Concept Design Optimization for OSVs Operating on the Flemish Pass Basin

by © Nicholas Boyd

A Thesis submitted to the School of Graduate Studies

in partial fulfillment of the requirements for the degree of

Master of Ocean and Naval Architectural Engineering

Faculty of Engineering and Applied Science

Memorial University of Newfoundland

May 2021

St. John's, Newfoundland and Labrador

Abstract

Significant oil discoveries in the Flemish Pass Basin off the coast of Newfoundland and Labrador have given rise to interest in studying the capabilities of offshore support vessels (OSVs) to provide logistics support to an operating offshore oil installation.

The Flemish Pass Basin represents a departure from current operational environments, characterized by longer distances, deeper waters, and a harsher metocean climate, which raises concerns as to the suitability of existing vessel design configurations.

As a result, this study has been performed into the optimization of the design of offshore support vessels, to develop a high-level optimized concept design which can support oil and gas development on the Flemish Pass Basin.

First, a high-level review of existing approaches to optimizing the design of OSVs and their logistics was examined. These approaches, though powerful for their individual optimization goals, failed to tie all the optimization requirements and logistics together into a holistic understanding of the most efficient design of hull and fleet to meet the operational requirements. The works presented in this paper show the process used to tie these approaches together into a complete optimization algorithm, to develop a fit for purpose fleet of OSVs.

To support this algorithm, a series of computer simulations were performed to develop sets of equations to describe the seakeeping, resistance, and stability performance of OSVs. These simulations were performed on 4 principal hull designs: axe bow, bulbous bow, vertical bow, and X bow, which are representative of many state-of-the-art vessels currently operating.

Using the derived equations, a computerized algorithm was developed which takes account of sea state probabilities and operational requirements to relate the vessel performance, downtime, scheduling, and design to minimize fleet annual cost. The algorithm automatically rejects any hull or fleet mix designs which cannot achieve the required delivery performance, and any which due to their excessive speed, weights, or lack of stability could not be operated.

A result of running this algorithm showed an optimized OSV design consisting of a fleet of 2 vessels based on the vertical bow hull form, with 100 m length, 25 m beam, and a 4 m draft. In general, the results showed a strong cost efficiency of using large, low displacement hulls and fewer voyages.

The sensitivity of the results was studied, and it was found that the algorithm output can significantly vary with little change on the input. Further, the algorithm has a margin of error which can impact which vessel is ultimately recommended, which indicates a need for more detailed studies beyond the concept design phase, to ensure that the optimum design has been selected.

Acknowledgements

I would like to thank Peter Van Diepen at Naviform Consulting and Research Ltd, Chris Tibbo at Maersk Supply Service, Tom Swift at Atlantic Towing, and Rick Strong at Husky Energy for their helpful input, and David Molyneux for his continuing input, support, advice, and encouragement.

I also wish to thank the Government of Newfoundland and Labrador who have provided the funding to support the OSV optimization project.

I would also like to thank my wonderful Fiancée Jillian Thistle for standing beside me, supporting me, and inspiring me to get through the challenges, long nights, and weekends preparing this work.

I must also acknowledge my parents who inspired and encouraged a curiosity about naval architecture in their young son, who told me I could do anything I set my mind to, and without whom I would not be half the man I am today.

And finally, to all the friends, teachers, and professors who have supported me on my way, and pushed me to perform at my best, I thank you.

Table of Contents

List of Figures

List of Tables

Nomenclature

AHTS	Anchor Handling Tug Supply
APR	Annual Percentage Rate
BM	Metacenter Height Above Center of Buoyancy
CFD	Computational Fluid Dynamics
FPSO	Floating Production Storage and Offloading Vessel
GM	Metacentric Height
IFO	Intermediate Fuel Oil
KB	Vertical Center of Buoyancy
KM	Metacenter Height Above Keel
OSV	Offshore Support Vessel
NL	Newfoundland and Labrador
USD	United States Dollar
VCG	Vertical Center of Gravity
VLCC	Very Large Crude Carrier

1. Chapter 1: Introduction

1.1. Overview of OSVs

Marine offshore installations rely on the use of Offshore Support Vessels (OSVs) as an essential link to ensure their continued operation in remote marine environments. These vessels perform a variety of roles, including re-supply, search and rescue, personnel transfer, and emergency standby. On the Grand Banks they perform the additional task of ice management. Without regular supply by OSV, offshore installations would be forced to stop operating. This results in significant economic loss of oil production and may also result in significant hazards to the safety of personnel on the offshore facilities.

As a result, it is necessary that a suitable fleet of OSVs are provided that can function in the operating environment. However, to maximize the potential profitability of offshore work, it is essential that this fleet is the optimal combination of performance at the minimal cost.

With the increasing demand for oil extraction, fields which were previously not viable, due to distance offshore or increased depth of water begin to enter consideration for viability. It is not known if existing OSV fleets / designs are up to the challenges imposed by these new developments.

One frontier of interest is the Flemish Pass Basin offshore from Newfoundland and Labrador. This field represents one of the most significant offshore oil discoveries in recent years but is further offshore and in deeper water than has previously ever been developed in Canada. Its environment sees severe weather, including strong winds, high waves, reduced visibility due to fog, and a significant number of iceberg incidents.

An overall study into OSV design has been supported by the Government of Newfoundland and Labrador, Canada to study these challenges and the design of OSVs, to provide an understanding of the requirements for vessels to operate in this new frontier.

1.2. Project Overview

This work fits into a larger scope of an overall project aimed at optimizing the design and operation of offshore support vessels for harsh environments.

This project was spurred by the announcement of significant oil discoveries in the Flemish pass basin in 2014, located in waters 10 times deeper and 1.4 times further offshore than fields previously developed in NL. It was recognized that existing vessels were not designed for these environments and no studies had been done to determine the impact of this environment on vessels in general, which the research project was suggested to address.

The research project consists of two overall themes, OSV design tools, and modeling offshore support vessels within an operating system.

Theme 1 is focused around studying the relationships between vessel tasks and performance, rather than the traditional method of performing vessel design by adapting a similar vessel design.

The near-term objectives are to develop mathematical models to relate vessel design, performance in waves, resistance and powering, and cost, with the goal of developing a preliminary design suitable for operation on the Flemish Pass Basin. The overall goal of this work is to develop a tool suitable for designing vessels for any operating environment based on these mathematical models.

Longer term goals include developing detailed models for specific ship performance requirements and improving upon the developed tools to produce an overall design tool which may be suitable for commercialization.

Theme 2 is focused on modeling the overall performance of a fleet of OSVs. This work would be focused on studying the mix of potential vessels within a fleet which result in the maximum efficiency and lowest cost overall for all vessels.

The near-term objectives of this work are to develop models of the Flemish pass basin operations, including the environmental effects, port operations, level of downtime due to weather, and the effect of unreliable helicopter operations. The overall goal is to develop a complete model of vessel operations offshore NL, which can be benchmarked against existing operations to determine where efficiencies exist.

Longer term goals of this work would be to model, in detail, areas of deficiency in the operational model to maximize efficiencies, as well as to expand the model to include other vessel types and possibly other operating scenarios such as exploration activities.

The major theme of this thesis is primarily focused on developing the models and high-level tools for generating optimal concept design vessels as presented in Theme 1. However, some aspects of Theme 2 have been incorporated in this work, such as consideration for the specific operating environment and required scheduling to achieve the required overall fleet performance. The resulting analysis will also recommend the number of vessels to be procured of a certain size, which can achieve the required overall performance of the fleet mix of vessels, rather than just a recommended best overall vessel for the Flemish Pass Basin.

1.3. Objective of Thesis

This thesis is aimed at determining the optimal concept design hull form for OSVs to operate on the Flemish Pass Basin, to support an overall goal of developing the optimal OSV for this environment and the development of OSV design tools.

To support this goal this work included performing studies into the seakeeping and resistance performance of OSV hulls. These studies were aimed at developing sets of empirical formulas for hull performance which can be used to mathematically determine the optimal mix of vessels to support the Flemish Pass Basin oil discovery.

In order to accomplish this objective, the following requirements are met:

- Develop a test program to measure the vessel response to operating environments using potential flow computer code and 3d models.
- Develop a test program to model the predicted resistance and propulsion of vessels using existing software packages.

- Develop a set of empirical formulas which describe the relationship between principal particulars and operating environment / conditions, to model the data collected from the test programs for each primary generic hull type.
- Develop and run an optimization algorithm to determine the optimal combination of vessel seakeeping performance and cost to operate, to ensure that the offshore field achieves the required delivery rate, while ensuring the combination of vessels is the lowest cost.
- Develop a design tool based on this algorithm to suggest an ideal vessel design for any operating environment.
- Propose an optimal concept design OSV which achieves the optimal performance, which can then be carried forward into additional studies to further refine the design and maximize cost savings.

1.4. Organization of Thesis

This thesis is organized into several chapters detailing each of the required steps to achieve the objectives of this thesis.

Chapter 1 introduces the OSV Design Optimization project sponsored by the Government of Newfoundland and provides a broader context to the works of this thesis.

Chapter 2 provides a summary review of existing papers which have investigated the design optimization of OSVs and indicates how these are relevant to or support the work of this thesis. It also introduces the main theories used in this thesis including those which are used as the underlying theories of the software packages used in the computer simulations.

Chapter 3 describes the mathematical modelling of motions, ship resistance, and stability performed to support this thesis.

Chapter 4 describes the work done to optimize the concept design for an OSV to operate on the Flemish Pass Basin.

Chapter 5 summarizes the conclusions of the research and provides recommendations for future work, to develop detailed designs for OSVs for the Flemish Pass Basin.

2. Chapter 2: Background

2.1. Literature Review

Reviewing existing papers on this topic reveals two major overarching themes related to the overall goals of the project, one where the focus is on the parametric design of OSVs and the other on managing the logistics of OSV fleet operation. As this work is aimed at performing a parametric design of an OSV in order to fit into an overall OSV logistical system, it is key to understand each of these themes in detail.

2.1.1. Parametric Design of OSVs

Recent studies of OSV design have been aimed at displacing the traditional approach to design of OSVs in which a design is selected by comparing the vessel against an existing design of similar function, by use of parameter based design methods to choose the ideal design for the intended function.

One aspect of conceptual ship design is the complexity of the problem due to the nature of ships as an integrated system. An approach to handling this complexity by decomposition and encapsulation has been explored [1]. Decomposition refers to simplifying systems to their basic parts and considering them independently. Encapsulation then refers to capturing all the decomposed parts bounding the information to one function, constraining all aspects in the design into one purpose.

Once the problem of how to simplify the complexity of vessel design has been resolved, it is then necessary to examine how to approach the design of the simplified attribute. A study into this design has been presented [2] which offers a new approach to design, referred to as system based design. In the traditional design method, the designer is essentially “locked-in” to their initial design choice. The systems design method which instead defines the ship tasks and functional requirements then selects various parameters to define the hull which are varied to achieve the goals, this parameter-based design is then optimized and evaluated. Further studies into design under a system-based design scenario include the use of concept exploration models, [3] in which design parameters are varied to generate candidate designs which are evaluated using simulations to help determine the best design.

When using the system-based design method it is necessary to derive relationships between the functions and the corresponding design requirements. A more traditional approach to this would be the use of parametric design based on studies of existing vessel data. In one study [4] they define the parametric model of an OSV by fitting relationships to the data on existing OSVs to define hull parameters suitable for optimization studies, including relationships between block coefficient and size, Froude number against block coefficient, breadth over depth vs length, and deadweight against hull volume for a block coefficient of 1.0. It then groups similar designs into clusters of similar design types which can be used to quickly filter and select the best set of hull designs for further study when selecting an optimal design. Further parametric studies [5] include defining the curves of a ship hull parametrically using B-splines, allowing for a complete hull design to be derived due to the variation of these parameters, these variations can then be compared against the overall performance requirements of the design.

As these previous studies have been focused on optimization to a specific design case and were very intensive in the required amount of information, additional studies have been done in an attempt to quantify the relationships between design parameters and resulting performance to allow for quicker optimization of design parameters. One study [6] was aimed at optimizing the design of OSVs to minimize the required power per tonne of cargo transported, making use of computational fluid dynamics and varying hull shapes to determine the overall effect on each shape parameter on the resulting performance. Similar studies have been performed [7] using simple computational fluid dynamics (CFD) tools and precise hull shapes, to determine the effect of these shapes on the calculated hydrodynamic drag coefficients and then used these tools to estimate the optimal hull shape for minimum drag of a given hull.

Studies have also been done to try and optimize the performance for seakeeping [8]. In this study the parametric curves of the ship hull are varied as part of an optimization process to determine the most efficient hull design parameters for seakeeping performance. Further studies have tried to quantify the relationship between overall seakeeping performance and principal hull design parameters [9]. In this study the principal dimensions and key hull parameters were varied to generate conceptual hull designs, and then determine the resulting response amplitude operators for each of the hull designs, which allowed for direct comparison on the effect of changing each hull parameter. This study however was limited to RAOs and therefore could not quantify the specific effect of hull design in a random seaway overall, without much more analysis.

2.1.2. OSV Logistics

Due to the harsh nature of the operating environment for OSVs, fleets often experience significant downtime when waiting for a weather window to perform their operations. As this results in significant wasted resources, there is a growing demand for ways in which to organize the logistics of OSVs to maximize utility and minimize wasted time for fleets in operation.

A review of studies into the logistics of OSV scheduling and fleet sizing reveals the importance of discrete event simulations [10] and their use in simulating the full regular operating cycle of OSVs. This simulation allows for breaking down vessel schedules into discrete activities that must be performed and can have times assigned to these activities individually, to simulate an ideal schedule developed using stochastic models of the effects of weather on scheduling.

Another study of particular interest looked at potential areas of the design of OSVs which could be optimized to improve the logistics of the offshore operations [11]. This paper principally examined the roles performed by OSVs on the Norwegian continental shelf, and the capability of these vessels. The authors identified the principal drivers which can be varied in tradeoffs to develop the overall best fleet mix. The objective was to trade off vessel sailing capability (seakeeping etc.) and the carrying capacity. It describes a way of optimizing the fleet by first determining the required capacity to service the field, and then determining which vessels make up the best fleet to achieve this capacity with maximum efficiency, considering the impacts of speed and size of the vessels on their overall performance.

The next step was to develop a means to mathematically solve the optimized fleet schedule [12] thereby solving the optimization challenge noted in the previous paper. This was done first by developing a mathematical model to describe the number of vessels available, the number of facilities to service, the schedule of depots, and costs. This model can then be mathematically optimized to develop the lowest cost of chartering vessels. It then captures a method of expanding the model to take account of the stochastic nature of sea states, which would impact the delivery schedule. It does this by including "slack" in the overall schedule of the vessel to account for time waiting on weather. As the effect of a given sea state on operations is known, and the weather data is well known, this allows for modeling the amount of slack needed in the schedule to account for downtime and create an optimized schedule which accounts for weather.

2.1.3. Commentary

The works described in the literature review above represent a good pedigree for advancing the optimization of design of offshore supply vessels, however, gaps are noted in these studies which this work seeks to fill.

First of all, notably the works on parametric design of offshore supply vessels are focused in primarily on optimizing only around the individual performance of a vessel, either for resistance or seakeeping. They make use of algorithms to develop concepts and evolve designs which suit the needs of their specific objective. This approach is effective when designing a one-off vessel but fails to consider the needs of vessels to meet multiple performance objectives simultaneously, as part of a larger operating framework of a vessel fleet.

Further, many of these optimization approaches are designed around the idea of having a concept design in mind and making parametric changes to improve performance. This approach works well when designing for a familiar environment and role, but when moving into new fields the design assumptions may no longer prove valid, and a higher-level approach to optimization is required to select a base concept before hull optimization can occur.

As well, many of these optimization approaches optimize around a fixed performance objective, which fails to account for the stochastic nature of the marine environment and operations. Though the vessel may be optimized for one design state, it is not optimized for others, and the resulting performance trade-offs need to be considered holistically as part of a probabilistic model.

The approaches to the managing of OSV logistics typically face the opposite issue to that of parametric optimization; through the use of discrete event simulations and probabilistic models, they can design optimal scheduling requirements for a large fleet framework, fully addressing the competing optimization requirements of each sea condition. These approaches can even identify required performance changes to improve the overall fleet performance. However, these studies do not go far enough as to examine how the vessel design could be optimized to better suit the scheduling and operational requirements.

The goal of this work is to bridge the gaps in these approaches by bringing them together in a larger optimization approach. This is done by creating a model to describe the performance of a fleet of vessels in the stochastic marine environment. The model uses the seakeeping performance based on probability of occurrence to determine the effects on vessel downtime, which in turn is used in a discrete event model of the fleet operation to determine the required vessel operating speeds. The model makes no assumptions about the optimal hull design and considers all options for fleet make-up. Each vessel's design and performance are brought back to their effect on the total annualized cost to operate the fleet, to propose a high-level concept fleet which is the optimal combination of schedule, seakeeping performance, and resistance. This results in the lowest total cost to operate, fit for purpose for the specific environment and operational objectives.

2.2. Theory

The works described herein rely on specific theories to allow for the computer prediction and analysis of information. In order to understand these works it is first necessary to be familiarized with several key theories, these include the way in which ships move, their resistance and propulsion, mathematical optimization for ship designs, fluid potential flow theory, and the design of experiments methods.

2.2.1. Ship Motions

To understand the goals of this work it is essential to understand that ships are dynamic systems, which are unconstrained and are free to move in 6 degrees of freedom. Vessels respond to the passage of waves in complex ways combining motions in multiple directions simultaneously. The principal motions of a vessel are described as follows:

Surge: Horizontal Translation along the X-Axis

Sway: Horizontal Translation along the Y-Axis

Heave: Vertical Translation along the Z-Axis

Roll: Rotation about the X-Axis

Pitch: Rotation about the Y-Axis

Yaw: Rotation about the Z-Axis

The orientation of the axis' and positive directions are defined in the figure below.

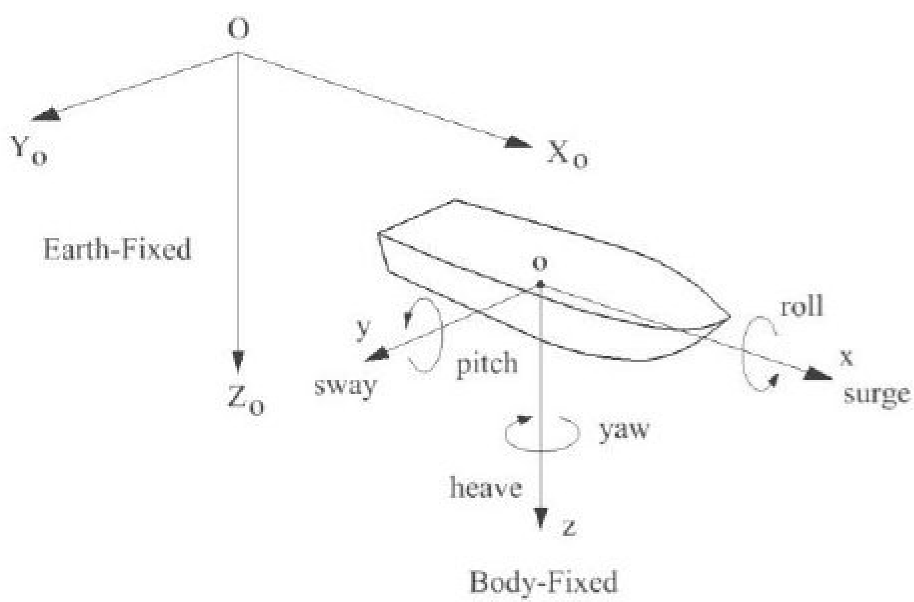


Figure 2-1 - Ship Axis' and positive directions [13]

These motions significantly complicate the tasks which a vessel must undertake offshore when compared with the same operation on land. For OSVs a critical design case for the motion of the vessel is during lifting operations offshore for cargo or personnel transfer.

Whereas on land these operations would be performed considering only the lift speed, as they are being lifting from the stationary ground, offshore the lift operations are likely performed by transferring an object between two dynamically moving objects.

Due to the design limitation for containers and personnel transfer operations, there are limits on the motion response of vessels which are tolerable to perform these operations. For personnel transfers, the limits are based on maximum relative vertical velocity of the transfer device and the deck to prevent personal injury.

A key part of vessel design is therefore selection of a vessel design which will perform in its given marine environment within an acceptable limit.

This, however, is complicated by the fact that sea states, and therefore the resulting motions of the vessel are stochastic processes which cannot be easily explicitly predicted. Instead, probabilistic terms are used to define the sea and vessel response, with a suitable probability of exceedance being used to define the operational limits of a vessel.

The probabilistic sea state model is typically defined using two terms, Significant Wave Height and Spectral Peak Period.

The significant wave height is used as a term to describe the general state of wave heights in a given random sea surface. This wave height corresponds to 4 times the 0^{th} moment of wave amplitude in a data set, or if measuring observed waves corresponds to the average height of the highest 1/3 of all waves. In this way, a probabilistic model of all wave heights can be approximated around the significant wave height based on deviations.

Wave heights in a given sea state roughly follow a Rayleigh distribution for probability of wave height.

The spectral peak period describes the highest energy wave period in a spectrum defining the energy of all periods for the wave components of a sea state, and therefore best approximates the period which corresponds to the overall sea. This also allows a probabilistic determination of all periods based on a specific spectral shape. There are theoretical spectral shapes suggested for a variety of different operating environments, the discussion of which is outside the scope of this research.

2.2.2. Resistance

Although a ship must be designed to operate within certain performance requirements offshore, there are additional considerations in ship design, related to the commercial viability of a ship design.

Of special concern is the resistance and propulsion requirements of a vessel. In operation, one of the most significant costs which can be easily influenced is the cost of fuel for the ship. The fuel required is directly related to the overall resistance of the vessel, as the selected engines and propellers can be chosen to maximize their efficiency, such that the only driver on cost is the amount of power required to move the vessel at a given speed.

Resistance refers to the required force needed to push a vessel along at a specific speed due to the combination of two major water resistance factors, frictional resistance and wave making resistance.

The first component of a ship's resistance is its frictional resistance. This is generated due to the boundary between the vessel hull and the water, where the water particles are stationary. As the vessel moves, it forces these stationary water particles to slide past other particles generating resistance to this motion.

Another component of ship resistance is the wave making resistance. This results from the fact that as a ship moves through water, a wave is generated radiating the energy outward from the vessel. The faster the vessel is moving the larger this generated wave is. As the vessel moves, it is constantly losing energy to these generated waves, increasing the resistance.

When these two components are combined, the vessel overall resistance can be determined allowing for determination of the required thrust of the vessel. At low speeds, the frictional resistance dominates the total required power but at higher speeds, wave making resistance is dominant.

As for a given size of vessel, the cost of build and crewing requirements are usually very similar, the focus for efficiency of a hull design is minimizing the resistance and therefore reducing the required fuel costs.

2.2.3. Potential Flow and Wave Response

The most detailed way to fully define the behavior of fluids is to make use of the Navier-Stokes equations shown below.

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+\rho g_x \text{ (Equation 2.1)}$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+\rho g_y \text{ (Equation 2.2)}$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho g_z \text{ (Equation 2.3)}$$

These equations however, are very difficult and time consuming to solve requiring numerical methods, and so it is desirable to use another theory to simplify this problem. The first simplification we can do is to treat water as an incompressible fluid. In doing so, we develop an understanding that continuity of the control volume is maintained. Because of this, all fluid in must be equal to the fluid out of a control volume which allows us to define the mathematical formulation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \text{ (Equation 2.4)}$$

When we also include assumptions that fluid particles are inviscid and irrotational, things simplify greatly. These effects can be ignored as viscous effects are limited to within a thin layer adjacent to bodies known as the boundary layer, when the overall goal is to define the velocity field everywhere within a fluid.

To define this velocity field, we make use of a potential function Φ(x,y,z,t) which is a function that satisfies the laws of fluid mechanics, such as conservation of mass and conservation of momentum. The unique feature of this potential function is that at any given point and time, the velocity of the fluid can be determined by:

$$v(x,y,z,t) = \nabla \Phi \text{ (Equation 2.5)}$$

This is useful for assessing loads on objects, as this velocity potential can then be used to calculate pressures at a given point using the Bernoulli equations as follows:

$$\rho\left[\frac{\partial}{\partial t}\nabla\varphi + \frac{1}{2}(\nabla\varphi)^2\right] + \nabla p + \rho g \nabla z = 0 \text{ (Equation 2.6)}$$

Integrating these pressures gives the overall hydrostatic force acting on a body.

By substituting potential into the continuity equation, we derive the following partial differential equation, known as the Laplace equation:

$$\frac{\partial^2\Phi}{\partial x^2} + \frac{\partial^2\Phi}{\partial y^2} + \frac{\partial^2\Phi}{\partial z^2} = 0 \text{ (Equation 2.7)}$$

This potential function is defined as the combination of 3 components when looking to determine the surface pressures on a body, Froude-Krylov, Diffraction, and Radiation, each with their own velocity potential. This is needed to take account of the effects which occur when a wave interacts with a body.

Froude-Krylov is also known as the incident wave potential which defines a velocity potential of the wave which is interacting with the body.

This Froude-Krylov force is derived by solving the Laplace equation with boundary conditions of a seabed and a dynamic free surface which varies with time. In doing so, the velocity potential of a wave is defined as follows:

$$\Phi(\mathrm{x},\mathrm{y},\mathrm{z},\mathrm{t}) = \frac{\zeta_a g}{\omega}\frac{\cosh\left(k(h+z)\right)}{\cosh(kh)}\sin(kx\cos\mu + ky\sin\mu - \omega t) \text{ (Equation 2.8)}$$

Where k is the wave number which satisfies the following dispersion relationship:

$$\omega^2 = kg\tanh(kh) \text{ (Equation 2.9)}$$

Radiation refers to the velocity potential of waves which are generated by the movement of a floating object.

To properly understand the radiation forces it is necessary to first understand the equation of motion for a floating object. This equation takes the following form, with a separate equation each describing the 6 degrees of freedom:

$$(m + a)\frac{\partial^2 z}{\partial t^2} + b\frac{\partial z}{\partial t} + cz = F_w \text{ (Equation 2.10)}$$

In this equation, terms of note are the a and b terms, refer to added mass and hydrodynamic damping, respectively. Collectively they are the hydrodynamic coefficients and are a specific property of the vessel under consideration. These hydrodynamic coefficients can be determined either experimentally by oscillating the model and measuring the required force to perform this oscillation, or through the use of known formulas.

Diffraction is the potential that arises due to the reflection of waves backwards from the object when the wave interacts with it.

To solve the radiation and diffraction potentials it is advantageous to solve the problem in the frequency domain. In doing so the velocity potential due to radiation and diffraction are defined as when using a source and sink model of flow:

$$\Phi(\mathrm{x}) = \frac{1}{4\pi}\int_{S_b} G(x, x_s, U, \omega_e)\sigma(x_s)dS \text{ (Equation 2.11)}$$

Xs is the source location on the ship's hull

G(x,xs) is the green function describing flow at x caused by a source of unit strength at xs

σ(xs) is the strength of the source at xs

To solve this the boundary conditions are defined as follows:

For the determining radiation potential, the hull boundary condition is

$$\frac{\partial \Phi_r(x)}{\partial n} = i\omega_e n_r \text{ (Equation 2.12)}$$

For diffraction potential the hull boundary condition is

$$\frac{\partial \Phi_D(x)}{\partial n} = -\frac{\partial \Phi_1(x)}{\partial n} \text{ (Equation 2.13)}$$

In this work, potential flow theory is used in the computer program which derives the motions of the vessel being studied. This code works by solving the wave, radiation, and diffraction potentials for a large variety of frequencies and wave heights as well as numerically determining the hydrodynamic coefficients.

This is done by discretizing the hull into a series of flat panels which allows for solving these equations at each point.

The program then generates a random sea based on a specified sea state and calculates the hydrodynamic forces by integrating the potentials corresponding to the encountered wave height and frequency over each panel and time stepping the vessel motions in response.

The vessel motion statistics are then read from this resulting time stepping to determine RMS response of the vessel and average zero crossing period.

2.2.4. Design of Experiments – Uniform Design and Analysis of Variance

The design of experiments method is a technique used to define how an experiment can be planned to maximize the information generated while minimizing the required number of runs.

This in particular, allows for measuring of interactions between factors, which would be difficult by traditional experimental methods such as varying a single variable.

This method allows multiple variables to be varied per test run so that the combined effects of variables on each other can be determined.

There are a variety of techniques used in the design of experiments in order to properly model the behavior, one of which is the Uniform Design Method.

The Uniform design method is a space-filling design and is the preferred experiment design for computer-based predictions. This is because the Uniform design spaces the design points out such that for a given number of runs, the entire experiment space is as spread out as possible. This allows for the best possible model of error free processes such as computer simulations, as the goal is to fully replace the simulation of the entire design space with an overall model which is accurate in the conditions under consideration.

Uniform design is also a powerful tool when performing experiments which are very time consuming, such as CFD and ship motion calculations, as it allows for an ideal experiment design based on a predetermined number of test runs, allowing for the selection of an experiment design that falls within time and budget constraints, while maximizing the availability of information.

The technique used for analyzing the results of a design of experiments method is referred to as the analysis of variance method.

First, the method determines an estimate of the experimental error, based on all the values to determine how uncertain the data is.

This method then compares the average difference in output between sets of tests where a particular variable is at a high value and when it is at a low value, giving the average effect of that variable on the results. This variance is then checked based on its probability of occurring due to the experimental error.

The person analyzing the data then reviews these values and chooses the variables which are used to build the model based on their probability, this is usually based on a 10 or 5 per cent probability of the variance occurring due to experimental noise. The model then fits a regression based on the selected variables. The residual is then compared to the experimental error to ensure that there is not a significant lack of fit for the model.

When reviewing computer-based simulations, this process is also used, but the way it is interpreted is different. In a computer simulation, there is no experimental error, and all the inputs are influencers on the model. Instead in this case, the use of ANOVA can help determine which of the variables significantly impact the resulting model, and which have a very small effect. When this is done, the model can therefore be greatly reduced to only the key variables which impact the results in a meaningful way, simplifying the regression equation while still providing a good fitting model.

2.2.5. Ship Optimization

The design of ships is a complex design case combining many competing requirements and multiple engineering disciplines. As a result, in order to determine the best choice of design it is necessary to do some form of optimization in the design.

The main focus of hull design requirements is designing a vessel that for a given capacity, offers the best sea keeping performance at the lowest operating cost. However, often the vessel which offers the best sea keeping performance may not have the lowest cost due to higher resistance, and vice versa that a very efficient hull may not have very good performance in waves.

A typical method for optimization for selecting a design would be to use mathematical optimization, in which case a desired result is chosen, and the effect of various parameters on this is shown. The optimization is then choosing the combination of parameters which results in a maximum or minimum.

When multiple objectives are required simultaneously the maxima and minima approach breaks down and instead it is necessary to make use of multi-objective optimization processes. The decision of which is the optimal must be with the decision maker to define based on the relative importance of each objective, or overall limitations on the acceptable levels of each outcome. In such a way the tradeoff between changes which result in performance increases or decreases on each objective can be quantified, and impossible sets outright eliminated.

2.3. Hull Form Study

As part of selecting the hulls to study for this research the existing hull forms in operation for various ship types were considered, including their development history, to understand their properties and what advantages they would offer for a vessel built using this hull form. The hull forms chosen include vertical bow hull form PSVs, X-bow type OSVs, axe bow crew boats, and high-speed bulbous bow OSVs. These were chosen as each represent a similar role to what would be expected for a high-speed Flemish Pass Basin OSV, and each may bring features that could perform best overall in the role.

2.3.1. Vertical Bow Hulls

Offshore oil development began shortly after World War Two and by 1947 development off the coast of Louisiana beyond the sight of land had begun. The first types of ship used to supply these fields were fishing vessels, small freighters, and amphibious assault vessels. However, these vessels had limitations which made them not ideal for this support role. To alleviate this the first purpose built OSV was completed in 1956, the MV Ebb Tide. It featured a traditional bow, forward wheelhouse, and a long clear deck space aft. [14]

Figure 2-2 - MV Ebb Tide

What followed was a long history of improvements inspired by this original design.

The vertical bow style OSV design is similar to the traditional style bow design exhibited by the MV Ebb Tide, featuring no bulb and a flared hull above the waterline. The vertical bow below the waterline creates a blockier hull design, similar to the conventional bow shape, allowing for higher transport capacities on board, consistent with bulk cargo vessels, while the flared design is consistent with the approach of traditional bow vessels to reduce bow plunging in rough seas and to deflect sea spray away from the bridge.

These vessel designs have been popular for use in the NL offshore to date, including vessels such as the Maersk Detector and Atlantic Hawk.

This is considered to be the "base case" OSV design and will be investigated as an option for an optimized design.

2.3.2. Bulbous Bow Hulls

Bulbous bows are a descendant of the Ram bow design used historically by warships. It was observed that these ram designs contributed to reduced resistance of the vessel at speed.

By designing vessels which used a bulbous bow a higher speed could be achieved using the same power resulting in a more efficient vessel.

This discovery can be credited to several people, but of particular interest is William Froude, who originated the towing tank process for estimating ship resistance still used to this day. In his studies he observed that the ram bow designed vessels exhibited lower resistance at higher speeds, which was a surprise due to the increased frictional area. [15]

This work inspired David Taylor, a Naval Captain in the US who developed a bulbous forefoot concept which was used on the battleship Delaware to great effect. [15]

Seeing the benefits of this bulbous bow concept, it was quickly adopted by merchant shipping, with the first use on the passenger ship Malalo in 1925, and later it was used in 1926 for the German passenger vessels Bremen and Europa, which captured the blue ribband for the fastest Atlantic ocean crossings. [15]

Figure 2-3 - Bremen under construction showing its bulbous bow design [16]

This success proved the quality of the concept and it received widespread adoption in both the military and civilian fleets and remains a popular choice for efficient shipping to this day.

Among OSV fleets, the use of bulbous bows is similar to any other vessel type. Due to the nature of OSVs typically operating on a predictable route, at consistent speeds, a bulbous bow design can be easily optimized which improves the efficiency of the hull by reducing resistance.

Bulbous bow designs are used in the NL offshore including vessels such as the Maersk Clipper and Atlantic Merlin.

This concept will be investigated as part of this study to determine if the bulb design concept will offer a more efficient tradeoff for an optimized vessel.

2.3.3. Axe Bow Hulls

The sea axe concept was developed as the result of studies into improving high speed vessel performance in the 1990's involving a collaboration between Damen and Technical University Delft.

The first of these studies introduced that of the Enlarged Ship Concept, which took conventional designs and proposed a design concept of a lengthened hull, the effect of which was to reduce wave slam events allowing the vessel to operate at higher speeds in rougher sea states. This concept revealed a few key findings that improved high speed ship performance:

- Less bow flare is favourable
- V-shaped hulls are favourable
- Deeper bow than keel is favourable
- High bows are favourable for reserve buoyancy

An optimization of these key findings into a hull gave way to the sea axe design concept. A large model test program was performed at Marin to refine the concept and in 2006 the concept had been advanced to a level that commercialization could begin. [17]

Figure 2-4 - Sea Axe Test Model

Sea Axe designs are currently not in service in the NL offshore, but have found use in the high-speed crew boats in use in the Gulf of Mexico.

Due to a potential need for high speed operations in rough seas, this concept may be a good fit for an optimized design for an OSV operating on the Flemish pass basin. However, the requirements for this environment would require a design which is much larger than the typical vessel of this design.

2.3.4. X-Bow Hulls

The X-bow design is a recent hull development, originating is 2003-2004 and revealed in 2005 with the contract to build the first of concept vessel *Bourbon Orca.*

The concept originated from Ulstein for use in offshore support vessels operating in harsh environments such as the North Sea. The vessel has a slender waterline and a recurve bow flair to improve handling and reduce pitching motions in large seas.

Extensive model testing showed increased seakeeping performance, crew comfort, and reduced resistance compared to conventional vessel designs, which has proven to be true in operation. [18]

Figure 2-5 - X-Bow Vessel

X-bow concepts are currently used in the offshore supply industry, particularly in the North Sea. Some X-bow design vessels have been used in roles in the NL offshore related to offshore construction and diving support, however none of the typical operating OSVs are equipped with this design.

The X bow concept has been selected for investigation as the sea-keeping performance may reduce vessel downtime in the harsh NL offshore and therefore offer a more efficient fleet, which can operate at lower speed due to reduced time spent waiting on a weather window.

3. Chapter 3: Mathematical Modelling

3.1. Motions Prediction

3.1.1. Introduction

In order to support the optimization work, it was necessary to develop sets of equations to quantify the relationship between the vessel hull design and its resulting seakeeping performance.

It was decided to make use of design of experiments methods to develop a series of computer simulations measuring the seakeeping performance calculated by the 3d potential flow software known as ShipMo3D; to which a model could be fitted to in order to develop empirical equations relating hull design and seakeeping performance.

3.1.2. Design of Experiments Method

When preparing to use design of experiments methods, the first challenge was to determine the set of variables which should be considered in the model. In my previous paper on seakeeping performance [19] the effects of several hull parameters were shown to affect seakeeping performance including midbody length, bow shape, stern shape, and bottom shape, however these were qualitative studies and were not suitable for use in describing a formulaic relationship between design and behavior. They did, however, give an idea of what the model variables should be. In doing so it was chosen that the test program should consist of 4 separate test sets capturing 4 parent hull shapes which are varied in principal particulars.

These 4 parent hulls consisted of conventional hull shapes with both vertical stems and bulbous bows, as well as more recent hull designs including the wave piercing axe bow shape and the recurved x-bow shape. OSVs with each of these hull types are shown in the figure below [20] [21] [22] [23]:

Figure 3-1 - OSV Hull Types

These generic hull shapes would be scaled in principal particulars based on the required test case to generate a hull of the general shape, with the required particulars.

As part of seakeeping analysis, it was also necessary to define the sea state which the vessel responded to, for the purposes of this concept level model, it was chosen to define the sea state using a Bretschneider spectrum, which is a good model for unlimited fetch seas in a general case where a more specific spectrum is not defined (such as the JONSWAP spectrum for the limited fetch North Sea). This is ideal [24] for a concept level optimization to be used on a global basis. This spectrum allows for defining the sea state using only two parameters, the significant wave height, and the peak energy period. The directionality of the sea was ignored as it is considered that wherever possible the OSV would weathervane, with bow into the waves, during lifting operations to increase safety to crews. Although in practice weathervaning is not always possible, it is considered that these occurrences are not frequent enough to significantly impact the overall performance of the optimized OSV concept level design, and was therefore neglected due to the additional complexity in probabilistic modeling of the ship due to the sea direction relative to the vessel. This would introduce significant additional complications in modeling the vessel behavior, additional scope of testing, with little to no net result on outcome.

As a result, the total program was determined as consisting of 4 separate test sets, each with 5 factors: Length, Beam, Draft, Significant Wave Height, and Peak Period.

Next, to define the required number of test cases it is necessary to determine the required number of "levels" for each factor, this defines the number of possible states each variable could be set at in a test case. As this model incorporates sea states, it was thought likely that higher order effects may be significant. Based on this it was determined that the program of tests should be suitable for building a model up to the 4th order. This resulted in a required model with 5 levels as the number of levels required is defined as n = order + 1.

As a result, the required program of tests is 4 separate test sets, each with 5 factors, each of which having 5 levels, this poses a problem when considered using traditional modeling approaches or even using factorial models in the design of experiments method as the required number of test runs would be 4 x 5^5 = 12500 test cases.

It is instead necessary to make use of a reduced program, which in this case was chosen as a Uniform design due to its limited runs, robust design, and space filling nature. The set of runs for a uniform design were chosen based on the optimal uniform design tables [25]. The design of the test program should be chosen such that the design results in the minimum discrepancy while still minimizing runs. In this case it was chosen that the design test program should have a discrepancy of less than 0.025 indicating that the model is very well spread out across the design space. Using the tables for a 5 factor 5 level experiment with a discrepancy less than 0.025 results in a required test program of 35 runs for each general hull for a total program size of 140 test cases. The required design is summarized in the table below:

Table 3-1 – Motion Test Program Uniform Design

Run Number	Factor Variable Level				
	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
1	3	1	4	5	4
2	2	5	2	4	1
3	3	1	2	3	2
4	5	2	5	2	4
5	3	3	3	3	3
6	5	3	2	2	1
7	2	3	3	5	4
8	4	1	4	1	2
9	1	5	1	3	4
10	5	4	2	1	3
11	4	1	2	4	5
12	5	5	4	5	2
13	5	2	4	3	5
14	3	5	5	1	4
15	1	2	2	1	4
16	4	5	3	2	5
17	3	4	2	5	5
18	5	1	3	4	1
19	1	3	1	5	2
20	4	2	1	5	3
21	1	2	3	4	2
22	2	2	5	5	1
23	1	4	5	4	5
24	4	4	5	3	1
25	4	3	5	4	3
26	1	4	4	2	1
27	2	3	4	1	5
28	2	5	4	3	3
29	4	5	1	2	2
30	3	2	1	1	1
31	2	4	3	1	2
32	1	1	5	2	3
33	5	4	1	4	4
34	3	3	3	3	3
35	2	1	1	2	5

Each test set was repeated 4 times for each of the parent hull forms.

Once the overall design was chosen it was necessary to assign values to each of the test levels, this was done by considering the general range that most OSVs would be operating at to allow the data to be a good fit to a model of the circumstances of normal OSVs.

Factor 1 was chosen to represent the vessel length between perpendiculars and was assigned based on the size of typical OSVs, the lowest level being assigned as 60m which corresponds to small PSVs and crew boats operating in the Gulf of Mexico, all the way up to 120m which corresponds to the largest OSVs operating on the North Sea.

Factor 2 was chosen as the breadth and was varied between 15m and 25m, representing the overall beam of most vessels in the range of lengths specified for factor 1.

Factor 3 was assigned as the draft of the vessel and was varied between 4m and 8m, representing small shallow water OSVs all the way up to deep seagoing high-capacity vessels.

Factor 4 was considered as the significant wave height which was assigned as 2m all the way up to 6m, this corresponds to typical offshore wave heights in normal cases, [26] which the vessel is to be optimized around (extreme return period sea states e.g.,100 year were not considered).

Factor 5 was considered as the peak period defined from 4 sec to 12 sec, which represents the peak periods that would typically correspond to each wave height specified. [26]

With the test program design complete in accordance with a Uniform design, it is then necessary to prepare and run the predictions. The resulting test cases generated are summarized in the table below:

Table 3-2 - Motion Prediction Test Cases

Run Number	Length (m)	Beam (m)	Draft (m)	Hs (m)	Tp (s)
1	90	15	7	6	10
2	75	25	5	5	4
3	90	15	5	4	6
4	120	17.5	8	3	10
5	90	20	6	4	8
6	120	20	5	3	4
7	75	20	6	6	10
8	105	15	7	2	6
9	60	25	4	4	10
10	120	22.5	5	2	8
11	105	15	5	5	12
12	120	25	7	6	6
13	120	17.5	7	4	12
14	90	25	8	2	10
15	60	17.5	5	2	10
16	105	25	6	3	12
17	90	22.5	5	6	12
18	120	15	6	5	4
19	60	20	4	6	6
20	105	17.5	4	6	8
21	60	17.5	6	5	6
22	75	17.5	8	6	4
23	60	22.5	8	5	12
24	105	22.5	8	4	4
25	105	20	8	5	8
26	60	22.5	7	3	4
27	75	20	7	2	12
28	75	25	7	4	8
29	105	25	4	3	6
30	90	17.5	4	2	4
31	75	22.5	6	2	6
32	60	15	8	3	8
33	120	22.5	4	5	10
34	90	20	6	4	8
35	75	15	4	3	12

3.1.3. Test Run Characterization

The test program was run in ShipMo3D, which solves potential flow for panelized hull forms to determine seakeeping performance. To support this test hull models had to be developed.

The test hulls were developed by creating 4 parent hulls in the 3D hull model program DelftShip, each representing a general shape which corresponds roughly to existing OSV designs. The 4 parent hulls are shown below:

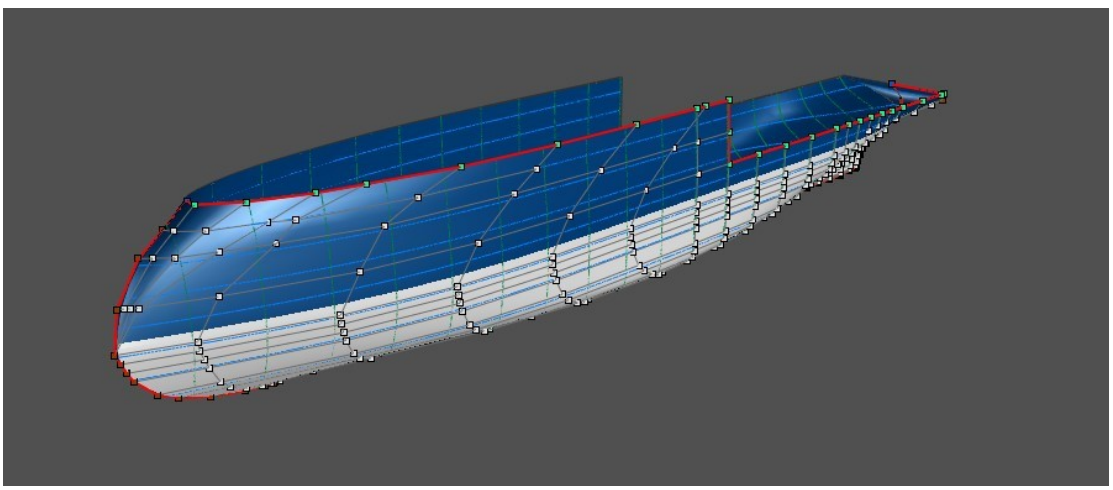


Figure 3-2 - X Bow Parent Hull

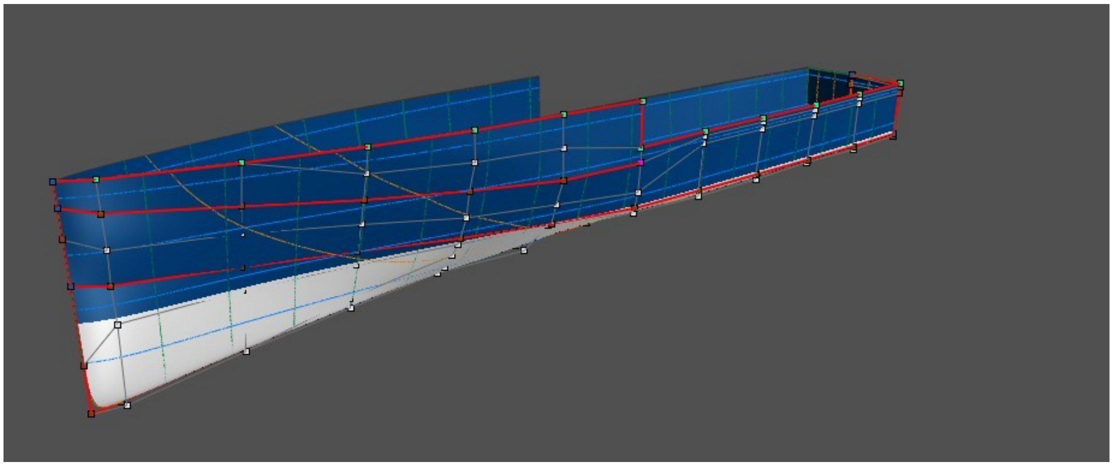


Figure 3-3 - Axe Bow Parent Hull

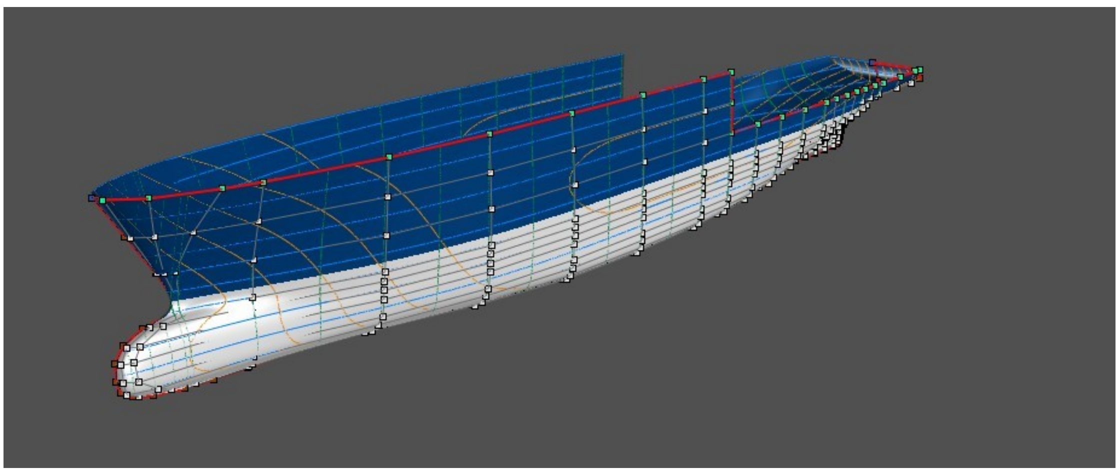


Figure 3-4 - Bulbous Bow Parent Hull

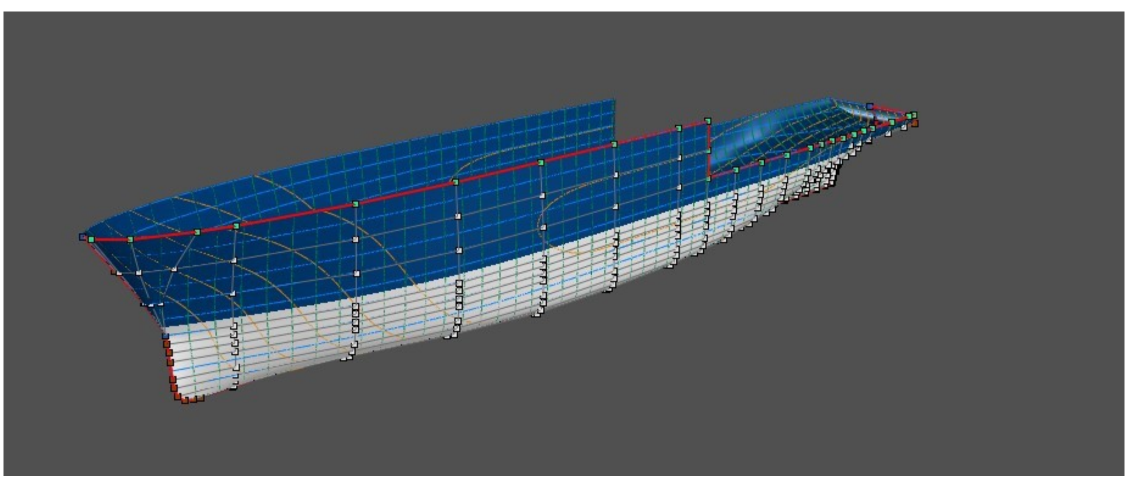


Figure 3-5 - Vertical Bow Parent Hull

Each parent hull has the same length, beam and draft, the non-dimensional properties of each of the parent hulls are described in the table below for relative comparison:

Table 3-3 - Parent Hull Non-Dimensional Parameters

Hull Type	**Block Coefficient**	**Midship Coefficient**	**Prismatic Coefficient**	**Vertical Prismatic Coefficient**	**Waterplane Coefficient**
X Bow	0.632	0.972	0.65	0.764	0.827
Axe Bow	0.180	0.244	0.738	0.275	0.655
Bulbous Bow	0.627	0.972	0.645	0.785	0.799
Vertical Bow	0.646	0.972	0.664	0.774	0.835

Note that apart from the Axe bow design which has a deep V chined hull form, the base concepts use identical parallel midbody and stern sections to ensure that only the relative effects of the bow shape influence the resulting performance. The axe bow design is more of a total overhaul of hull design by comparison and the effect of its overall performance relative to the others can be compared.

