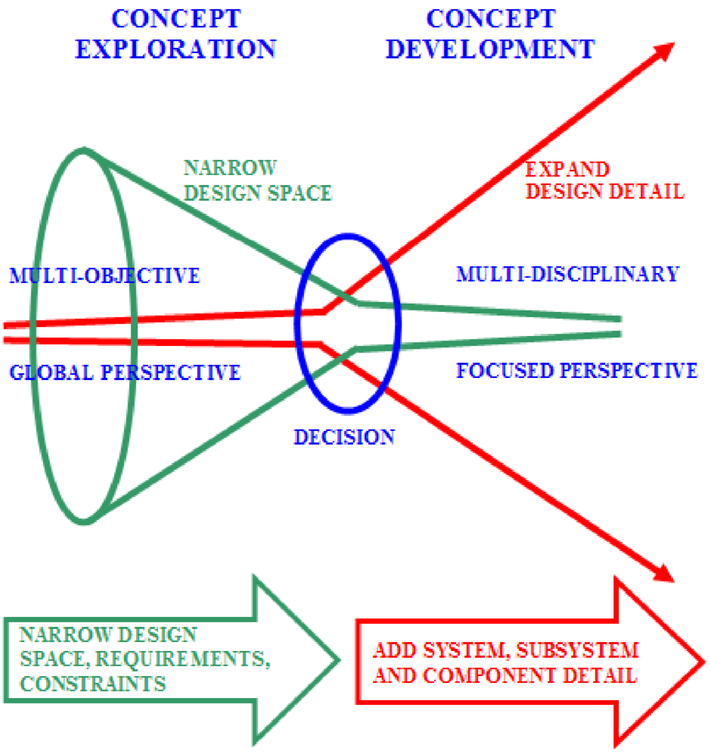


Figure 10- Concept Exploration and Concept Development Relationship (Brown, 2018)

The concept exploration process initially considers a broad design space, which is gradually narrowed down based on design space explorations applying constraints and thresholds to identify feasible designs. This is followed by a multi-objective optimization which performs a systematic search of the remaining design space searching for non-dominated (Pareto optimal) designs until a non-dominated frontier is identified from which preferred design options are selected. This is a systematic and rational process using metrics developed from the mission definition and applicable technologies. The concept development process begins after the conclusion of the concept exploration phase and concentrates on expanding design details through adding system, subsystem, and component particulars with the goal of reducing design risk. This reduction of an initially large design space is illustrated in Figure 10. (Waltham-Sajdak & Brown, 2015)

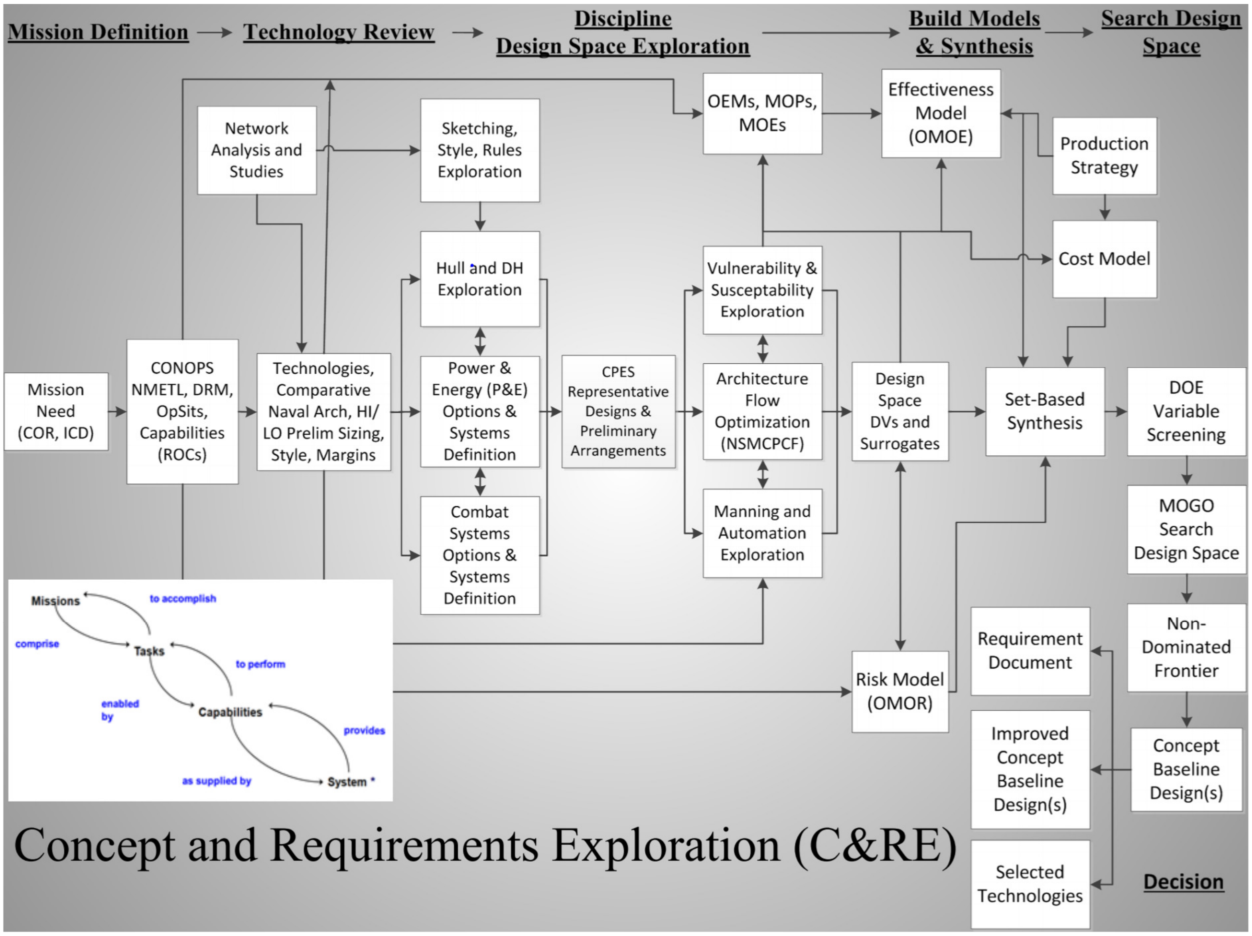


Figure 11- Virginia Tech Concept and Requirements Exploration Flowchart (Brown, 2018)

The current VT concept and requirements exploration (C&RE) process is illustrated in Figure 11. Although the design process for a sailboat must vary significantly from that of a large naval ship, there are various elements which can be brought from this model to the sailboat concept exploration process. Both procedures must begin by identifying the baseline mission, goals and thresholds for the design. In Figure 11 this is accomplished in the "Mission Need" and "Required Capabilities" blocks. The general process flow shown in Figure 11 follows Mission Definition with a Technology Review, Discipline Design Space Explorations, Definition of Objective Attributes, Model Building and Synthesis, and the Design Space Search. Each of these high-level process steps is totally applicable to the Sailboat Design Process. (Waltham-Sajdak & Brown, 2015)

Individual exploration blocks include hullform, power and energy systems, combat systems, survivability and manning; and these explorations are performed using representative designs. Most of these explorations and the use of representative designs have counterparts in the sailboat process including hullform, keel, rudder, sail, accommodations and sea-worthiness / damage stability. Both concept exploration processes synthesize and identify balanced designs in the context of a multi-objective optimization (MOGO), identify a "Non-Dominated Frontier" and finish with the selection of a "Concept Baseline Design." These aspects of the process are largely systems-engineering operations intended to gather information and narrow the initially broad design space. (Waltham-Sajdak & Brown, 2015)

In terms of differences between the two (2) concept exploration processes: the sailboat concept exploration involves fewer systems and fewer system options; the assessment of operational effectiveness, cost and risk is more simplified; and system interdependence is less about energy flow and more about force and moment balance. Sailboat design poses its own unique problems including the interdependence of hullform, keel, rudder and sail, and the dependence of all of these on wind conditions and the desired heading.

The concept development portion of the VT design process incorporates elements similar to those discussed in *Principles of Yacht Design* and is provided for reference in Figure 12. Again, it is important to note that this design spiral was previously established for large naval ships and must be adapted accordingly for the sailboat design process.

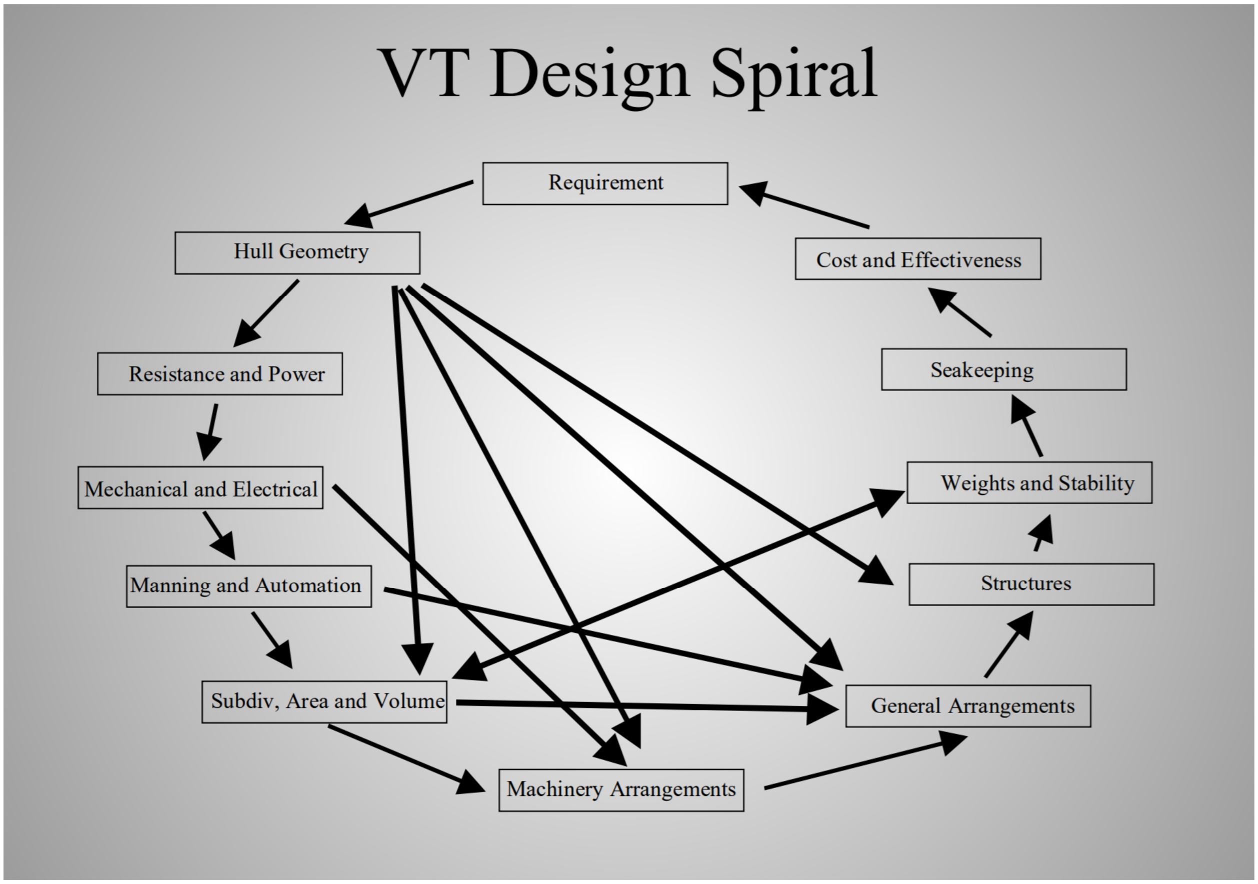


Figure 12- Virginia Tech Design Spiral (Brown, 2018)

2.1.4 New Sailboat Concept Exploration Process

In support of sailboat designs in the VT Ocean Vehicle Design course, a new sailboat design process and tools were developed by adapting a combination of two previously established design processes, the VT naval ship design process and the traditional sailboat design process with modern tools.

The interdependency of different segments of the sailboat design process was not fully appreciated at first. Naval ships require many systems which are not found on sailboats and although these systems are also very interdependent, they depend primarily on energy flow as mechanical and electrical power and heat. Sailboats are all about force balance and sailboats cannot be adequately evaluated at zero trim, heel angle and yaw since they will rarely, if ever, be used in such a condition. A sailboat is constantly subjected to changing rotational and translational forces that depend on relative wind direction and speed.

Critical sailboat systems to be designed in this process include:

- Hullform
- Sails
- Keel
- Rudder
- Topsides (hull and deckhouse)
- Arrangements
- Boat structure and materials
- Rigging
- Auxiliary propulsion

Some of these systems receive more attention in concept exploration (hullform, keel, rudder, sails); all are developed and refined in concept development. Everything begins with the hullform, keel and rudder which collectively make up the underwater body. Hydrostatic forces and hydrodynamic forces all act on these systems. Aerodynamic forces act on the sails and the topsides. In a quasi-steady state sailing condition, at an equilibrium angle of heel, trim and yaw, and for a given relative wind angle and speed, all forces and moments must balance. This requirement strongly couples the design of these four systems.

Considering all of these intricacies of sailboat design and with applications and gradual improvement over three designs, a new sailboat concept exploration process model shown in Figure 13 has evolved. Specific attention is paid in this process to the evolution of the ordering and analysis of each segment of the concept exploration phase. It begins with the owner's requirements and the projected operational environment. The process continues with comparative naval architecture to identify designs with similar desirable characteristics (representative designs) and produce an initial range or design space of design characteristics. These characteristics may become design variables (DVs, different for different designs) or Design Parameters (DPs, same for all designs). During this step of the design process, representative design hull models may be developed and analyzed using CAD. As an example, an owner interested in developing a twenty-foot sailboat, would begin by modeling several sailboats of similar length, perhaps ranging from seventeen to twenty-three feet. The range of values for the design variables considered can be as expansive or narrow as the designer wishes, but would generally include values for these representative designs. A more expansive range will yield more data to evaluate and can sometimes result in "strange" results. The collection of design variables with the desired minimum and maximum values to be evaluated is the design space.

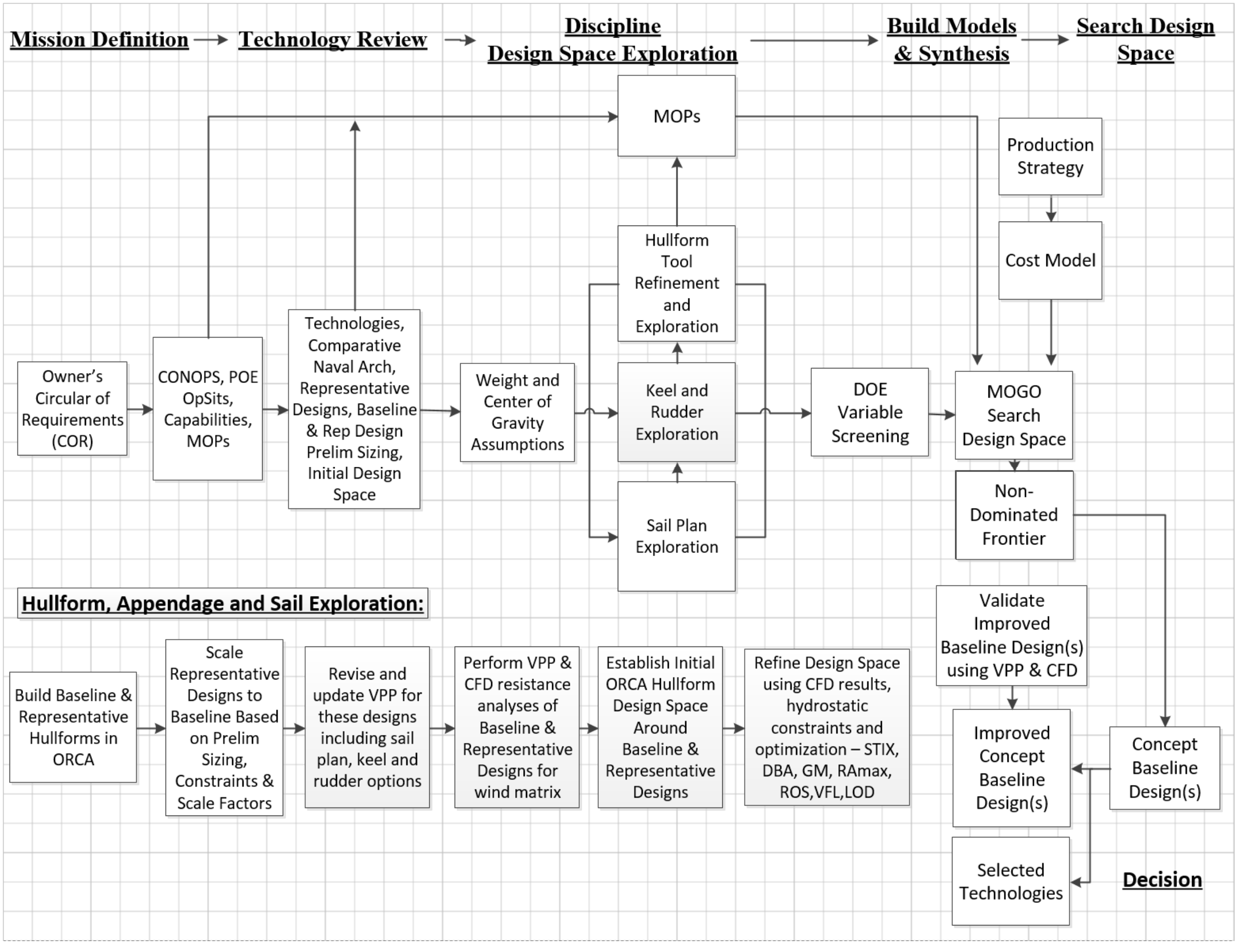


Figure 13- Sailboat Concept Exploration Process

After the representative designs are generated using CAD, hydrostatic data can be generated. By gathering this data, an exploration baseline weight and center of gravity can be estimated. These values serve as an input for several evaluation tools. Next, two (2) steps are explored in concert. The first is the development of measures of performance (MOPs). MOPs provide criteria by which design options are evaluated. MOPs can usually be gathered from the owner's requirements for the design, and/or based on designer experience. The design of a sailboat necessitates the generation of hullform, keel, rudder and sail plan options. This exploration requires the use of evaluation tools and techniques such as the VPP and CFD.

After the hullform, appendage and sail exploration are completed, a method must be used to efficiently sample combinations of these inputs in order to capture the behavior of the entire design space and corresponding data. Once this data has been collected, the importance of particular inputs on MOPs can be determined. To accomplish this, a design of experiments (DOE) is carried out. A DOE allows for a number of inputs to be manipulated while measuring their effect on a desired response. Multiple DOEs may be performed as the design space is refined and DV sensitivity is assessed.

After processing the data provided by additional DOE's, a response surface model (RSM) tool is utilized. The RSM tool takes an input of data from the DOE and creates surrogate models that approximate the response data for each selected input design variable. The RSM tool allows us to use an optimization tool in significantly less time, as it will approximate desired Rhino values, instead of actually creating the hullform in Rhino, as is done in a DOE.

The optimization process is considered "multi-objective" in nature, because it aims to generate a group of boats that perform well considering multiple MOPs. MOPs may also be grouped into measures of effectiveness (MOEs) or a single overall measure of effectiveness (OMOE) depending on the complexity of the owner's requirement. The product of the multi-objective optimization is a non-dominated design frontier similar to Figure 14. In this case, the y-axis, x-axis and color of the result represent a design's performance against a specific MOP or objective. Models located on the knee of the curve, as shown below, often indicate a preferred design, but all non-dominated designs may be considered optimal.

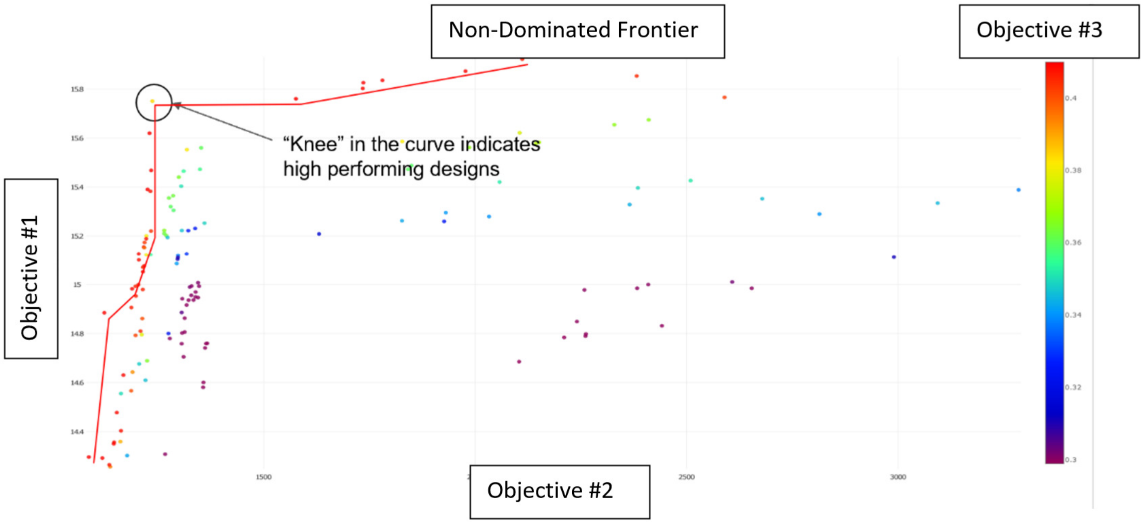


Figure 14 – Non-Dominated Frontier

Once the non-dominated frontier is produced, an initial concept baseline design can be selected and refined. Once refined to a satisfactory degree, an improved concept baseline design is achieved, which is marks the end of the concept exploration phase.

The next design stage is concept development. The purpose of concept development is to add detail and reduce design risk. During the concept development, other aspects of the design are considered, including topsides (hull and deckhouse), arrangements, boat structure and materials, rigging and auxiliary propulsion. Most importantly, thorough structural fabrication and weight analyses are performed to ensure exploration balance and stability analyses were sufficiently correct. If a large discrepancy is found, iteration all the way back to concept exploration may be required.

2.2 Tools and Standards Used in Concept Exploration

2.2.1 Sailboat Assistant and Hullform Exploration

Hull exploration begins with comparative naval architecture to produce an initial hullform design space. Next are hull geometry creation and analysis. At Virginia Tech, two primary tools are used for this purpose: Rhino and Orca3D. Rhino is a 3D modeling computer-aided design (CAD) software and is primarily a free form surface modeler that uses the non-uniform rational B-spline (NURBS) mathematical model. Orca3D is a plug-in for Rhino that provides various boat design and hydrostatic analysis tools. A Rhino/ORCA3D sailboat geometry is illustrated in Figure 15.

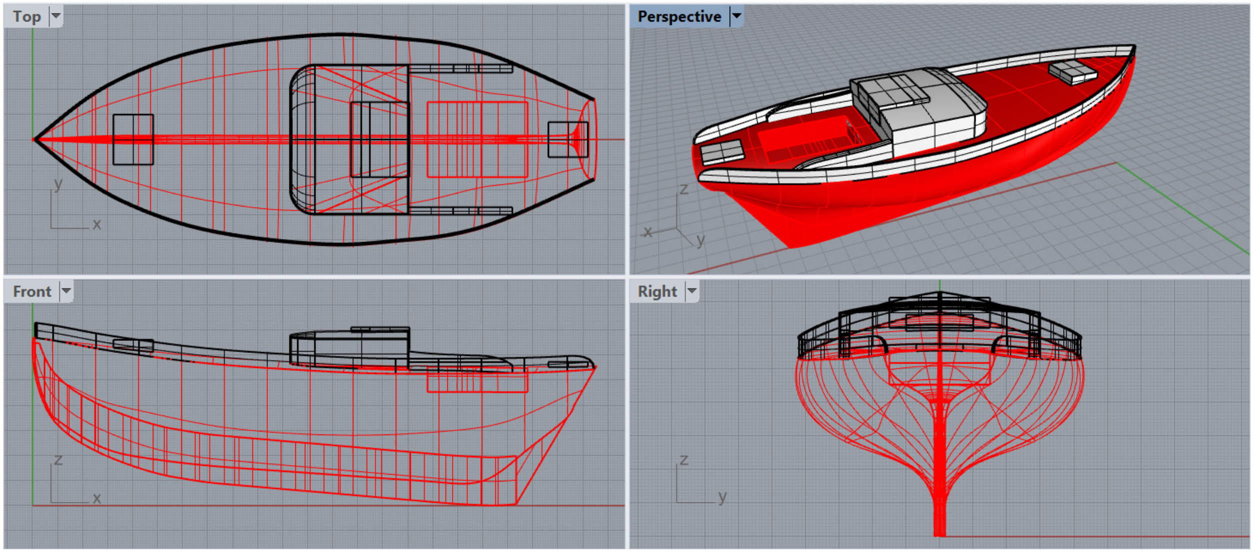


Figure 15 – Rhino/ORCA3D Sailboat Geometry

Rhino and Orca3D provide multiple tools to create a boat hull. The "Sailboat Assistant" tool within Orca3D is used to quickly create a hull model in Rhino using specific design variables. Design variables are, "entities that can change the shape or properties of the model within a specified range during a sensitivity or optimization design study." There are sixteen (16) variables used in Sailboat Assistant. They are categorized based on whether their main effect is on hull dimensions or shape (Table 1).

Table 1- Orca3D Design Variables in Sailboat Assistant

Orca3D Design Variables	
DVs Based on Hull Dimension	**DVs Based on Hull Shape**
Length on Deck	Bow Rake
Beam on Deck	Transom Rake
Deck Height at Bow	Sheer Height
Deck Height at Transom	Beam at Transom
Transom Height	Deck Beam Position
Canoe Body Draft	Canoe Body Draft Position
	Deadrise
	Flare/Tumblehome
	Bilge Tightness
	Forefoot Shape

This tool is used extensively throughout the concept exploration process. The shape of the hull and its corresponding dimensions have a significant impact on stability and speed, and must be determined to best meet the owner's requirements. It is important to note that these design variables only affect the hull, and not appendage sizing or shaping. The "canoe body" is a term that refers only to the hull, without appendages such as the keel and rudder. The keel and rudder are modeled separately, either manually in Rhino or using ORCA3D's "Foil Assistant." Depending on designer preference, the appendages may also be developed using other CAD software before being imported into Rhino and attached to the hullform.

The sailboat assistant inputs are shown in relation to the sailboat geometry in Figure 16 through Figure 19. Each variable plays a significant role in the production of the desired hullform and they are presented here because, although they are very intuitive and useful, they are different from the typical dimension, area and volume ratios often used by naval architects to describe a hullform. Many parameters are entered as fractions of other parameters that have dimensionalized values. For example, sheer height position and canoe body draft position are entered as a fraction of the length on deck, while sheer height is a fraction of the deck height at bow. Beam on deck represents the boat's full beam, while beam at transom is defined as a fraction of that value. A value of zero for beam at transom would lead to the transom being tapered to a point, as is seen in the Egret design, while a value of one would produce a transom with beam equal to the beam on deck.

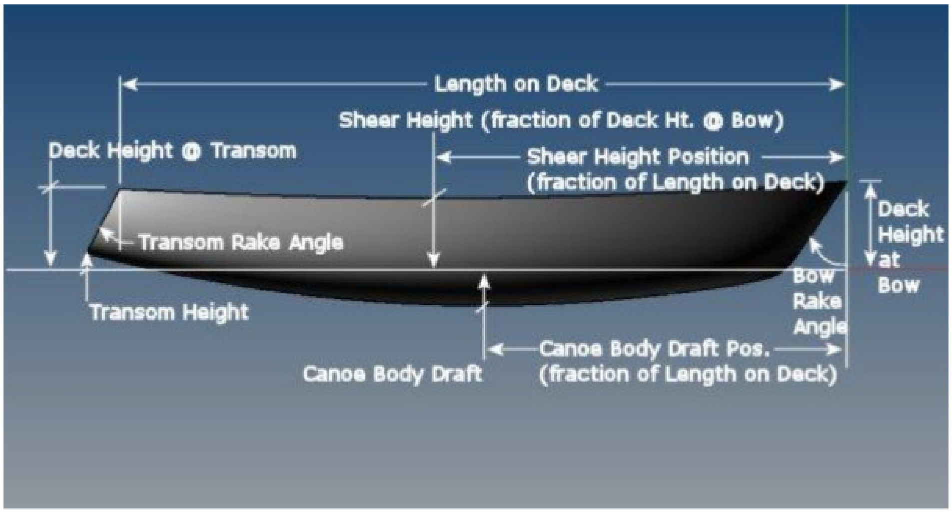


Figure 16 – Sailboat Assistant Inputs 1 (Rhino/ORCA3D, 2019)

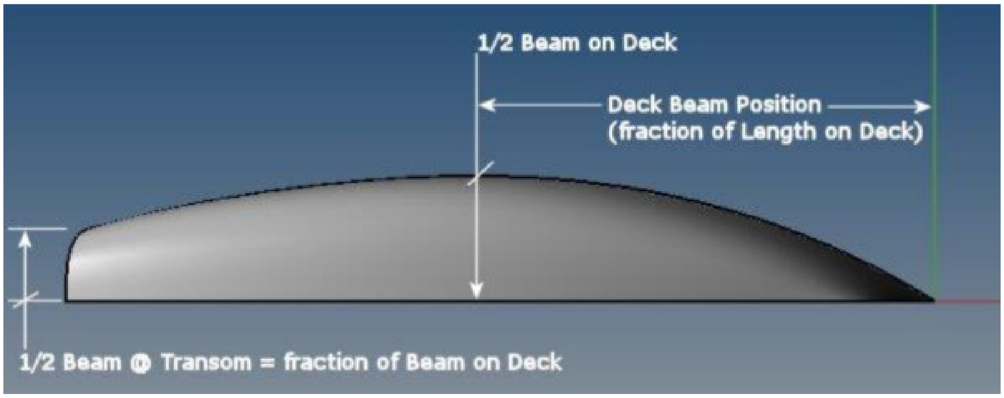


Figure 17 – Sailboat Assistant Input 2 (Rhino/ORCA3D, 2019)

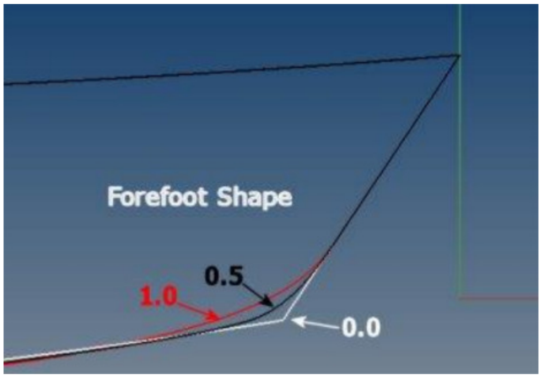


Figure 18 – Sailboat Assistant Input 3 (Rhino/ORCA3D, 2019)

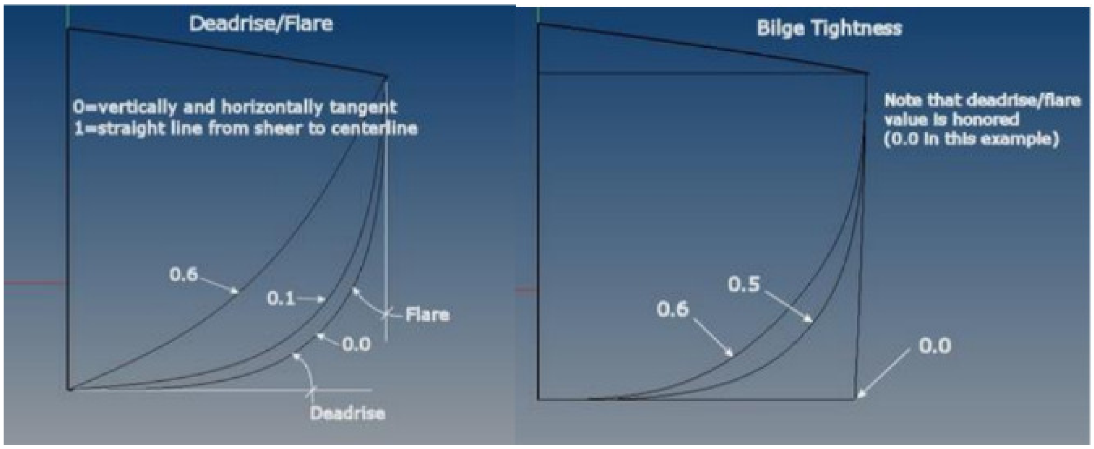
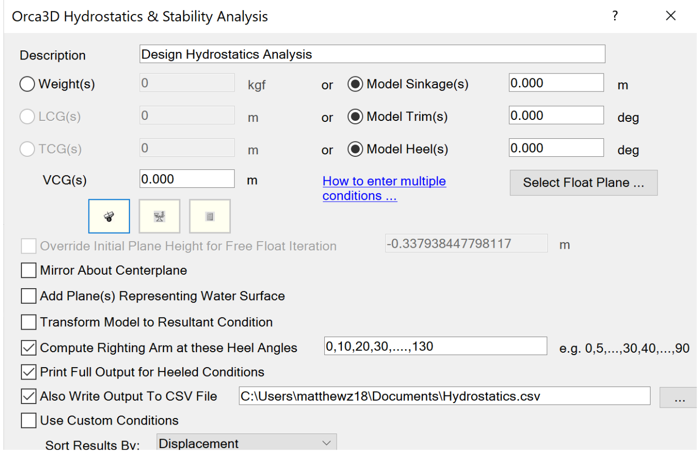


Figure 19 – Sailboat Assistant Input 4 (Rhino/ORCA3D, 2019)

Deadrise and flare may be changed for different sharpie designs, allowing for either a flat-bottom type or more of a V-bottom shape. For a sharpie the deadrise and bilge tightness are set at or near zero to create a sharp chine and flat (transverse) bottom.

Once hulls are created using sailboat assistant, Orca3D can also perform hydrostatic and stability analysis. The inputs for this feature are shown in Figure 20. The user can either manually input the weight and center of gravity location or Orca3D can generate the weight and center of gravity locations based on sinkage, trim and heel.



Description: Design Hydrostatics Analysis

○ Weight(s) 0 kgf or ● Model Sinkage(s) 0.000 m
○ LCG(s) 0 m or ● Model Trim(s) 0.000 deg
○ TCG(s) 0 m or ● Model Heel(s) 0.000 deg
VCG(s) 0.000 m

☐ Override Initial Plane Height for Free Float Iteration -0.337938447798117 m
☐ Mirror About Centerplane
☐ Add Plane(s) Representing Water Surface
☐ Transform Model to Resultant Condition
☑ Compute Righting Arm at these Heel Angles 0,10,20,30,....,130 e.g. 0,5,...,30,40,...,90
☑ Print Full Output for Heeled Conditions
☑ Also Write Output To CSV File C:\Users\matthewz18\Documents\Hydrostatics.csv
☐ Use Custom Conditions
Sort Results By: Displacement

Figure 20- Orca3D's Hydrostatic & Stability Analysis Inputs

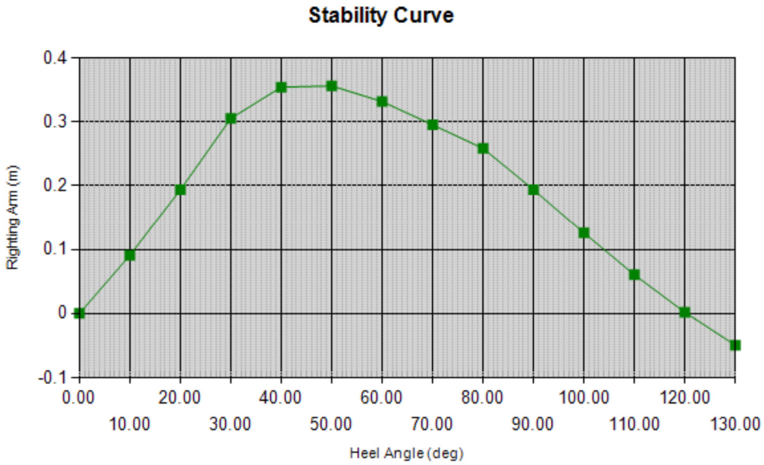
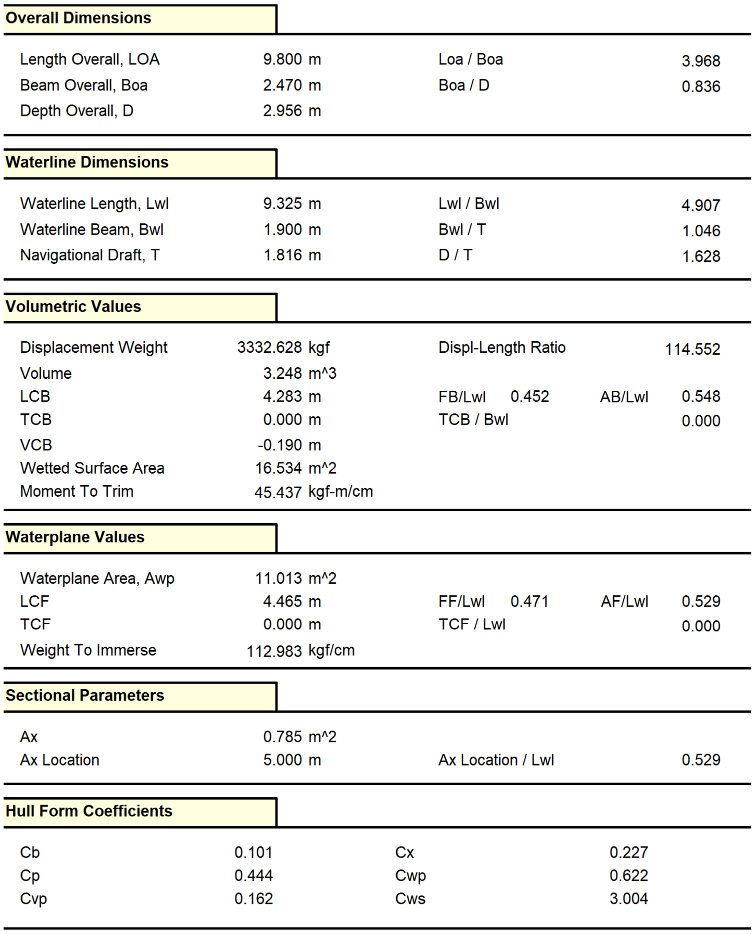


Figure 21- Orca3D's Righting Arm Curve

The user also has the ability to generate righting arm values at desired heel angles, as seen in Figure 21. During the case study the righting arm values for all heel angles from zero to one hundred and thirty in increments of ten were used. This input would produce all necessary information to produce an accurate righting arm curve to be used in the VPP and stability calculations.



Overall Dimensions

Length Overall, LOA	9.800	m	Loa / Boa		3.968
Beam Overall, Boa	2.470	m	Boa / D		0.836
Depth Overall, D	2.956	m			

Waterline Dimensions

Waterline Length, Lwl	9.325	m	Lwl / Bwl		4.907
Waterline Beam, Bwl	1.900	m	Bwl / T		1.046
Navigational Draft, T	1.816	m	D / T		1.628

Volumetric Values

Displacement Weight	3332.628	kgf	Displ-Length Ratio				114.552
Volume	3.248	m^3					
LCB	4.283	m	FB/Lwl	0.452		AB/Lwl	0.548
TCB	0.000	m	TCB / Bwl				0.000
VCB	-0.190	m					
Wetted Surface Area	16.534	m^2					
Moment To Trim	45.437	kgf-m/cm					

Waterplane Values

Waterplane Area, Awp	11.013	m^2				
LCF	4.465	m	FF/Lwl	0.471	AF/Lwl	0.529
TCF	0.000	m	TCF / Lwl			0.000
Weight To Immerse	112.983	kgf/cm				

Sectional Parameters

Ax	0.785	m^2		
Ax Location	5.000	m	Ax Location / Lwl	0.529

Hull Form Coefficients

Cb	0.101	Cx	0.227
Cp	0.444	Cwp	0.622
Cvp	0.162	Cws	3.004

Figure 22- Orca3D's Hydrostatic Analysis Outputs

Based on the inputs, Orca3D will produce a PDF for review and write all results to a CSV file which is then saved to the requested location (Figure 22).

2.2.2 Velocity Prediction Program (VPP)

The Velocity Prediction Program (VPP) is one of the most important tools available to the professional yacht designer today. In addition to predicting speed based on wind speed and angle, the VPP predicts heel and lee angles. As such, the VPP plays an essential role in the design process. The VPP developed and used for VT sailboat concept exploration is heavily based on the methods and equations provided in *Principles of Yacht Design* by Lars Larson, Rolf E. Eliasson and Michael Orych. Their equations are largely based on empirical data available from various model and full scale tests. Aerodynamic formulae, for example, rely on wind-tunnel tests and full-scale experiments, while hydrodynamic formulae rely on yacht testing completed by Delft University of Technology. The figure below outlines the layout of the *Principles of Yacht Design* VPP. (Larsson & Eliasson, Principles of Yacht Design, 2007)

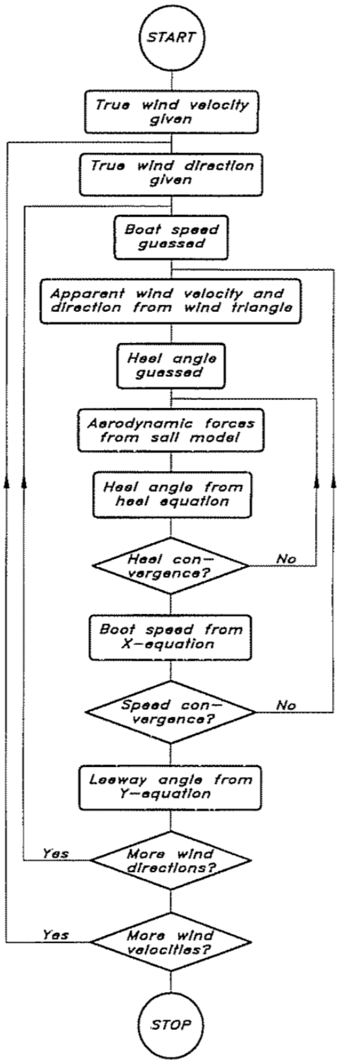


Figure 23 – VPP Flow Diagram (Larsson & Eliasson, 2000)

2.2.2.1 Aerodynamic Force Calculations

As can be seen in Figure 23, the VPP begins with two (2) inputs, which are true wind velocity and direction. After these inputs are provided, the VPP estimates a nominal boat speed. This begins the "speed loop" which converges after the aerodynamic and hydrodynamic forces are balanced. The next step is to calculate the apparent wind velocity and apparent wind direction. The equations for these values are based on the vector diagram in Figure 24 and Equations 1 and 2.

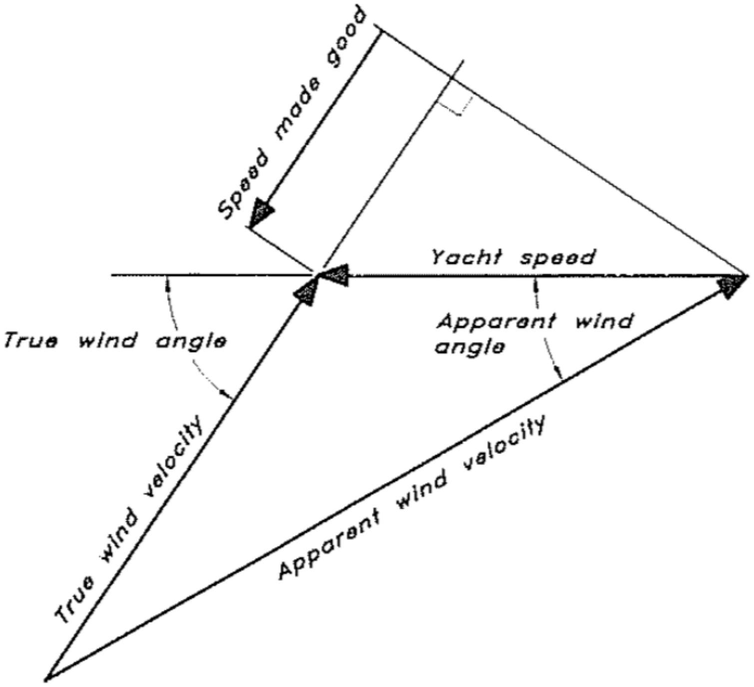


Figure 24 – Apparent Wind Triangle (Larsson & Eliasson, 2000)

$$\mathit{Apparent\ Wind\ Velocity} = \sqrt{\mathit{True\ Wind\ Speed}^2 + \mathit{Boat\ Speed}^2 - 2 * \mathit{True\ Wind\ Speed} * \mathit{Boat\ Speed} * \cos(180 -} \qquad 1)$$

$$\mathit{Apparent\ Wind\ Direction} = \cos^{-1}\left(\frac{\mathit{Boat\ Speed}^2 - \mathit{True\ Wind\ Speed}^2 + \mathit{Apparent\ Wind\ Velocity}^2}{2 * \mathit{Boat\ Speed} * \mathit{Apparent\ Wind\ Velocity}}\right) \qquad 2)$$

The next step in the VPP involves guessing the boat's heel angle. After this angle is guessed with a nominal value, we begin to calculate the aerodynamic forces. This requires first computing the effective apparent wind velocity and direction. This step represents the start of the "heel loop" and is based on the vector diagram in Figure 25 and Equations 3 and 4.

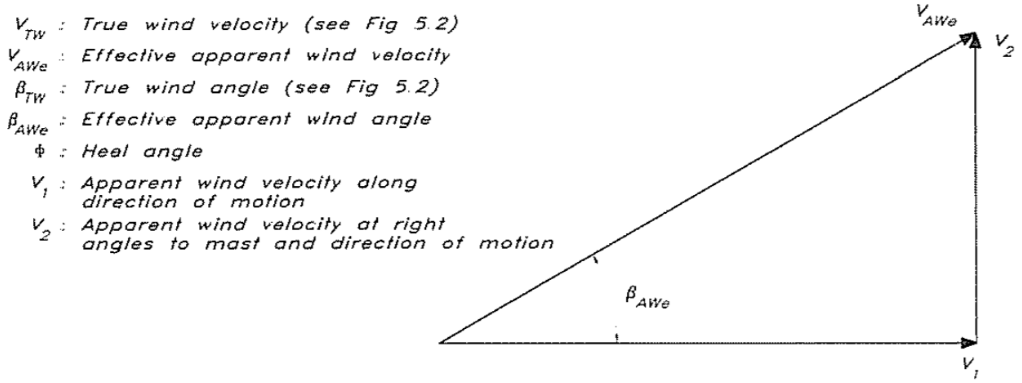


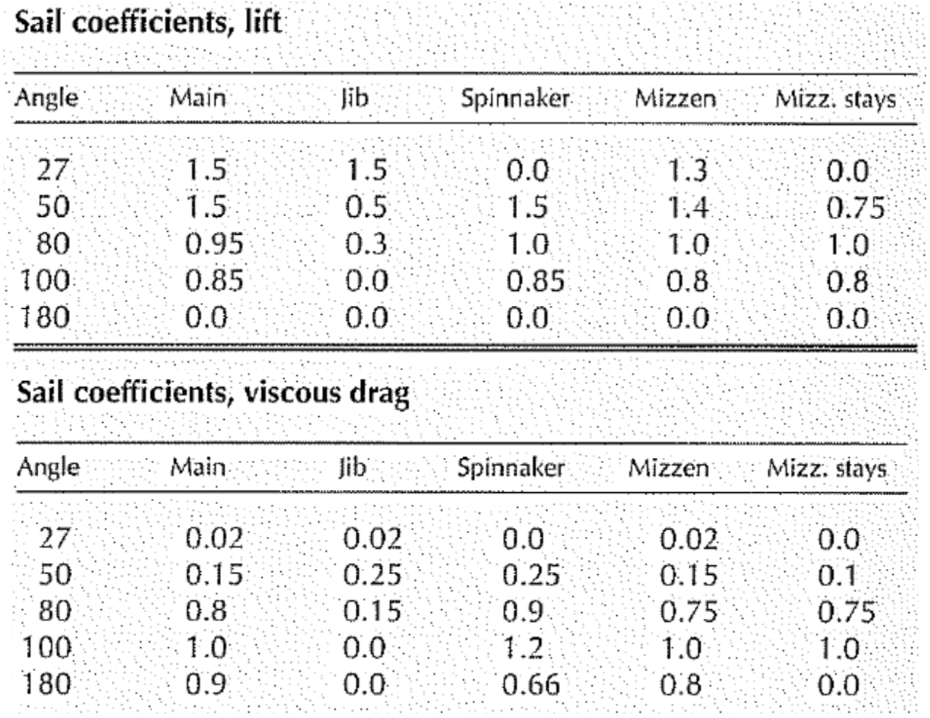
Figure 25 – Effective Apparent Wind at Non-Zero Heel Angle (Larsson & Eliasson, 2000)

$$V_{AWe} = \sqrt{V_1^2 + V_2^2} \tag{3}$$

$$\beta_{AWe} = cosd^{-1}\left(\frac{V_1}{V_{AWe}}\right) \tag{4}$$

The effective apparent wind angle is used to calculate a specific viscous drag coefficient based on the type of sail (main, jib, spinnaker, etc.) as listed in Table 2.

Table 2 – Sail Coefficients (Larsson & Eliasson, 2000)



Sail coefficients, lift

Angle	Main	Jib	Spinnaker	Mizzen	Mizz. stays
27	1.5	1.5	0.0	1.3	0.0
50	1.5	0.5	1.5	1.4	0.75
80	0.95	0.3	1.0	1.0	1.0
100	0.85	0.0	0.85	0.8	0.8
180	0.0	0.0	0.0	0.0	0.0

Sail coefficients, viscous drag

Angle	Main	Jib	Spinnaker	Mizzen	Mizz. stays
27	0.02	0.02	0.0	0.02	0.0
50	0.15	0.25	0.25	0.15	0.1
80	0.8	0.15	0.9	0.75	0.75
100	1.0	0.0	1.2	1.0	1.0
180	0.9	0.0	0.66	0.8	0.0

The next step is to calculate the sail center of effort, as well as the overall lift and drag coefficients. To do this we use the Hazen Model for rig and sail aerodynamics. This model starts with calculating the sail areas.

$$Area_{main} = 0.5 * Mainsail\ Hoist * Foot\ of\ Mainsail \tag{5}$$

$$Area_{jib} = 0.5 \ast \sqrt{Ht.of\ Foretriangle^2 + Base\ of\ Foretriangle^2} \ast Perpendicular\ of\ Longest\ Jib \tag{6}$$

$$Area_{spinnaker} = 1.15 \ast Spinnaker\ Leech\ Length \ast Base\ of\ Foretriangle \tag{7}$$

$$Area_{mizzen} = 0.5 \ast Mizzen\ Hoist \ast Foot\ of\ Mizzen \tag{8}$$

$$Area_{mizzen}staysail = 0.5 \ast Mizzen\ Staysail\ Depth \ast (Mizzen\ Staysail\ mid + Mizzen\ Staysail\ Foot) \tag{9}$$

$$Area_{foretriangle} = 0.5 \ast Ht.of\ Foretriangle \ast Base\ of\ Foretriangle \tag{10}$$

$$Area_{nominal} = Area_{foretriangle} + Area_{main} + Area_{mizzen} \tag{11}$$

After the requisite area values are computed, center of effort locations are calculated for individual sails. Similar to calculations for the sail area, the center of effort equations vary based on the sail shape.

$$CE_{main} = (0.39 \ast Mainsail\ Hoist + Height\ of\ Main\ Boom\ Above\ Sheer) \ast Reefing\ Factor \tag{12}$$

$$CE_{jib} = (0.39 \ast Ht.of\ Foretriangle) \ast Reefing\ Factor \tag{13}$$

$$CE_{spinnaker} = (0.59 \ast Ht.of\ Foretriangle) \ast Reefing\ Factor \tag{14}$$

$$CE_{mizzen} = (0.39 \ast Mizzen\ Hoist + Ht.of\ Mizzen\ Boom\ Above\ Sheer) \ast Reefing\ Factor \tag{15}$$

$$CE\_mizzen\ staysail = 0.39 \ast Mizzen\ Hoist + Ht.of\ Mizzen\ Boom\ Above\ Sheer) \ast Reefing\ Factor \tag{16}$$

$$CE = (CE\_main \ast A\_main + CE\_jib \ast A\_jib + CE\_spinnaker \ast A\_spinnaker + CE\_mizzen \ast A\_mizzen + CE\_mizzen \ast A\_mizzen + CE\_(mizzen\ staysail) \ast A\_(mizzen\ staysail))/(A\_main + A\_spinnaker + A\_mizzen + A\_(mizzen\ staysail)\ ) \tag{17}$$

Next the lift coefficient is calculated:

$$C\_L = ((C\_(L, main) \ast A\_main + C\_(L, jib) \ast A\_jib + C\_(L, spinnaker) \ast A\_spinnaker + C\_(L, mizzen) \ast A\_mizzen + C\_(L, mizzen\ staysail) \ast A\_(mizzen\ staysail))/A\_nominal\ ) \ast F \ast R\text{^}2 \tag{18}$$

To calculate the overall drag coefficient, the induced and viscous drag coefficients are calculated first. These must also consider the drag contributed by the sailboat's masts. The aspect ratio may be defined as the span squared divided by the area, since the projected area is equal to the span times the average chord. However, if the sailboat is close-hauled the effective span is taken to be 110% of the height of the masthead above the water due to some mirror effect of the water surface.

$$\begin{aligned} C\_DV = ((C\_(D, main) * A\_main + C\_(D, jib) * A\_jib + C\_(D, spinnaker) \\ * A\_spinnaker + C\_(D, mizzen) * A\_mizzen \\ + C\_(D, mizzen\ staysail) * A\_(mizzen\ staysail))/A\_nominal\ ) \\ * Reefing\ Factor^\wedge 2 \end{aligned} \tag{19}$$

$$C_{DI} = C_L^2 * \left(\frac{1}{\pi * AR} + 0.005\right) \tag{20}$$

$$AR = \frac{\big(1.1 * (EHM + FA)\big)^2}{A_{nominal}} \quad * For\ close\ hauled\ condition * \tag{21}$$

$$AR = \frac{(1.1 * Mast\ Height\ Above\ Sheer)^2}{A_{nominal}} \tag{22}$$

$$\begin{aligned} C\_(drag, mast) \\ = (1.13 * (BMAX * Freeboard) + (Mast\ Ht. Above\ Sheer \\ * Avg. Mast\ Diameter))/A\_nominal \end{aligned} \tag{23}$$

$$C_D = C_{DV} + C_{DI} + C_{mast,topside\ drag} \tag{24}$$

Once the lift and drag coefficients have been calculated from the Hazen Model, we are able to calculate the corresponding lift and drag forces as follows:

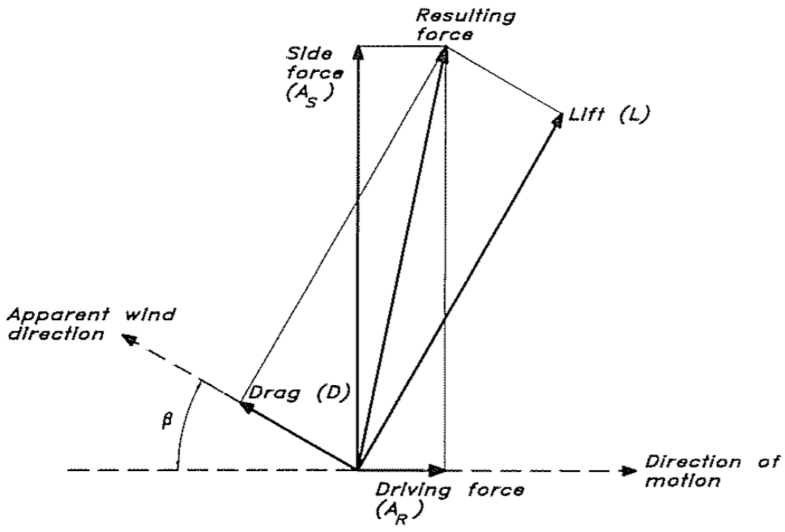
$$\boldsymbol{Sail\ Lift\ Force = \frac{\rho * C_D * Sail\ Area * Apparent\ Wind\ Velocity^2}{2}} \tag{25}$$

$$Sail\ Drag\ Force = \frac{\rho * C_D * Sail\ Area * Apparent\ Wind\ Velocity^2}{2} \tag{26}$$

The next step in this block is to calculate the aerodynamic side and driving forces. These equations are based on the relationship between the aerodynamic force components as illustrated in Figure 26.

$$\begin{aligned} Aerodynamic\ Side\ Force \\ = Lift * \cos(Apparent\ Wind\ Direction) + Drag \\ * sind(Apparent\ Wind\ Direction) \end{aligned} \tag{27}$$

$$\begin{aligned} Aerodynamic\ Driving\ Force \\ = Lift * sind(Apparent\ Wind\ Direction) - Drag \\ * cosd(Apparent\ Wind\ Direction) \end{aligned} \tag{28}$$



$$A_S = L \cdot \cos(\beta) + D \cdot \sin(\beta)$$
$$A_R = L \cdot \sin(\beta) - D \cdot \cos(\beta)$$

Figure 26 – Aerodynamic Force Components (Larsson & Eliasson, 2000)

The last step in the aerodynamic force calculation finds the heeling moment from the sail based on the equations below. The equations require an accurate hydrodynamic center of lateral pressure, located on the boat's keel. *Principles of Yacht Design* provides different methods to determine hydrodynamic center of lateral pressure based on chord length and draft, as seen in Figure 27.

$$Center\ of\ Lateral\ Pressure = Draft_{CN} + 0.45 * Draft \tag{29}$$

$$Sail\ Arm = Center\ of\ Effort + Avg. Freeboard + Center\ of\ Lateral\ Pressure \tag{30}$$

$$Heel\ Moment\ from\ Sail = Side\ Driving\ Force * Sail\ Arm * \cos(heel) \tag{31}$$

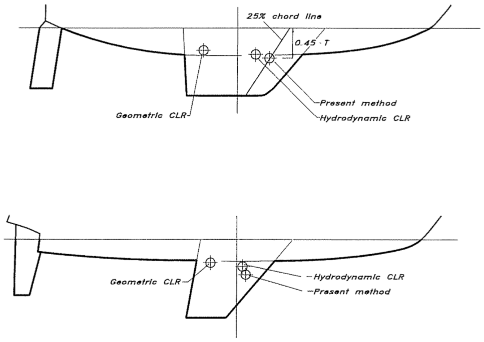


Figure 27 – Hydrodynamic Center of Lateral Pressure (Larsson & Eliasson, 2000)

2.2.2.2 Hydrodynamic Force Calculations

After aerodynamic forces are calculated, the restoring moment is calculated, which involves both hydrostatic and hydrodynamic forces (Figure 28). The restoring moment must balance the heeling moment at the equilibrium heel angle.

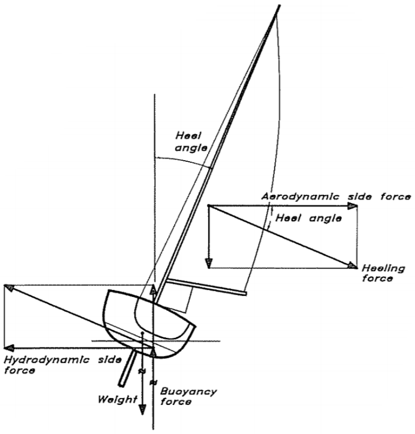


Figure 28 – Forces on a Sailing Yacht (Larsson & Eliasson, 2000)

Calculating the hydrostatic righting moment is the first step in determining the overall righting moment. This uses a fairly simple formula that involves multiplying the righting arm at the given heel angle and the displacement of the boat. The vector diagram used in the derivation of this formula is shown in Figure 29.

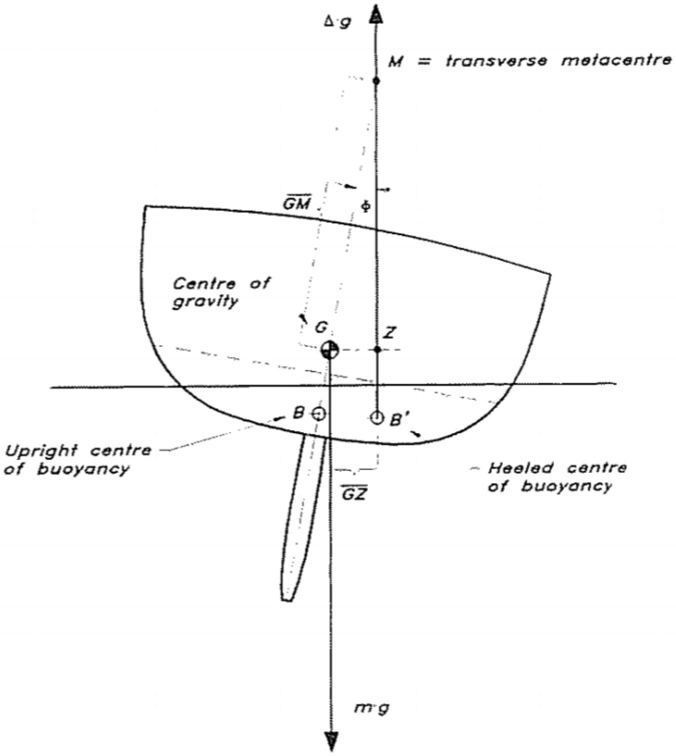
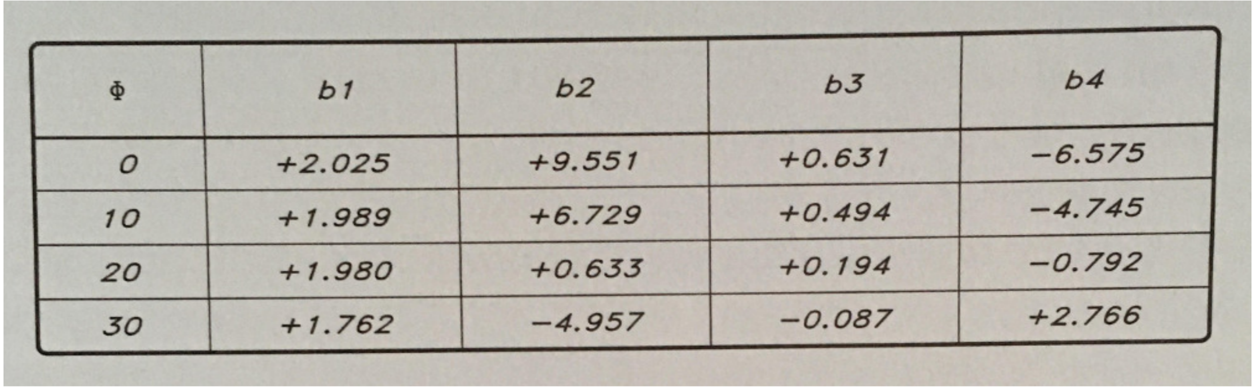


Figure 29 – Transverse Stability Relations (Larsson & Eliasson, 2000)

$$Righting\ Moment = Displacement * GZ\ [heel] \tag{32}$$

Although lifting line theory is a useful approach for optimizing individual appendages, if the side force and induced resistance of the whole yacht are to be considered, there are more effects to consider. There are three (3) bodies contributing to the overall side force including the hull, keel, and rudder, and this force distribution is far from elliptic. There is also the effect of the water surface, which is impacted by these three (3) bodies, especially as the boat heels. Although no simple relations exist for this flow, the VPP utilizes a simplified method for predicting side force based on systematic keel variations at Delft University of Technology. While this method's accuracy is too low for optimizing appendages, it does consider the keel, rudder, and hull in a reasonable estimate for the total side force of the sailboat (Larsson & Eliasson, Principles of Yacht Design, 2007). It is important to note that this method requires leeway angle as an input which is not included as a step in Figure 23 – VPP Flow Diagram . The diagram provided in Figure 30 provides the basis for the leeway angle calculation. The side force hydrodynamic coefficient is a function of heel angle and is populated from *Principles of Yacht Design* (Table 3).

Table 3 – Lift Coefficient Based on Heel Angle (Φ) (Larsson & Eliasson, 2000)



Φ	b1	b2	b3	b4
0	+2.025	+9.551	+0.631	−6.575
10	+1.989	+6.729	+0.494	−4.745
20	+1.980	+0.633	+0.194	−0.792
30	+1.762	−4.957	−0.087	+2.766

$$\begin{aligned} &Leeway\ Angle \\ &\quad = \tan\hat{}(-(Aerodynamic\ Side\ Force/(0.5 \\ &\quad * Hydrodynamic\ Coefficient * \rho * Speed\hat{}2 \\ &\quad * Wetted\ Surface\ Area\_Canoe\ ))\ ) \end{aligned} \tag{33}$$

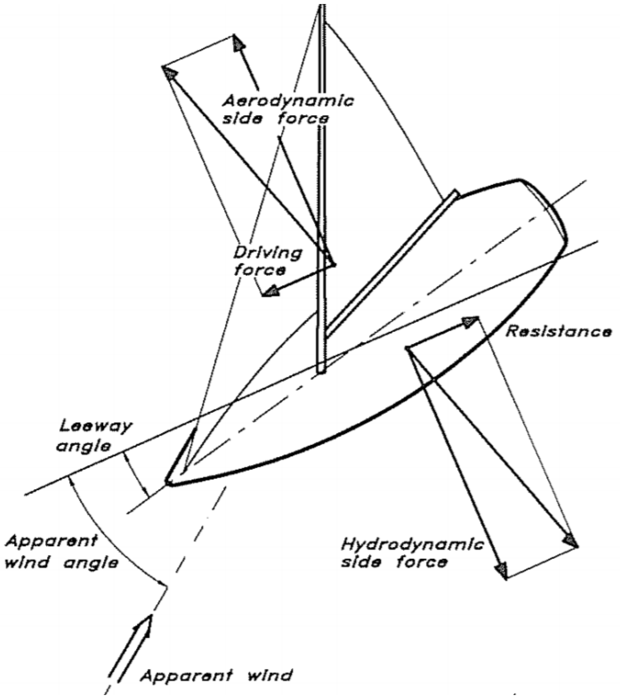


Figure 30 - Leeway Angle (Larsson & Eliasson, 2000)

Once the leeway angle is calculated, the lift produced by the rudder and keel and the equilibrium heel angle can be calculated. Calculations begin by finding the effective aspect ratio of the rudder and keel. Next, the downwash angle is considered. Downwash angle is the change in direction of the fluid deflected by the action of the keel. Downwash angle is affected by "a0" which represents a hull effect factor. Once the downwash angle has been calculated, the leeway of the rudder can be found. Once the leeway rudder is established the rudder's lift coefficient and lift force can be produced.

$$AR_{effective,rudder} = 2 * AR \tag{34}$$

$$AR_{effective,keel} = 2 * AR \tag{35}$$

$$Downwash\ Angle\ = a0 * \left(\frac{C_{L,K}}{AR_{effective,keel}}\right)^{0.5} \tag{36}$$

$$Rudder\ Leeway = Leeway\ Angle - Downwash\ Angle \tag{37}$$

$$C\_(L,r) = (5.7 * AR\_(effective, rudder))/(1.8 + cosd(sweep\ angle) * ((AR\_(effective, rudder)\text{^}2)/(\cos\ \text{^}4\ (sweep\ angle) + 4\ ))\text{^}0.5 * Rudder\ Leeway \tag{38}$$

$$L_r = C_{L,R} * 0.5 * \rho * (0.9 * V)^2 * A_r \tag{39}$$

After the rudder lift is computed, the keel lift must be accounted for. The formulae used to find this value is similar to formulae used to calculate the rudder lift coefficient.

$$C\_(L,k) = (5.7 * AR\_(e, keel))/(1.8 + \cos\,(sweep\ angle) * ((AR\_e{}^\wedge 2)/(\cos\ {}^\wedge 4\ (sweep\ angle) + 4\ ))^\wedge 0.5 * Leeway \tag{40}$$

$$L_k = C_{L,k} * 0.5 * \rho * (0.9 * V)^2 * A_k \tag{41}$$

Once the lift forces are calculated for the keel and rudder, the hydrodynamic side force may be calculated. This set of formulae used, incorporate the hull's contribution.

$$c_{hull} = 1.8 * \left(\frac{T_c}{T}\right) + 1 \tag{42}$$

$$c_{heel} = 1 - 0.382 * (heel\ angle) \tag{43}$$

$$Hydrodynamic\ Side\ Force, keel = L_k * c_{hull} * c_{heel} \tag{44}$$

$$Hydrodynamic\ Side\ Force, rudder = L_r * c_{hull} * c_{heel} \tag{45}$$

$$Hydrodynamic\ Side\ Force = Side\ Force, keel + Side\ Force, rudder \tag{46}$$

Similar to the aerodynamic forces section of the VPP, we conclude the hydrodynamic forces section calculating the overall moment. This value must converge with the previously calculated heeling moment from the sail. This is the end of the "heel loop".

$$Restoring\ Moment_{keel} = Side\ Force, keel * 0.45 * T \tag{47}$$

$$Restoring\ Moment_{rudder} = Side\ Force, rudder * 0.5 * Rudder\ Span \tag{48}$$

$$Restoring\ Moment = RM_{keel} + RM_{rudder} \tag{49}$$

2.2.2.3 Resistance Calculations

Once the aerodynamic and hydrodynamic forces have been calculated, the next big step is closing the "speed loop." In order to do this, resistance and aerodynamic driving forces must converge. There are four resistance components that must be considered before the overall resistance value can be computed. These components include frictional, pressure, roughness and residuary resistance. The following formulae are used to calculate the frictional resistance. The frictional resistance for each component is calculated individually and then summed together to find the overall frictional resistance value.

$$RN_{Hull} = \frac{Velocity * (0.7 * LWL)}{Kinematic\ Viscosity} \tag{50}$$

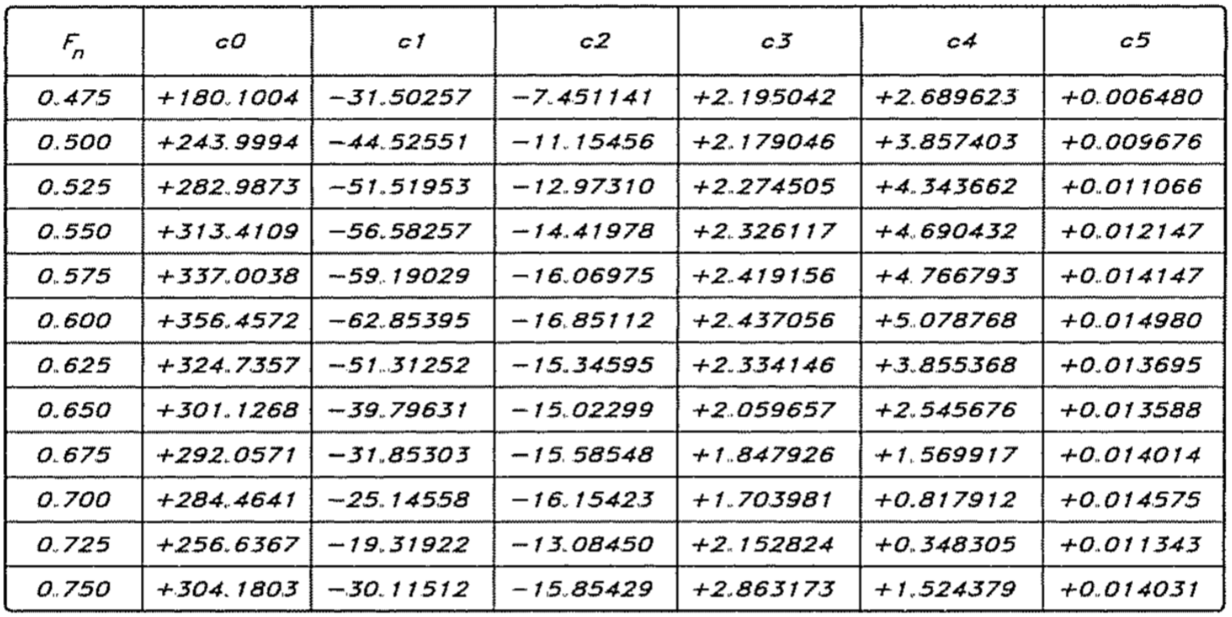
$$RN_{Appendage} = \frac{Velocity * Mean\ Chord}{Kinematic\ Viscosity} \tag{51}$$

$$C_f = \frac{0.075}{Log(RN-2)^2} \tag{52}$$

$$Frictional\ Resistance = C_f * 0.5 * \rho * Velocity^2 * Wetted\ Surface\ Area \tag{53}$$

Next, the viscous-pressure and roughness components of the resistance are calculated. According to *Principles of Yacht Design,* a sailing yacht will experience a viscous-pressure resistance value of approximately 5-10% of the direct frictional force and is heavily dependent on the shape of the hull. This resistance can be minimized by properly designing the stern. A blunter stern will cause a larger pressure drop. The effects are small as long as separation is avoided. If the flow separates a large reduction in pressure can occur and the viscous-pressure resistance will be significantly larger than 5-10%. Separation is also a viscous effect, but differs from flat plate in that it is also affected by shape. It is often accounted for in a form factor. CFD considers viscosity and shape more correctly. The VPP approximates the viscous-pressure resistance to be ten percent of the frictional force. The frictional resistance relies significantly on wetted surface area. Roughness resistance is not considered a significant value from a design perspective and estimated to be ten percent of the frictional resistance.

Table 4 – Residuary Resistance Coefficient Based on Froude Number (Larsson & Eliasson, 2000)



F_n	c0	c1	c2	c3	c4	c5
0.475	+180.1004	−31.50257	−7.451141	+2.195042	+2.689623	+0.006480
0.500	+243.9994	−44.52551	−11.15456	+2.179046	+3.857403	+0.009676
0.525	+282.9873	−51.51953	−12.97310	+2.274505	+4.343662	+0.011066
0.550	+313.4109	−56.58257	−14.41978	+2.326117	+4.690432	+0.012147
0.575	+337.0038	−59.19029	−16.06975	+2.419156	+4.766793	+0.014147
0.600	+356.4572	−62.85395	−16.85112	+2.437056	+5.078768	+0.014980
0.625	+324.7357	−51.31252	−15.34595	+2.334146	+3.855368	+0.013695
0.650	+301.1268	−39.79631	−15.02299	+2.059657	+2.545676	+0.013588
0.675	+292.0571	−31.85303	−15.58548	+1.847926	+1.569917	+0.014014
0.700	+284.4641	−25.14558	−16.15423	+1.703981	+0.817912	+0.014575
0.725	+256.6367	−19.31922	−13.08450	+2.152824	+0.348305	+0.011343
0.750	+304.1803	−30.11512	−15.85429	+2.863173	+1.524379	+0.014031

Residuary resistance is calculated separately for the hull, rudder and keel. These values are summed to find the overall residuary resistance value. It should be noted that a0, a1, a2, and a3 are functions of Froude Number and are populated from *Principles of Yacht Design* (Table 4). Z_{CBk} represents the distance from the center of buoyancy of the keel to the bottom of the hull.

$$Froude\ Number = \frac{Velocity}{\sqrt{g * Depth}} \tag{54}$$

$$\frac{\frac{Residuary\ Resistance}{\nabla_C * \rho * g} = a0 + a1 * \frac{T}{BWL} + a2 * \frac{T_c + Z_{CBk}}{\nabla^{\frac{1}{3}}} + a3 * \nabla_c}{\nabla} \tag{55}$$

2.2.2.4 Final Convergence

Once the four resistance components are calculated, resistance must converge with the aerodynamic driving force value to close the speed loop. The VPP process begins at the start of the speed loop, for as many wind directions and velocities as are provided as input. It is important to note that although boat speed is an important output, other significant outputs which are used later in the design process are heel and lee angles and various force values.

2.2.3 ORCA3D Computational Fluid Dynamics (CFD)

Orca3D also interfaces with Simerics-MP to provide a computational fluid dynamics (CFD) component. This uses Rhino surface meshes as inputs to provide automated CFD volume meshing in Simerics-MP. Simerics-MP utilizes a Reynolds-averaged Navier-Stokes (RANS) finite volume based approach to solve compressible, incompressible, laminar and turbulence fluid flows. Using this tool we are able to compute the flow around the hull and its components. In addition, Simerics-MP computes both water and air streamlines. The specific marine module within Simerics-MP provides values for Total Resistance, Water Resistance, Air Resistance, Effective Horsepower, and Velocity. The motions of the boat are captured through an embedded six degrees of freedom dynamic solver. (Simerics: Technology by Design, 2014)

This CFD capability is of particular importance because of the unique nature in which a sailboat operates. Rarely is a sailboat operating without a heel and yaw (or lee) angle. As the model can be rotated in Rhino before generating a mesh in Simerics-MP, various asymmetrical simulations can be completed, and data can be collected on how these angles influence resistance. In order to determine this effect, representative wind speed and directions at which the sailboat is likely to be operating should be established. This collection of wind speeds and directions can be considered as “representative conditions.” The representative conditions are inputs into the VPP. Once simulated in the VPP, the resulting heel and lee angles can be collected.

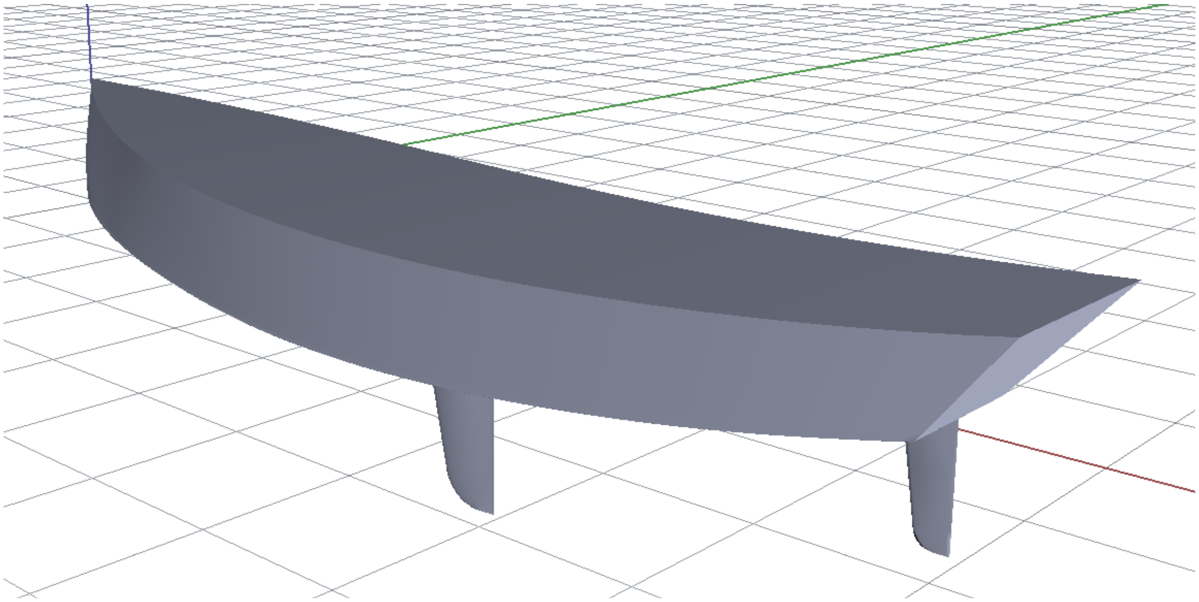
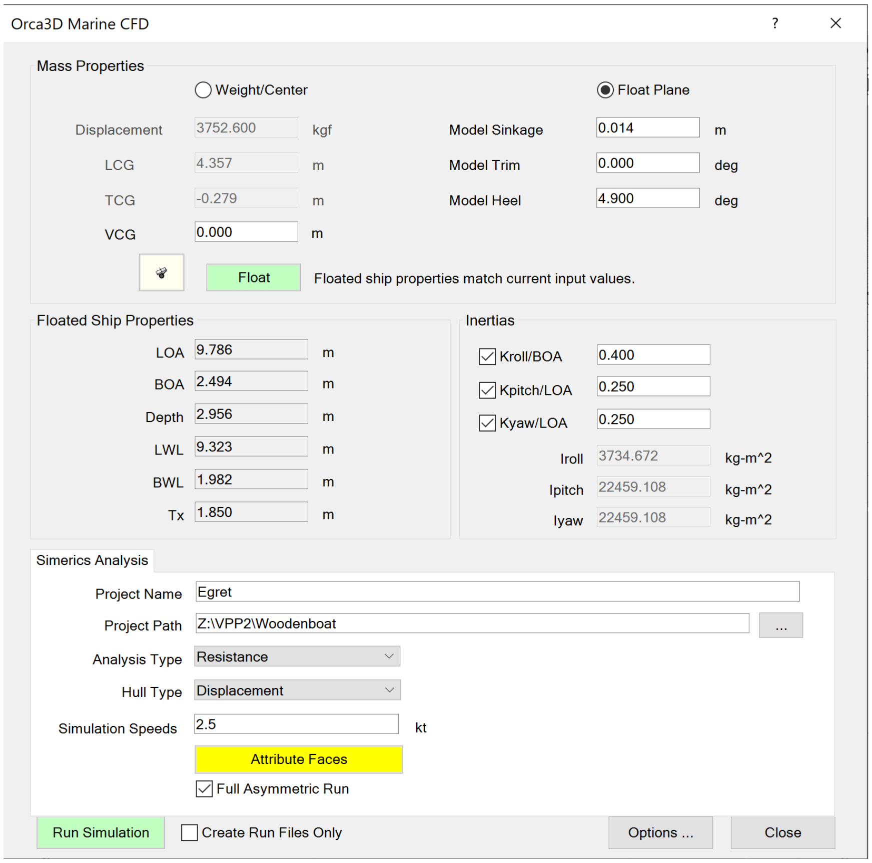


Figure 31 – Albemarle Sound Sharpie Hull in Rhino

Next, the boat is rotated in Rhino to the lee angle specified by the VPP. Once the boat is rotated as desired, the Orca3D Marine CFD plug-in is opened. After input, the input screen should appear as in Figure 32. The "Full Asymmetric Run" option should be selected consistent with having set the model yaw to be greater than zero. The "Float Plane" option should be selected, heel angle set to the angle specified by the VPP, trim set to zero, and sinkage adjusted to achieve the required displacement using the "Float" calculation. Weight and hence displacement must be constant in all runs consistent with the calm water, usually full load condition. Simulation speeds must also be provided.



Mass Properties

○ Weight/Center ● Float Plane

Displacement 3752.600 kgf

LCG 4.357 m

TCG -0.279 m

VCG 0.000 m

Model Sinkage 0.014 m

Model Trim 0.000 deg

Model Heel 4.900 deg

Floated ship properties match current input values.

Floated Ship Properties

LOA 9.786 m

BOA 2.494 m

Depth 2.956 m

LWL 9.323 m

BWL 1.982 m

Tx 1.850 m

Inertias

☑ Kroll/BOA 0.400

☑ Kpitch/LOA 0.250

☑ Kyaw/LOA 0.250

Iroll 3734.672 kg-m^2

Ipitch 22459.108 kg-m^2

Iyaw 22459.108 kg-m^2

Simerics Analysis

Project Name Egret

Project Path Z:\VPP2\Woodenboat

Analysis Type Resistance

Hull Type Displacement

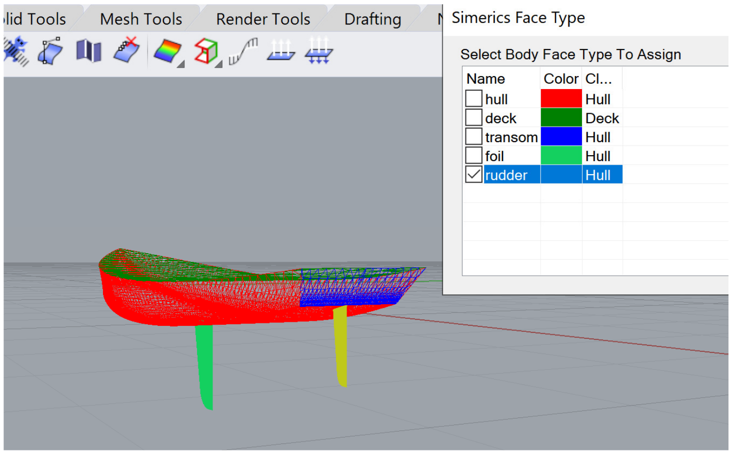
Simulation Speeds 2.5 kt

☑ Full Asymmetric Run

☐ Create Run Files Only

Figure 32 – Orca 3D CFD Inputs

In order to calculate physical metrics for individual components, such as the shear force on the keel, face types are assigned for each part of the boat. As shown in Figure 33, each face and appendage must be accounted for and clearly identified. This process includes identifying the hull, deck, transom, foil and rudder.



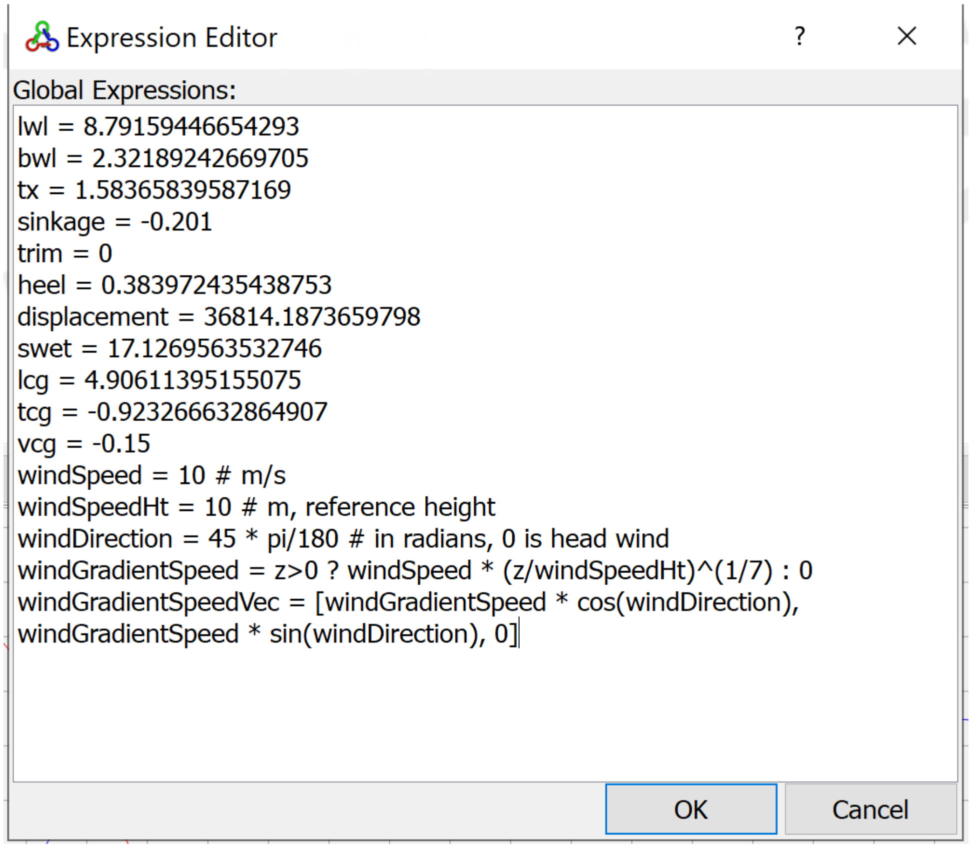
Simerics Face Type

Select Body Face Type To Assign

Name	Color	Cl...
☐ hull	🟥	Hull
☐ deck	🟩	Deck
☐ transom	🟦	Hull
☐ foil	🟩	Hull
☑ rudder	🟦	Hull

Figure 33 – Assigning Face and Appendage Type to the Hull

Once the required inputs have been entered, Orca3D builds and exports the mesh and geometry to Simerics MP. In Simerics MP, the mesh can be adjusted as needed. Normally, mesh adjustment is not needed for reasonable results. Wind speed and direction can also be adjusted to simulate sailing conditions. This is done by first selecting the "Marine" module in the Model window and in the Properties window changing the Setup Options from "Template Mode" to "Extended Mode". After this is completed, the "A=?" icon in the upper right corner of the Properties window is selected to open the Expression Editor. Once the Expression Editor is opened, necessary lines specifying wind speed, direction, and height are added, as shown in Figure 34.



```
lwl = 8.79159446654293
bwl = 2.32189242669705
tx = 1.58365839587169
sinkage = -0.201
trim = 0
heel = 0.383972435438753
displacement = 36814.1873659798
swet = 17.1269563532746
lcg = 4.90611395155075
tcg = -0.923266632864907
vcg = -0.15
windSpeed = 10 # m/s
windSpeedHt = 10 # m, reference height
windDirection = 45 * pi/180 # in radians, 0 is head wind
windGradientSpeed = z>0 ? windSpeed * (z/windSpeedHt)^(1/7) : 0
windGradientSpeedVec = [windGradientSpeed * cos(windDirection),
windGradientSpeed * sin(windDirection), 0]
```

Figure 34- Adding Wind Speed and Direction to CFD Simulation

In the Geometric Entities window under "Volumes", the "marine" volume option is selected. Then in the Properties window “Flow, Mixture, Initial Condition” is expanded and “Velocity as a windGradientSpeedVec" is set. In order to set the boundary conditions so that flow velocity is continuous throughout the simulation, the four marine boundaries under Geometric Entities are selected (front, back, port, starboard). Lastly “Under Flow, Velocity Profile” is expanded and Back Flow Velocity is set to "windGradientSpeedVec".

Once necessary adjustments are made, the simulation is started. During the simulation, Simerics MP outputs resistance, heave, pitch, pressure, torque, etc. as time progresses to the final steady-state speed. As seen in Figure 35, Simerics MP allows for results to be plotted as the simulation is ongoing. Specific values under the “Marine” tab include total resistance, effective horsepower, heave, pitch, forward velocity, air resistance and water resistance.

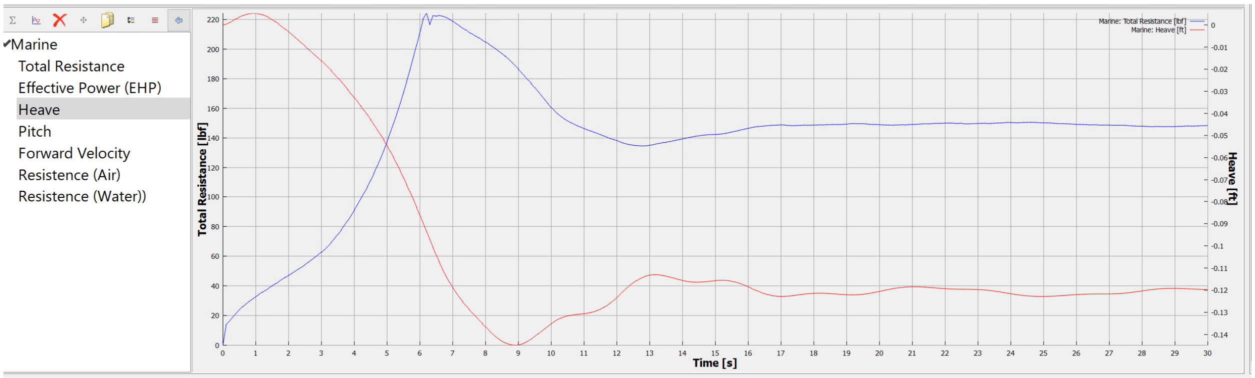
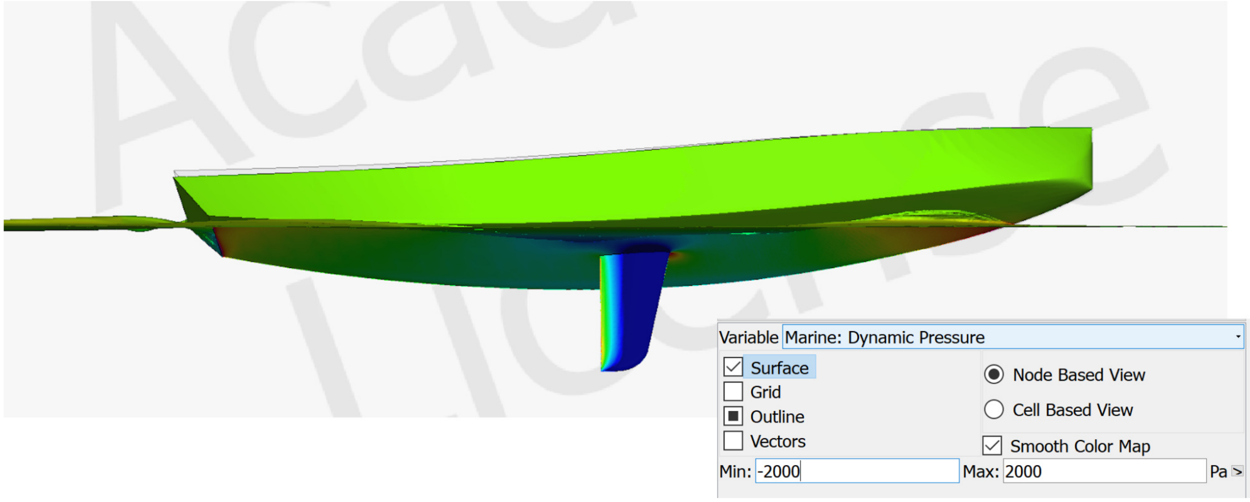


Figure 35- Simerics MP Output Plot

In addition to the "Marine" tab, Simerics MP also provides results under the "Translation" and "Rotation" tabs. Under the "Translation" tab, values for displacement, velocity, acceleration, net force, fluid force, spring force and damping force are found. The "Rotation" tab has results for angular displacement, angular velocity, angular acceleration, net torque, fluid torque, spring torque, and damping torque.

Results can be further separated by direction (x, y or z) and "face", which is assigned in Rhino. As an example, net torque on the rudder in x-direction can be found. All of these values are populated within Simerics MP and are automatically saved as a .txt file within the same folder in which the simulation is opened.


Variable: Marine: Dynamic Pressure

☑ Surface
☐ Grid
☒ Outline
☐ Vectors

● Node Based View
○ Cell Based View
☑ Smooth Color Map

Min: -2000 Max: 2000 Pa

Figure 36 – North Carolina Sharpie in CFD Simulation

During the case study, it was found that the convergence of results is usually achieved within a thirty second simulation. The thirty second simulation is usually completed within six to ten hours of real time.