The dimensions of the control points defining the hull shape were then scaled proportionally to match the required dimensions of each test case in the program.

Each model was then exported as a CFD mesh which was suitable for use in ShipMo3D. A total 140 unique hull form models were developed for this program.

To build this model, each hull had to be individually run through the ShipMo3D workflow to define the overall vessel performance.

This workflow begins on the project definition page shown below:

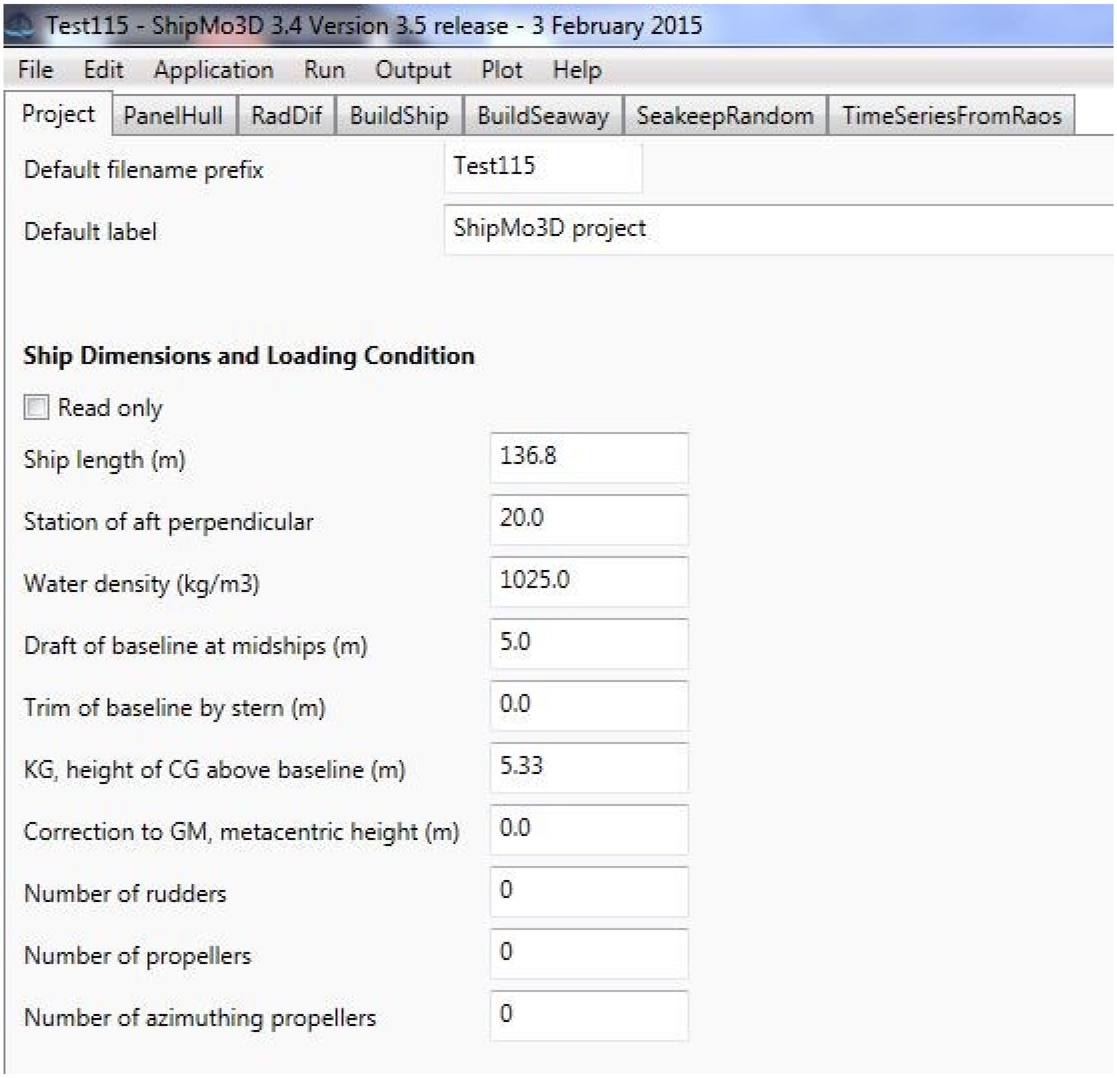


Figure 3-6 - ShipMo3D Project Definition

In this page, the vessel particulars are defined for the test case, the notable item of additional consideration is the KG value, which indicates the vessel center of gravity height. As this is a property of the construction and not the model this value was approximated based on existing vessel data. Using the known values for the OSVs Atlantic Hawk and Atlantic Merlin, the VCG as a ratio of vessel depth was determined as a representative sample of typical vessel design conditions.

Based on the stability booklet of each vessel the VCG was determined in accordance with the following table:

Table 3-4 – VCG Vs. D of Existing Vessels

Vessel	Depth (m)	VCG – Loaded (m)	VCG/D
Atlantic Hawk	8	5.86	0.73
Atlantic Merlin	9	7.8	0.87
		Average	0.80

Based on these results it is estimated the VCG of the vessel will be located at approximately 0.8 times the depth of the vessel. Using this assumption for all vessels ensures consistency in comparing the results as the performance is related to this VCG height and is a property of the placement of steel and machinery within the hull design itself.

Having defined the basic project parameters, the next screen is to develop the paneled hull model.

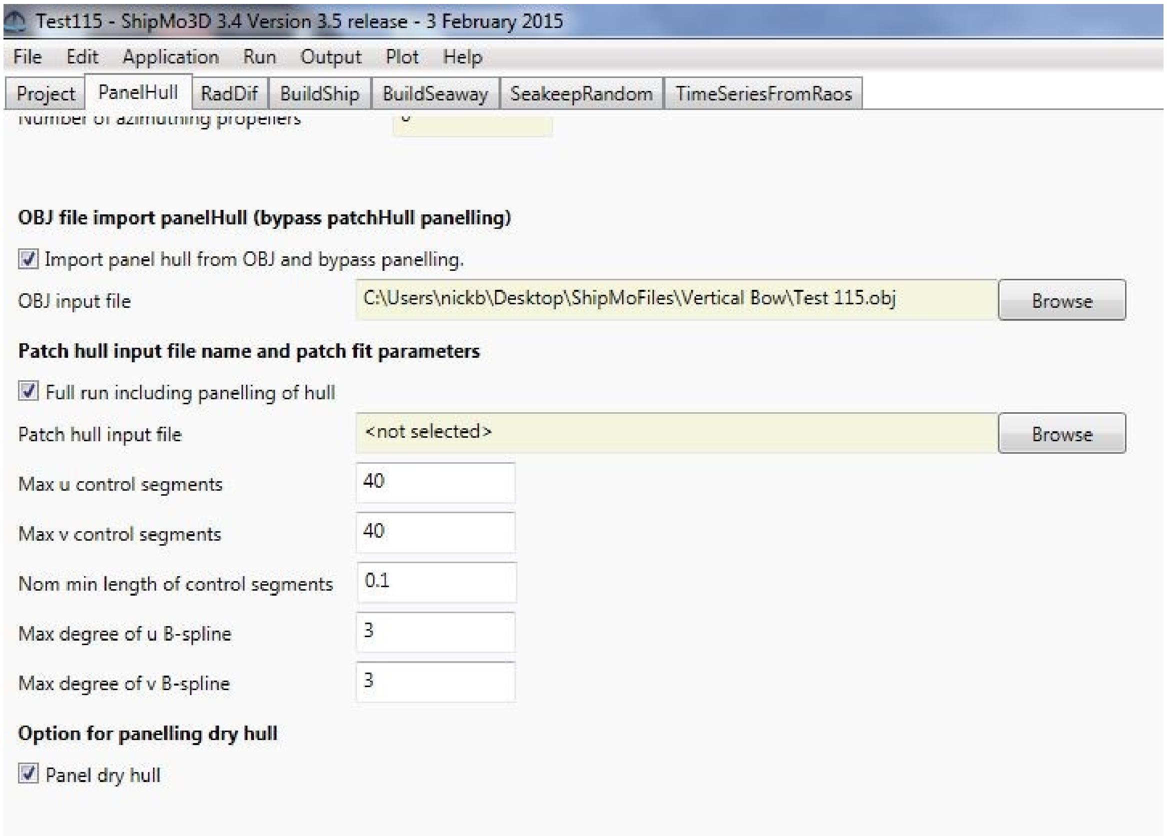


Figure 3-7 - ShipMo3D Panel Hull Setup

This can either be done by writing a file describing the hull curves and panelizing in the program, or by uploading a panel mesh in the OBJ format as was done for this test.

The first calculation steps are to determine the radiation and diffraction values, this is done in the RadDif workflow, in this case the test made use of default values when possible as this is best unless more detailed experiments are performed to determine the exact values that should be used.

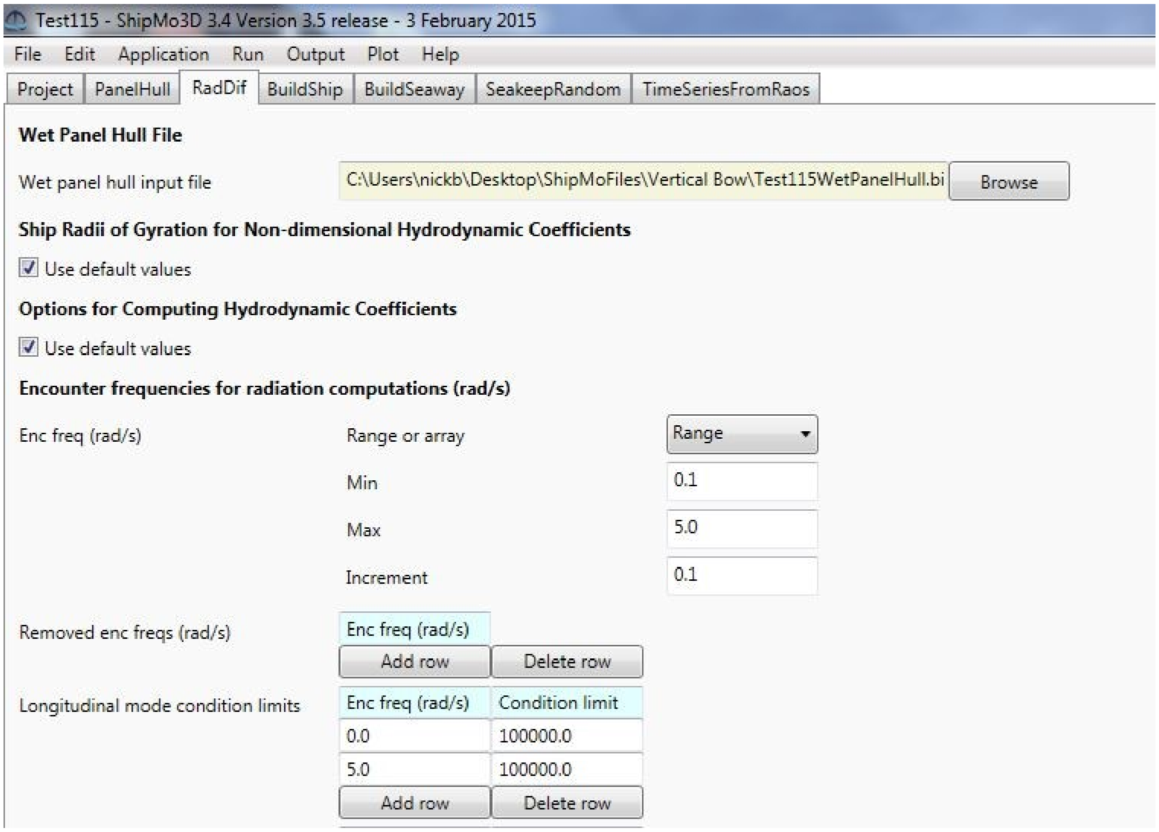


Figure 3-8 - ShipMo3D RadDif

The encounter frequencies for waves were considered up to 5 rad/s, as this was thought to likely cover all likely frequencies within the random sea state.

The parameters for diffraction are then listed below these radiation parameters.

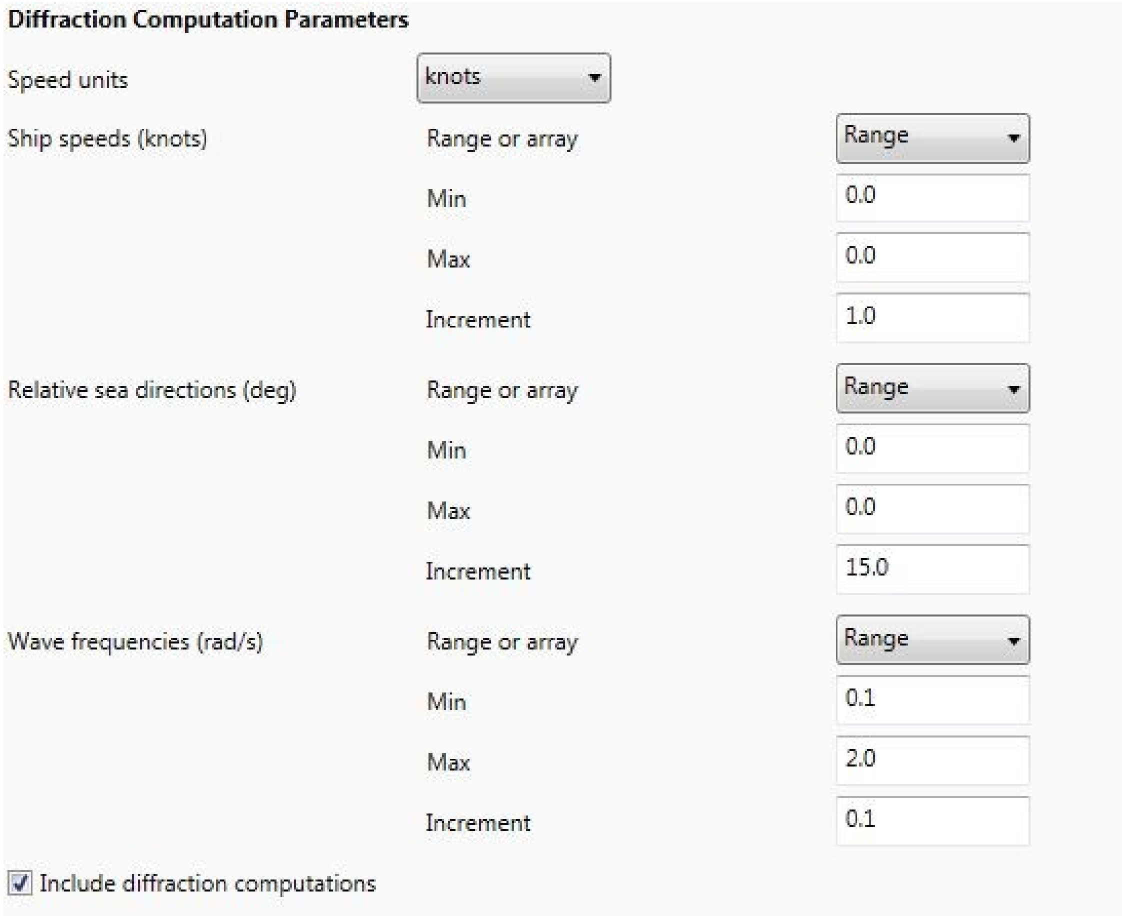


Figure 3-9 - ShipMo3D Diffraction Computation

Here the vessel speed was assigned at 0 as we are only interested in the hull performance during loading and unloading operations, which are performed under dynamic positioning assistance, the sea direction was also considered only at 0 as it is expected that the vessel under normal operating conditions with weathervane into the seas, the wave frequencies were defined from 0.1 to 2 rad/s as this is thought to likely cover almost all possible wave periods of the sea state. It is key to ensure that the calculation is set to include diffraction computations, this is very computationally intensive but is necessary to accurately define the vessel response.

The next step is to build a complete model of the vessel behavior combining the hull panel shape with the corresponding hydrodynamic parameters.

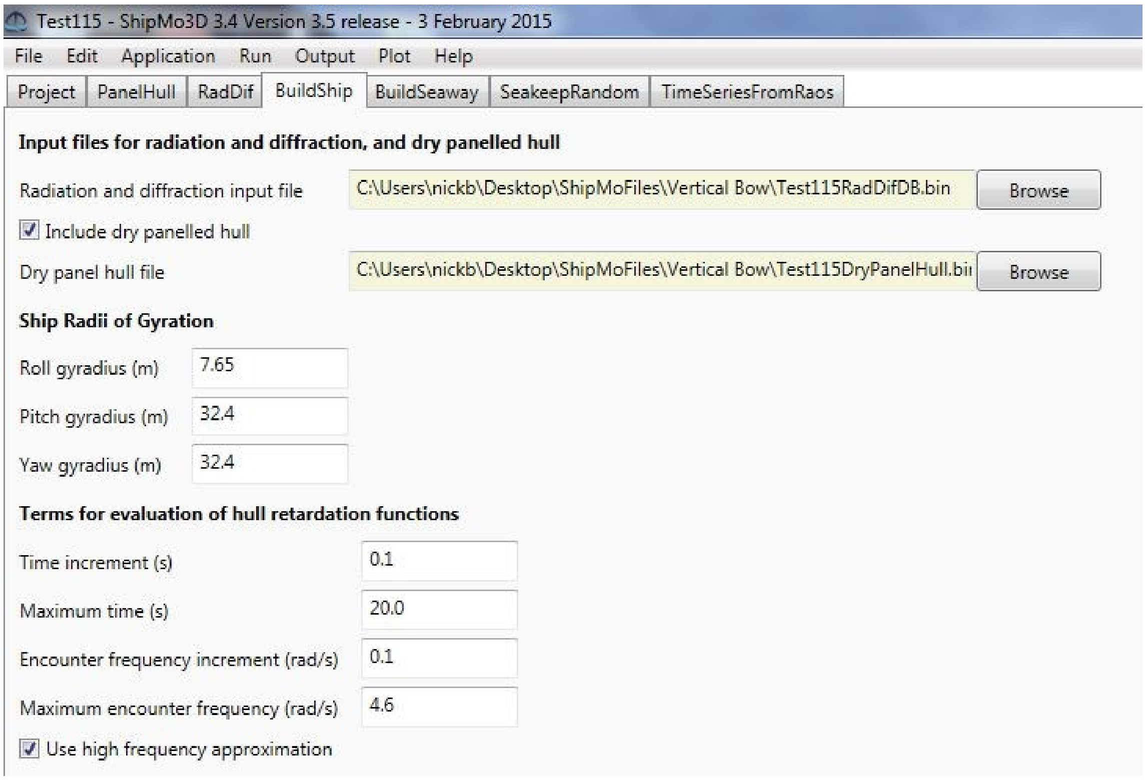


Figure 3-10 - ShipMo3D BuildShip

In this case the simulation included the dry portion of the hull in its model to determine its effect on the hull performance.

The vessel radii of gyration are a property of the mass of the vessel related to the distribution of weight in the construction, which is not known in detail at a concept design phase. Instead, these were estimated using traditional methods for estimating radii of gyration based on the hull principal particulars. The roll gyradius was taken as 0.34 x the moulded breadth and the pitch and yaw gyradii were taken as 0.27 x the length.

The hull retardation factors are evaluated over a range of time, which in this case was limited to 20 seconds as it is expected that the vessel will fully respond within this time frame.

A high frequency approximation is used to simplify calculations but is not expected to influence the results as high frequencies will likely have very little impact on the vessel.

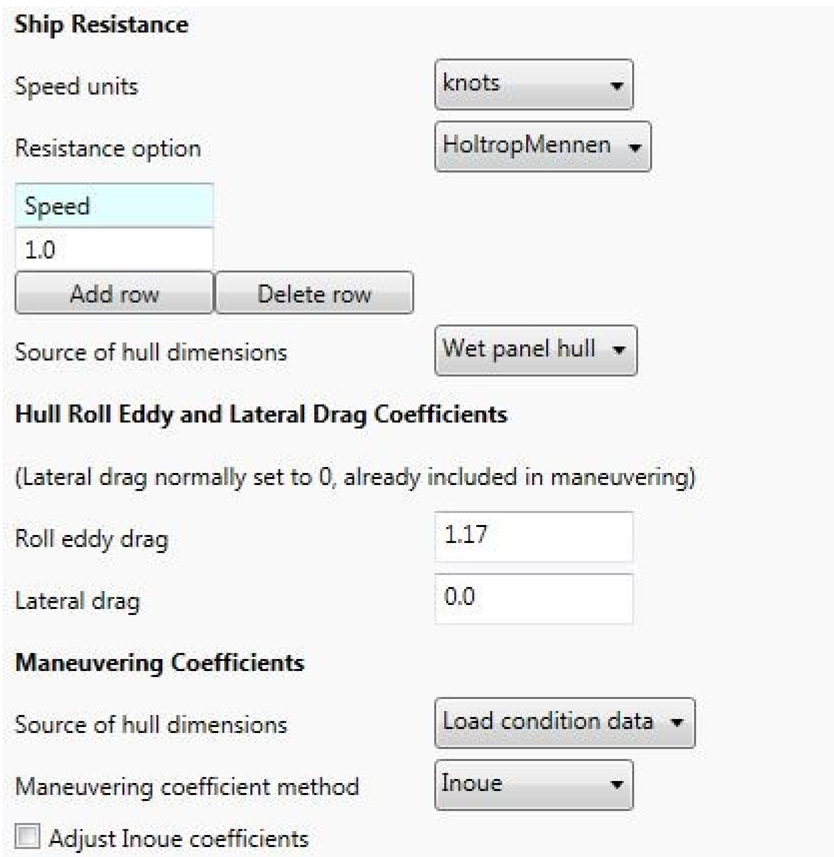


Figure 3-11 - ShipMo3D BuildShip Resistance Parameters

The hull is further defined by defining the speed for which resistance is calculated in the wave. This is a necessary input, but as we are not concerned with the resistance, this value can be ignored and left at the default 1 knot.

The roll eddy drag has been set to the default value of 1.17 as without detailed studies of the actual eddy drag of a specific vessel there is no better value to be chosen and this allows for like comparison of design.

The lateral drag is set to 0 as this is calculated separately in the maneuvering calculations in a seaway.

The next workflow step is associated with defining the random sea way that the vessel operates in.

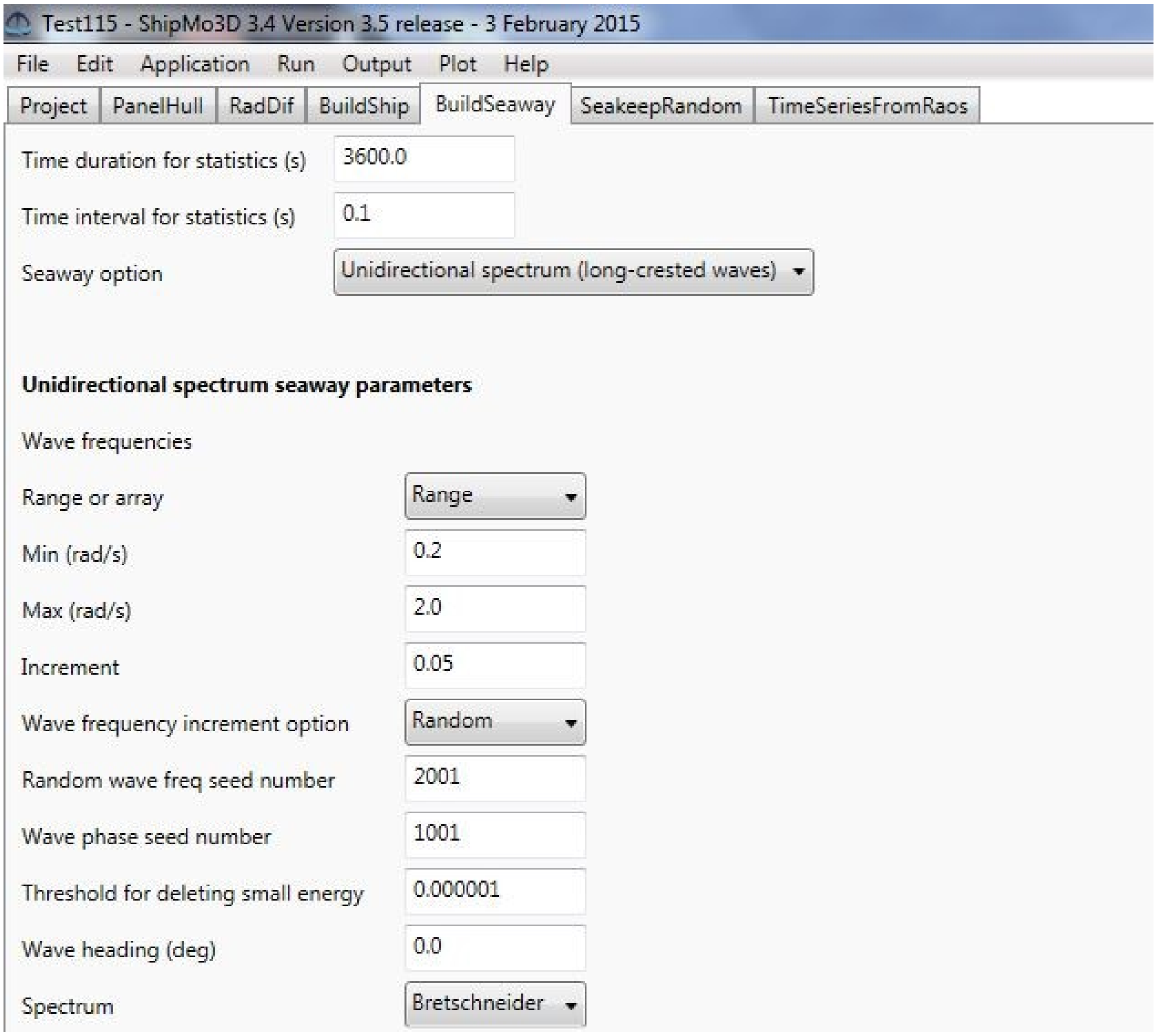


Figure 3-12 - ShipMo3D Seaway Definition

For the seaway tab, we define details of the sea conditions. The first part is to define the length of the simulation, in this case 3600 seconds was chosen as it defines a whole hour of operations which is thought to give a good idea of the level of motions which the vessel would be expected to see.

The range of wave frequencies was defined over the range, which is expected, consistent with those defined earlier.

The random seeds are arbitrary and just define what the random pattern would occur as and is unlikely to influence results in any meaningful way.

The wave heading was defined at 0 degrees consistent with the heading of the vessel to represent weathervaning, and the spectrum was defined as a Bretschneider sea spectrum consistent with that defined for the test program.

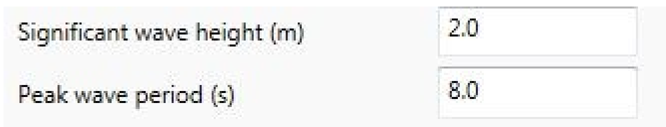


Figure 3-13 - ShipMo3D Sea State Definition

The overall sea state was then defined to develop an overall random seaway.

The next workflow step is to determine the seakeeping performance of the vessel in a random seaway to determine the vessel RAOs.

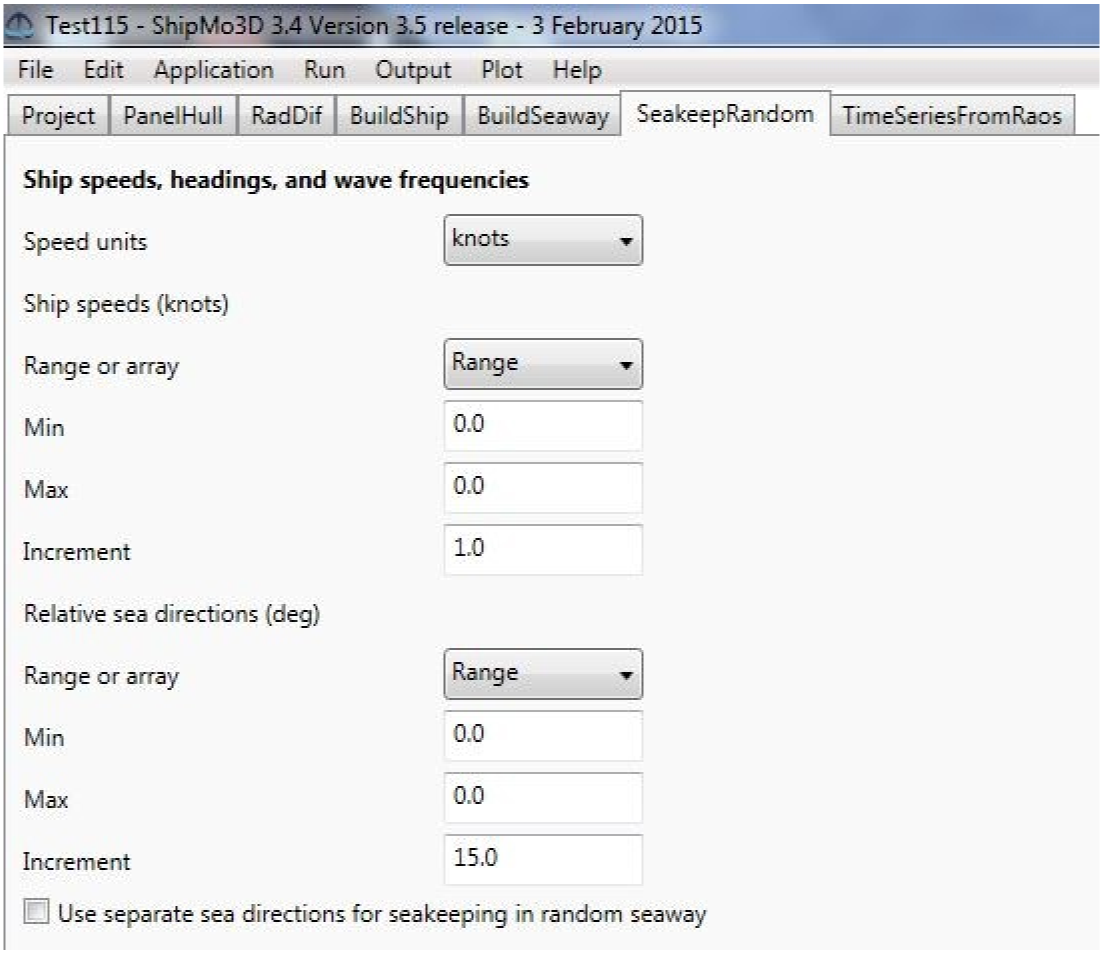


Figure 3-14 - ShipMo3D Seakeeping RAO Setup

Here the vessel was shown at 0 speed consistent with the desired output at a heading of 0 degrees to the sea state.

The sea that the vessel operates in is defined here as well:

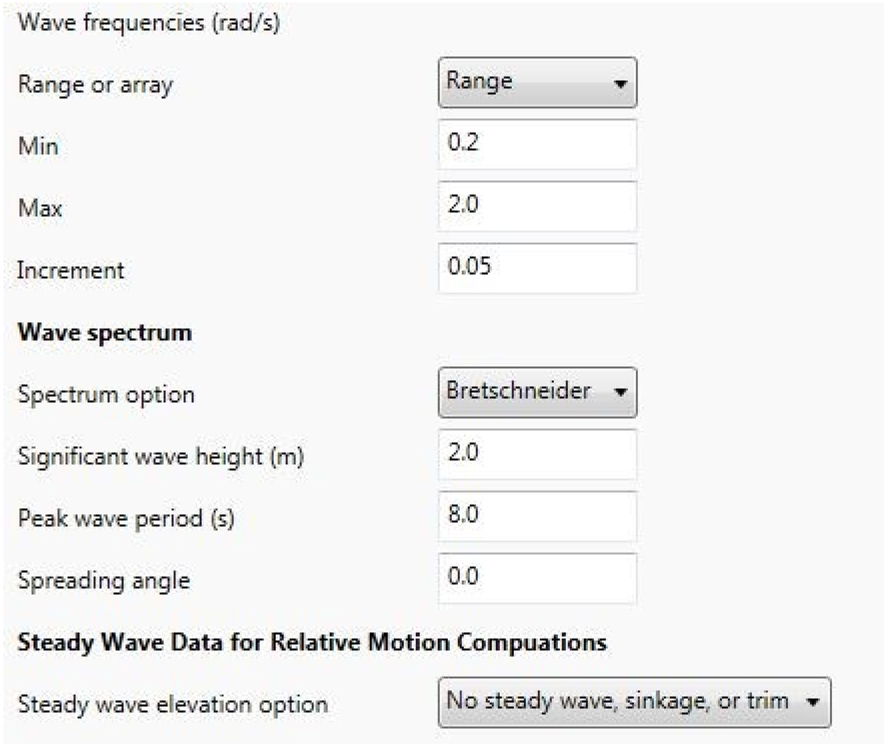


Figure 3-15 - ShipMo3D RAO Frequency Setup

The values chosen were consistent with the previous frequencies, with the addition that 0 spreading angle is indicated to ensure the waves are consistently in the 0 degree heading and there is no steady wave, sinkage, or trim specified for the vessel as it is assumed that it is not a storm surge condition under consideration, the vessel is undamaged, and is loaded so that there is 0 trim.

Having defined the RAOs of the vessel, it is then possible to combine this with the randomly generated sea to develop a time history of the vessel response in the seaway.

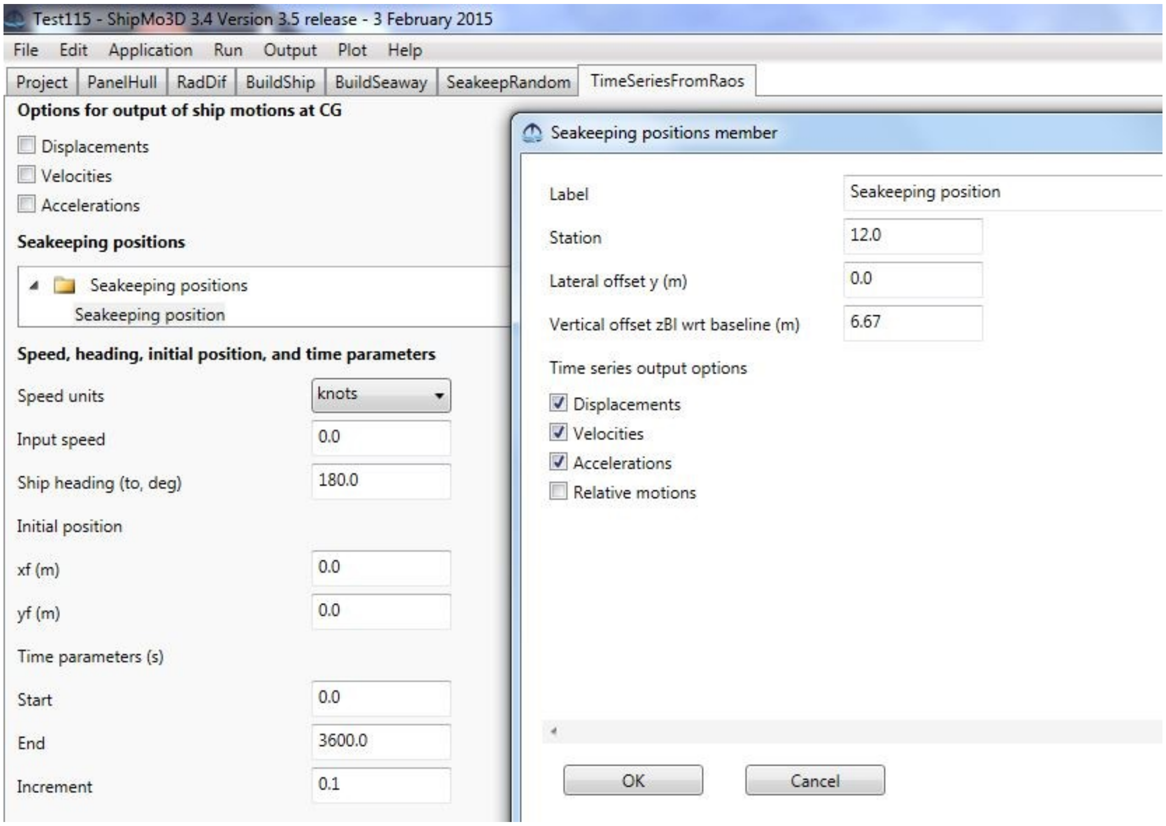


Figure 3-16 - ShipMo3D Time Series Generation

This is done in the TimeSeriesFromRaos workflow. Here the vessel speed and heading are defined. Note that this heading indicates the direction the vessel is heading towards and is therefore the opposite of the angle at which it is heading relative to waves in a head seas condition.

The vessel is defined at an initial position in the seaway of 0,0 which is thought unlikely to influence results. The time parameter is then defined to describe the duration of the simulation, consistent with the time duration defined for the seaway which was generated.

The position at which the results are to be measured is defined in the seakeeping position. Here, this position was chosen as a point on the open aft deck, corresponding to a clear space near the vessel midship which is thought to be the safest place on the deck from which to perform crew lifting operations.

The checkboxes indicate the desire to output the displacement, velocity, and acceleration time histories at this point.

When all results are run, a time history is developed showing the vessel motions at each 0.1s interval over 3600 seconds, which when analyzed allows for a statistical interpretation of the vessel response.

This process was run for each of the 140 tests, and the resulting time series history was examined. For each one, the standard deviation of displacement, velocity, and acceleration were recorded at the lifting position on the deck. These were then converted to the significant response by multiplying them by 2, as they follow a wave pattern the ratio between amplitude of the significant response and standard deviation of response is 2, consistent with the definition of significant wave height, in which the significant wave height is defined as 4 x the standard deviation of surface elevation (amplitude is half the wave height for sinusoidal waves). [27]

The significant response was chosen for analysis as it provides a single value which represents the overall vessel performance and it is believed that due to the short duration of contact with the deck during lifting operations, the probability of exceedance of the significant value is suitably low that the operations can be defined safely based on a significant response limit.

With all the data collected, it is then necessary to perform analysis of the data to fit a model.

3.1.4. Results

All data collected in this test program has been provided in Appendix A – Motion Test Program Data, this data was then imported into Design Expert software for analysis.

For each hull form, analysis of variance was performed on the data and the model was built using the Corrected Aikaike Information Criterion with forward regression, and then reduced by removing terms which minimally impact outcomes. Although as this is a computer model with 0 random error and therefore all terms contribute to the outcome, using this approach ensures the model only captures the variables which have a significant impact on the predictions. Other variables typically have very small coefficients and would not impact the results of the calculation significantly and therefore can be safely ignored. The resulting model Analysis of Variance and residuals are presented below to demonstrate the model quality of the displacement of a vessel with an x-bow shape.

Response 1: Displacement

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	9.80	10	0.9803	609.46	< 0.0001	significant
A-Length	0.4787	1	0.4787	297.63	< 0.0001	
C-Draft	0.0199	1	0.0199	12.39	0.0018	
D-Wave height	2.23	1	2.23	1389.06	< 0.0001	
E-Peak Period	5.96	1	5.96	3707.65	< 0.0001	
AD	0.0457	1	0.0457	28.41	< 0.0001	
AE	0.1006	1	0.1006	62.54	< 0.0001	
DE	0.7509	1	0.7509	466.83	< 0.0001	
A^2	0.0191	1	0.0191	11.88	0.0021	
E^2	0.0085	1	0.0085	5.30	0.0303	
AE^2	0.0290	1	0.0290	18.04	0.0003	
Residual	0.0386	24	0.0016			
Lack of Fit	0.0386	23	0.0017			
Pure Error	0.0000	1	0.0000			
Cor Total	9.84	34				

Figure 3-17 - Motion Test Displacement ANOVA

Examining the ANOVA table, we see that the model terms all have a P-value indicating a very low probability of occurring due to random noise, this indicates that these terms most likely are a good fit for modeling the data.

Fit Statistics

Std. Dev.	0.0401		**R^2**	0.9961
Mean	0.7381		**Adjusted R^2**	0.9944
C.V. %	5.43		**Predicted R^2**	0.9903
			Adeq Precision	88.7412

Figure 3-18 - Motion Test Displacement Model Fit

Using the terms specified from the ANOVA, the equation of the model is predicted, and the model statistics are used to verify the quality of the data fit. A perfect model has an R^2 of 1, in this case the adjusted R^2 indicates that the selected terms are a very good selection, and the predicted R^2 shows that this is a very strong model for predicting results of the model.

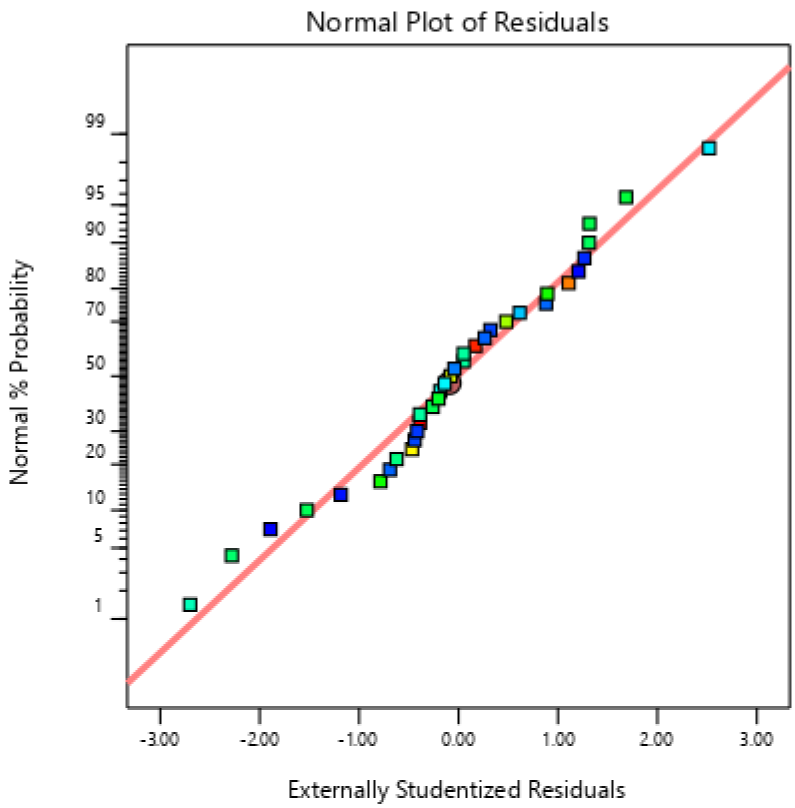


Figure 3-19 - Motion Test Displacement Normal Plot

In addition to the model statistics, we can use plots to visualize the model quality. In this case the plot examined is the normal plot of residuals. In this plot a good fitting model will not deviate far from the bisecting red line, indicating that the errors in the prediction do not statistically vary far from the prediction. Large variances indicate results that deviate beyond what can be explained by random noise. In this case, the points follow pretty reasonably along the line indicating a good model fit.

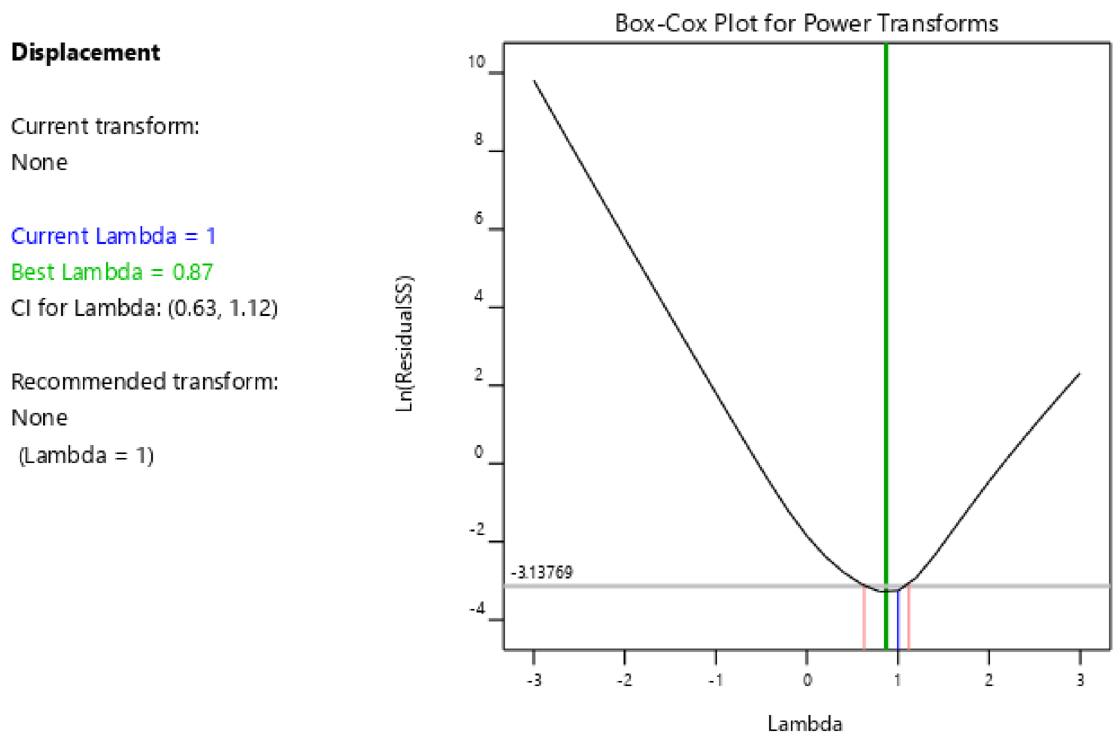


Figure 3-20 - Motion Test Displacement Box-Cox Plot

In addition to the fit data, we also can check to make sure the data does not require transformation for good modeling (such as using a logarithmic scale), this is checked using the box-cox plot. This calculates an ideal lambda value to describe the shape of the data. If lambda = 0 this indicates a log transform is recommended and at lambda = 0.5 a square root transform is recommended. In this case the closest lambda value is 1, which indicates no transform is needed for the data.