2.2.4 Stability Index (STIX)

STIX was the product of a need for an evaluation tool in the maritime community for evaluating the stability of yachts. Although various techniques for evaluating the stability of larger ships have existed for a much longer period, a metric was needed to do the same for marine craft of smaller size. STIX was developed in large part due to Working Group 22 of Technical Committee 188 of the ISO, which formed after the European Union issued a Directive on Pleasure Craft. With the implementation of this new directive all newly built pleasure craft to be marketed in the European Union were required to comply with this new stability standard being developed as of June 1998. Initially this group collected stability data for approximately 115 sailing yachts of different types. Special attention was given to yachts that sustained a knockdown which they did not recover from, a capsize or inversion, a sinking, or other stability-related casualty. The resulting database was, “analyzed with a view to obtaining insight as to the range of values of various stability parameters associated with a stability casualty and with a well-behaved vessel in this respect.” Results found that parameters of particular significance included the angle of vanishing stability, the value of the boat’s righting arm at 90° of heel, as well as the area under the righting moment curve up to the angle of vanishing stability. The group also concluded that the heel angle at which a critical amount of water enters the non-self-draining part of the hull (or downflooding angle), plays an important role in the righting characteristics of a yacht after a knock-down or an inversion. The importance of these values is evident when analyzing the formulae that comprise the STIX calculation (Oossanen, 1997).

Eight “factors” are used in the STIX calculation:

1) Base Length Factor (LBS) is indicative of the yacht’s size, which is, “the single most important parameter when assessing safety at sea, since it defines a scale with which to measure the waves. The larger the yacht, the smaller the relative size of the waves.” Using this approach, size is a weighted average of the overall length and length along waterline. As waterline length is twice as important as overall length, boats with overhangs are penalized, while yachts with square ends are rewarded (Larsson & Eliasson, Principles of Yacht Design, 2016).

$$\boldsymbol{Base\ Length\ Factor = (Hull\ Length + 2 * \frac{Length\ at\ Waterline}{3})} \tag{56}$$

2) Displacement Length Factor (FDL) penalizes boats with a light displacement relative to the size of the yacht, as this may be considered a disadvantage from a control point of view. A “normal” yacht produces a value in the data of 1.0. The minimum and maximum values for the factor in the data are 0.75 and 1.25 respectively. Although it is documented that boats of light displacement have fared well in rough weather previously (Fastnet Race in 1979 and Sydney-Hobart Race in 1998), the ISO does not account for experienced or additional crew. Instead, the ISO standard assumes a minimum crew that may be inexperienced. In this case, a very responsive and sensitive yacht is considered disadvantageous (Larsson & Eliasson, Principles of Yacht Design, 2016).

$$Length\ Factor = \left(\frac{Base\ Length\ Factor}{11}\right)^{.2} \tag{57}$$

$$\begin{aligned} &Displacement\ Length\ Factor \\ &\qquad = (0.6 + (15 * mass * Length\ Factor)/(Base\ Length\ Factor{}^\wedge 3 \\ &\qquad * (0.333 - 8 * Base\ Length\ Factor\ )\ )){}^\wedge 0.5 \end{aligned} \tag{58}$$

3) Beam Displacement Factor (BDF). Based on research carried out by the Society of Naval Architects and Marine Engineers (SNAME) and the Wolfson Unit in Southampton, England, a large beam combined with a light displacement increases the risk of a wave-induced capsize. This figures significantly into the beam displacement factor. A small beam to displacement ratio also carries a negative effect on form stability, so aberrations in both directions are penalized. Interesting to note, *Principals of Yacht Design* specifically references, “old English plank-on-the-edge cutters” as “particularly bad examples of narrow beam yachts… with almost no form of stability. They were developed from a bad rating rule and depended on heavy ballast at a low position. The heel angle was excessive even in normal sailing conditions and the risk of downflooding was large.” As mentioned previously, this type of cutter rivaled the sharpie design late in the nineteenth century. The central factor in the beam displacement factor formulae is beam factor, which represents the ratio of beam to the third root of displacement. Normal values for beam factor range in the data between 1.45 and 2.2, while the minimum and maximum values possible in the data are 0.75 and 1.25. (Larsson & Eliasson, Principles of Yacht Design, 2016)

$$Beam\ Factor = \frac{3.3 * Beam}{(0.03 * mass)^{\frac{1}{3}}} \tag{59}$$

$$Beam\ Displacement\ Factor = \left(\frac{13.31 * B_{WL}}{B_H * F_B^3}\right)^{0.5} \quad if\ Beam\ Factor > 2.2 \tag{60}$$

$$Beam\ Displacement\ Factor = \left(\frac{B_{WL} * F_B^2}{1.682 * B_H}\right)^{0.5} \quad if\ Beam\ Factor < 1.45 \tag{61}$$

$$Beam\ Displacement\ Factor = 1.118 * \left(\frac{B_{WL}}{B_H}\right)^{0.5} \quad if\ 1.45 \le\ Beam\ Factor \le 2.2 \tag{62}$$

4) The Knockdown Recovery Factor (FKR) is indicative of a yacht’s ability to spill water out of its sails after a knockdown. The main factor in this set of formulae is knockdown factor, which symbolizes the, “ratio of the right moment and heeling moment with sails just dipped into the water.” The minimum and maximum values for this factor in the data are 0.5 and 1.5 respectively (Larsson & Eliasson, Principles of Yacht Design, 2016).

$$Knockdown\ Factor = \frac{GZ\ at\ 90° * mass}{2 * Sail\ Area * Height\ of\ Center\ of\ Effort} \tag{63}$$

$$Knockdown\ Recovery\ Factor = 0.875 + 0.0883 * Knockdown\ Factor \quad if\ Knockdown\ Factor \ge 1.5 \tag{64}$$

$$Knockdown\ Recovery\ Factor = 0.5 + 0.333 * Knockdown\ Factor \quad if\ Knockdown\ Factor < 1.5 \tag{65}$$

5) A boat's ability to recover unaided after an inversion is represented by the Inversion Recovery Factor (FIR). A boat's angle of vanishing stability plays an important role in the calculation of this factor. The minimum and maximum values for this factor in the data are 0.4 and 1.5 respectively. (Larsson & Eliasson, Principles of Yacht Design, 2016)

$$Inversion\ Recovery\ Factor = \frac{(Angle\ of\ Vanishing\ Stability)}{125 - \frac{mass}{1600}} \qquad (66)$$
$$if\ mass < 40\ tons$$

$$Inversion\ Recovery\ Factor = \frac{\text{Angle of Vanishing Stability}}{100} \qquad (67)$$
$$if\ mass \geq 40\ \text{tons}$$

6) The Dynamic Stability Factor (FDS) is proportional to the area under the righting arm (GZ) curve for the entire range of stability, or up to the angle of vanishing stability. This area under the GZ curve, "represents the work needed by external forces (from wind and waves) to heel the yacht to this angle." STIX utilizes the righting arm curve instead of the righting moment curve in this factor, as the righting moment curve is used in the base length factor calculation. A repeat use of the righting moment curve would lend too much credit to larger yachts. Minimum and maximum values for this factor in the data are 0.5 and 1.5 respectively. It should be noted that A_{GZ} is the positive area under the curve. (Larsson & Eliasson, Principles of Yacht Design, 2016)

$$Dynamic\ Stability\ Factor = \left(\frac{A_{GZ}}{15.81 * \sqrt{Hull\ Length}}\right)^{0.3} \qquad (68)$$

7) The Wind Moment Factor (WMF) signifies the risk of downflooding due to, "a gust heeling the unreefed yacht." This factor cannot exceed one and reaches this value if the hull has a downflooding angle in excess of 90̊. Assuming that hatches are closed, most ballasted yachts with "normal" deck openings have downflooding angles in excess of 90̊. Nonetheless, if a boat has a downflooding angle of less than 90̊, it must withstand an apparent wind speed of 33 knots while carrying full sail to achieve the maximum wind moment factor value in the data of 1. "VAW" represents the steady apparent wind speed to heel to the downflooding angle when the boat is carrying full sail. (Larsson & Eliasson, Principles of Yacht Design, 2016)

$$Wind\ Moment\ Factor = 1.0 \qquad (69)$$
$$if\ Downflooding\ Angle > 90°$$

$$Wind\ Moment\ Factor = \frac{VAW}{17} \qquad (70)$$
$$if\ Downflooding\ Angle < 90°$$

$$\begin{aligned}VAW = 13 * m * (&GZ\ at\ Downflooding\ Angle)/(Sail\ Area\\ &* (Height\ of\ Center\ of\ Effort\\ &+ Height\ of\ Lateral\ Underwater\ Pressure\ )\\ &* \ \llbracket \cos\,(Downflooding\ Angle\ ) \rrbracket\ \hat{}1.3\ ))\hat{}0.5\end{aligned} \tag{71}$$

The downflooding angle is defined as, "the heel angle at which the first downflooding opening becomes immersed. The opening may be either a main companionway hatch, to a cockpit that is not quick-draining or into the hull itself." The most crucial point for a boat with a quick-draining cockpit is the top corner of the companionway hatch, as opposed to the lower corner where it meets the cockpit sole as shown in Figure 37. As such, if the boat does not have any abnormally large ventilation openings in the hull, the upper corner of the companionway hatch signifies the downflooding angle.

8) The Downflooding Factor (FDF) is proportional to the downflooding angle and represents the risk of downflooding in a knockdown scenario. Guidance for finding a boat's downflooding angle is provided by ISO 12217-2 in Figure 38.

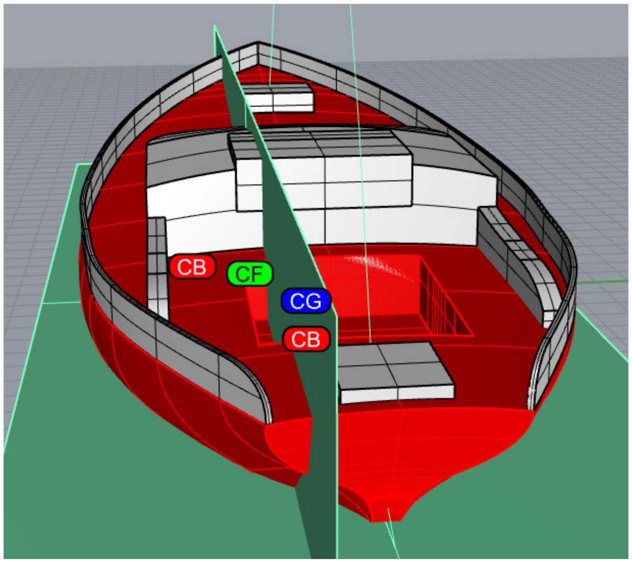


Figure 37 - Downflooding at 90 deg

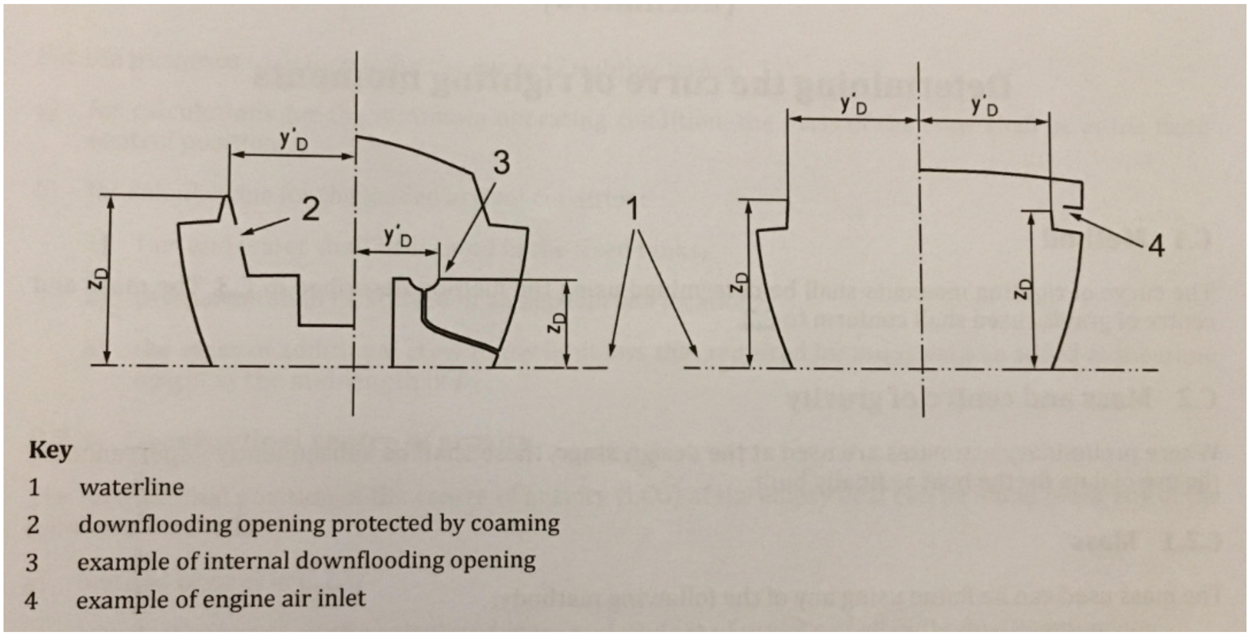


Figure 38 - Approximate Method for Downflooding Angle (ISO 12217-2, 2015)

$$\text{Downflooding Angle} = \tan^{-1}\left(\frac{z_D}{y_D'}\right) \tag{72}$$

$$z_D = height\ of\ downflooding\ point\ above\ waterline$$
$$y_D' = transverse\ distance\ of\ the\ downflooding\ point\ from\ centerline\ of\ vessel$$

The downflooding angle for a light displacement boat is usually around 125°, while heavy yachts with the hatch on the centerline possess a downflooding angle of approximately 115°. The minimum and maximum values for this factor in the data are 0.5 and 1.25 respectively. (Larsson & Eliasson, Principles of Yacht Design, 2016)

$$Downflooding\ Factor = \frac{Downflooding\ Angle}{90} \tag{73}$$

The final stability index value is calculated using the formula below:

$$\begin{aligned} STIX = {} & (7 + 2.25 * Base\ Length\ Factor\ ) \\ & * (Displacement\ Length\ Factor \\ & * Beam\ Displacement\ Factor \\ & * Knockdown\ Recovery\ Factor \\ & * Inversion\ Recovery\ Factor * Dynamic\ Stability\ Factor \\ & * Wind\ Moment\ Factor * Downflooding\ Factor)^{0.5} \end{aligned} \tag{74}$$

Based on their STIX value, yachts are placed into one of four categories, A-D. A yacht in category D should be used only in sheltered waters, while a boat in category A should be fit for open ocean passages. Boats of category A or B must also have a quick-draining cockpit and a downflooding angle of at least 90°. (Larsson & Eliasson, Principles of Yacht Design, 2016).

Table 5 - Summary of Design Category Descriptions (ISO 12217-2 43)

STIX	STIX Category	Meaning
32	A	Designed to operate on extended voyages across oceans in waves up to 7 m and wind speeds up to 24.4 m/s.
23	B	Designed to operate on offshore voyages of sufficient length in waves up to 4 m and wind speeds up to 20.7 m/s.
14	C	Designed to operate on exposed inland waters or coastal waters in moderate weather in waves up to 2 m and wind speeds up to 13.8 m/s.
5	D	Designed to operate on sheltered inland waters in wave heights up to 0.5 m and wind speeds up to 7.9 m/s.

2.2.5 Sailboat Concept Exploration Model

The sailboat concept exploration model is integrated and run using Phoenix Integration's Model Center as shown in Figure 39, to assemble several modules together, collect and analyze data and run optimizations. Each module and its significance to the calculation is discussed below.

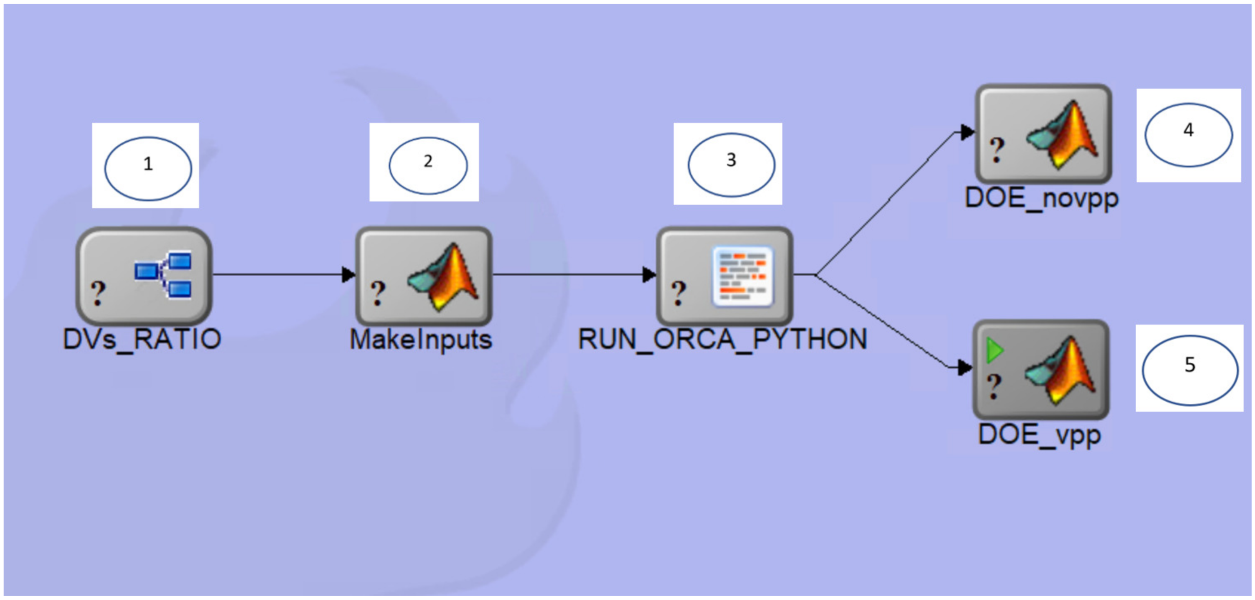
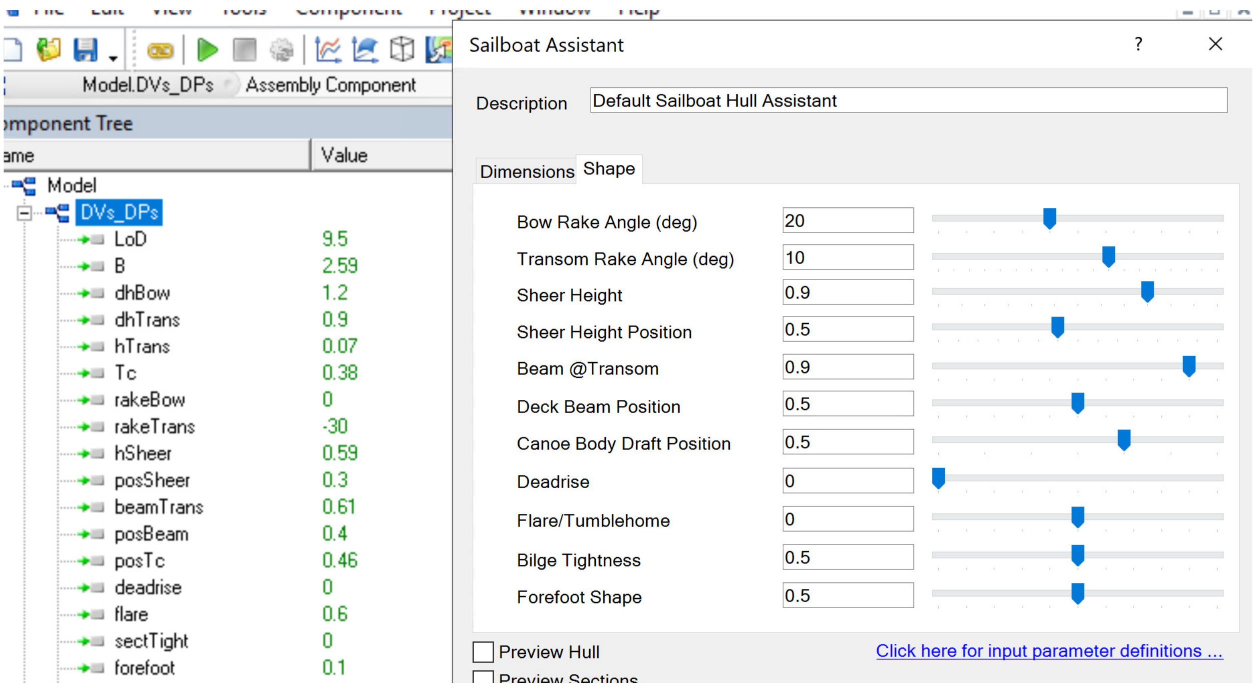


Figure 39 – Sailboat Concept Exploration Model

1) Module 1 - DVs_DPs collects the design variable and design parameter values that define the dimensions and shape of each boat and provides these to the sailboat hull assistant. Figure 40 shows the DVs and DPs corresponding to the required sailboat assistant inputs and a representative set of values. An additional variable may be added identifying the keel. If a keel is added, hydrostatic information will be calculated for the boat with and without the keel.



ame	Value
Model	
DVs_DPs	
LoD	9.5
B	2.59
dhBow	1.2
dhTrans	0.9
hTrans	0.07
Tc	0.38
rakeBow	0
rakeTrans	-30
hSheer	0.59
posSheer	0.3
beamTrans	0.61
posBeam	0.4
posTc	0.46
deadrise	0
flare	0.6
sectTight	0
forefoot	0.1

Description: Default Sailboat Hull Assistant

Bow Rake Angle (deg)	20
Transom Rake Angle (deg)	10
Sheer Height	0.9
Sheer Height Position	0.5
Beam @Transom	0.9
Deck Beam Position	0.5
Canoe Body Draft Position	0.5
Deadrise	0
Flare/Tumblehome	0
Bilge Tightness	0.5
Forefoot Shape	0.5

☐ Preview Hull

Click here for input parameter definitions ...

☐ Preview Sections

Figure 40 – Sailboat Assistant Design Variables / Model Center Inputs

2) Module 2 – "MakeInputs" is a MATLAB script that inputs the DVs and DPs from Module 1 and generates a comma delimited text file named "inputs.txt", which lists the same input data in a form more suitable to Python input by Module 3.

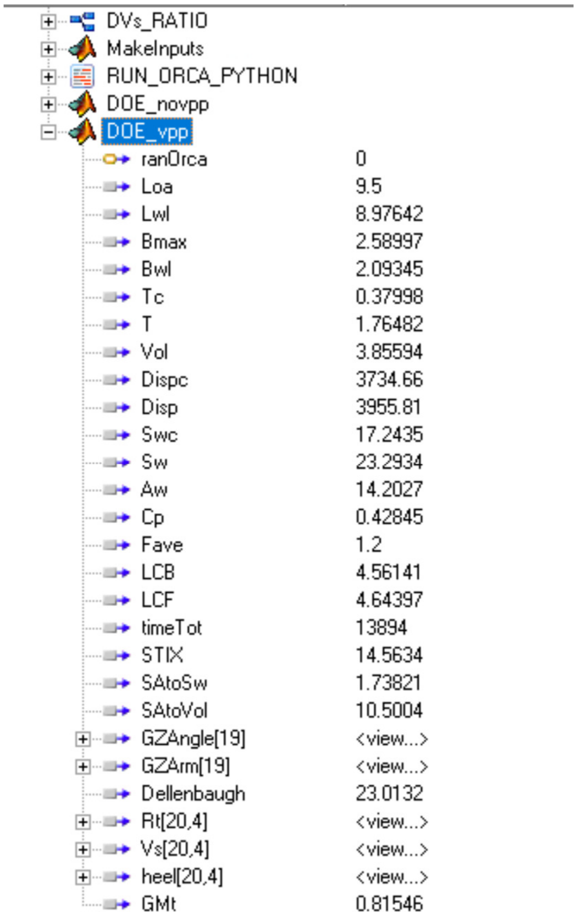
3) Module 3 – "RUN_ORCA_PYTHON" is a VBScript, or a Microsoft Visual Basic Script which first opens Rhino and then runs a Python script named "runSailboatAsst.py". The Python script is a function, which is also named "runSailboatAssist". The function accomplishes several important tasks and is important to understand.

The first part of the Python script defines the function "runSailboatAssist". The remainder of the function defines additional variables and functions used to extract necessary hydrostatic data from the hull models constructed using the design variables and parameters. This hydrostatic data is necessary for the VPP. The beginning of the Python "runSailboatAssist()" function first clears the Rhino workspace and prepares the program for the next hull creation. Next, the inputs needed for the sailboat assistant tool in Orca3D from the outputs of Module 2. The Python script, specifically "-OrcaCreateSailboat" calls the inputs defined earlier to generate the boat hull in the Orca3D Sailboat Assistant from Model Center. The next section of the script runs hydrostatic analysis of the boat's canoe body, while computing the righting arm at the specified angles of heel (here zero to one hundred and thirty degrees, in intervals of ten). All of the hydrostatic information is output to a file "canoeHydrostatics.csv." After the canoe body hydrostatics are completed, the script checks to see if a keel has been added for consideration. If there is a keel, hydrostatics are computed for the boat with the keel considered. The hydrostatic information of the boat with a keel is output into file "fullHydrostatics.csv." If there is no keel, the canoe body hydrostatics will be identical to the "full hydrostatics" values. A full copy of the script is provided in Appendix A – Sailboat Concept Exploration Model Python Script.

The remainder of the script creates a function which opens the data in “inputs.txt” and builds Excel files that contain all pertinent hydrostatic information which is read by the VPP in MATLAB.

4) Module 4 - ORCA_NoVPP calculates STIX using the “runSailboatAssist()” ORCA3D geometry and hydrostatics output. This module does not require the VPP script and was created to expedite stability analysis of the hullforms. The VPP calculations are substantially lengthier, and take longer to complete. The STIX and Dellenbaugh Angle calculations are in MATLAB wrapped in Model Center.

5) Module 5 – DOE_VPP runs the VPP and the STIX and calculates STIX and Dellenbaugh Angle. It is typically used in a DOE to collect sailing performance data for multiple hullforms. It is also written in MATLAB and wrapped in Model Center. Once the DOE_VPP is run, all sailing performance outputs, such as boat speed, heel, lee, etc. populate in Model Center, as shown in Figure 41 and are stored in the Model Center Data Collector.



DVs_RATIO	
MakeInputs	
RUN_ORCA_PYTHON	
DOE_novpp	
DOE_vpp	
ranOrca	0
Loa	9.5
Lwl	8.97642
Bmax	2.58997
Bwl	2.09345
Tc	0.37998
T	1.76482
Vol	3.85594
Dispc	3734.66
Disp	3955.81
Swc	17.2435
Sw	23.2934
Aw	14.2027
Cp	0.42845
Fave	1.2
LCB	4.56141
LCF	4.64397
timeTot	13894
STIX	14.5634
SAtoSw	1.73821
SAtoVol	10.5004
GZAngle[19]	<view...>
GZArm[19]	<view...>
Dellenbaugh	23.0132
Rt[20,4]	<view...>
Vs[20,4]	<view...>
heel[20,4]	<view...>
GMt	0.81546

Figure 41- “DOE_vpp” Results in Model Center

2.3 Concept Exploration Process Steps

This section discusses the Concept Exploration design process, step by step, using a simple Sharpie sailboat design as a case study for discussion and examples. The case study is extracted from a sailboat design assignment given to a team of students in the 2018 VT Ocean Vehicle Design class. The improved design process has evolved over multiple design classes and incorporates components of the VT naval ship design process, *Principles of Yacht Design* and various tools as discussed in Sections 2.1 and 2.2. The influence of the prospective owner is unique to the sailboat design process and is reflected at various points throughout the new concept exploration process. The objectives of the sailboat design process are to design a boat based on very different criteria than the VT ship design process, but many of the steps are very similar or at least analogous. Ultimately, similar to the VT naval ship design process, the sailboat concept exploration phase produces an improved concept baseline design for further development in concept development. The Section 2.3 discussion closely follows the steps shown in Figure 13.

2.3.1 Owner's Requirements and Projected Operational Environment

While ships used for commercial purposes are designed to carry cargo in an efficient manner, a recreational sailboat is very much created to suit the exact needs and preferences of a prospective customer. The owner's requirements are the first step of the concept exploration and represent the beginning of the design process. As an example, the customer requirements for the Sharpie sailboat case study are provided below for reference:

- be a cruising sailboat based on the Sharpie design
- participate in racing events such as small regattas
- have a draft of eighteen inches or less
- have a centerboard or innovative keel design
- satisfy ISO's Stability Index (STIX) requirements for Category B (offshore use)
- sleep four (4) adults
- be trailerable without having to get special permissions
- have alternative propulsion
- be inexpensive to build

Since the owner wants the boat to be trailerable without a special permit, the boat's beam cannot exceed eight feet and six inches per North Carolina Department of Transportation. (Connect NCDOT, n.d.).

The owner intends to use this boat for day cruises, all-day regattas, and extended offshore sails up to four days long. These activities require rudimentary sailboat operations including anchoring, docking, launching, or being towed in a rescue scenario. The design should also provide enough storage space for cruising by maximizing internal volume and seating room.

2.3.2 Projected Operational Environment

The projected operational environment is critical in determining necessary characteristics for a sailboat design. The projected operational environment should also be consistent with the owner's requirements. As an example, a twenty foot sailboat may not be suitable for operating in an open ocean environment. The projected operational environment for the case study used here is the Albemarle Sound in North Carolina which forms part of the Atlantic Intracoastal Waterway as shown in Figure 42. The Albemarle Sound consists of shallow water which is consistent with the owner's need for a small draft design. The owner's desire to use the boat for offshore cruising necessitates the requirement for the boat to achieve the specified STIX rating.

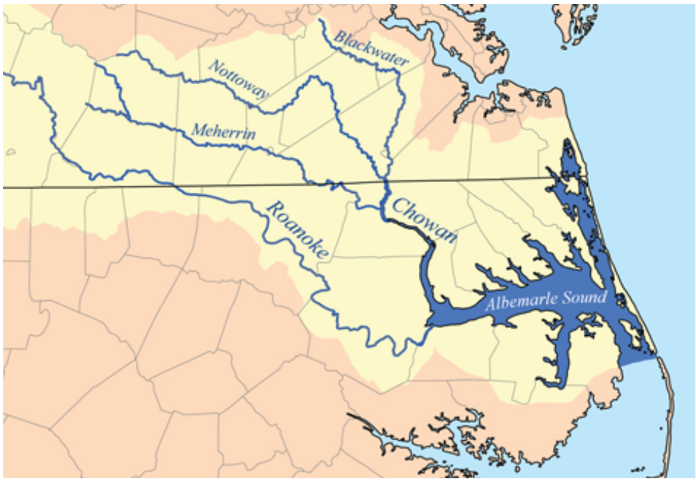


Figure 42- Albemarle Sound, NC (Albemarle Sound, 2019)

2.3.3 Comparative Naval Architecture, Representative Designs, and Preliminary Sizing

Preliminary sizing of the boat is primarily driven by the owner's requirements, and specifically overnight accommodations with consideration of other (representative) designs. It is necessary to consider the need for an anchor forward, space aft for the cockpit and lazarette, and space inside for the galley and head. Most importantly, the owner has indicated that overnight accommodations must be included for four people. Given the stack-up length of these components, it is reasonable to estimate a boat of twenty-eight to thirty-two feet length on deck (LOD). The values for maximum beam and draft are also specified in the owner's requirements. Ratios are used as design variable (DVs) to calculate these dimensions from the LOD because they better maintain relative proportions and work best in optimization. These ratios can be determined through experience or comparative naval architecture.

Comparative naval architecture provides additional information to formulate an initial design space. For this step of the design process, five Sharpie sailboat designs were constructed in Rhino using Orca3D's sailboat assistant tool including the 27' New Haven Sharpie, 35' New Haven Sharpie, 28' Parker Egret Sharpie, 28' Woodenboat Egret Sharpie, and 33' North Carolina Sharpie. For the purpose of the design process, these boats are considered "representative designs", and are used extensively for comparison. After developing these models, their various hydrostatic characteristics including waterplane area, and coefficients of form are compared using Orca3D's hydrostatic analysis tools. Specific attention is paid to their minimum and maximum design variable values listed in Table 6.

Table 6 – Range of Hull Characteristics from Comparative Naval Architecture

Design Variable	Min. Value	Max Value
Length on Deck (LOD)	27.83'	35.58'
Length to Beam (LtoB)	3.74	4.69
Length to Deck Ht. at Bow (LtoD)	6.70	8.99
Deck Ht. at Transom to Deck Ht. at Bow	0.62	0.87
Transom Ht. to Deck Ht. at Transom	0.20	0.61
Sheer Ht. Ratio	0.55	0.70

Sheer Ht. Position	0.22	0.73
Beam to Transom Ratio	7.16	8.97
Transom at Rake	-32°	0°
Deck Beam Position	0.40	0.59
Draft Position	0.36	0.46
Flare	0.40°	0.73°
Deadrise	0	0
Bilge Tightness	0	0

These ratios and values are used to develop an initial design space, or a range of desired values. The representative designs all have similar uses and sizes to the boat the owner has requested. Parameters that were not explored further during the formulation of the initial design space include deadrise and bilge tightness. Zero deadrise produces a bottom with single curvature in the longitudinal direction (rocker) that is characteristic of a Sharpie. Zero bilge tightness creates a hard chine on the hull, making the hull easily developable and is also characteristic of a Sharpie. Both of these are set as design parameters (DPs), constant for all designs. Beam at transom was also initially set to zero to create a hull similar to the Egret, which is unique in its double-ended shape. This was later adjusted to allow for additional exploration, as several original Sharpie designs including the North Carolina Sharpie displayed a significant beam at the transom.

Afterwards, using the model-based engineering software, Model Center by Phoenix Integration, the initial design space can be created to reflect minimum and maximum desired boat characteristics. This design space is primarily based on the range of hydrostatic characteristics found using comparative naval architecture. The design space can be further adjusted to meet the owner's requirements and to facilitate the production of a boat with adequate space for accommodations. The initial design space for the case study is provided in Table 7.

Table 7 – Initial Design Space

Design Variable	Min Value	Max Value	Reasoning
Length on Deck	28.0'	33.1'	Owner's Requirements
Beam on Deck	6.9'	8.5'	Owner's Requirements Comparative Naval Architecture
Deck Ht. at Bow	2.5'	4.9'	Comparative Naval Architecture
Deck Ht. at Transom	2.5'	4.9'	Comparative Naval Architecture
Transom Ht.	0.5	0.7	Comparative Naval Architecture
Cn. Body Draft	1.0'	1.3'	Owner's Requirements
Bow Rake Angle (Deg)	0°	25°	Open for Exploration
Transom Rake Angle (Deg)	-30°	10°	Comparative Naval Architecture
Sheer Ht.	0.5	0.8	Comparative Naval Architecture
Sheer Ht. Position	0.3	0.7	Comparative Naval Architecture
Beam at Transom	0	1.3'	Open for Exploration
Deck Beam Position	0.4	0.6	Comparative Naval Architecture
Cn. Body Draft Position	0.3	0.6	Comparative Naval Architecture
Deadrise	0	0	Sharpie, developable Hull
Flare / Tumblehome	0.4	0.7	Developable Hull
Bilge Tightness	0	0	Sharpie, developable Hull
Forefoot Shape	0	0.1	Developable Hull

2.3.4 Measures of Performance (MOPs)

Measures of performance (MOPs) are metrics used to measure a boat's ability or performance to execute required capabilities consistent with the mission. Measures of effectiveness are indicative of performance applied to a specific mission. Depending on the requirements, type and purpose of the boat, MOPs may also be MOEs. A critical part of using MOPs is developing and/or refining tools which can quantify the MOP. For example, if stability is chosen as an MOP, there must be an evaluation tool or technique used to calculate stability metric(s).

2.3.4.1 Speed

Speed is a common measure of performance for sailboats, especially those for which are intended for racing. Since the customer in this case study intends to use this boat to, "participate in racing events such as small regattas", part of the concept exploration process is focused on developing a sailboat that will exhibit acceptable speed attributes. In order to evaluate and quantify this MOP, both the VPP and CFD tools are used. To gain a more in-depth look at a design's speed performance, a smaller script was incorporated within the VPP script, to simulate a boat completing a standard regatta.

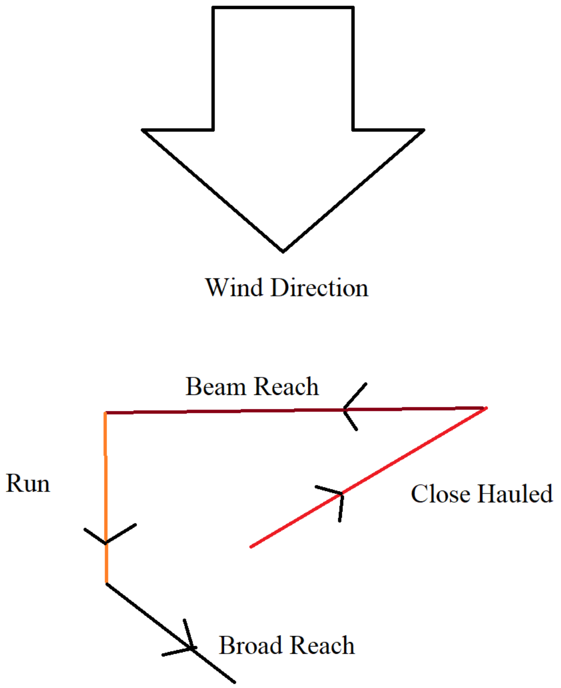


Figure 43 – Standard Regatta in VPP

The regatta was run at several different wind speeds from approximately four to twenty knots. After simulating the boat completing the regatta at different wind speeds, the times from each simulation are added for the total time. Regatta total time is the MOP. Later in the design process, this MOP is selected as an objective considered within the multi-objective genetic optimization (MOGO).

2.3.4.2 Stability and Seaworthiness

Stability plays an important role in the design of any ship or boat. If a boat is unstable, its performance suffers and the safety of its passengers and operators is in jeopardy. In this case study, the owner explicitly states that the boat must be compliant with the ISO's stability index (STIX) Category B classification. The STIX metric is both a stability metric and a seaworthiness metric. It is very important and specifically called out by the owner. This MOP also serves as an objective for the case study design in the MOGO.

2.3.4.3 Dellenbaugh Angle (Constraint)

The Dellenbaugh Angle also provides a relatively quick method of judging a boat's operational stability and approximates a boat's heel angle when sailing to windward in an 8 m/s breeze (Larsson & Eliasson, Principles of Yacht Design, 2000). Figure 44 shows typical values of Dellenbaugh Angle for sailboats as a function of LWL.

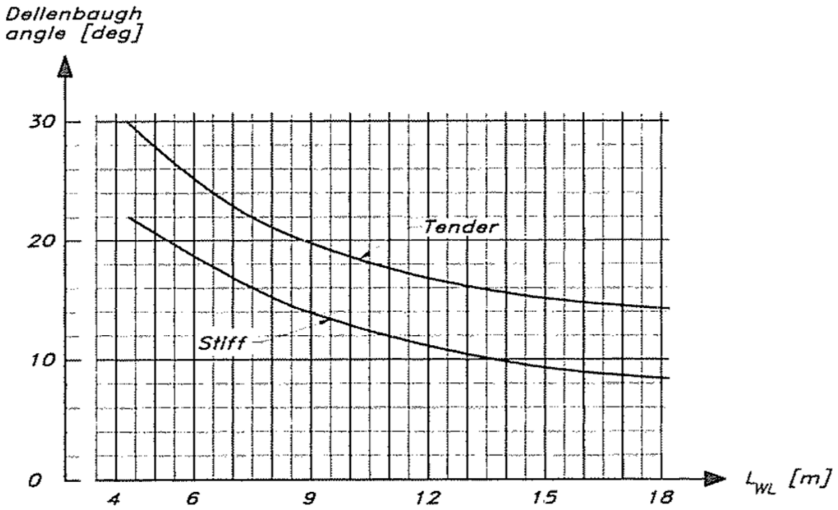


Figure 44 - Dellenbaugh Angle (Larsson & Eliasson, 2000)

The heeling arm is defined as, "the vertical distance between the center of effort of the sails and the center of lateral resistance of the underwater body." The majority of modern yachts possess Dellenbaugh Angles within the range illustrated by the figure above, and the difference between a tender and stiff boat is approximately 6° for all lengths. For a boat with length along waterline of 10 m, the Dellenbaugh Angle should be between 13° and 19°. The 13° value symbolizing a stiffer yacht, while the 19° value representing a more tender yacht. It is important to note that the Dellenbaugh Angle does not address boat stability at large angles of heel (Larsson & Eliasson, Principles of Yacht Design, 2007).

The Dellenbaugh Angle MOP is used during the concept exploration process as a constraint in order to eliminate designs that represent extremely tender boats. Extremely tender boats will be uncomfortable for passengers, as the boat will heel excessively at even moderate wind speeds.

$$Dellenbaugh\ Angle = 279 * \frac{Sail\ Area * Heeling\ Arm}{Mass * Metacentric\ Ht.} \tag{75}$$

2.3.4.4 Boat Dimensions

Boat size can very often be used as an MOP, as sailboat owners may have certain restrictions and preferences which cannot be overlooked. In this case study, draft is an important MOP specified by the owner and is very low for a boat of this size. Due to the extremely shallow nature of this boat's depth, the impact of this dimension on hull shape is very restrictive. Furthermore, in order to provide enough space for the requisite accommodations and equipment, it was ultimately decided that the minimum draft needed to be very close to the 18" maximum value specified by the owner. As such, the boat's draft was considered a constraint later in the concept exploration process with a very narrow design space allowed for the B/T ratio design variable.

2.3.4.5 Cost

There is no simple solution for pre-determining boat building costs, although the designer's ability to produce plans which thoroughly outline the structure, rig and intended equipment will help provide a fair estimate. Differences in a builder's efficiency, overhead, design interpretation and local labor costs all play integral roles in calculating final production cost. Thorough communication between the owner, designer and builder will help to avoid unwanted surprises. Clear expectations set forth by the designer and owner helps to clarify the scope of completion, build timing and any other factors which may impact the builder's costs. The owner may choose to have the hull manufactured professionally, while handling other construction details themselves. (Kasten, 2016)

The designer has done a disservice to the owner if the final design is significantly more expensive than originally budgeted for. If the final design is more expensive than the owner is willing to pay, then the design is essentially infeasible. To simply minimize cost as an objective, would be relatively easy. However, this is short-sighted, and would lead to sacrificing the effectiveness of other MOPs. The designer must be able to balance all MOPs and cost to best satisfy and present non-dominated options to the customer.

2.3.4.6 Appearance

The boat must be aesthetically pleasing to the prospective owner. While this MOP may be the most difficult to quantify, allowing the owner input on decisions relating to boat appearance should sufficiently satisfy this requirement. Providing the owner multiple options in terms of design is also a method used to address this MOP. It is important that the designer recognize the importance of aesthetics early in the design process, as the prospective owner may have such a strong opinion on this MOP that logical and scientific contentions may become secondary considerations.

2.3.5 Weight and Center of Gravity Estimate

To complete the concept exploration process, two assumptions must be made regarding the boat's displacement and vertical center of gravity until additional details are available in concept development. Displacement weight must be equivalent to the weight of the boat and its contents. In the case study, it was assumed that the boat's displacement is 8,267 pounds. This assumption is based on the hydrostatic analysis of the representative designs which formed a range of realistic displacement values. The mean value of these was chosen for the case study design. When the actual weight of all components except ballast is known, the ballast weight must make up the difference to achieve displacement weight. The second major assumption is the boat's vertical center of gravity. A typical early estimate for medium to large sailboats is that the VCG is at the waterline.

It is necessary to make these assumptions fairly early in the concept exploration process as the boat's displacement and center of gravity are required inputs for the VPP, STIX, and CFD. Making these two (2) assumptions allows progress in the concept exploration process which would otherwise be stagnated. It is also beneficial to consider the idea that ballast could be added or removed in certain locations along the boat to adjust the displacement and center of gravity as needed. Once the concept exploration process has concluded, and concept development has begun, specific weights of hull structures, and payload items can be accounted for, yielding a more accurate value for displacement and center of gravity. If there is a large disparity between the calculated values and assumed values, which cannot be rectified by adjusting ballast, additional iterations of the design process may be necessary.

2.3.6 Sail Design Exploration

There are several points of consideration with regard to sails and rigging, including the number of masts, size configuration of mast(s) and sail(s), as well as sail type. Again, customer input at this juncture is important in order to create an optimal product. General ideas of rig and sail plan are discussed in the concept exploration process, while the concept development portion of the design process focuses on expanding these details. In the case study, conversation between the designer and customer indicated that two masts were preferred, rather than one. Taller masts tend to have higher aspect ratios and better performance, while two masts lower the center of effort on the sails as well as the boat's center of gravity. Two masts allow for better stability, which is critical for this design. Two smaller masts are also easier to raise than one large one. Based on historical research, it was also determined that most Sharpies greater than twenty-five feet in length had two masts rather than one.

It was also decided that a gaff rig would have advantages over a Marconi or Bermuda rig for this sailboat design. The gaff rig is a four-cornered, fore and aft rig setup that is controlled at its peak. This layout allows the rig to carry twenty-five percent more sail than an equivalent Bermuda rig, while having a shorter mast. The gaff rig allows for sufficient sail area without requiring a mast of excessive height, and a corresponding center of effort which lends to potential stability issues (Leather, 2001). Figure 45 shows examples of two main mast configurations considered, schooner and ketch type. However, after further discussion with the customer, the final design was based on the plan shown in Figure 46. This design was used on historical Sharpie designs, specifically the North Carolina 33 and New Haven 35 Sharpies.

The sprit rig is much lighter and easier to handle than a traditional gaff rig layout. Rather than having an outhaul and a boom vang to control sail shape, this style requires only a "snotter." The snotter is a rope used to tension the sprit by pulling the lower end towards the mast. The plan is modified by giving the sails square tops with battens to provide the same advantages as a gaff rig without the extra rigging.

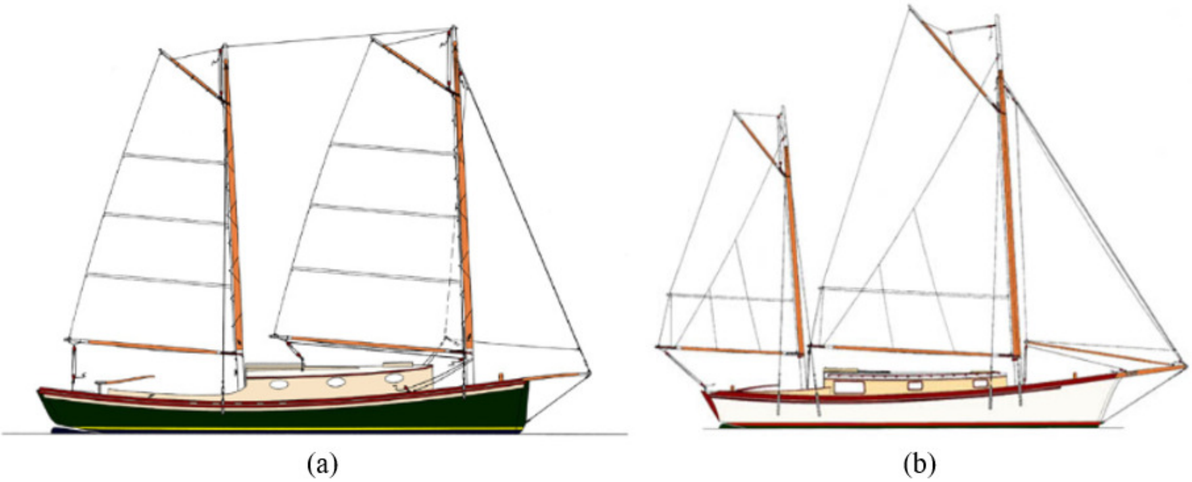

(a) (b)

Figure 45 – Schooner vs. Ketch Sail Design

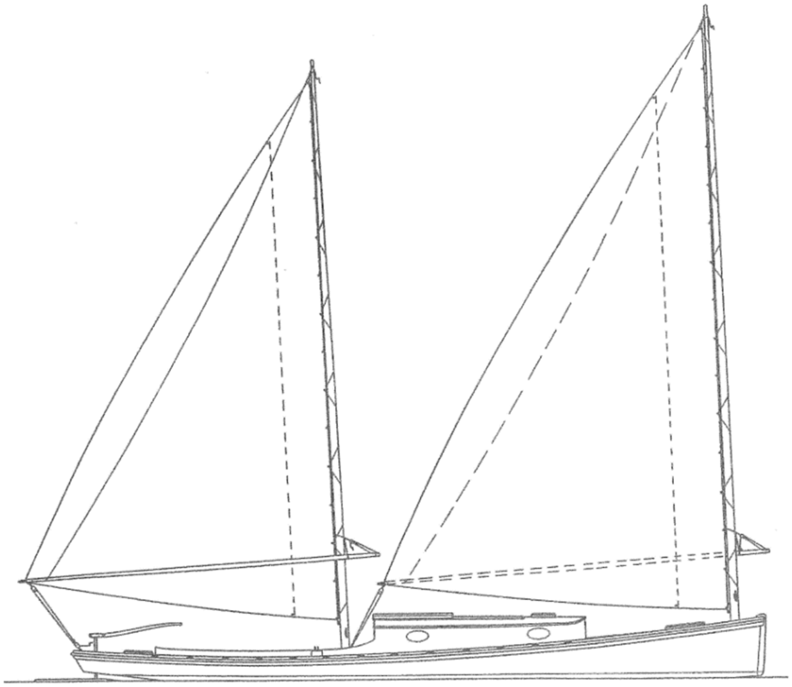


Figure 46 – Preliminary Sail Design

A disadvantage to a sprit rig is that when the wind is on the opposite side of the sail as the sprit, the wind pushes the sail against the sprit. This disrupts the flow and lowers performance. The solution to this is to use wishbone booms. These are used on windsurfers as well as some larger sized yachts, as shown in Figure 47. The wishbone boom curves around both sides without contacting the sail. During sail exploration, it was discovered that a modern, Sharpie-based design called the Presto 30 (bottom right in Figure 47) also uses wishbone booms.

Figure 47 – Wishbone Booms

Once the sail design is better established, calculation of the necessary sail area and center becomes a critical part of the sail design exploration process. Keel and rudder areas can also be estimated based on this sail area. The sail area is also critical in serving as a measure of obtainable driving force for the sailboat. In the VPP, the boat's driving force, must converge with the overall resistance produced at the equilibrium speed. To compare the driving force and resistance, it is important to consider the boat's wetted surface area and displacement. Wetted surface area plays a large role in determining friction, which is especially prevalent at low speeds. Displacement is an important property for wave resistance, which becomes an important factor at higher speeds. Therefore, significant ratios to examine are sail area to wetted surface area and sail area tovolume displacement^(2/3). Statistics provided by the International Measurement System (IMS) fleet, presented in *Principles of Yacht Design*, show that nearly all boats have a sail area to wetted surface area between two and 2.5. It is also noted that there does not seem to be any perceivable correlation between this ratio and yacht size. In terms of the sail area to displacement ratio previously discussed, most boats fall between fifteen and twenty-two, with an average value of nineteen. (Larsson & Eliasson, Principles of Yacht Design, 2007)

Due to the unique nature of the Sharpie design in the case study, comparative naval architecture was completed to examine sail characteristics of historical Sharpie designs. As previously discussed, the sail area to wetted surface area ratio and the sail area to $\text{displacement}^{\frac{2}{3}}$ are of particular importance. These results are shown in Figure 48, and are mostly consistent with the data presented in *Principles of Yacht Design*. This provides additional information to review when determining how much sail area is needed.

Name	Lwl (m)	B (m)	T (m)	Sw (m^2)	SA (m^2)	SA/Sw	Displacement	SA/Displament^(2/3)
Sharpie 24 Hampton Flattie	6.91	2.36	0.76	17.42	24.43	1.40	4.70	14.59
Ohio Sharpie	6.02	2.13	0.30	9.13	22.76	2.49	1.48	19.97
Sharpie 36	11.07	3.00	0.61	27.13	52.68	1.94	7.65	26.74
Kirby Sharpie	9.52	2.29	0.46	17.54	41.81	2.38	3.76	26.88
28 Egret	8.53	2.29	0.25	12.47	24.80	1.99	1.87	20.12
Minocqua 2	8.99	2.84	0.61	21.66	61.32	2.83	5.89	33.95
New Haven	12.22	3.05	0.71	32.41	71.91	2.22	9.99	33.38
45 San Juan Islands	13.27	3.05	0.76	36.36	69.96	1.92	11.65	30.86
20ft Bjorn Thomasson	6.00	2.06	0.22	7.88	21.00	2.66	1.03	20.81
Average	**9.17**	**2.56**	**0.52**	**20.22**	**43.41**	**2.21**	**5.34**	**25.26**

Figure 48 – Comparative Naval Architecture for Sail Sizing

2.3.7 Keel and Rudder Design Exploration

For our case study, the keel design space was narrowed down quickly based on the owner's need for a shallow draft boat. Most standard keel designs add significant permanent draft to the boat and were eliminated. A swing keel with a trapezoidal plan shape was determined to be the best fit for the shallow water sailing conditions expected. The area of the keel is 3.5% of the sail area as recommended in the Principles of Yacht Design. The depth of the keel is maximized to lower the center of gravity for static stability and increase the aspect ratio for efficiency and lift.

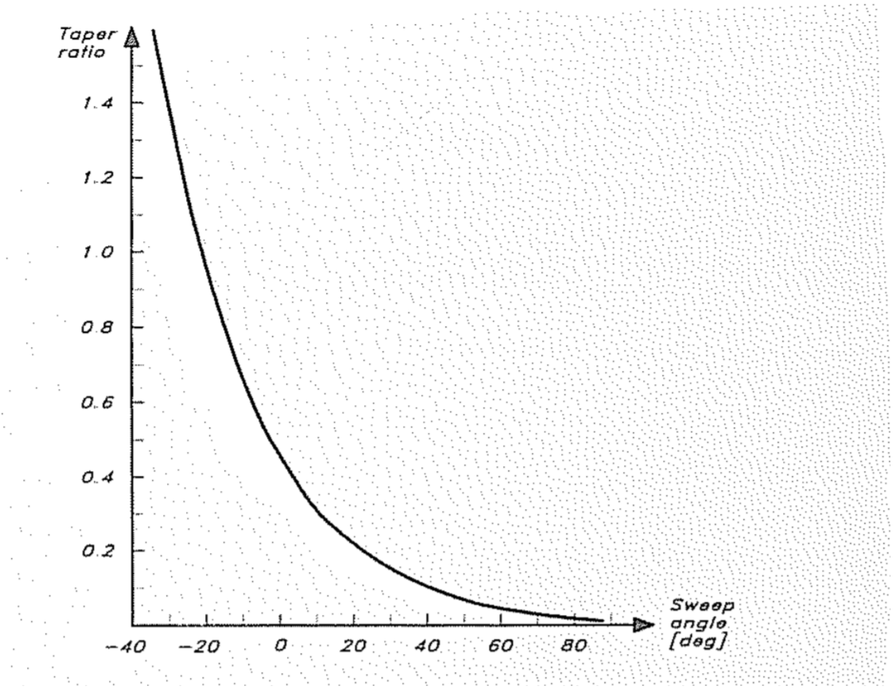


Figure 49- Taper Ratio vs. Sweep Angle

After the keel type is explored, foil shape is considered. *Principles of Yacht Design* provides valuable recommendations in this regard, and focuses on aspect ratio, taper ratio, and cross section. Figure 49 shows optimal taper ratio for a given sweep angle. Variance from these taper ratios can cause an unnecessary increase in drag force, as seen in Figure 50. Most keels have a sweep angle of 20°-30° which gives an optimal taper ratio of approximately 0.1.

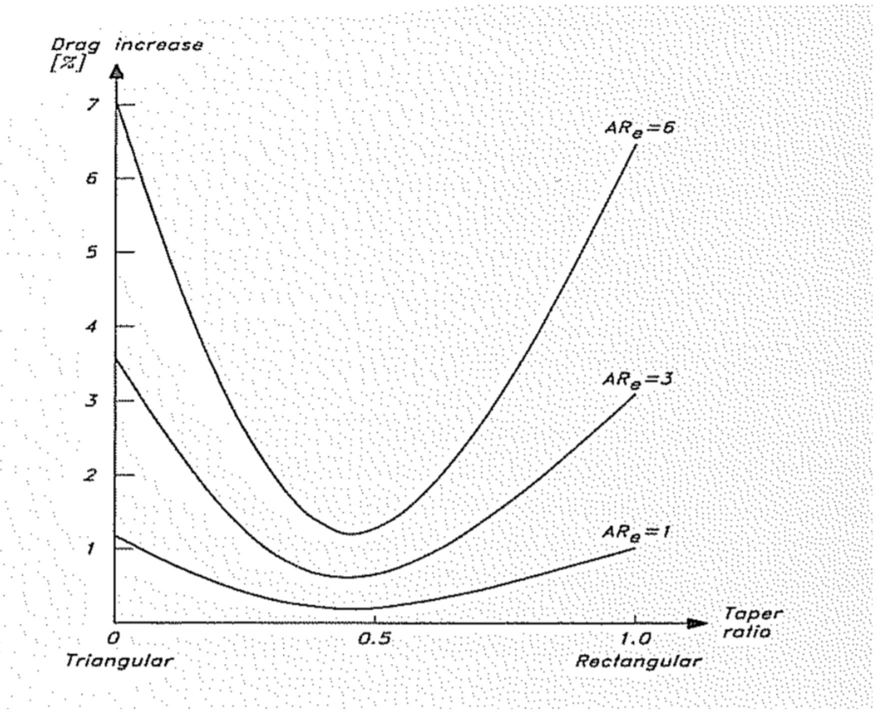


Figure 50- Drag Increase vs. Taper Ratio

With respect to specific hydrofoil series, *Principles of Yacht Design* provides specific analysis on four respective foils, which all belong to the NACA 6-series. Two 21% max thickness foils and two 9% max thickness foils are analyzed, respectively. As can be seen in Figure 51, the thin sections have the smallest drag at small angles of attack, while the thicker sections cause lower drag values at higher angles of attack.

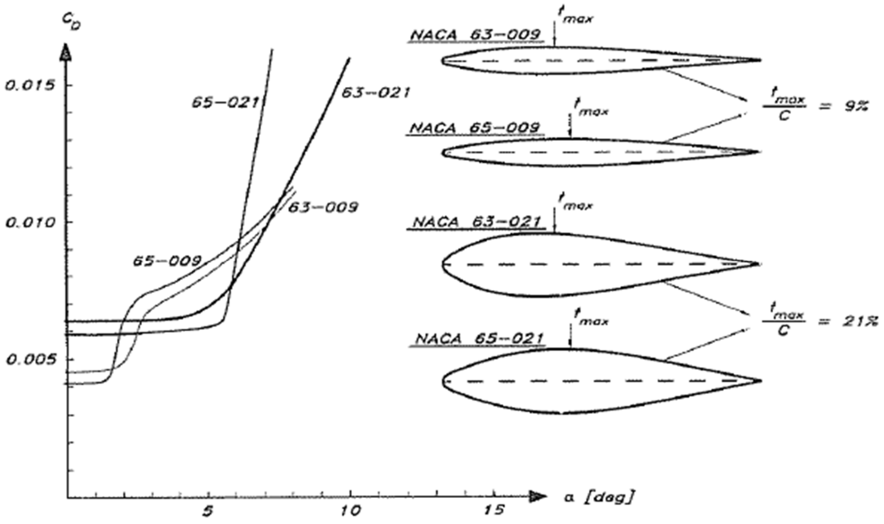


Figure 51- Influence of Section Shape on Drag

In further analyzing the NACA 65-021 hydrofoil, the center of pressure is closer to the center of the chord rather than the quarter chord which allows for improved lift with a relatively small thickness leading to decreased drag. As such, a keel using this hydrofoil provides better performance in low-speed conditions. Figure 52 provides a visual representation of the hydrofoil profile. This hydrofoil shape is much more efficient than a large round centerboard shape creating significantly less drag.

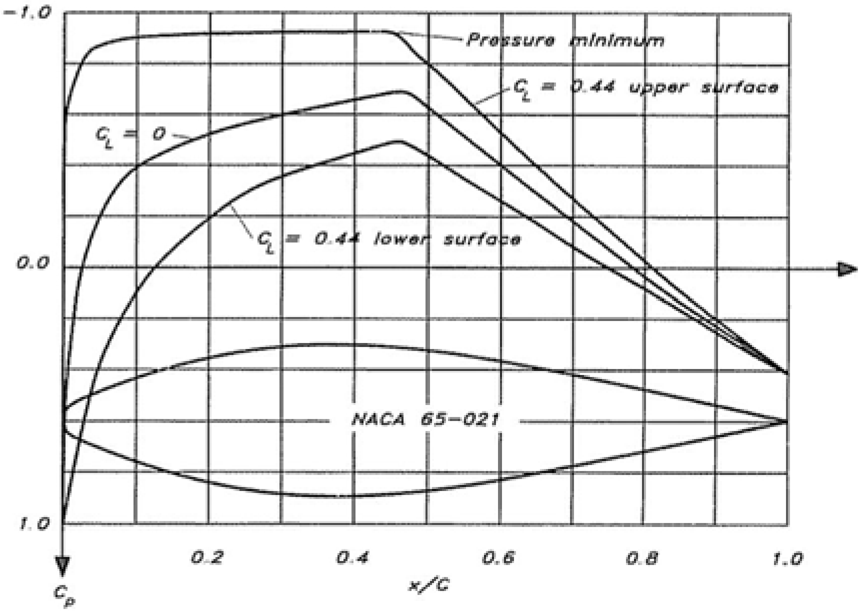


Figure 52 – Pressure vs. Chord Length for NACA 65-021

The shape chosen in our case study starts at the root (hull) as a NACA 63-012 hydrofoil and transitions to a NACA 65-015 hydrofoil as it reaches the tip. The reasoning for this shape is that a thinner hydrofoil section with less lift is optimal closer to the hull in order to avoid unnecessary wave making while the boat is heeled. A thicker hydrofoil section near the tip creates necessary lift while ensuring the keel is structurally sound as the chord length shortens in a trapezoidal plan shape. The keel's shape is designed with an elliptically rounded tip to avoid hydrodynamic vortices. The resulting keel is shown in Figure 53.

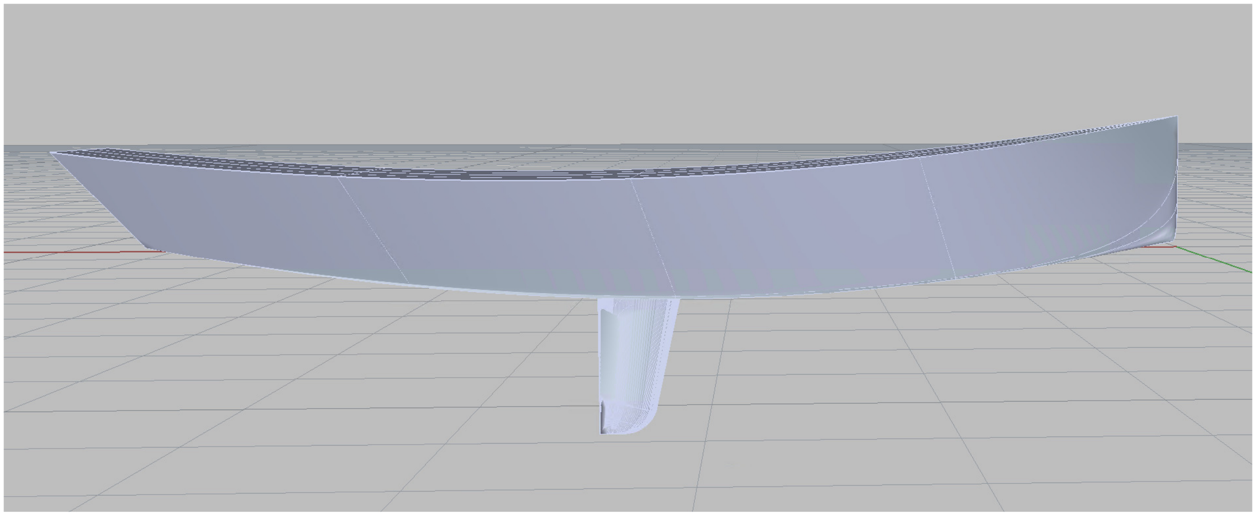


Figure 53- Keel Design from Case Study

For more general keel design exploration, several different types of keels should be explored to determine how type and sizing affect the stability and speed of the hull (Figure 54). The area of the keel should be approximately 3.5% - 4% of the sail area, hence the importance of a thorough sail design exploration.

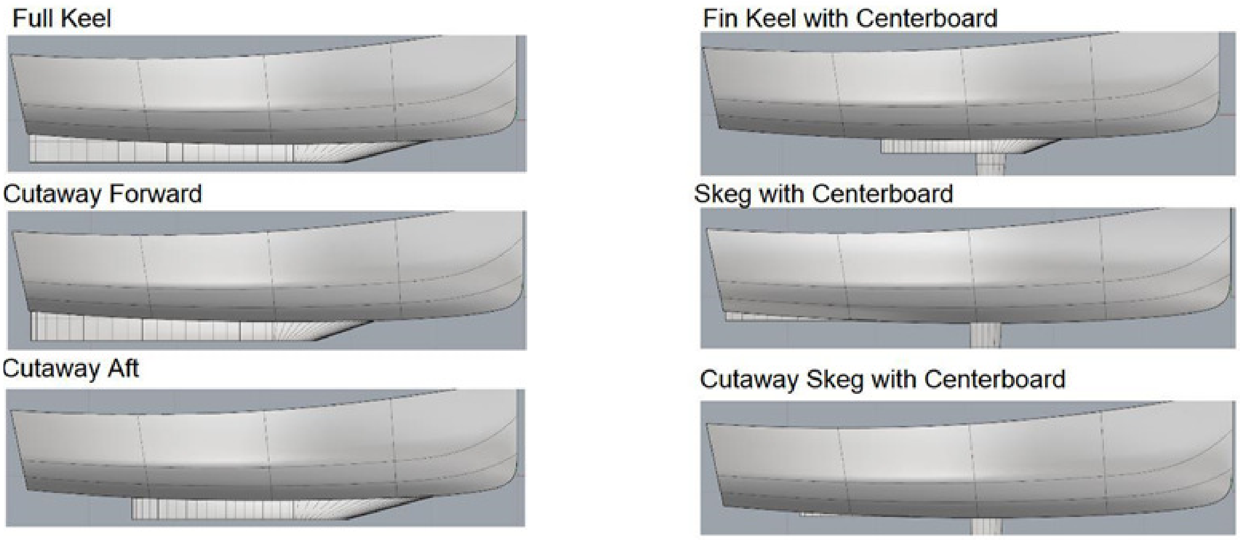


Figure 54 – Keels Initially Considered

Since the Sailboat Assistant can only generate a canoe body and in order to search the keel design space hands-off in Model Center, significant effort went into creating scalable keel segments able to generate the range of keel types and sizes shown in Figure 54.

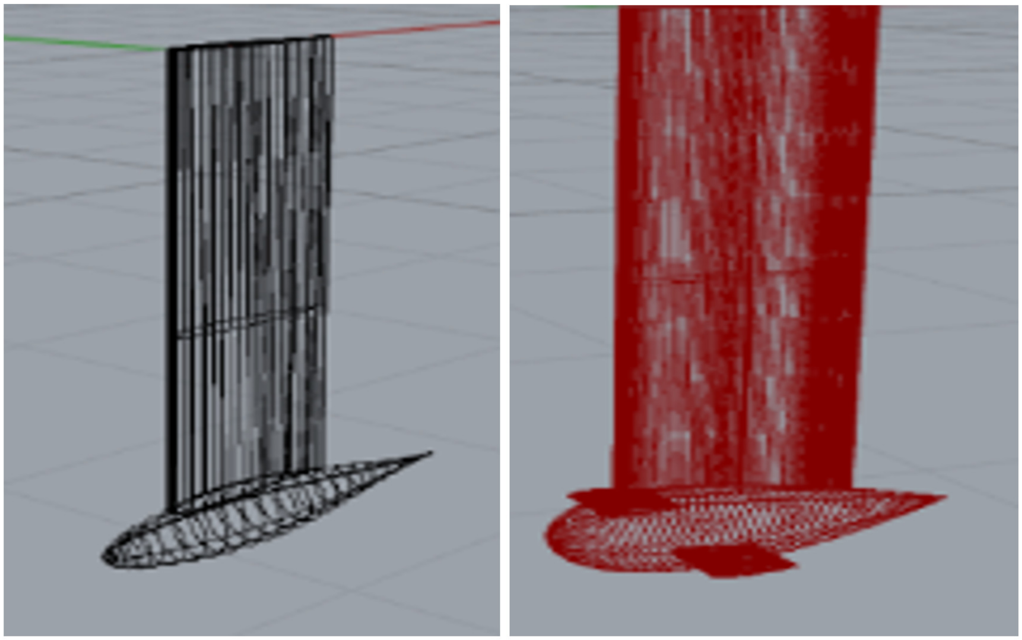


Figure 55 -Keel Designs with Bulb and Winglets

Two additional keel options may also be explored. The first option includes a keel with a bulb, while the second adds winglets to the bulb (Figure 55). These keels may be installed as linear drop keels if the operator needs to pull the keel up into the hull when entering shallow water. If this is the case, the designer must consider the effects of storing the keel inside the hull on interior volume.

Each of the keel type and shaping options shown in Figure 54 can be constructed and analyzed using CAD. Consideration should be given to the owner's preference as well as the keel's effect on speed, stability, and size.

Individual pieces of the keel are sized/scaled independently in Model Center, allowing for a variety of designs. To explore different combinations and sizes, the following variables were created to scale the keels. Scaling factors were calculated individually for each keel option using the Model Center design variables KeelX, KeelY, and KeelZ. These variables represent ratios extending from zero (0) to one (1). More information on these variables are found in Table 8 and Figure 56.

Table 8 – Keel Sizing Variables

Variable	Description
KeelXScaleF	Length of forward section of keel in chordwise direction
KeelXScaleB	Length of aft section of keel in chordwise direction
KeelZScale	Distance from waterline to the top of the keel
KeelXLoc	Distance along waterline from forward perpendicular to intersection of fore and aft keel sections
KeelYScale	Baseline thickness of hydrofoil

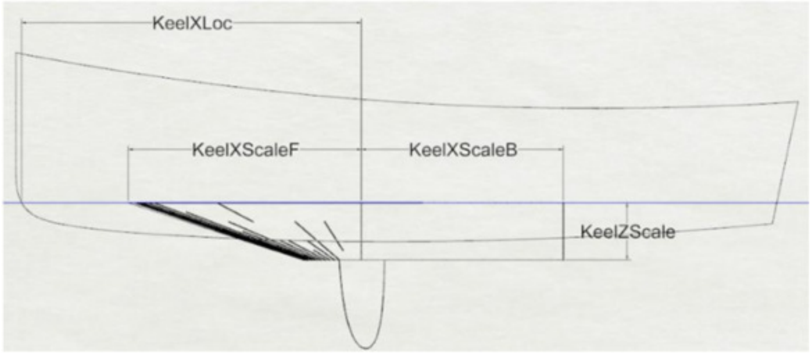


Figure 56 – Keel Sizing Variables

In order to generate the different keel types in CAD automatically from Model Center, different sections are developed. The first section is the foremost portion of the keel. This piece has a rounded nose and tapers down in chord length moving further from the waterline. The second section is the aftmost part of the keel. This portion of the keel tapers off the fore section when combined (Figure 57). The two parts are sized independently.

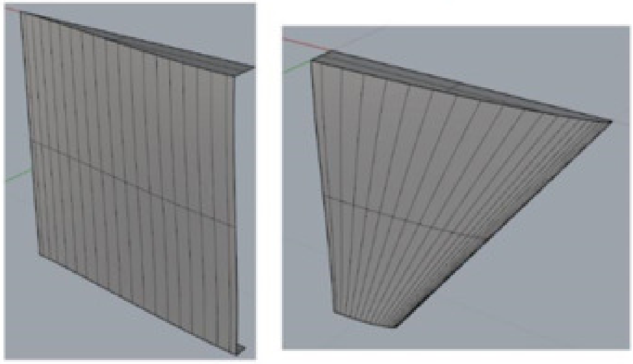


Figure 57 – Fore and Aft Keel Sections

The rudder design process is similar to the keel design process, in terms of considerations and need for owner's preference. *Principles of Yacht Design* recommends that the rudder should use the NACA 4-series hydrofoil shape, as this class performs better under high angles of attack than the previously discussed NACA 6-series.

The rudder location is also likely to change depending on the boat's arrangements. Two different locations were explored during the case study, and illustrate common issues found during the appendage exploration segment. The first location is designed for performance and involves the rudder post going through the transom of the boat, allowing the rudder to pivot through its center of pressure. This connection keeps the rudder balanced and allows for a shorter tiller arm. The shorter tiller arm makes for an easier, smaller turning radius. It also enables more of a flat plate mirror image effect that increases the effective rudder aspect ratio. The second option is more traditional and aesthetically pleasing. This option involves a transom mounted rudder post. The tiller arm in this case, goes past the transom and connects to the transom mounted rudder post. A disadvantage of this design option is that the rudder is hinged from an unbalanced position. The hinge position, along with the longer tiller arm makes for more difficult steering.

In keeping with the owner's requirements of the case study, the rudder should not add to the boat's canoe body draft. As such, each rudder design option considered should have the capability of being pulled or swung up as to not impede the boat's maneuverability in shallow water. A visual representation of each design option, with the preliminary swing techniques is shown in Figure 58 and Figure 59.

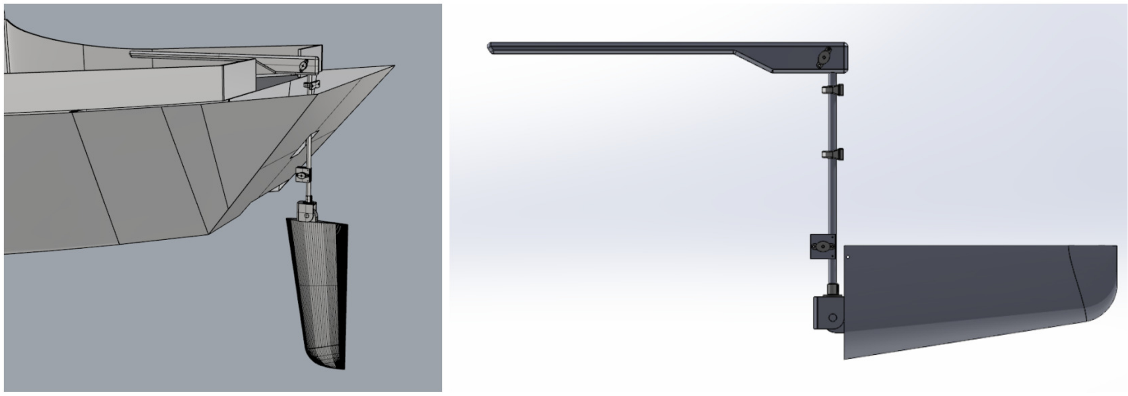


Figure 58 – Keel Option #1 with Swing Mechanism

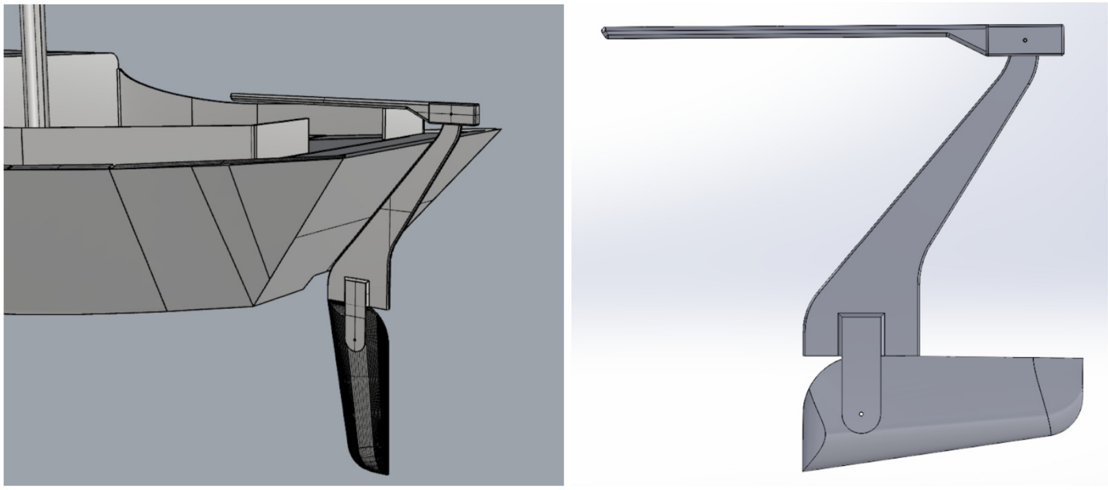
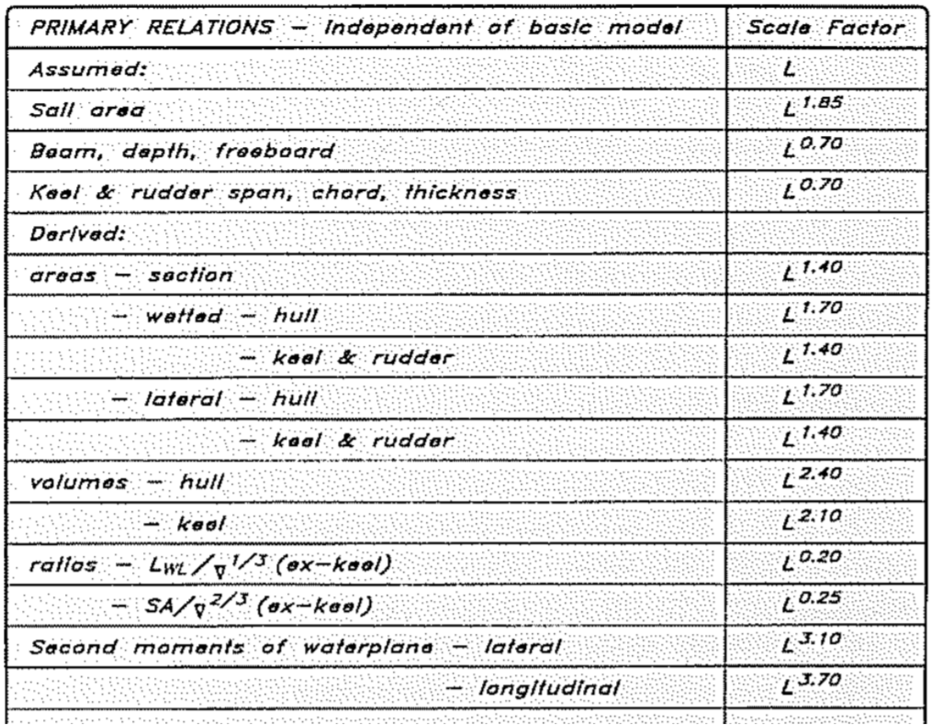


Figure 59 – Keel Option #2 with Swing Mechanism

2.3.8 Hullform Tool Refinement and Exploration

To begin hullform exploration, representative and exploration baseline designs are constructed in Rhino and evaluated using Rhino's marine plug-in, Orca3D. Exploration baseline designs are initial designs which combine several characteristics of the representative designs. Orca3D can evaluate wetted surface area and displacement. This provides a basis for initial sail and rudder areas. Sail plan, appendage and hullform exploration processes are iterative by nature because of their dependence on each other. The sail area is first determined based on initial hull wetted surface area and/or displacement. Sail area then provides a baseline for determining keel and rudder area. According to *Principles of Yacht Design*, optimal fin-keel area is typically 3.5% of the sail area, while balanced fin-rudder area is approximately 1.4%.

Before using evaluation tools for hullform comparison, it is important to scale all designs so that they have the same displacement and similar length overall. *Principles of Yacht Design* provides a basis for scaling the depth and beam of boats based on their length, stating that the change in length should be raised to the power of 0.7 in order to determine the change in beam and depth. Recommendations for additional scaling factors to consider are shown in Figure 60. Two representative designs used extensively during the case study for comparison purposes are the 28' Woodenboat Egret and the 33' North Carolina Sharpie. These boats were scaled to 32' based on the preliminary sizing analysis which is based on owner requirements and comparative naval architecture. The displacement of all designs was also fixed and adjusted to 8,267 pounds.



PRIMARY RELATIONS — Independent of basic model	Scale Factor
Assumed:	L
Sail area	$L^{1.85}$
Beam, depth, freeboard	$L^{0.70}$
Keel & rudder span, chord, thickness	$L^{0.70}$
Derived:	
areas — section	$L^{1.40}$
— wetted — hull	$L^{1.70}$
— keel & rudder	$L^{1.40}$
— lateral — hull	$L^{1.70}$
— keel & rudder	$L^{1.40}$
volumes — hull	$L^{2.40}$
— keel	$L^{2.10}$
ratios — $L_{WL}/\nabla^{1/3}$ (ex-keel)	$L^{0.20}$
— $SA/\nabla^{2/3}$ (ex-keel)	$L^{0.25}$
Second moments of waterplane — lateral	$L^{3.10}$
— longitudinal	$L^{3.70}$

Figure 60- Scale Factors (Larsson & Eliasson, Principles of Yacht Design, 2000)

Once the representative designs are scaled appropriately, the VPP input must be updated to include the latest information regarding sail and appendage areas. These are vital inputs to the VPP, as they play a large role in calculating heel and lee angles, and predicting boat speed. If the heel and lee angles are not calculated accurately, the underwater hull shape will not be correct in the CFD simulations.

The equations for calculating resistance in the VPP are based on typical modern yachts. If there is any question as to their applicability to a particular design, the speed predicted by the VPP should be assessed and validated using CFD and the VPP results should be adjusted as required for later use in the hullform optimization. This was the case for the Sharpie hullform. In order to do this, the representative design speeds are evaluated at "design conditions" by the VPP and CFD. Design conditions are representative wind speeds and directions which a sailboat is likely to encounter during normal operation. The wind speeds used during the case study are 3.9, 9.7, and 15.6 knots (2, 5 and 8 m/s), and the wind directions are 45°, 90°, and 135° relative to the boat's heading (close-hauled, beam and broad reach). This yields nine different operating conditions for which the designs are assessed by the VPP and CFD. To do this, the boats are first evaluated by the VPP to determine their speed, heel, lee angle, and resistance values in the different wind conditions. The boats are then rotated for the CFD simulation based on the heel and lee (yaw) angles predicted by the VPP. Since velocity is an input for the Orca3D CFD simulation, the resistance from CFD is generated and recorded. CFD input speed is then adjusted until the resistance value predicted by CFD is equal to the VPP value where resistance equals driving force. The corresponding CFD speed is recorded. Generally, CFD is considered more accurate than VPP, as the VPP is based on empirical formulae. CFD is able to more accurately capture the unique dimensions of the Sharpie design. Based on the discrepancies of the results, the VPP results can be adjusted to produce velocity results similar to CFD. During the case study a “wind/boat speed comparison matrix” was generated which compared the boat speed results of three representative designs evaluated by both the VPP and CFD. The results are recorded in **Table 9**.

Table 9 - Boat Speed Comparison Matrix

Average Speed Ratio (CFD/VPP)			
	3.9 Knot Wind Speed	**9.7 Knots Wind Speed**	**15.6 Knots Wind Speed**
Close Hauled	1.25	1.10	1.11
Beam Reach	1.30	1.21	1.21
Broad Reach	1.41	1.25	1.24

In order to adjust the VPP so that its boat speed results are consistent with the CFD results, a parametric correction factor equation is added to the VPP boat speed calculation. In the case study, Model Center is used to determine the correction factor equation as a response surface model (RSM) function of wind speed and direction, fitting the data in Table 9.

The “linear plus quadratic interaction terms” and the “linear plus quadratic and cubic interaction terms” correlations were tried. A comparison of the errors for these two correlations is shown in Figure 61. “Vratio” is the ratio between the CFD and VPP boat speed results for a given wind speed and direction. The error produced by the linear plus quadratic and cubic interaction terms is substantially less than the equation without the cubic interaction terms and this RSM is used. The VPP incorporates this equation accordingly.

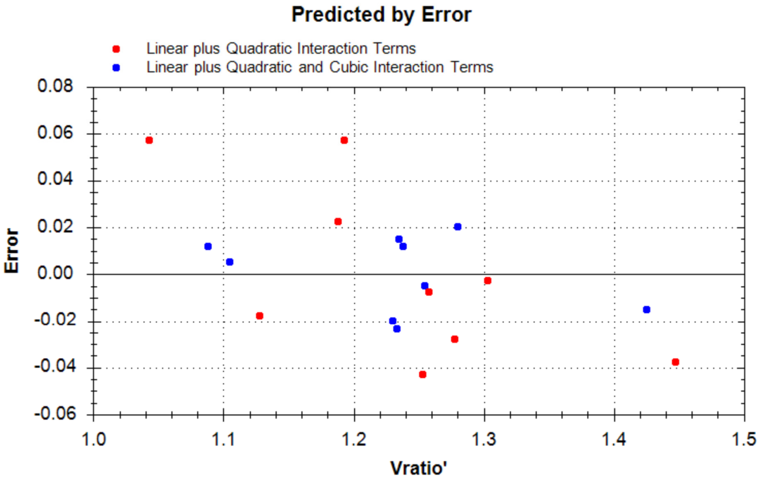


Figure 61 - Correlation of Speed Adjustment Factors

The validated VPP is able to complete evaluations in a matter of seconds, while CFD simulations take hours. Although the initial design space is based on the comparative naval architecture study, the VPP is used to collect data spanning the full design space using a Design of Experiments (DOE). The DOE data is used to refine the initial design space before final optimization.

2.3.9 Design of Experiments (DOE) and Response Surface Models (RSM)

The refinement of the initial design space during hullform, appendage and sail design exploration is followed by a series of DOEs performed using the Model Center DOE tool. Initial DOEs are completed to collect data, assess variable influence, and refine DVs and their design space. The most important feature of the DOE is the ability to apply constraints to the collected responses and then adjust the design space in order to maximize the number of feasible designs prior to running an optimization. This scenario is illustrated in Figure 62. As a new constraint is applied, such as a decrease in draft, this results in the elimination of designs which are no longer feasible (white). The portion of the histogram in red represents still feasible designs given the new constraint(s).

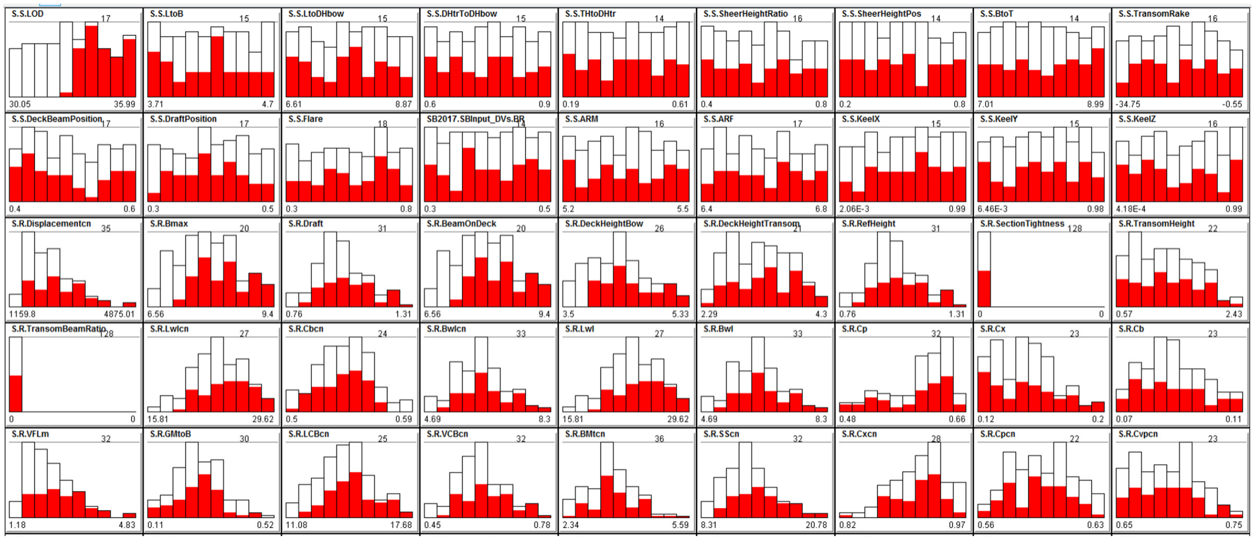


Figure 62 – New Constraints Result in Decrease of Feasible Designs (Red)

Relationships and trends between inputs and outputs are also explored. More specifically, the effect of certain design variables on response variables or MOPs is assessed. Figure 63 shows which design variables have the most influence on the STIX MOP and objective attribute, which serves as the response variable. Here it can be seen that STIX depends strongly on LOD and all DVs that increase freeboard and hull depth. Based on these effects, refinements to the design space can be made and some DVs may become DPs with optimum fixed values.

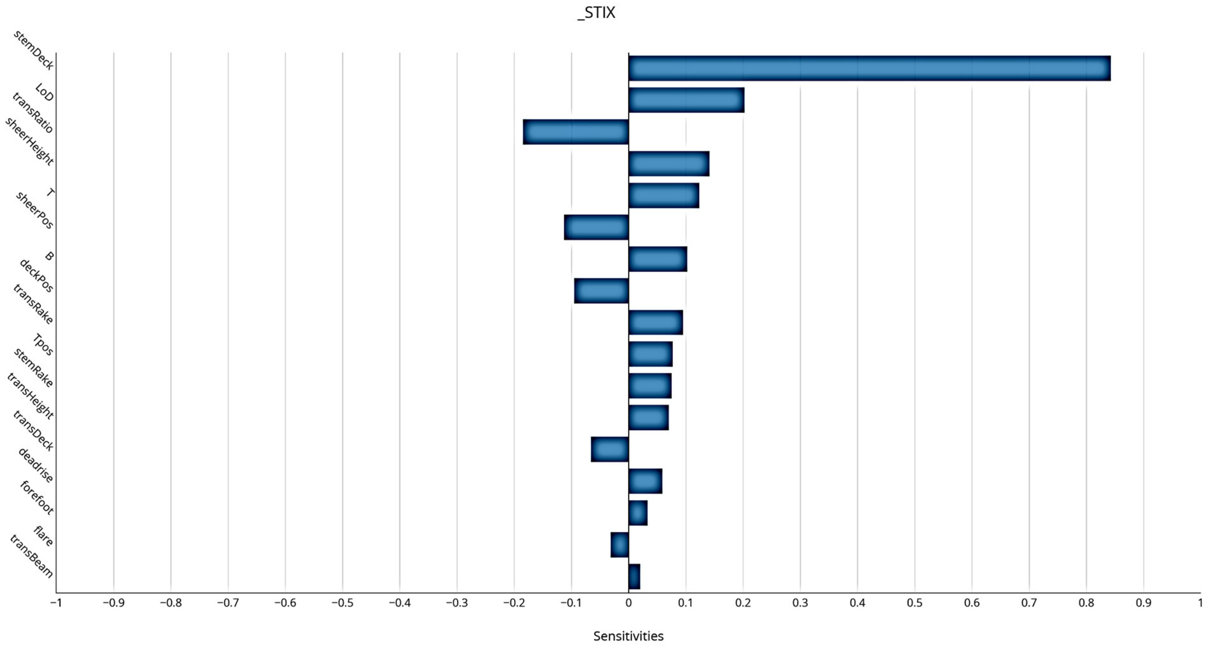


Figure 63- STIX MOP Sensitivity to Design Variables

After initial DOEs are completed and necessary adjustments are made to the design space, hullforms are then reevaluated and data collected. The output values are indicative of the design's feasible performance as evaluated by the geometry, hydrostatics, VPP and STIX calculations.

In the case study and after design space adjustment, the DOE produced numerous hull models with characteristics that are within the specified design space. Each of these hullforms were constructed in Rhino and hydrostatically evaluated by Orca3D. The populated hydrostatic data is then used as input for the VPP and STIX calculations. Roughly three hundred hullforms were generated using a Latin hypercube sampling method. Latin hypercube sampling is a statistical method for generating a random sample of parameter values from a multidimensional distribution which covers the full range of each variable by dividing the full range of each into non overlapping equal intervals. Using the data provided by the DOE the design space can again be adjusted as necessary to meet desired objectives. Notable changes made to the design space during this phase of the case study included lowering the transom height and moving the maximum draft location to between 40 and 45 percent down the hull length.

Once a satisfactory amount of data has been extracted from the DOE, a final response surface model (RSM) is produced. This RSM allows faster calculations with regard to hullform exploration as hull models without running Rhino/ORCA3D and the VPP. This speed is very helpful in running later optimizations where 1000s of designs may be evaluated.

2.3.10 Production Strategy

Production method and strategy is another segment of the design process which may be heavily dictated by owner preference. Based on hull dimensions, the materials which are best suited for construction are determined, a production method is selected and a production plan is made.

Our owner indicated a preference for wood and there is significant production advantage of the Sharpie hullform for lower cost because of its single curvature surfaces. This enables the use of plywood or larger planks. The hull of a wooden boat normally consists of planking fastened to frames. Frames traditionally consist of a hardwood such as oak, while planking may be softwood such as pine, larch or cedar. Marine plywood is also a popular construction material, but hulls built using plywood before the use of modern adhesives, sealants and epoxy were not rot resistant and plywood gained a bad reputation. In our case study, the owner indicates that plywood is the preferred material for construction and cold-molded epoxy construction, which is shown in Figure 64, is the preferred production method. As such, this method was investigated.

Plywood is one of the least expensive and easiest boat building materials available to work with. Over the last two decades, epoxy resins have become the preferred adhesive and sealer choice in many different methods of wood construction including strip plank and plywood. If the hull is made up of single curvature surfaces, plywood becomes particularly attractive. Other adhesive choices which are not as reliable or long lasting as epoxy include polyester resins. Polyesters are less flexible and resilient, so they tend to crack more easily as time goes on. Cracks in the adhesive can lead to water settling behind the sheathing. When boats are constructed with plywood and an epoxy encapsulation system, only tools in the average home workshop are needed (Glen L Marine Designs, 2019).