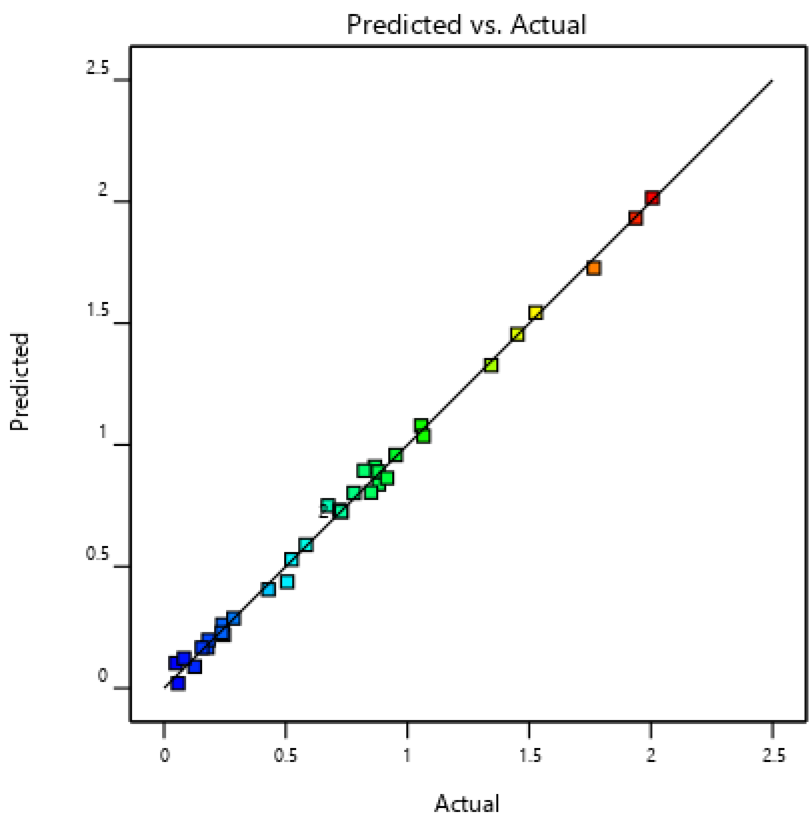


Figure 3-21 - Motion Test Displacement Predicted Vs. Actual

Finally, having verified the data, we can use a predicted vs. actual plot to verify how well the test data corresponds to the model built from the data. The goal is for the results to be as close as possible to the predicted line, in this case the data points are all close to the line indicating the model performs very well for the data.

The remainder of the models have been built using similar methods and their detailed results are presented in Appendix D: Additional ANOVA for Motions Prediction.

Having built a model for all the data and verified the quality of the model fit, it is then possible to estimate the coefficients in the equations which describe the model. The resulting determined equations relating significant vessel motion amplitudes and hull design are presented below:

X Bow Type Hulls

$D_{vert} = -1.21 + 0.0058\,L + 0.017\,T - 0.017\,H_s + 0.42\,T_p - 0.0013\,L\,H_s - 0.0043\,L\,T_p + 0.039\,H_s\,T_p + 0.000063\,L^2 - 0.021\,{T_p}^2 + 0.00021\,L\,{T_p}^2$ (Equation 3.1)

$\sqrt{V_{vert}} = -1.20 - 0.0036\,L + 0.093\,H_s + 0.68\,T_p - 0.0020\,L\,T_p + 0.0068\,H_s\,T_p + 0.000036\,L^2 - 0.0073\,{H_s}^2 - 0.064\,{T_p}^2 + 0.00012\,L\,{T_p}^2 + 0.0018\,{T_p}^3$ (Equation 3.2)

$\log_{10} A_{vert} = -3.055 - 0.0062\,L - 0.0043\,B + 0.013\,T + 0.27\,H_s + 0.87\,T_p - 0.019\,{H_s}^2 - 0.096\,{T_p}^2 + 0.0033\,{T_p}^3$ (Equation 3.3)

Axe Bow Type Hulls

$D_{vert} = -0.097 - 0.0043\,L - 0.0073\,H_s + 0.076\,T_p - 0.0016\,L\,H_s - 0.00092\,L\,T_p + 0.041\,H_s\,T_p + 0.000062\,L^2$ (Equation 3.4)

$\sqrt{V_{vert}} = 0.24 - 0.0080\,L - 0.025\,T + 0.12\,H_s + 0.11\,T_p - 0.00043\,L\,H_s + 0.0024\,T\,T_p + 0.0075\,H_s\,T_p + 0.000032\,L^2 - 0.0071\,{H_s}^2 - 0.0063\,{T_p}^2$ (Equation 3.5)

$\sqrt{A_{vert}} = 0.40 - 0.0083\,L - 0.03\,T + 0.15\,H_s + 0.089\,T_p - 0.00052\,L\,H_s + 0.0027\,T\,T_p - 0.0028\,H_s\,T_p + 0.000034\,L^2 - 0.0059\,{H_s}^2 - 0.0058\,{T_p}^2$ (Equation 3.6)

Bulbous Bow Type Hulls

$D_{vert} = 0.86 - 0.0089\,L - 0.082\,B + 0.013\,T + 0.0054\,H_s + 0.073\,T_p - 0.0016\,L\,H_s - 0.00097\,L\,T_p + 0.039\,H_s\,T_p + 0.000089\,L^2 + 0.0021\,B^2$ (Equation 3.7)

$\sqrt{V_{vert}} = 0.58 - 0.014\,L - 0.12\,T + 0.039\,H_s + 0.25\,T_p - 0.000012\,L\,T_p + 0.033\,T\,T_p + 0.0068\,H_s\,T_p + 0.000056\,L^2 - 0.037\,{T_p}^2 - 0.0019\,T\,{T_p}^2 + 0.0018\,{T_p}^3$ (Equation 3.8)

$\log_{10} A_{vert} = -2.32 - 0.0089\,L + 0.12\,H_s + 0.75\,T_p + 0.00032\,L\,T_p - 0.087\,{T_p}^2 + 0.0031\,{T_p}^3$ (Equation 3.9)

<u>Vertical Bow Type Hulls</u>

$D_{vert} = 0.71 - 0.0081L - 0.07B + 0.0096T + 0.017H_s + 0.075T_p - 0.0017L\,H_s - 0.00097L\,T_p + 0.039H_s\,T_p + 0.000086L^2 + 0.0017B^2$ (Equation 3.10)

$\sqrt{V_{vert}} = -1.11 + 0.0035L + 0.031H_s + 0.58T_p - 0.0022L\,T_p + 0.0072H_s\,T_p - 0.053{T_p}^2 + 0.00014L\,{T_p}^2 + 0.0014{T_p}^3$ (Equation 3.11)

$\log_{10} A_{vert} = -1.07 - 0.0064L - 0.20T + 0.12H_s + 0.36T_p + 0.051T\,T_p - 0.056{T_p}^2 - 0.0029T\,{T_p}^2 + 0.0026{T_p}^3$ (Equation 3.12)

3.1.5. Model Verification

The quality of each model was assessed by using the model to predict design points which were not modeled and comparing the measured results to the predicted values, the result of these tests is shown below. For each model, an additional 5 test runs were performed, these runs were developed by randomly selecting a set of design points, each chosen as the midpoint between the parameters used in the original test program, in this way the quality of the model between design points can be estimated. The test runs are described below.

Table 3-5 – Motions Model Verification Tests

Run No.	Length (m)	Beam (m)	Draft (m)	Significant Wave Height (m)	Peak Period (s)
1	97.5	21.25	6.5	5.5	7
2	82.5	18.75	5.5	2.5	7
3	67.5	23.75	6.5	3.5	7
4	112.5	21.25	4.5	5.5	9
5	82.5	16.25	7.5	2.5	11

Table 3-6 – X Bow Motions Verification Results

X Bow Tests									
Run	D_{pred}	V_{pred}	A_{pred}	$D_{measured}$	$V_{Measured}$	$A_{Measured}$	%D	%V	%A
1	0.727	0.644	0.667	0.748	0.674	0.646	2.8	4.7	3.3
2	0.404	0.399	0.368	0.394	0.364	0.363	2.5	9.6	1.4
3	0.706	0.672	0.636	0.692	0.634	0.620	2.0	6.0	2.6
4	0.947	0.671	0.489	0.912	0.628	0.475	3.8	6.8	2.9
5	0.787	0.442	0.335	0.780	0.472	0.324	0.9	6.4	3.4
						Average Percent Difference	2.4	6.7	2.7

As can be seen the error even for points spaced well away from the data points show a very good agreement with the actual measured results, showing an error of less than <+/- 10%, and therefore the x-bow equations are a good model for the behavior of this hull and suitable for use in the optimization.

Table 3-7 – Axe Bow Motions Verification Results

Axe Bow Tests									
Run	D_{pred}	V_{pred}	A_{pred}	$D_{measured}$	$V_{Measured}$	$A_{Measured}$	%D	%V	%A
1	0.681	0.516	0.462	0.602	0.508	0.463	13.1	1.6	0.2
2	0.355	0.299	0.272	0.342	0.288	0.265	3.8	3.8	2.6
3	0.609	0.501	0.458	0.628	0.536	0.493	3.0	6.5	7.1
4	0.986	0.657	0.481	0.942	0.626	0.457	4.7	5.0	5.3
5	0.771	0.464	0.302	0.804	0.476	0.306	4.1	2.5	1.3
Average Percent Difference							5.7	3.9	3.3

The error in the axe bow results shows that this model provides a good fit for the prediction of future points (<+/-10% Error), indicating the model is suitable to use in the design optimization.

Table 3-8 – Bulbous Bow Motions Verification Results

Bulbous Bow Tests									
Run	D_{pred}	V_{pred}	A_{pred}	$D_{measured}$	$V_{Measured}$	$A_{Measured}$	%D	%V	%A
1	0.631	0.587	0.583	0.63	0.57	0.55	0.2	3.0	6.0
2	0.311	0.314	0.319	0.328	0.3	0.296	5.2	4.7	7.8
3	0.62	0.566	0.531	0.616	0.568	0.562	0.6	0.4	5.5
4	0.873	0.586	0.465	0.818	0.55	0.41	6.7	6.5	13.4
5	0.729	0.411	0.285	0.752	0.45	0.304	3.1	8.7	6.3
Average Percent Difference							3.2	4.6	7.8

The model shows general agreement in patterns with the predicted data, and an acceptable average error <+/-10%, only one case shows an error which exceeds this value and this can primarily be explained by the prediction being a low value and therefore the absolute error which is found to be in line with other test case results in a higher percentage error, this has been deemed acceptable in this case as the absolute predicted value is more important than the relative accuracy of the value and therefore the model is found to be suitable for use in future predictions.

Table 3-9 – Vertical Bow Motions Verification Results

Vertical Bow Tests									
Run	D_{pred}	V_{pred}	A_{pred}	$D_{measured}$	$V_{Measured}$	$A_{Measured}$	%D	%V	%A
1	0.636	0.586	0.587	0.634	0.568	0.541	0.3	3.2	8.5
2	0.317	0.362	0.301	0.332	0.300	0.294	4.5	20.7	2.4
3	0.618	0.581	0.516	0.610	0.556	0.545	1.3	4.5	5.3
4	0.883	0.596	0.424	0.83	0.56	0.417	6.4	6.4	1.7
5	0.728	0.436	0.297	0.752	0.448	0.301	3.2	2.7	1.3
Average Percent Difference							3.1	7.5	3.8

The model shows general agreement in patterns with the predicted data, and an acceptable average error <+/-10%, only one case shows an error which exceeds this value and this can primarily be explained by the prediction being a low value and therefore the absolute error which is found to be in line with other test case results in a higher percentage error, this has been deemed acceptable in this case, as the absolute predicted value is of more importance than the relative accuracy value, and the model is found to be suitable for use in future predictions.

3.2. Resistance Prediction

3.2.1. Introduction

Once it was possible to predict the performance of a vessel, it is then necessary to predict the cost to operate to allow for an optimization between performance and cost. For most vessels, the costs are fixed, but there is one easily variable cost, which makes up a large portion of the annual operating costs. This is the fuel cost of the vessel.

The required fuel is directly related to the resistance of the vessel, and so it was determined that a test program should be run to quantify the relationship between the vessel design and its resistance. Typically, this is done using computational methods, however as the goal is to simplify the model and allow for quick comparison of multiple options, it was instead chosen to build a mathematical model to represent the results of these computational predictions over the range of vessels considered.

To do this, the resistance and propulsion prediction software NavCAD by HydroComp is used to calculate the resistance of the vessel designs at various speeds and sea states.

It is noted that NavCAD can be used to output both resistance and effective power requirements of the vessel; although the power output would be directly useful to cost estimation, knowing the resistance will be of more use to designers at the start of design, as it will quickly identify the thrust required in the propellor design, and the power can easily be calculated from this. As a result, this test program has focused on creating equations to define the resistance for each vessel type, with the effective power being determined as part of the optimization algorithm.

3.2.2. Design of Test Program

In order to build this mathematical model another uniform design was chosen to represent the design space. In this case, the test program was also divided into 4 separate hull types, each of which with its own uniform design.

The parameters for the model consisted of hull parameters, sea states, and operating speed, as these are known to be significant in the resulting resistance response.

The hull is once again defined using length, beam, and draft, each a scaled hull parameter based on a parent hull form.

The sea state was again defined using a Bretschneider Spectrum, requiring the significant wave height and peak period.

The vessel speed is defined based on the average transit speed in the seas over distance to account for variations in instantaneous speed when encountering waves.

The Length has been defined between 60m and 120m as this represents the range of vessels which may be expected in an OSV fleet, and the beams and drafts have been chosen on a range which correspond to typical values that match vessels of each given length.

The sea state has been defined for significant wave heights between 2m and 6m with corresponding periods assigned between 8 seconds and 16 seconds which represents typical normal sea states throughout the year on the Grand Banks [26]. As it is very complicated to predict the direction which the seas will be coming from as the vessel maneuvers, the seas have been considered as head seas only. This is the most conservative possible resistance to be predicted.

The speed has been chosen as a range of 10 to 30 knots, as it is expected no vessel would have a design speed below 10 knots, however as the distances involved may require higher speed vessels, the range of speeds has been extended up to 30 knots, well beyond the typical maximum speeds of existing vessels.

The number of levels for each factor were again chosen as 5 to capture any higher order behaviors.

Making use of the uniform design tables [25] for a 6 factor 5 level experiment, the chosen uniform design was a 25-run test set. This gives a discrepancy of 0.035, which although not as low as desired, is a good model, as choosing any further runs experience significant diminishing returns in discrepancy reduction. This brings the total test program size to 100 test cases. The required program is summarized in the table below. Note that this test set is different from the test set used for the seakeeping analysis due to the addition of a speed factor.

Table 3-10 – Resistance Test Program Uniform Design

Run Number	Length (m)	Beam (m)	Draft (m)	Hs (m)	Tp (s)	V (knots)
1	90	22.5	8	2	16	30
2	75	15	8	4	14	25
3	90	15	4	6	8	15
4	105	20	8	5	10	15
5	105	17.5	4	2	12	25
6	60	25	8	6	12	10
7	60	15	7	2	10	20
8	105	25	7	4	8	30
9	90	17.5	7	5	14	10
10	120	20	7	6	16	25
11	60	17.5	5	4	16	15
12	75	25	4	5	16	20
13	105	15	6	3	16	10
14	120	17.5	8	3	8	20
15	90	25	5	3	10	25
16	75	17.5	6	6	10	30
17	90	20	6	4	12	20
18	120	22.5	4	4	10	10
19	120	15	5	5	12	30
20	60	22.5	6	5	8	25
21	75	22.5	7	3	12	15
22	60	20	4	3	14	30
23	75	20	5	2	8	10
24	105	22.5	5	6	14	20
25	120	25	6	2	14	10

Having built a program consistent with a uniform design, it is then necessary to prepare and run the tests.

3.2.3. Test Run Characterization

The resistance tests were performed using the resistance predictions of the NavCAD program.

To do this, a series of hulls were generated based on the designed test program as shown below:

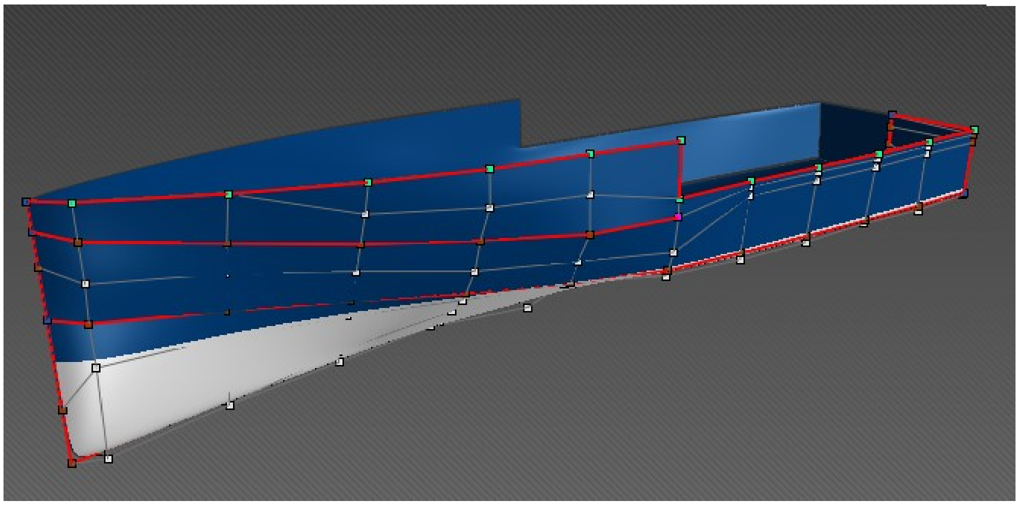


Figure 3-22 - Axe Bow Resistance Hull

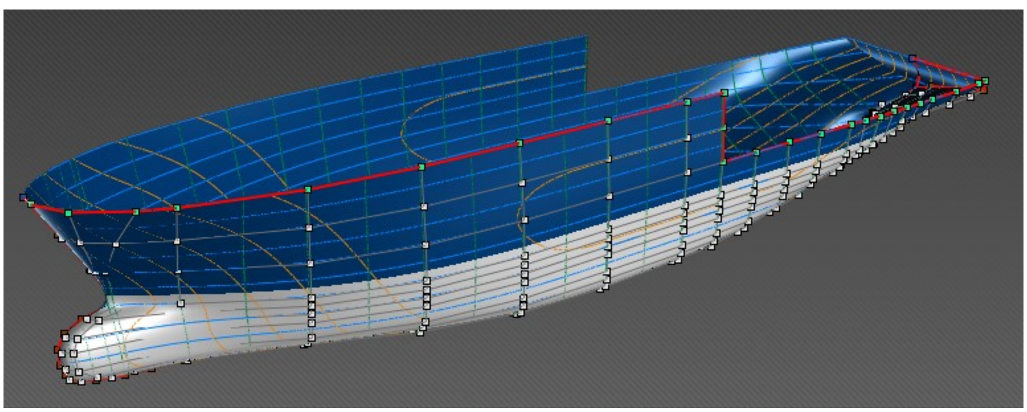


Figure 3-23 - Bulbous Bow Resistance Hull

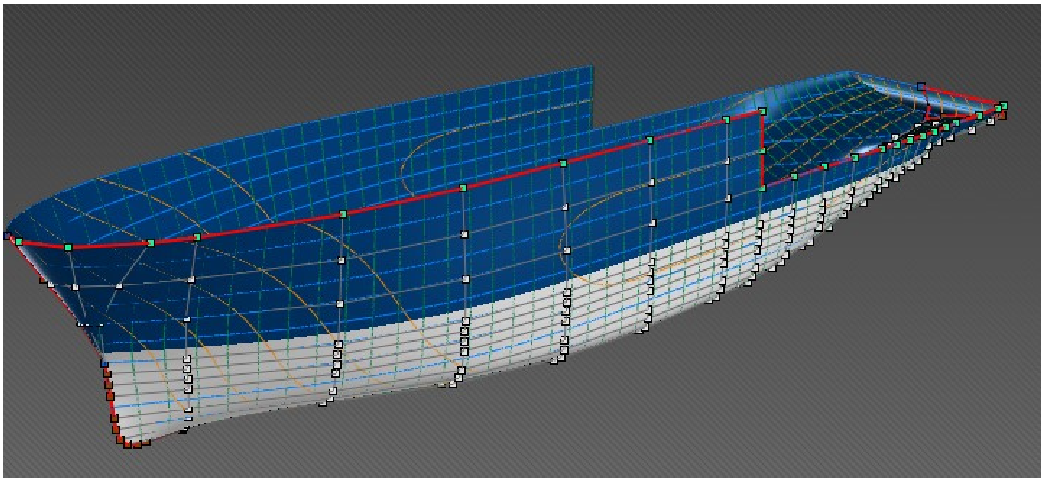


Figure 3-24 - Vertical Bow Resistance Hull

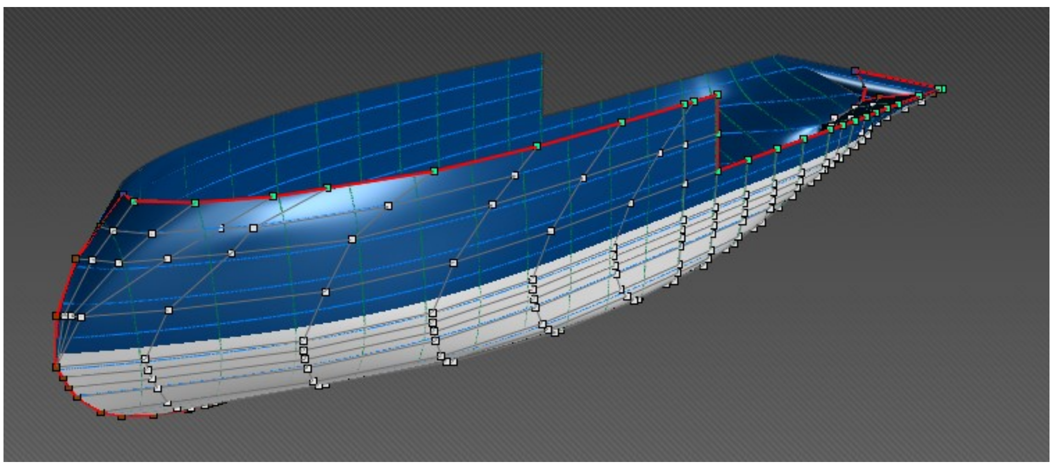


Figure 3-25 - X Bow Resistance Hull

For each hull, hydrostatic properties are then extracted from a report in Delfsthip which provides the required details to predict resistance in NavCAD. A sample report is shown below:

Design hydrostatics report

Design hydrostatics report

Supplier

Designer			
Created by			
Comment			
Filename	Test B1.fbm		
Design length	90.000 (m)	**Midship location**	45.000 (m)
Length over all	102.80 (m)	**Relative water density**	1.0250
Design beam	22.500 (m)	**Mean shell thickness**	0.0000 (m)
Maximum beam	22.502 (m)	**Appendage coefficient**	1.0000
Design draft	8.000 (m)		

Volume properties		Waterplane properties	
Moulded volume	11512.6 (m^3)	Length on waterline	98.524 (m)
Total displaced volume	11512.6 (m^3)	Beam on waterline	22.321 (m)
Displacement	11800.4 (tonnes)	Entrance angle	74.083 (Degr.)
Block coefficient	0.6271	Waterplane area	1833.4 (m^2)
Prismatic coefficient	0.6452	Waterplane coefficient	0.7990
Vert. prismatic coefficient	0.7849	Waterplane center of floatation	38.354 (m)
Wetted surface area	2938.8 (m^2)	Transverse moment of inertia	63807 (m^4)
Longitudinal center of buoyancy	44.518 (m)	Longitudinal moment of inertia	1130978 (m^4)
Longitudinal center of buoyancy	-0.490 %		
Vertical center of buoyancy	4.403 (m)		
Total length of submerged body	102.80 (m)		
Total beam of submerged body	22.321 (m)		

Midship properties		Initial stability	
Midship section area	173.6 (m^2)	Transverse metacentric height	9.946 (m)
Midship coefficient	0.9721	Longitudinal metacentric height	102.64 (m)

Lateral plane	
Lateral area	763.0 (m^2)
Longitudinal center of effort	45.335 (m)
Vertical center of effort	4.081 (m)

The following layer properties are calculated for both sides of the ship

Location	Area (m^2)	Thickness (m)	Weight (tonnes)	LCG (m)	TCG (m)	VCG (m)
Group 1	4396.1	0.000	0.0	47.248	0.000 (CL)	5.949
Group 2	67.3	0.000	0.0	-7.324	0.000 (CL)	9.227
Total	**4463.4**		**0.0**	**0.000**	**0.000 (CL)**	**0.000**

Sectional areas

Location (m)	Area (m^2)	Location (m)	Area (m^2)	Location (m)	Area (m^2)	Location (m)	Area (m^2)	Location (m)	Area (m^2)
0.000	25.7	22.500	141.2	45.000	173.6	67.500	146.2	90.000	20.4
4.500	52.9	27.000	155.5	49.500	173.6	72.000	125.9	90.386	18.8
9.000	76.6	31.500	165.2	54.000	172.6	76.500	100.2	91.286	16.0
13.500	99.5	36.000	170.6	58.500	168.8	81.000	70.6	92.571	12.0

10/4/2020 DELFTship 12.20 (321) 1

Figure 3-26 - Hydrostatic Report

With the required data, NavCAD is run and the basic hull information is entered; each hull and test case were set up as a new NavCAD file. The file presented above is used as an example case to show the method of performing the tests, the hull is shown in the figure below:

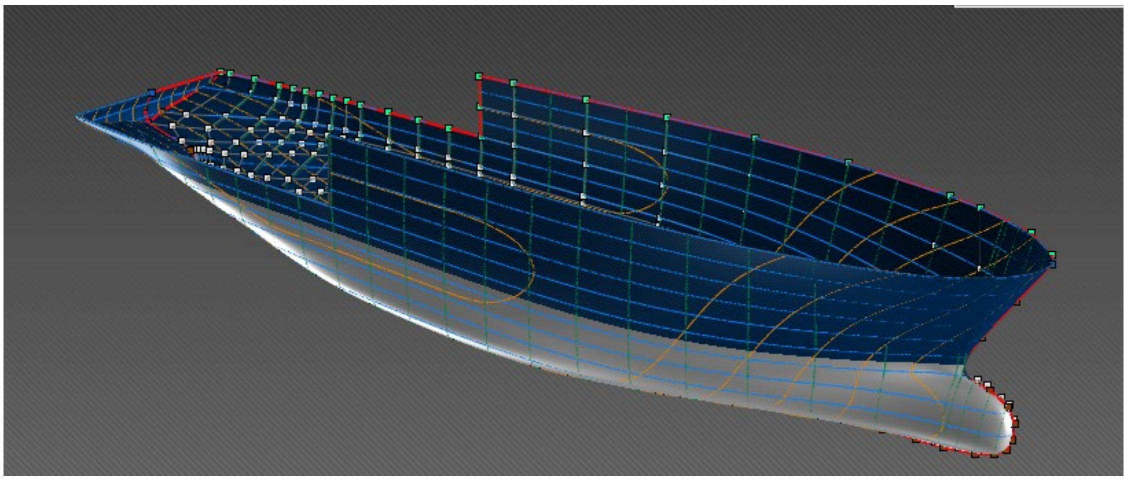


Figure 3-27 - Example Resistance Case Hull

The basic info is entered into the appropriate tab shown below:

Project		
Project ID:		
Description:		
Summary		
Scope:	Undefined	
Configuration:	Monohull	
Chine type:	Round/multiple	
Length on WL:	98.524	m
Displacement:	11800.40	t
Propulsor type:	Propeller	
Count:	0	
Water properties		
Water type:	Salt	
Density:	1026.00	kg/m3
Viscosity:	1.18920e-6	m2/s
Speeds		
Speed [01]	30.00	kt
Speed [02]		kt
Speed [03]		kt
Speed [04]		kt
Speed [05]		kt
Speed [06]		kt
Speed [07]		kt
Speed [08]		kt
Speed [09]		kt
Speed [10]		kt
Design condition		
Design speed:	30.00	kt

Figure 3-28 - NavCAD Project Definition

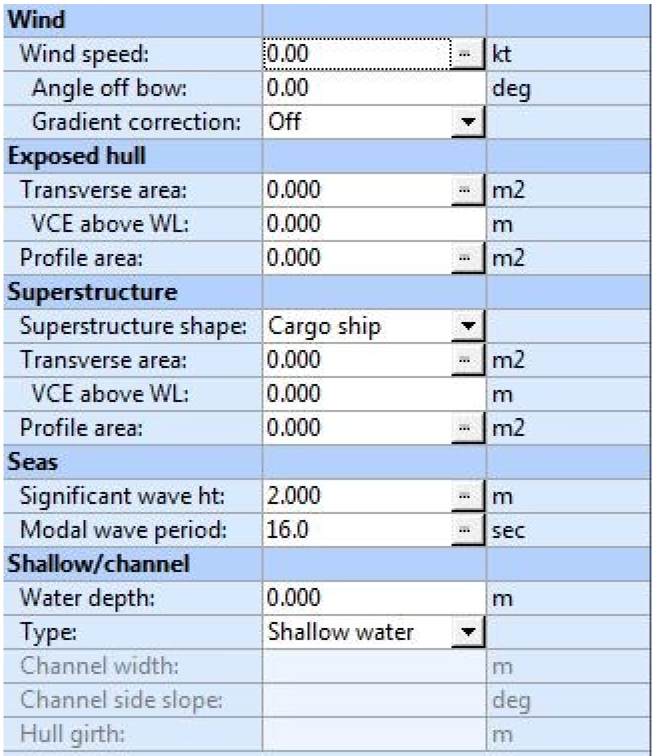
With the basic information entered, the next step is to fill in detailed hull parameters, which are derived from the hydrostatic file.

Hull		
Configuration:	Monohull	
Chine type:	Round/multiple	
General		
Length on WL:	98.524	m
Max beam on WL:	22.321	m
Max molded draft:	8.000	m
Displacement:	11800.40	t
Wetted surface:	2938.800	m2
Demi-hull spacing:		m
ITTC-78 (CT)		
LCB fwd TR:	44.518	m
LCF fwd TR:	38.354	m
Max section area:	173.600	m2
Waterplane area:	1833.400	m2
Bulb section area:	16.000	m2
Bulb ctr below WL:	4.440	m
Bulb nose fwd TR:	102.650	m
Imm transom area:	9.500	m2
Transom beam WL:	12.000	m
Transom immersion:	1.780	m
Half entrance angle:	37.04	deg
Bow shape factor:	0.0	[AVG flow]
Stern shape factor:	0.0	[AVG flow]

Figure 3-29 - NavCAD Hull Parameters

The parameters are read directly for each hull, with the exception of the shape factors, which are assigned using a dropdown to select the coefficient which best described the hull type, for example a V or U shaped hull uses a different shape factor.

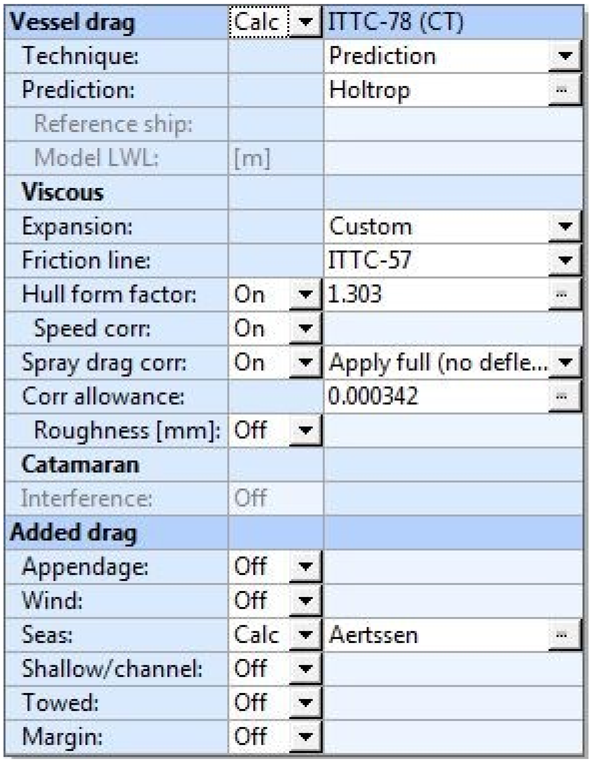
To add the effects of waves, an added drag calculation is performed. In this case the effect of wind has been ignored, as the calculation is trying to isolate the effect of waves specifically, and the waves may not correspond directly with any specific wind scenario. The sea state is specified using significant wave height and peak period.



Wind		
Wind speed:	0.00	kt
Angle off bow:	0.00	deg
Gradient correction:	Off	
Exposed hull		
Transverse area:	0.000	m2
VCE above WL:	0.000	m
Profile area:	0.000	m2
Superstructure		
Superstructure shape:	Cargo ship	
Transverse area:	0.000	m2
VCE above WL:	0.000	m
Profile area:	0.000	m2
Seas		
Significant wave ht:	2.000	m
Modal wave period:	16.0	sec
Shallow/channel		
Water depth:	0.000	m
Type:	Shallow water	
Channel width:		m
Channel side slope:		deg
Hull girth:		m

Figure 3-30 - NavCAD Sea State Parameters

Having entered all the data, it is then necessary to choose the appropriate calculation formulas as listed on the following screen:



Vessel drag	Calc	ITTC-78 (CT)
Technique:		Prediction
Prediction:		Holtrop
Reference ship:		
Model LWL:	[m]	
Viscous		
Expansion:		Custom
Friction line:		ITTC-57
Hull form factor:	On	1.303
Speed corr:	On	
Spray drag corr:	On	Apply full (no defle...
Corr allowance:		0.000342
Roughness [mm]:	Off	
Catamaran		
Interference:	Off	
Added drag		
Appendage:	Off	
Wind:	Off	
Seas:	Calc	Aertssen
Shallow/channel:	Off	
Towed:	Off	
Margin:	Off	

Figure 3-31 - NavCAD Calculation Parameters

First, the method of predicting bare hull resistance is chosen, to do so, the dropdown is selected next to “Prediction” Here a list of possible prediction formulas will be listed, with the best fitting methods being listed near the top.

Method	Speed	Hull	Details
Holtrop	OK	OK	Uncertain
Oortmerssen	OK	Uncertain	OK
Fung (CRTS)	OK	Uncertain	OK
Fung (HSTS)	OK	Fail	OK
Jin (1988)	OK	Fail	OK
DeGroot (RB)	OK	Fail	OK
DeGroot (HC)	OK	Fail	OK
Mercier	OK	Fail	OK
Simple Planing	OK	Uncertain	Uncertain
Delft Series (2)	OK	Fail	Uncertain

Ranking: Best Good Fair Poor

Parameters		
FN [design]	0.06‥0.59	0.50
CP	0.55‥0.85	0.67
LWL/BWL	3.90‥14.90	4.41
BWL/T	2.10‥4.00	2.79
Lambda	0.01‥0.86	0.84

Figure 3-32 - NavCAD Bare Hull Prediction Method Selection

When selecting a method, the required range over which the method is valid is shown on the dialogue window to the right, this way the hull parameters can be confirmed to be within the range for which the prediction method is valid.

Next a hull form factor is selected:

Method	
Holtrop [ITTC57]	1.303
MARIN [Grigson]	1.296
Kostov	0.654
Hamburg EWB Series	1.370
BSRA Series	1.385
Granville	1.410

Parameters		
FN [design]	0.06‥0.59	0.50
CP	0.55‥0.85	0.67
LWL/BWL	3.90‥14.90	4.41
BWL/T	2.10‥4.00	2.79
Lambda	0.01‥0.86	0.84

Figure 3-33 - NavCAD Hull Form Factor

Which is determined in a similar way to the calculation method.

Similarly, the formulation for determining the effect of added drag is selected. In this case the best fit is the Aertssen method, which is a method used for predicting the effect of waves on high speed, slender hulls with bulbs, such as container ships. As the hull under consideration is a high speed, slender hull with a bulb this is a good choice.

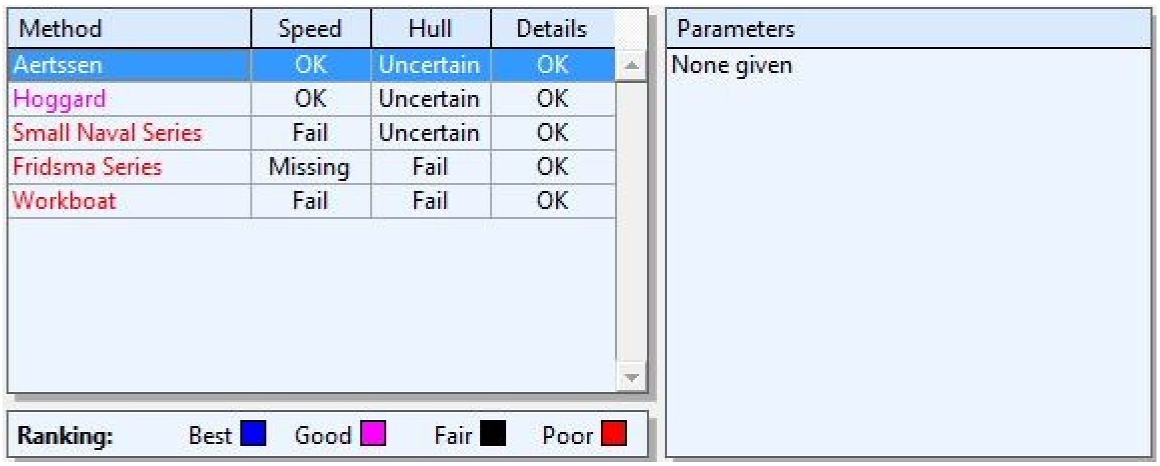
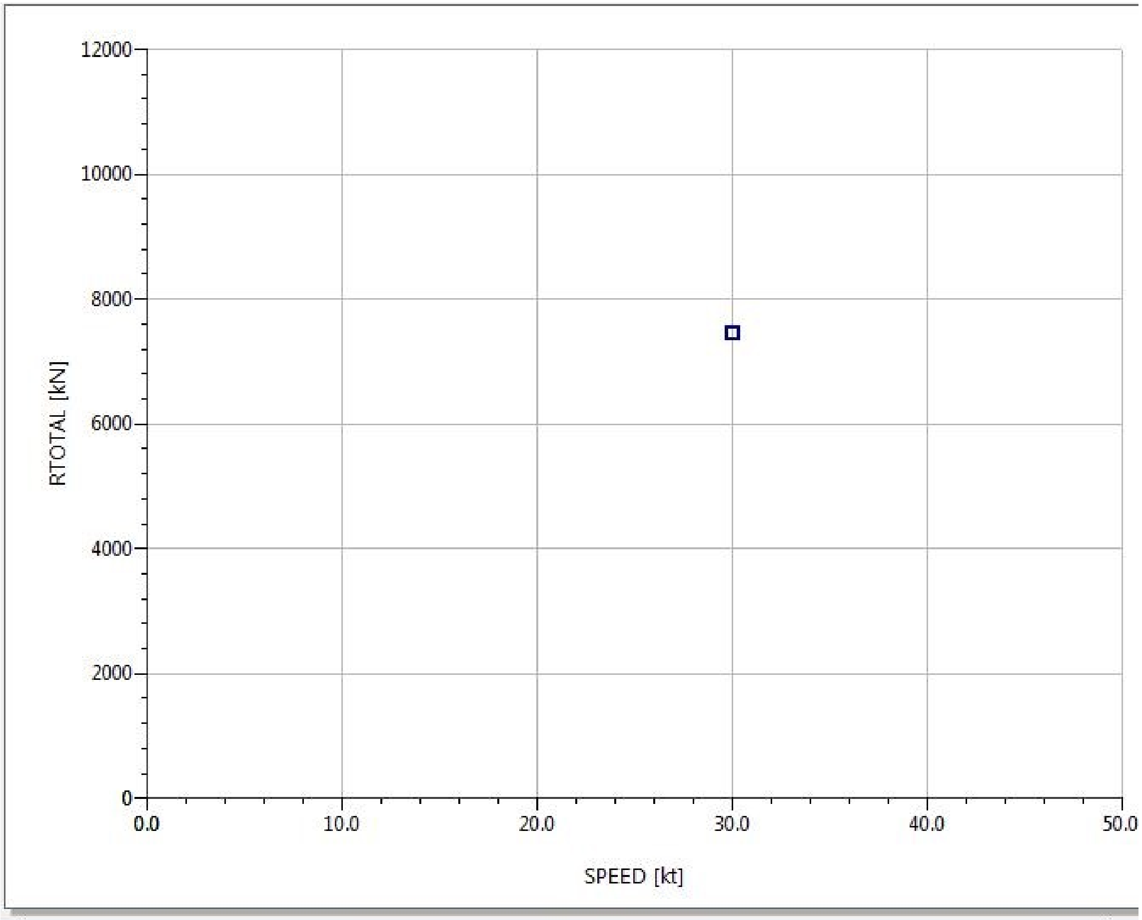


Figure 3-34 - NavCAD Wave Added Resistance Method Selection

With all the types of calculations and data entered, the resistance can then be calculated; a resistance plot is output from which the data can be read.



RESISTANCE AND EFFECTIVE POWER										
RBARE [kN]	RAPP [kN]	RWIND [kN]	RSEAS [kN]	RCHAN [kN]	RTOWED [kN]	RMARGIN [kN]	RTOTAL [kN]	PEBARE [kW]	PETOTAL [kW]	
6901.70	0.00	0.00	564.90	0.00	0.00	0.00	7466.60	106516.3	115234.6	0.2

Figure 3-35 - NavCAD Resistance Prediction

This was repeated for each of the 100 test cases to collect the required data, the raw results are presented in Appendix B – Resistance Test Program Data.

3.2.4. Results

The data collected was entered into the program Design Expert, in which ANOVA was performed to fit models to the data and develop prediction equations. This was done for each hull form; an example analysis is included below.

First, a model was fitted to the data; presented below is the model fitted using ANOVA to the data for an axe bow type of hull.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	4.98	10	0.4977	100.85	< 0.0001	significant
A-Length	0.0880	1	0.0880	17.84	0.0009	
B-Beam	0.1401	1	0.1401	28.38	0.0001	
C-Draft	0.3479	1	0.3479	70.50	< 0.0001	
D-Wave Height	0.0001	1	0.0001	0.0134	0.9093	
E-Peak Period	0.0004	1	0.0004	0.0750	0.7881	
F-Speed	4.23	1	4.23	857.78	< 0.0001	
AC	0.0723	1	0.0723	14.66	0.0018	
A^2	0.0326	1	0.0326	6.62	0.0221	
D^2	0.0191	1	0.0191	3.88	0.0690	
F^2	0.0344	1	0.0344	6.98	0.0193	
Residual	0.0691	14	0.0049			
Cor Total	5.05	24				

Figure 3-36 - Axe Bow Resistance ANOVA

This model was built using the Corrected Aikaike Information Criterion with forward regression, followed by removing terms which did not significantly impact the model fit to simplify the model. All lower terms required to ensure model hierarchy were included. The P-values of all terms other than those included for hierarchy show a very low probably of arising due to error, indicating they are larger influences on the outcome. The resulting model fit is checked by examining the model statistics below.

Std. Dev.	0.0702		**R^2**	0.9863
Mean	2.57		**Adjusted R^2**	0.9765
C.V. %	2.74		**Predicted R^2**	0.9497
			Adeq Precision	31.2864

Figure 3-37 - Axe Bow Resistance Model Fit

As can be seen from the predictors above the model shows a strong fit for the data collected, with an adjusted R^2 value of 0.9765.

To make sure that no other transform is needed we need to examine the box-cox plot to determine the best transform for the data.

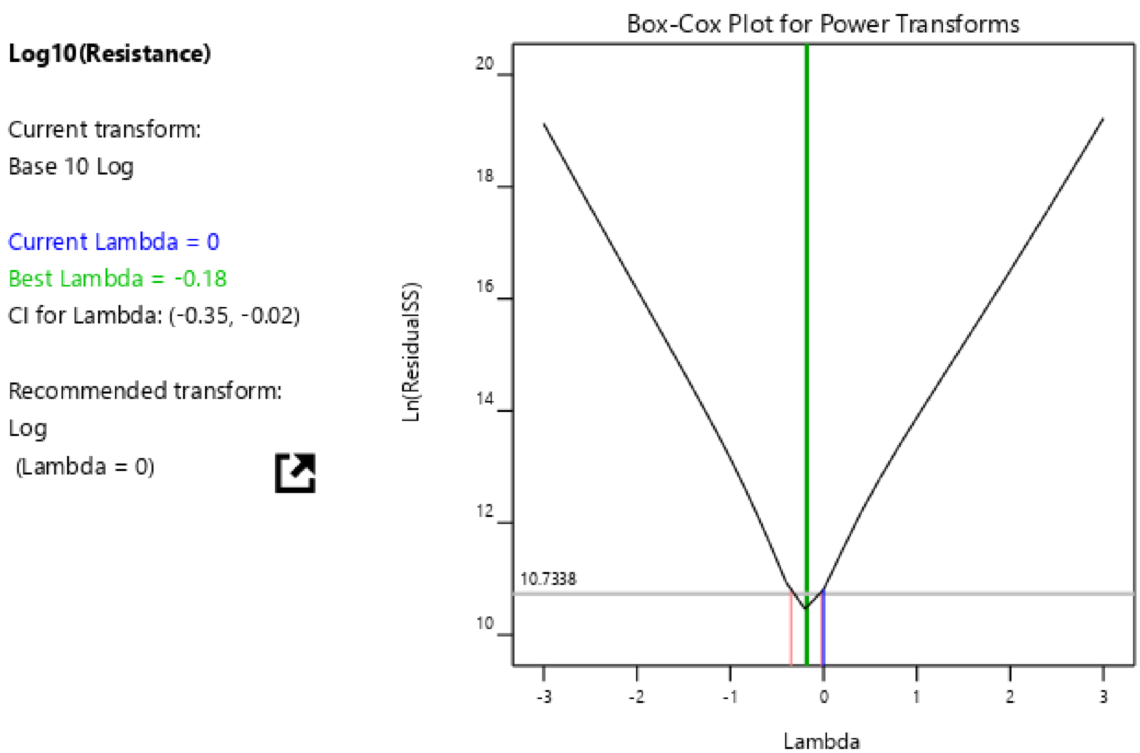


Figure 3-38 - Box-Cox Plot for Axe Bow Resistance

This plot shows that the transform selected (log transform) is a fairly good fit for the data presented, offering the closest value to the peak. The model quality can also be checked by examining the normal plot of residuals to look for any outliers which do not agree closely with the normal probability line, as these may indicate the model has not accurately captured the behavior at this point.

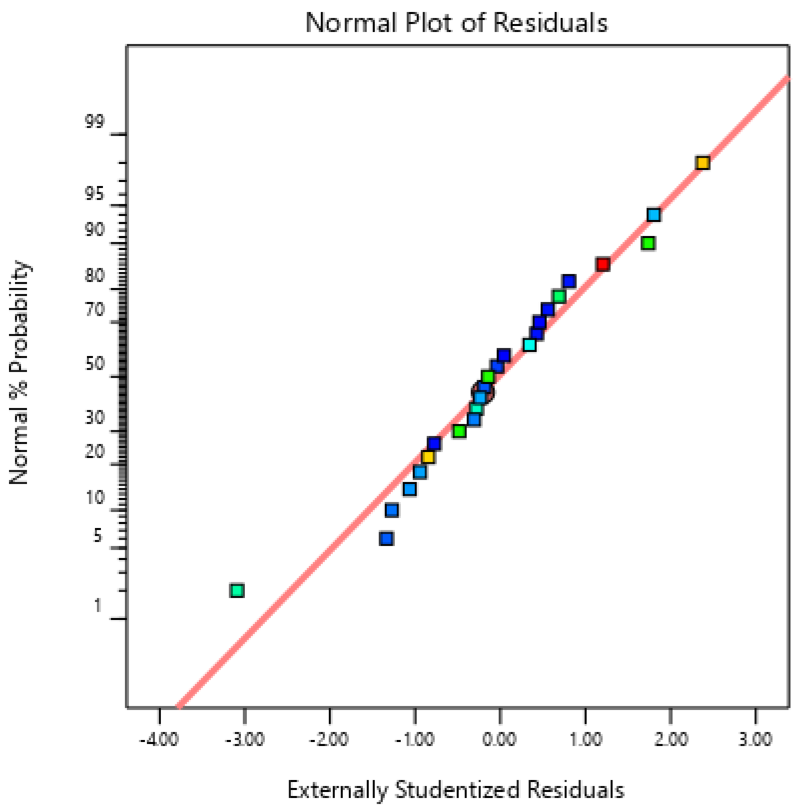


Figure 3-39 - Plot of Residual Axe Bow Resistance

This plot shows the error between the model and the predicted as a probability of occurring due to noise. The closer the points fall to the line, the better the fit. In this case all the points show a good alignment with the normal probability line, indicating that the model has fit the data well. We can also check the quality of the model by comparing the predicted values based on the model to the real data set, as shown below.