Figure 64- Sharpie Cold Molded Construction Plywood/Epoxy

Building of this boat can be accomplished using a “cold molded” construction technique. The phrase “cold-molded” is due to the fact that this procedure is carried out at room temperature and does not require any machine induced heat. Early water-resistant glues required heating before use. These types of water-resistant glues however, have been phased out with the invention of epoxy resins. In this method, thin plywood boards are pressed down and layered together with other boards and are then laminated with epoxy resin to create a lightweight, strong and watertight hullform. A thin layer of xynole, which is a polyester resin is also added to improve abrasion and impact resistance. Construction of the boat in this manner provides solid multi-directional strength when compared to other planking methods. A sheet of plywood has omnidirectional tensile and compressive strength once it is fastened around its perimeters. There are no seams which can work against each other or flex in and out, and the layers of wood grain alternately placed at right angles to each other create a membrane much stronger than a material with primarily unidirectional strength, such as a plank. Well-executed plywood planking has structural characteristics, for its weight, that compare favorably to those of aluminum and steel. Furthermore, with the popularity of fabric-covering systems for wood and highly evolved paint systems, cold molded wood constructed boats can possess longevity and durability that meet and exceed the possibilities presented by steel, aluminum, and fiberglass construction. This approach provides the boat with suitable strength and stiffness for a reasonable cost and weight (Parker, 1994).

Specific construction of the Sharpie in the case study consists of two layers of marine plywood set in different directions, fully coated with epoxy to achieve a composite strength pattern. A liberal application of epoxy should ensure the boat's watertight integrity while maintaining high strength and flexibility. The specific epoxy should be chosen based on curing time and environmental conditions. Of course, environmental conditions can mostly be controlled by constructing the boat in a climate-controlled structure. For structural support longitudinally, chine logs can be used.

After the hull is generated the interior can be further evaluated for design considerations. Bulkheads and frames can be fitted into the hull while the boat is upside down. Construction of the boat upside down is a popular option as work can be done on the interior and exterior simultaneously. Another benefit is that sawdust and shavings fall straight to the ground as opposed to falling within the hull. The boat's transom will be left open for easy access to the hull.

Figure 65- Strip Planking Construction (Selway Fisher Design, 2009)

Another construction method, which is common for wooden boat building is a technique called strip planking. In this method, strips are cut out in square shapes and attached using an adhesive on their entire length, edge to edge. This is generally considered a very strong and watertight procedure which does not leak. When exterior sheathing is used, a thin layer of xynole is added to create a polyester layer. This layer, similar to fiberglass leads to better abrasion resistance but does not stay as thick or dense as fiberglass. The drawback of this construction technique is that it provides most strength in one direction, as there is very little inherent diagonal strength across the seams. Regardless of how well secured individual planks are, the edges will try to work and slide against each other at some point, which will deteriorate the boat's condition (Parker, 1994).

In a more general sense, production strategy can also consider boats which use other materials for construction such as fiberglass and steel. Fiberglass construction of a boat usually begins with a "female mold." First, the mold is sprayed with gelcoat, before a fiberglass cloth is applied. Then a resin is used to saturate the fiberglass. As the resin cures, a hull is generated. Stringers, bulkheads, and other types of structural reinforcements can be molded separately and fiberglassed to the hull. Before the hull is closed with a deck, the items below deck level can be added, such as the fuel and water tanks. If the boat has an inboard engine, this may be added to the construction process before the deck as well. Wiring and plumbing can also be installed. (Boatbuilding Methods: Strip Planking, n.d.)

As detailed, the intricacies of the production strategy very much depend on the design, and specifically the material by which the design is being constructed. As is true throughout the sailboat design process, communication between the designer and prospective owner is critical at this stage to minimize any future confusion. The designer must ensure that the materials used for construction are suitable for the owner's requirements and projected operational environment. (Rudow, 2020)

2.3.11 Cost Model

Generally, a larger boat is going to cost more to produce than a smaller boat of the same type. Considering this, it seems obvious to build the boat as small as possible, as building cost depends directly on size (or weight), but cost and size generally trades off with performance. To minimize weight, the designer may also choose to use exotic materials and more complex building procedures. In using these materials and procedures, cost may actually increase. Alternatively, heavy building methods necessary for boats made of steel and Ferro cement provide less expensive materials, but result in larger displacement, more resistance, less speed and higher fuel costs to power.

Another means of increasing usable space is to allow areas and compartments to overlap one another. Having the full cabin height carried throughout the full length of the boat is not always necessary. As an example, a head can be located under a cockpit seat, while the rest of the head area is located under the deck house. It is better for the designer to picture the space as a three-dimensional puzzle in order to utilize the space optimally. However, the designer must strike the right balance between simple and complicated, as complicating arrangements may also raise costs.

Equipment also plays a large role in the overall cost of the boat, regardless of displacement and size. Equipment considerations which can quickly increase overall cost include air conditioner or heater, running hot and cold water, freezer/refrigerator, electric winches, full electronics including radar, self-furling sails and so forth. (Larsson & Eliasson, Principles of Yacht Design, 2007)

The designer must develop a cost model which most encapsulates the range and impact of the most significant variables moving forward toward the optimization. If displacement largely contributes to an MOP which is being maximized during the MOGO, it may be prudent to make cost a function of displacement. As an example, the designer believes displacement will be a key contributor to construction costs, but larger displacement contributes to greater speed and seaworthiness. It then is sensible to make cost a function of displacement. This will help to yield results which achieve greater speed at lower displacement values. Communication between the designer and prospective owner is vital at this point so that cost does not provide a problem moving forward.

Data is required to build a definitive cost model and we do not have much boat cost data. As an effective alternative, displacement or length can be minimized as an objective while maximizing performance and applying other constraints. This provides an effective trade-off. After a thorough design space exploration, it is also reasonable to just constrain displacement or length to be less than a reasonable value that allows some or most of the desired performance without being overly extravagant. The customer can then just choose from the non-dominant frontier a compromise that best suits them.

2.3.12 Multi-Objective Genetic Optimization (MOGO)

After exploring hull, keel, rudder and sail options and variables, and building an effective model that is able to predict performance, a multi-objective genetic optimization (MOGO) is performed. This allows for several MOPs to be optimized under a set of constraints. Model Center searches the entire refined design space, possibly using the RSMs for faster calculations, and identifies a non-dominated frontier. It is important for the designer to understand which MOPs should be maximized or minimized and which MOPs are better as constraints. At various points in the case study, Dellenbaugh Angle and sizing dimensions such as draft and length overall were used as constraints and maximized MOPs included speed or minimized regatta time and seaworthiness (STIX). These two MOPs were ultimately chosen as the objective attributes for the final MOGO. If more than two or three MOPs are determined to be very important, they may be organized into measures of effectiveness (MOEs) or an overall measure of effectiveness for optimization.

2.3.13 Non-Dominated Frontier

The non-dominated frontier is the product of the MOGO and is characterized as a “collection of best designs.” An example of the non-dominated frontier from the case study is shown in Figure 66 with STIX on the y-axis and the regatta time from the VPP on the x-axis. The color represents the length overall, with blue being the smallest value and red being the largest. During this time in the case study, the owner sought a boat with a shorter length overall to minimize cost. As such, minimizing cost as a function of length is also an objective. As seen in the non-dominated frontier, the optimization sought to maximize STIX, while minimizing length and regatta time. There are several designs located on the knee of the curve that indicate preferred designs. This is the left uppermost corner of the non-dominated frontier where the regatta time is low and STIX is high.

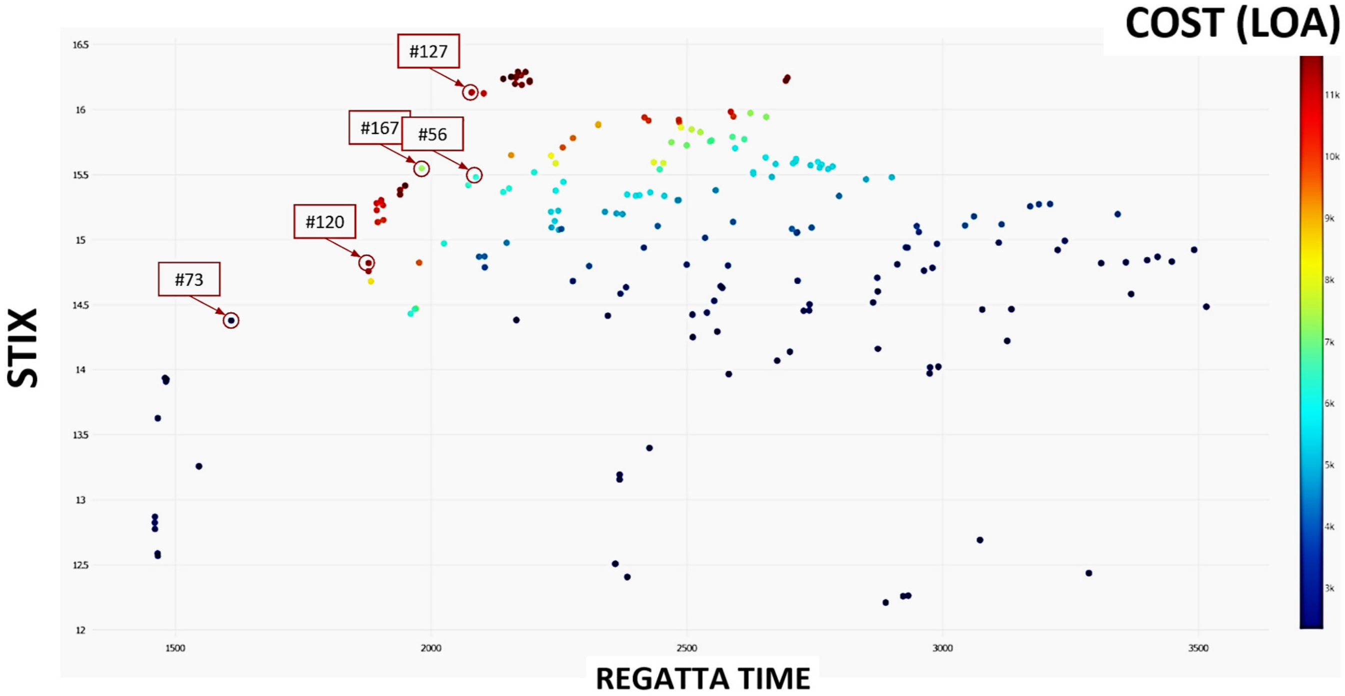


Figure 66 – Non-Dominated Frontier

2.3.14 Concept Baseline Design Selection

The concept baseline design is selected by further exploring the hullforms located around the knee of the curve. These hulls represent the highest performing hulls in the series of best designs. The design variable values from each of these hulls can be extracted from the MOGO results and constructed in Rhino for examination by the customer. This is a necessary step as the production of an aesthetically pleasing hull is an important MOP. As appearance is a difficult MOP to quantify, owner input at this stage is essential. The characteristics of the hulls from the case study are listed in Table 10.

Table 10 – Preferred Hull Design Characteristics

Design #	LOA	B	T	Regatta Time	STIX
56	31.06’	7.35’	1.48’	2087	15.4
73	27.89’	9.01’	1.36’	1609	14.3
120	32.92’	7.15’	1.29’	1877	14.8
127	32.71’	7.84’	1.41’	2079	16.1
167	31.53’	7.18’	1.45’	1981	15.5

As a result of this initial hullform exploration, optimization, and non-dominated frontier analysis, “Hull 56” was selected in the case study for its performance which appealed to the customer. Hull 56 is shown in Figure 67. Although the performance of this design was good, the customer did not really like its appearance, the sheer was too flat and the bottom too arched. The customer was also interested in comparing performance to the representative designs. It was decided to make this comparison, adjust the design space and perform another MOGO.

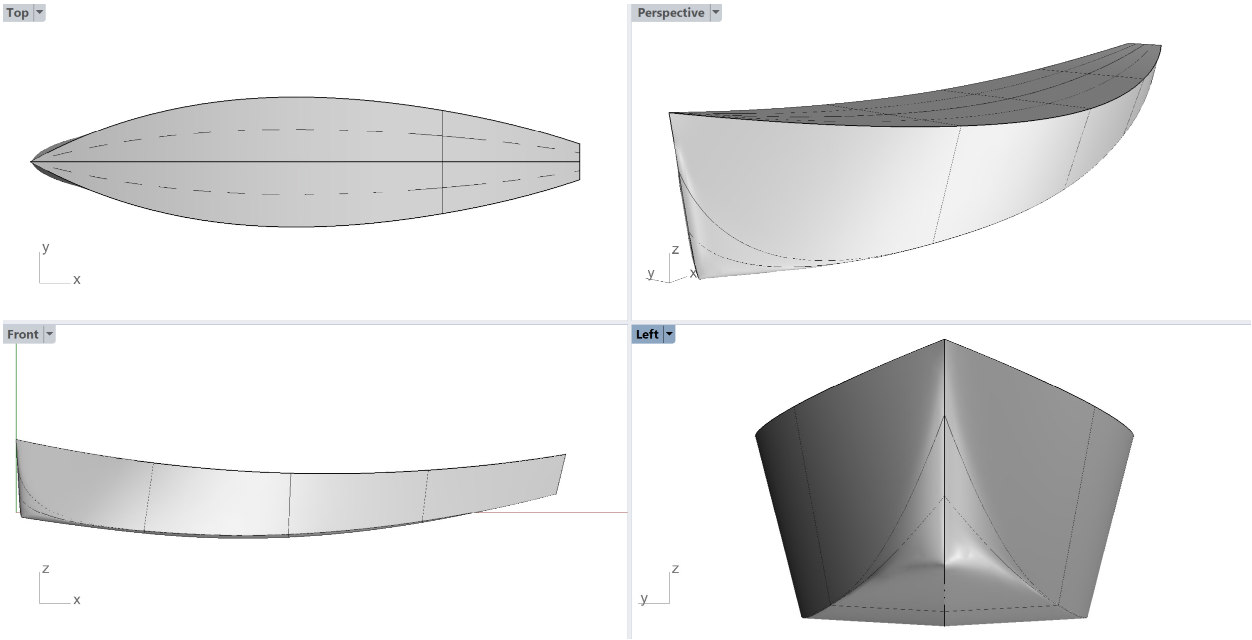


Figure 67 – Initial Baseline Design, Hull 56

2.3.15 Validate Improved Baseline Designs

In order to better understand and improve the concept baseline design, it was further evaluated by comparison to the representative designs, comparing STIX, VPP performance, CFD speed and other characteristics. A comparison of righting arm values at different angles of heel is shown in Figure 68. In terms of initial stability, the North Carolina Sharpie outperformed the other hullforms. This can be attributed mainly to the North Carolina's larger beam, while the Hull 56 and Egret show comparable results for initial stability. The North Carolina Sharpie also possesses the greatest righting arm value but does have a lower range of stability than both the Hull 56 and Egret. Hull 56 possesses the greatest range of stability, followed by the Egret. The Hull 56 also has a greater maximum righting arm value than the Egret. Righting arm is a big driver for STIX and Hull 56 has an excellent STIX score compared to the representative designs.

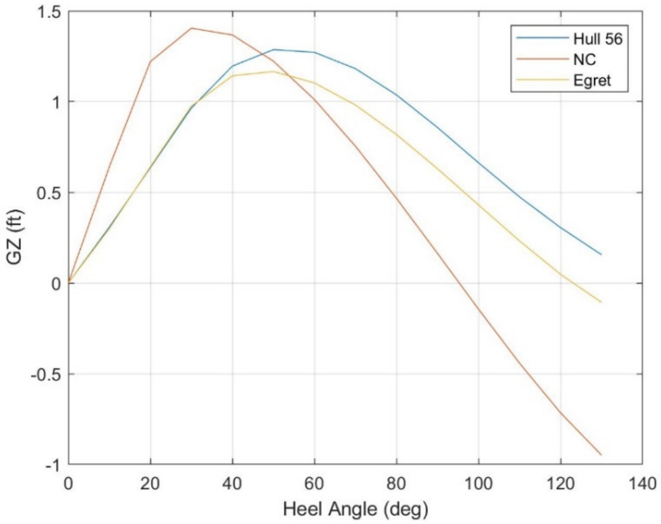


Figure 68 – Righting Arm Comparisons

The case study also compared the concept baseline design against the representative designs using CFD. The results of a CFD simulation completed at 6 knots are shown in Figure 69, and show that the concept baseline design did not perform as well as the other representative designs. These initial CFD simulations in the case study were completed without heel and yaw (lee) angles considered, as the VPP was still being refined. Boat speeds used for initial CFD simulations were 2, 4, and 6 knots, respectively. Wind speed and direction inputs were also not considered at this point. Given these conditions the North Carolina Sharpie performed the best in the CFD simulations at all speeds.

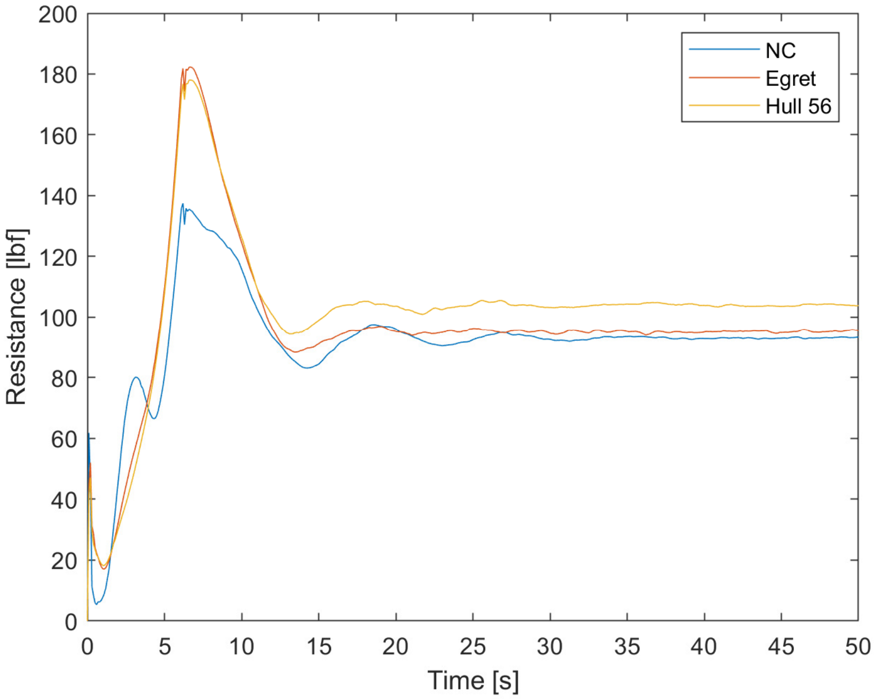


Figure 69 – Resistance Comparison to Representative Designs at 6 knots (canoe body)

Based on the CFD results, differences in the hull characteristics of the North Carolina Sharpie and Hull 56 were explored. Figure 70 provides reference for the differences in hullform characteristics that were discovered between the Hull 56 and North Carolina Sharpie. The plan (top) view shows that the beam, particularly at the North Carolina's transom, is substantially larger than that of the Hull 56. The profile (front) view shows that Hull 56 has a larger sheer height throughout the boat's length than the North Carolina. It also shows that the transom of Hull 56 is significantly higher than that of the North Carolina and has a maximum draft position farther forward. The body (left) view provides further evidence of the North Carolina's markedly larger beam.

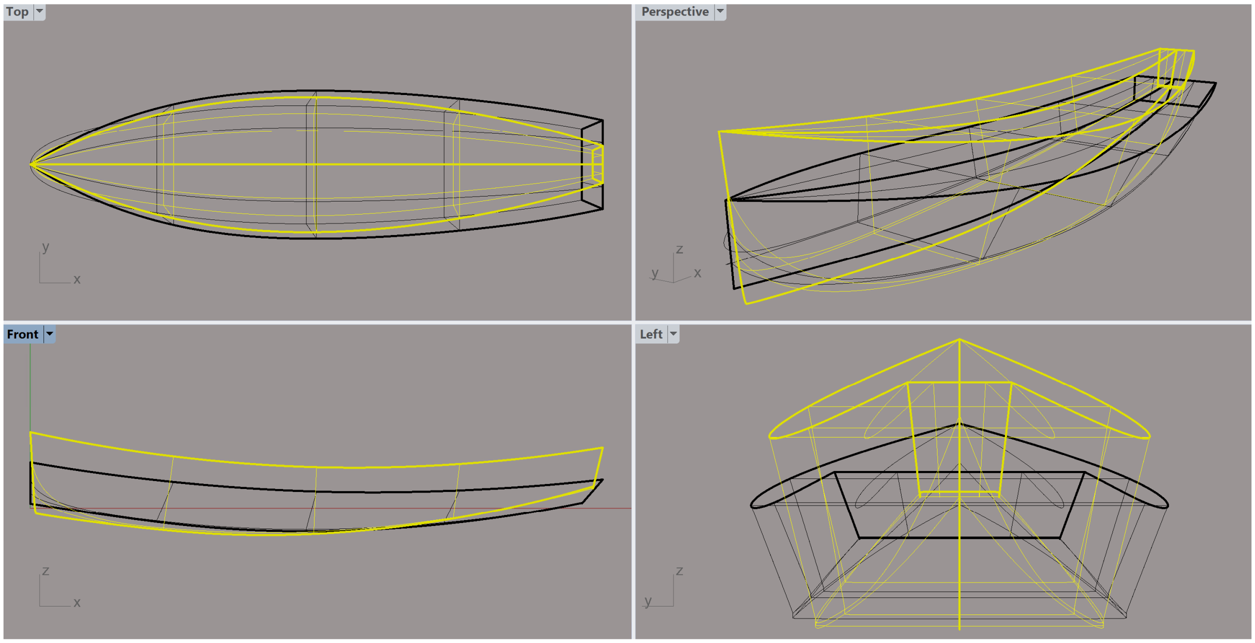


Figure 70 – Comparison of Hull 56 (yellow) and NC (black)

2.3.16 Repeat MOGO and Improved Baseline Design

Since an additional MOGO was needed, the design space of the case study was adjusted to produce hullforms with similar underwater characteristics to the North Carolina Sharpie, while maintaining hull characteristics above the waterline to achieve satisfactory STIX and righting arm characteristics. Specifically, the "canoe body draft position" range, or the position of the maximum draft was moved aft. The transom height was also lowered, while the transom rake angle was increased. Lastly, the design's draft forward of the midbody was decreased. Specific changes to the design space are shown in Table 11.

Table 11 – Adjustments to Design Space

Design Variable	Original Design Space (Hull 56)	Adjusted Design Space (DB Hulls)
Length on Deck (ft)	27.9' – 33.0'	31' - 32.8'
Beam (ft)	7.0' – 9.0'	7.2' - 9.5'
Deadrise	0 – 0.01	0 - 0.01
Deck Beam Position	0.4 – 0.6	0.4 - 0.6
Flare	0.4 – 0.7	0.4 - 0.7
Forefoot	0 – 0.1	0 - 0.2

Bilge Tightness	0 – 0.01	0 - 0.01
Sheer Ht. Ratio	0.4 – 0.6	0.4 - 0.6
Sheer Ht. Position	0.3 – 0.7	0.3 - 0.7
Deck Height at Bow (ft)	1.0 – 1.52	0.75 - 1.52
Bow Rake Angle (deg)	0° – 5°	0° - 5°
Draft (ft)	0.98' – 1.48'	0.98' – 1.31'
Draft Position	0.4- 0.44	0.46 - 0.50
Beam at Transom	0.0 – 0.7	0.0 -0.7
Deck Height at Transom (ft)	3.28' – 4.9'	1.6' – 4.9'
Transom Height (ft)	0.3' – 3.3'	0.3' – 3.3'
Transom Rake Angle (deg)	0° – 27°	0° - 40°

Once the design space of the case study was adjusted to reflect design variable values which more closely resemble the NC31 characteristics, an additional optimization was performed. This optimization yielded three specific hulls of interest, termed the "DB hulls." The "DB3" is shown in Figure 71 alongside Hull 56 and shows the difference in hull characteristics. Most notably, the DB3 is longer, has a greater beam at the transom, and carries its maximum draft more aft than the Hull 56. The DB3 also has a lower transom height and a greater transom rake angle. The sheer height between the two vessels is mostly similar.

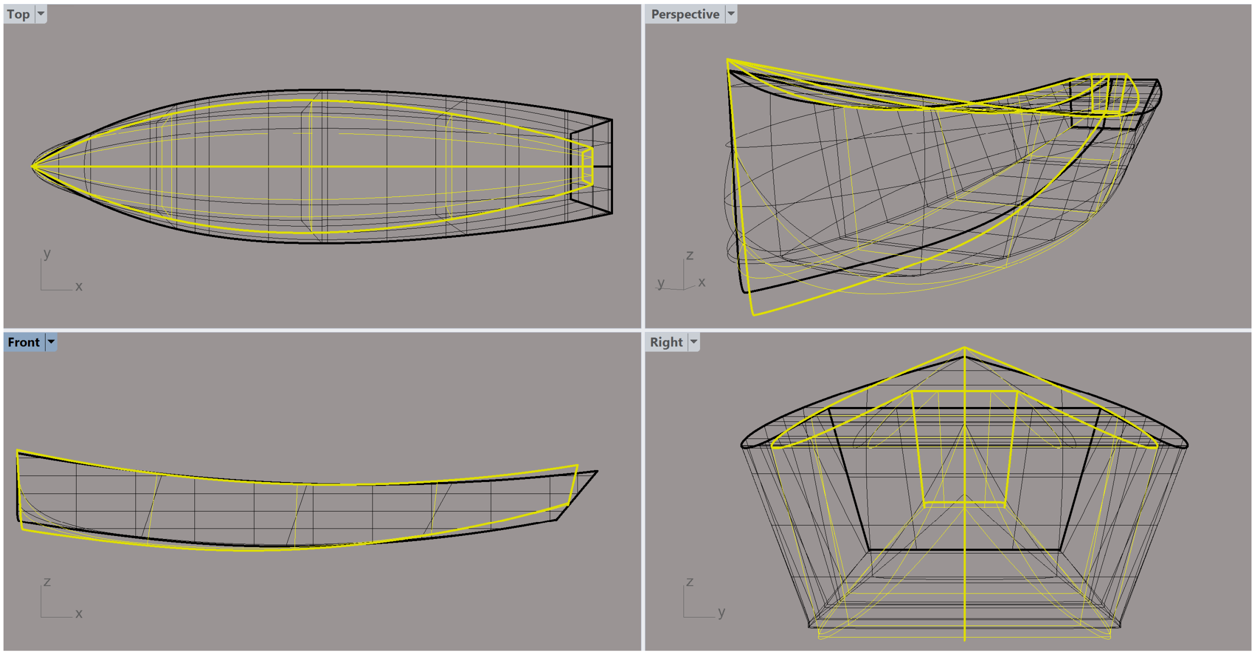


Figure 71- Hull 56 (yellow) and DB3 (black)

The DB hulls displayed underwater characteristics consistent with the NC31 while featuring a greater sheer height to achieve a greater downflooding angle and thereby a higher STIX number. The "DB3" was chosen as the final hullform in the case study based on its performance and topside characteristics. As displayed in Figure 72, this hull shares an underwater hullform very similar to the North Carolina Sharpie. Above the waterline however, significant differences in sheer height exist. This hull is called “the Albemarle Sound Sharpie” due to its projected operational environment.

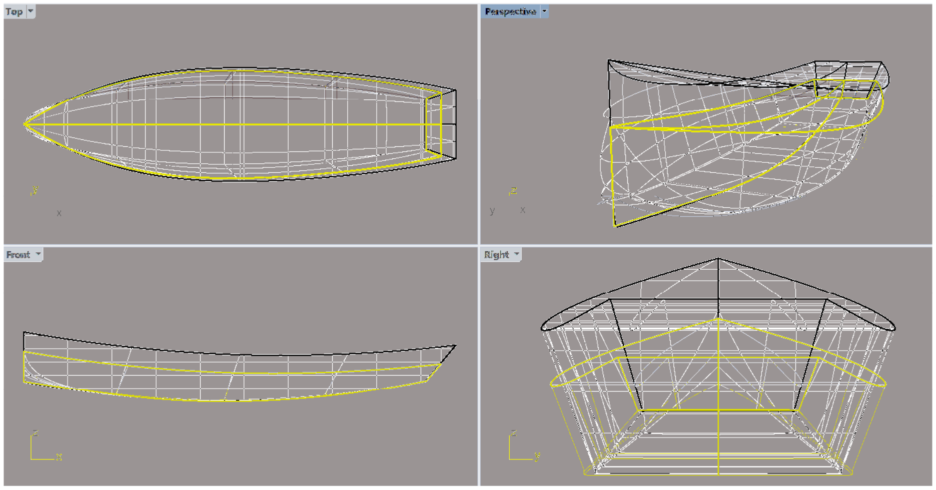


Figure 72 – Albemarle Sound Sharpie (black) and NC (yellow)

Table 12 provides design variable values for the initial baseline design (Hull 56), the improved baseline design (Albemarle Sound), as well as the representative designs. As discussed, there are major differences existing between the initial and improved baseline designs. Most notably, the Albemarle Sound Sharpie has an expanded beam, a lower transom height, and a greater transom rake angle than the Hull 56. The North Carolina Sharpie and Egret have been scaled to the same length as the Albemarle Sound Sharpie. The Albemarle Sound Sharpie has a similar beam at transom, canoe body draft and canoe body draft position as the North Carolina Sharpie. The Albemarle Sound Sharpie has a much greater sheer height than the North Carolina.

Table 12 – Design Variable Comparison

	Hull 56	**Albemarle Sound**	**NC**	**Egret**
Length on Deck (ft)	31.1’	32.1’	32.1’	32.1’
Beam on Deck (ft)	7.3’	8.5’	8.2’	8.1’
Deck Height at Bow (ft)	4.1’	3.9’	2.5’	3.7’
Deck Height at Transom (ft)	3.3’	3.0’	1.7’	3.0’
Transom Height (ft)	1.0’	0.2’	0.3’	0.9’
Canoe Body Draft (ft)	1.5’	1.2’	1.3’	1.4’
Bow Rake Angle (deg)	3.2	0	0	0
Transom Rake Angle (deg)	-13.5	-40	-39	-30
Sheer Height	0.5	0.59	0.3	0.45
Sheer Height Position	0.5	0.38	0.6	0.38
Beam at Transom	0.3	0.61	0.6	0
Deck Beam Position	0.4	0.4	0.4	0.5
Canoe Body Draft Position	0.4	0.46	0.48	0.41
Deadrise	0	0	0	0
Flare/Tumblehome	0.5	0.6	0.4	0.8
Bilge Tightness	0	0	0	0
Forefoot Shape	0.1	0.1	0	0.4

An important part of the repeated optimization process of the case study was maintaining significant sheer height in order to preserve sufficient stability characteristics. Figure 73 shows the righting arm comparison of the Albemarle Sound Sharpie, Hull 56, and the other representative designs. The Albemarle Sound Sharpie boasts much greater initial stability values than the Hull 56. This can mainly be attributed to the increased beam. The Albemarle Sound Sharpie exceeds all other designs with regard to maximum righting arm and shares the same range of stability as the Egret. The Albemarle Sound Sharpie has significantly more area under its righting arm curve than the other designs. These are all important characteristics for computing STIX.

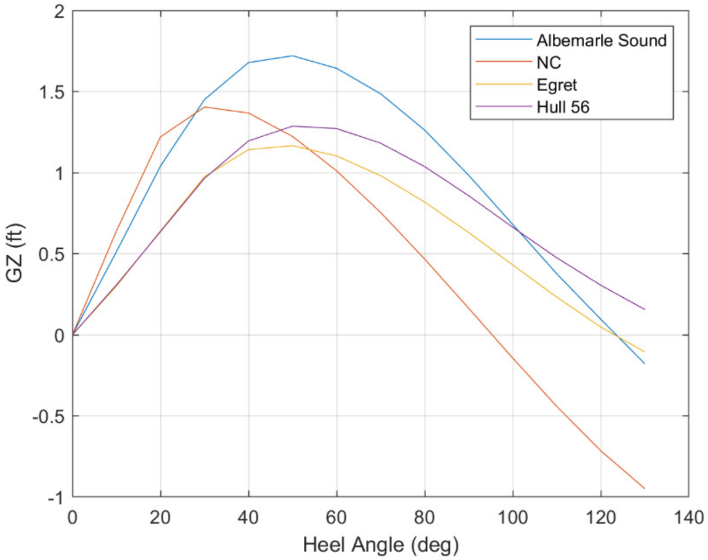


Figure 73- Righting Arm Comparison with Improved Baseline Design

While the hull characteristics above the waterline were established for stability purposes, the hull characteristics below the waterline were adjusted for speed purposes. Figure 74 shows the results of an initial CFD simulation, in which the resistance values for all boats transiting at six knots were generated. Heel and lee angles were not considered. Wind speed and direction were also not considered for these initial CFD simulations. The Albemarle Sound Sharpie produced similar resistance values to the North Carolina Sharpie while performing markedly better than the initial baseline design, Hull 56. Further resistance analysis is shown in Table 13. The initial baseline design is slightly shorter in length overall and wetted surface area, contributing to its lower friction resistance value, while the Albemarle Sound Sharpie exhibits a lower overall resistance value due to its more streamlined design and reduced form drag as reflected in its lower Residuary resistance.

Table 13- Resistance Comparison of Baseline Designs

	Hull 56	**Albemarle Sound Sharpie**
Air Resistance (lbf)	8.1	10.4
Friction Resistance (lbf)	21.2	24.9
Residuary Resistance (lbf)	74.6	62.6
Total Resistance (lbf)	103.9	98.2

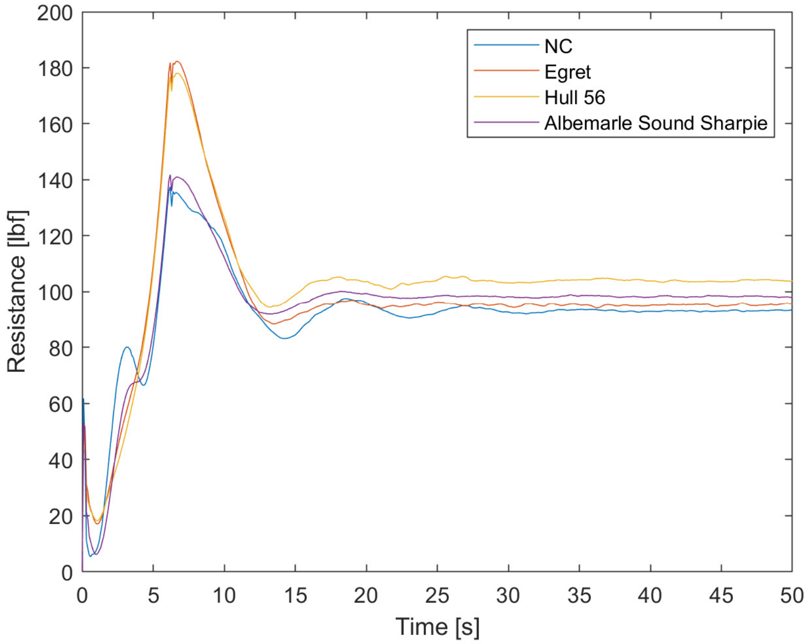


Figure 74- CFD Comparison with Improved Baseline Design

This instance in the case study is an example of how the concept baseline design can be improved following the initial non-dominated frontier with a second MOGO after further refining the design space. After the stability and speed of the initial baseline design was studied, the corresponding refinement of the design space led to a higher performing boat. This is shown through the results referenced in Table 14. The improved baseline design boasted significantly improved stability and speed metrics. The Albemarle Sound Sharpie possesses a significantly better Dellenbaugh Angle, while also producing less resistance in the CFD simulation. It is also important to note that the owner much preferred the appearance of the Albemarle Sound Sharpie rather than the Hull 56. Of particular interest, is the boat's sheer, bottom curvature, transom height and bow rake. A straight bow rake is also more producible.

Table 14 – MOP Comparison

	Albemarle Sound	**Hull 56**	**Egret**	**North Carolina**
STIX	27.6	27.5	25.5	17.4
CFD Resistance at 6 Knots	98.2 lbf	103.9 lbf	95.5 lbf	93.4 lbf
Dellenbaugh Angle	22.2˚	35.4˚	32.6˚	15.5˚
Length	32.1'	31.1'	32.1'	32.1'
Displacement	8,267 lbs	8,267 lbs	8,267 lbs	8,267 lbs

Continuous evaluation and refinement of the design space can lead to a significantly superior boat (Figure 75). While the initial baseline design possessed excellent seaworthiness and stability characteristics, it did not meet appearance or speed MOPs to the satisfaction of the owner. As such additional analysis and refinement of the design space followed by a second multi-objective optimization with a refined design space that produced an improved baseline design. This improved baseline design not only maintained suitable stability traits, but also satisfied appearance and speed

MOPs. The next step of the design cycle is the concept development process. This process will focus on evaluating and validating the improved baseline design.

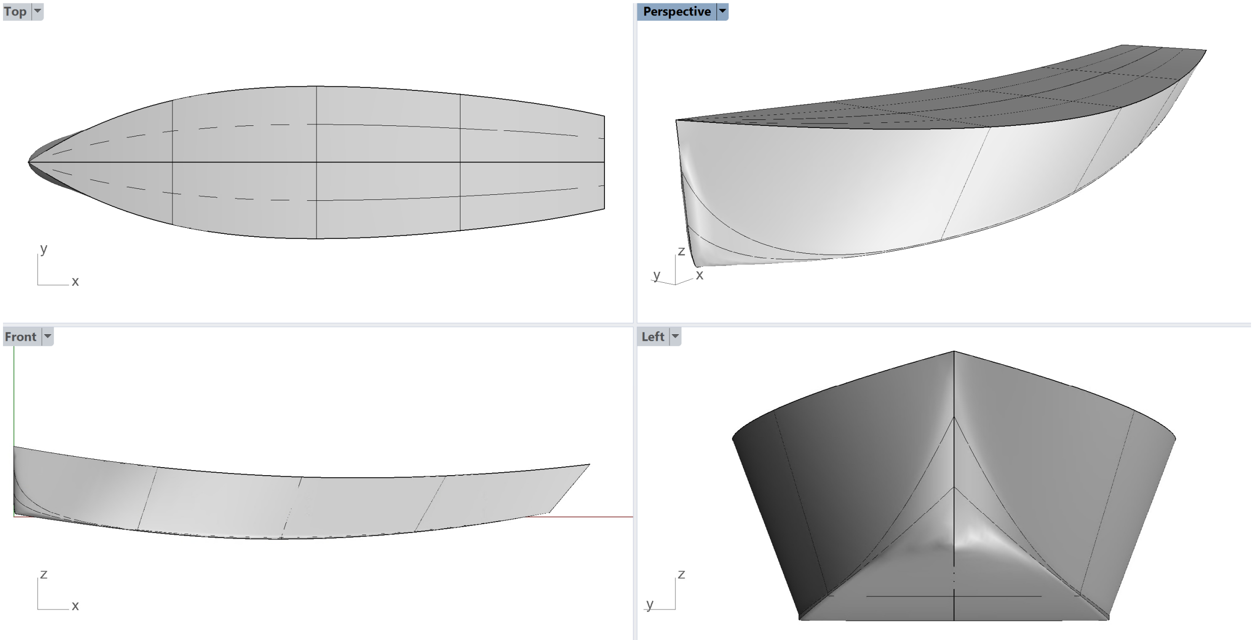


Figure 75 – Albemarle Sound Sharpie Hullform

2.4 Conclusions

The concept exploration process spans from the time a prospective owner presents their requirements and preferences for a product until an improved concept baseline design is generated. There are several important steps and subprocesses which must be properly executed prior to production of an improved baseline design. This was demonstrated in the case study, with the design segments leading up to the generation of the improved concept baseline design, the Albemarle Sound Sharpie.

In our case study, after this new concept exploration process, when compared to other representative designs, the Albemarle Sound Sharpie performed favorably boasting a better righting arm curve than Hull 56, Egret and North Carolina Sharpies and similar speed results to Egret and North Carolina Sharpies. Its appearance was much preferred by the owner; it satisfied accommodation and draft requirements; and its critical MOPs were superior. It was a total winner.

Reuel Parker, a prolific wooden boatbuilder and author states in *The Sharpie Book,* "[the Egret] is truly in a class by herself. She is widely acknowledged to be the most seaworthy of all sharpies, and I personally believe she is" (Parker, 1994). The Egret, which was the product of a trial and error process common in the time of her construction was improved upon by improving the design process. In the new sailboat concept exploration process, a main objective based on owner preference was seaworthiness which was evaluated using the industry standard STIX calculation. Through a systems-engineering approach, adapted from a naval ship design process, a sailboat design resulted which ultimately displayed greater stability and seaworthiness characteristics than the Egret, in the Albemarle Sound Sharpie. This comparison helps to support that this process is in fact, improved and superior to the past sailboat design processes discussed.

After analyzing the results of the case study, it is concluded that this new sailboat concept exploration process will effectively yield a non-dominated preferred design for the purposes specified by the owner’s requirements. The importance of certain MOPs is totally based on owner preference. The next design phase after concept exploration is Concept Development. Concept development will expand the details of the design and its components and reduce overall design risk.

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3 Improvement of Concept Development Process and Tools (Paper #2)

3.1 Introduction

For centuries, sailboats have played an important part of the marine transportation system on both a national and global scale. However, the modern design processes of fuel-powered ships have surpassed that of sailboats in terms of tools and methods, and few of the existing sailboat design methods benefit from a modern systems-engineering approach.

This paper focuses on the concept development phase of the sailboat design process and continues from an earlier paper, the "Improvement of Concept Exploration Process and Tools for Sailboat Design" (Zanella and Brown, 2020), that proposed a new sailboat concept exploration process by combining elements of two previously established design methods. These elements are Virginia Tech's (VT) naval ship design process (Waltham-Sajdak & Brown, 2015)and the sailboat design spiral method presented in *Principles of Yacht Design* (Larsson, L., & Eliasson, R. E., 2016).

The objective in generating a new concept development process is to incorporate tools used to reduce overall design risk, while also presenting feasible technology options and tradeoff scenarios for the owner's consideration. Of particular interest is the order and layout of the concept development process, to ensure that the interdependency of the design segments is fully appreciated and appropriately evaluated. Previous concept development processes for sailboat design have not been thoroughly developed.

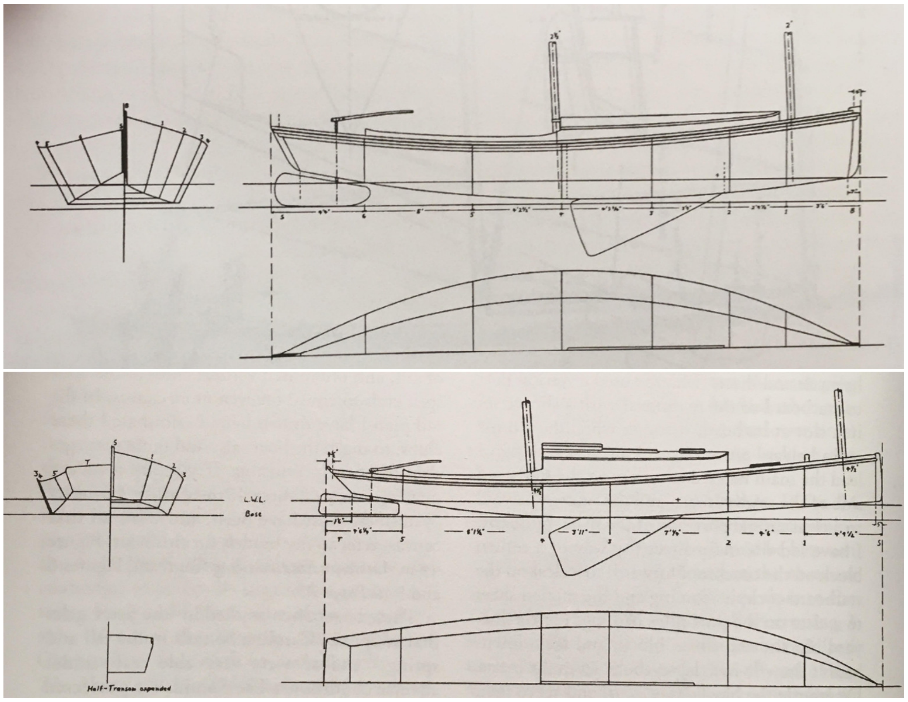


Figure 76- Egret (top) and North Carolina Sharpie (bottom)

The case study for this paper specifies a Sharpie design. Sharpies are a unique type of workboat that enjoyed a time of popularity consistent with other small sailboats in the 1800's. During this time period approximately two hundred different types of small boats propelled by sail were used in North America. Each type of craft was, "developed to work in its home waters and weather conditions and to meet the physical requirements of its employment" (Parker, 1994). An example of popular sharpie hulls which are used during the case study for comparison purposes is provided in Figure 76. Sharpies are mainly characterized by their flat single curvature (longitudinal) bottoms and sides which are flat transversely.

The concept exploration process spans from the time a prospective owner presents their requirements and preferences until an improved concept baseline design is generated. There are several important steps and subprocesses which must be properly executed to search the design space and specify an improved baseline design. This was described and demonstrated in the case study, concluding in an improved concept baseline design, the Albemarle Sound Sharpie.

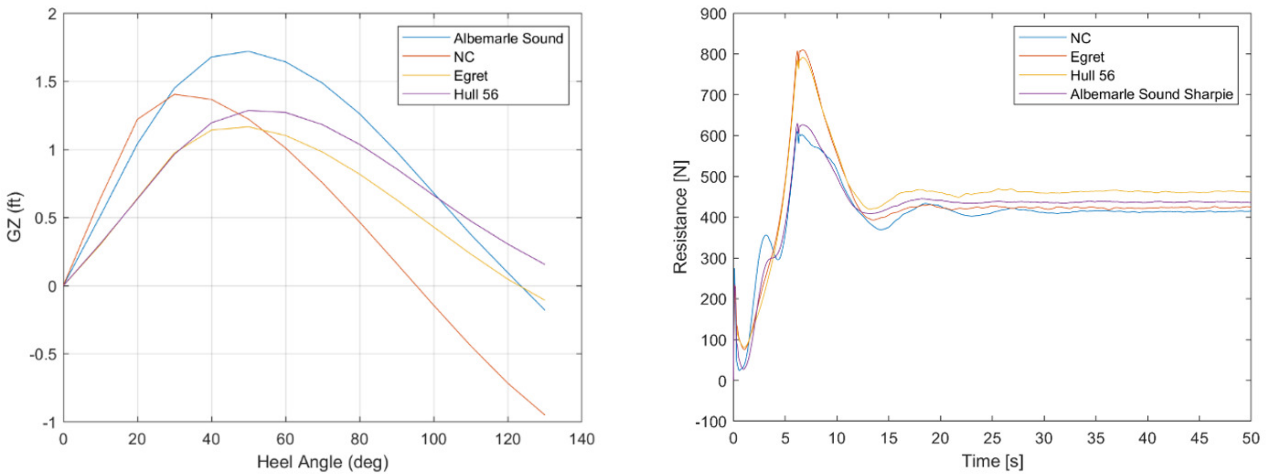


Figure 77- Righting Arm (left) and CFD Comparison (right) with Improved Baseline Design

Speed, stability, seaworthiness, appearance, and proper sizing were selected as measures of performance (MOPs) in the case study. Measures of performance (MOPs) are metrics used to measure a boat's ability or performance to execute required capabilities consistent with the mission. A critical part of using MOPs is developing and/or refining tools which can quantify the MOP. After this new concept exploration process was completed, in which evaluation tools were refined and applied including two multi-objective optimizations (MOGOs), the Albemarle Sound Sharpie exhibited superior critical MOP values which are listed in Table 15. Stability Index (STIX) represents a single value stability and seaworthiness rating promulgated by the International Standards Organization (ISO), and is used as an evaluation metric for prospective designs. The Albemarle Sound Sharpie displayed a better STIX rating and righting arm curve than Hull 56 (initial baseline design), Egret and North Carolina Sharpies and produced similar speed results to Egret and North Carolina Sharpies (Figure 77). Its appearance was much preferred by the owner (Figure 78); it satisfied accommodation and draft requirements; and its critical MOPs were non-dominated and preferred by the owner.