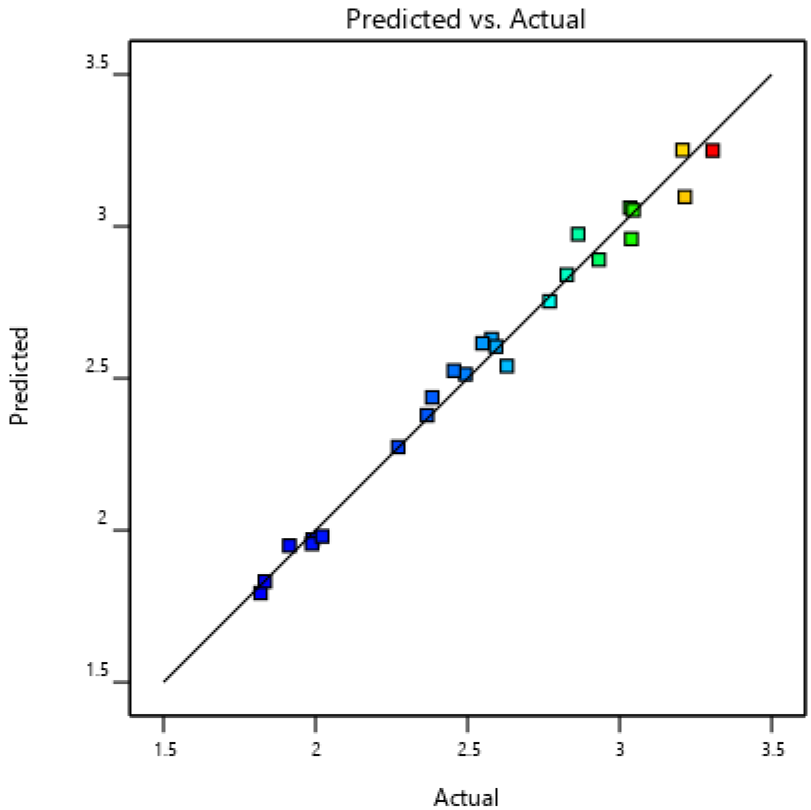


Figure 3-40 - Axe Bow Resistance Model Fit

This plot shows the fit of the data points versus the predicted value from the formula, as can be seen the line of the prediction is a good fit for the data input and shows a strong model for this data.

Similar model fitting approaches were taken for the other hull types; additional analysis of variance tables and plots of their fit characteristics are shown in Appendix E: Additional ANOVA Results for Resistance Prediction

Having analyzed the data, equations were developed to represent each of the models, and are summarized below:

Axe Bow Resistance:

$\log_{10} R = -0.085 - 0.0087\,L + 0.021\,B + 0.25\,T + 0.14\,H_s + 0.094\,V - 0.0019\,L\,T + 0.000096\,L^2 - 0.017\,{H_s}^2 - 0.00091\,V^2$ (Equation 3.13)

Bulbous Bow Resistance:

$log_{10} R = -0.94 + 0.010\,L + 0.025\,B + 0.19\,T + 0.032\,H_s + 0.14\,V - 0.0013\,L\,T - 0.00035\,L\,V - 0.00069\,V^2$ (Equation 3.14)

Vertical Bow Resistance:

$log_{10} R = -4.16 - 0.012\,L - 0.087\,B + 1.19\,T + 0.10\,H_s + 1.19\,T_p + 0.054\,V + 0.00024\,L\,B - 0.19\,T\,T_p - 0.0049\,H_s\,T_p + 0.0023\,B^2 - 0.049\,{T_p}^2 + 0.0080\,T\,{T_p}^2$

(Equation 3.15)

X Bow Resistance:

$\log_{10} R = -2.32 - 0.0029\,L + 0.027\,B + 0.65\,T + 0.036\,H_s + 0.59\,T_p + 0.070\,V - 0.00015\,L\,V - 0.098\,T\,T_p - 0.025\,{T_p}^2 + 0.0042\,T\,{T_p}^2$ (Equation 3.16)

3.2.5. Model Verification

In order to assure the quality of the model, the equations were used to predict points which were then verified by testing. To do so an additional 5 test cases were chosen at random as follows:

Table 3-11 – Resistance Model Verification Tests

Run Number	L	B	T	H_s	T_p	V
1	67.5	18.75	6.5	3.5	13	22.5
2	112.5	23.75	6.5	5.5	11	22.5
3	67.5	16.25	6.5	2.5	9	27.5
4	82.5	23.75	7.5	4.5	13	17.5
5	82.5	21.25	4.5	5.5	13	27.5

Each random case option was assigned at the midpoints of existing data to capture the behavior of the model between datapoints.

The test cases were run for each hull and show the results as follows:

Table 3-12 – Axe Bow Resistance Verification Results

Axe Bow Validation			
Run Number	R Predicted	R Actual	Percent Error
1	789	898.95	12.2
2	639	521.08	22.6
3	1147	1054.83	8.7
4	516	513.06	0.6
5	739	607.17	21.7
		Average Error	13.2

Though these results show that the model is not ideal, in this case it is acceptable due to a few special considerations as follows.

First of all, as this data has been transformed by the logarithm the resulting values are the exponent of 10^x which for these values, a very small error in the calculated log value results in a much larger overall error, for example for a 899 kN resistance, a 12.2 percent error as calculated corresponds to only a 1.7 % error in the log value calculated. This model is intended to simplify a complex calculation for concept level estimates, therefore due to the complexity of the original model, it is not likely that a better fitting simplified model could be developed from the data, unless the model is very complicated, which defeats the purpose of developing a simplified model.

Also, as this data will be used across many different operating conditions, and the resulting fuel requirements averaged over a year of varying conditions, the overall average accuracy is a better indicator of the quality of the predictor. In this case, though some results individually are not seeing great accuracy, the overall accuracy of the predictor is generally acceptable when averaged out over multiple cases.

Table 3-13 – Bulbous Bow Resistance Verification Results

Bulbous Bow Validation			
Run Number	R Predicted	R Actual	Percent Error
1	1973	2637.43	25.2
2	1641	1664.10	1.4
3	4070	3937.34	3.4
4	1079	1009.06	6.9
5	3461	4455.93	22.3
		Average Error	11.8

Similarly to the axe bow validation, these these results are not ideal, they do nonetheless show a model which fits close enough for the purposes of simplifying and selecting concept level designs, once accounting for the logarithmic transform and the effect of averaging over multiple operating conditions.

Table 3-14 – Vertical Bow Resistance Verification Results

Vertical Bow Validation			
Run Number	R Predicted	R Actual	Percent Error
1	2507	3339.58	24.9
2	2366	2240.80	5.6
3	4136	5159.35	19.8
4	1830	1828.21	0.1
5	4110	4706.83	12.7
		Average Error	12.6

The vertical bow model shows a validated accuracy consistent with those used for other hull types and therefore has been considered acceptable.

Table 3-15 – X Bow Resistance Verification Results

X Bow Validation			
Run Number	R Predicted	R Actual	Percent Error
1	2496	3058.84	18.4
2	2128	2017.74	5.5
3	4138	4836.71	14.4
4	1852	1681.54	10.1
5	3698	4408.36	16.1
		Average Error	12.9

The X bow model shows a validated accuracy consistent with those used for other hull types and therefore has been considered acceptable.

3.3. Stability & Displacement Prediction

3.3.1. Introduction

Having determined the performance of a hull in seas and its corresponding resistance, it is also necessary to consider the initial stability of the vessel. The results above can point to an efficient hull design; however, they fail to reject vessels which due to their design would have a negative GM value and would therefore be unsuitable. Further, it is essential that the vessel cargo carrying capacity is understood and so it is also necessary to determine the displacement of the vessel. As a result, a model was developed to predict the initial stability and displacement of the hull forms to allow for quick rejection of those which are unsuitable.

The stability of the vessels was determined using the calculated KM values and known KB values shown in DelftShip for the hull chosen. The displacement was read directly for each hull form.

This allows for the fitting of a model to predict the BM and displacement of any of the hulls, as these are a property of the hull shape itself. When combined with the known KB for the hull and subtracting the estimated VCG of the hull, the initial stability GM of the hull can be determined. Vessel cargo capacity can be determined by subtracting an empirically derived lightship weight of the hull from the total displacement.

3.3.2. Design of Test Program

The method chosen to develop this model was the uniform design method as higher order responses were expected (BM may depend on the cube of beam for example) and the model is based on a computer prediction. To account for this higher order, the model consists of 3 factors, 5 levels. These factors are length, beam, and draft, as these are the only varied parameters in the model.

The length has been constrained between 60 and 120 m as this is the expected maximum range for an OSV design, the beam has been constrained between 15 and 25 m as this represents the full range of typical breadths expected, and drafts have been varied between 4 and 8 m representing the full range of expected drafts.

A uniform design of 15 runs was chosen for each hull as it offers a good discrepancy value of 0.0131, and additional runs experience significant diminishing returns. The resulting test program design was as follows:

Table 3-16 – Stability Prediction Uniform Design

Run Number	Length (m)	Beam (m)	Draft (m)
1	60	25	6
2	60	15	4
3	90	17.5	5
4	90	15	8
5	75	20	5
6	105	17.5	7
7	120	15	6
8	105	22.5	5
9	75	17.5	7
10	120	25	8
11	105	22.5	6
12	60	20	8
13	75	22.5	7
14	120	20	4
15	90	25	4

3.3.3. Test Run Characterization

To determine stability and displacement a series of hull models were generated in DelftShip based on the above test program, generated from the 4 primary hull types used in the previous models. An example hull is shown below:

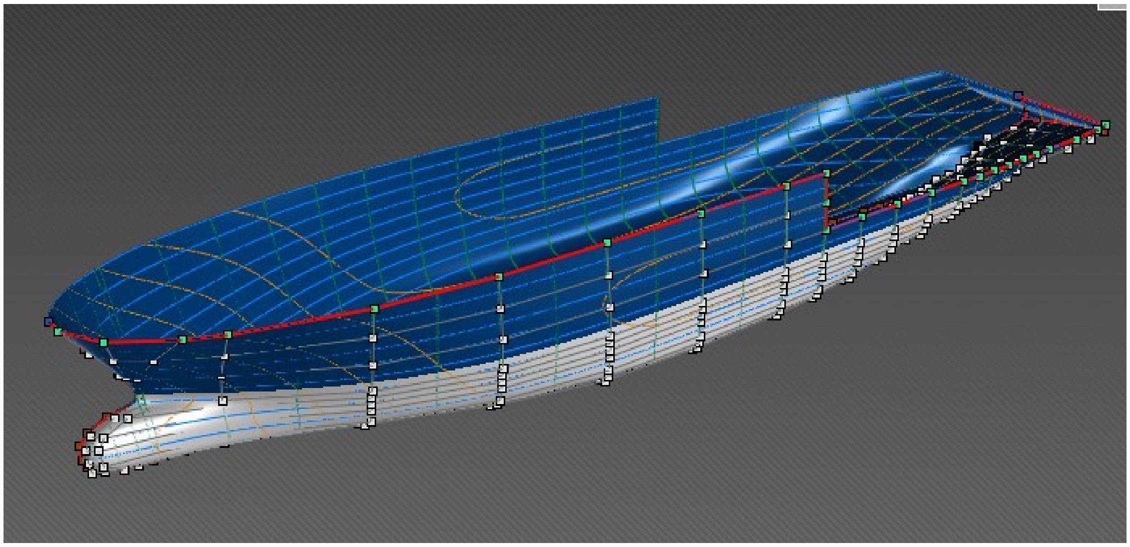


Figure 3-41 - Example Stability and Displacement Hull

In each case, the design hydrostatics report was consulted based on the hull, to determine the value for BM and displacement corresponding to each hull. This was repeated for each hull and each parent hull type for a total of 60 test runs.

The data collected is shown in Appendix C - Stability and Displacement Test Program Data.

3.3.4. Results

The first result observed from the data was to determine the position of the VCB of each hull. This was found to be a consistent ratio of the vessel draft for each hull as expected due to the scaling of the hulls.

This ratio was found as follows:

Axe Bow Hull: KB = 0.81725 T

Bulbous Bow Hull: KB = 0.5505 T

Vertical Bow Hull: KB = 0.55225 T

X Bow Hull: KB = 0.5584 T

The second result observed was the determination of a model to predict the BM and displacement of a vessel. This was done by analyzing the data in the DesignExpert software and fitting a model similar to that performed for the motions and resistance test programs. ANOVA for the Axe Bow model stability is demonstrated below. Additional ANOVA for stability and displacement for each hull type is included in Appendix F: Additional ANOVA for Stability Prediction.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.5543	4	0.1386	44178.24	< 0.0001	significant
B-Beam	0.2255	1	0.2255	71878.74	< 0.0001	
C-Draft	0.1678	1	0.1678	53479.16	< 0.0001	
B^2	0.0019	1	0.0019	594.86	< 0.0001	
C^2	0.0017	1	0.0017	532.45	< 0.0001	
Residual	0.0000	10	3.137E-06			
Cor Total	0.5544	14				

Figure 3-42 - BM ANOVA Table

Std. Dev.	0.0018		**R^2**	0.9999
Mean	1.13		**Adjusted R^2**	0.9999
C.V. %	0.1574		**Predicted R^2**	0.9999
			Adeq Precision	725.5618

Figure 3-43 - BM Model Accuracy

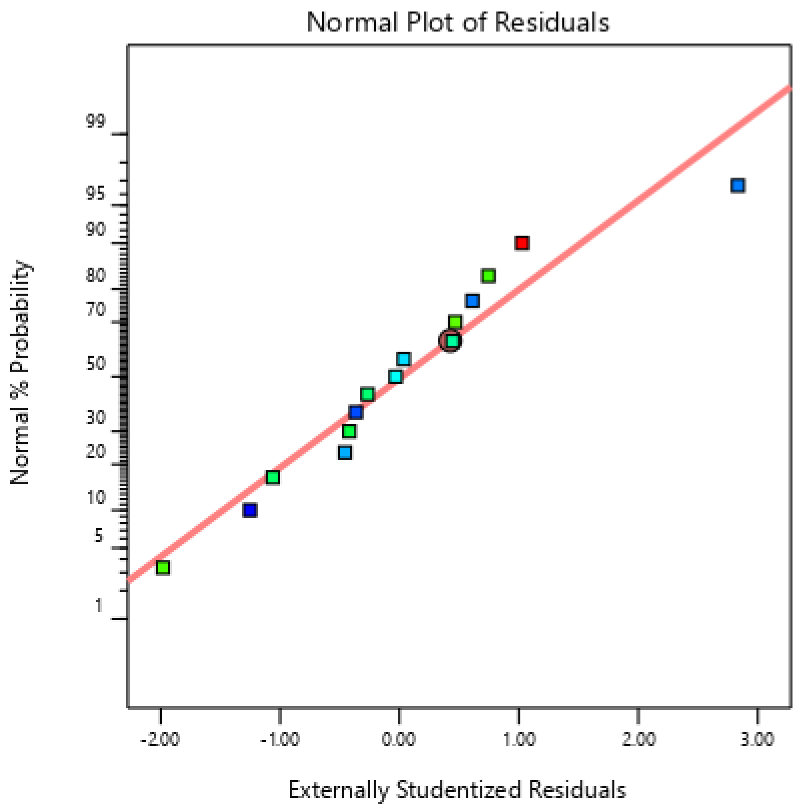


Figure 3-44 - BM Normal Plot

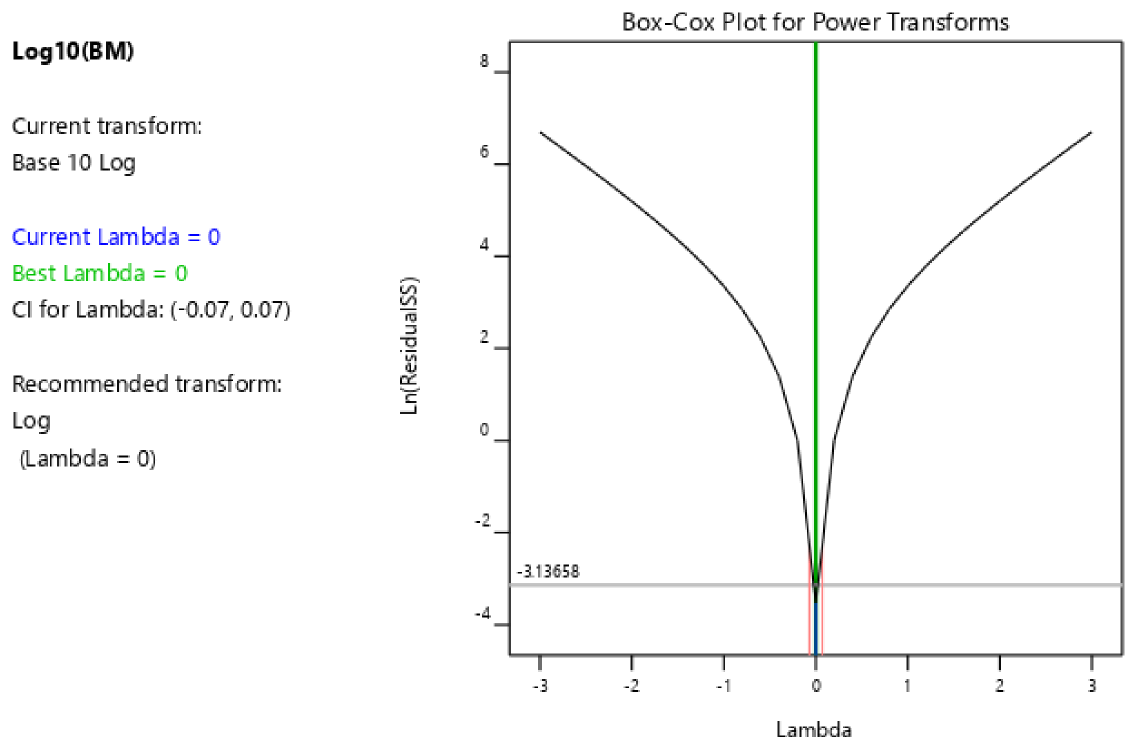


Figure 3-45 - BM Box-Cox Plot

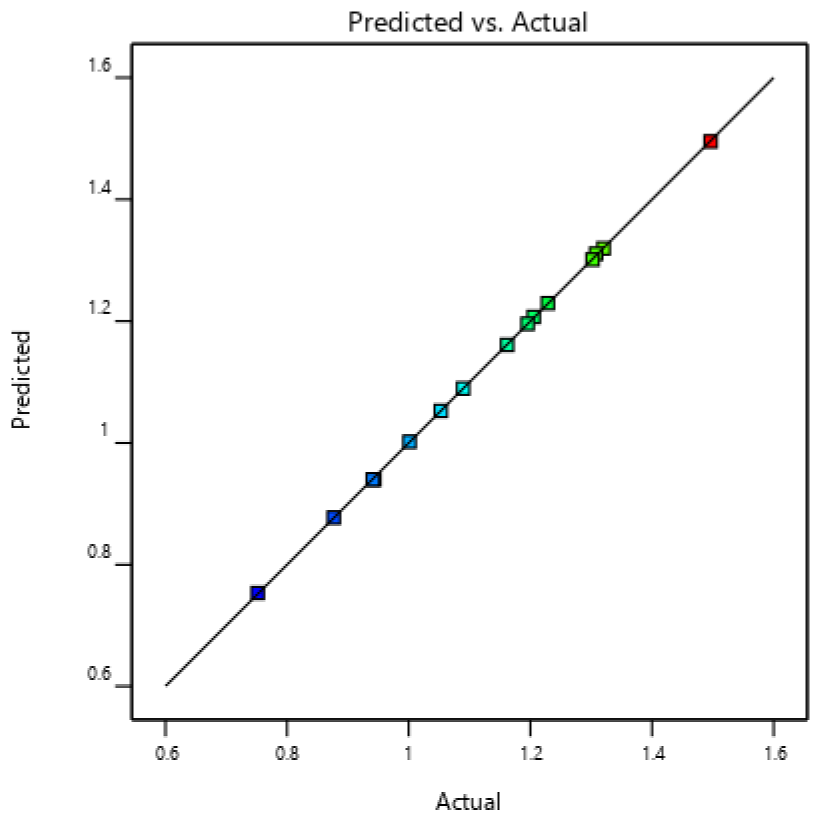


Figure 3-46 - BM Model Accuracy Plot

The resulting equations describing the stability and displacement of the hulls is as described below:

<u>Axe Bow Hulls</u>

$\log_{10} BM = 0.49 + 0.088\,B - 0.15\,T - 0.0011\,B^2 + 0.0065\,T^2$ (Equation 3.17)

$\Delta = 1860.05 - 22.78\,L - 97.21\,B - 325.45\,T + 1.11\,L\,B + 3.70\,L\,T + 16.61\,B\,T$ (Equation 3.18)

<u>Bulbous Bow Hulls</u>

$\log_{10} BM = 0.12 + 0.088\,B - 0.15\,T - 0.0011\,B^2 + 0.0064\,T^2$ (Equation 3.19)

$\Delta = 7358.70 - 86.22\,L - 384.20\,B - 1287.21\,T + 4.39\,L\,B + 14.63\,L\,T + 65.66\,B\,T$ (Equation 3.20)

Vertical Bow Hulls

$\log_{10} BM = 0.13 + 0.088\,B - 0.15\,T - 0.0011\,B^2 + 0.0064\,T^2$ (Equation 3.21)

$\Delta = 7253.76 - 84.99\,L - 378.88\,B - 1268.95\,T + 4.32\,L\,B + 14.42\,L\,T + 64.75\,B\,T$ (Equation 3.22)

X Bow Hulls

$\log_{10} BM = 0.13 + 0.088\,B - 0.15\,T - 0.0011\,B^2 + 0.0064\,T^2$ (Equation 3.23)

$\Delta = 7086.32 - 83.04\,L - 369.82\,B - 1239.96\,T + 4.22\,L\,B + 14.09\,L\,T + 63.23\,B\,T$ (Equation 3.24)

3.3.5. Validation

The stability and displacement models fitted were then validated by comparing the predicted value for BM and displacement based on the model against a calculated BM and displacement for the same hull, based on a design which falls between the datapoints. To do so an additional 5 test cases were chosen at random as follows:

Table 3-17 – Stability Model Verification Tests

Case	Length (m)	Beam (m)	Draft (m)
1	112.5	21.25	4.5
2	97.5	23.75	4.5
3	67.5	21.25	7.5
4	67.5	18.75	6.5
5	67.5	21.25	5.5

The test cases were run for each hull and show the results as follows:

Table 3-18 – Axe Bow Stability Verification Results

Axe Bow Validation						
Run Number	BM Predicted	BM Actual	Percent Error	Displacement Predicted	Displacement Actual	Percent Error
1	20.24	20.15	0.4%	1990	1982	0.4%
2	25.30	25.16	0.6%	1928	1920	0.4%
3	12.07	12.09	0.2%	1993	1982	0.6%
4	10.79	10.86	0.6%	1502	1516	0.9%
5	16.53	16.48	0.3%	1439	1453	1.0%
		Average Error	0.4%	Average Error		0.7%

Table 3-19 – Bulbous Bow Stability Verification Results

Bulbous Bow Validation						
Run Number	BM Predicted	BM Actual	Percent Error	Displacement Predicted	Displacement Actual	Percent Error
1	8.83	8.79	0.5%	7869	7836	0.4%
2	11.04	10.98	0.5%	7625	7590	0.5%
3	5.27	5.27	0.0%	7880	7836	0.6%
4	4.71	4.74	0.6%	5938	5992	0.9%
5	7.22	7.19	0.4%	5689	5747	1.0%
		Average Error	0.4%	Average Error		0.7%

Table 3-20 – Vertical Bow Stability Verification Results

Vertical Bow Validation						
Run Number	BM Predicted	BM Actual	Percent Error	Displacement Predicted	Displacement Actual	Percent Error
1	8.96	8.91	0.6%	7761	7728	0.4%
2	11.19	11.13	0.5%	7520	7486	0.5%
3	5.34	5.35	0.2%	7772	7728	0.6%
4	4.78	4.80	0.4%	5856	5910	0.9%
5	7.32	7.29	0.4%	5611	5667	1.0%
		Average Error	0.4%	Average Error		0.7%

Table 3-21 – X Bow Stability Verification Results

X Bow Validation						
Run Number	BM Predicted	BM Actual	Percent Error	Displacement Predicted	Displacement Actual	Percent Error
1	9.00	8.96	0.4%	7579	7547	0.4%
2	11.25	11.19	0.5%	7344	7311	0.4%
3	5.37	5.38	0.2%	7589	7547	0.6%
4	4.80	4.83	0.6%	5719	5772	0.9%
5	7.36	7.33	0.4%	5480	5535	1.0%
		Average Error	0.4%	Average Error		0.7%

Based on these results, it can be observed that the models proposed are a very strong fit for predicting the stability and displacement values for these vessels and can be suitably used in the optimization problem.

4. Chapter 4: Design Optimization for Offshore NL

4.1. Introduction

Having developed models to predict the response of vessel designs, the next step is to use these models to optimize a design for the Flemish Pass basin.

Optimization is a complex process which relies on a variety of inputs, design options, and competing priorities, which are not easily solved. To get past this, a probabilistic model based on a Monte Carlo simulation is used to generate likely sea states over the vessel life, which is then used as an input to analyze many possible hull designs and select the most cost effective based on total cost to operate.

4.2. Environmental and Operational Characterization

4.2.1. Environmental Conditions

To analyze the performance of various designs, it is necessary to first understand probabilistically the likely sea states and their distribution. This is done by fitting a regression curve to the wave height and peak period data.

The data selected for this was the hindcast data from MSL WW3 Global ST4 0.5° at 47.5° N, 46.5° W, [26] which corresponds approximately to the location of the Bay du Nord well in the Flemish Pass. [28]

This data set includes joint probability data showing the recorded counts for wave heights and periods. By taking the total datasets and plotting histograms of the wave heights and periods it is possible to fit a probability density curve that represents the data well. Histograms of the data are shown below:

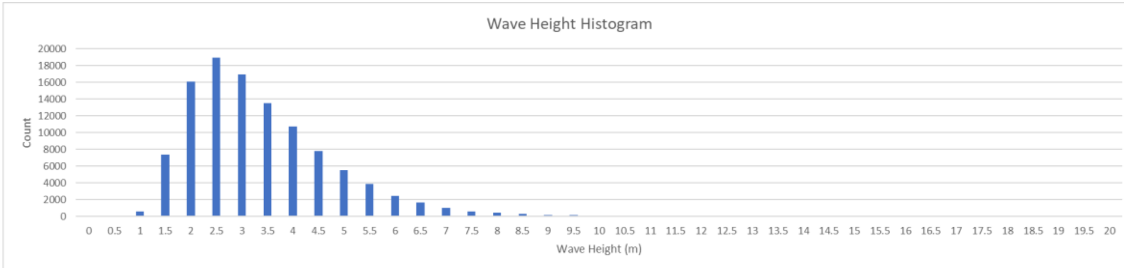


Figure 4-1 - Wave Height Distribution Histogram

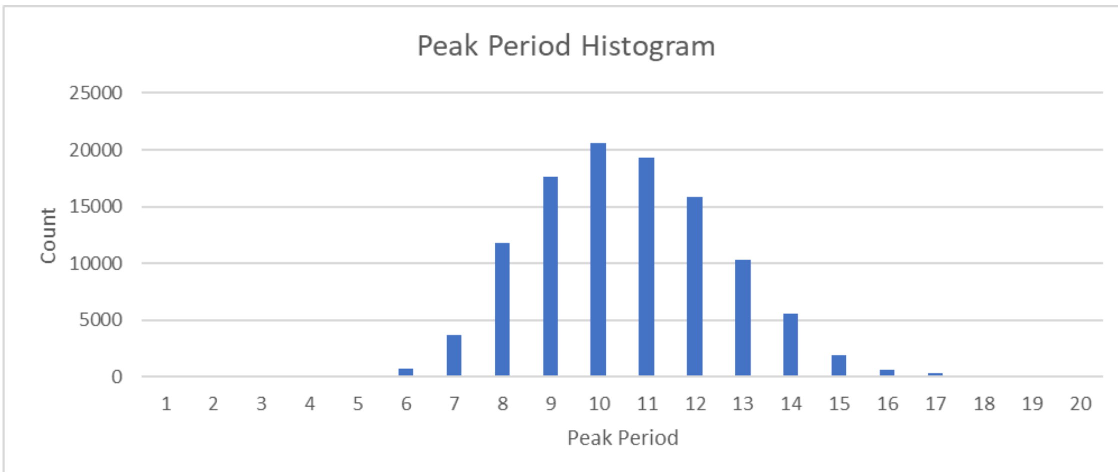


Figure 4-2 - Peak Period Distribution Histogram

Having developed histograms, it is then possible to fit a representative curve to the data to estimate the probability of occurrence for given sea states. Based on the histogram shapes, the proposed models are a Gumbel distribution for the wave heights and a normal distribution for the peak period.

As the data above only defines the relative probability of a range, it does not fully capture a proper probability density function; instead a cumulative probability function can be written based on the combined probability of all events below a specific value.

For the wave heights, a Gumbel plot was regressed onto this cumulative density function giving the parameters μ =2.458 and β = 1.101, these parameters show a strong model fit, giving an R-squared of 0.9996. The cumulative and probability density functions are shown below.

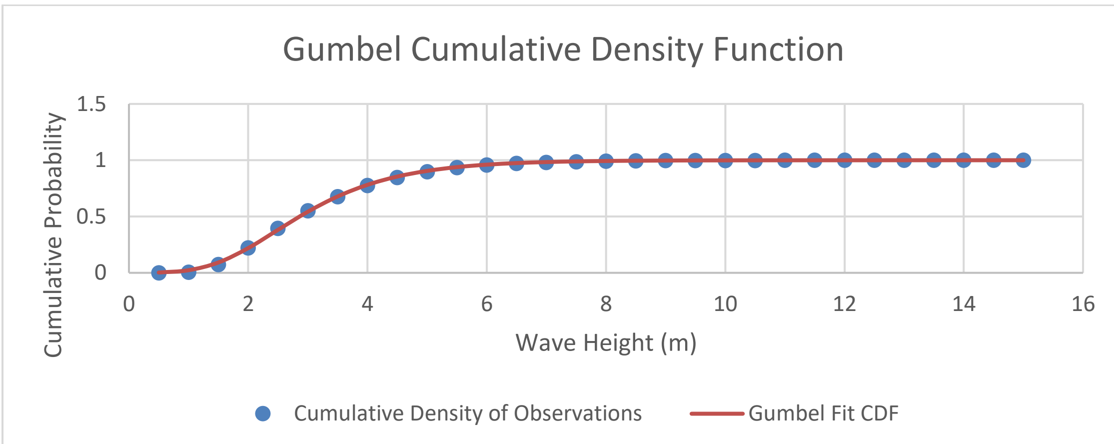


Figure 4-3 - Wave Height Gumbel Cumulative Probability Function

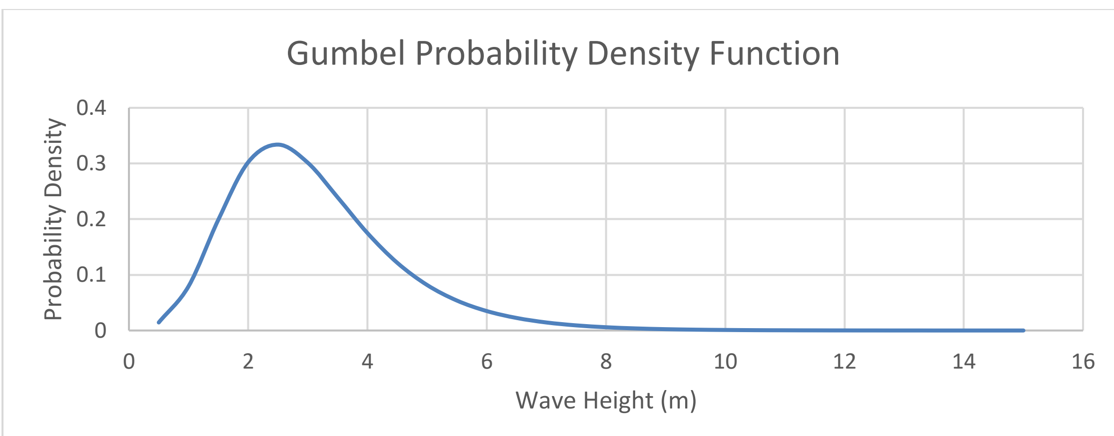


Figure 4-4 - Wave Height Gumbel Probability Density Function

Similarly, for wave height, the period distribution was determined using the cumulative probabilities of wave records, fitting a normal distribution gives a μ of 10.05 and a σ of

2.008 with an R-squared of 0.9996. The cumulative and probability density plots are shown below:

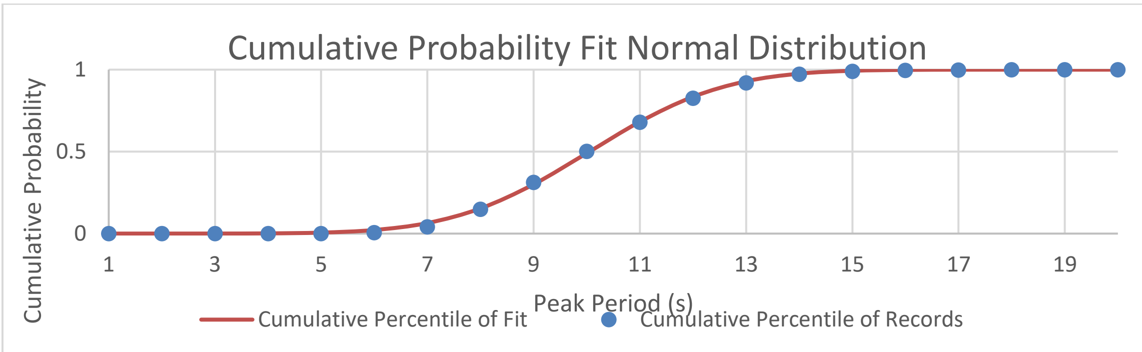


Figure 4-5 - Peak Period Cumulative Distribution Fit

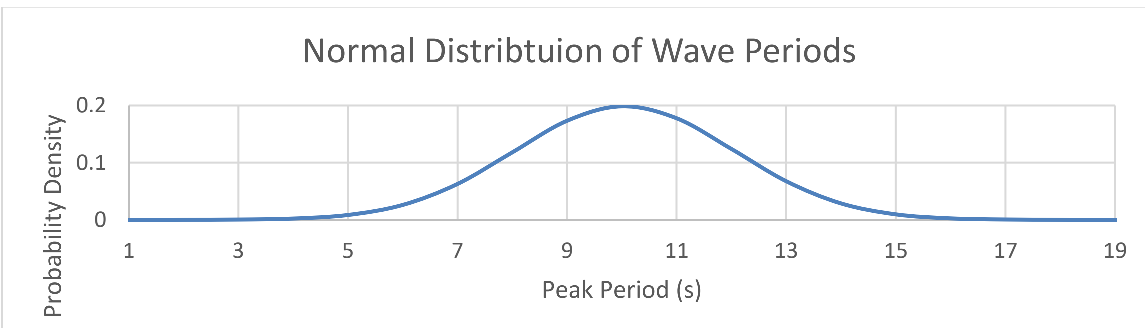


Figure 4-6 - Peak Period Probability Density Function

These distributions will be useful when generating sea states from a Monte Carlo simulation, as the input into the optimization algorithm.

It is noted that this approach assumes independence of the wave height and period variables, which does not quite represent reality as these are somewhat correlated; in particular, the resulting simulation can produce waves which due to large wave height and short period would break up in reality.

To address this, the algorithm includes a break to eliminate impossible sea states and regenerate new cases. Using the wave and period joint probability for the Flemish Pass Basin it is observed that the boundary of possible sea states occurs approximately when $H_s <= T_p - 2$. [29]

This is a simplified model; a more accurate model would require a full 2D joint probability. Such a model, though more precise, would be difficult to represent mathematically and would prove difficult to build an efficient method for generating random samples for the Monte Carlo simulation.

It is expected that the chosen simplification will not significantly impact the results of this study, as the probability plots are derived directly from hindcast sea states and as a result, though they are assumed as independent, the combined probabilities of outcomes occurring will closely align with the 2D joint probability.

Despite the suitability of the simplified model, it is suggested that future studies be performed with a better sea state probability definition to determine the sensitivity of the results to fringe cases.

4.2.2. Operational Requirements

In addition to wave states it is necessary to understand the operational requirements and limits for the field to support the vessel design requirements.

The first characteristic required is to determine the distance vessels must travel to the offshore site. Assuming a base of operations at St. John's and the field location at 47.5 N 46.5 W, the distance results in an estimated voyage of 250 Nautical Miles.

Logistics of platform support typically dictates a continuous cargo schedule which repeats to provide consistent deliveries of supplies without overloading vessels or platform storage capacity. The details of these deliveries have been taken as a specific case based on the cargo operations of the Hebron platform, an existing platform on the Grand Banks [30]. A schedule cycle has been taken at 72 hours per cycle consistent with the OSV Atlantic Hawk, which is a vessel representative of typical OSVs operating on the Grand Banks. The platform is estimated to require deliveries totaling 10,200 m^2 of deck area and 21,000 m^3 of bulk cargo per month, giving 1006 m^2 and 2071 m^3 respectively per cycle.

One of the major considerations for the development of vessels operating on the Flemish Pass Basin is both the distance and presence of fog offshore. Due to the distance of the field, it is out of the range of a fully loaded Sikorski S-92 Helicopter, the typical helicopter used in the NL offshore industry. Further, fog conditions prevent the helicopter from landing on the platform making crew change difficult [31]. Vessels operating on the Flemish Pass Basin therefore are very likely to have to take on significant crew change roles, requiring personnel transfer offshore using personnel transfer devices [32]. An example of such a device is the Frog-6 Personnel Transfer Device by Reflex Marine, which has been the assumed transfer device for the purposes of this study. As crew need to be safely moved and have lower movement limits than general cargoes, it is expected that the maximum movement criteria for the Frog capsule will determine whether it is safe to operate the vessel or if the vessel should wait on a weather window. Assuming a

Frog-6 personnel transfer device, the vertical velocity for ship operations is limited by a total impact velocity of 4.0 m/s [33].

At the depth of water in the Flemish Pass Basin, it is unlikely that fixed platforms would be used, most likely based on what is currently operating in the NL offshore, we would be looking at the use of a Floating Production Storage and Offloading Vessel (FPSO).

The total relative velocity between an FPSO, the Vessel, and the crane hook velocity is found by using the formula [33]:

$$Relative\ Velocity = Hook\ Velocity + \sqrt{Vessel\ Deck\ Velocity^2 + Crane\ Tip\ Velocity^2}$$

(Equation 4.1)

The Frog-6 user manual considers that the hook velocity typical for lifts under 5 mt is 1.67 m/s, and therefore the limiting velocity, based on equation 4.1, for the FPSO and vessel is limited to a maximum of 2.33 m/s.

In order to determine a vessel limit, it would be necessary to perform a study in every sea state in which the FPSO motions are estimated at the same time; however, this would require an understanding of the FPSO design in detail. In this case to allow for preliminary design, the motions of an FPSO have been estimated based on a typical FPSO built from a converted Very Large Crude Carrier (VLCC). These FPSO's rely on a turret in the middle and weathervane with the sea conditions.

Using the paper *The modeling of seakeeping qualities of Floating Production, Storage and Offloading (FPSO) sea-going ships in preliminary design stage* [34] based on an

FPSO with the length of the Terra Nova FPSO currently operating in the NL Offshore (292m), and a peak sea state of 3.0m significant wave height (the maximum wave condition recommended for transfer from an FPSO per the frog manufacturer), corresponding to a peak period of around 10 seconds, the amplitude of the heave and pitch velocity can be estimated. Deriving the heave and pitch motion for a period corresponding to the peak period, the deck velocity and pitch rate are found. The velocity due to pitch is considered in a worst-case scenario that the cranes of the FPSO are located at the vessel extremities, where pitch introduces the maximum velocity. Combining these allows for an estimate of the total combined deck velocity of the FPSO.

Given this, the FPSO deck velocity has been estimated to 1.99 m/s significant velocity. Working backwards from the maximum combined velocity of 2.33 m/s this imposes a limit on the OSV deck velocity for crew transfer of 1.21 m/s. Given that these are both significant velocities, there remains some risk of exceeding these velocities, which the Frog-6 cannot accommodate, to provide a factor of safety the maximum velocity has been decreased by a factor of 2 to 0.6 m/s.

This approach is a simplification of the FPSO motions due to a lack of detail about the FPSO and operating conditions. It is not expected to have a very large effect in this case, as the allowable motions have been derated to account for uncertainty and allows for a like for like comparison between vessels at a concept level. A more detailed design study can be performed incorporating direct simulation of both and OSV and FPSO simultaneously in the same sea states, to determine the relative motions and velocities between the vessels. This would allow us to fully understand the maximum operable sea states, to support more detailed operational planning and refinement of concept level designs.

It is required in the NL offshore that a vessel must always be on standby, and therefore, we must always account for one vessel to be in the field.

Another operational requirement of interest is that of the vessel Bollard Pull, this is not of interest to all OSVs, but for Anchor Handling Tug Supply Vessels (AHTS) operating on the grand banks significant ice management roles exist for which a significant bollard pull is required.

As this is secondary to the cargo and crew resupply role the bollard pull has not been added to the optimization algorithm. Further, the required bollard pull requirement is not fully understood for the Flemish pass basin region, as this region will experience different iceberg conditions than those typical of the Grand Banks.

Instead, the bollard pull is checked for the optimized concepts based on their required power, which the designer can then review and confirm if the bollard pull is sufficient for their needs.

The bollard pull is determined using the equations for estimating bollard pull during concept design by Wartsila: [35]

$$BP = \frac{2}{3} \times \frac{D \times P_d \times k_1 \times k_2}{9.81} \text{ (Equation 4.2)}$$

Where:

- BP = Bollard Pull (ton)
- K_1 = 0.9 (Efficiency loss)
- K_2 = 1.2 (Efficiency gain for propellor in nozzle)
- D = Propellor diameter (m)
- P_d = Delivered power (kW)

The delivered power is known for the vessels due to the resistance and powering calculations in the optimization algorithm, however the propellor diameter is not known at the time of study.

The propellor diameter is estimated based on typical hull values and is taken as 0.65 times the draft of the vessel, consistent with bulk cargo vessels. [36]

4.2.3. Typical Vessel Parameters

For high level optimization it is necessary to determine several characteristics common to OSVs to ensure that the vessels can accommodate the operational requirements, including cargo parameters, cost to build, crewing costs, and dynamic positioning fuel costs for standby vessels.

First it was necessary to estimate the coefficients relating cargo capacities to vessel displacement and size. This was done by taking values from datasheets for several vessels operating in similar environments to the Newfoundland Offshore. [37] [38] [39] [40] [41] [42] These were used to calculate parameters for the vessels relating bulk cargo volume to displacement and deck area to block waterplane area, which were then averaged to find a representative parameter value for vessel design optimization. The results of this are shown in the table below:

Table 4-1 – Cargo Coefficient Determination

Ship / Design	Displacement (Estimated)	Bulk Cargo (m^3)	Block Area (m^2)	Deck Area (m^2)	Bulk Ratio	Area Ratio
Wartsila VS 4622	8280	3000	1675	750	0.36	0.45
PSV 5000	7895	2970	1870	940	0.38	0.50
UT 722 L	5351	800	1247	570	0.15	0.46
Maersk Clipper	9655	5126	1857	545	0.53	0.29
Maersk Detector	8968	4654	1839	755	0.52	0.41
Maersk Leader	10529	4000	2076	810	0.38	0.39
Maersk Handler	6178	1949	1440	527	0.32	0.37
				Average	0.38	0.41

Next it was necessary to estimate the construction costs for OSVs. This is typically a closely guarded trade secret of shipyards, however an approach to preliminary cost estimation has been presented in the article *Parametric Method of Preliminary Prediction of the Ship Building Costs,* by Jan P. Michalski [43].

This paper divides vessel costing into 3 components: Hull, Equipment, and Power Plant, each of which features a regression model to estimate cost based on the weight of the vessel, which can be estimated by subtracting the deadweight capacity from the displacement. This has been used as a base estimate cost for the vertical hull OSV design (considered the baseline), which will be factored to account for the other vessel types.

Using this paper, the OSV costs have been assessed using the cost estimates of a single deck hull, with high standard equipment (due to the high demands of the Newfoundland

Offshore and Canadian flag state). This results in providing a cost estimate for the vessel of $C = qs * ms + qh * me + qp * mp$ (Equation 4.3)

Where:

qs = Unit cost of the hull per ton

qh = High unit cost of equipment per ton

qp = Unit cost of plant per ton

ms = lightship weight of the hull

me = weight of equipment

mp = weight of power plant.

The weight of the equipment was estimated to be proportional to lightship consistent with the container ship in the report, due to similar securing arrangement requirements for open decks on an OSV.

The weight estimate of the power plant has been estimating by fitting a curve to the weight against installed power of the SINE 202, 203, and 204 data presented in the report, in order to develop a formula to estimate the required machinery plant weight.

This results in a weight estimation formula of:

me = 0.0376 * P – 24.491 (Equation 4.4)

where P = installed power (kW)

This equation has an R^2 of 0.9918.

The remaining lightship weight is assigned to the hull and the build cost is estimated. If the lightship value is lower than expected to be possible, the vessel equipment and plant are too heavy for the required displacement, and this vessel is therefore not a possible option and must be rejected.

For bulbous bow vessels, a build cost correction is added to account for the extra cost of the bulb. This cost can be determined using the bulb cost estimation in the paper *Bulbous Bow Design Optimization for Fast Ships* by Georgios Kyriazis [44], using the weight determined by the difference in displacement between a vertical bow ship and the equivalent sized bulbous bow vessel.

Due to its similarity with conventional vessels, it is expected that the axe bow design concept would not incur additional costs over an equivalent displacement conventional vessel.

It has been noted that the X-Bow concept resulted in a 15% reduction in labour costs for the assembly of x-bow vessels compared to conventional construction. [45] To account for this, the cost of material is subtracted from the cost per ton estimated for the hull to determine the labour costs, these costs are then reduced correspondingly to find the overall cost of the x-bow vessel. Shipbuilding typically follows cycles of low steel cost; if it is assumed building would be done during periods of below average cost, we would estimate the steel cost at 500$ per ton, using historical price benchmarks for Chinese steel. [46]

Next, we want to assess the operating costs of the vessel, these include crew costs, stores, insurance, maintenance, and administrative costs of operating the vessels. Crewing costs are highly variable costs, but should be largely similar between each of the vessels under consideration, due to their same operating environment, types of crew, and likelihood to be drawn from the same labour markets. These would be fixed annual costs per ship, rather than particularly dependent on ship size. An approach to estimating these costs is presented in the paper *An Estimate of Operating Costs for Bulk, RO-RO and Container Ships* [47]. This analysis was done for the Australian Market which can be expected to have similar vessel operating markets to the Canadian markets, and therefore it would be expected that the Newfoundland offshore would have similarly high costs. To account for the age of this publication, costs have been scaled based on the inflation since the date of publication. The vessel type chosen to be most similar in this case for cost estimating are coastal ro-ro vessels.

This paper also provides formulations for estimating the remaining operating costs for each vessel, such as spares, victuals, insurance, and repairs which have been accounted for in the optimization algorithm described below.

Next it is necessary to consider the costs of having a vessel operate on standby and dynamic positioning during unloading operations. As the crewing costs are already accounted for in these ships, the only additional costs to be considered are the fuel costs needed for station-keeping in the field. A method of estimating the required dynamic positioning power is presented in the paper *A Procedure for the Dynamic Positioning*

Estimation in Initial Ship-Design [48] which has been used to develop estimates of the required station keeping power of the standby vessel, assuming the standby vessel will orient to the principal wind and wave direction.

The station-keeping requirements have also been estimated for vessels during the unloading operation, which are also considered to orient to wind and wave direction. This paper uses an equivalent static loading method, which combines wind, wave, and current forces to determine the required thrust of dynamic positioning systems. By applying these to all possible sea conditions which the vessel operates under and averaging over a year of operation, we can estimate the annual costs for these operations.

As part of this paper, the classification formulas for estimating dynamic positioning loading have been used as specified by DNV-GL. [49]

4.3. Optimization Algorithm

To perform the optimization of the design, an algorithmic approach was taken to determine the best performing fleet design mix of ships. Many different definitions of "optimized" design may be present for designers, and to develop an optimized concept it is first necessary to determine what the optimization criteria are. In this case, this report is written to assist operators in procuring vessels which are optimal for operating in their environment and assist designers to provide the best design for meeting their client's needs. As a result, the optimization has been based on selecting vessels which are stable, capable of serving the needs of the field, and offer the lowest total annual cost to operate. Other optimization goals of lowest fuel consumption (pollution), best seakeeping (downtime), etc. have not been considered, except insofar as they contribute to the other optimization goals.

The algorithm follows a logical process of studying all possible combinations of vessel parameters, types, and numbers to determine their overall cost to operate under the proscribed requirements of the operating environment and selects the most cost effective.

The logical process starts by generating a representative set of possible sea states from a Monte Carlo simulation, and then calculating the percentage of time the vessel would be in downtime based on its seakeeping performance, determined from the model formulas above. It can therefore find the remaining time available for deliveries, loading and unloading consistent with the approach presented in the paper *Scheduling of offshore support vessels on the Grand Banks*. [50]

From this, and the known distance of the field, the required vessel average speed can be determined. Using the formulas for the resistance of the vessel and known sea conditions, it is then possible to determine the total cost to operate the fleet on a yearly basis.

Any unstable or loadline non-compliant designs can be automatically rejected.

Finally, the resulting list of designs can be sorted to find the most cost-efficient designs which meet the operational requirements.

The resulting algorithm for determining an optimal hull design configuration is shown in Appendix G: Logic Flow Chart for Optimization Algorithm.

4.4. Optimization Process

The algorithm described above was used to perform the design optimization, however this algorithm would require an excessive amount of calculation to be performed manually and instead it was decided to develop a computerized code to perform the optimization algorithm and return the ideal concept designs.

This process begins with a Monte Carlo simulation approach to study likely sea states consistent with the field requirements. This then acts as an input to determine the overall performance of each fleet design in the project specific sea environment.

First, the code performs the Monte Carlo simulation to randomly generate 73,000 possible sea states consistent with the wave height and period probability distributions described above; regenerating cases for any situation where an impossible sea state is generated. This represents 25 years of 3-hour possible sea states, which is believed to capture enough of the possible sea states to give meaningful results, as it represents the full expected life of the vessel.

Using nested for loops, the code runs through every combination of number of ships in fleet, type of design, length, beam, and draft, at each point finding the percentage of time it would be in downtime in this environment and all the possible conditions it might sail under.

This is done in several steps, first the algorithm selects a vessel from the next in sequence, it then runs a check for the vessel stability and freeboard to ensure that it meets these minimum criteria, any failing vessels are rejected, and the algorithm moves on to the next step.

Next, the vessel significant motions are calculated using the equations derived above for each of the 73,000 sea states stored. The percentile that exceeds the allowable maximum deck velocity is returned to indicate the percentage of time the vessel would be forced to wait for a weather window, assuming the vessel would not sail if there was not a weather window for the voyage. Sea states under which the vessel would sail are stored in a list of possible sailing states to be used as part of the cost optimization.

The total time available for all ship operations is calculated based on the time not spent waiting on a weather window per cycle, multiplied by the number of vessels.

Based on the cargo capacities of the vessel, the number of required voyages per cycle is determined. This is then multiplied by 8 hours in port and 8 hours offshore estimated to be the time required to perform loading and unloading operations and deducted from the available time. This is consistent with the approach to estimating scheduling presented in the paper *Scheduling of Offshore Support Vessels on the Grand Banks* [50].

The remaining time after accounting for downtime and the loading deductions is divided by the number of voyages and divided in half (accounting for a return voyage) to determine the sailing time per voyage. Given this sailing time and known distance, the required average vessel speed can be determined.

A requirement for a vessel to remain on standby is accounted for by deducting one ship worth of time per cycle before accounting for downtime, assuming the vessel in the field remains on standby regardless of sea state.

With the known downtime, sailing sea states, and required speed, the cost optimization can be performed.

Using all the possible sailing states as determined previously and the downtime it is possible to determine the required speed combined with the sea states from which resistance of the vessel, and therefore annual fuel costs, can be derived.

This fuel cost is calculated over several steps:

First, the annualized average resistance resulting across all sea states is calculated.

This is then multiplied by the required velocity to find the average effective power.

From the effective power, the required engine power is determined by adding factors to account for losses; in this case a diesel-electric propulsion system has been assumed. These factors include:

- Quasi Propulsive Coefficient = 0.55 to account for hull efficiency, open water efficiency, and relative rotative efficiency. Though this typically ranges 0.55-0.65, it is expected that efficiency will be on the lower end due to high thrust requirements and small propellor diameters in a twin-propellor configuration, which will not allow for good optimization of the propellor.
- Gearbox Efficiency = 0.95

- Shaft Efficiency = 0.98
- Switchboard Efficiency = 0.998
- Frequency Convertor Efficiency = 0.985
- Electric Motor Efficiency = 0.97

These factors were determined based on typical vessel efficiencies. [51] [52]

Having determined the required engine power, this is then multiplied by the total run-time of the engine during the delivery and return voyage, and multiplied by the overall engine fuel efficiency, to find the total fuel consumption per voyage. In this case the fuel consumption rate has been taken at 190 g/kwh, consistent with the published efficiency of Wärtsilä 20 Medium Speed Diesel Engines. [53]

This total fuel consumption is then multiplied by the cost of IFO 180, taken as 423 USD per metric ton at the time of the study, to find the total fuel cost per voyage.

This cost per voyage is then multiplied out over the number of annual voyages to find the total annualized average fuel cost.

The fuel consumption used during station-keeping for offloading and standby operations are similarly determined, by using the required power estimated per section 4.2, and applying the engine fuel consumption, total operating time, and fuel cost, which is then annualized and applied to the fleet overall.

The operating costs such as insurance, crew, victuals, and repairs are assigned, as per the paper detailed in section 4.2.

The build costs as determined in 4.2 are allocated on an annual basis, assuming the vessel is amortized over the 25 year life of the vessel at a 5% APR (approximately the average mortgage interest rate for 5 year fixed terms between 2010 and 2020), assuming monthly payments.

When the total fuel costs are added to the vessel amortization and operating costs, a total annual cost can then be estimated.

This total annual cost is then stored as a data point for the specific vessel type, length, and beam, in a list of all stable vessel configurations.

The range of cases considered include fleets between 2 and 6 ships, lengths between 60 m and 120 m, beams between 15 m and 25 m, and drafts between 4 m and 8 m, consistent with the ranges studied in the computer modelling.

The increment in length has been done in 5 m intervals, although any size interval can be selected, this allows for quickly narrowing down the range of the most efficient designs, from which a more refined study could be done to investigate trade-offs in smaller variations. The beams have been varied by 2 m per interval and the draft has been varied in 1 m increments for similar reasons.

The number of ships has been varied only by one in each run, as there is a significant step cost between each additional vessel, which leads difficulty when comparing fleets with too great a difference in fleet size.

The list of all the resulting fleet costs is then sorted, and the resulting costs and hull designs are output to a comma separated file for analysis and visualization by the designer, who may then choose a concept to bring forward.

The source code used to implement the optimization algorithm and find the optimal concept is presented in Appendix H: Python Source Code, an Anaconda python environment is required to run this code.

This code was verified to produce accurate results by following a regimented debugging process during development, in which every function and output was checked against calculated values at every stage of development, thus ensuring that each equation output corresponds to the expected values from the input formulas and models.

Once all the elements were tied together in the code, a series of text outputs were used to verify the flow of information through the program and check the correct results of calculations through every step to the final output.

4.5. Optimized Design Overview

Using the code described above, the optimization algorithm is run with the parameters as described above. The results of this algorithm suggested a possible 3815 fleet designs which would meet the operational requirements. For a sample we can examine the following design options as the top 5 performing fleet designs:

Table 4-2 - Top 5 Performing Fleet Designs

Hull Type	**Number**	**Length (m)**	**Beam (m)**	**Draft (m)**	**Speed (knots)**	**Power (kW)**	**Cost ($M/year)**	**Bollard Pull (Ton)**
Vertical Bow	2	100	25	4	12	2432	12.07	226
Vertical Bow	2	115	23	5	11	1657	12.20	193
Vertical Bow	2	110	23	5	12	2190	12.30	255
Vertical Bow	2	120	21	6	11	1645	12.40	230
Bulbous Bow	2	115	23	5	16	2506	12.58	292

As these results are very close and depend on imperfect input models, it is necessary to estimate the level of uncertainty in costs due to the potential for overlap between the designs in this list.

This algorithm, however, considers many possible outcomes based on probabilities in aggregate, and so it is not possible to directly trace the resulting accuracy of the outcomes from the predicted accuracy of the input models. It is however possible to estimate the overall accuracy by varying the model predicted values to account for their uncertainty.

This was done by adding correction coefficients to the model equations in the algorithm, corresponding the average model accuracy determined by the model verification conducted in chapter 3. Using these corrected models, it is possible to determine a likely upper and lower bound of potential cost, from which it is possible to estimate the overall accuracy of the predictions. This was done for the 5 suggested designs and the overall accuracy of the algorithm was determined as follows:

Table 4-3 - Algorithm Accuracy Estimation

Case	Estimated Cost ($M per year)	Lower Bound Cost ($M per year)	Upper Bound Cost ($M per year)	Estimated +/- Accuracy
1	12.07	11.94	12.38	-1.1% / +2.6%
2	12.20	12.10	12.44	-0.8% / +2.0%
3	12.30	12.07	12.42	-1.9% / +1.0%
4	12.40	12.30	12.64	-0.8% / +1.9%
5	12.58	12.32	13.15	-2.1% / +4.5%
			Average	-1.3% / +2.4%

This estimated accuracy shows two possible conclusions; first the predicted costs from the algorithm have little variance due to the uncertainty in the input values, indicating the quality of the algorithm when estimating costs.

The second conclusion that can be noted is that this choice of 5 top candidate designs is appropriate as the range of potential lower and upper bound estimates show that any one of these 5 options may be the most efficient.

It should be noted that although the 5 top performing cases are very similar in cost, this is only due to very similar overall fleet performance between these specific cases, the range of possible design outcomes can vary quite significantly. This can be seen when looking at the overall performance of all 3815 possible designs, as summarized by the below statistics:

Table 4-4 - Fleet design statistics

Design Type	$M per year	Design Type	$M per year
Axe Bow Average	25.0	Axe Bow Standard Deviation	4.4
Bulbous Bow Average	26.8	Bulbous Bow Standard Deviation	6.3
Vertical Bow Average	26.9	Vertical Bow Standard Deviation	6.2
X Bow Average	28.8	X Bow Standard Deviation	6.6
Overall Average	26.8	Overall Standard Deviation	6.1

These statistics show some interesting results, first it shows that the overall average for axe bow designs tends to be lower, with less variability in the potential costs. Despite this, the middle of the road costs of bulbous and vertical bow costs in this case allow for more efficient designs, likely due to costs on the low end of the variance. These designs are more efficient than the average design efficiency by 2.25-2.4 standard deviations, which would estimate their efficiency to be around the 99th percentile of possible results, further demonstrating the relative efficiency of these designs vs. alternatives.

All these concepts also show relatively high estimated Bollard Pull capacity, which is likely to be sufficient for the proposed operating environment.

It is to be noted that these results have been based on the simplified equations derived from the tests using ShipMo3D and NavCAD. As a result, the values should be taken with a degree of uncertainty.

First, ShipMo3D makes use of linear assumptions and RAOs to predict time history wave response, this linearity is generally not an issue, but its performance may break down at higher sea states where non-linear behavior starts to become significant. It is suggested that a series of follow up experiments could be performed using models to verify the accuracy of seakeeping model used in this work.

Furthermore, NavCAD makes use of regressions from historical model test sets for specific hulls which allows only for an estimate of resistance; although the tests performed fell generally within the bounds of the experimental data in NavCAD, the hull forms vary from those used in those studies, and as a result these predicted resistances are not ideal. It is suggested that a series of follow up tests could be performed using either CFD or model tests to estimate the resistance and validate the models used in this work more precisely.

To demonstrate the sensitivity of the algorithm to design parameters, the fleet was checked when a single parameter is varied at a time, showing the relative cost, and in some cases demonstrating vessels for which either displacement, loadline compliance, or stability is problematic for the fleet:

Table 4-5 Algorithm Sensitivity to Input Change

	Hull Type	Number	Length (m)	Beam (m)	Draft (m)	Speed (knots)	Power (kW)	Cost ($M/year)
Base Case	Vertical Bow	2	100	25	4	12	2432	12.07
Change in Hull	X Bow	2	100	25	4	11	3364	12.73
Change in Number	Vertical Bow	3	100	25	4	10	1581	16.85
Change in Length	No Possible Hull							
Change in Beam	No Possible Hull							
Change in Draft	Vertical Bow	2	100	25	8	12	7460	15.76

Interpretation of these relative effects can tell us several details; first, it demonstrates the cost savings of using one hull type vs. another is relatively small. The results also show that the proportion of annual cost which is due to the vessel amortized cost is relatively high.

The results further show a performance improvement for longer vessels with light displacement and shallow draft; however, these low displacement shallow vessels are sensitive to changes in length and beam and their resulting effect on displacement, stability, and loadline compliance. This shows a complex optimization result whereby there is a set of high efficiency vessel designs for which any small change may be problematic. This indicates a need for such designs to be carefully assessed as part of a more detailed design study to ensure that uncertainties in the design do not render the design impossible.

For comparison against current vessel options, a few fleets are proposed below with proportions which are approximately consistent with state-of-the-art existing vessels operating on the Grand Banks. It is to be noted that these results were generated using the algorithm to allow for a like for like comparison of the optimal results. Annual cost data for these hypothetical fleets is not available for the Flemish Pass Basin, however, operational data could be collected as part of another study to benchmark these values.

Table 4-6 - Results Comparison Against Existing Fleet

Hull Model	Hull Type	Number	Length (m)	Beam (m)	Draft (m)	Speed (knots)	Power (kW)	Cost ($M/year)
VS 4622	Bulbous Bow	5	85	23	8	16	4818	32.42
PSV 5000	Vertical Bow	3	90	23	7	13	6124	22.05
UT 722L	Vertical Bow	4	70	19	7	11	4127	24.80
Maersk Moose Class	Bulbous Bow	5	85	23	8	16	4818	32.42

These results show that for currently operating vessels, additional vessels will be required to meet the logistics needs; likely due to high downtime waiting on weather, and therefore a need for sufficient capacity to make the required deliveries during the cycle. The costs associated with using these traditional vessels are significantly higher than those estimated for the new optimized designs. Their large draft and non-sleek hulls also require more engine power to achieve the same speeds as the optimized vessels, which results in higher operational costs and increased emissions. Though these are approximated results which should be subject to further evaluation when considering vessels to serve in a region, they do show that existing vessel designs are likely to be inadequate to serve the Flemish pass basin due to the increased sailing time required and the harsh environment. That said, if it is desired to make use of existing vessels, these results indicate that the PSV 5000 design concept is likely to be the most efficient.

For the purposes of this paper, the optimized design has been brought forward as the most cost-effective concept derived from the optimization program developed above.

This concept suggests the optimal configuration for the fleet is 2 vessels, each based on the Vertical Bow vessel, with the following principal particulars:

Table 4-7 - Optimized Design Principal Particulars

Length (m)	100
Beam (m)	25
Draft (m)	4
Displacement (Tonnes)	7150
Deck Area (m^2)	~1025
Bulk Volume (m^3)	~2700
Deadweight (Tonnes)	~3400
Design Speed (Knots)	12
Minimum Power (kW)	2432
Bollard Pull (t)	226

A render of the proposed vessel design is shown in the figures below:

Figure 4-7 - Optimized Design Render 1

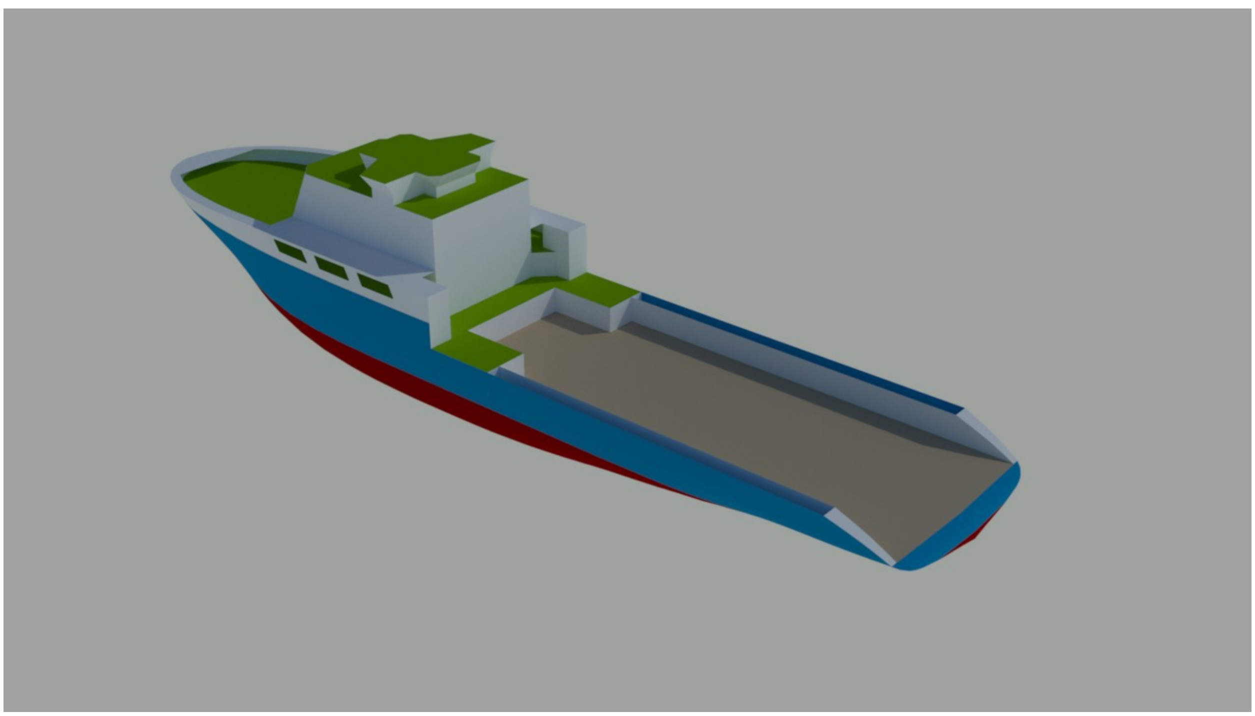


Figure 4-8 - Optimized Design Render 2

A high-level general arrangement of this vessel is shown below:

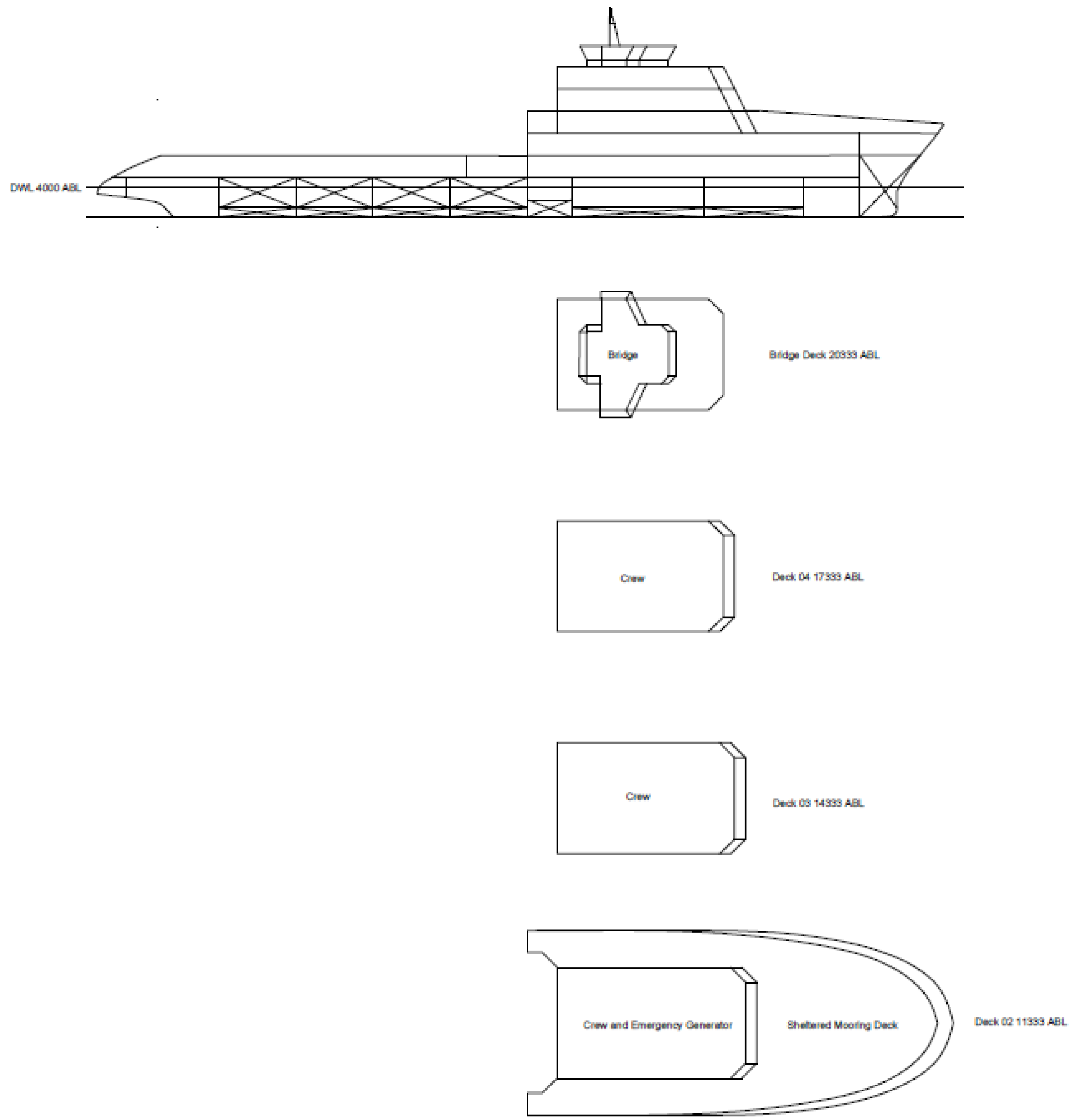


Figure 4-9 - Optimal Design General Arrangement Page 1

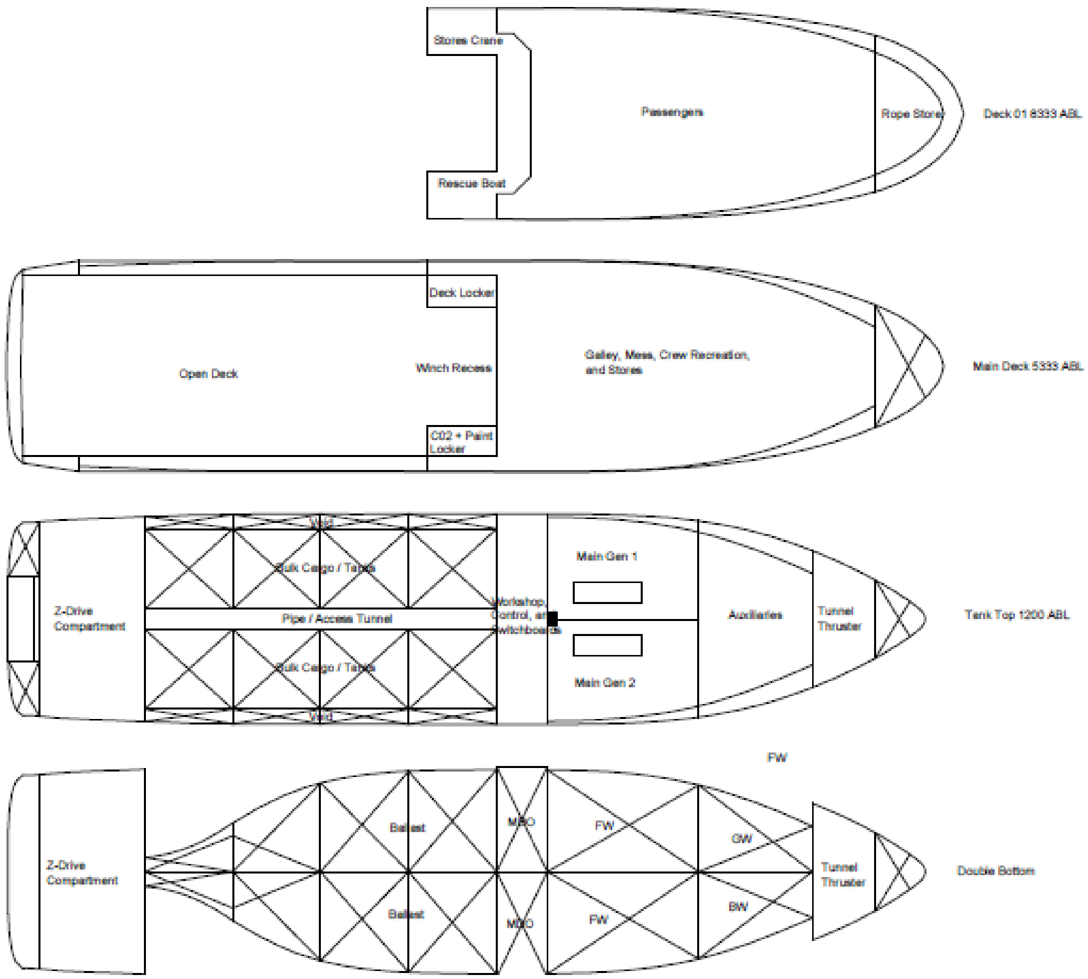


Figure 4-10 - Optimal Design General Arrangement Page 2

The vessel incorporates 2x Wartsila 8L26 generators for its main propulsion, providing full propulsion redundancy in separated compartments. Additional space is available to supply further propulsive power, or to divide the power between multiple generators for redundancy and flexibility. A large space has also been provided for auxiliaries to supply the needs of the vessel, cranes, pumps, and related equipment.

The control room, main switchboard and workshop spaces are proposed to be located adjacent to each other for engineering convenience and feature nearby direct access to both main generator spaces.

The vessel makes use of diesel-electric propulsion configurations, with electric z-drives at the stern and a tunnel thruster at the bow for dynamic positioning.

The hull has been allocated a large amount of space for passengers to support crew transfers, allowing for sufficient capacity to perform a full crew transfer of an FPSO in a single voyage. Due to the increased size of the vessel, it also has significant room afforded for crew quarters and recreation. Due to the larger voyage length required for this environment these facilities will prove useful.

Further, the bulk tank areas are protected all around by a double bottom and double side tanks and features a tunnel which allows below deck access fore and aft.

The crew areas on deck are well sheltered from the seas by way of high bulwarks and a sheltered mooring deck, which improves performance in the cold harsh winter seas of the offshore NL.

A large space has been allocated for a powerful winch to support AHTS roles, and open decks are available at the bridge level for fire monitors to be fitted.

5. Chapter 5: Conclusions

5.1. Conclusions

A series of empirical equations have been derived from computer simulations to describe the seakeeping, resistance, and stability performance of OSVs in the typical size ranges currently operating worldwide.

A design tool has been developed using computerized code to suggest optimal hull designs, based on total annual cost of ownership, taking account of stochastic sea states and in accordance with the logistical needs and schedule. This tool can be adapted to make predictions for any field in any environment by assigning appropriate values in the main program file. This tool was validated as part of a detailed debugging process, in which all the internal equations were checked against known values, and through text outputs in the code during a full calculation to verify the correct flow of data through the program. This design tool is therefore suitable for immediate use in other design environments.

Using the design tool, the 5 most efficient design options were studied, as the difference in total costs between each design varied by less than 5%. The overall accuracy of the predictions was estimated to be in the range of -1.3% / +2.4%, this resulted in the estimated upper and lower bounds of any of these 5 design options overlapping, which indicates any of the 5 options may be the most efficient.

These 5 cases, though very similar, are a subset of 3815 possible designs with significant variability in costs. Notably these designs are in the range of 2.25-2.4 standard deviations more efficient than the average design, and so there is little to discourage pursuing any of these options.

For the sake of design study, the estimated most efficient design on the list of 5 was taken forward as a concept level design and arrangement.

The sensitivity of the algorithm was checked by varying parameters of the most efficient design, which showed that the optimal designs are very sensitive to small design changes.

A comparison against existing vessels was also performed using the the algorithm, which estimates that this optimal design is significantly more efficient in this environment than the most efficient existing vessel design.

Overall, these results show an interesting departure vs. typical operations on the Grand Banks, as they show a relative cost efficiency of the following for the larger offshore distances versus current operations:

1) The results show a strong benefit to operating larger sleeker hull forms with light displacements and shallow drafts when compared with currently operating vessel fleets.
2) At the distances involved, it is more efficient to operate a large vessel that can make the entire cycle delivery amount in a single voyage. This vessel would operate efficiently at a low speed, with one vessel on standby, as soon as a weather window is available and would also have more frequent weather windows due to better seakeeping characteristics.

3) A larger number of smaller vessels is impractical for this operation, the extra flexibility of delivery they add is lost due to increased downtime. This results in requiring additional vessels to have sufficient schedule slack to complete the deliveries, at significantly higher cost.

5.2. Future Research

1) The optimized concept design can be taken forward to carefully study the detailed effects of hull form changes based on an optimized overall concept, to develop a detailed optimized design.
2) A more complete computerized tool can be developed starting with the current optimization algorithm, in the form of a full computer program that allows for determining the optimized concept automatically for any offshore environment, based on user input with a user interface.
3) The models could be updated to also account for directionality of sea states and combined with wave direction probabilities to further refine the prediction of weather downtime for vessels which cannot weathervane.
4) Further model and CFD tests could be performed to collect better data for the seakeeping and resistance performance of the vessels and improve the equations derived therefrom.
5) The optimization algorithm could be updated to directly take account of an input joint probability plot of significant wave height and peak period when determining the Monte Carlo data points, rather than the assumed independence used in the current model.

6) A detailed relative motion study can be undertaken to simulate both and OSV and FPSO operating side by side in the same sea states to determine the limitations on operational sea conditions more precisely. This information could be fed back to operators to improve the operational limitations for their existing fleet as well.
7) Similar processes can be expanded for the optimization of other vessels which perform predictable and repeated activities.
8) Operator feedback can be sought to study the favorability of the optimal design, and to further refine an ideal concept.
9) Operator cost data can be collected on existing vessels operating in the region to benchmark the predictions of the model against real costs.

6. Bibliography

[1] H. M. Gaspar, A. M. Ross, D. H. Rhodes and S. O. Erikstad, "Handling Complexity Aspects in Conceptual Ship Design," in *International Maritime Design Conference*, Glasgow, 2012.

[2] S. O. Erikstad and K. Lavander, "System Based Design of Offshore Support Vessels," in *International Marine Design Conference*, Glasgow, 2012.

[3] V. Bertram and G. D. Thiart, "Simulation-Based Ship Design," in *Oceans - Europe*, 2005.

[4] A. Ebrahimi, P. O. Brett, H. M. Gaspar, J. J. Garcia and Ø. Kamsvåg, "Parametric OSV Design Studies - Precision and Quality Assurance Via Updated Statistics".

[5] C. Abt, S. D. Bade, L. Birk and S. Harries, "Parametric Hull Form Design - A Step Towards One Week Ship Design," in *Practical Design of Ships and Other Floating Structures*, Oxford, Elsevier Science LTD, 2001, pp. 67-74.

[6] P. M. Van Diepen, R. A. Titman and M. M. Belko, "A step towards an optimum PSV hull form," in *World Maritime Technology Conference*, 2015.

[7] S. Percival, D. Hendrix and F. Noblesse, "Hydrodynamic Optimization of Ship Hull Forms," *Applied Ocean Research,* vol. 23, no. 6, pp. 337-355, 2001.

[8] E. Sarıoz, "Inverse design of ship hull forms for seakeeping," *Ocean Engineering,* vol. 36, no. 17-18, pp. 1386-1395, 2009.

[9] S. Ozum, B. Sener and H. Yilmaz, "A parametric study on seakeeping assessment of fast ships in conceptual design stage," *Ocean Engineering,* vol. 38, no. 13, pp. 1439-1447, 2011.

[10] Y. Maisuk and I. Gribkovskaia, "Fleet Sizing for Offshore Supply Vessels with Stochastic Sailing and Service Times," *Procedia Computer Science,* vol. 31, pp. 939-948, 2014.

[11] A. Bjornar, O. Halskau Sr and S. W. Wallace, "The Role of Supply Vessels in Offshore Logistics," *Maritime Economics & Logistics,* vol. 11, no. 3, pp. 302-325, 2009.

[12] E. E. Halvorsen-Weare and K. Fagerholt, "Robust Supply Vessel Planning," in *International Conference on Network Optimization*, Hamburg, 2011.

[13] M. Altosole, G. Benvenuto, M. Figari and U. Campora, "Real-time simulation of a COGAG naval ship propulsion system," *Journal of Engineering for the Maritime Environment,* vol. 223, no. 1, pp. 47-62, 2009.

[14] D. Bryant, "MV Ebb Tide," Marine Logistics Professional, 28 March 2014. [Online]. Available: https://www.maritimeprofessional.com/blogs/post/mv-ebb-tide-13523. [Accessed 19 September 2020].

[15] L. D. Ferreiro, "The Social History of the Bulbous Bow," *Technology and Culture,* vol. 52, no. 2, pp. 335-359, 2011.

[16] German Federal Archives, *Bremen, Stapellauf des Dampfers "Bremen",* Bremen, 1928.

[17] J. L. Gelling and J. A. Keuning, "Recent developments in the design of fast ships," *Ship Science & Technology,* vol. 5, no. 9, pp. 57-68, 2011.

[18] Ulstein, "X-BOW - HOW IT STARTED," 10 March 2020. [Online]. Available: https://ulstein.com/news/2018/x-bow-10-years. [Accessed 19 September 2020].

[19] N. Boyd and D. Molyneux, "Analysis of Variance to Determine the Effect of Hull Form Parameters on Resistance and Seakeeping Performance for PSV Hulls," in *OMAE*, Trondheim, 2016.

[20] Marine Traffic, "ATLANTIC HAWK," 2020. [Online]. Available: https://www.marinetraffic.com/fr/ais/details/ships/shipid:380102/mmsi:316002110/imo:9199115/vessel:ATLANTIC_HAWK. [Accessed 26 09 2020].

[21] Marine Traffic, "MAERSK CLIPPER," 2020. [Online]. Available: https://www.marinetraffic.com/en/ais/details/ships/shipid:383292/mmsi:316026728/imo:9649926/vessel:MAERSK_CLIPPER. [Accessed 26 09 2020].

[22] Damen, "Damen Takes a Bow," 2020. [Online]. Available: https://www.damen.com/en/innovation/some-key-projects/sea-axe-design. [Accessed 26 09 2020].

[23] Marine Traffic, "Bourbon Orca," 2020. [Online]. Available: https://www.marinetraffic.com/en/ais/details/ships/shipid:312025/mmsi:258511000/imo:9352377/vessel:BOURBON_ORCA. [Accessed 26 09 2020].

[24] A. H. Hetchet, *MIT Ocean Engineering 13.42 Lecture: Ocean Waves,* Cambridge, 2005.

[25] K. Yeung, "The Uniform Design," Hong Kong Baptist University, 2004. [Online]. Available: http://www.math.hkbu.edu.hk/UniformDesign/. [Accessed 30 March 2018].

[26] Meteorological Service of New Zealand Ltd., "Metocean View - MSL WW3 GLOBAL ST4 0.5° 47.5N 46.5W," 2019. [Online]. Available: https://app.metoceanview.com/hindcast/sites/ww3_cfsr_glob-st4/47.5/-46.5. [Accessed 14 06 2020].

[27] L. H. Holthuijsen, Waves in Oceanic and Coastal Waters, Cambridge: Cambridge University Press, 2010.

[28] C-Core, "Metocean Climate Study Offshore Newfoundland and Labrador - Study Main Report - Volume 2 Regional Trends and Comparisons With Other Regions," Nalcor Energy Oil and Gas, St. John's, 2015.

[29] C-Core, "MetOcean Climate Study Phase II Offshore Newfoundland and Labrador Cell Report Cell # 356," Nalcor Energy, St. John's, 2017.

[30] P. Gauthier and D. Molyneux, "A COST-DRIVEN, HIGH-LEVEL OPTIMIZATION OF OSV OPERATIONS IN THE FLEMISH PASS," in *International Conference on Ocean, Offshore and Arctic Engineering*, Madrid, 2018.

[31] D. Campbell, "Is it time for a return to night flights in Newfoundland's offshore oil and gas sector?," Natural Resources Magazine, 03 July 2015. [Online]. Available: https://www.naturalresourcesmagazine.net/article/grounded/. [Accessed 10 10 2020].

[32] Canadian Association of Petroleum Producers, "CODE OF PRACTICE - Transportation of Employees by Vessel to or from a Workplace in the Offshore Petroleum Industry - Newfoundland and Labrador," March 2017. [Online]. Available: https://www.cnlopb.ca/wp-content/uploads/cop/transportcop.pdf. [Accessed 10 October 2020].

[33] Reflex Marine, "Frog-6 User Manual," 22 05 2012. [Online]. Available: https://mediacache5.viking-life.com/4a/ea/540b-d2cc-41e7-ae6c-d419946e3287/1052206_mls_user%20manual_22-04-2013.pdf. [Accessed 01 08 2020].

[34] T. Cepowski, "The modeling of seakeeping qualities of Floating Production, Storage and Offloading (FPSO) sea-going ships in preliminary design stage," *POLISH MARITIME RESEARCH,* vol. 17, no. 4, pp. 3-12, 2010.

[35] Wartsila, "Wärtsilä Encyclopedia of Marine Technology: Bollard Pull," 2020. [Online]. Available: https://www.wartsila.com/encyclopedia/term/bollard-pull. [Accessed 2 October 2020].

[36] MAN Energy Solutions, "Basic Principals of Ship Propulsion," October 2018. [Online]. Available: https://marine.man-es.com/docs/librariesprovider6/propeller-aftship/5510-0004-04_18-1021-basic-principles-of-ship-propulsion_web.pdf?sfvrsn=c01858a2_8. [Accessed 2 October 2020].

[37] Wartsila Ship Design, "VS 4622 AHTS," 2009. [Online]. Available: https://cdn.wartsila.com/docs/default-source/product-files/sd/offshore/ahts/data-sheet-ship-design-ahts-vs4622-3664.pdf?sfvrsn=ae6cc745_5. [Accessed 27 09 2020].

[38] Damen, "PLATFORM SUPPLY VESSEL 5000 IRM," 2017. [Online]. Available: https://products.damen.com/-/media/Products/Images/Clusters-groups/Offshore-and-Transport/Platform-Supply-Vessel/PSV-5000-IRM/Documents/Product_Sheet_Damen_Platform_Supply_Vessel_5000_IRM_PAUL_A_SACUTA.pdf. [Accessed 27 09 2020].

[39] DOF, "Rolls Royce AHTS UT 722 L," [Online]. Available: http://www.dof.no/Files/System/dof2008/pdf/Newbuilding/RR_AHTS_UT722L.pdf. [Accessed 27 09 2020].

[40] Maersk Supply Service, "Maersk Clipper," [Online]. Available: https://www.maersksupplyservice.com/wp-content/uploads/2020/06/HTML-Maersk-Clipper-1790.pdf. [Accessed 27 09 2020].

[41] Maersk Supply Service, "Maersk Detector," [Online]. Available: https://www.maersksupplyservice.com/wp-content/uploads/2020/06/HTML-Maersk-Detector-1756.pdf. [Accessed 27 09 2020].

[42] Maersk Supply Service, "Maersk Handler," [Online]. Available: https://www.maersksupplyservice.com/wp-content/uploads/2020/06/HTML-Maersk-Handler-1750.pdf. [Accessed 27 09 2020].

[43] J. P. Michalski, "Parametric Method of Preliminary Prediction of the Shipbuilding Costs," *Polish Maritime Research,* vol. S1, pp. 16-19, 2004.

[44] G. KYRIAZIS, "BULBOUS BOW DESIGN OPTIMIZATION FOR FAST SHIPS," MASSACHUSETTS INSTITUTE OF TECHNOLOGY, Cambridge, 1996.

[45] Ulstein Group, "SIMPLIFIED SHIPBUILDING," [Online]. Available: https://ulstein.com/shipbuilding/simplified-shipbuilding. [Accessed 27 06 2020].

[46] Steel Benchmarker, "Steel Benchmarker Price History," 22 06 2020. [Online]. Available: http://steelbenchmarker.com/files/history.pdf. [Accessed 27 06 2020].

[47] Bureau of Transport Economics, "An Estimate of Operating Costs for Bulk, Ro-Ro and Container Ships," AUSTRALIAN GOVERNMENT PUBLISHING SERVICE, Canberra, 1982.

[48] S. M. U. Hasan, "A Procedure for the Dynamic Positioning," University of Rostock, Rostock, 2018.

[49] DNV-GL, "Recommended Practice - Dynamic Positioning vessel design philosophy guidelines," July 2015. [Online]. Available: http://rules.dnvgl.com/docs/pdf/dnvgl/RP/2015-07/DNVGL-RP-E306.pdf. [Accessed 14 July 2020].

[50] D. Molyneux and N. Boyd, "Scheduling of Offshore Support Vessels on the Grand Banks," in *International Conference on Ocean, Offshore and Arctic Engineering*, Busan, 2016.

[51] S. Chakraborty, "How The Power Requirement Of A Ship Is Estimated?," Marine Insight, 7 October 2019. [Online]. Available: https://www.marineinsight.com/naval-architecture/power-requirement-ship-estimated/#:~:text=The%20ratio%20of%20the%20effective,obtained%20at%20the%20shaft%20output.. [Accessed 1 October 2020].

[52] Man Diesel and Turbo, "Diesel Electric Propulsion Plants: A brief guideline on how to engineer a diesel-electric propulsion system," [Online]. Available: https://marine.mandieselturbo.com/docs/librariesprovider6/marine-broschures/diesel-electric-drives-guideline.pdf. [Accessed 1 10 2020].

[53] Wärtsilä, "Wärtsilä 20," Wärtsilä, [Online]. Available: https://www.wartsila.com/marine/build/engines-and-generating-sets/diesel-engines/wartsila-20. [Accessed 1 October 2020].

[54] Damen Magazine, "DAMEN’S SEA AXE DEVELOPMENT," Damen Shipyard's Group, 10 July 2017. [Online]. Available: https://magazine.damen.com/editors-choice/unrivalled-seakeeping-behavior-of-high-speed-vessels/. [Accessed 19 September 2020].

Appendix A – Motion Test Program Data

Table A-1 – X Bow Motions Test Data

Run	Length	Beam	Draft	Significant Wave	Peak Period	Significant Displacement	Significant Velocity	Significant Acceleration
	m	m	m	m	s	m	m/s	m/s^2
1	90	15	7	6	10	1.527	0.986	0.72594
2	75	25	5	5	4	0.178	0.232	0.32373
3	90	15	5	4	6	0.429	0.45	0.50031
4	120	17.5	8	3	10	0.583	0.372	0.26487
5	90	20	6	4	8	0.728	0.595	0.53955
6	120	20	5	3	4	0.049	0.066	0.083385
7	75	20	6	6	10	1.766	1.162	0.86328
8	105	15	7	2	6	0.182	0.182	0.1962
9	60	25	4	4	10	1.344	0.902	0.67689
10	120	22.5	5	2	8	0.245	0.188	0.15696
11	105	15	5	5	12	1.452	0.786	0.47088
12	120	25	7	6	6	0.506	0.488	0.4905
13	120	17.5	7	4	12	1.056	0.564	0.33354
14	90	25	8	2	10	0.524	0.344	0.25506
15	60	17.5	5	2	10	0.674	0.456	0.34335
16	105	25	6	3	12	0.882	0.48	0.2943
17	90	22.5	5	6	12	1.938	1.07	0.65727
18	120	15	6	5	4	0.126	0.168	0.22563
19	60	20	4	6	6	0.866	0.878	0.95157
20	105	17.5	4	6	8	0.822	0.638	0.53955
21	60	17.5	6	5	6	0.85	0.89	0.981
22	75	17.5	8	6	4	0.24	0.3	0.3924
23	60	22.5	8	5	12	2.006	1.196	0.812423
24	105	22.5	8	4	4	0.082	0.104	0.13734
25	105	20	8	5	8	0.78	0.628	0.53955
26	60	22.5	7	3	4	0.156	0.2	0.26487
27	75	20	7	2	12	0.72	0.412	0.26487
28	75	25	7	4	8	0.88	0.714	0.62784
29	105	25	4	3	6	0.238	0.232	0.23544
30	90	17.5	4	2	4	0.058	0.076	0.10791
31	75	22.5	6	2	6	0.286	0.292	0.31392
32	60	15	8	3	8	0.916	0.824	0.80442
33	120	22.5	4	5	10	0.952	0.592	0.40221
34	90	20	6	4	8	0.728	0.596	0.53955
35	75	15	4	3	12	1.066	0.6	0.37278

Table A-2 – Axe Bow Motions Test Data

Run	Length	Beam	Draft	Significant Wave	Peak Period	Significant Displacement	Significant Velocity	Significant Acceleration
	m	m	m	m	s	m	m/s	m/s^2
1	90	15	7	6	10	1.586	0.988	0.664
2	75	25	5	5	4	0.172	0.234	0.334
3	90	15	5	4	6	0.31	0.31	0.335
4	120	17.5	8	3	10	0.6	0.36	0.234
5	90	20	6	4	8	0.68	0.508	0.413
6	120	20	5	3	4	0.056	0.076	0.108
7	75	20	6	6	10	1.82	1.172	0.82
8	105	15	7	2	6	0.122	0.12	0.129
9	60	25	4	4	10	1.378	0.922	0.678
10	120	22.5	5	2	8	0.234	0.176	0.144
11	105	15	5	5	12	1.522	0.816	0.475
12	120	25	7	6	6	0.34	0.33	0.34
13	120	17.5	7	4	12	1.112	0.582	0.332
14	90	25	8	2	10	0.534	0.334	0.227
15	60	17.5	5	2	10	0.69	0.46	0.334
16	105	25	6	3	12	0.916	0.494	0.291
17	90	22.5	5	6	12	2.006	1.106	0.669
18	120	15	6	5	4	0.092	0.124	0.177
19	60	20	4	6	6	0.86	0.858	0.923
20	105	17.5	4	6	8	0.824	0.612	0.502
21	60	17.5	6	5	6	0.696	0.682	0.719
22	75	17.5	8	6	4	0.176	0.244	0.352
23	60	22.5	8	5	12	2.01	1.178	0.764
24	105	22.5	8	4	4	0.072	0.096	0.135
25	105	20	8	5	8	0.694	0.51	0.407
26	60	22.5	7	3	4	0.126	0.172	0.246
27	75	20	7	2	12	0.736	0.416	0.259
28	75	25	7	4	8	0.846	0.644	0.528
29	105	25	4	3	6	0.216	0.216	0.23
30	90	17.5	4	2	4	0.058	0.082	0.119
31	75	22.5	6	2	6	0.214	0.21	0.219
32	60	15	8	3	8	0.778	0.6	0.497
33	120	22.5	4	5	10	0.998	0.608	0.405
34	90	20	6	4	8	0.68	0.508	0.412
35	75	15	4	3	12	1.096	0.62	0.385

Table A-3 – Bulbous Bow Motions Test Data

Run	Length	Beam	Draft	Significant Wave	Peak Period	Significant Displacement	Significant Velocity	Significant Acceleration
	m	m	m	m	s	m	m/s	m/s^2
1	90	15	7	6	10	1.44	0.912	0.654
2	75	25	5	5	4	0.21	0.278	0.383
3	90	15	5	4	6	0.352	0.366	0.405
4	120	17.5	8	3	10	0.532	0.334	0.239
5	90	20	6	4	8	0.618	0.492	0.431
6	120	20	5	3	4	0.05	0.066	0.089
7	75	20	6	6	10	1.682	1.084	0.782
8	105	15	7	2	6	0.168	0.172	0.182
9	60	25	4	4	10	1.298	0.852	0.619
10	120	22.5	5	2	8	0.208	0.16	0.133
11	105	15	5	5	12	1.4	0.74	0.435
12	120	25	7	6	6	0.424	0.41	0.413
13	120	17.5	7	4	12	1.008	0.528	0.31
14	90	25	8	2	10	0.488	0.314	0.227
15	60	17.5	5	2	10	0.652	0.43	0.319
16	105	25	6	3	12	0.846	0.454	0.273
17	90	22.5	5	6	12	1.918	1.124	0.79
18	120	15	6	5	4	0.106	0.14	0.191
19	60	20	4	6	6	0.84	0.89	1.006
20	105	17.5	4	6	8	0.73	0.562	0.481
21	60	17.5	6	5	6	0.778	0.826	0.918
22	75	17.5	8	6	4	0.228	0.286	0.373
23	60	22.5	8	5	12	1.988	1.19	0.825
24	105	22.5	8	4	4	0.076	0.096	0.126
25	105	20	8	5	8	0.688	0.56	0.492
26	60	22.5	7	3	4	0.146	0.186	0.246
27	75	20	7	2	12	0.702	0.396	0.252
28	75	25	7	4	8	0.79	0.64	0.566
29	105	25	4	3	6	0.214	0.212	0.22
30	90	17.5	4	2	4	0.056	0.076	0.106
31	75	22.5	6	2	6	0.242	0.248	0.266
32	60	15	8	3	8	0.812	0.698	0.657
33	120	22.5	4	5	10	0.876	0.536	0.363
34	90	20	6	4	8	0.618	0.49	0.431
35	75	15	4	3	12	1.038	0.578	0.358

Table A-4 – Vertical Bow Motions Test Data

Run	Length	Beam	Draft	Significant Wave	Peak Period	Significant Displacement	Significant Velocity	Significant Acceleration
	m	m	m	m	s	m	m/s	m/s^2
1	90	15	7	6	10	1.448	0.92	0.658
2	75	25	5	5	4	0.206	0.274	0.377
3	90	15	5	4	6	0.354	0.366	0.4
4	120	17.5	8	3	10	0.538	0.338	0.24
5	90	20	6	4	8	0.63	0.496	0.432
6	120	20	5	3	4	0.062	0.08	0.11
7	75	20	6	6	10	1.692	1.094	0.789
8	105	15	7	2	6	0.164	0.166	0.176
9	60	25	4	4	10	1.31	0.878	0.662
10	120	22.5	5	2	8	0.212	0.162	0.134
11	105	15	5	5	12	1.402	0.744	0.439
12	120	25	7	6	6	0.418	0.402	0.403
13	120	17.5	7	4	12	1.012	0.532	0.313
14	90	25	8	2	10	0.492	0.316	0.227
15	60	17.5	5	2	10	0.654	0.432	0.319
16	105	25	6	3	12	0.848	0.458	0.276
17	90	22.5	5	6	12	1.906	1.094	0.745
18	120	15	6	5	4	0.102	0.136	0.186
19	60	20	4	6	6	0.88	0.932	1.05
20	105	17.5	4	6	8	0.742	0.574	0.488
21	60	17.5	6	5	6	0.766	0.81	0.898
22	75	17.5	8	6	4	0.222	0.28	0.366
23	60	22.5	8	5	12	1.976	1.174	0.804
24	105	22.5	8	4	4	0.074	0.094	0.124
25	105	20	8	5	8	0.688	0.55	0.477
26	60	22.5	7	3	4	0.142	0.182	0.241
27	75	20	7	2	12	0.704	0.396	0.25
28	75	25	7	4	8	0.794	0.634	0.555
29	105	25	4	3	6	0.212	0.206	0.212
30	90	17.5	4	2	4	0.072	0.098	0.135
31	75	22.5	6	2	6	0.238	0.242	0.257
32	60	15	8	3	8	0.792	0.672	0.628
33	120	22.5	4	5	10	0.886	0.544	0.369
34	90	20	6	4	8	0.626	0.492	0.426
35	75	15	4	3	12	1.04	0.58	0.361