Table 15- MOP Comparison

	Albemarle Sound	**Hull 56**	**Egret**	**North Carolina**
STIX	27.6	27.5	25.5	17.4
CFD Resistance at 6 Knots	436.3 N	461.7 N	424.4 N	414.9 N
Dellenbaugh Angle	22.2˚	35.4˚	32.6˚	15.5˚
Length	32.1’	31.1’	32.1’	32.1’
Displacement	8,267 lbs	8,267 lbs	8,267 lbs	8,267 lbs

After analyzing the results of the case study, it is fair to conclude that this new sailboat concept exploration process will effectively yield a non-dominated preferred design for the purposes specified by the owner’s requirements in a rational, quantitative and consistent manner. The importance of certain MOP’s is based on owner preference. The next design phase after concept exploration is concept development. Concept development expands on the details of the design and its components, validates concept exploration results and reduces overall design risk.

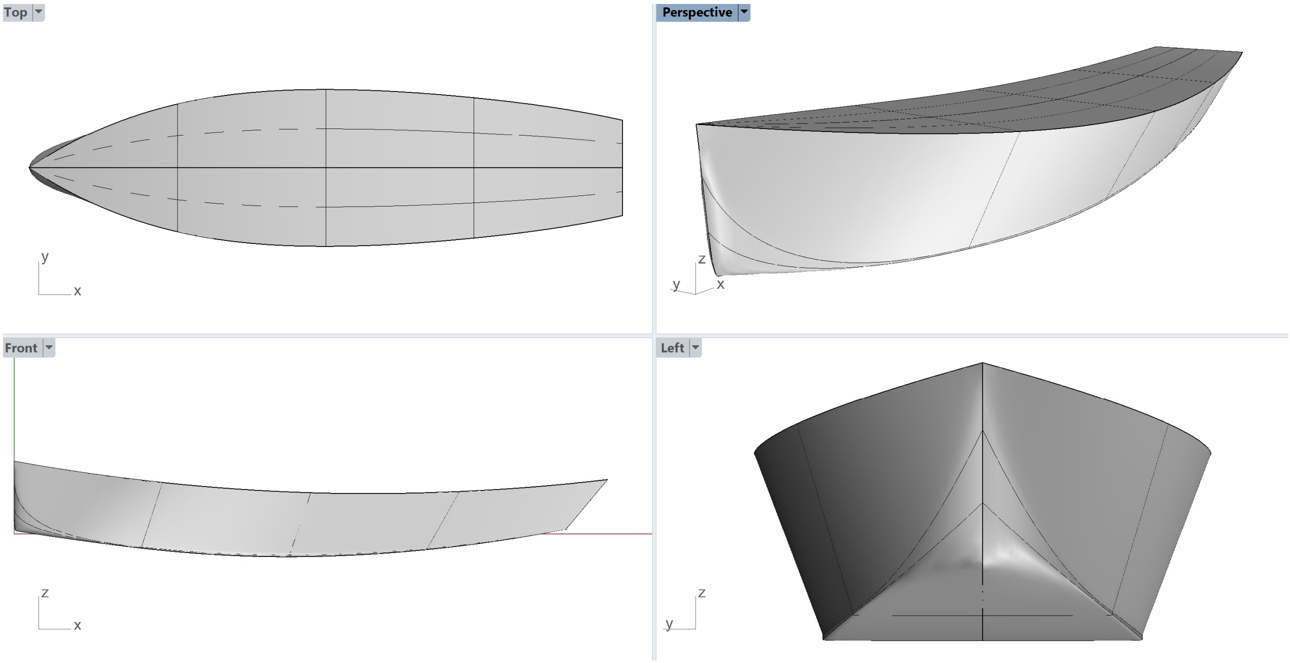


Figure 78 – Albemarle Sound Sharpie Hullform

3.2 New Sailboat Concept Development Process

This paper focuses on expanding system and component details of the improved concept baseline design. The proposed concept development process is shown in Figure 79. The first step of the concept development phase is updating the preliminary arrangement. Like most steps of the sailboat design process, this requires significant owner input and includes tradeoffs between safety, structural integrity, comfort and accessibility, while meeting all of the client’s living condition requirements.

After preliminary arrangements have been determined; structures, subdivision and topside design can be defined. This step in the concept development phase has significant impact on other aspects of the design, but particularly the weight and center of gravity location of the boat. Other aspects of the design such as sail plan, rig and auxiliary propulsion are also important. It may also be necessary to refine the boat's keel and rudder designs.

In concept exploration of the case study, the boat's weight was assumed to be 8,267 pounds (equal to displacement), with a vertical center of gravity located at the waterline. In order to confirm this assumption, weights and center of gravity locations must be determined for the hull, appendages, sails, rig, internal components and loads. Ballast weight is determined last as the difference between displacement and sum of all other weights. It should be a reasonable percentage of total displacement. Once the COG is calculated, it is compared to the assumptions and overall performance revisited if there is a significant discrepancy.

Lastly, the final hullform evaluation must be completed which includes the seakeeping assessment of the improved concept baseline design. Seakeeping represents the behavior of a boat in waves. Evaluation of the improved concept baseline design is done by computing significant characteristic values and comparing them to the values for the representative designs.

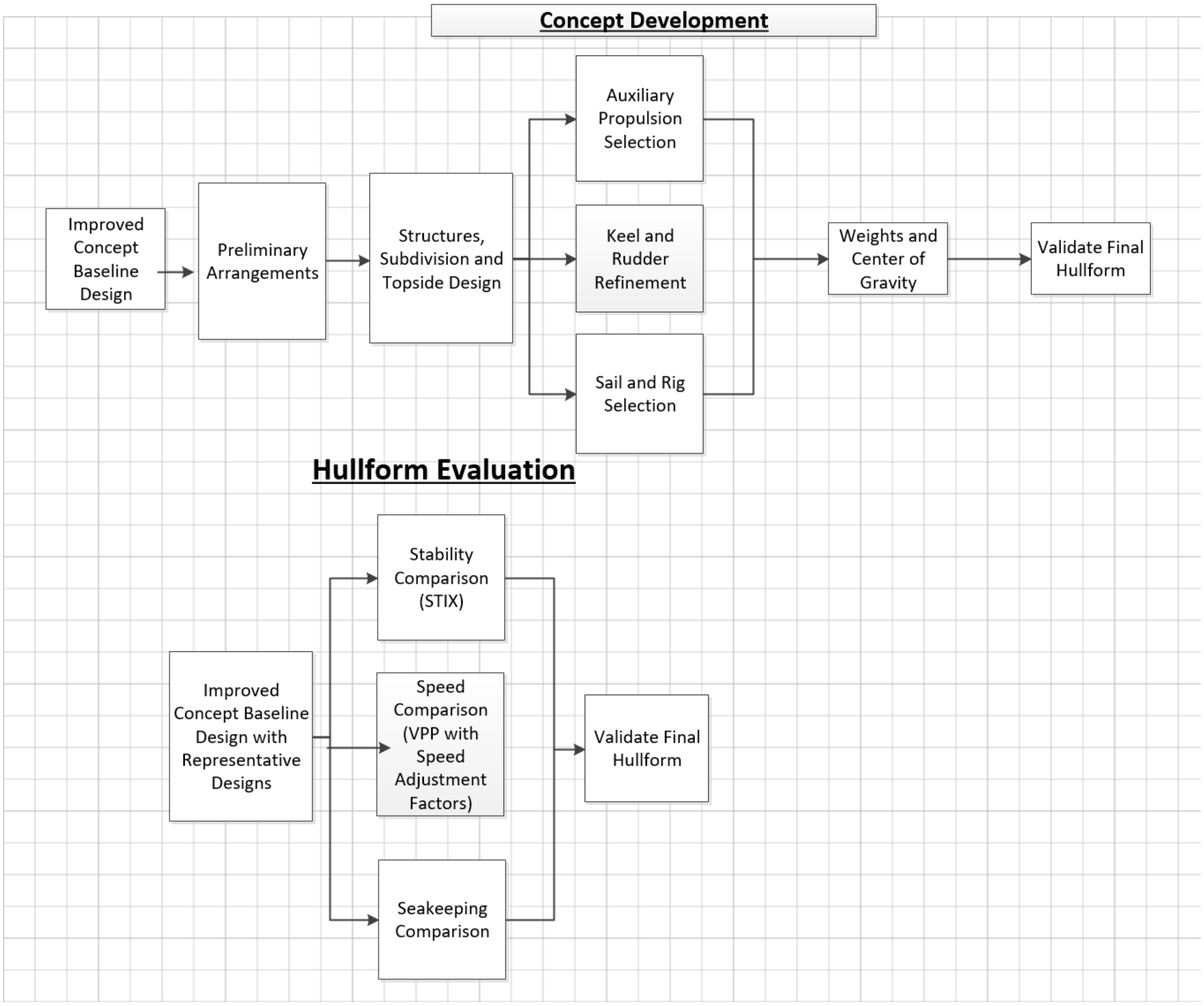
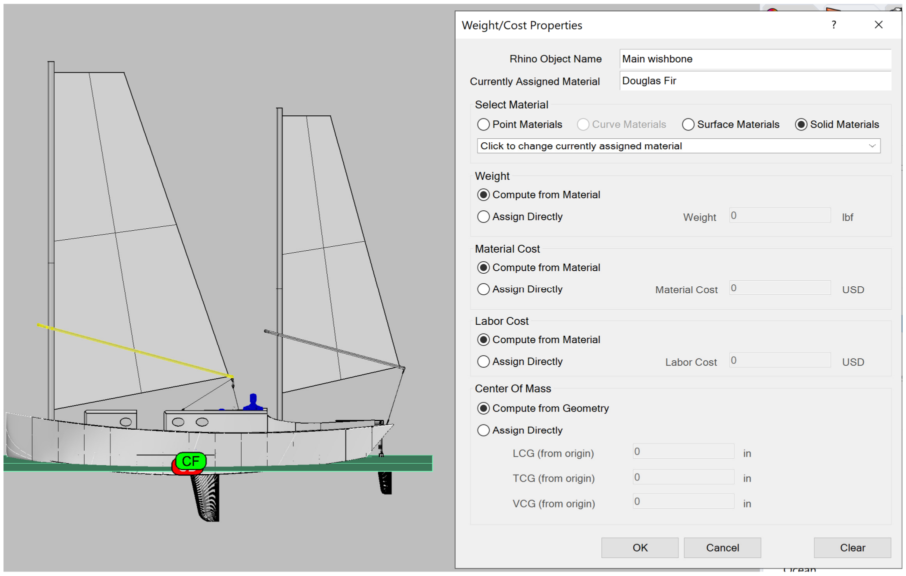


Figure 79 - Concept Development Process

3.3 Tools Used in Concept Development

3.3.1 Orca3D Weight Report

The Orca3D weight report is an extremely useful tool for determining the sailboat's overall weight and center of gravity. Orca3D's weight management tools allow for a reasonably accurate determination of weight and center of gravity. A material library is created with the different materials that will be used to build the sailboat. The material's mass, mass per unit length, mass per unit area or density are specified depending on whether the object is a point, curve, surface or solid material, respectively. For example, a material used in the case study sailboat's construction is Douglas fir wood. Douglas fir wood is a solid and has a density of 33 pounds per foot cubic foot. The wishbone booms are made of Douglas fir. Once the object geometry is created and selected, the object is assigned weight properties. The object is assigned Douglas fir and the weight and center of gravity is calculated based on the material assigned as shown in Figure 80. Alternatively, objects may be assigned weight and center of gravity locations directly in Orca3D.



Rhino Object Name: Main wishbone
Currently Assigned Material: Douglas Fir

Select Material
○ Point Materials ○ Curve Materials ○ Surface Materials ● Solid Materials
Click to change currently assigned material

Weight
● Compute from Material
○ Assign Directly Weight 0 lbf

Material Cost
● Compute from Material
○ Assign Directly Material Cost 0 USD

Labor Cost
● Compute from Material
○ Assign Directly Labor Cost 0 USD

Center Of Mass
● Compute from Geometry
○ Assign Directly
LCG (from origin) 0 in
TCG (from origin) 0 in
VCG (from origin) 0 in

Figure 80- Assigning Weight Properties to Sailboat Components

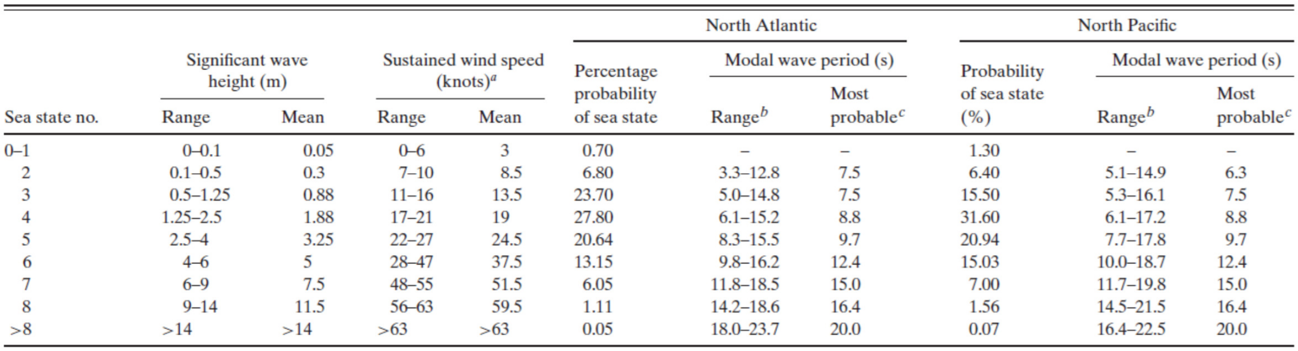
Once all of the objects onboard the boat are accounted for, it is helpful to separate groups of objects depending on their function. *Principles of Yacht Design* organizes the sailboat's components and equipment using 14 groups: structures, forepeak, forward cabin, saloon, navigation station, galley, head, aft cabin, cockpit stow and lazarette, installations, deck equipment, rig and sails, ballast and payload. The objects in Rhino are broken down in a similar manner and a full weight report is generated which is exported to an Excel spreadsheet where weights and centers of gravity can be compared and analyzed. For weights that are not calculated explicitly, *Principles of Yacht Design's* weight breakdown is used as a rough estimate of how weight should be allocated to each group by percentage of total weight.

3.3.2 Public Domain Strip (PDSTRIP)

Seakeeping can be defined as, "the study of the motions of a ship or floating structure, when subjected to waves, and the resulting effects on humans, systems, and mission capability." (U.S.

Naval Academy, 2020) The assessment of seakeeping performance is complex as various different sea conditions may constrain the boat's ability to carry out its function. As such, it is useful to consider the boat's, "typical operating pattern over a period long enough to cover all significant activities." In order to do this, the following must be established:

- likelihood of encountering different sea conditions by utilizing statistics of wave conditions in different areas of the world
- probable boat velocity and direction in these seas
- boat responses that are likely to be critical for operations



					North Atlantic			North Pacific		
	Significant wave height (m)		Sustained wind speed (knots)[a]		Percentage probability of sea state	Modal wave period (s)		Probability of sea state (%)	Modal wave period (s)	
Sea state no.	Range	Mean	Range	Mean		Range[b]	Most probable[c]		Range[b]	Most probable[c]
0–1	0–0.1	0.05	0–6	3	0.70	–	–	1.30	–	–
2	0.1–0.5	0.3	7–10	8.5	6.80	3.3–12.8	7.5	6.40	5.1–14.9	6.3
3	0.5–1.25	0.88	11–16	13.5	23.70	5.0–14.8	7.5	15.50	5.3–16.1	7.5
4	1.25–2.5	1.88	17–21	19	27.80	6.1–15.2	8.8	31.60	6.1–17.2	8.8
5	2.5–4	3.25	22–27	24.5	20.64	8.3–15.5	9.7	20.94	7.7–17.8	9.7
6	4–6	5	28–47	37.5	13.15	9.8–16.2	12.4	15.03	10.0–18.7	12.4
7	6–9	7.5	48–55	51.5	6.05	11.8–18.5	15.0	7.00	11.7–19.8	15.0
8	9–14	11.5	56–63	59.5	1.11	14.2–18.6	16.4	1.56	14.5–21.5	16.4
>8	>14	>14	>63	>63	0.05	18.0–23.7	20.0	0.07	16.4–22.5	20.0

Figure 81- Probability of Sea States and Significant Wave Heights (Brizzolara)

In order to evaluate seakeeping, Public Domain Strip Method (PDSTRIP) is utilized. This program is based on strip theory. Basic assumptions made in strip theory include, "linear motion, a rigid and wall-sided hull, negligible viscous effects apart from roll damping and that the presence of the hull has no effect upon the waves." The hull is composed of a number of strips or thin transverse slices. The flow around each strip of the hull is assumed to be two-dimensional, as if the body were, "an infinitely long oscillating cylinder of that cross section." The assumed linearity of the system allows for the breakdown of a complex problem into a series of simpler ones. It should be noted that large roll angles are difficult to predict due to non-linear effects. (Tupper, 2013)

PDSTRIP solves the equations of motion in the frequency domain and provides response amplitude operator (RAO) values for translations in directions of x, y, and z of the ship-fixed coordinate origin, as well as rotations around the three (3) coordinate axes. RAO's are "a measure of the response to a regular wave of unit amplitude" (Zubaly, 2015). PDSTRIP is also able to handle asymmetrical bodies. This is especially useful because a sailboat heels and lees at significant angles during normal operating conditions which results in asymmetrical underwater hullforms. (Program PDSTRIP: Public Domain Strip Method)

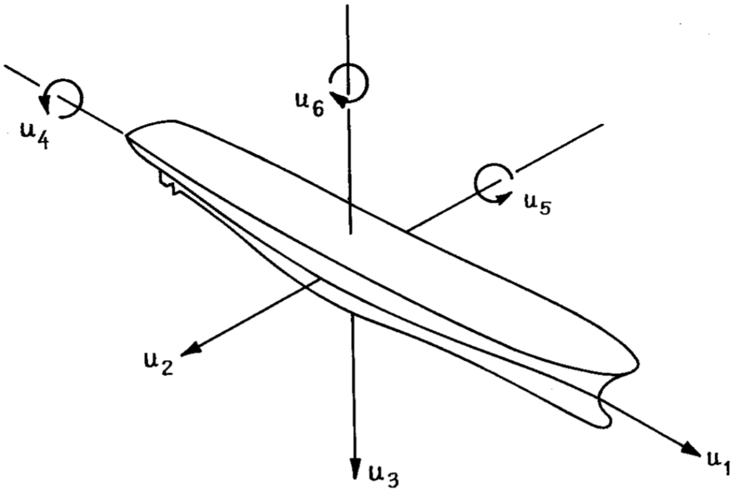


Figure 82- Directions of Coordinate Axes in PDSTRIP (Program PDSTRIP: Public Domain Strip Method)

The RAO values themselves do not provide all of the information necessary to complete the seakeeping evaluation. In order to do this, we must calculate the significant motion amplitudes in terms of heave, pitch, and roll. The first step is to dimensionalize the RAO's provided. For example, the heave RAO is provided as the heave response divided by the wave amplitude. To dimensionalize, we simply multiply this RAO value by the wave amplitude.

The next step is to account for the encountering frequency spectrum. The wave energy spectra formulae provide the wave energy spectrum for a fixed point in the ocean. It is necessary to transform this information to the reference frame of the moving ship. It is useful to note that the encounter frequency (ω_e) is greater than wave frequency (ω) in head seas, and less than wave frequency in following seas. As such the wave energy spectrum is shifted along the frequency axis to a different range of frequencies. (U.S. Naval Academy)

$$\omega_e = \omega - \omega^2 * \left(\frac{U}{g}\right) * \cos(\mu) \tag{76}$$

In order to predict ship motions in irregular waves, we express sea spectra using formulae that approximate measured spectra at different levels of sea severity. There are various spectra that have been formulated by oceanographers which can be used to represent idealized spectra in terms of some particular measures of sea severity, such as wind speed or significant wave height. (Zubaly, 2015) Of particular importance for this case, is the Bretschneider spectrum and the Jonswap spectrum. The Bretschneider spectrum is also referred to as the "two-parameter spectrum" because it considers significant wave height and modal frequency. This spectrum is used for open ocean evaluation of marine vehicle seakeeping.

$$\omega_0 = \frac{2 * \pi}{1.2957 * T} \tag{77}$$

$$S_{ff} = \left(\frac{1.25}{4}\right)\left(\frac{\omega_0^4}{\omega^5}\right)(Hs^2) * \exp\left(-1.25\left(\frac{\omega_0}{\omega}\right)^4\right) \tag{78}$$

The other sea spectra that is of particular importance for this case study is the Jonswap spectra. The Jonswap spectrum is the product of an extensive wave measurement program known as the "Joint North Sea Wave Project", which was completed in 1969. This spectrum represents, "wind generated seas with fetch limitation, and wind speed and fetch length are inputs to this formulation." (Pawlowski) This spectrum is important because it provides a more accurate spectra for near shore and coastal waves, as measurements were made in the North Sea at, "13 stations up to 160 km from the coast under various wave conditions." Two (2) main parameters for this spectrum are the fetch (F) and wind velocity measured at ten (10) meters above the surface (U_{10}). Both of these factors are considered by the modal frequency (ω_0).

$$\alpha = 0.076 * \left(\frac{U_{10}^2}{F * g}\right)^{0.22} \tag{79}$$

$$\omega_0 = 22 * \left(\frac{g^2}{U_{10} * F}\right)^{\frac{1}{3}} \tag{80}$$

$$\sigma = 0.07 \; if \; \omega \leq \; \omega_0 \tag{81}$$

$$\sigma = 0.09 \; if \; \omega > \omega_0 \tag{82}$$

$$r = \exp\left(-\frac{(\omega - \omega_0)^2}{2 * \sigma^2 \omega_0^2}\right) \tag{82}$$

$$S_{ff}(\omega) = \frac{\alpha * g^2}{\omega^5} * \exp\left(-\frac{5}{4} * \left(\frac{\omega_0}{\omega}\right)^4\right) 3.30^r \tag{83}$$

Using the sea spectra, the encounter frequency spectra, and the dimensionalized RAO values, the energy spectrum of the response is calculated by multiplying the wave energy spectrum and the square of the RAO.

The last step is to integrate the response spectra with respect to the encounter frequency and multiply the square root of this value by two (2). This represents the significant motion amplitude value which can be used for seakeeping comparison between sailboat designs.

$$m_n = \int_0^\infty \omega_e * S_{ff}(\omega)\, d\omega \tag{84}$$

$$x_{\frac{1}{3}} = 2 * \sqrt{m_n} \tag{85}$$

3.4 Concept Development Process

3.4.1 Improved Concept Baseline Design

The improved concept baseline design represents the conclusion of the concept exploration process and the beginning of the concept development process. During the concept development process the details of the improved concept baseline design are refined and finalized. The case study's improved concept baseline design is called, "the Albemarle Sound Sharpie", due to its projected operational environment. As can be seen in Figure 83, the boat's underwater characteristics are similar to the North Carolina Sharpie with an expanded freeboard for improved stability and seaworthiness. Changes to the hullform design space were adjusted to yield designs similar to the North Carolina Sharpie after a thorough speed analysis was completed. The North Carolina Sharpie is a representative design which was used for comparison throughout the design process.

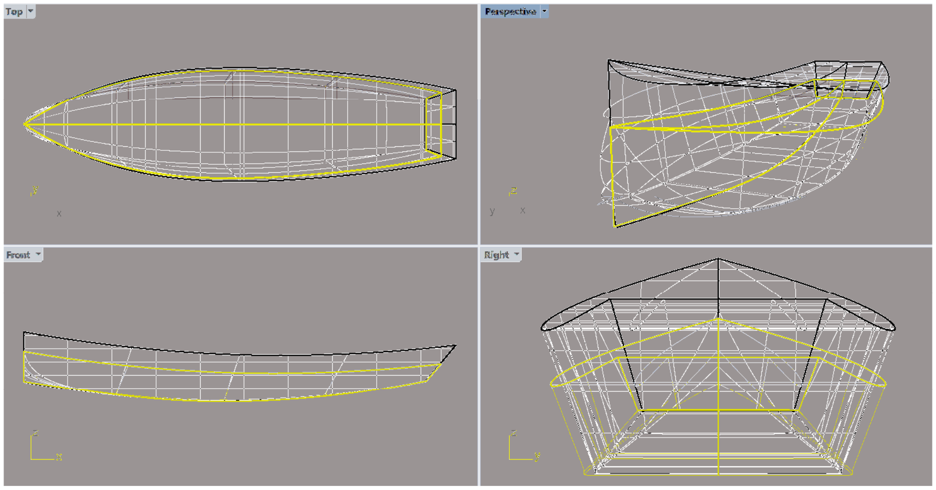


Figure 83 – Albemarle Sound Sharpie (black) and NC (yellow)

3.4.2 Preliminary Arrangements

The arrangements of the case study's Albemarle Sound Sharpie involve tradeoffs between safety, structural integrity, comfort and accessibility, while meeting all of the client's living condition requirements. For this process, *Principles of Yacht Design* is used as a primary resource as it provides necessary dimensions for a human to operate and live aboard a sailboat. Significant measurements are provided in Table 16.

Table 16- Standard Accommodation Measurements (Larsson & Eliasson, Principles of Yacht Design, 2000)

Dimension	Distance (inches)
Standing Height	71
Seated Height	55
Shoulder Width	22
Foot Length	10

Preliminary sketches were generated for the case study as shown in Figure 84. During this part of the design process significant dialogue is needed with the customer in order to avoid unintended confusion and achieve maximum client satisfaction. Main takeaways from communication with the customer included the desire to maintain a split cabin deckhouse to ensure five separate watertight compartments for damage stability, and to lower the deckhouses in order to reduce wind resistance while increasing cockpit visibility. The split cabin arrangement also allows for easier access to forward berthing, thus removing the need to bend down and crawl forward from the main berthing section.

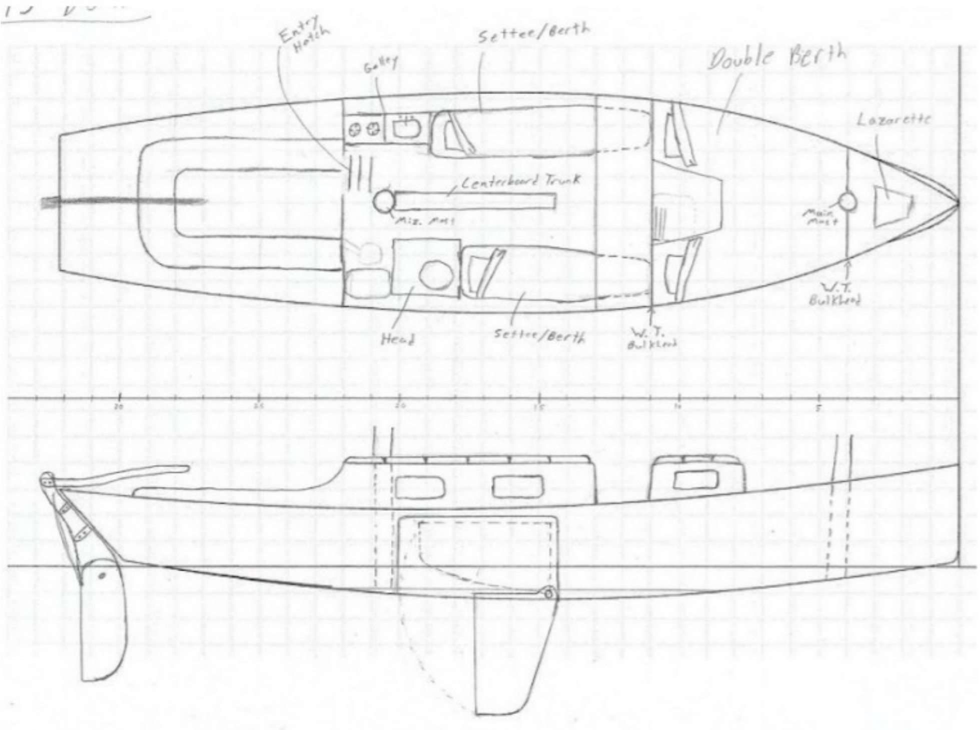


Figure 84- Arrangements Concept Sketch

Specific needs are initially addressed in the main berthing compartment which was required to have sleeping arrangements for two people, a head, galley and keel trunk. Sleeping arrangements were located at the forward end of the compartment which allowed for the head and galley to be placed at the aft end near the main companionway hatch with the possibility for additional headroom when open.

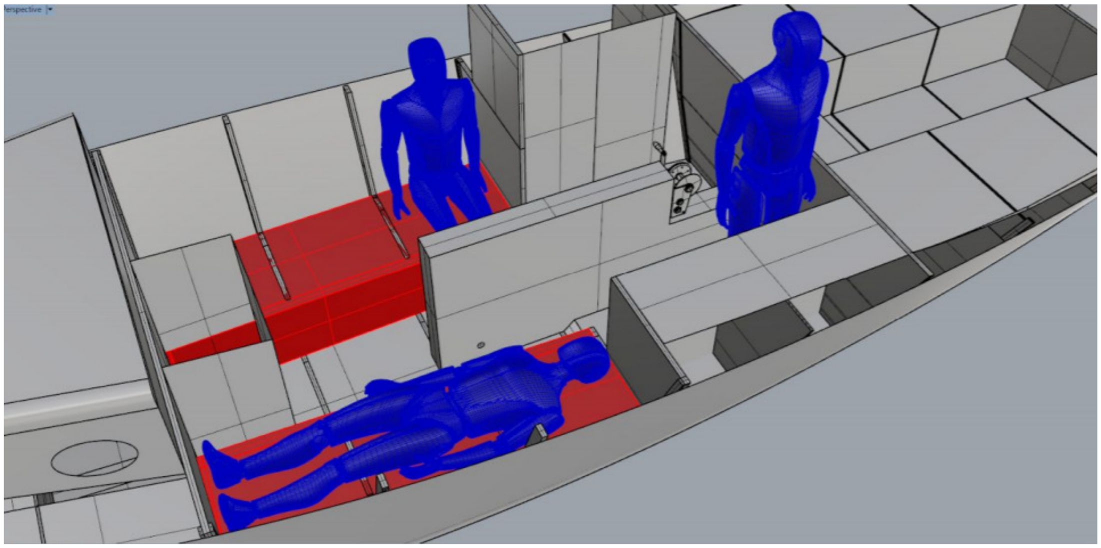


Figure 85- Main Cabin Sleeping Arrangements (aft to right)

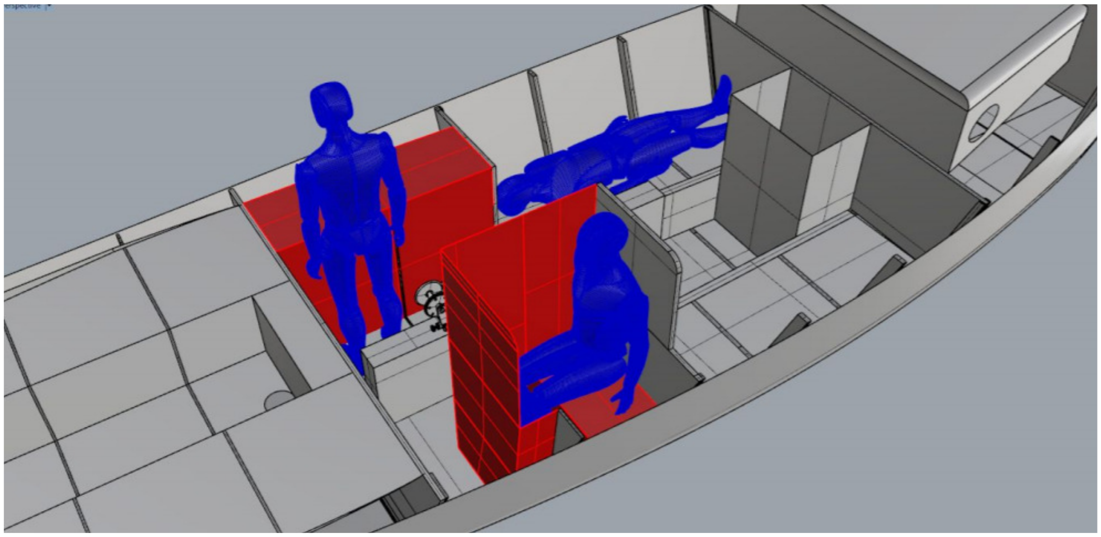


Figure 86- Main Cabin Head and Galley (aft to left)

The space aft of the head contains shelves meant to hold instrumentation and equipment, while the forward space between the two (2) berths is used for hanging locker storage. The galley is positioned such that there is standing space in the companionway hatch cutaway in the deckhouse. The head has limited space, which increases towards midship as the beam increases. In order to take full advantage of the yacht's width, accommodations were placed as far outboard as possible, which also increased interior deck space, while maintaining a minimum bulkhead and frame transverse width of 1.5 inches. Figure 87 provides the vertical dimensions of the main berthing compartment.

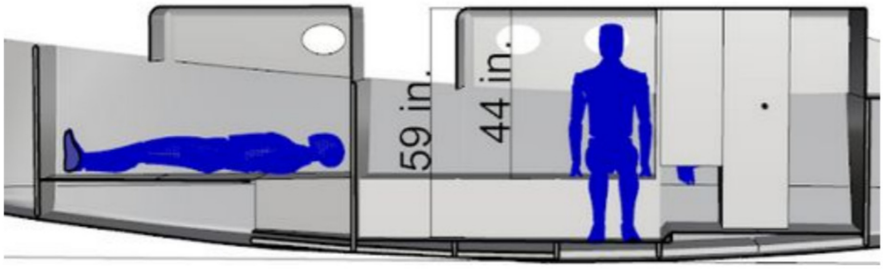


Figure 87 - Main Berthing Dimensions

The forward berthing compartment is very limited in size, and only provides space for two people sitting or lying down. With the main and forward berthing compartments, the owner's requirement to accommodate four people is satisfied. In front of the forward berthing arrangement is the forepeak which provides storage for the anchor and chain.

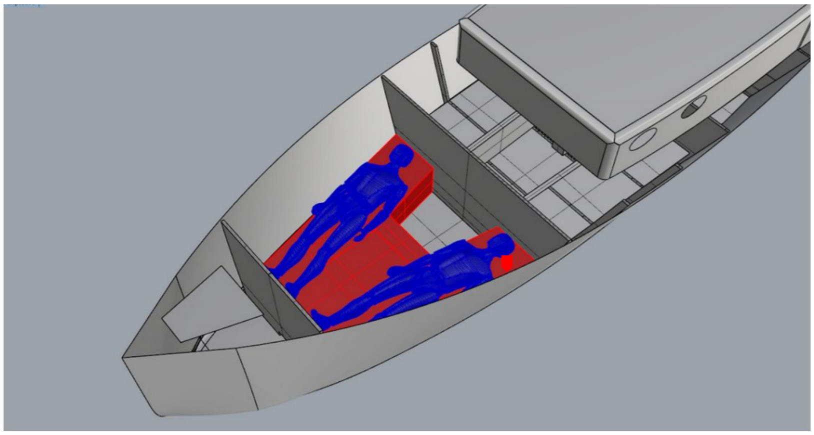


Figure 88- Forepeak and Forward Cabin

The design of the cockpit provides ease of sailing, safety and comfort. It is sized fit six (6) passengers. The tiller is accessible from the cockpit for maneuvering purposes. The engine well is located just aft of the cockpit.

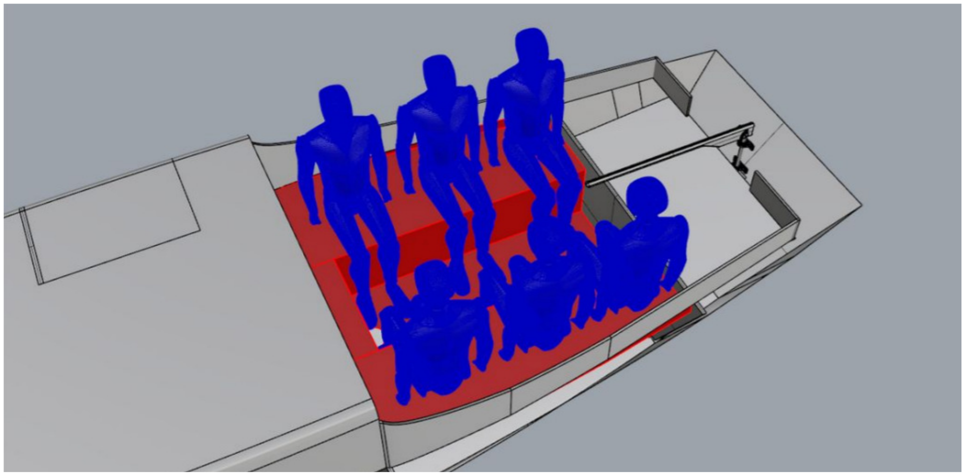


Figure 89- Cockpit Arrangement

Deck space inside the cockpit is kept at a minimum in order to reduce any flooding potential. Deck coaming has been built around the cockpit in order to raise the downflooding point of the sailboat. These features become important to maintaining a favorable STIX rating. Dimensions of the final arrangements are shown in Figure 90.

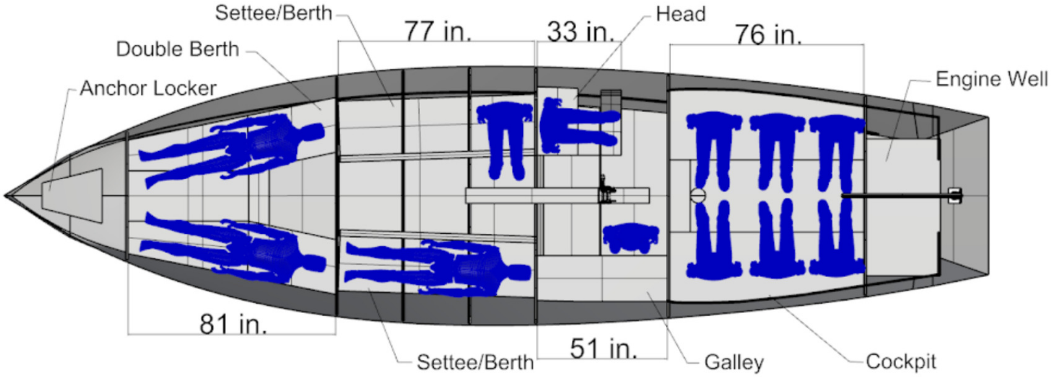


Figure 90- Dimensions of Final Arrangements

3.4.3 Structures, Subdivision and Topside Design

The structural design of the sailboat relies heavily on guidance from Dave Gerr's *Elements of Boat Strength* (2000). This resource provides an empirical method for determining boat dimensions, weights and shapes of a boat's structural members. First, the scantling number, Equation 86, must be calculated, which considers the length, beam and depth of the hull. Due to the flat bottom and hard flaring sides of the sharpie, wood allows for a much more convenient material than fiberglass. The scantling number is used to size structural members utilizing equations specifically purposed for plank-on-frame wooden boats (Gerr, 2000). The scantling number in this case study is 1.42.

$$Scantling\ No. = \frac{LOA * Beam * Depth}{1000} \tag{86}$$

After the scantling number has been determined, bulkheads and frames can be determined and sized as shown in Figure 91. Bulkheads and frames increase the transverse structural rigidity of the boat while also creating watertight compartments. Four bulkheads are used in the design of the Albemarle Sound Sharpie, which results in five watertight compartments. Partial frames are added throughout the boat to increase support, while being altered to allow for internal arrangement spacing.

In order to properly support the bulkheads and frames, additional structural members are added as shown in Figure 92. Along the centerline of the Albemarle Sound Sharpie, a structural keel, which acts as the main longitudinal structural member, and helps to support the relatively large loads placed on the hull by the keel and masts. At the intersection of the masts and the keel at the bottom of the hull, additional support blocks called "mast steps", have been added to provide support for expectant forces.

Due to the unique nature of the sharpie design, internal chine logs are added to provide additional support where the flat bottom meets the sides of the hull.

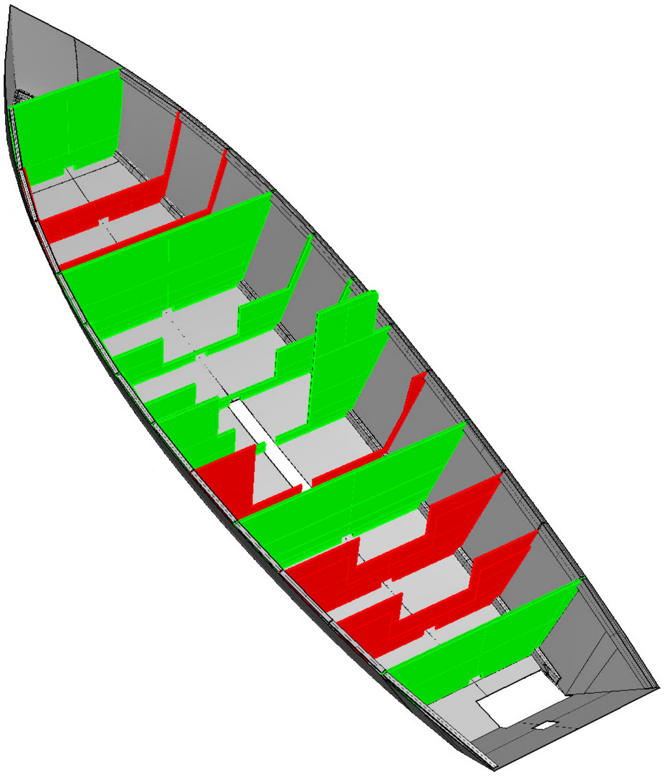


Figure 91- Bulkheads (green) and Frames (red) on Albemarle Sound Sharpie

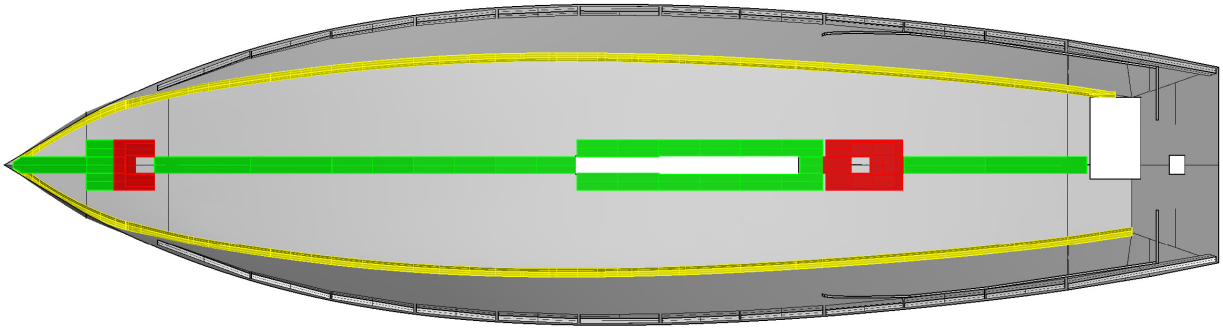


Figure 92- Structural Keel (green), Chine Logs (yellow), and Mast Steps (red) on the Albemarle Sound Sharpie

The topsides of the Albemarle Sound Sharpie include a deck composed of ¾" plywood, which provides a suitable amount of support for the hull and thickness for walking on the deck. Transverse support of the deck is provided by deck beams, while the deck is supported longitudinally at the intersection of the hull and deck by a shelf and clamp.

The shelf and clamp arrangement is shown in further detail in Figure 93. This system provides similar structural support to the chine log at the base of the hull sides. As the scantling number for this case is less than 2.5, the shelf only needs to be fastened through the clamp. Two different beam sizes are used for this design. A larger beam size is used at the fore and aft ends of each berth and mast, as well as the cockpit. Fasteners can be temporary only when epoxy adhesive is used.

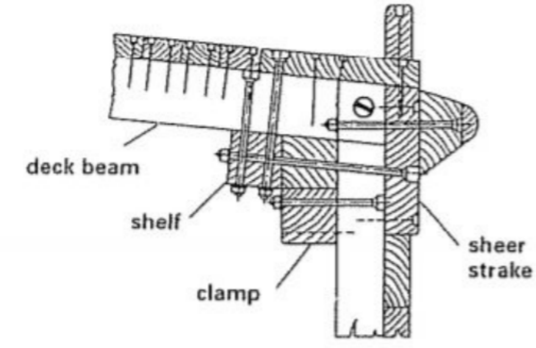


Figure 93- Shelf and Clamp Arrangement

Rather than a single deck house, this design incorporates a split arrangement, with forward and main deckhouses respectively. This arrangement allows for adequate space that does not compromise the five watertight compartments. Along the sides of each deck house is approximately six to twelve inches of space allowing passengers and crew to walk along the deck on the topside. Each berth has an entrance hatch on the top of the deck house.

3.4.4 Auxiliary Propulsion Selection

As specified by the owner in the case study, the Albemarle Sound Sharpie must have an alternative propulsion system. Sail will be the boat's main propulsion method, but several other auxiliary propulsion systems are investigated. These systems include straight-shaft inboard diesel engine, electric drive, water jet and outboard engine. There are pros and cons to each of these options. The straight-shaft inboard diesel engine is available in a variety of sizes and most mechanics are experienced in working on them. However, having an inboard engine occupies valuable space in a boat where size is very much constrained by the owner's requirements. In addition, the diesel weight will increase draft permanently. An electric motor provides reduced noise and emissions, when compared to a diesel or gasoline engine. The drawbacks to an electric motor include a limitation of range due to battery capacity. These motors may also be more expensive than a traditional diesel or gasoline engine of the same size. Using a water jet allows for both inboard and outboard assemblies, while adding minimal draft. The water jet also eliminates the need for a rudder, as the boat is steered by directing the flow of water coming from the nozzle. However, the water jet is less fuel efficient than a gasoline or diesel engine. It is also difficult to steer the boat with a water jet at low speeds, as less water is passing through the nozzle.

A diesel or gasoline powered outboard engine provides an engine, transmission, and propeller as one packaged assembly. These engines are available in a variety of different horsepower options and can be removed easily for service. An outboard engine can be bolted on to the transom or on a bracket at a variety of positions on the transom, depending on the rudder and steering arrangement.

An outboard diesel or gasoline engine is selected for the Albemarle Sound Sharpie for a few reasons. First, it can be raised out of the water while the sailboat is cruising and does not greatly increase the drag when it is in the water. Second, the outboard engine provides better handling at low speeds even better than the water jet. Last, this option allows for continued flexibility moving forward in terms of arrangements. An inboard engine arrangement would permanently restrict arrangement options in the aft end of the boat.