Appendix B – Resistance Test Program Data

Table B-1 – X Bow Resistance Test Data

Length (m)	Beam (m)	Draft (m)	Significant Wave Height (m)	Peak Period (s)	Speed (kts)	Resistance (kN)
90	22.5	8	2	16	30	9374.4
75	15	8	4	14	25	3495.32
90	15	4	6	8	15	345.67
105	20	8	5	10	15	962.54
105	17.5	4	2	12	25	1000.38
60	25	8	6	12	10	1202.33
60	15	7	2	10	20	1693.56
105	25	7	4	8	30	8431.56
90	17.5	7	5	14	10	436.61
120	20	7	6	16	25	2204.16
60	17.5	5	4	16	15	622.67
75	25	4	5	16	20	1092.71
105	15	6	3	16	10	231.11
120	17.5	8	3	8	20	1185.68
90	25	5	3	10	25	2827.49
75	17.5	6	6	10	30	6173.73
90	20	6	4	12	20	1268.2
120	22.5	4	4	10	10	226.86
120	15	5	5	12	30	2224.96
60	22.5	6	5	8	25	5542.51
75	22.5	7	3	12	15	969.01
60	20	4	3	14	30	4652.37
75	20	5	2	8	10	244.82
105	22.5	5	6	14	20	1189.39
120	25	6	2	14	10	326.62

Table B-2 – Axe Bow Resistance Test Data

Length (m)	Beam (m)	Draft (m)	Significant Wave Height (m)	Peak Period (s)	Speed (knots)	Resistance (kN)
90	22.5	8	2	16	30	2024.16
75	15	8	4	14	25	1083.43
90	15	4	6	8	15	97.91
105	20	8	5	10	15	232.9
105	17.5	4	2	12	25	379.49
60	25	8	6	12	10	242.04
60	15	7	2	10	20	588.9
105	25	7	4	8	30	1610.85
90	17.5	7	5	14	10	97.31
120	20	7	6	16	25	671.1
60	17.5	5	4	16	15	187.11
75	25	4	5	16	20	426.04
105	15	6	3	16	10	65.98
120	17.5	8	3	8	20	392.32
90	25	5	3	10	25	854.96
75	17.5	6	6	10	30	1110.41
90	20	6	4	12	20	353.96
120	22.5	4	4	10	10	82.06
120	15	5	5	12	30	1093.14
60	22.5	6	5	8	25	1639.36
75	22.5	7	3	12	15	311.43
60	20	4	3	14	30	730.4
75	20	5	2	8	10	68.23
105	22.5	5	6	14	20	285.1
120	25	6	2	14	10	105.18

Table B-3 – Bulbous Bow Resistance Test Data

Length (m)	Beam (m)	Draft (m)	Significant Wave Height (m)	Peak Period (s)	Speed (knots)	Resistance (kN)
90	22.5	8	2	16	30	7466.6
75	15	8	4	14	25	2877.37
90	15	4	6	8	15	236.77
105	20	8	5	10	15	392.62
105	17.5	4	2	12	25	914.11
60	25	8	6	12	10	346.86
60	15	7	2	10	20	1269.53
105	25	7	4	8	30	7644.36
90	17.5	7	5	14	10	121.83
120	20	7	6	16	25	1775.46
60	17.5	5	4	16	15	350.1
75	25	4	5	16	20	868.72
105	15	6	3	16	10	90.8
120	17.5	8	3	8	20	737.49
90	25	5	3	10	25	2364.38
75	17.5	6	6	10	30	6676.01
90	20	6	4	12	20	899.54
120	22.5	4	4	10	10	119.34
120	15	5	5	12	30	2045.23
60	22.5	6	5	8	25	5433.79
75	22.5	7	3	12	15	411.69
60	20	4	3	14	30	4136.15
75	20	5	2	8	10	83.86
105	22.5	5	6	14	20	972.64
120	25	6	2	14	10	136.91

Table B-4 – Vertical Bow Resistance Test Data

Length (m)	Beam (m)	Draft (m)	Significant Wave Height (m)	Peak Period (s)	Speed (knots)	Resistance (kN)
90	22.5	8	2	16	30	10046.94
75	15	8	4	14	25	3772.79
90	15	4	6	8	15	363.15
105	20	8	5	10	15	1007.02
105	17.5	4	2	12	25	1155.77
60	25	8	6	12	10	1245.16
60	15	7	2	10	20	1896.23
105	25	7	4	8	30	9070.29
90	17.5	7	5	14	10	450.68
120	20	7	6	16	25	2389.67
60	17.5	5	4	16	15	676.06
75	25	4	5	16	20	1209.69
105	15	6	3	16	10	238.42
120	17.5	8	3	8	20	1276
90	25	5	3	10	25	3223.25
75	17.5	6	6	10	30	6584.77
90	20	6	4	12	20	1413.35
120	22.5	4	4	10	10	233.19
120	15	5	5	12	30	2363.94
60	22.5	6	5	8	25	5888.3
75	22.5	7	3	12	15	1025.22
60	20	4	3	14	30	5022.21
75	20	5	2	8	10	252.52
105	22.5	5	6	14	20	1308.75
120	25	6	2	14	10	336.26

Appendix C - Stability and Displacement Test Program Data

Table C-1 – Axe Bow Stability Prediction Data

Run	Length	Beam	Draft	KM	KB	KB/T	BM	Displacement
1	60	25	6	25.813	4.903	0.817167	20.91	1658
2	60	15	4	14.561	3.269	0.81725	11.292	663
3	90	17.5	5	16.376	4.086	0.8172	12.29	1451
4	90	15	8	12.184	6.538	0.81725	5.646	1990
5	75	20	5	20.133	4.086	0.8172	16.047	1381
6	105	17.5	7	14.499	5.721	0.817286	8.778	2369
7	120	15	6	12.431	4.903	0.817167	7.528	1990
8	105	22.5	5	24.412	4.086	0.8172	20.326	2176
9	75	17.5	7	14.449	5.721	0.817286	8.728	1692
10	120	25	8	22.223	6.538	0.81725	15.685	4422
11	105	22.5	6	21.841	4.903	0.817167	16.938	2612
12	60	20	8	16.567	6.538	0.81725	10.029	1768
13	75	22.5	7	20.239	5.721	0.817286	14.518	2176
14	120	20	4	23.328	3.269	0.81725	20.059	1768
15	90	25	4	34.641	3.269	0.81725	31.372	1658

Table C-2 – Bulbous Bow Stability Prediction Data

Run	Length	Beam	Draft	KM	KB	KB/T	BM	Displacement
1	60	25	6	12.427	3.303	0.5505	9.124	6556
2	60	15	4	7.128	2.202	0.5505	4.926	2622
3	90	17.5	5	8.114	2.752	0.5504	5.362	5735
4	90	15	8	6.867	4.403	0.550375	2.464	7867
5	75	20	5	9.757	2.752	0.5504	7.005	5463
6	105	17.5	7	7.683	3.853	0.550429	3.83	9367
7	120	15	6	6.587	3.303	0.5505	3.284	7867
8	105	22.5	5	11.62	2.752	0.5504	8.868	8604
9	75	17.5	7	7.683	3.853	0.550429	3.83	6691
10	120	25	8	11.247	4.403	0.550375	6.844	17484
11	105	22.5	6	10.692	3.303	0.5505	7.389	10325
12	60	20	8	8.779	4.403	0.550375	4.376	6990
13	75	22.5	7	10.187	3.853	0.550429	6.334	8604
14	120	20	4	10.953	2.202	0.5505	8.751	6990
15	90	25	4	15.889	2.202	0.5505	13.687	6556

Table C-3 – Vertical Bow Stability Prediction Data

Run	Length	Beam	Draft	KM	KB	KB/T	BM	Displacement
1	60	25	6	12.567	3.314	0.552333	9.253	6466
2	60	15	4	7.205	2.209	0.55225	4.996	2586
3	90	17.5	5	8.199	2.761	0.5522	5.438	5656
4	90	15	8	6.916	4.418	0.55225	2.498	7759
5	75	20	5	9.861	2.761	0.5522	7.1	5386
6	105	17.5	7	7.75	3.866	0.552286	3.884	9238
7	120	15	6	6.644	3.314	0.552333	3.33	7759
8	105	22.5	5	11.755	2.761	0.5522	8.994	8486
9	75	17.5	7	7.75	3.866	0.552286	3.884	6599
10	120	25	8	11.359	4.418	0.55225	6.941	17243
11	105	22.5	6	10.808	3.314	0.552333	7.494	10183
12	60	20	8	8.856	4.418	0.55225	4.438	6894
13	75	22.5	7	10.29	3.866	0.552286	6.424	8486
14	120	20	4	11.084	2.209	0.55225	8.875	6894
15	90	25	4	16.09	2.209	0.55225	13.881	6466

Table C-4 - X Bow Stability Prediction Data

Run	Length	Beam	Draft	KM	KB	KB/T	BM	Displacement
1	60	25	6	12.652	3.35	0.558333	9.302	6315
2	60	15	4	7.256	2.234	0.5585	5.022	2526
3	90	17.5	5	8.258	2.792	0.5584	5.466	5524
4	90	15	8	6.978	4.467	0.558375	2.511	7577
5	75	20	5	9.929	2.792	0.5584	7.137	5260
6	105	17.5	7	7.813	3.909	0.558429	3.904	9022
7	120	15	6	6.698	3.35	0.558333	3.348	7577
8	105	22.5	5	11.831	2.792	0.5584	9.039	8287
9	75	17.5	7	7.813	3.909	0.558429	3.904	6444
10	120	25	8	11.443	4.467	0.558375	6.976	16839
11	105	22.5	6	10.883	3.35	0.558333	7.533	9945
12	60	20	8	8.928	4.467	0.558375	4.461	6732
13	75	22.5	7	10.366	3.909	0.558429	6.457	8287
14	120	20	4	11.154	2.234	0.5585	8.92	6732
15	90	25	4	16.186	2.234	0.5585	13.952	6315

Appendix D: Additional ANOVA for Motions Prediction

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.77	10	0.1774	200.43	< 0.0001	significant
A-Length	0.1629	1	0.1629	184.06	< 0.0001	
D-Wave height	0.5509	1	0.5509	622.37	< 0.0001	
E-Peak Period	0.0217	1	0.0217	24.47	< 0.0001	
AE	0.0001	1	0.0001	0.1041	0.7498	
DE	0.0236	1	0.0236	26.67	< 0.0001	
A^2	0.0060	1	0.0060	6.74	0.0159	
D^2	0.0047	1	0.0047	5.37	0.0294	
E^2	0.1420	1	0.1420	160.48	< 0.0001	
AE^2	0.0090	1	0.0090	10.17	0.0039	
E^3	0.0210	1	0.0210	23.73	< 0.0001	
Residual	0.0212	24	0.0009			
Lack of Fit	0.0212	23	0.0009	4399.83	0.0119	significant
Pure Error	2.099E-07	1	2.099E-07			
Cor Total	1.80	34				

Figure D-1 - X Bow Velocity Anova

Std. Dev.	0.0298		**R^2**	0.9882
Mean	0.6942		**Adjusted R^2**	0.9832
C.V. %	4.29		**Predicted R^2**	0.9750
			Adeq Precision	50.3134

Figure D-2 - X Bow Velocity Model Fit Statistics

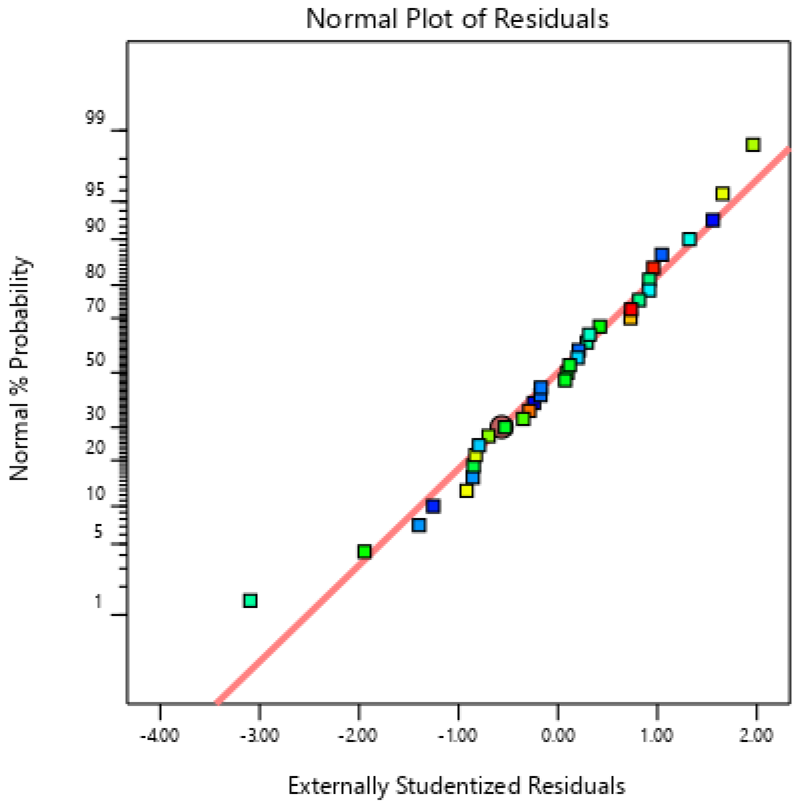


Figure D-3 - X Bow Velocity Normal Plot

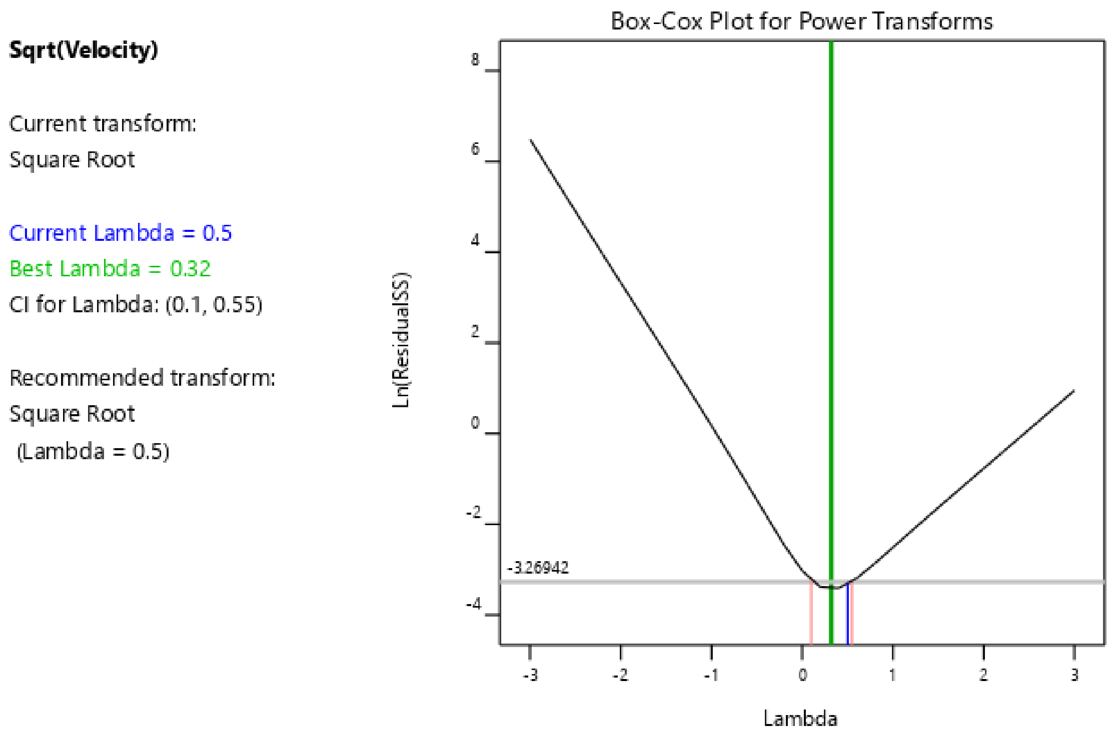


Figure D-4 - X Bow Velocity Box-Cox

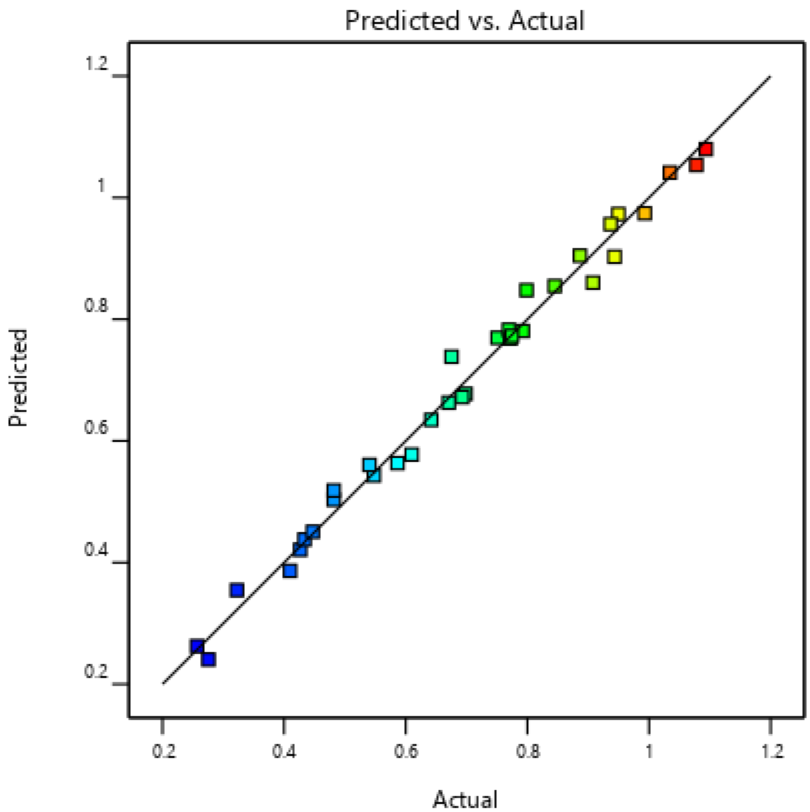


Figure D-5 - X Bow Velocity Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2.37	8	0.2961	123.35	< 0.0001	significant
A-Length	0.5946	1	0.5946	247.75	< 0.0001	
B-Beam	0.0079	1	0.0079	3.28	0.0818	
C-Draft	0.0115	1	0.0115	4.80	0.0377	
D-Wave height	0.9429	1	0.9429	392.85	< 0.0001	
E-Peak Period	0.0041	1	0.0041	1.70	0.2031	
D^2	0.0335	1	0.0335	13.97	0.0009	
E^2	0.3720	1	0.3720	154.98	< 0.0001	
E^3	0.0701	1	0.0701	29.19	< 0.0001	
Residual	0.0624	26	0.0024			
Lack of Fit	0.0624	25	0.0025			
Pure Error	0.0000	1	0.0000			
Cor Total	2.43	34				

Figure D-6 - X Bow Acceleration Anova

	Std. Dev.	0.0490		**R^2**	0.9743
	Mean	-0.4199		**Adjusted R^2**	0.9664
	C.V. %	11.67		**Predicted R^2**	0.9528
				Adeq Precision	40.1778

Figure D-7 - X Bow Acceleration Model Fit

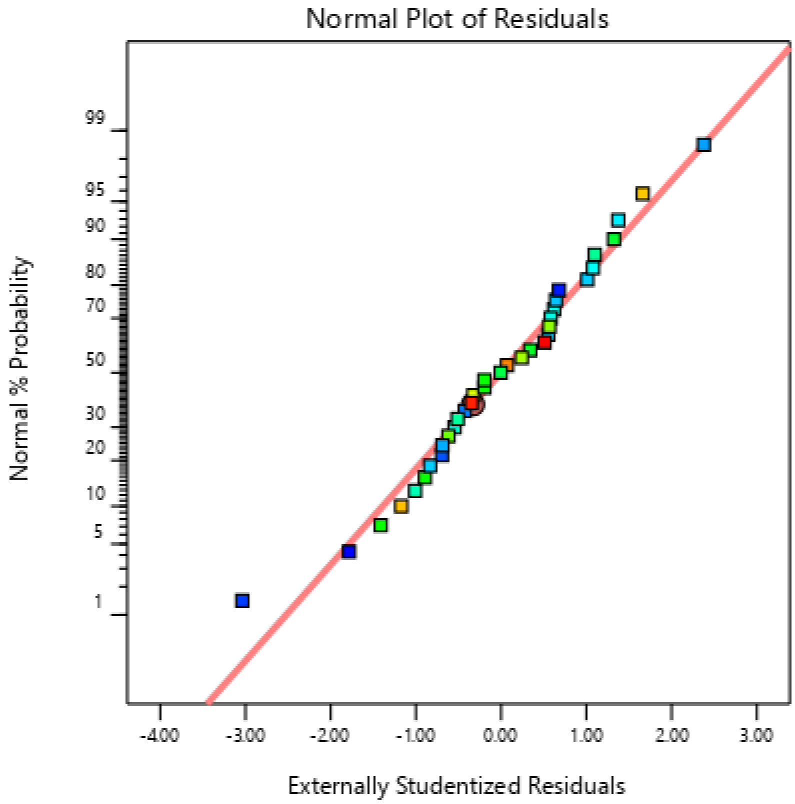


Figure D-8 - X Bow Acceleration Normal Plot

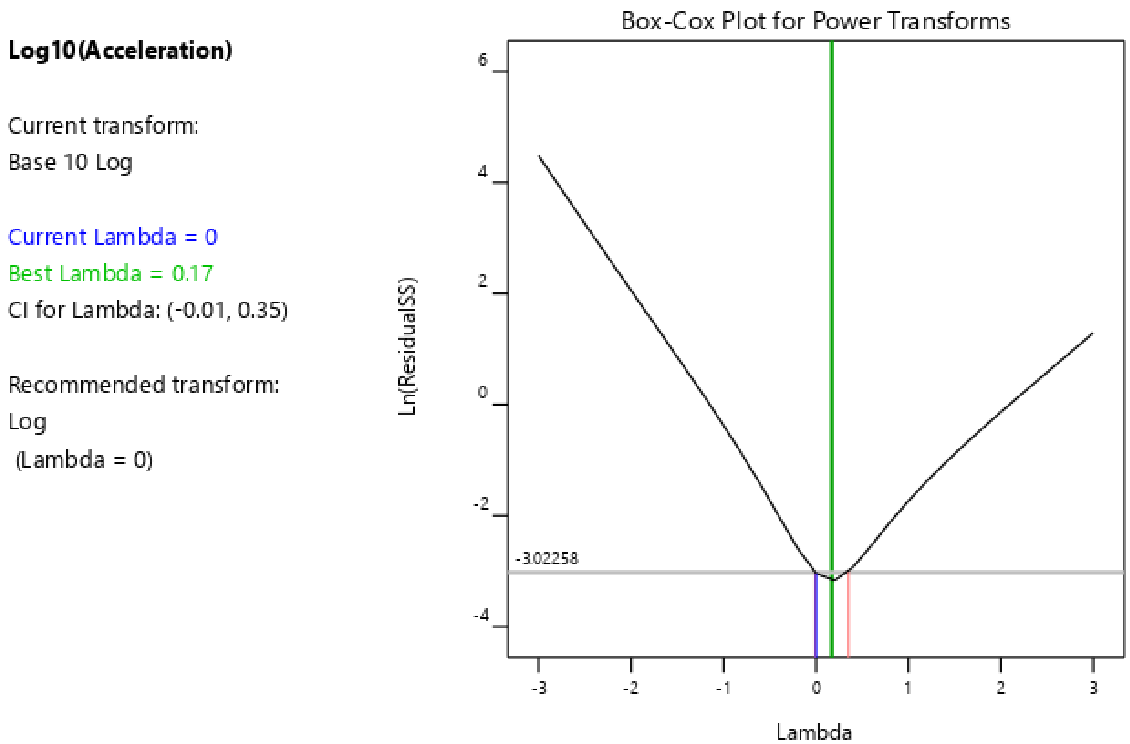


Figure D-9 - X Bow Acceleration Box-Cox

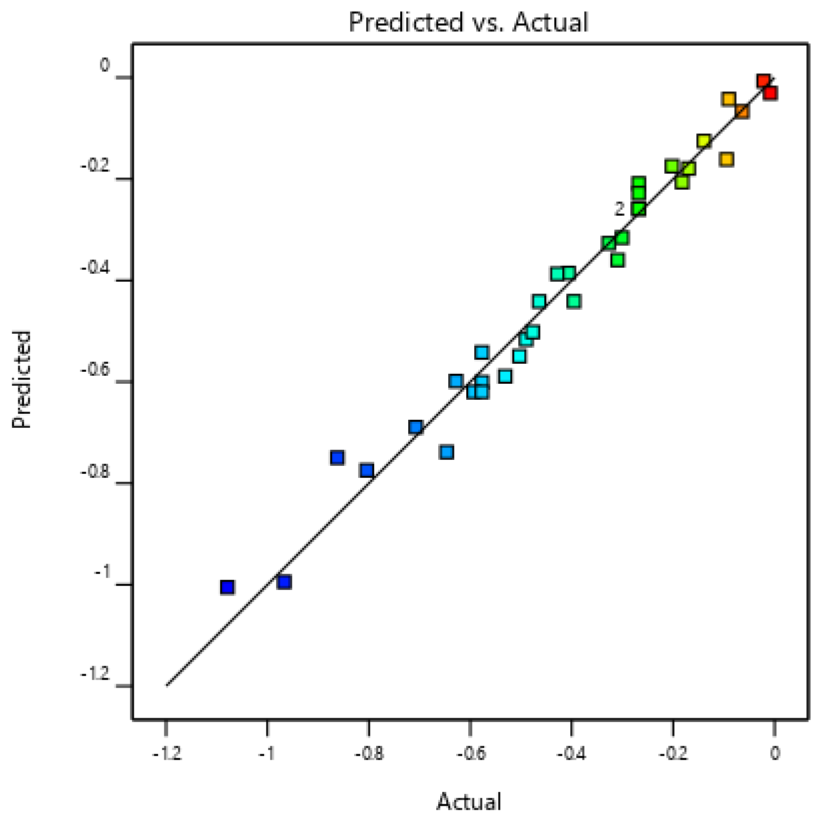


Figure D-10 - X Bow Acceleration Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	10.85	7	1.55	557.35	< 0.0001	significant
A-Length	0.7167	1	0.7167	257.64	< 0.0001	
D-Wave height	2.22	1	2.22	799.64	< 0.0001	
E-Peak Period	6.99	1	6.99	2511.69	< 0.0001	
AD	0.0697	1	0.0697	25.05	< 0.0001	
AE	0.1031	1	0.1031	37.06	< 0.0001	
DE	0.8653	1	0.8653	311.06	< 0.0001	
A^2	0.0187	1	0.0187	6.72	0.0152	
Residual	0.0751	27	0.0028			
Lack of Fit	0.0751	26	0.0029			
Pure Error	0.0000	1	0.0000			
Cor Total	10.93	34				

Figure D-11 - Axe Bow Displacement Anova Table

Std. Dev.	0.0527		**R^2**	0.9931
Mean	0.7214		**Adjusted R^2**	0.9913
C.V. %	7.31		**Predicted R^2**	0.9877
			Adeq Precision	83.4955

Figure D-12 - Axe Bow Displacement Model Statistics

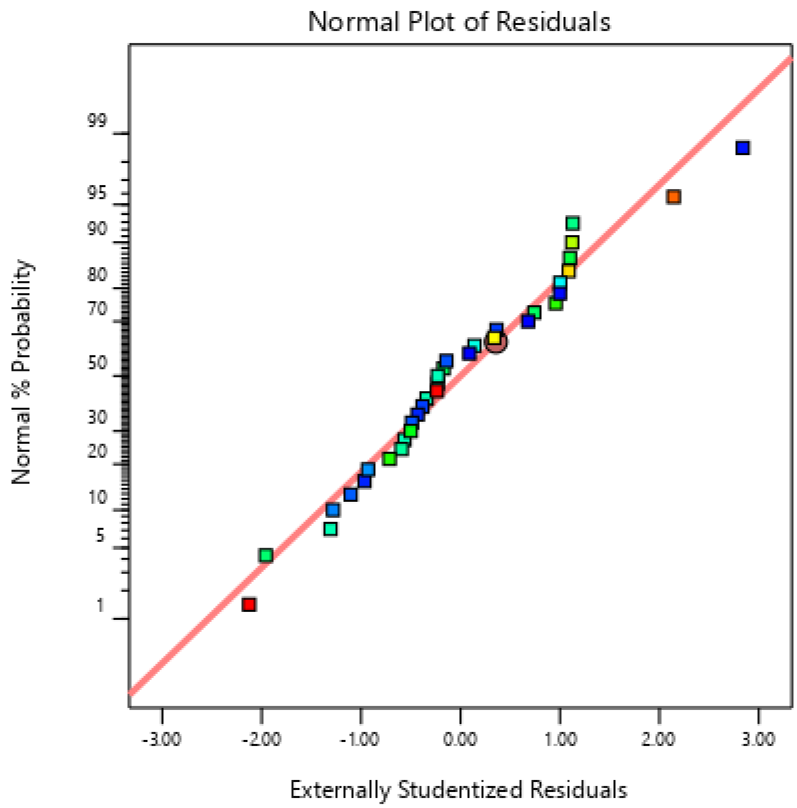


Figure D-13 - Axe Bow Displacement Normal Plot

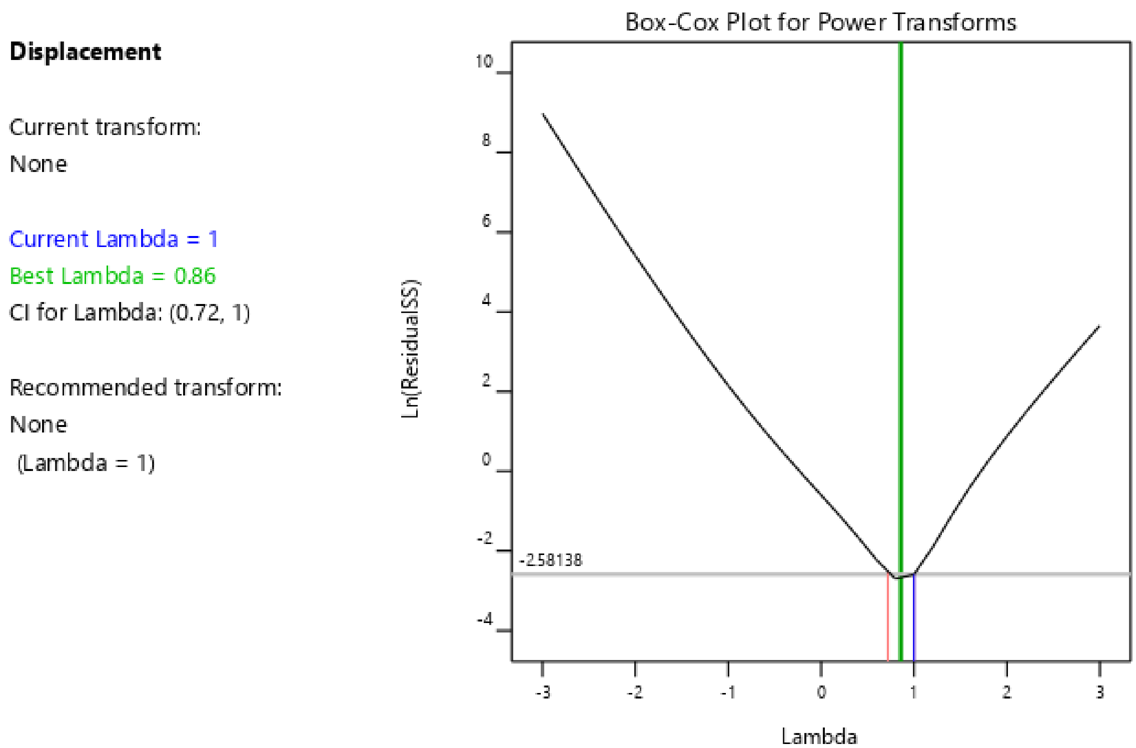


Figure D-14 - Axe Bow Displacement Box-Cox

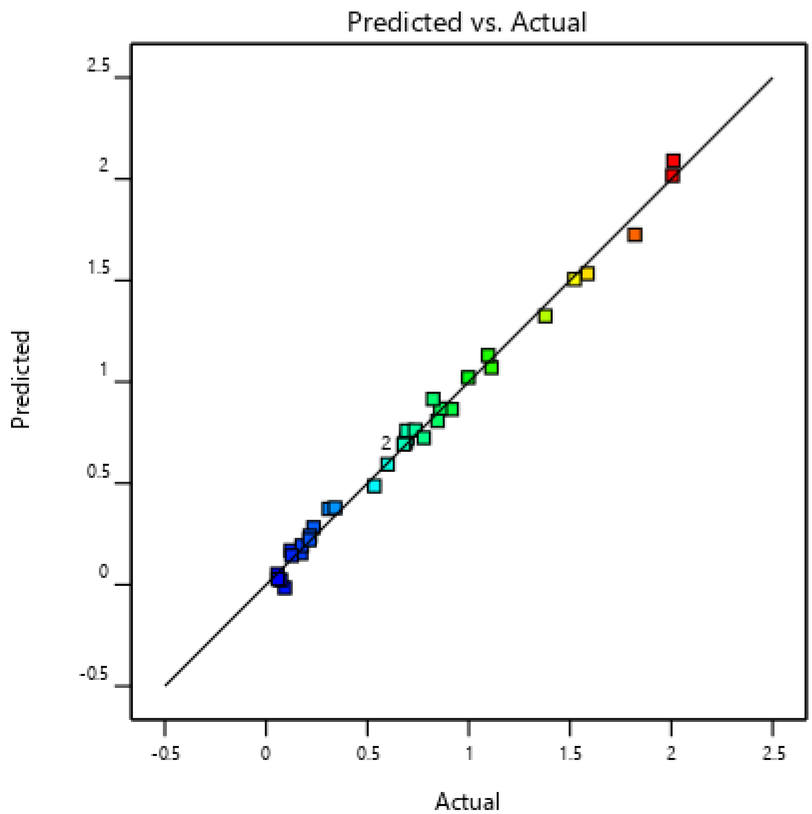


Figure D-15 - Axe Bow Displacement Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.84	10	0.1844	300.01	< 0.0001	significant
A-Length	0.2534	1	0.2534	412.38	< 0.0001	
C-Draft	0.0025	1	0.0025	4.05	0.0554	
D-Wave height	0.5130	1	0.5130	834.75	< 0.0001	
E-Peak Period	0.9307	1	0.9307	1514.63	< 0.0001	
AD	0.0048	1	0.0048	7.80	0.0101	
CE	0.0027	1	0.0027	4.38	0.0472	
DE	0.0268	1	0.0268	43.61	< 0.0001	
A^2	0.0047	1	0.0047	7.70	0.0105	
D^2	0.0047	1	0.0047	7.64	0.0108	
E^2	0.0608	1	0.0608	98.96	< 0.0001	
Residual	0.0147	24	0.0006			
Lack of Fit	0.0147	23	0.0006			
Pure Error	0.0000	1	0.0000			
Cor Total	1.86	34				

Figure D-16 - Axe Bow Velocity Anova Table

Std. Dev.	0.0248		**R^2**	0.9921
Mean	0.6657		**Adjusted R^2**	0.9888
C.V. %	3.72		**Predicted R^2**	0.9789
			Adeq Precision	62.9051

Figure D-17 - Axe Bow Velocity Model Statistics

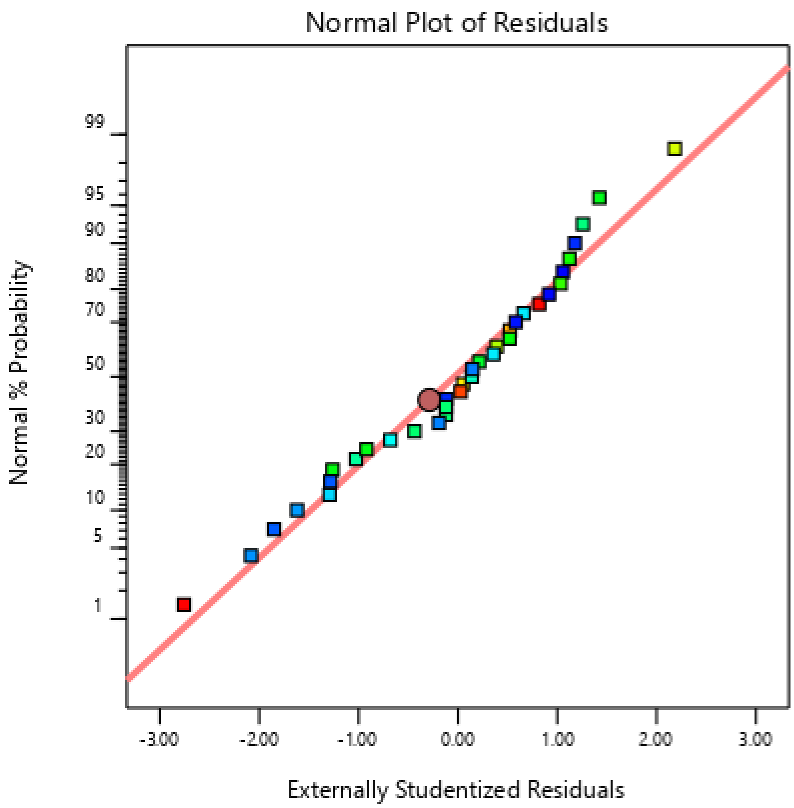


Figure D-18 - Axe Bow Velocity Normal Plot

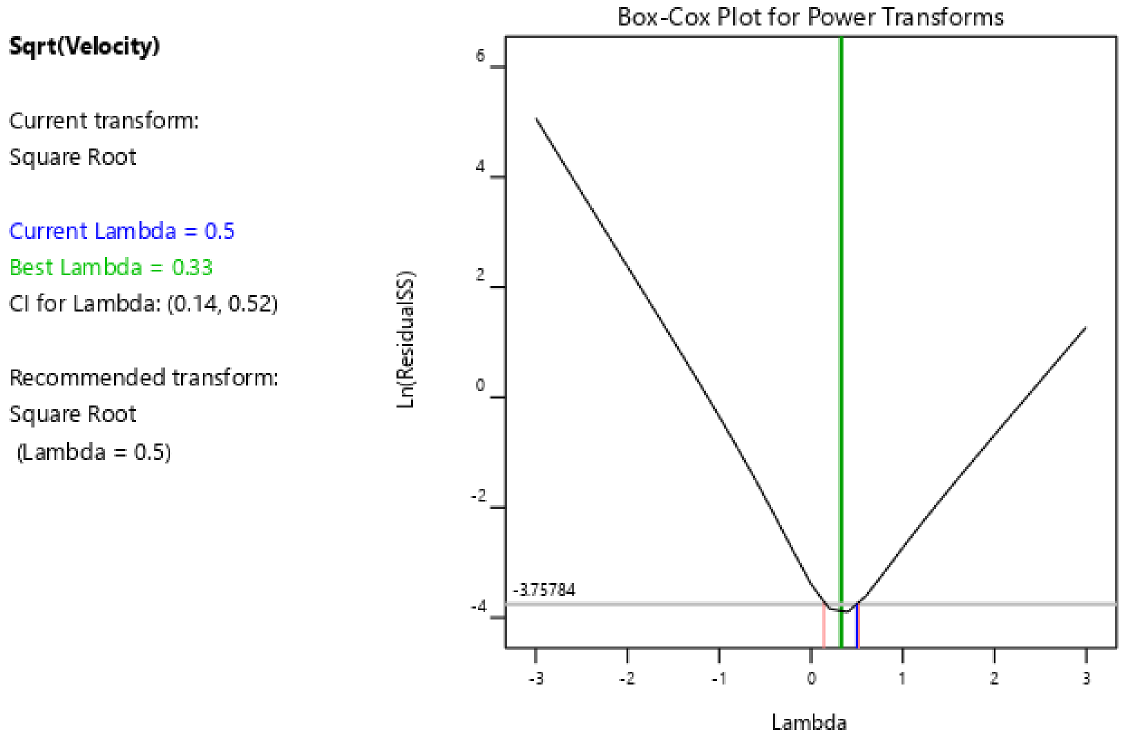


Figure D-19 - Axe Bow Velocity Box-Cox

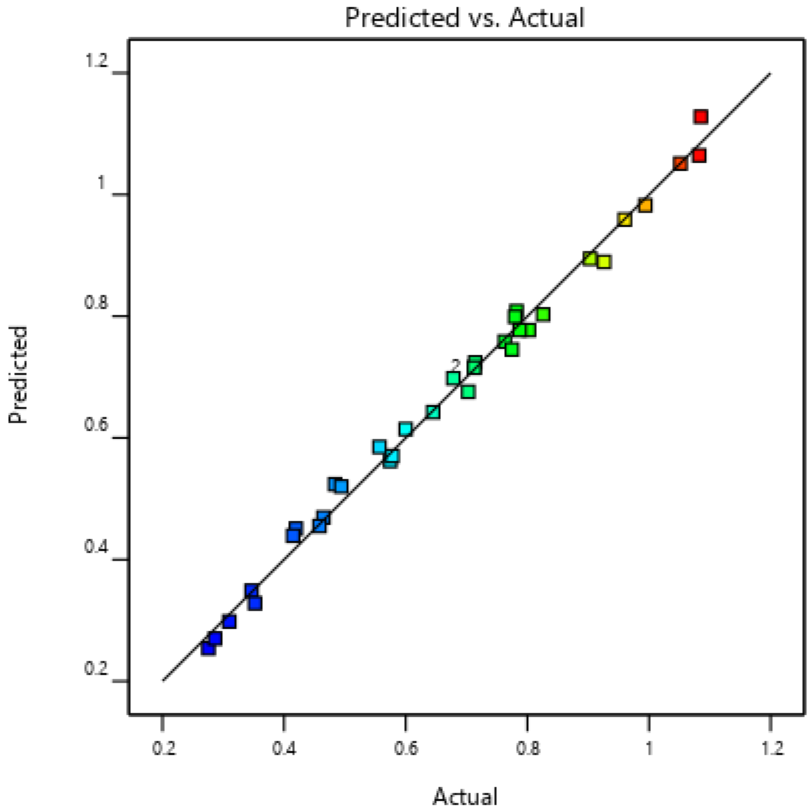


Figure D-20 - Axe Bow Velocity Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.9605	10	0.0960	176.99	< 0.0001	significant
A-Length	0.2647	1	0.2647	487.78	< 0.0001	
C-Draft	0.0050	1	0.0050	9.27	0.0056	
D-Wave height	0.4261	1	0.4261	785.24	< 0.0001	
E-Peak Period	0.1642	1	0.1642	302.62	< 0.0001	
AD	0.0068	1	0.0068	12.47	0.0017	
CE	0.0034	1	0.0034	6.18	0.0203	
DE	0.0038	1	0.0038	6.91	0.0147	
A^2	0.0056	1	0.0056	10.27	0.0038	
D^2	0.0033	1	0.0033	6.03	0.0217	
E^2	0.0513	1	0.0513	94.49	< 0.0001	
Residual	0.0130	24	0.0005			
Lack of Fit	0.0130	23	0.0006	1868.66	0.0183	significant
Pure Error	3.030E-07	1	3.030E-07			
Cor Total	0.9735	34				

Figure D-21 - Axe Bow Acceleration Anova Table

Std. Dev.	0.0233		**R^2**	0.9866
Mean	0.6055		**Adjusted R^2**	0.9810
C.V. %	3.85		**Predicted R^2**	0.9629
			Adeq Precision	45.1751

Figure D-22 - Axe Bow Acceleration Model Statistics

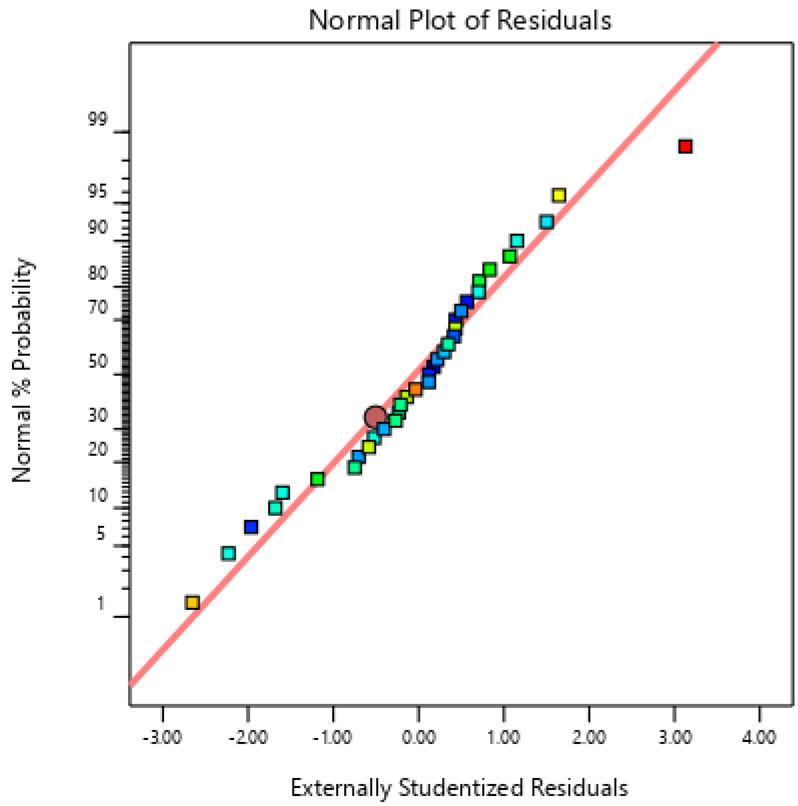


Figure D-23 - Axe Bow Acceleration Normal Plot

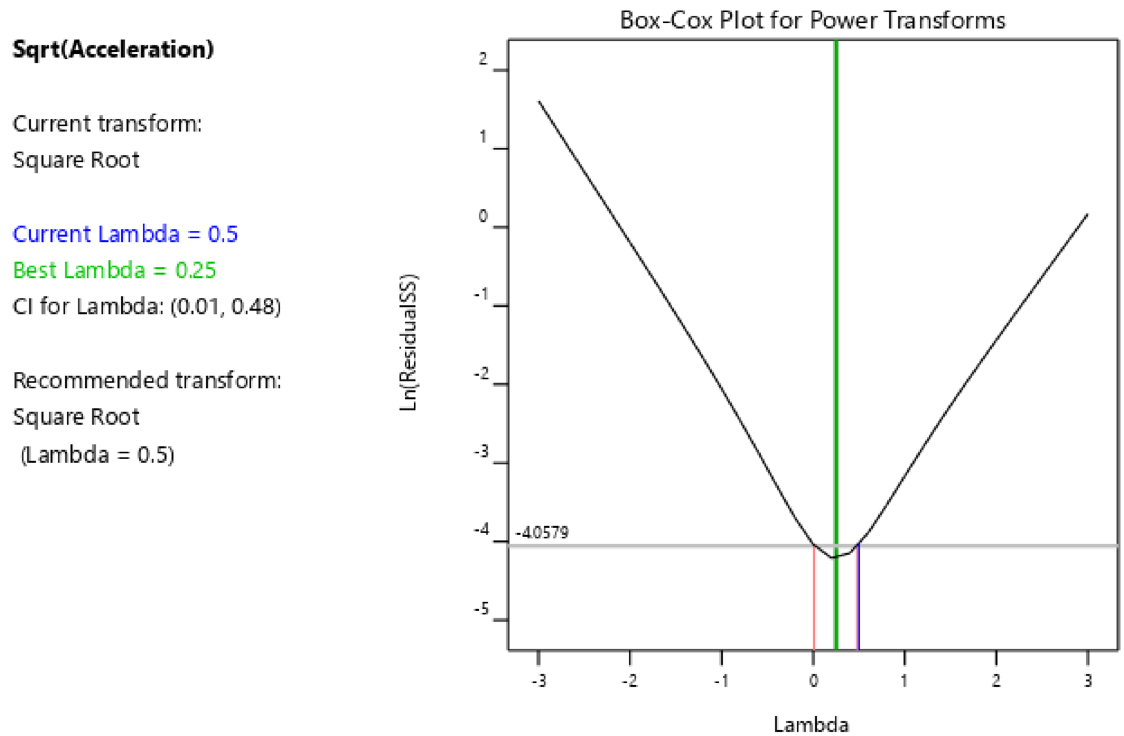


Figure D-24 - Axe Bow Acceleration Box-Cox

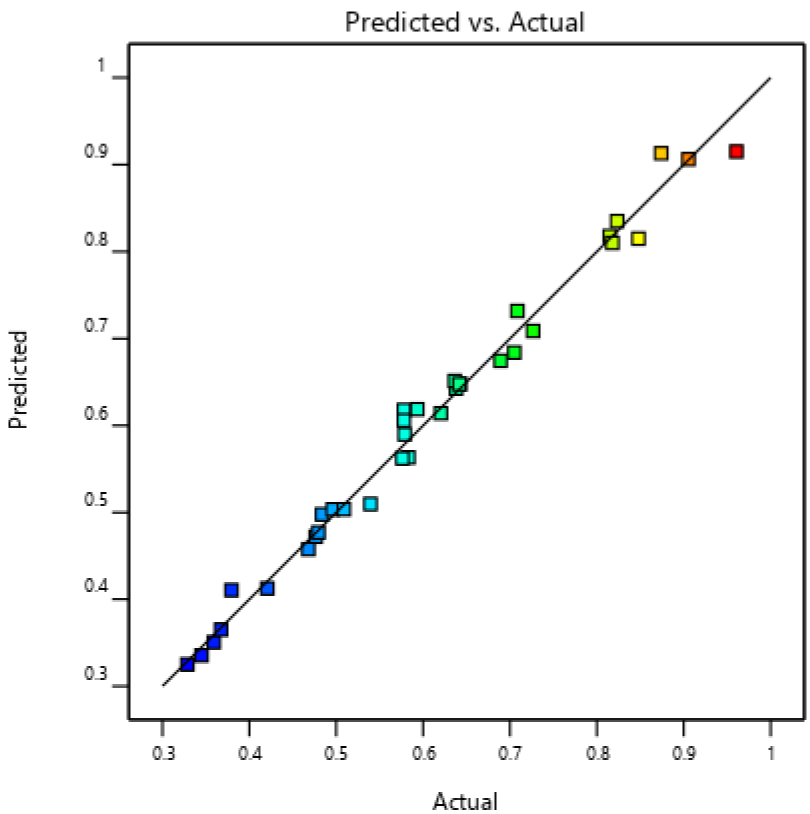


Figure D-25 - Axe Bow Acceleration Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	9.37	10	0.9374	542.08	< 0.0001	significant
A-Length	0.8293	1	0.8293	479.61	< 0.0001	
B-Beam	0.0000	1	0.0000	0.0256	0.8742	
C-Draft	0.0119	1	0.0119	6.90	0.0148	
D-Wave height	2.06	1	2.06	1191.19	< 0.0001	
E-Peak Period	5.69	1	5.69	3290.22	< 0.0001	
AD	0.0718	1	0.0718	41.51	< 0.0001	
AE	0.1155	1	0.1155	66.77	< 0.0001	
DE	0.7470	1	0.7470	431.99	< 0.0001	
A^2	0.0371	1	0.0371	21.45	0.0001	
B^2	0.0149	1	0.0149	8.61	0.0072	
Residual	0.0415	24	0.0017			
Lack of Fit	0.0415	23	0.0018			
Pure Error	0.0000	1	0.0000			
Cor Total	9.42	34				

Figure D-26 - Bulbous Bow Displacement Anova Table

Std. Dev.	0.0416		**R^2**	0.9956
Mean	0.6921		**Adjusted R^2**	0.9938
C.V. %	6.01		**Predicted R^2**	0.9898
			Adeq Precision	87.0712

Figure D-27 - Bulbous Bow Displacement Model Statistics

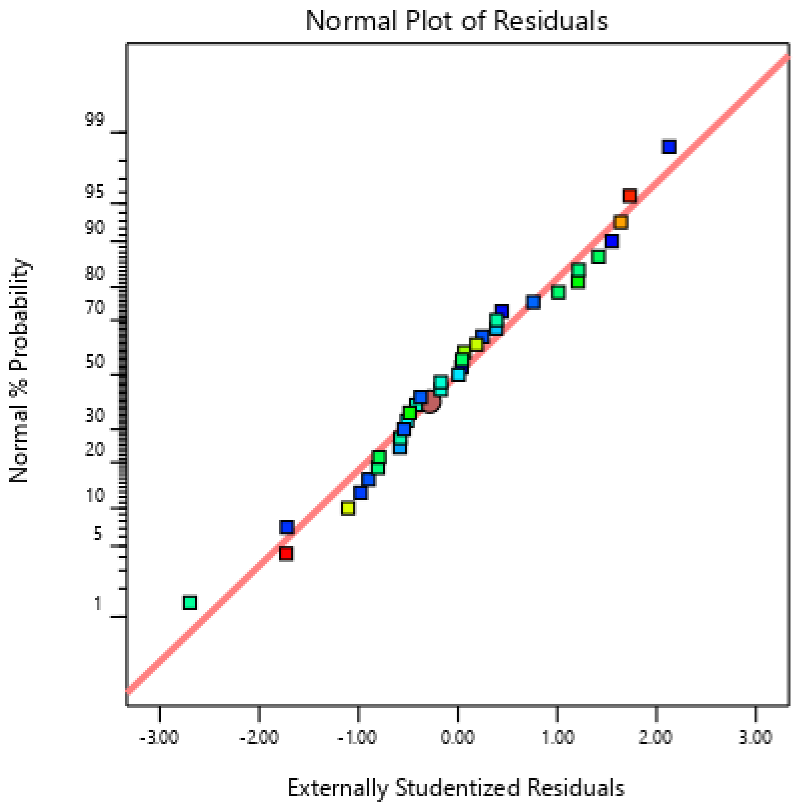


Figure D-28 - Bulbous Bow Displacement Normal Plot

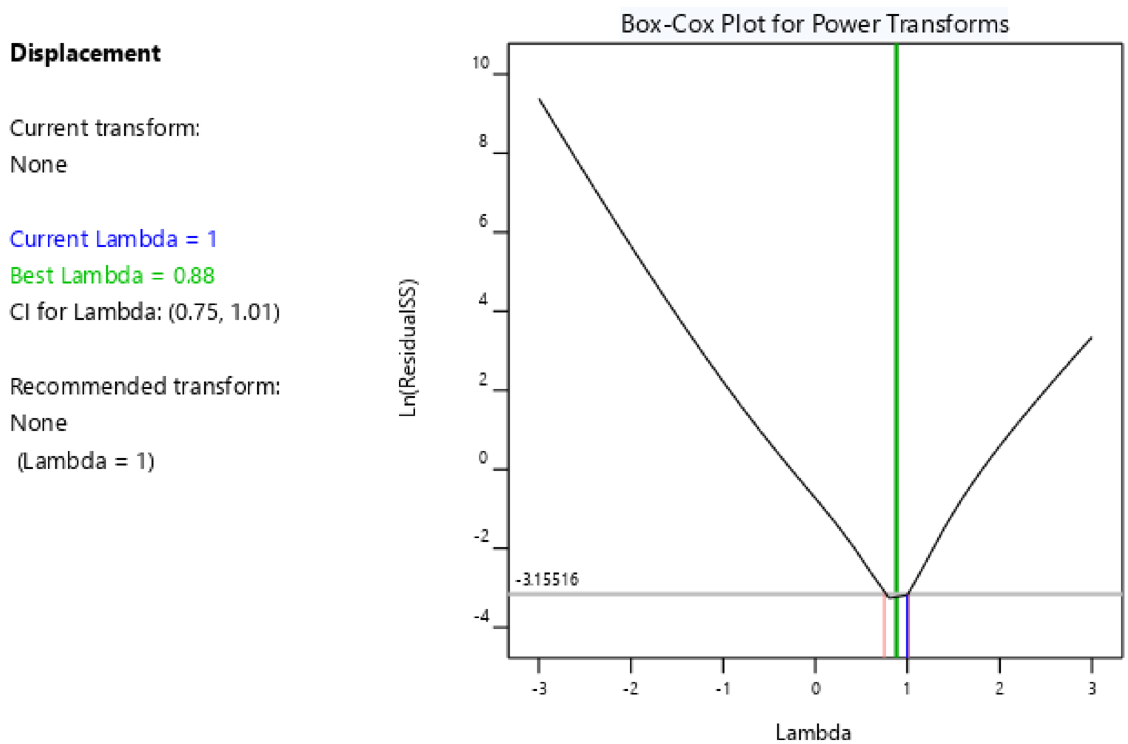


Figure D-29 - Bulbous Bow Displacement Box-Cox

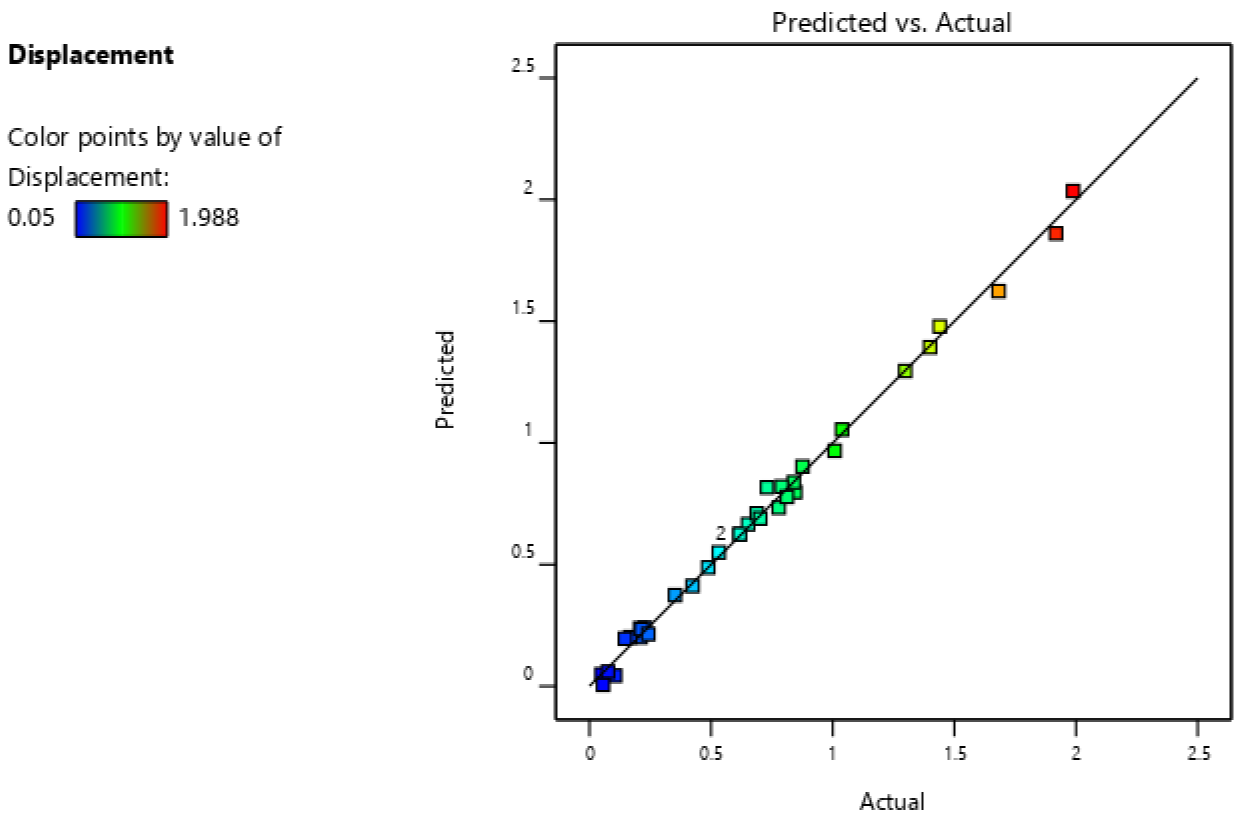


Figure D-30 - Bulbous Bow Displacement Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.72	11	0.1560	223.14	< 0.0001	significant
A-Length	0.3046	1	0.3046	435.64	< 0.0001	
C-Draft	0.0093	1	0.0093	13.26	0.0014	
D-Wave height	0.5562	1	0.5562	795.61	< 0.0001	
E-Peak Period	0.0205	1	0.0205	29.35	< 0.0001	
AE	0.0000	1	0.0000	0.0246	0.8768	
CE	0.0022	1	0.0022	3.13	0.0903	
DE	0.0215	1	0.0215	30.73	< 0.0001	
A^2	0.0142	1	0.0142	20.30	0.0002	
E^2	0.0650	1	0.0650	92.95	< 0.0001	
CE^2	0.0098	1	0.0098	14.09	0.0010	
E^3	0.0194	1	0.0194	27.74	< 0.0001	
Residual	0.0161	23	0.0007			
Lack of Fit	0.0161	22	0.0007	717.70	0.0294	significant
Pure Error	1.018E-06	1	1.018E-06			
Cor Total	1.73	34				

Figure D-31 - Bulbous Bow Velocity Anova Table

Std. Dev.	0.0264		**R^2**	0.9907
Mean	0.6675		**Adjusted R^2**	0.9863
C.V. %	3.96		**Predicted R^2**	0.9761
			Adeq Precision	55.3976

Figure D-32 - Bulbous Bow Velocity Model Statistics

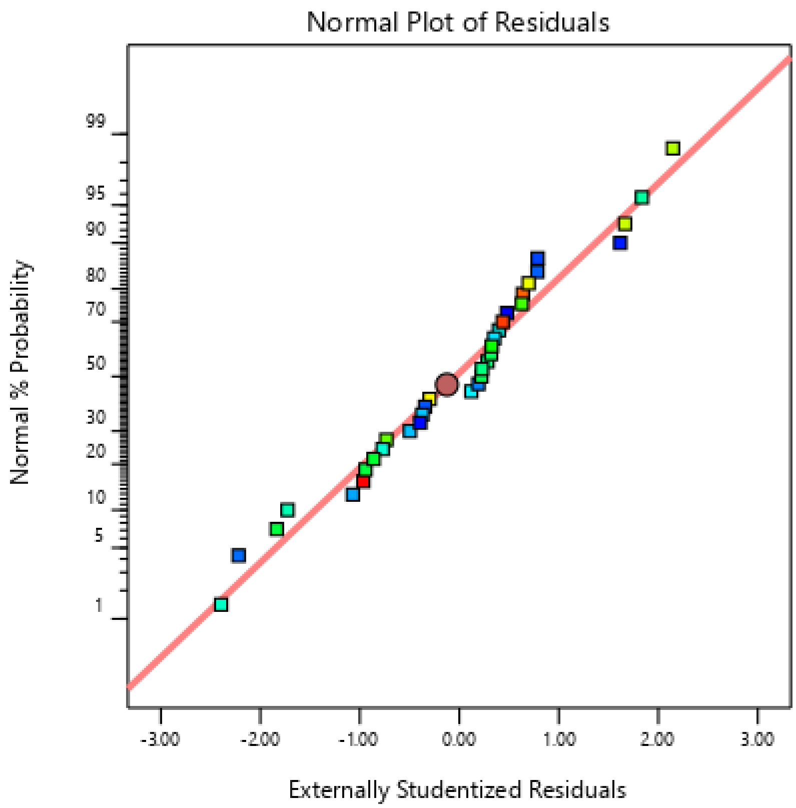


Figure D-33 - Bulbous Bow Velocity Normal Plot

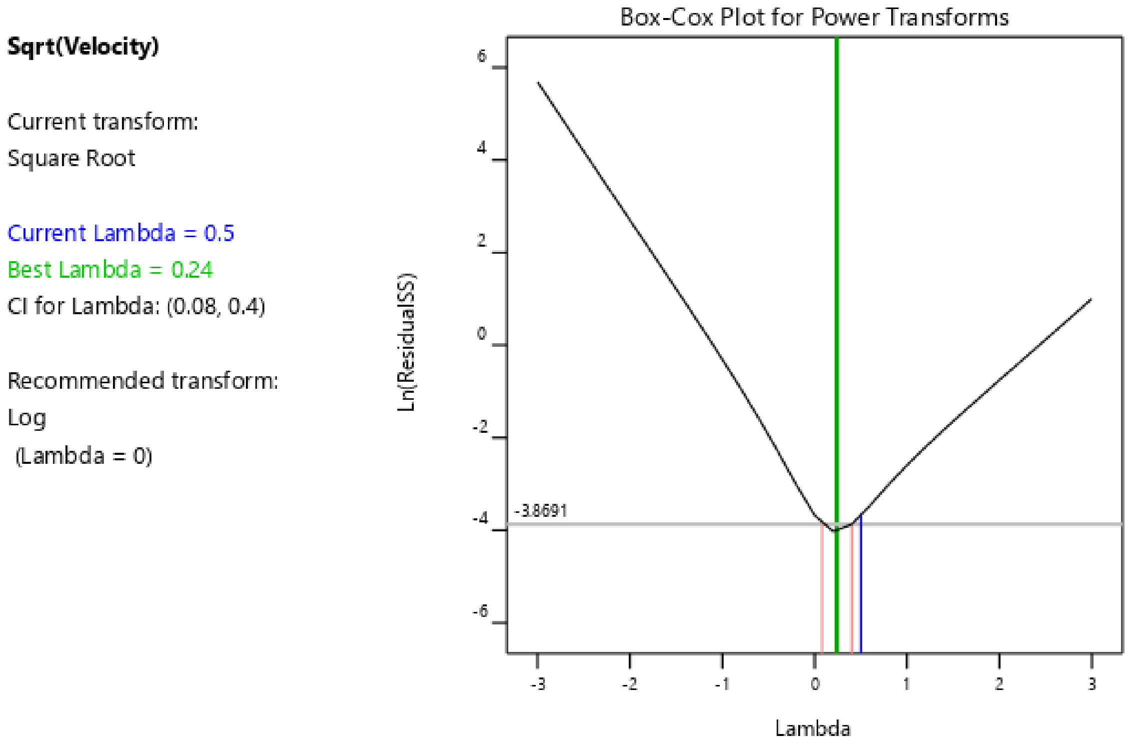


Figure D-34 - Bulbous Bow Velocity Box-Cox

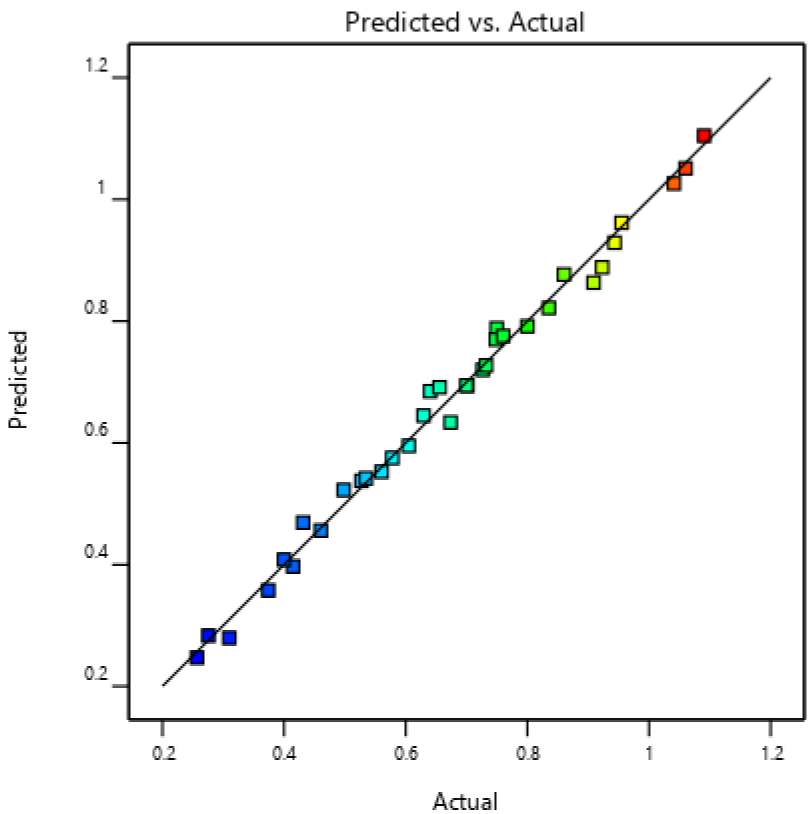


Figure D-35 - Bulbous Bow Velocity Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2.35	6	0.3918	145.92	< 0.0001	significant
A-Length	0.6405	1	0.6405	238.54	< 0.0001	
D-Wave height	1.01	1	1.01	376.42	< 0.0001	
E-Peak Period	0.0025	1	0.0025	0.9284	0.3435	
AE	0.0124	1	0.0124	4.60	0.0407	
E^2	0.2049	1	0.2049	76.32	< 0.0001	
E^3	0.0637	1	0.0637	23.73	< 0.0001	
Residual	0.0752	28	0.0027			
Lack of Fit	0.0752	27	0.0028			
Pure Error	0.0000	1	0.0000			
Cor Total	2.43	34				

Figure D-36 - Bulbous Bow Acceleration Anova Table

Std. Dev.	0.0518		**R^2**	0.9690
Mean	-0.4546		**Adjusted R^2**	0.9624
C.V. %	11.40		**Predicted R^2**	0.9507
			Adeq Precision	47.3694

Figure D-37 - Bulbous Bow Acceleration Model Statistics

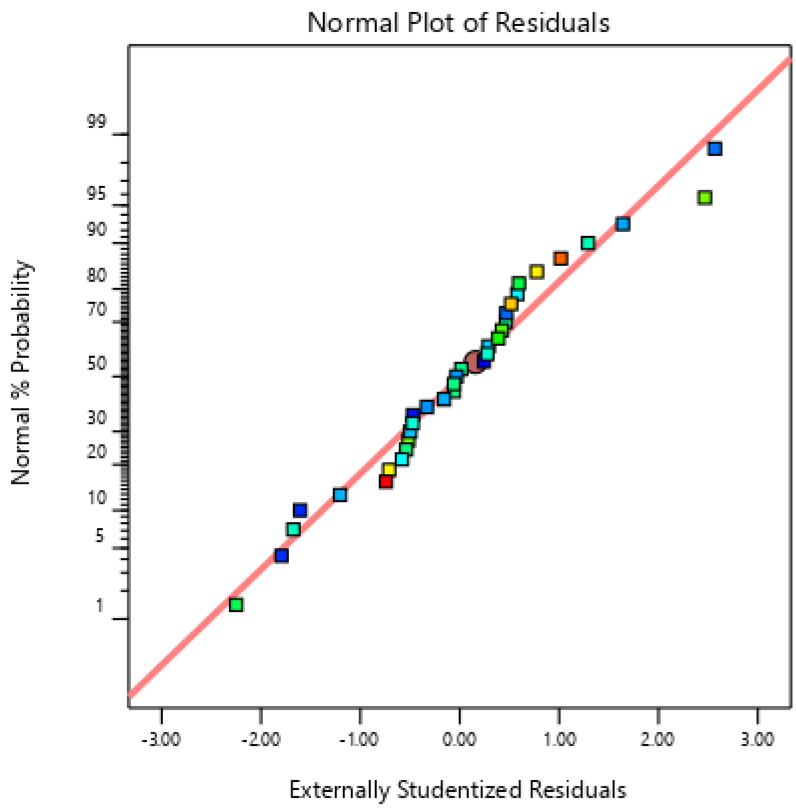


Figure D-38 - Bulbous Bow Acceleration Normal Plot

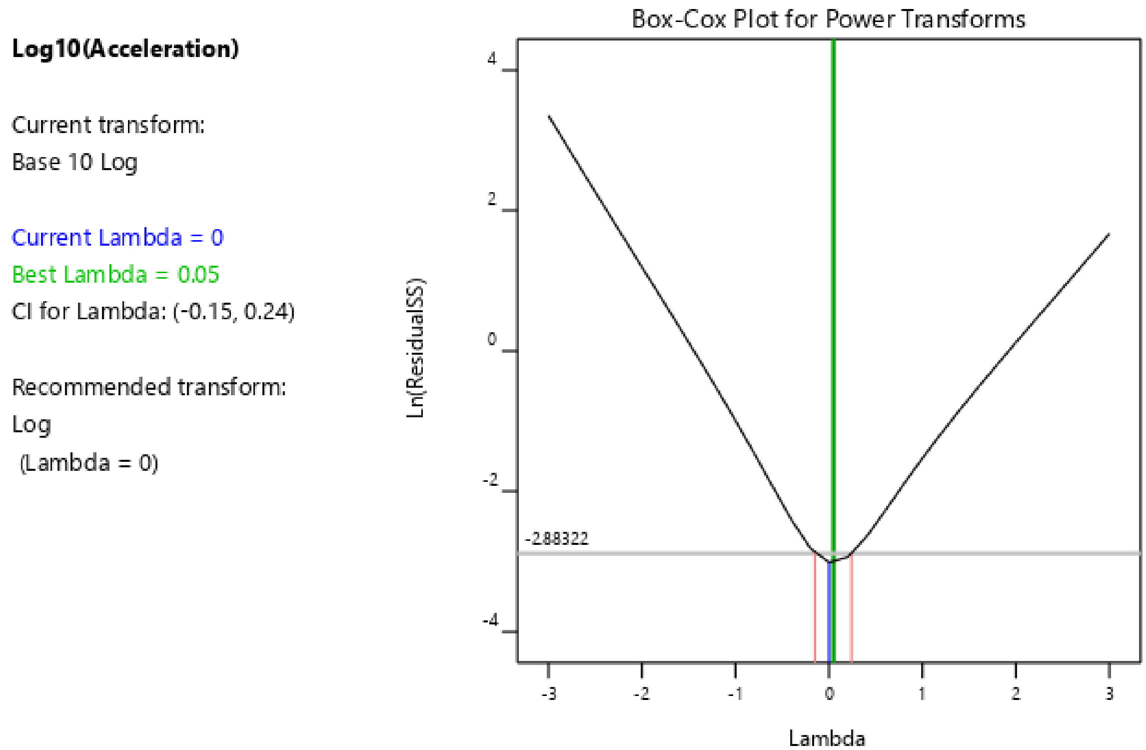


Figure D-39 - Bulbous Bow Acceleration Box-Cox

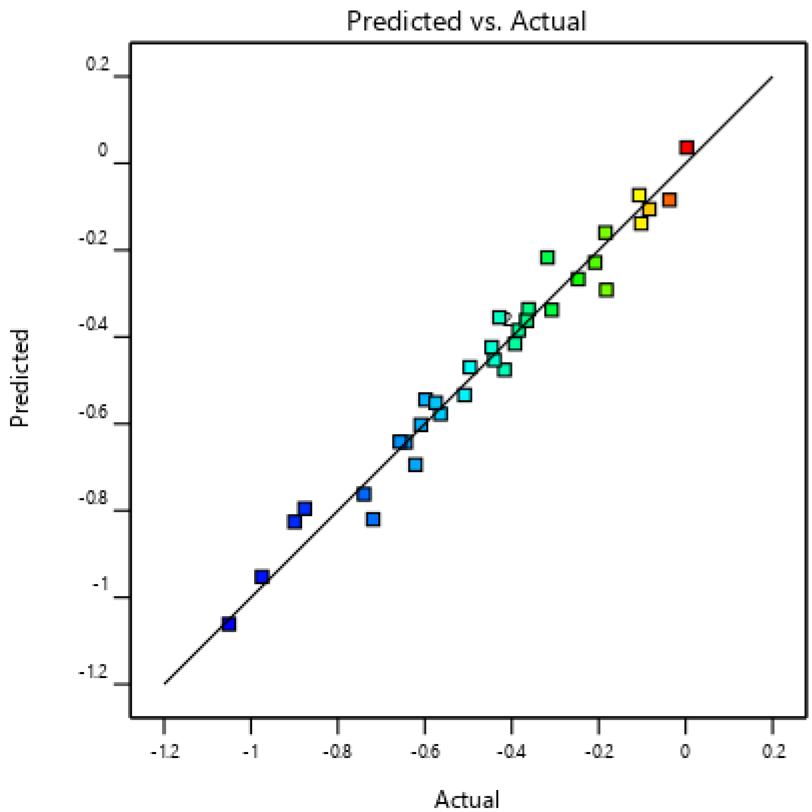


Figure D-40 - Bulbous Bow Acceleration Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	9.37	10	0.9368	562.25	< 0.0001	significant
A-Length	0.8168	1	0.8168	490.19	< 0.0001	
B-Beam	0.0000	1	0.0000	0.0223	0.8827	
C-Draft	0.0062	1	0.0062	3.70	0.0664	
D-Wave height	2.06	1	2.06	1238.07	< 0.0001	
E-Peak Period	5.70	1	5.70	3420.24	< 0.0001	
AD	0.0789	1	0.0789	47.36	< 0.0001	
AE	0.1134	1	0.1134	68.04	< 0.0001	
DE	0.7281	1	0.7281	436.94	< 0.0001	
A^2	0.0349	1	0.0349	20.96	0.0001	
B^2	0.0108	1	0.0108	6.49	0.0177	
Residual	0.0400	24	0.0017			
Lack of Fit	0.0400	23	0.0017	217.29	0.0535	not significant
Pure Error	8.000E-06	1	8.000E-06			
Cor Total	9.41	34				

Figure D-41 - Vertical Bow Displacement Anova Table

Std. Dev.	0.0408		**R^2**	0.9957
Mean	0.6944		**Adjusted R^2**	0.9940
C.V. %	5.88		**Predicted R^2**	0.9899
			Adeq Precision	88.0677

Figure D-42 - Vertical Bow Displacement Model Statistics

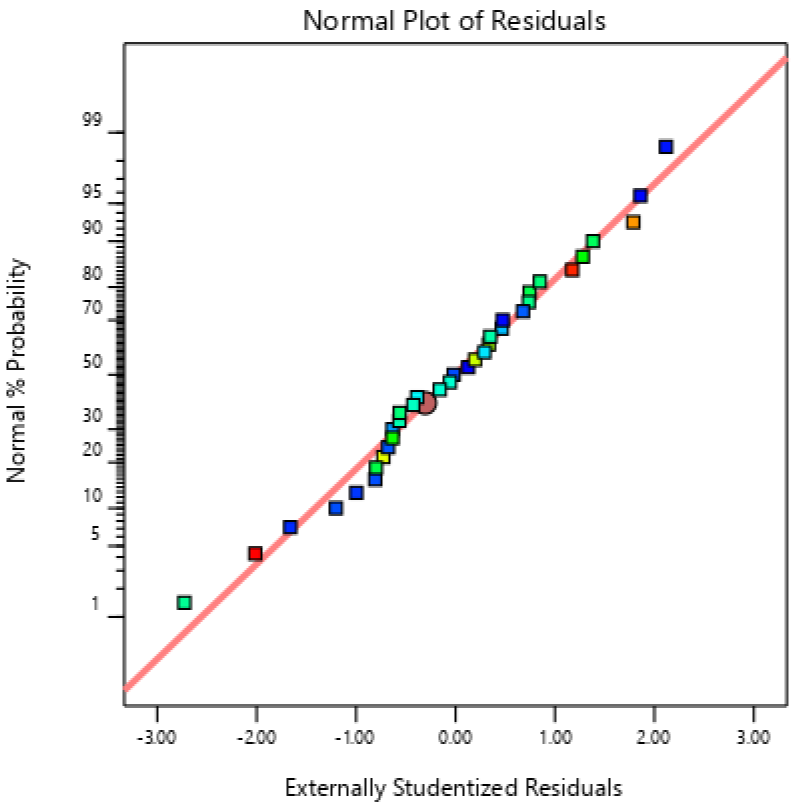


Figure D-43 - Vertical Bow Displacement Normal Plot

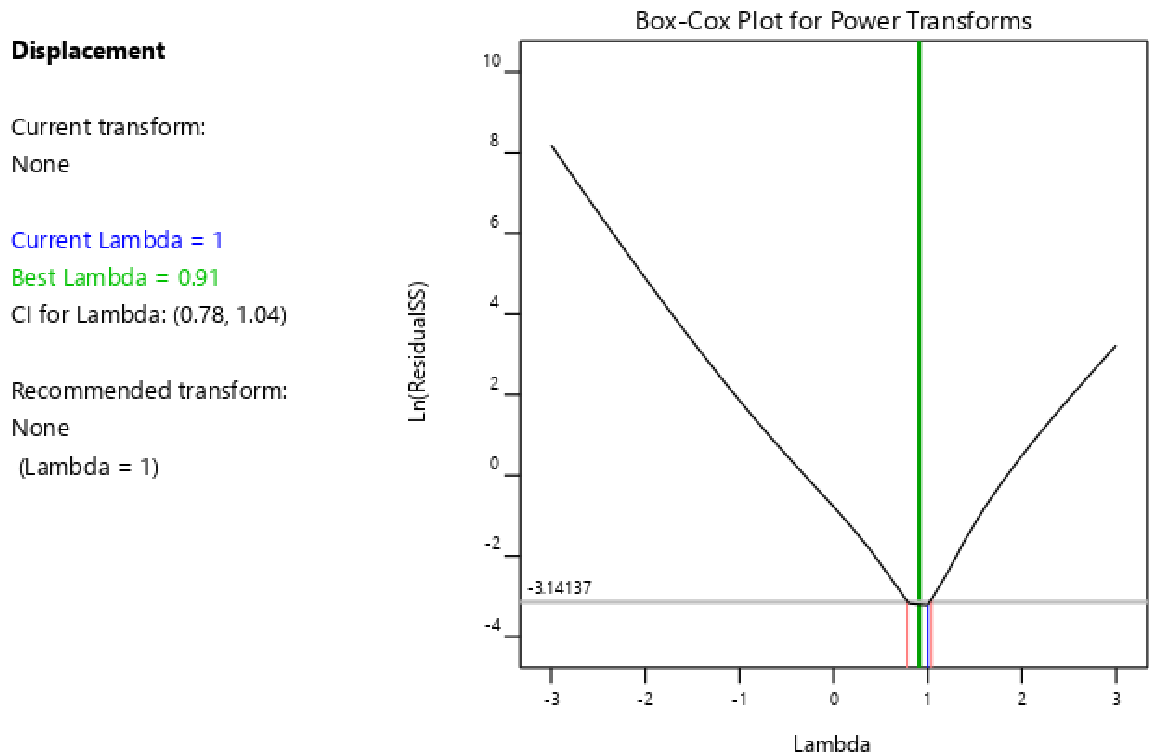


Figure D-44 - Vertical Bow Displacement Box-Cox

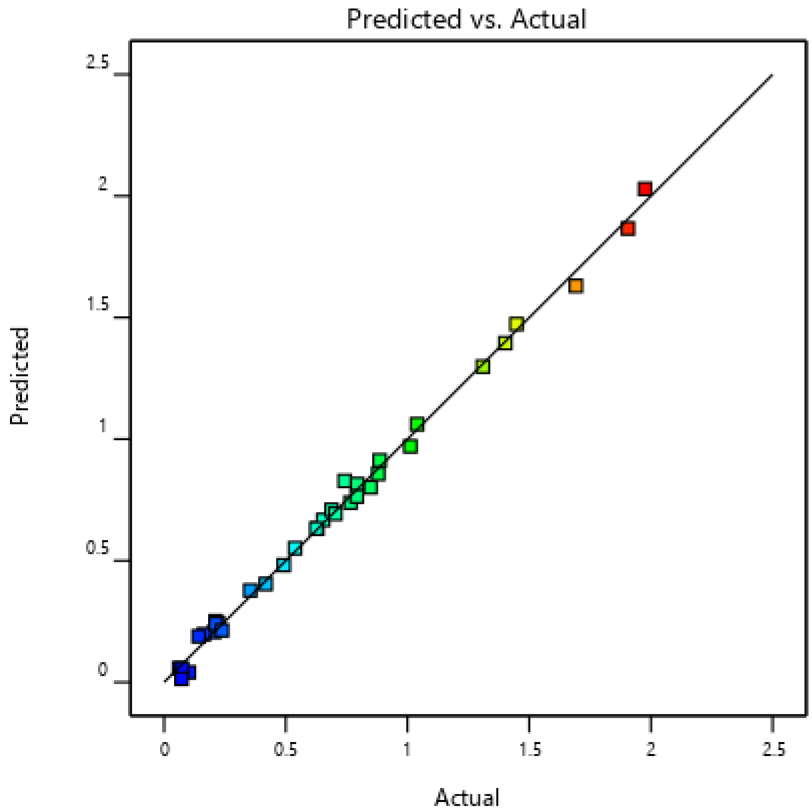


Figure D-45 - Vertical Bow Displacement Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.67	8	0.2087	166.52	< 0.0001	significant
A-Length	0.1838	1	0.1838	146.69	< 0.0001	
D-Wave height	0.5394	1	0.5394	430.45	< 0.0001	
E-Peak Period	0.0295	1	0.0295	23.57	< 0.0001	
AE	1.340E-07	1	1.340E-07	0.0001	0.9918	
DE	0.0269	1	0.0269	21.44	< 0.0001	
E^2	0.0702	1	0.0702	55.98	< 0.0001	
AE^2	0.0127	1	0.0127	10.14	0.0037	
E^3	0.0127	1	0.0127	10.14	0.0037	
Residual	0.0326	26	0.0013			
Lack of Fit	0.0326	25	0.0013	321.87	0.0440	significant
Pure Error	4.049E-06	1	4.049E-06			
Cor Total	1.70	34				

Figure D-46 - Vertical Bow Velocity Anova Table

Std. Dev.	0.0354		**R^2**	0.9809
Mean	0.6686		**Adjusted R^2**	0.9750
C.V. %	5.29		**Predicted R^2**	0.9632
			Adeq Precision	45.4826

Figure D-47 - Vertical Bow Velocity Model Statistics

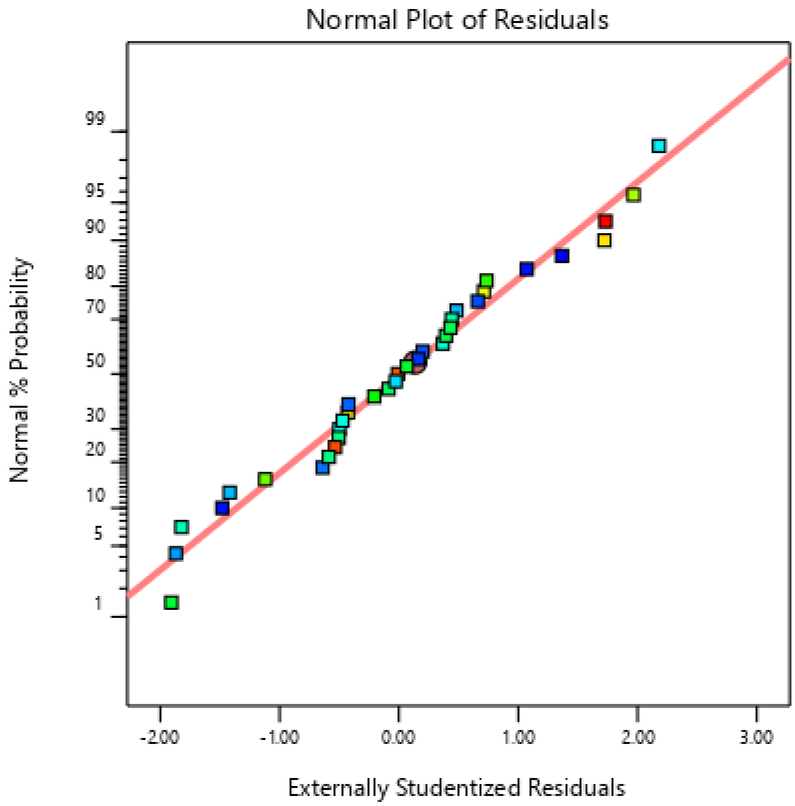


Figure D-48 - Vertical Bow Velocity Normal Plot

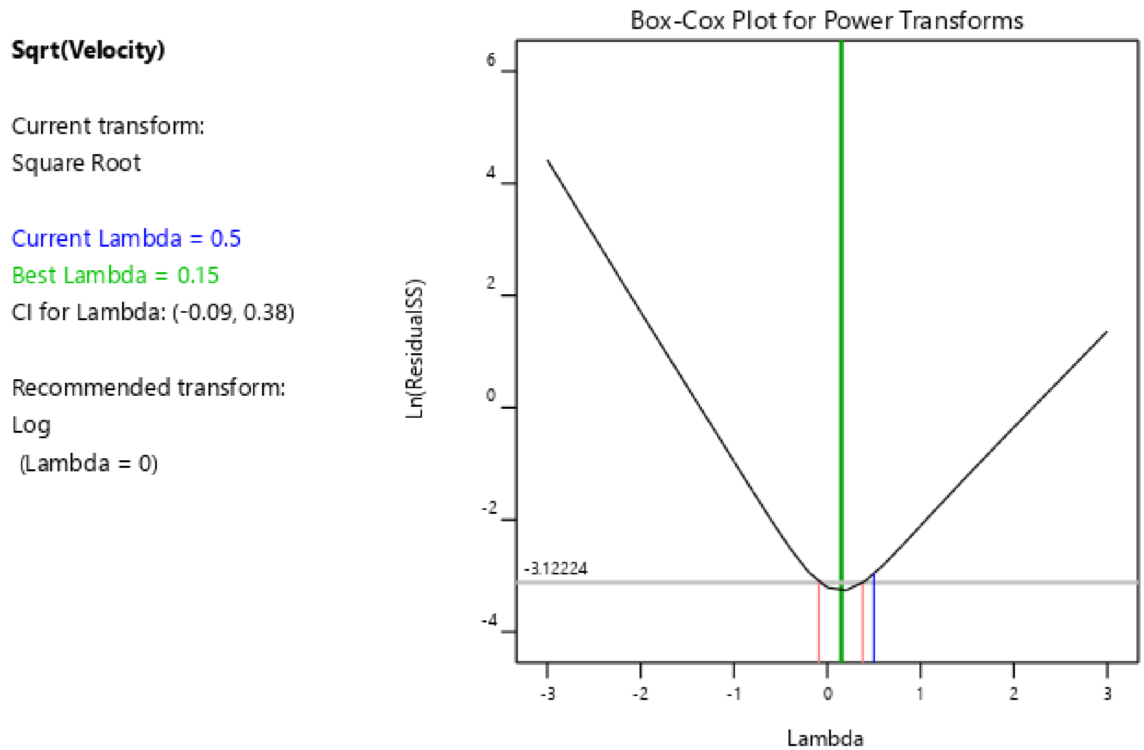


Figure D-49 - Vertical Bow Velocity Box-Cox

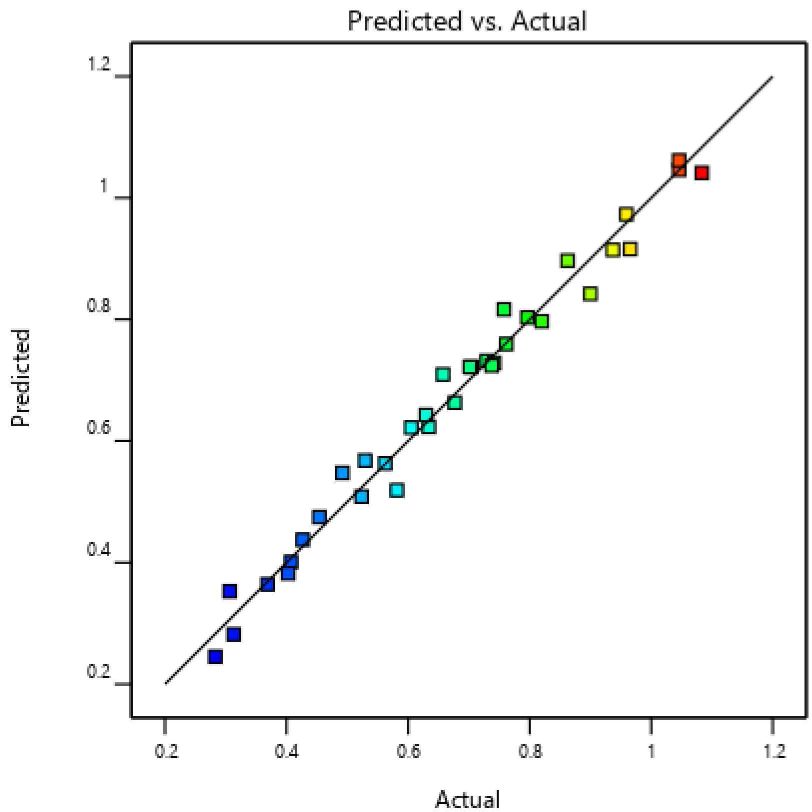


Figure D-50 - Vertical Bow Velocity Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2.19	8	0.2738	137.09	< 0.0001	significant
A-Length	0.6373	1	0.6373	319.10	< 0.0001	
C-Draft	0.0135	1	0.0135	6.77	0.0151	
D-Wave height	1.00	1	1.00	502.59	< 0.0001	
E-Peak Period	0.0006	1	0.0006	0.2845	0.5983	
CE	0.0094	1	0.0094	4.71	0.0392	
E^2	0.1631	1	0.1631	81.68	< 0.0001	
CE^2	0.0246	1	0.0246	12.31	0.0017	
E^3	0.0439	1	0.0439	21.99	< 0.0001	
Residual	0.0519	26	0.0020			
Lack of Fit	0.0519	25	0.0021	112.55	0.0743	not significant
Pure Error	0.0000	1	0.0000			
Cor Total	2.24	34				

Figure D-51 - Vertical Bow Acceleration Anova Table

Std. Dev.	0.0447		**R^2**	0.9768
Mean	-0.4521		**Adjusted R^2**	0.9697
C.V. %	9.88		**Predicted R^2**	0.9558
			Adeq Precision	42.8391