Once this propulsion method is decided upon, specific characteristics of the engine are established. Although *Principles of Yacht Design* provides a basic recommendation of 3-4 kW per ton of displacement for pure sailing yachts, and 5-6 kW per ton for motor sailors, a more rigorous approach for determining the appropriate size of the engine was undertaken as part of the case study.

There are certain circumstances which would necessitate the use of the auxiliary engine for a sailboat, including maneuvering in a harbor, if sailing conditions are less than perfect, and also as a life-saving piece of machinery when facing dire conditions in rough weather.

Principles of Yacht Design provides methods to establish the calm water resistance values as well as a series of formulae which calculate components of resistance in rough weather. The calm water resistance value is comprised of two components, residuary and frictional. Computations for rough weather include formulae for finding added resistance in waves, as well as a specific air resistance calculation.

The first component is residuary resistance. Although this resistance is accounted for in the VPP with heel and yaw, we are now interested in the sailboat being upright in calm water. Therefore, we do not need to consider induced resistance, and as long as the hull is not too fouled, the roughness resistance can also be eliminated. Figure 94 provides an approximate estimate of residuary resistance for this case.

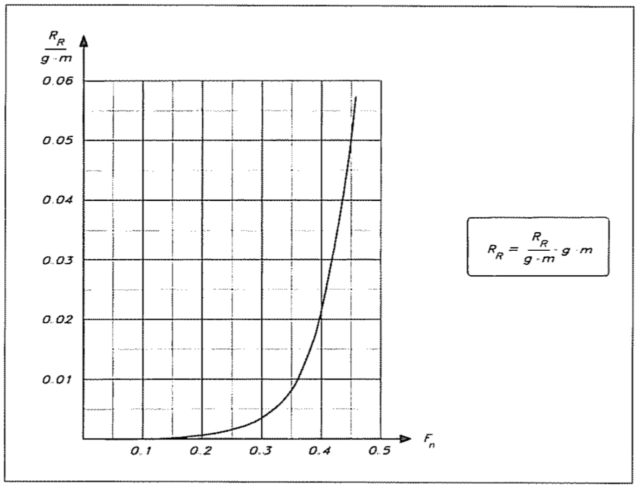


Figure 94- Estimation of Residuary Resistance

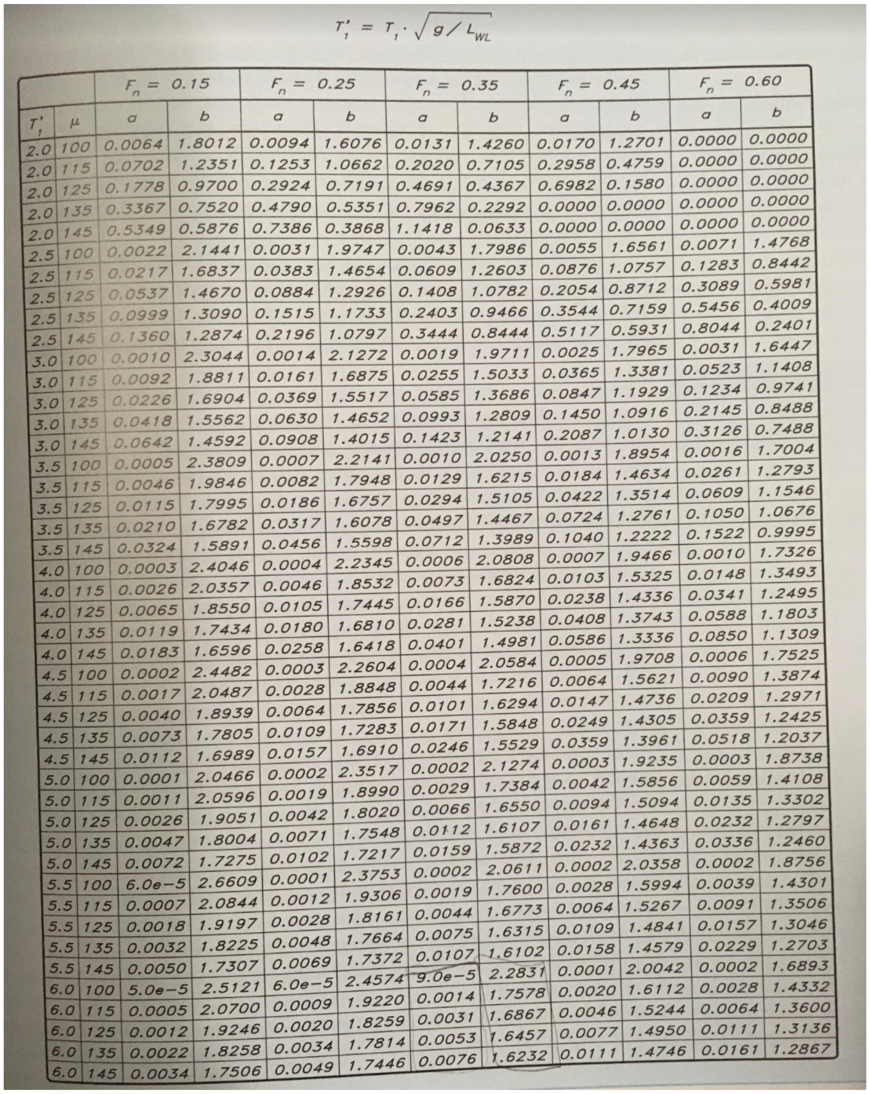
Next, the frictional resistance component is estimated. The frictional resistance coefficient is a function of Reynold’s Number. The most popular equation for finding this value was adopted by the International Towing Tank Conference (ITTC) in 1957. Once this value is computed, frictional resistance is calculated using the boat’s hydrostatic characteristics and boat speed.

$$C_F = \frac{0.075}{(\log_{10} R_n - 2)^2} \tag{87}$$

$$R_{TFriction} = C_F * 0.5 * \rho * V^2 * Wetted\ Surface\ Area \tag{88}$$

Principles of Yacht Design recommends finding a separate value for additional resistance in waves during rough weather. The first step in calculating this value is found from a lookup table in *Principles of Yacht Design* shown in Table 17, by non-dimensionalizing the wave period. It is worth noting that these coefficients are not for straight upwind conditions, so the calculations have been carried out for 35° upwind. While this may slightly underestimate added resistance, the approximation is relatively small compared to the uncertainty of the wave climate. In the case of rough weather, a wave period, wave height, and apparent wind speed values corresponding with sea state four are used. Once the wave period has been non-dimensionalized, appropriate coefficients can be extracted and plugged into the equation for this additional resistance value.

Table 17- Coefficient for Added Resistance in Waves



$$T'_1 = T_1 \cdot \sqrt{g / L_{WL}}$$

		$F_n = 0.15$		$F_n = 0.25$		$F_n = 0.35$		$F_n = 0.45$		$F_n = 0.60$	
T'_1	μ	a	b	a	b	a	b	a	b	a	b
2.0	100	0.0064	1.8012	0.0094	1.6076	0.0131	1.4260	0.0170	1.2701	0.0000	0.0000
2.0	115	0.0702	1.2351	0.1253	1.0662	0.2020	0.7105	0.2958	0.4759	0.0000	0.0000
2.0	125	0.1778	0.9700	0.2924	0.7191	0.4691	0.4367	0.6982	0.1580	0.0000	0.0000
2.0	135	0.3367	0.7520	0.4790	0.5351	0.7962	0.2292	0.0000	0.0000	0.0000	0.0000
2.0	145	0.5349	0.5876	0.7386	0.3868	1.1418	0.0633	0.0000	0.0000	0.0000	0.0000
2.5	100	0.0022	2.1441	0.0031	1.9747	0.0043	1.7986	0.0055	1.6561	0.0071	1.4768
2.5	115	0.0217	1.6837	0.0383	1.4654	0.0609	1.2603	0.0876	1.0757	0.1283	0.8442
2.5	125	0.0537	1.4670	0.0884	1.2926	0.1408	1.0782	0.2054	0.8712	0.3089	0.5981
2.5	135	0.0999	1.3090	0.1515	1.1733	0.2403	0.9466	0.3544	0.7159	0.5456	0.4009
2.5	145	0.1360	1.2874	0.2196	1.0797	0.3444	0.8444	0.5117	0.5931	0.8044	0.2401
3.0	100	0.0010	2.3044	0.0014	2.1272	0.0019	1.9711	0.0025	1.7965	0.0031	1.6447
3.0	115	0.0092	1.8811	0.0161	1.6875	0.0255	1.5033	0.0365	1.3381	0.0523	1.1408
3.0	125	0.0226	1.6904	0.0369	1.5517	0.0585	1.3686	0.0847	1.1929	0.1234	0.9741
3.0	135	0.0418	1.5562	0.0630	1.4652	0.0993	1.2809	0.1450	1.0916	0.2145	0.8488
3.0	145	0.0642	1.4592	0.0908	1.4015	0.1423	1.2141	0.2087	1.0130	0.3126	0.7488
3.5	100	0.0005	2.3809	0.0007	2.2141	0.0010	2.0250	0.0013	1.8954	0.0016	1.7004
3.5	115	0.0046	1.9846	0.0082	1.7948	0.0129	1.6215	0.0184	1.4634	0.0261	1.2793
3.5	125	0.0115	1.7995	0.0186	1.6757	0.0294	1.5105	0.0422	1.3514	0.0609	1.1546
3.5	135	0.0210	1.6782	0.0317	1.6078	0.0497	1.4467	0.0724	1.2761	0.1050	1.0676
3.5	145	0.0324	1.5891	0.0456	1.5598	0.0712	1.3989	0.1040	1.2222	0.1522	0.9995
4.0	100	0.0003	2.4046	0.0004	2.2345	0.0006	2.0808	0.0007	1.9466	0.0010	1.7326
4.0	115	0.0026	2.0357	0.0046	1.8532	0.0073	1.6824	0.0103	1.5325	0.0148	1.3493
4.0	125	0.0065	1.8550	0.0105	1.7445	0.0166	1.5870	0.0238	1.4336	0.0341	1.2495
4.0	135	0.0119	1.7434	0.0180	1.6810	0.0281	1.5238	0.0408	1.3743	0.0588	1.1803
4.0	145	0.0183	1.6596	0.0258	1.6418	0.0401	1.4981	0.0586	1.3336	0.0850	1.1309
4.5	100	0.0002	2.4482	0.0003	2.2604	0.0004	2.0584	0.0005	1.9708	0.0006	1.7525
4.5	115	0.0017	2.0487	0.0028	1.8848	0.0044	1.7216	0.0064	1.5621	0.0090	1.3874
4.5	125	0.0040	1.8939	0.0064	1.7856	0.0101	1.6294	0.0147	1.4736	0.0209	1.2971
4.5	135	0.0073	1.7805	0.0109	1.7283	0.0171	1.5848	0.0249	1.4305	0.0359	1.2425
4.5	145	0.0112	1.6989	0.0157	1.6910	0.0246	1.5529	0.0359	1.3961	0.0518	1.2037
5.0	100	0.0001	2.0466	0.0002	2.3517	0.0002	2.1274	0.0003	1.9235	0.0003	1.8738
5.0	115	0.0011	2.0596	0.0019	1.8990	0.0029	1.7384	0.0042	1.5856	0.0059	1.4108
5.0	125	0.0026	1.9051	0.0042	1.8020	0.0066	1.6550	0.0094	1.5094	0.0135	1.3302
5.0	135	0.0047	1.8004	0.0071	1.7548	0.0112	1.6107	0.0161	1.4648	0.0232	1.2797
5.0	145	0.0072	1.7275	0.0102	1.7217	0.0159	1.5872	0.0232	1.4363	0.0336	1.2460
5.5	100	6.0e−5	2.6609	0.0001	2.3753	0.0002	2.0611	0.0002	2.0358	0.0002	1.8756
5.5	115	0.0007	2.0844	0.0012	1.9306	0.0019	1.7600	0.0028	1.5994	0.0039	1.4301
5.5	125	0.0018	1.9197	0.0028	1.8161	0.0044	1.6773	0.0064	1.5267	0.0091	1.3506
5.5	135	0.0032	1.8225	0.0048	1.7664	0.0075	1.6315	0.0109	1.4841	0.0157	1.3046
5.5	145	0.0050	1.7307	0.0069	1.7372	0.0107	1.6102	0.0158	1.4579	0.0229	1.2703
6.0	100	5.0e−5	2.5121	6.0e−5	2.4574	9.0e−5	2.2831	0.0001	2.0042	0.0002	1.6893
6.0	115	0.0005	2.0700	0.0009	1.9220	0.0014	1.7578	0.0020	1.6112	0.0028	1.4332
6.0	125	0.0012	1.9246	0.0020	1.8259	0.0031	1.6867	0.0046	1.5244	0.0064	1.3600
6.0	135	0.0022	1.8258	0.0034	1.7814	0.0053	1.6457	0.0077	1.4950	0.0111	1.3136
6.0	145	0.0034	1.7506	0.0049	1.7446	0.0076	1.6232	0.0111	1.4746	0.0161	1.2867

$$\frac{\bar{R}_{AW} * 10^2}{\rho * g * L_{WL} * H_{\frac{1}{3}}^2} = a * \left(10^2 * \left(\frac{\nabla^{\frac{1}{3}}}{L_{WL}} \right) * \left(\frac{k_{yy}}{L_{WL}} \right) \right)^b \tag{89}$$

$\nabla = Volume\ Displacement$
$a = coefficient\ for\ added\ resistance\ in\ waves$
$b = coefficient\ for\ added\ resistance\ in\ waves$
$H_{\frac{1}{3}} = Significant\ Wave\ Height$
$k_{yy} = Longitudinal\ Radius\ of\ Gyration$

Lastly the windage resistance is calculated, and specifically windage resistance of the hull and mast. The frontal area of the hull is approximately the product of the beam and average freeboard. The frontal area of the mast is the product of the diameter multiplied by the height above deck.

$$R_{AHull} = \frac{1}{2} * \rho_{air} * Wind\ Speed * C_D * Beam * Avg.Freeboard \tag{90}$$

$$R_{AMast} = \frac{1}{2} * \rho_{air} * Wind\ Speed * C_D * Mast\ Diameter * Mast\ Height \tag{91}$$

$$R_T = R_{TFriction} + R_R + R_{AW} + R_{AMast} + R_{AHull} \tag{92}$$

The total resistance is calculated by adding the resistance components. In the case study, this value is 188.6 lbf at six knots in sea state four conditions (approximately six-foot seas and twenty knot winds). In order to validate this calculation, Orca3D's CFD was used. It was found that at six knots of boat speed, the corresponding resistance value in a steady state environment was 120.3 lbf. The CFD predicted resistance was lower than the value from the rough weather calculation, as predicted. The majority of the difference between these values can be attributed to the simulated wind and sea conditions. The rough weather calculation represents a conservative value, and a potential worst-case scenario for the operator. The two resistance values that have been tabulated for discussion with the owner. A comparison of the results are shown in Table 18.

Table 18- Comparison of Resistance Calculations

	Orca3D CFD	PYD Rough Weather
Residuary (lbf)	-	66.2
Frictional (lbf)	-	51.9
Calm Water (lbf)	111.4	118.1
Air (lbf)	8.9	63.4
Added Resistance in Waves (lbf)	-	7.1
Total Resistance (lbf)	120.3	188.6
EHP (hp)	2.24	4.3
DHP (hp) w/25% margin	5.2	8.2

Once the resistance has been accounted for, the appropriate horsepower for an auxiliary engine can be computed. In order to begin this series of calculations, the block coefficient (C_B) of the boat must be established. Orca3D hydrostatic analysis was used to compute this value for the Albemarle

Sound. It is also fair to assume an open water efficiency (η_O) of 55% for an auxiliary sailboat propeller in rough waters. The case study also assumed a six-knot boat velocity.

$$EHP = R_T * V \tag{93}$$

$$Wake\ Fraction\ (w) = 2 * C_B * (1 - C_B) + 0.04 \tag{94}$$

$$Thrust\ Fraction\ (t) = 0.7 * w + 0.06 \tag{95}$$

$$Speed\ of\ Advance\ (V_a) = V * (1 - w) \tag{96}$$

$$Thrust\ (T) = \frac{Resistance}{1 - t} \tag{97}$$

$$Thrust\ Horsepower\ (THP) = T * V_A \tag{98}$$

$$DHP_O = \frac{THP}{\eta_O} \tag{99}$$

If we consider the steady state resistance value the calculation for delivered horsepower yields a value of 5.2 horsepower, while the rough weather calculation produces a value of 8.2 horsepower. As the second calculation is conservative in nature, and through discussion with the owner, an outboard engine of ten horsepower was felt to be appropriate.

In terms of arrangement, this engine should sit in an engine well, which will allow for a tiller to be hung off the stern of the boat. This will also enable an arrangement in which the tiller handle is closer to the sailor. The engine will be in a fixed position along the longitudinal centerline and the tiller will be used for steering both under power and sail. Figure 95 shows possible engine and tiller arrangements.

Figure 95 – Engine Well and Tiller Arrangement

A ten-horsepower outboard gasoline engine was selected in the case study. A gasoline-powered outboard engine provides an engine, transmission, and propeller as one packaged assembly, while also allowing for easy removal from the boat for service. The owner also indicated that a gasoline engine is more appealing than a diesel engine because gasoline engines are generally considered more expensive and heavier than their diesel counterparts. Although a four stroke engine weighs slightly more than a two stroke engine, it also runs quieter and cleaner while using less fuel.

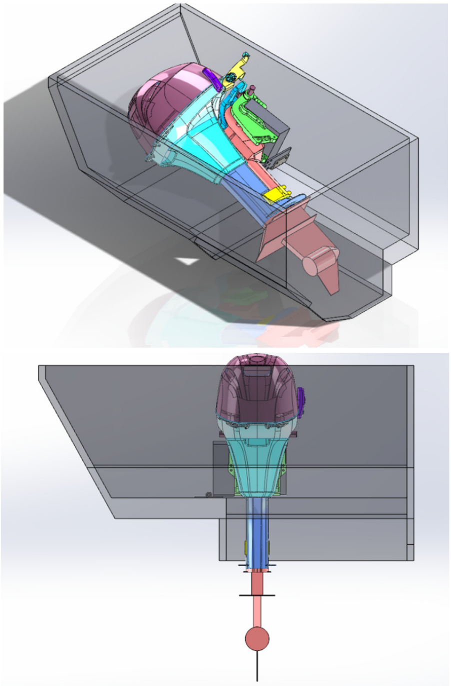


Figure 96- Auxiliary Propulsion Setup

The engine is located in a well just aft of the cockpit. The space between the cockpit and the transom is limited so the engine is mounted on a hinge which pivots transversely. The engine is mounted in a singular stationary position and is steered using the rudder through the transom.

3.4.5 Keel and Rudder Refinement

As described in Section 2.3.7, *Principles of Yacht Design* heavily influenced the development of the final keel in the case study which is trapezoidal in shape with an elliptically rounded tip. The tip is designed this way in order to avoid hydrodynamic tip vortices. The shape begins as a NACA 63-012 hydrofoil at the hull/root chord and transitions into a NACA 65-015 hydrofoil as it extends down towards the tip. A thinner hydrofoil section with less lift is ideal closer to the hull so that unnecessary wave making resistance is avoided as the hull heels. The thicker hydrofoil section near the tip creates the necessary lift force, while also ensuring that the keel is structurally sound as the chord length lessens near the bottom of the appendage.

In determining the final keel dimensions, *Principles of Yacht Design* recommends that cruising yachts have a keel area approximately 3.5% of the boat's sail area, while, "percentages below 2.75% are found on pure racing yachts." In the Albemarle Sound Sharpie, the keel area is approximately 2.9% of the boat's sail area. Length is largely limited by handling for raising and lowering, draft and boat structural loads. The final keel is shown on the boat in Figure 97 with dimensions listed in Table 19.

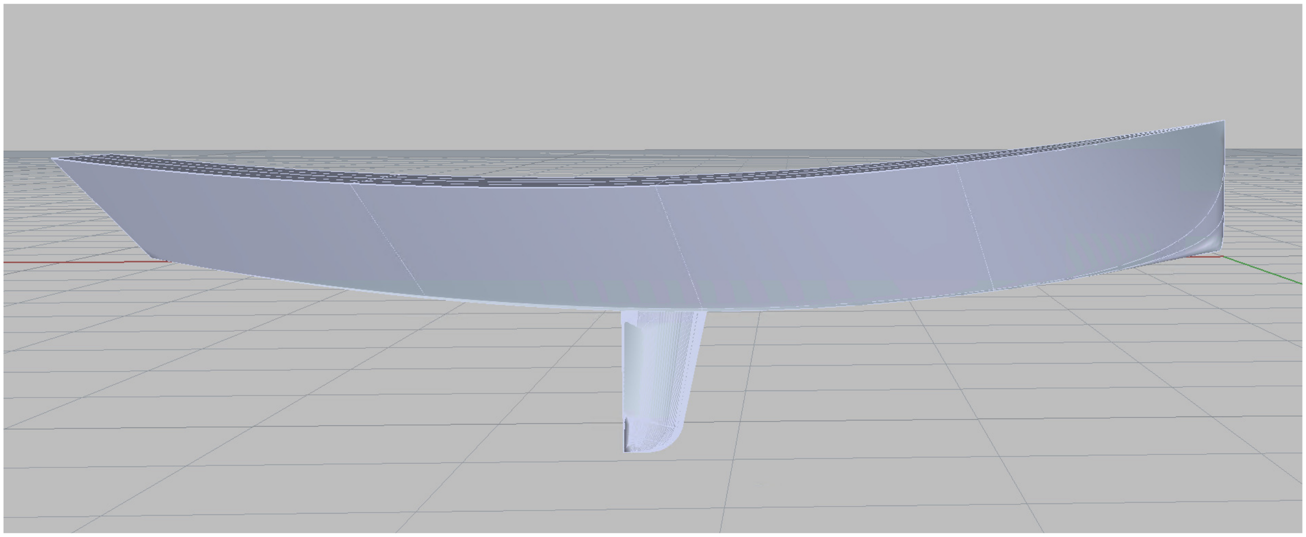


Figure 97 **- Albemarle Sound Sharpie Keel**

Table 19- Final Keel Dimensions

Length	54”
Trapezoidal Section Length	46”
Top Chord Length	30”
Bottom Chord Length	10”
Tip Ellipse Radius	12”

As specified by the prospective owner, the keel must have the capability of being raised and lowered to provide a raised draft not exceeding one foot six inches. A swing keel was selected for safety as it rises automatically if the boat grounds. The swing mechanism has a pin near the leading edge of the root chord as shown in Figure 98. The keel rotates around this pin when swinging up into the box. The keel is raised and lowered using a hand winch that is connected to a pulley attached to an eye bolt near the trailing edge of the root chord. The keel stays down once lowered due to its weight.

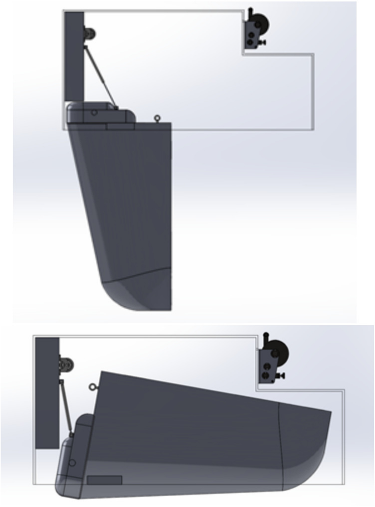


Figure 98- Keel Swing Mechanism

The rudder also has a trapezoidal shape with an elliptically rounded tip. The rudder uses a NACA 4-series hydrofoil shape, NACA 0012, which performs better at high angles of attack than the NACA 6-series. It has the minimum chord thickness required to withstand the forces expected to be applied on the rudder. *Principles of Yacht Design* states that typical modern cruisers have a rudder area that is 1.4% of the boat's sail area. The Albemarle Sound Sharpie's rudder area is 0.85% of the sail area. It is shown in Figure 99 and its final dimensions are listed in Table 20. The owner observed the rudder is very small and asked that a balanced rudder be designed with a much larger area.

Table 20- Final Rudder Dimensions

Length	36”
Trapezoidal Section Length	32”
Top Chord Length	15”
Bottom Chord Length	5”
Tip Ellipse Radius	5”

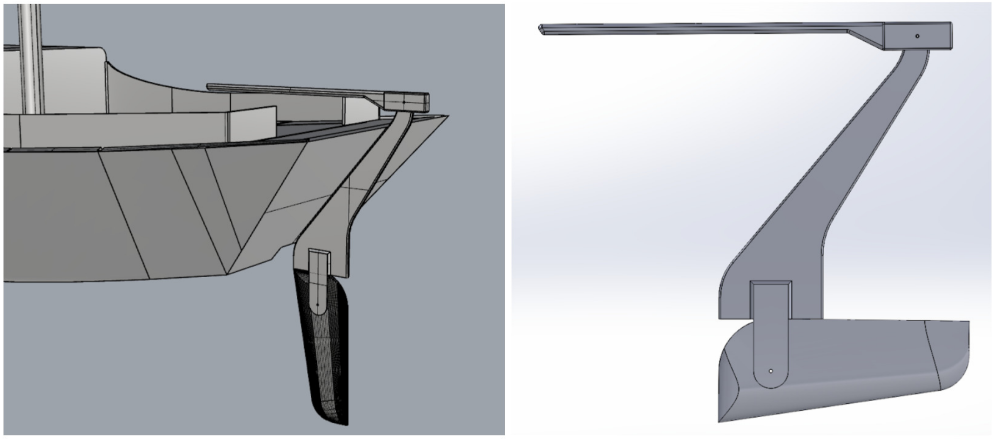


Figure 99- Rudder Swing Mechanism

3.4.6 Sail and Rig Selection

The final sail plan of the Albemarle Sound Sharpie has a total sail area of 429 square feet. This value is based on VPP runs with Dellenbaugh Angle and sail area ratio constraints completed in the concept exploration phase of the design process. During this study important ratios for determining sail area such as sail area to wetted surface area and sail area to volume displacement$^{\frac{2}{3}}$ were examined. *Principles of Yacht Design* states that industry standards for these ratios are 2-2.5 and 15-22, respectively. The comparative naval architecture study supported these statements. Additional dimensions for the sail plan are provided in given in Table 21. Two masts are used to keep the center of effort low which helps to increase stability and sail performance. The two-mast configuration also makes the sails and masts easier to handle for the operator.

Table 21- Sail Plan Dimensions

	Luff	Foot	Leech	Head	Area	Aspect Ratio
Main	27’11”	14’9”	26’8”	5’10”	276 ft^2	1.9
Mizzen	23’	10’	21’7”	4’	153 ft^2	2.4

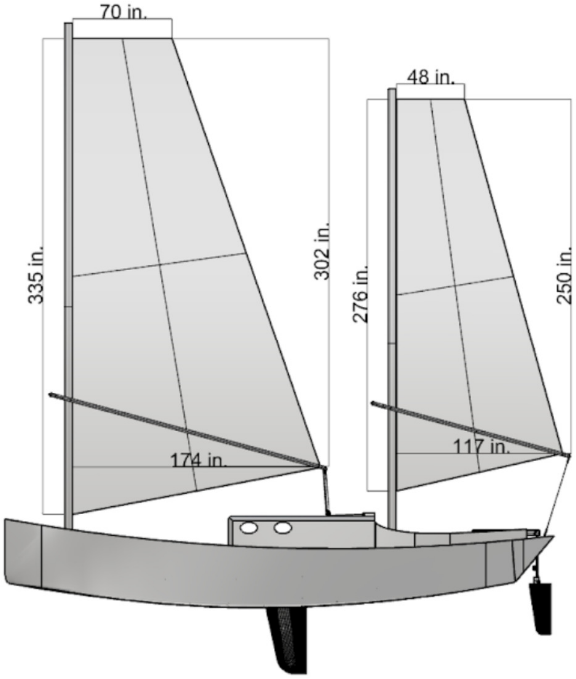


Figure 100- Primary Sail Dimensions

The sharpie masts are freestanding (no standing rigging), and keel stepped. The main and mizzen have a height of 33.3 feet and 29.9 feet, respectively. They are located 3.7 feet and 22.67 feet aft of the bow. The booms are 16.4 feet and 11.67 feet long. Each wishbone boom extends about a foot in front of the mast and is attached as shown in Figure 101. The fixed point on the mast is on a track in order to allow the front of the boom to be moved up and down, thereby adjusting the boom angle as needed.

Figure 101- Wishbone Boom Attached to Mast

The mizzen halyard and snotter are fixed to cleats on the mizzen mast. The main halyard and snotter run to the base of the main mast, through guides along the deck and over the aft deck house back to the cockpit, shown in Figure 102.

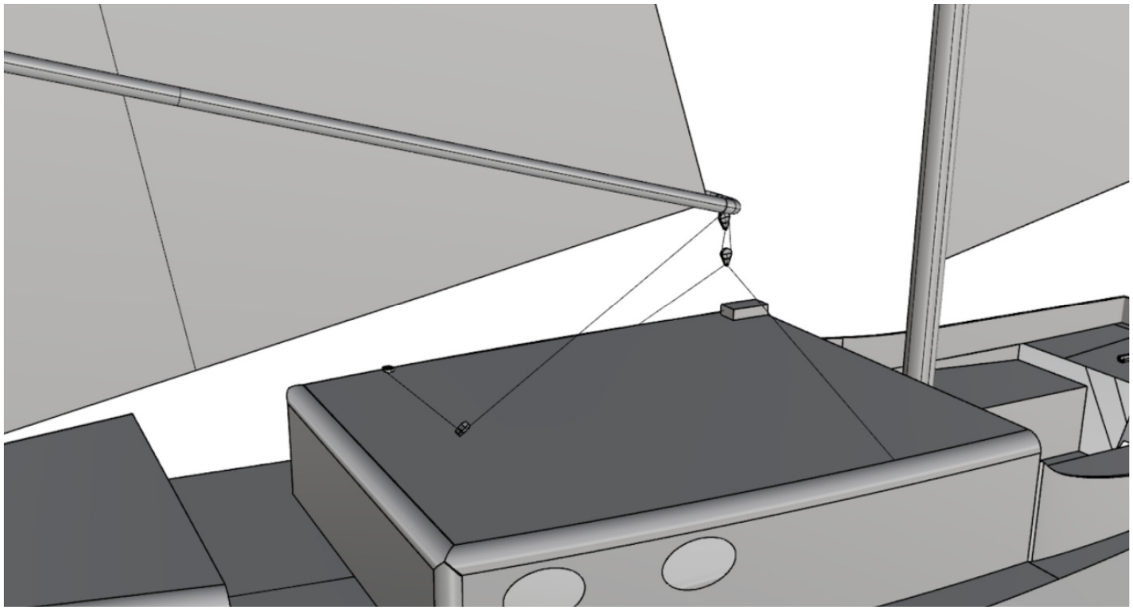


Figure 102- Single Main Sheet

The main sheet is a single sheet which runs forward of the companionway hatch before going back to the cockpit. The wishbone boom negates the need to have a traveler for the mizzen sheet, since it always provides downward tension on the leech of the sail. This setup allows the single mizzen sheet to come down to the center of the transom behind the tiller.

All rigging will use double braided polyester lines. The halyards and snotter will use 5/16”, and the sheets will use 3/8" diameter line as recommended by the Annapolis Performance Sailing (APS) line selection guide. Figure 103 provides a diagram of the running rigging plan for the case study.

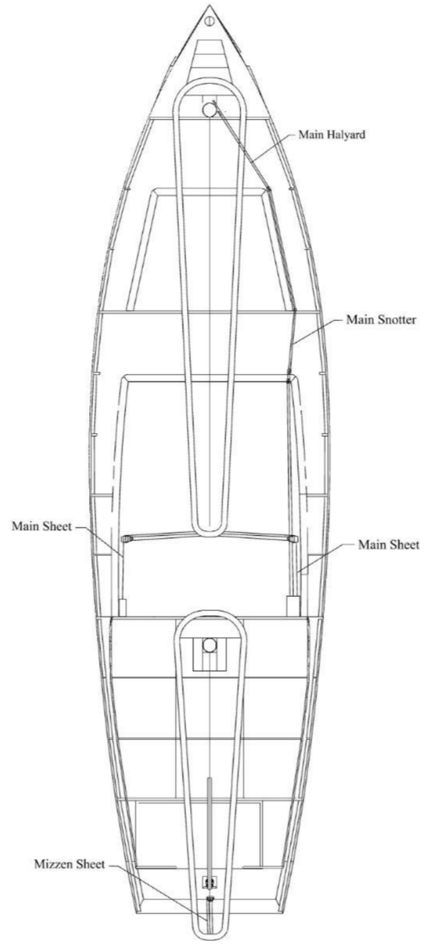


Figure 103- Running Rigging Plan

3.4.7 Weights and Center of Gravity

A critical part of the concept development process is to verify the boat's weight and center of gravity. Near the beginning of the concept exploration process in the case study, it was assumed that the boat's weight would equal the boat's full load design displacement (8,267 pounds) and have a vertical center of gravity at the waterline. Based on this assumption, simulations were run in the VPP and Orca3D CFD. Additionally, STIX and Dellenbaugh Angle were calculated based on these assumed values. Once the final model of the Albemarle Sound Sharpie was created in Rhino, and materials were assigned to all objects an Orca3D weight report was generated. This report provided the weight and center of gravity locations for a large portion of the weight anticipated onboard. Other items including navigation equipment, galley equipment, electrical equipment, and piping are estimated based on the information provided in *Principles of Yacht Design.*

Table 22 provides a breakdown of the weights and corresponding center of gravity locations for each component of the sailboat. Appendix B – Weight Calculation by Group provides the weight and center of gravity location for each item within the listed components. The components were organized to match the breakdown provided in *Principles of Yacht Design* for comparison purposes. There is no distinct navigation station on our sailboat, but the equipment expected to be found in this compartment is found in others. Ballast weight is used to adjust the total weight to match displacement.

Table 22- Summary of Weights by Group

Item	Weight (lbs)	LCG (in)	VCG (in)
Structure	1517.3	192.3	7.2
Forepeak	30.9	26.8	30.4
Fwd. Cabin	111.2	82.4	16.7
Saloon	55.4	165.3	20.9
Nav. Station	0	0	0
Galley	97.2	212.8	11.5
Head	95.1	261.5	14.8
Aft Cabin	70.2	252.9	19.5
Cockpit and Lazarette	16.1	333.6	9.9
Installations	538.4	274.3	9.5
Deck Equipment	206.3	135.4	41.5
Rig and Sails	397.1	172.1	127.4
Ballast	3689.8	185.8	-15.7
Payload	1442.2	209.9	2.1
Total	8267.3	195.0	3.4

The calculated VCG is 3.4 inches higher than the waterline estimate. In an effort to assess the effect that this new vertical center of gravity would have on boat performance, VPP runs were completed with the new data. STIX and Dellenbaugh Angle were also re-calculated. As shown in Table 23, the higher vertical center of gravity results in higher Dellenbaugh Angle and lower STIX values. Figure 104 compares their righting arm curves.

Table 23- Effect of VCG on Dellenbaugh Angle and STIX

VCG	Dellenbaugh Angle (Deg)	STIX
0”	22.2	27.6
3.4”	23.9	24.8

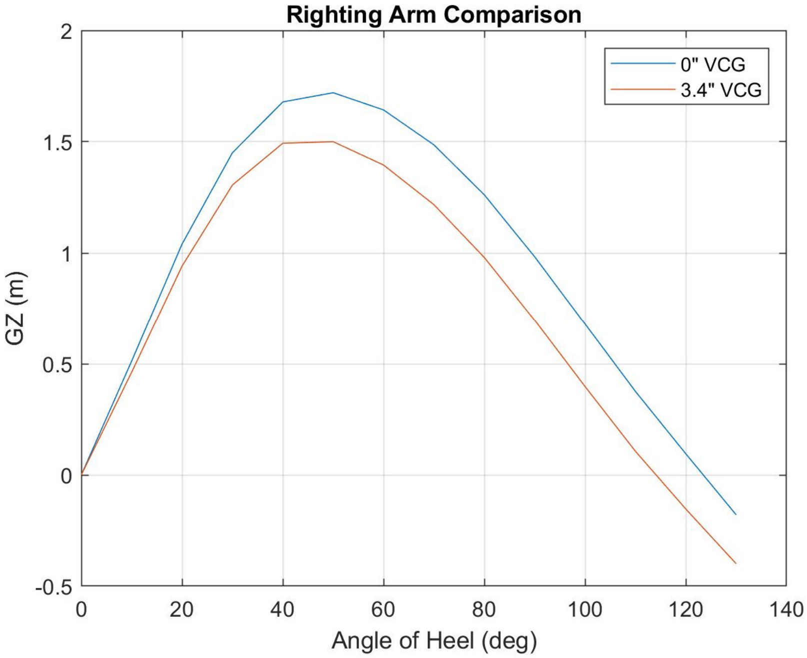


Figure 104- Effect of VCG on Boat's Righting Arm

The updated VPP also predicts more heel with the increase in vertical center of gravity, but only slightly more yaw (or lee) on a beam reach. These results are shown in Figure 105. Effects of the vertical center of gravity did not have a significant impact on boat speed. At some point, if performance differences are large enough, concept exploration and the MOGO should actually be rerun to correct the VCG location assumption, in this case with a value slightly above the DWL.

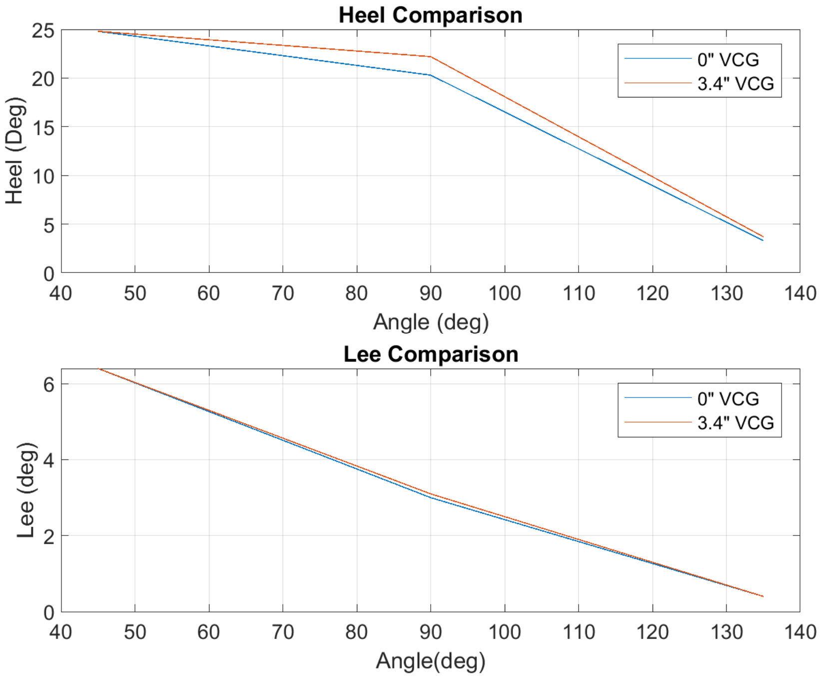


Figure 105 – VPP Heel and Lee Angle Comparison with Adjusted VCG

3.4.8 Validate Final Hullform

3.4.8.1 STIX Comparison

Seaworthiness is of crucial importance in this design. The owner in the case study requires that the boat must have a STIX rating above Category B in order to operate safely on offshore voyages. Therefore, the boat must have a STIX rating of at least twenty-three (23).

As can be seen in Table 24, both the Albemarle Sound Sharpie and the Egret achieve Category B STIX ratings. The rows of the table represent the STIX factors which are used to calculate the final STIX rating.

$$STIX = (7 + 2.25 * LBS\,) * (FDL * FBD * FKR * FIR * FDS * FWM * FDF)^{0.5} \qquad (100)$$

Table 24- STIX Comparison Between Representative Designs

	Albemarle Sound	**NC33**	**Egret**	**Hull 56**
LBS	9.1	9.1	9.5	8.4
FDL	0.9	0.9	0.9	1.0
FBD	1.0	1.1	1.0	1.0
FKR	1.1	0.7	1.1	1.1
FIR	1.0	0.8	1.0	1.2
FDS	0.9	0.8	0.8	0.9
FWM	1.0	1.0	1.0	1.0
FDF	1.0	1.0	1.0	1.0
STIX	27.6	17.4	25.5	27.5

The North Carolina Sharpie has the lowest STIX rating mostly due to the fact that the sailboat's righting arm curve is inferior to the Egret and Albemarle Sound Sharpie (Figure 106). Although the North Carolina Sharpie has good initial stability due to its larger beam, its angle of vanishing stability is approximately ninety-five degrees, which is significantly less than the Albemarle Sound and Egret's angle of vanishing stability which are both approximately one hundred and twenty-three degrees. The main reason for this disparity is the North Carolina's significantly lower sheer height.

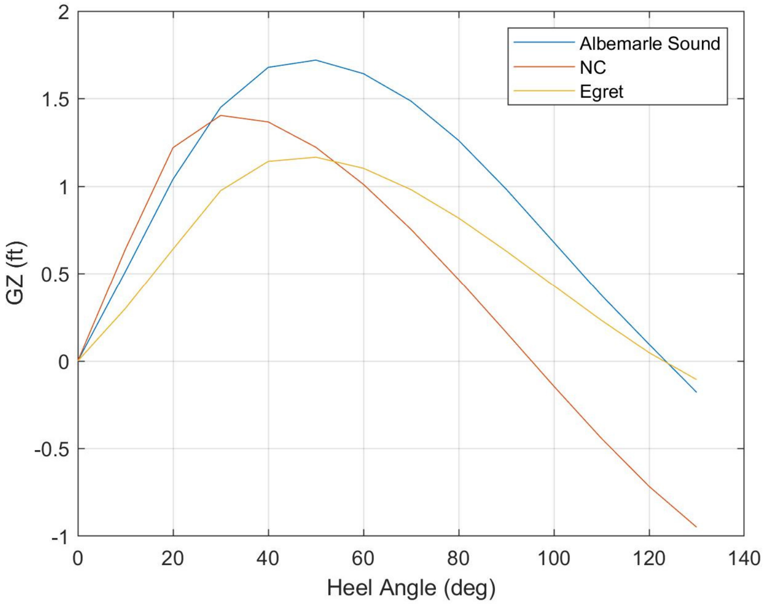


Figure 106- Righting Arm Comparison of Representative Designs

The Egret has the longest length along the waterline value, which leads to its high score in the Base Length Factor (LBS). However, the Egret ultimately loses to the Albemarle Sound Sharpie in the Dynamic Stability Factor (FDS) because it has significantly less area under the righting arm curve. The Albemarle Sound Sharpie and Egret have similarly shaped righting arm curves, but the Egret's curve has significantly less magnitude throughout their period of positive stability.

Based on the STIX rating governed by the International Standards Organization (ISO), the Albemarle Sound Sharpie presents as the sailboat with the greatest seaworthiness characteristics.

3.4.8.2 CFD Comparison

To provide a thorough speed comparison between the Albemarle Sound Sharpie and the other representative designs in the case study, we used three main operating conditions for the sailboat in terms of wind angle: close-hauled at a forty-five-degree angle from the sailboat's bow; beam reach at ninety degrees; and broad reach at one hundred and thirty-five degrees. Next, at each wind angle, we used three different wind speeds: 3.9, 9.7 and 15.6 knots. Each of these speeds and directions are inputs for the VPP and yielded nine different heel, lee angle, boat speed and driving force results. The boat in Rhino was then rotated to accurately reflect the VPP output and run for each condition in a CFD simulation using Orca3D and Simerics. Wind speed and direction were added to the Simerics interface to most accurately reflect operating conditions. As the boat speed is an input to the CFD simulation, calculated resistance is monitored. When the resistance value output from the CFD matches the calculated resistance / driving force from the VPP, the input speed is considered the boat speed at that particular operating condition.

Table 25- Speed Comparison of Representative Designs (Knots)

	Close Hauled	Beam Reach	Broad Reach	Overall Avg.
Albemarle Sound	4.63	6.30	5.50	5.48
North Carolina	4.80	6.20	5.47	5.49
Egret	4.50	6.03	5.37	5.30

The results of these simulations based on wind direction can be seen in Table 25. Considering all of the outlined operating conditions, the North Carolina has the highest average velocity by a very slight margin over the Albemarle Sound Sharpie. However, the Albemarle Sound Sharpie is faster in both beam reach and broad reach conditions.

3.4.8.3 Seakeeping Comparison

The last aspect of our case study's comparison between the Albemarle Sound Sharpie and the other representative designs is seakeeping. For this comparison, we again used the same heel and lee angles calculated by the VPP at the nine described operating conditions. Accordingly, the boat was rotated in Rhino, and offsets of the boat were generated. The PDStrip input file was set up to model an asymmetric hull with these offsets to include the speed of the boat at this condition, as calculated by CFD, as well as the wind speed and direction. Wave direction was adjusted to come from the same direction as the wind. From this point, PDStrip generated response amplitude operators (RAO's) which were then used to calculate significant values for pitch and roll, and both the Jonswap and Bretschneider Spectrums respectively. The Jonswap spectrum better representing in-shore conditions, while Bretschneider was used to better simulate offshore conditions. Results of the seakeeping analysis are provided in Table 26 through Table 29.

Table 26- Jonswap Significant Pitch Comparison (deg)

	Close Hauled	Beam Reach	Broad Reach	Average
Albemarle Sound	1.35	0.45	0.11	0.64
North Carolina	1.35	0.36	0.12	0.61
Egret	1.38	0.39	0.13	0.63

Table 27- Jonswap Significant Roll Comparison (deg)

	Close Hauled	Beam Reach	Broad Reach	Average
Albemarle Sound	1.44	0.73	0.16	0.78
North Carolina	1.29	1.04	0.18	0.83
Egret	1.40	0.94	0.16	0.84

Table 28- Bretschneider Significant Pitch Comparison (deg)

	Close Hauled	Beam Reach	Broad Reach	Average
Albemarle Sound	2.66	0.81	0.52	1.33
North Carolina	2.56	0.69	0.53	1.26
Egret	2.71	0.74	0.55	1.33

Table 29- Bretschneider Significant Roll Comparison (deg)

	Close Hauled	**Beam Reach**	**Broad Reach**	**Average**
Albemarle Sound	2.86	2.20	0.46	1.84
North Carolina	2.61	2.22	0.47	1.76
Egret	2.87	2.12	0.50	1.83

As the difference in the results between the Albemarle Sound Sharpie and the other representative designs were not significant enough to draw substantial conclusions, we compared the Albemarle Sound Sharpie with a more traditional and deeper keel design. In order to carry out this comparison, the Alden 25 was used, which is a centerboard sloop featuring a cast iron keel extending from the front of the bow until becoming flush with the transom (Figure 107).

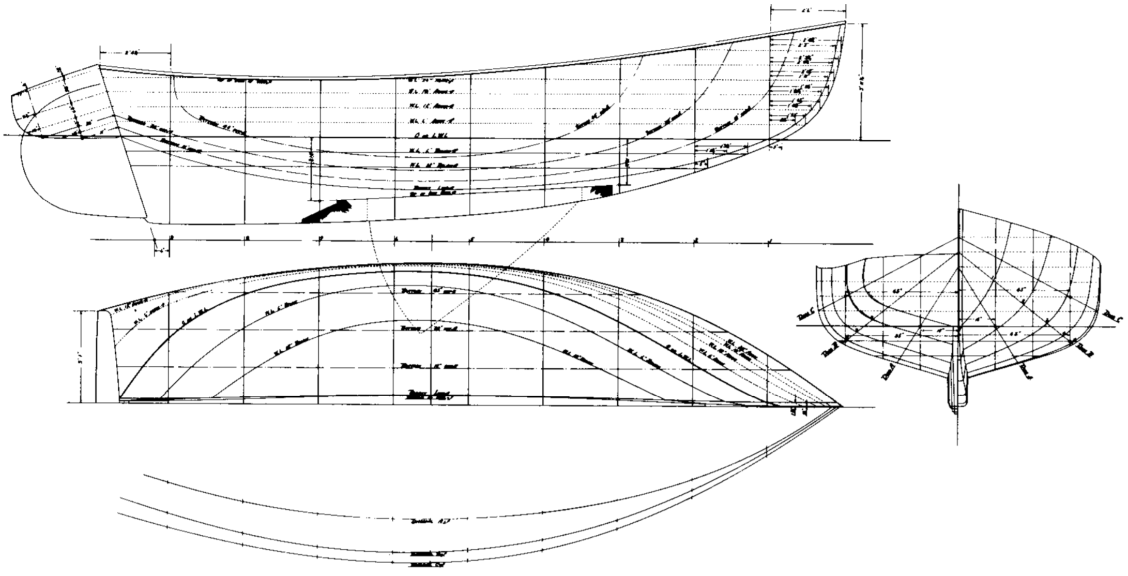
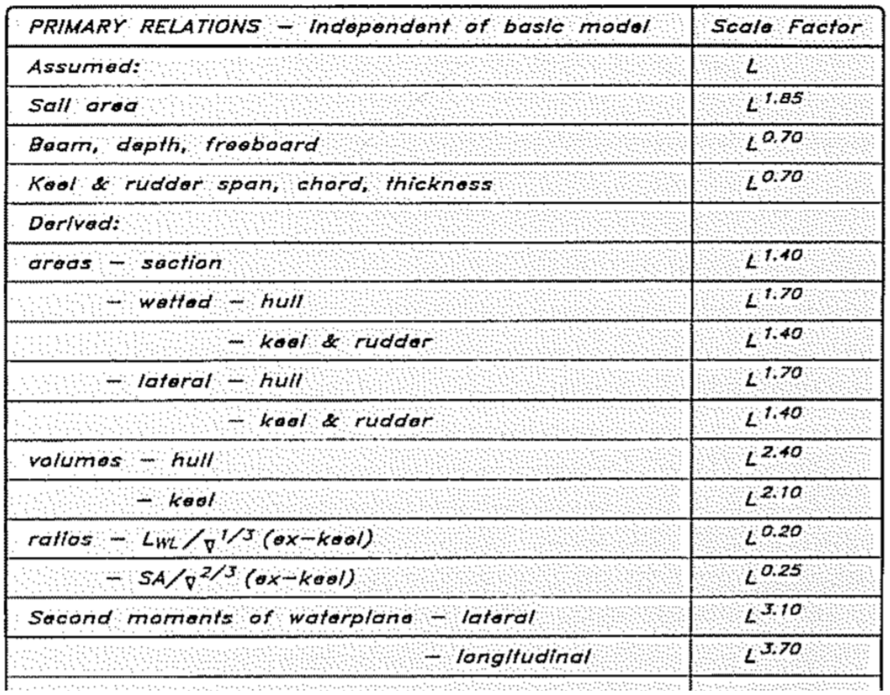


Figure 107- The Alden 25 (Alden)

For a fair comparison, the length of the Alden 25 was scaled to match the length of the Albemarle Sound Sharpie. The beam and depth were then scaled in accordance with guidance provided in *Principles of Yacht Design.* As seen in Figure 108, the variable "L", represents the amount that the length is scaled. In order to properly scale the beam and depth, the "L" is raised to the 0.70 power. This value represents how much the beam and depth should be either raised or lowered. For example, a boat extended from twenty feet to thirty feet has been extended 1.5 times its original length. In order to find beam and depth 1.5 would be raised to the 0.70 power, which would lead to dimensions approximately 1.33 times their original measurements.



PRIMARY RELATIONS — Independent of basic model	Scale Factor
Assumed:	L
Sail area	$L^{1.85}$
Beam, depth, freeboard	$L^{0.70}$
Keel & rudder span, chord, thickness	$L^{0.70}$
Derived:	
areas — section	$L^{1.40}$
— wetted — hull	$L^{1.70}$
— keel & rudder	$L^{1.40}$
— lateral — hull	$L^{1.70}$
— keel & rudder	$L^{1.40}$
volumes — hull	$L^{2.40}$
— keel	$L^{2.10}$
ratios — $L_{WL}/\nabla^{1/3}$ (ex-keel)	$L^{0.20}$
— $SA/\nabla^{2/3}$ (ex-keel)	$L^{0.25}$
Second moments of waterplane — lateral	$L^{3.10}$
— longitudinal	$L^{3.70}$

Figure 108- Scale Factors (Larsson & Eliasson, Principles of Yacht Design, 2000)

The boats were compared at the three representative conditions previously discussed using PDStrip and computing their significant values via the Jonswap and Bretschneider Spectrums. Discrepancies between significant values in pitch were minimal, while the values for roll are shown in Figure 109. The difference in these values is also slight, although it is worth noting that the Albemarle Sound has less of a significant roll value at both beam and broad reach than the Alden 25.

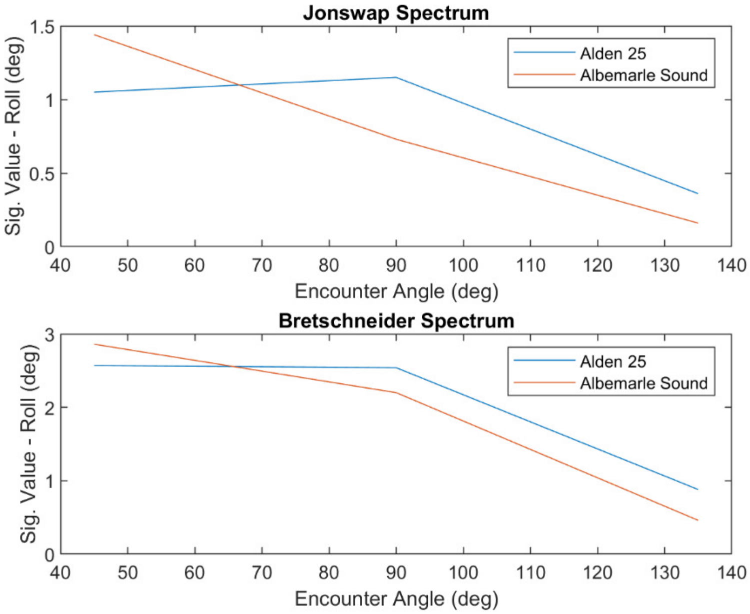


Figure 109- Significant Value Comparison

Although large differences in seakeeping performance were not found, the deeper keeled boat did not significantly outperform the sharpie designs with only a centerboard instead of a full keel. The Alden 25 has a draft almost two feet greater than the Albemarle Sound Sharpie.

3.5 Conclusions

The concept development process begins with the improved concept baseline design and focuses on expanding the details of the design and its components while reducing overall design risk using additional, more complete assessment tools.

The preliminary arrangements segment of the concept development process involved communication with the owner, as owner preference dictates the location and spacing allocations of compartments. The designer must be flexible in this regard, and present the owner with options which maximize internal space.

Following preliminary arrangements, structures, subdivision and topside design are completed. It is important for the designer to keep in mind the interdependence of this segment and the weight and center of gravity location. The boat's structural members should be implemented to maximize safety and specifically watertight integrity, without negatively impacting the weight and center of gravity location. Adverse effects to the boat's weight and center of gravity could negate execution of other critical MOPs.

Sail, rig, appendage and auxiliary propulsion possibilities were also researched in order to provide the owner with sufficient data with for a decision. The auxiliary propulsion segment was explored using a conservative resistance analysis technique and then refined completely within the concept development portion of the design process. While the sail, rig and appendage exploration had taken place during the concept exploration process, these segments were then refined within concept development based on industry standard, design requirements and owner preference.

From the outset of the design process, owner's requirements in the case study dictated that the final product be a Sharpie design sailboat which exhibited a draft of less than eighteen inches due to its projected operational environment (Albemarle Sound, NC), and a beam of less than 8.5 feet, so that it would be trailerable without the need for a permit. The boat needed to have overnight accommodations for four people while having both racing and cruising abilities. The sailboat was also required to have alternative propulsion. During the concept development portion of the design process, each of these criteria was met with adequate supporting research, information and owner approval in a manner which consistently lowered the overall design risk.

The additional assessment in concept development included the following:

- A seakeeping evaluation of the improved baseline design and other representative designs using PDStrip. A sailboat with a more traditional, deeper keel was evaluated in addition to the sharpies and did not perform significantly better than the improved concept baseline design or representative designs.
- An additional CFD analysis was completed in which designs were evaluated at specific points of sail, rather than a steady state environment. The CFD comparison revealed that the North Carolina and Albemarle Sound Sharpie averaged approximately 0.2 knots faster than the Egret. The North Carolina and Albemarle Sound Sharpie are separated by only 0.01 knots.

- The seaworthiness and stability analyses were updated with a slightly higher VCG. The North Carolina Sharpie still scored significantly less than both the Albemarle Sound Sharpie and the Egret in STIX. While the Albemarle Sound Sharpie finished with the highest STIX rating of 27.6, the Egret also received a score of 25.5 which is commensurate with a Category B rating for safe offshore use. The NC did not receive a Category B score and finished with an overall rating of 17.4.

Thomas Clapham, a popular boatbuilder in the 1800's and a strong proponent of the Sharpie design, would be supported in his claims that a boat of shallow draft could be made seaworthy for offshore sailing. The STIX ratings of the Egret and Albemarle Sound Sharpie support this. Additionally, the PDSTRIP results show no significant difference in seakeeping ability between the Sharpie design and a traditional deep keel cutter design.

Through this portion of the concept development, the objective of providing the owner with feasible options for arrangements and technologies specifically, have been achieved. This was accomplished by thoroughly researching various industry standard alternatives, while complying with the owner's initial requirements and considering interdependency of design segments. The weight and center of gravity segment of the concept development process, in particular, is dependent upon several other design segments including structures and subdivision. Structures and subdivision are addressed through this concept development process by using an industry standard approach for the applicable boatbuilding material. By addressing this design segment prior to establishing final weight and center of gravity location we ensure that the design will have appropriate dimensions and watertight integrity. After this module is complete and by integrating Orca3D weight report, the weight and center of gravity location is further established, helping to lower overall design risk. By incorporating a seakeeping analysis tool, the overall design risk is again lowered.

After analyzing the results of the case study, it is concluded that this new sailboat concept development process, as with the concept exploration process described in the earlier paper, produces an optimized design which can adequately suit the needs outlined by the owner. The owner plays a particularly important role in the concept development process, as component details are refined and established. This concept development provides a pathway for the designer to present multiple component possibilities for the owner's review, while also ensuring that the highest performing hullform is obtainable. Through this method, the overall design risk is significantly reduced.

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4 Conclusions and Future Work

This thesis describes the development of an improved sailboat design process with a specific focus on the tools used for evaluation purposes. The two manuscripts included in this thesis have demonstrated the effectiveness of applying a systems-engineering approach with elements of a traditional sailboat design process in order to create an optimized product. These tools and operational methods contained within provide a foundation for future sailboat design teams at Virginia Polytechnic Institute and State University (VT).

4.1 Conclusions

The new sailboat design process is comprised of the new concept exploration and concept development phases. The concept exploration process spans from the time a prospective owner presents their requirements and preferences for a product until an improved concept baseline design is generated. There are several important steps and subprocesses which must be properly executed prior to production of an improved baseline design. This was demonstrated in the case study, with the design segments leading up to the generation of the improved concept baseline design, the Albemarle Sound Sharpie.

During the concept exploration phase of the design process, the Albemarle Sound Sharpie boasted better stability characteristics than the other representative designs and the initial concept baseline design. The Albemarle Sound Sharpie also yielded similar results when compared using CFD for speed capabilities. The improved baseline design performed significantly better than the initial baseline design in this regard. The appearance of Albemarle Sound Sharpie was also much preferred by the owner and satisfied accommodation and size requirements.

The concept development process begins with the improved concept baseline design and focuses on expanding the details of the design and its components while reducing overall design risk. In order to reduce overall design risk, a seakeeping evaluation of the improved baseline design and other representative designs was completed. This evaluation did not produce any significant discrepancies in seakeeping capabilities. Furthermore, a sailboat with a more traditional, deeper keel was also evaluated, and did not perform better than the improved concept baseline design or representative designs which boasted significantly less depth.

In addition to the seakeeping study, additional CFD analysis was completed wherein designs were evaluated at specific points of sail, rather than a steady state environment. The CFD comparison revealed that the North Carolina and Albemarle Sound Sharpie were approximately 0.2 knots faster than the Egret, when averaging all of the simulations at representative conditions together. By the same comparison, the North Carolina and Albemarle Sound Sharpie are separated by approximately 0.01 knots, which is a relatively small amount.

Stability analysis for the case study did not require evolution from the concept exploration phase. The North Carolina Sharpie scored significantly less than both the Albemarle Sound Sharpie and the Egret in STIX. While the Albemarle Sound Sharpie finished with the highest stability rating of 27.6, the Egret also received a score of 25.5 which is commensurate with a Category B rating for safe offshore use. Meanwhile the NC did not receive a Category B score and finished with an overall rating of 17.4.

From the outset of the design process, owner's requirements in the case study dictated that the final product be a Sharpie design sailboat which exhibited a draft of less than eighteen inches due to its projected operational environment (Albemarle Sound, NC), and a beam of less than 8.5 feet, so that it would be trailerable without the need for a permit. The boat needed to have overnight accommodations for four people while having both racing and cruising abilities. The sailboat was also required to have alternative propulsion. During the concept development portion of the design process, each of these criteria was met with adequate supporting research, information and owner approval in a manner which consistently lowered the overall design risk. All appropriate characteristics of the Albemarle Sound Sharpie can be found in Appendix B – Weight Calculation by Group

Group 1 - Structure	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Hull side aft port fiberglass	2.39	355.83	19.15
Hull side aft stbd fiberglass	2.39	355.83	19.15
Hull sides fiberglass	60.81	160.45	11.34
Hull bottom fiberglass	39.76	187.21	-10.35
Hull transom fiberglass	4.22	373.66	20.96
Hull bottom cedar	264.13	187.21	-10.35
Hull sides cedar aft stbd	13.21	355.83	19.15
Hull sides cedar fwd	336.65	160.45	11.34
Hull sides cedar aft port	13.21	355.83	19.15
Hull transom douglas fir	28.03	373.66	20.96
hull transom epoxy	6.16	373.66	20.96
hull bottom epoxy	58.08	187.21	-10.35
Hull side aft port epoxy	3.49	355.83	19.15
Hull side aft stbd epoxy	3.49	355.83	19.15
Hull sides epoxy	88.83	160.45	11.34
WTB 9	78.92	260.50	9.50

WTB 1	56.00	48.25	18.42
WTB 4	93.18	130.50	10.12
Frame 2	11.89	78.25	2.15
Frame 3	15.40	103.75	-0.50
Frame 5	28.13	156.50	-2.33
Frame 6	28.30	182.50	-2.80
Cockpit combing stbd 4	0.02	366.32	36.66
Cockpit combing stbd 3	0.07	338.90	34.81
Cockpit combing stbd 2	0.04	299.96	32.75
Cockpit combing stbd 1	0.06	272.93	33.71
Cockpit combing port 1	0.06	272.93	33.71
Cockpit combing port 2	0.04	299.96	32.75
Cockpit combing port 3	0.07	338.90	34.81
Cockpit combing port 4	0.02	366.32	36.66
WTBHD 12	52.25	337.50	16.66
BHD 7 upper	15.34	208.50	37.82
BHD 11	20.98	311.74	10.23
BHD 10	27.97	285.75	9.15
Frame 8 stbd	3.70	233.75	0.61
BHD 7 stbd	29.78	208.50	7.55
BHD 7 port	25.41	208.50	6.13
Frame 8 port	10.58	233.75	7.40
Sheer Clamp port 1	4.25	63.38	35.88
Sheer Clamp port 2	3.64	91.00	32.61
Sheer Clamp port 3	3.79	117.00	30.09
Sheer Clamp port 4	3.65	143.50	28.06
Sheer Clamp port 5	3.65	169.50	26.52
Sheer Clamp port 6	3.65	195.50	25.53
Sheer Clamp port 7	3.57	221.25	25.09
Sheer Clamp port 8	3.79	247.00	25.18
Sheer Clamp port 9	3.58	273.25	25.79
Sheer Clamp port 10	3.71	298.72	26.91
Sheer Clamp port 11	3.66	324.47	28.51
Sheer Clamp port 12	5.73	359.68	31.71
Sheer Clamp stbd 12	5.73	359.68	31.71
Sheer Clamp stbd 11	3.66	324.47	28.51
Sheer Clamp stbd 10	3.71	298.72	26.91
Sheer Clamp stbd 9	3.58	273.25	25.79
Sheer Clamp stbd 8	3.79	247.00	25.18
Sheer Clamp stbd 7	3.57	221.25	25.09
Sheer Clamp stbd 6	3.65	195.50	25.53
Sheer Clamp stbd 5	3.65	169.50	26.52
Sheer Clamp stbd 4	3.65	143.50	28.06
Sheer Clamp stbd 3	3.79	117.00	30.09
Sheer Clamp stbd 2	3.64	91.00	32.61

Sheer Clamp stbd 1	4.25	63.38	35.88
chine log stbd 3	0.95	344.82	2.22
Group 1 Total	1517.27	192.32	7.23

Group 2 - Forepeak	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Sole	5.5125	44.81105	9.448824
Shelfs	6.615	32.00789	31.49608
Furler housing	15.435	16.00395	39.3701
Misc	3.3075	36.80907	21.65356
Group 2 Total	30.87	26.80661	30.44152

Group 3- Fwd. Cabin	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Fwd deckhouse side stbd	0.049	105.197	39.794
Fwd deckhouse side port	0.049	105.197	39.794
Fwd deckhouse back	0.089	130.000	38.525
fwd deckhouse transition 3	0.016	129.906	48.144
fwd deckhouse transition 6	0.019	104.789	48.560
fwd deckhouse transition 1	0.019	104.789	48.560
fwd deckhouse transition 4	0.017	79.128	48.565
surface	0.205	107.080	49.653
fwd deckhouse transition 2	0.004	78.888	41.571
Fwd deckhouse front	0.038	78.045	41.118
fwd deckhouse transition 5	0.004	78.888	41.571
Fwd berth front 1	0.029	117.309	-2.010
Fwd berth top 4	0.057	112.802	4.982
Fwd berth top 1	0.063	74.326	4.982
Fwd berth top 2	0.073	72.358	4.982
Fwd berth top 3	0.061	74.492	4.982
Fwd berth top 5	0.013	100.088	4.982
Fwd berth top 6	0.057	112.840	4.982
Fwd berth front 3	0.029	117.304	-2.011
Fwd berth sole	0.058	117.831	-9.041
Fwd berth front 2	0.023	103.997	-1.501
Chain Locker	22.046	76.179	0.000
Dresser	30.870	104.026	0.000
Overhead locker	19.845	66.256	42.520

Hanging locker	37.485	76.179	26.378
Group 3 Total	111.22	82.37	16.69

Group 4- Saloon	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Main Salon Sole fwd	0.16	169.06	-10.02
Main Salon Aft	0.24	235.60	-7.51
Main Salon Sole transition 2	0.02	210.62	-9.12
Main Salon Sole transition 1	0.02	210.62	-9.12
Bookshelves & lockers	30.00	171.24	35.43
Port cushions	14.00	153.64	3.94
Stbd cushions	11.00	162.28	3.94
Group 4 Total	55.44	165.32	20.88

Group 5- Navigation Station	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
-	-	-	-
Group 5 Total	0	0	0

Group 6- Galley	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Gally side	0.14	190.66	8.29
Galley top	0.07	190.71	26.63
Stove	48.51	220.21	18.50
Counter fronts and shelves	26.46	211.25	11.81
Taps & plumbing	22.05	198.45	-4.33
Group 6 Total	97.24	212.77	11.50

Group 7- Head	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Head seat	0.03	216.97	8.64
Head bulkhead upper	0.05	217.00	28.92
Head door	0.07	233.50	20.85
Head rear bulkhead 3	0.04	242.00	36.29
Head rear bulkhead 4	0.01	242.00	47.68
Head rear bulkhead 2	0.03	242.00	17.64
Head rear bulkhead 1	0.03	242.00	1.07
Head sole	0.02	233.15	-7.51
Head front	0.03	225.00	0.96
Counter tops	11.02	260.86	22.05
Counter fronts and shelves	13.23	257.98	5.91
Side Locker	15.43	256.70	38.19
WC and plumbing	33.07	268.55	3.15

Misc	22.05	257.02	17.72
Group 7 Total	95.11	261.47	14.83

Group 8- Aft Cabin	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
main deckhouse side stbd	0.13	212.47	36.31
main deckhouse side port	0.14	212.83	36.38
main deckhouse top	0.58	210.87	49.20
main deckhouse transition 1	0.04	209.28	48.11
main deckhouse transition 3	0.03	158.09	48.11
main deckhouse transiti5n 1	0.04	209.28	48.11
main deckhouse rear	0.14	259.94	37.91
main deckhouse fwd	0.09	157.00	37.35
main deckhouse transition 4	0.01	158.02	37.87
main deckhouse transition 2	0.01	158.02	37.87
Main berth stbd	0.24	168.14	1.99
Main berth port	0.24	167.92	1.62
Roof liner	15.44	212.21	39.37
Side liner	11.03	212.21	28.74
Cushions	20.00	279.11	5.12
Misc	22.05	281.99	12.99
Group 8 Total	70.18	252.88	19.48

Group 9- Cockpit Stow and Lazarette	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Cockpit seat/hatch stbd	0.15	297.26	26.67
Cockpit side 8	0.01	326.06	28.27
Cockpit side 7	0.00	302.12	27.48
Cockpit side 6	0.00	279.14	26.96
Cockpit side 5	0.08	303.02	18.67
Cockpit seat fwd	0.02	265.02	26.67
Cockpit sole	0.15	303.48	10.67
Cockpit front	0.04	269.04	18.67
Cockpit side 4	0.08	303.02	18.67
Cockpit seat/hatch port	0.15	297.26	26.67
Cockpit side 1	0.00	279.14	26.96
Cockpit side 1	0.00	302.12	27.48
Cockpit side 1	0.01	326.06	28.27
Misc	15.44	335.12	9.45
Group 9 Total	16.12	333.55	9.93

Group 10- Installations	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
motor well	0.68	352.00	17.84

Motor well fairing	0.03	361.36	31.67
Engine	75.00	257.34	-2.36
Shore power	13.23	283.27	-3.94
Batteries	110.25	289.35	-9.84
Wiring	82.69	259.26	15.75
Nav station instruments	10.00	199.09	39.37
Cool compressor & piping	14.33	201.65	-3.94
Heater & ducting	11.03	297.99	11.81
Rudder blade	28.67	362.01	-19.69
Rudder shaft	31.97	356.57	-2.76
Rudder sleeve	8.82	354.97	2.36
Rudder quadrant	3.31	354.65	17.32
Rudder linkage	8.82	330.32	15.75
Rudder wheel	4.41	313.04	59.06
Water tank & piping	41.90	183.09	-5.12
Holding tank & piping	12.13	265.67	7.87
Misc	81.16	266.31	0.39
Group 10 Total	538.42	274.30	9.53

Group 11- Deck Equipment	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Lazarette hatch	0.12	352.50	32.01
Hanging locker side port	0.06	139.94	9.81
Hanging locker side door	0.08	148.98	9.49
Chain plates	8.82	156.84	47.24
Bow roller	13.23	0.00	54.72
Bow anchor	25.00	-0.96	53.15
Anchor chain	30.00	67.86	0.00
Deckhouse windows	7.72	181.16	53.94
Deck ventilators	3.31	196.85	64.96
Misc	44.10	161.32	41.73
Stanchions	13.23	190.45	51.57
Pushpit	11.03	342.48	57.09
Lifelines	11.03	182.44	64.96
Sheer rail	30.87	184.05	0.00
Bollards	4.41	182.44	59.06
Mast turn blocks	3.31	157.80	64.96
Group 11 Totals	206.30	135.41	41.54

Group 12- Rig and Sails	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Mainsail	15.30	111.91	202.74
Mizzen sail	8.50	318.22	192.47
Main lower step 3	2.97	38.28	1.50

Main lower step 1	5.63	41.32	1.07
Main lower step 2	5.63	41.32	1.07
Main upper step 2	5.11	43.16	37.68
Main upper step 3	2.59	40.12	38.14
Main upper step 1	5.11	43.16	37.68
Mizzen lower step 5	4.52	280.32	-3.87
Mizzen lower step 3	10.71	273.24	-4.62
Mizzen lower step 2	4.75	280.57	-6.85
Mizzen lower step 4	10.71	273.24	-4.62
Mizzen lower step 1	3.94	264.50	-8.54
Mizzen mast	117.30	272.04	146.70
Main mast	130.60	44.75	163.40
Main wishbone	36.81	184.33	109.28
Mizzen wishbone	26.93	325.14	110.49
Group 12 Totals	397.11	172.07	127.43

Group 13- Ballast	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
keel5	11.38	91.00	-8.12
keel6	11.38	117.00	-10.48
keel7	11.38	143.00	-12.05
keel17	11.38	299.00	-4.55
keel2	9.52	36.88	-1.30
keel3	9.52	36.88	-1.30
keel16	10.71	273.24	-7.62
keel15	10.71	273.24	-7.62
keel9	11.38	195.00	-12.63
keel10	11.38	195.00	-12.63
keel13c	3.08	256.49	-9.29
Lead_5	464.76	169.52	-13.48
Lead_3	452.74	143.59	-12.76
Lead_12	292.36	246.85	-10.76
Lead_10	363.54	221.17	-12.41
Lead_8	383.06	195.46	-13.34
Lead_6	464.76	169.52	-13.48
Lead_4	452.74	143.59	-12.76
keel18	10.51	328.00	-0.23
keel13	8.13	247.19	-10.02
keel11	7.96	221.00	-11.70
keel12	7.96	221.00	-11.70
keel14	8.13	247.19	-10.02
Keel trunk	661.39	212.33	-30.00
Group 13 Totals	3689.82	185.82	-15.71

Group 14- Payload	Albemarle Sound Sharpie (lbs, inches)

Item	W	LCG	VCG
Crew	299.37	224.06	27.56
1/2 water	835.00	183.09	-5.91
1/2 fuel	167.50	310.48	-5.12
1/2 holding tank	83.50	265.67	7.87
Misc	56.86	285.08	-1.05
Group 14 Total	1442.23	209.94	2.12

Appendix C - Main Particulars of Albemarle Sound Sharpie.

1.1 Future Work

Work presented here has opened up new opportunities for future efforts and analyses built on the principles described in this thesis. These opportunities include the following:

1.1.1 Incorporate Seakeeping Analysis into Model Center

Seakeeping analysis, specifically Public Domain Strip (PDSTRIP) had been incorporated into Model Center as part of the VT naval ship design process's ship synthesis model. As a result, during concept exploration hundreds of hullforms were able to be evaluated using this tool. However, due to the Sharpie's unique dimensions, this tool was not able to be incorporated into the sailboat concept exploration model. As a result, seakeeping analysis was completed in the concept development portion of the design process by manually altering inputs for each boat based on the design condition. As a result, only a handful of designs were evaluated for their seakeeping attributes.

In the future, if a seakeeping analysis tool is able to be incorporated within Model Center, the hullform exploration segment of the concept exploration phase can include seakeeping analysis. Based on the limitations of the program, the seakeeping analysis tool may, or may not be PDSTRIP. Additional research on seakeeping analysis tools may lead to the discovery of a program which can be incorporated into Model Center and yield results in a time efficient manner. By being incorporated into Model Center, the seakeeping analysis tool will only provide more information for the designer and owner to consider as the design space is refined and progress towards a non-dominated design is made.

Appendix A – Sailboat Concept Exploration Model Python Script

```
try:
    import rhinoscriptsyntax as rs
except:
    print("Not RhinoScript Module")
import os, sys, shutil

def runSailboatAssist():
    #Change directory to working dir
    cwd = os.getcwd()
    os.chdir(cwd)

    #Clear rhino workspace
    rs.Command("-_SelAll")
    rs.Command("-_Delete")

    #Set units to meters
    rs.Command("-_DocumentProperties u u e enter enter enter")

    ##Run orca sailboat assistant
    #Define input vars
    params = readCSV("inputs.txt")
    print params

    deadrise = params['deadrise']
    flare = params['flare']
    forefoot = params['forefoot']
    LoD = params['LoD']
    posBeam = params['posBeam']
    posSheer = params['posSheer']
    posTc = params['posTc']
    rakeBow = params['rakeBow']
    rakeTrans = params['rakeTrans']
    sectTight = params['sectTight']
    hSheer = params['hSheer']
    beamTrans = params['beamTrans']
    B = params['B']
    Tc = params['Tc']
    dhBow = params['dhBow']
    dhTrans = params['dhTrans']
    hTrans = params['hTrans']
    keelName = cwd + "\\" + params['keelName']
```

```
    nRow = 6
    nCol = 7

    #Build command String
    buildHullCommand = """-OrcaCreateSailboat L {} B {}
                        T {} S {}
                        r {} a {}
                        D {} e {}
                        n {} h {}
                        i {} c {}
                        f {} Dea {}
                        Fl {} o {}
                        p {} u {}
                        m {} enter""".format(LoD, B, beamTrans, dhBow, dhTrans, hTrans,
Tc, rakeBow, rakeTrans, hSheer, posSheer, posBeam, posTc, deadrise, flare, sectTight, forefoot,
nRow, nCol)
    rs.Command(buildHullCommand, False)

    #Create Sections to find Cp
    rs.Command("-_SelAll")

    sectionsCommand = "-OrcaSections C S A 0,1,...,{} enter enter enter".format(LoD)
    rs.Command(sectionsCommand, False)

    #Run hydrostatics on canoe
    rs.Command("-_SelAll")
    canoeHydrostaticsCommand = """-OrcaHydrostatics M L S S 0.0 enter
                            R C H 0,10,...,180 enter
                            W canoeHydrostatics.csv enter"""
    rs.Command(canoeHydrostaticsCommand, False)

    # Check if there is a keel filename given
    if params['keelName']:
      # If there is run another hydrostatics with the keel
      print('Has Keel!')
      #Add in keel
      rs.Command("-Import {} enter".format(keelName))

      #Run hydrostatics on canoe + keel
      rs.Command("-_SelAll")
      fullHydrostaticsCommand = """-OrcaHydrostatics M L S S 0.0 enter
                            R C H 0,10,...,180 enter
                            W fullHydrostatics.csv enter"""
      rs.Command(fullHydrostaticsCommand, False)
    else:
```

```
        # If there is not just say that the full hydro = the canoe body hydro
        print('No Keel!')
        src = cwd + "\\" + "canoeHydrostatics.csv"
        dst = cwd + "\\" + "fullHydrostatics.csv"
        shutil.copyfile(src, dst)

    #Cleanup Orca Data Output
    cleanData("canoeHydrostatics.csv")
    cleanData("fullHydrostatics.csv")
    cleanGZ("fullHydrostatics.csv")

    print "Done!"


# Returns a new .csv with only the one main line of data from the hydrostatics.csv report
def cleanData(filename):
    os.chdir(os.path.dirname(os.path.realpath(__file__)))

    fnew = open("clean_" + filename, "w")
    with open(filename, "r") as f:
        for line in f:
            if "condition number" in line.lower():
                i = line.strip().split(",")
                i = str(i[2:]).replace("'", "")[1:-1]
                fnew.write(i + "\n")
            elif "condition" in line.lower() and "condition n" not in line.lower():
                i = line.strip().split(",")
                i = str(i[2:]).replace("'", "")[1:-1]
                fnew.write(i + "\n")
    fnew.close()

# Returns a new .csv that has only the GZ curve data in it
def cleanGZ(filename):
    os.chdir(os.path.dirname(os.path.realpath(__file__)))

    fnew = open("GZTable.csv", "w")
    buildGZ = False
    with open(filename, "r") as f:
        for line in f:
            if "heelangle" in line.lower():
                buildGZ = True
                continue
            if buildGZ:
                i = line.strip().split(",")
                i = str(i).replace("'", "")[1:-1]
                fnew.write(i + "\n")
```

```
    fnew.close()

# Reads input.txt file from makeInputs.m
def readCSV(filename):
    os.chdir(os.path.dirname(os.path.realpath(__file__)))

    # Build a table off all inputs from input.txt
    output = {}
    with open(filename, "r") as f:
        for line in f:
            ind = line.find(",")
            try:
                value = float(line[ind + 1:].strip())
            except:
                value = line[ind + 1:].strip()
            name = line[:ind - 1].strip()
            output[name] = value
    return output

# Just makes this script run (Python Stuff)
if __name__ == "__main__":
    # call the function defined above
    runSailboatAssist()
```

Appendix B – Weight Calculation by Group

Group 1 - Structure	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Hull side aft port fiberglass	2.39	355.83	19.15
Hull side aft stbd fiberglass	2.39	355.83	19.15
Hull sides fiberglass	60.81	160.45	11.34
Hull bottom fiberglass	39.76	187.21	-10.35
Hull transom fiberglass	4.22	373.66	20.96
Hull bottom cedar	264.13	187.21	-10.35
Hull sides cedar aft stbd	13.21	355.83	19.15
Hull sides cedar fwd	336.65	160.45	11.34
Hull sides cedar aft port	13.21	355.83	19.15
Hull transom douglas fir	28.03	373.66	20.96
hull transom epoxy	6.16	373.66	20.96
hull bottom epoxy	58.08	187.21	-10.35
Hull side aft port epoxy	3.49	355.83	19.15
Hull side aft stbd epoxy	3.49	355.83	19.15
Hull sides epoxy	88.83	160.45	11.34
WTB 9	78.92	260.50	9.50
WTB 1	56.00	48.25	18.42
WTB 4	93.18	130.50	10.12
Frame 2	11.89	78.25	2.15
Frame 3	15.40	103.75	-0.50
Frame 5	28.13	156.50	-2.33
Frame 6	28.30	182.50	-2.80
Cockpit combing stbd 4	0.02	366.32	36.66
Cockpit combing stbd 3	0.07	338.90	34.81
Cockpit combing stbd 2	0.04	299.96	32.75
Cockpit combing stbd 1	0.06	272.93	33.71
Cockpit combing port 1	0.06	272.93	33.71
Cockpit combing port 2	0.04	299.96	32.75
Cockpit combing port 3	0.07	338.90	34.81
Cockpit combing port 4	0.02	366.32	36.66
WTBHD 12	52.25	337.50	16.66
BHD 7 upper	15.34	208.50	37.82
BHD 11	20.98	311.74	10.23
BHD 10	27.97	285.75	9.15
Frame 8 stbd	3.70	233.75	0.61
BHD 7 stbd	29.78	208.50	7.55
BHD 7 port	25.41	208.50	6.13
Frame 8 port	10.58	233.75	7.40
Sheer Clamp port 1	4.25	63.38	35.88

Sheer Clamp port 2	3.64	91.00	32.61
Sheer Clamp port 3	3.79	117.00	30.09
Sheer Clamp port 4	3.65	143.50	28.06
Sheer Clamp port 5	3.65	169.50	26.52
Sheer Clamp port 6	3.65	195.50	25.53
Sheer Clamp port 7	3.57	221.25	25.09
Sheer Clamp port 8	3.79	247.00	25.18
Sheer Clamp port 9	3.58	273.25	25.79
Sheer Clamp port 10	3.71	298.72	26.91
Sheer Clamp port 11	3.66	324.47	28.51
Sheer Clamp port 12	5.73	359.68	31.71
Sheer Clamp stbd 12	5.73	359.68	31.71
Sheer Clamp stbd 11	3.66	324.47	28.51
Sheer Clamp stbd 10	3.71	298.72	26.91
Sheer Clamp stbd 9	3.58	273.25	25.79
Sheer Clamp stbd 8	3.79	247.00	25.18
Sheer Clamp stbd 7	3.57	221.25	25.09
Sheer Clamp stbd 6	3.65	195.50	25.53
Sheer Clamp stbd 5	3.65	169.50	26.52
Sheer Clamp stbd 4	3.65	143.50	28.06
Sheer Clamp stbd 3	3.79	117.00	30.09
Sheer Clamp stbd 2	3.64	91.00	32.61
Sheer Clamp stbd 1	4.25	63.38	35.88
chine log stbd 3	0.95	344.82	2.22
Group 1 Total	1517.27	192.32	7.23

Group 2 - Forepeak	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Sole	5.5125	44.81105	9.448824
Shelfs	6.615	32.00789	31.49608
Furler housing	15.435	16.00395	39.3701
Misc	3.3075	36.80907	21.65356
Group 2 Total	30.87	26.80661	30.44152

Group 3- Fwd. Cabin	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Fwd deckhouse side stbd	0.049	105.197	39.794
Fwd deckhouse side port	0.049	105.197	39.794
Fwd deckhouse back	0.089	130.000	38.525
fwd deckhouse transition 3	0.016	129.906	48.144
fwd deckhouse transition 6	0.019	104.789	48.560

fwd deckhouse transition 1	0.019	104.789	48.560
fwd deckhouse transition 4	0.017	79.128	48.565
surface	0.205	107.080	49.653
fwd deckhouse transition 2	0.004	78.888	41.571
Fwd deckhouse front	0.038	78.045	41.118
fwd deckhouse transition 5	0.004	78.888	41.571
Fwd berth front 1	0.029	117.309	-2.010
Fwd berth top 4	0.057	112.802	4.982
Fwd berth top 1	0.063	74.326	4.982
Fwd berth top 2	0.073	72.358	4.982
Fwd berth top 3	0.061	74.492	4.982
Fwd berth top 5	0.013	100.088	4.982
Fwd berth top 6	0.057	112.840	4.982
Fwd berth front 3	0.029	117.304	-2.011
Fwd berth sole	0.058	117.831	-9.041
Fwd berth front 2	0.023	103.997	-1.501
Chain Locker	22.046	76.179	0.000
Dresser	30.870	104.026	0.000
Overhead locker	19.845	66.256	42.520
Hanging locker	37.485	76.179	26.378
Group 3 Total	111.22	82.37	16.69

Group 4- Saloon	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Main Salon Sole fwd	0.16	169.06	-10.02
Main Salon Aft	0.24	235.60	-7.51
Main Salon Sole transition 2	0.02	210.62	-9.12
Main Salon Sole transition 1	0.02	210.62	-9.12
Bookshelves & lockers	30.00	171.24	35.43
Port cushions	14.00	153.64	3.94
Stbd cushions	11.00	162.28	3.94
Group 4 Total	55.44	165.32	20.88

Group 5- Navigation Station	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
-	-	-	-
Group 5 Total	0	0	0

Group 6- Galley	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG

Gally side	0.14	190.66	8.29
Galley top	0.07	190.71	26.63
Stove	48.51	220.21	18.50
Counter fronts and shelves	26.46	211.25	11.81
Taps & plumbing	22.05	198.45	-4.33
Group 6 Total	97.24	212.77	11.50

Group 7- Head	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Head seat	0.03	216.97	8.64
Head bulkhead upper	0.05	217.00	28.92
Head door	0.07	233.50	20.85
Head rear bulkhead 3	0.04	242.00	36.29
Head rear bulkhead 4	0.01	242.00	47.68
Head rear bulkhead 2	0.03	242.00	17.64
Head rear bulkhead 1	0.03	242.00	1.07
Head sole	0.02	233.15	-7.51
Head front	0.03	225.00	0.96
Counter tops	11.02	260.86	22.05
Counter fronts and shelves	13.23	257.98	5.91
Side Locker	15.43	256.70	38.19
WC and plumbing	33.07	268.55	3.15
Misc	22.05	257.02	17.72
Group 7 Total	95.11	261.47	14.83

Group 8- Aft Cabin	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
main deckhouse side stbd	0.13	212.47	36.31
main deckhouse side port	0.14	212.83	36.38
main deckhouse top	0.58	210.87	49.20
main deckhouse transition 1	0.04	209.28	48.11
main deckhouse transition 3	0.03	158.09	48.11
main deckhouse transiti5n 1	0.04	209.28	48.11
main deckhouse rear	0.14	259.94	37.91
main deckhouse fwd	0.09	157.00	37.35
main deckhouse transition 4	0.01	158.02	37.87
main deckhouse transition 2	0.01	158.02	37.87
Main berth stbd	0.24	168.14	1.99
Main berth port	0.24	167.92	1.62
Roof liner	15.44	212.21	39.37
Side liner	11.03	212.21	28.74
Cushions	20.00	279.11	5.12
Misc	22.05	281.99	12.99
Group 8 Total	70.18	252.88	19.48

Group 9- Cockpit Stow and Lazarette	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Cockpit seat/hatch stbd	0.15	297.26	26.67
Cockpit side 8	0.01	326.06	28.27
Cockpit side 7	0.00	302.12	27.48
Cockpit side 6	0.00	279.14	26.96
Cockpit side 5	0.08	303.02	18.67
Cockpit seat fwd	0.02	265.02	26.67
Cockpit sole	0.15	303.48	10.67
Cockpit front	0.04	269.04	18.67
Cockpit side 4	0.08	303.02	18.67
Cockpit seat/hatch port	0.15	297.26	26.67
Cockpit side 1	0.00	279.14	26.96
Cockpit side 1	0.00	302.12	27.48
Cockpit side 1	0.01	326.06	28.27
Misc	15.44	335.12	9.45
Group 9 Total	16.12	333.55	9.93

Group 10- Installations	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
motor well	0.68	352.00	17.84
Motor well fairing	0.03	361.36	31.67
Engine	75.00	257.34	-2.36
Shore power	13.23	283.27	-3.94
Batteries	110.25	289.35	-9.84
Wiring	82.69	259.26	15.75
Nav station instruments	10.00	199.09	39.37
Cool compressor & piping	14.33	201.65	-3.94
Heater & ducting	11.03	297.99	11.81
Rudder blade	28.67	362.01	-19.69
Rudder shaft	31.97	356.57	-2.76
Rudder sleeve	8.82	354.97	2.36
Rudder quadrant	3.31	354.65	17.32
Rudder linkage	8.82	330.32	15.75
Rudder wheel	4.41	313.04	59.06
Water tank & piping	41.90	183.09	-5.12
Holding tank & piping	12.13	265.67	7.87
Misc	81.16	266.31	0.39
Group 10 Total	538.42	274.30	9.53

Group 11- Deck Equipment	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Lazarette hatch	0.12	352.50	32.01

Hanging locker side port	0.06	139.94	9.81
Hanging locker side door	0.08	148.98	9.49
Chain plates	8.82	156.84	47.24
Bow roller	13.23	0.00	54.72
Bow anchor	25.00	-0.96	53.15
Anchor chain	30.00	67.86	0.00
Deckhouse windows	7.72	181.16	53.94
Deck ventilators	3.31	196.85	64.96
Misc	44.10	161.32	41.73
Stanchions	13.23	190.45	51.57
Pushpit	11.03	342.48	57.09
Lifelines	11.03	182.44	64.96
Sheer rail	30.87	184.05	0.00
Bollards	4.41	182.44	59.06
Mast turn blocks	3.31	157.80	64.96
Group 11 Totals	206.30	135.41	41.54

Group 12- Rig and Sails	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Mainsail	15.30	111.91	202.74
Mizzen sail	8.50	318.22	192.47
Main lower step 3	2.97	38.28	1.50
Main lower step 1	5.63	41.32	1.07
Main lower step 2	5.63	41.32	1.07
Main upper step 2	5.11	43.16	37.68
Main upper step 3	2.59	40.12	38.14
Main upper step 1	5.11	43.16	37.68
Mizzen lower step 5	4.52	280.32	-3.87
Mizzen lower step 3	10.71	273.24	-4.62
Mizzen lower step 2	4.75	280.57	-6.85
Mizzen lower step 4	10.71	273.24	-4.62
Mizzen lower step 1	3.94	264.50	-8.54
Mizzen mast	117.30	272.04	146.70
Main mast	130.60	44.75	163.40
Main wishbone	36.81	184.33	109.28
Mizzen wishbone	26.93	325.14	110.49
Group 12 Totals	397.11	172.07	127.43

Group 13- Ballast	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
keel5	11.38	91.00	-8.12
keel6	11.38	117.00	-10.48
keel7	11.38	143.00	-12.05
keel17	11.38	299.00	-4.55

keel2	9.52	36.88	-1.30
keel3	9.52	36.88	-1.30
keel16	10.71	273.24	-7.62
keel15	10.71	273.24	-7.62
keel9	11.38	195.00	-12.63
keel10	11.38	195.00	-12.63
keel13c	3.08	256.49	-9.29
Lead_5	464.76	169.52	-13.48
Lead_3	452.74	143.59	-12.76
Lead_12	292.36	246.85	-10.76
Lead_10	363.54	221.17	-12.41
Lead_8	383.06	195.46	-13.34
Lead_6	464.76	169.52	-13.48
Lead_4	452.74	143.59	-12.76
keel18	10.51	328.00	-0.23
keel13	8.13	247.19	-10.02
keel11	7.96	221.00	-11.70
keel12	7.96	221.00	-11.70
keel14	8.13	247.19	-10.02
Keel trunk	661.39	212.33	-30.00
Group 13 Totals	3689.82	185.82	-15.71

Group 14- Payload	Albemarle Sound Sharpie (lbs, inches)		
Item	W	LCG	VCG
Crew	299.37	224.06	27.56
1/2 water	835.00	183.09	-5.91
1/2 fuel	167.50	310.48	-5.12
1/2 holding tank	83.50	265.67	7.87
Misc	56.86	285.08	-1.05
Group 14 Total	1442.23	209.94	2.12

Appendix C - Main Particulars of Albemarle Sound Sharpie

$\mathbf{L_{OA}}$	32’2”	**E**	23’
$\mathbf{L_{WL}}$	27’3”	**SAF**	276 ft^2
$\mathbf{B_{MAX}}$	8’6”	**SAM**	153 ft^2
$\mathbf{B_{WL}}$	6’9”	**SA**	429 ft^2
$\mathbf{T_C}$	1’3”	$\mathbf{C_{KU}}$	2’6”
T	5’2”	$\mathbf{C_{KL}}$	0’10”
$\boldsymbol{\nabla_C}$	128.89 ft^3	$\mathbf{T_K}$	4’6”
$\mathbf{m_C}$	6,900 lb	$\mathbf{C_{RU}}$	1’3”
$\mathbf{SW_C}$	205.45 ft^2	$\mathbf{C_{RL}}$	1’0”
SW	239.75 ft^2	$\boldsymbol{\Lambda_K}$	25°
$\mathbf{A_W}$	149.6 ft^2	$\boldsymbol{\Lambda_R}$	25°
m	8,267.3 lb	$\mathbf{T_R}$	3’0”
Ballast	3689.8 lb	**LCB**	1’3”
I	14’6”	**LCF**	1’4”
J	27’11”	$\mathbf{C_P}$	0.52
P	9’9”	$\mathbf{C_{Mc}}$	0.52