Figure D-52 - Vertical Bow Acceleration Model Statistics

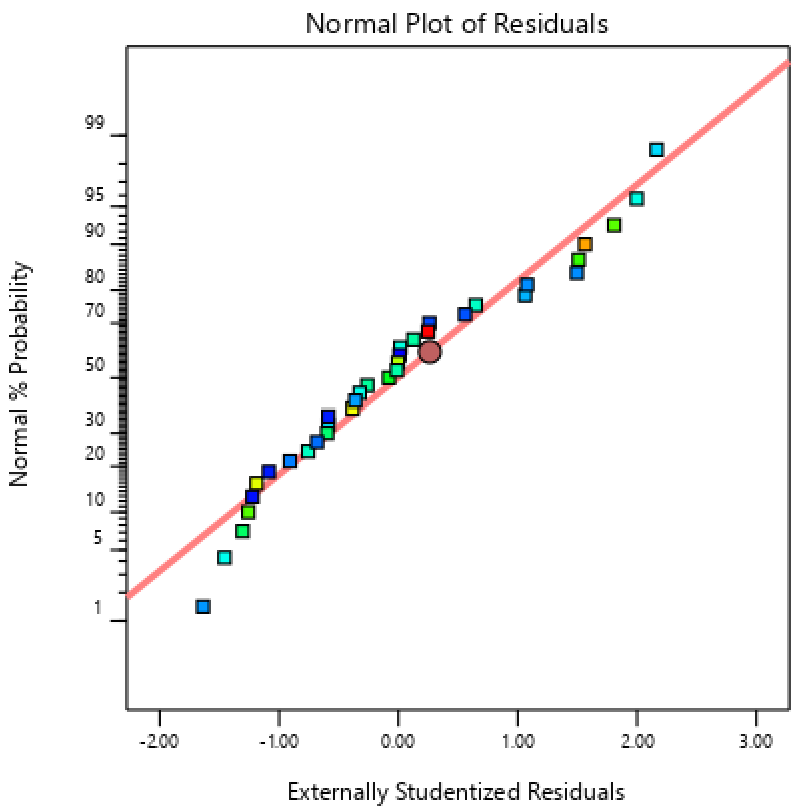


Figure D-53 - Vertical Bow Acceleration Normal Plot

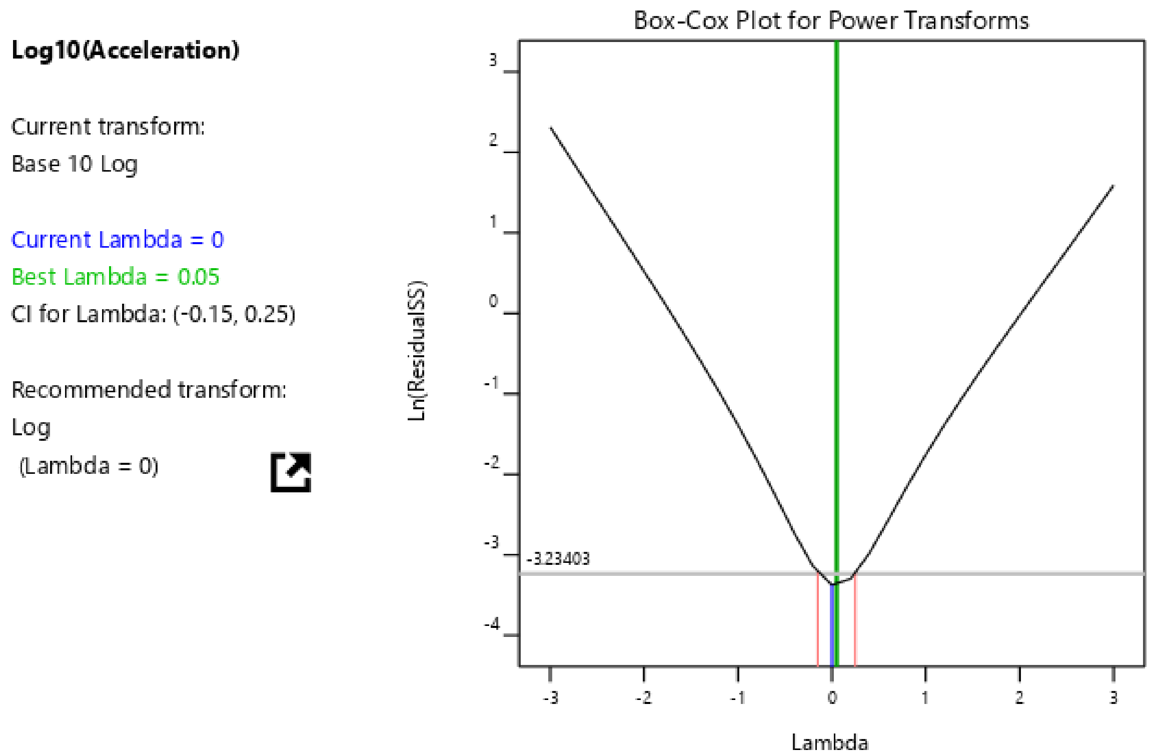


Figure D-54 - Vertical Bow Acceleration Box-Cox

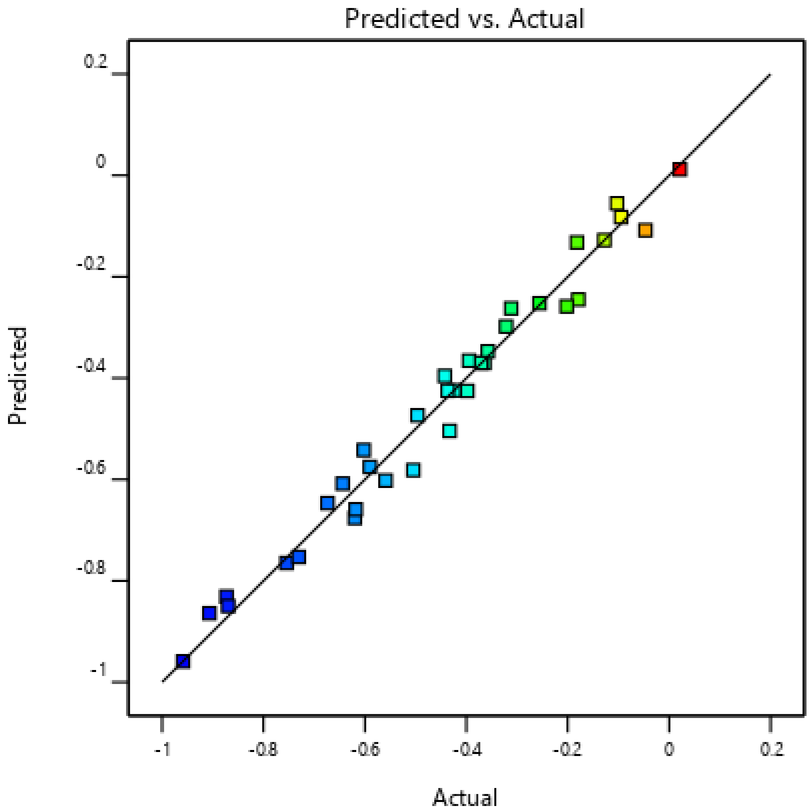


Figure D-55 - Vertical Bow Acceleration Prediction Accuracy

Appendix E: Additional ANOVA Results for Resistance Prediction

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	9.25	8	1.16	240.22	< 0.0001	significant
A-Length	0.2235	1	0.2235	46.42	< 0.0001	
B-Beam	0.1952	1	0.1952	40.56	< 0.0001	
C-Draft	0.2945	1	0.2945	61.18	< 0.0001	
D-Wave Height	0.0484	1	0.0484	10.06	0.0059	
F-Speed	8.17	1	8.17	1696.83	< 0.0001	
AC	0.0326	1	0.0326	6.76	0.0193	
AF	0.0679	1	0.0679	14.10	0.0017	
F^2	0.0202	1	0.0202	4.20	0.0572	
Residual	0.0770	16	0.0048			
Cor Total	9.33	24				

Figure E-1 - Bulbous Bow Resistance ANOVA

Std. Dev.	0.0694		**R^2**	0.9917
Mean	2.92		**Adjusted R^2**	0.9876
C.V. %	2.38		**Predicted R^2**	0.9801
			Adeq Precision	46.7661

Figure E-2 - Bulbous Bow Resistance Model Fit

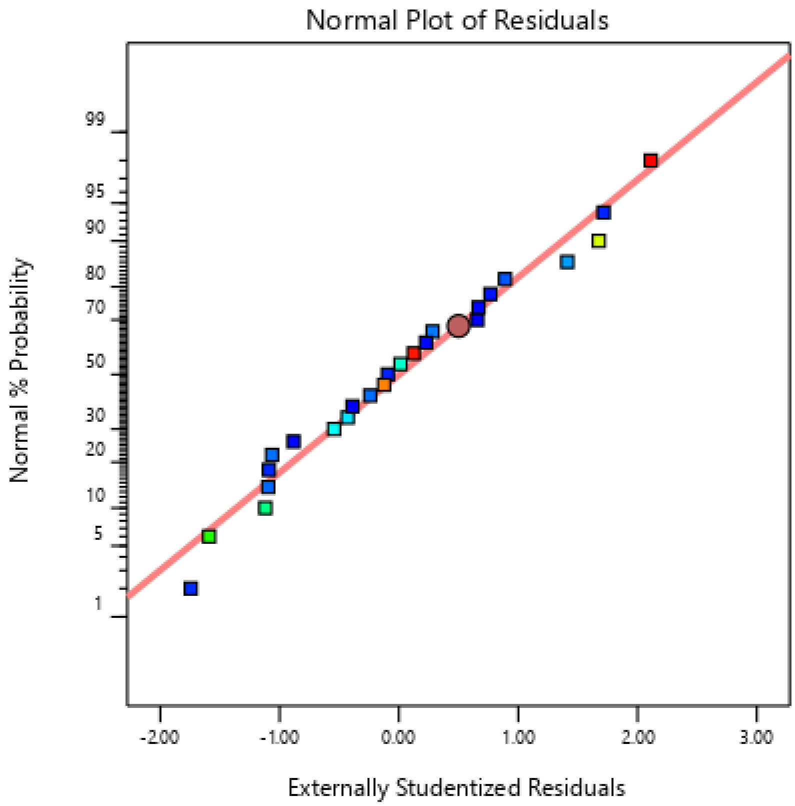


Figure E-3 - Bulbous Bow Resistance Normal Plot

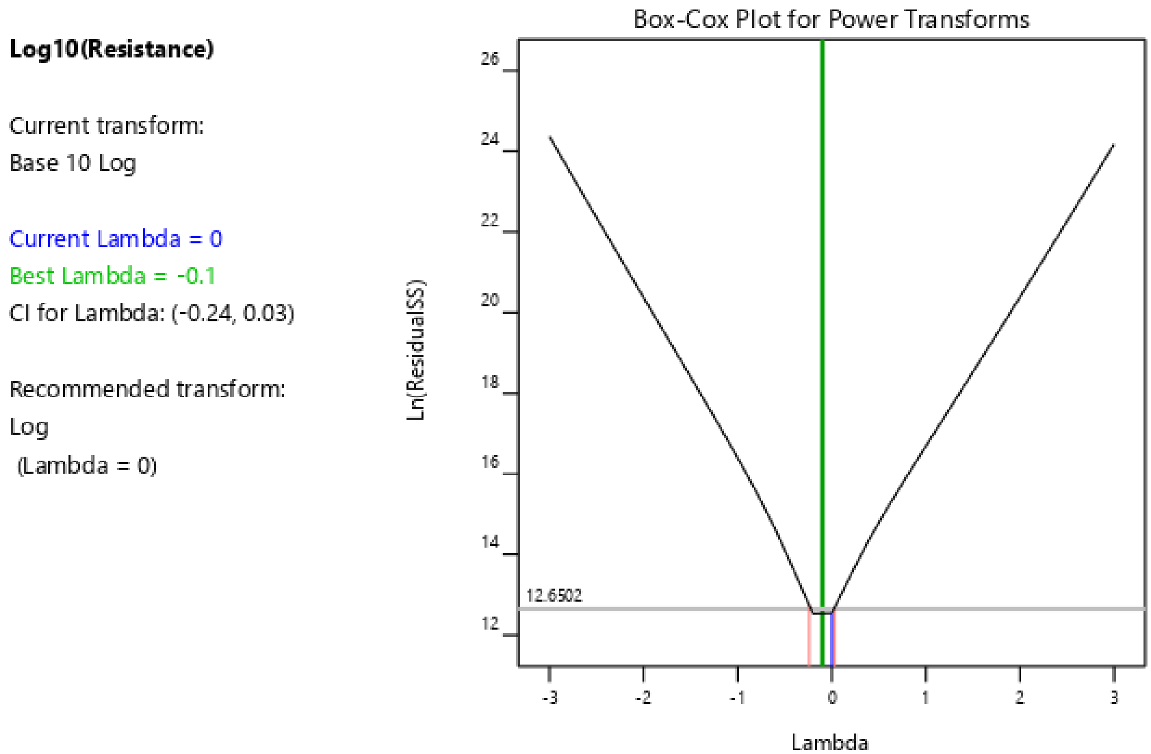


Figure E-4 - Bulbous Bow Resistance Box-Cox

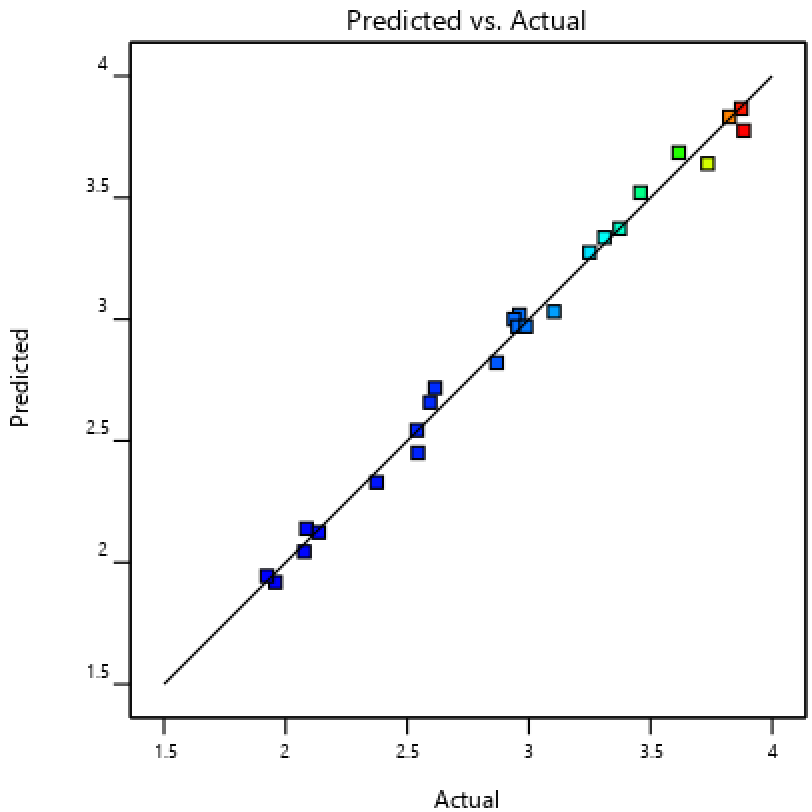


Figure E-5 - Bulbous Bow Resistance Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	5.84	12	0.4871	631.77	< 0.0001	significant
A-Length	0.1746	1	0.1746	226.47	< 0.0001	
B-Beam	0.1889	1	0.1889	244.98	< 0.0001	
C-Draft	0.0081	1	0.0081	10.48	0.0071	
D-Wave Height	0.0484	1	0.0484	62.80	< 0.0001	
E-Peak Period	0.0029	1	0.0029	3.77	0.0759	
F-Speed	1.46	1	1.46	1891.66	< 0.0001	
AB	0.0072	1	0.0072	9.31	0.0101	
CE	0.0002	1	0.0002	0.2046	0.6591	
DE	0.0082	1	0.0082	10.63	0.0068	
B^2	0.0097	1	0.0097	12.60	0.0040	
E^2	0.0009	1	0.0009	1.21	0.2936	
CE^2	0.0261	1	0.0261	33.84	< 0.0001	
Residual	0.0093	12	0.0008			
Cor Total	5.85	24				

Figure E-6 - Vertical Bow Resistance ANOVA

Std. Dev.	0.0278		**R^2**	0.9984
Mean	3.15		**Adjusted R^2**	0.9968
C.V. %	0.8819		**Predicted R^2**	0.9908
			Adeq Precision	82.8319

Figure E-7 - Vertical Bow Resistance Model Fit

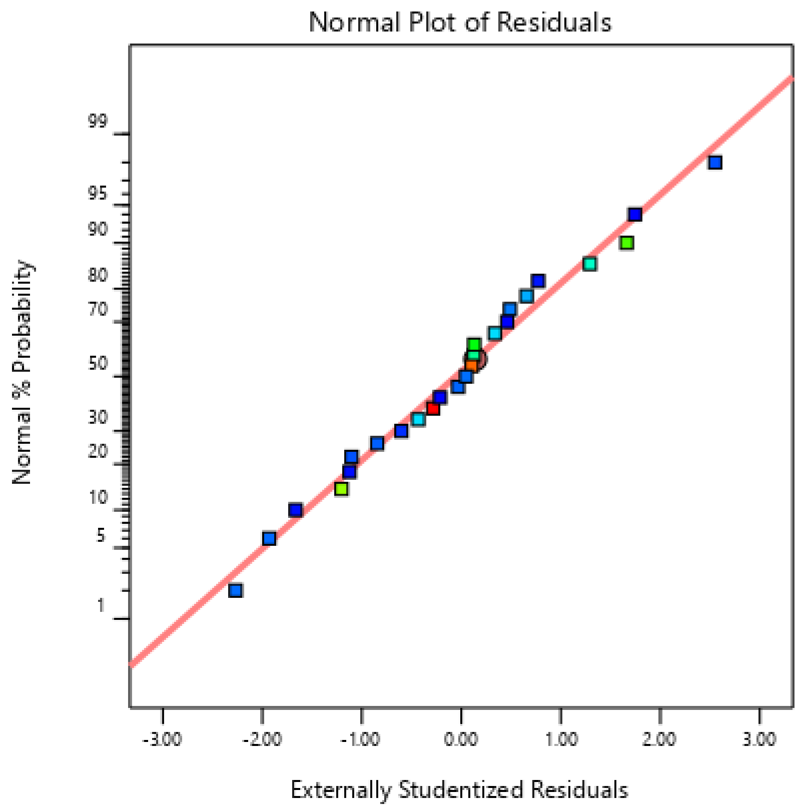


Figure E-8 - Vertical Bow Resistance Normal Plot

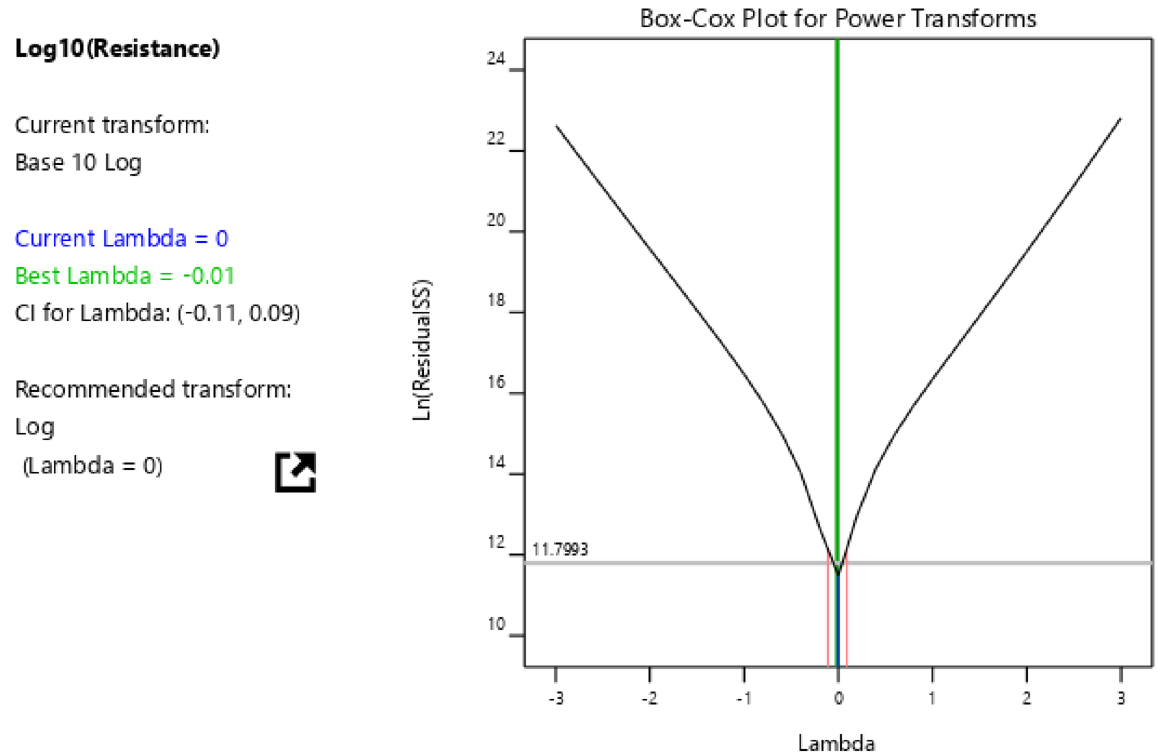


Figure E-9 - Vertical Bow Resistance Box-Cox

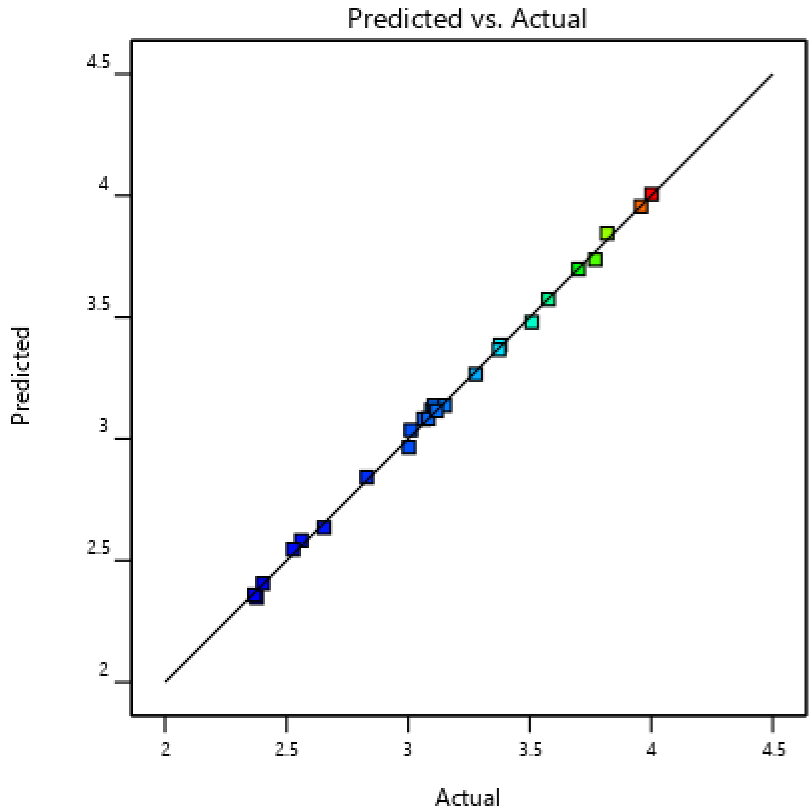


Figure E-10 - Vertical Bow Resistance Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	5.68	10	0.5682	267.56	< 0.0001	significant
A-Length	0.1787	1	0.1787	84.15	< 0.0001	
B-Beam	0.2207	1	0.2207	103.93	< 0.0001	
C-Draft	0.0410	1	0.0410	19.29	0.0006	
D-Wave Height	0.0407	1	0.0407	19.15	0.0006	
E-Peak Period	0.0037	1	0.0037	1.74	0.2082	
F-Speed	1.87	1	1.87	878.72	< 0.0001	
AF	0.0125	1	0.0125	5.88	0.0294	
CE	0.0017	1	0.0017	0.7889	0.3895	
E^2	0.0003	1	0.0003	0.1593	0.6958	
CE^2	0.0102	1	0.0102	4.79	0.0460	
Residual	0.0297	14	0.0021			
Cor Total	5.71	24				

Figure E-11 - X-Bow Resistance ANOVA

Std. Dev.	0.0461	**R^2**	0.9948
Mean	3.12	**Adjusted R^2**	0.9911
C.V. %	1.48	**Predicted R^2**	0.9801
		Adeq Precision	53.9682

Figure E-12 - X-Bow Resistance Model Fit

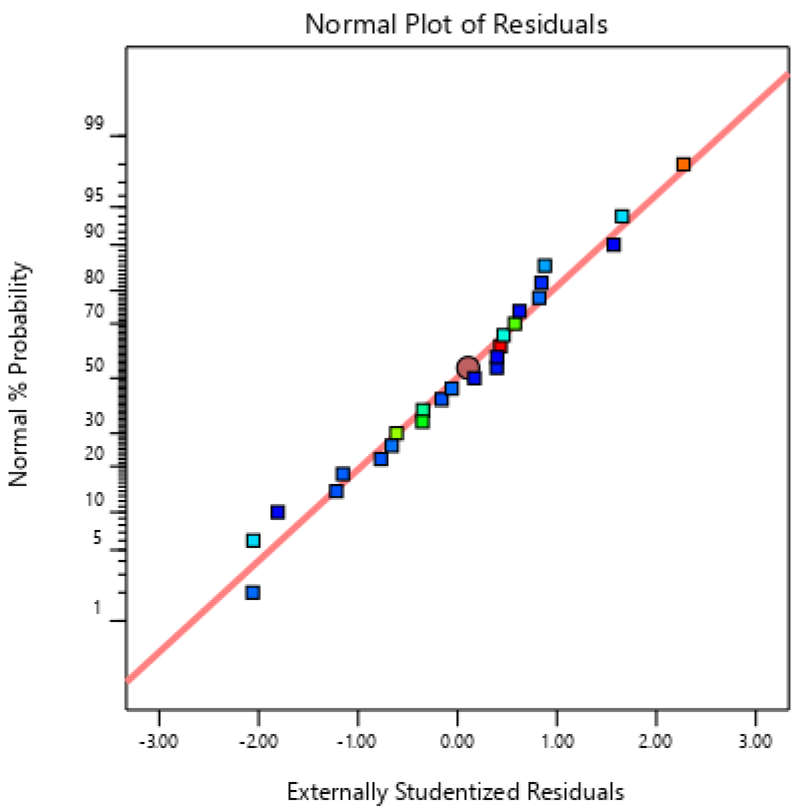


Figure E-13 - X-Bow Resistance Normal Plot

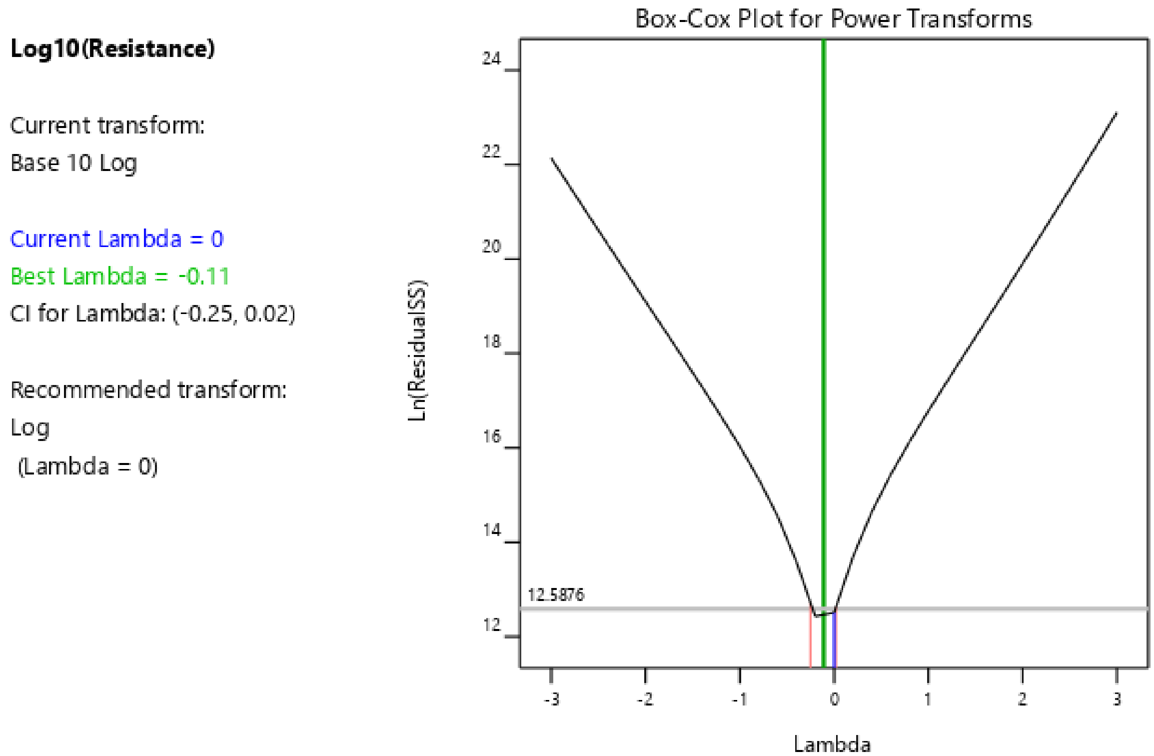


Figure E-14 - X-Bow Resistance Box-Cox

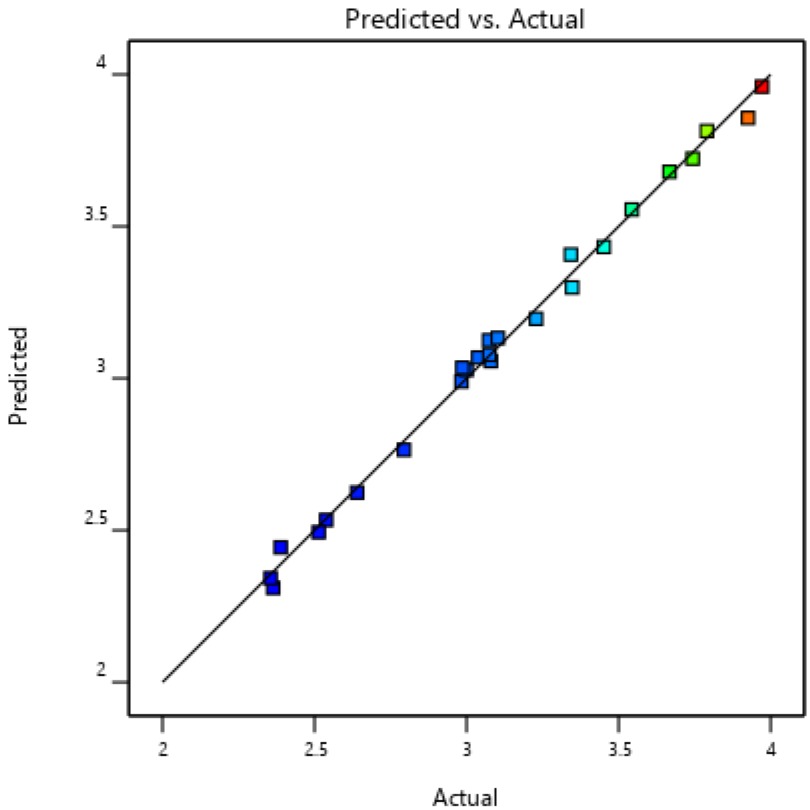


Figure E-15 - X-Bow Resistance Prediction Accuracy

Appendix F: Additional ANOVA for Stability Prediction

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	9.342E+06	6	1.557E+06	7453.72	< 0.0001	significant
A-Length	3.497E+06	1	3.497E+06	16739.54	< 0.0001	
B-Beam	1.946E+06	1	1.946E+06	9317.22	< 0.0001	
C-Draft	3.448E+06	1	3.448E+06	16503.45	< 0.0001	
AB	87931.64	1	87931.64	420.93	< 0.0001	
AC	1.512E+05	1	1.512E+05	723.80	< 0.0001	
BC	84813.37	1	84813.37	406.00	< 0.0001	
Residual	1671.19	8	208.90			
Cor Total	9.344E+06	14				

Figure F-1 - Axe Bow Displacement ANOVA

Std. Dev.	14.45		**R^2**	0.9998
Mean	1984.93		**Adjusted R^2**	0.9997
C.V. %	0.7282		**Predicted R^2**	0.9984
			Adeq Precision	378.3324

Figure F-2 - Axe Bow Displacement Model Fit

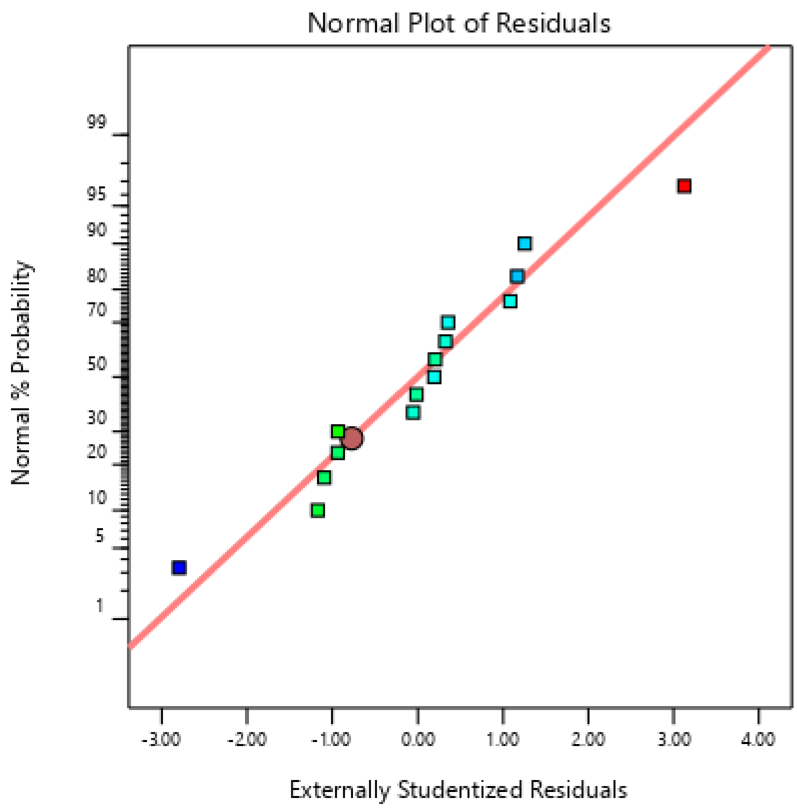


Figure F-3 - Axe Bow Displacement Normal Plot

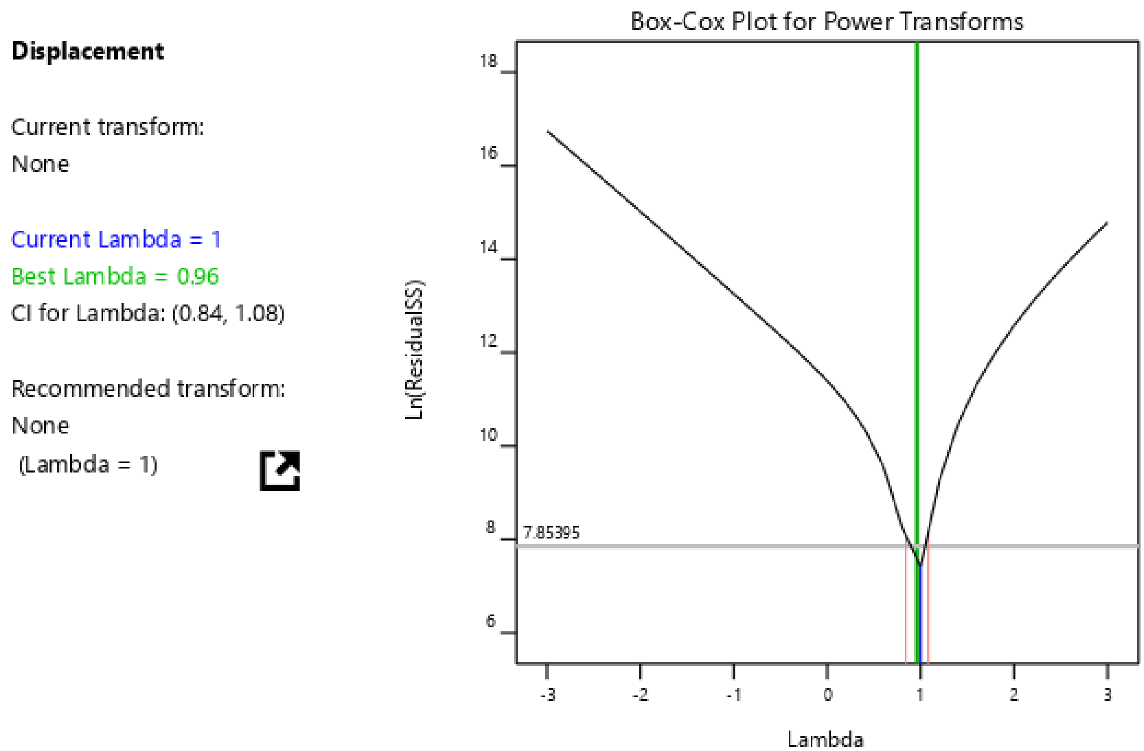


Figure F-4 - Axe Bow Displacement Box-Cox

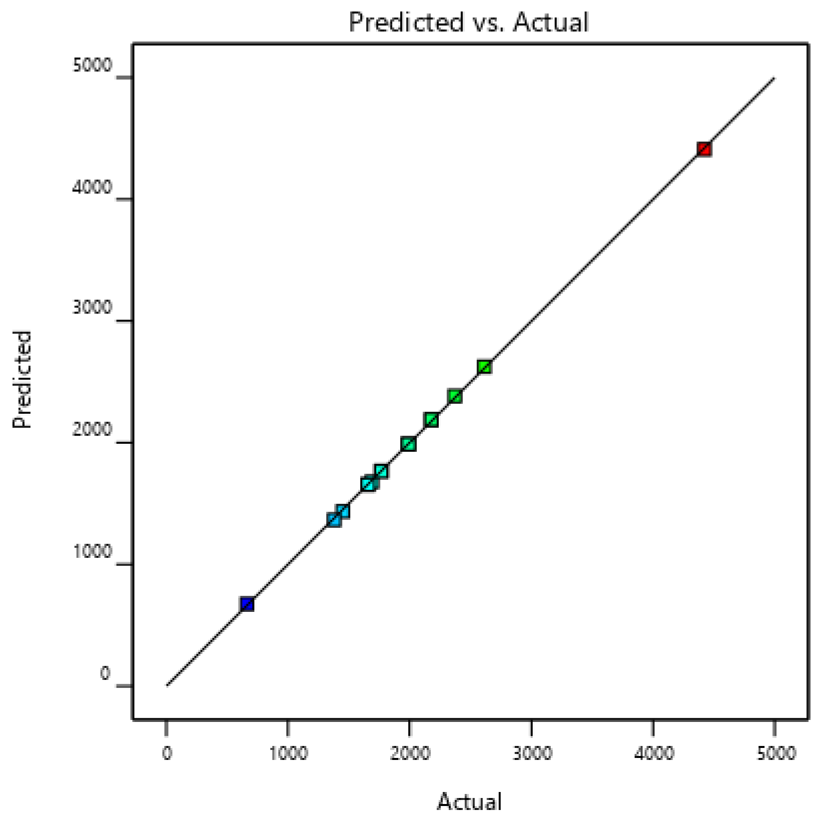


Figure F-5 - Axe Bow Displacement Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.5534	4	0.1383	34076.46	< 0.0001	significant
B-Beam	0.2249	1	0.2249	55407.00	< 0.0001	
C-Draft	0.1673	1	0.1673	41216.65	< 0.0001	
B^2	0.0019	1	0.0019	467.47	< 0.0001	
C^2	0.0016	1	0.0016	405.46	< 0.0001	
Residual	0.0000	10	4.060E-06			
Cor Total	0.5534	14				

Figure F-6 - Bulbous Bow Stability ANOVA

Std. Dev.	0.0020		**R^2**	0.9999
Mean	0.7650		**Adjusted R^2**	0.9999
C.V. %	0.2634		**Predicted R^2**	0.9999
			Adeq Precision	637.1842

Figure F-7 - Bulbous Bow Stability Model Fit

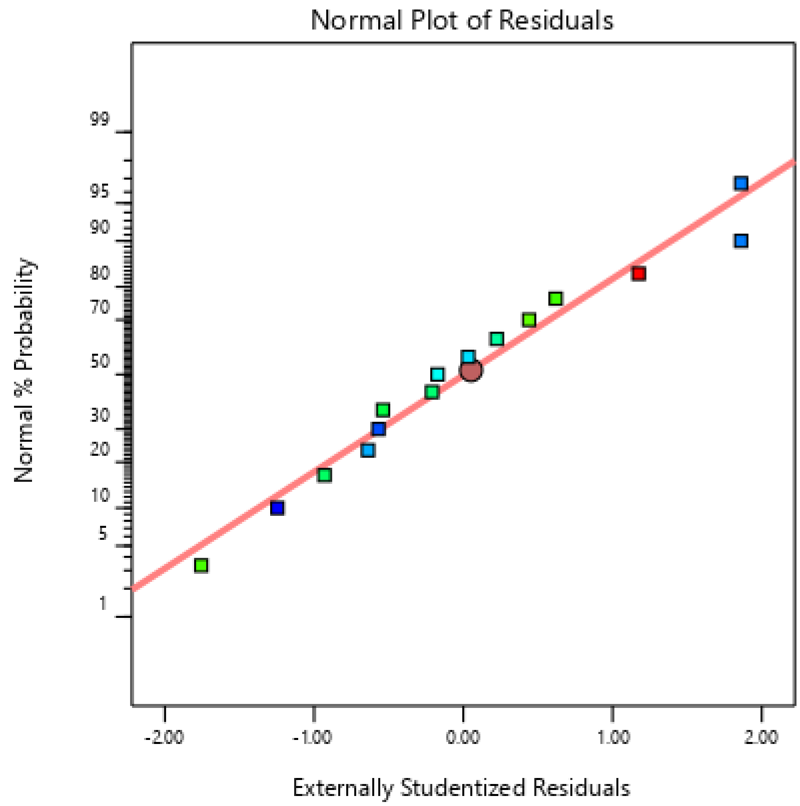


Figure F-8 - Bulbous Bow Stability Normal Plot

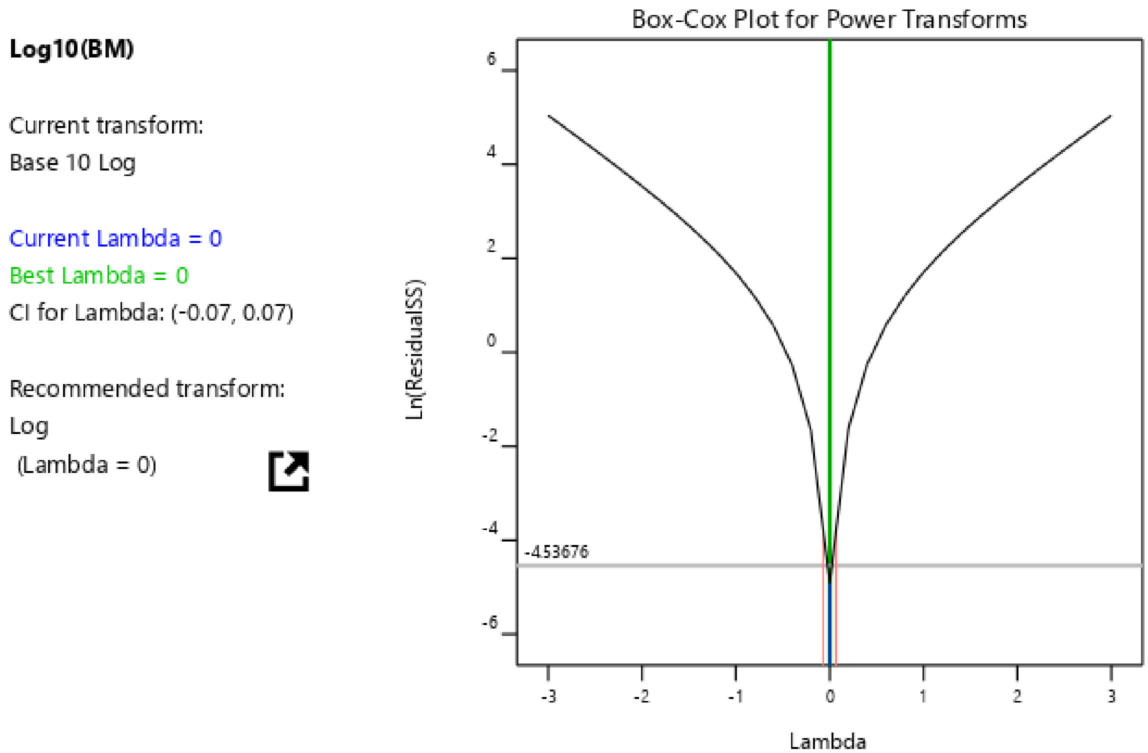


Figure F-9 - Bulbous Bow Stability Box-Cox

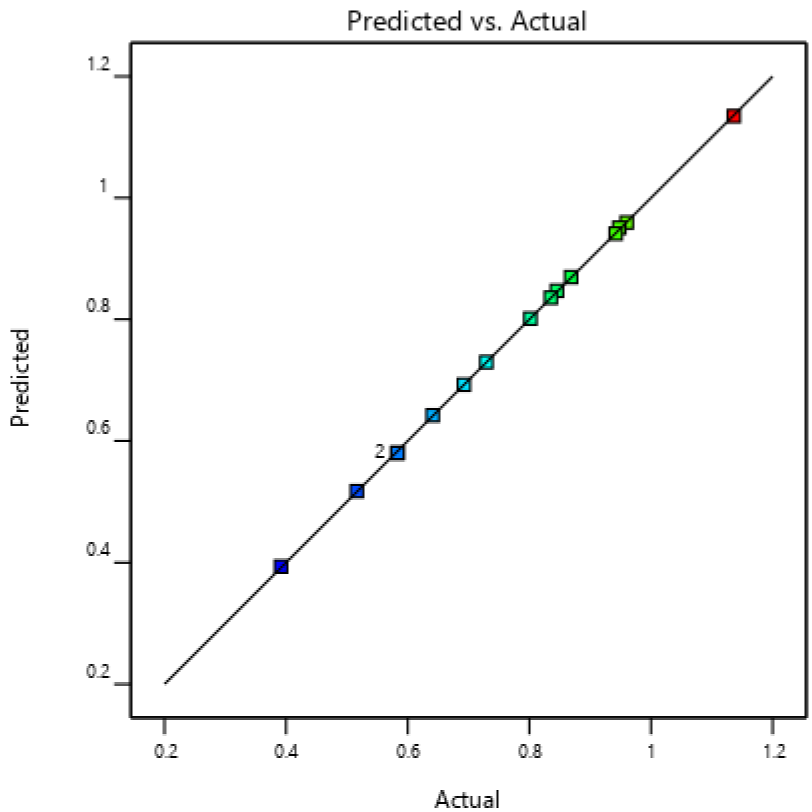


Figure F-10 - Bulbous Bow Stability Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.460E+08	6	2.434E+07	7376.59	< 0.0001	significant
A-Length	5.464E+07	1	5.464E+07	16560.61	< 0.0001	
B-Beam	3.044E+07	1	3.044E+07	9225.46	< 0.0001	
C-Draft	5.388E+07	1	5.388E+07	16331.85	< 0.0001	
AB	1.375E+06	1	1.375E+06	416.75	< 0.0001	
AC	2.366E+06	1	2.366E+06	717.26	< 0.0001	
BC	1.325E+06	1	1.325E+06	401.58	< 0.0001	
Residual	26394.54	8	3299.32			
Cor Total	1.461E+08	14				

Figure F-11 - Bulbous Bow Displacement ANOVA

Std. Dev.	57.44		**R^2**	0.9998
Mean	7848.07		**Adjusted R^2**	0.9997
C.V. %	0.7319		**Predicted R^2**	0.9984
			Adeq Precision	376.3678

Figure F-12 - Bulbous Bow Displacement Model Fit

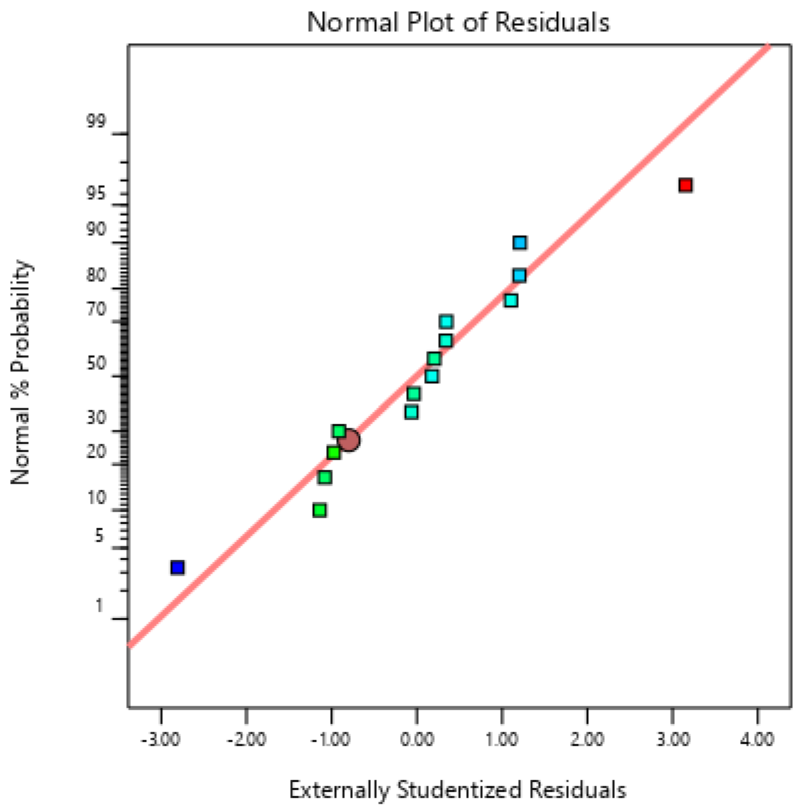


Figure F-13 - Bulbous Bow Displacement Normal Plot

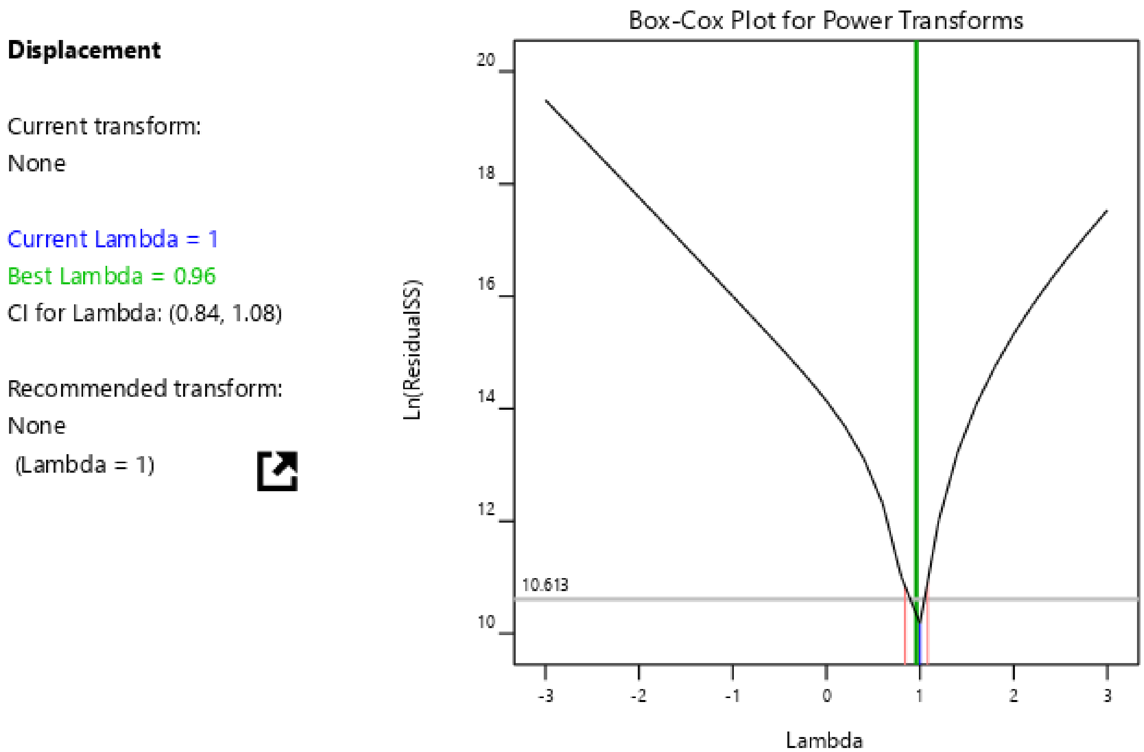


Figure F-14 - Bulbous Bow Displacement Box-Cox

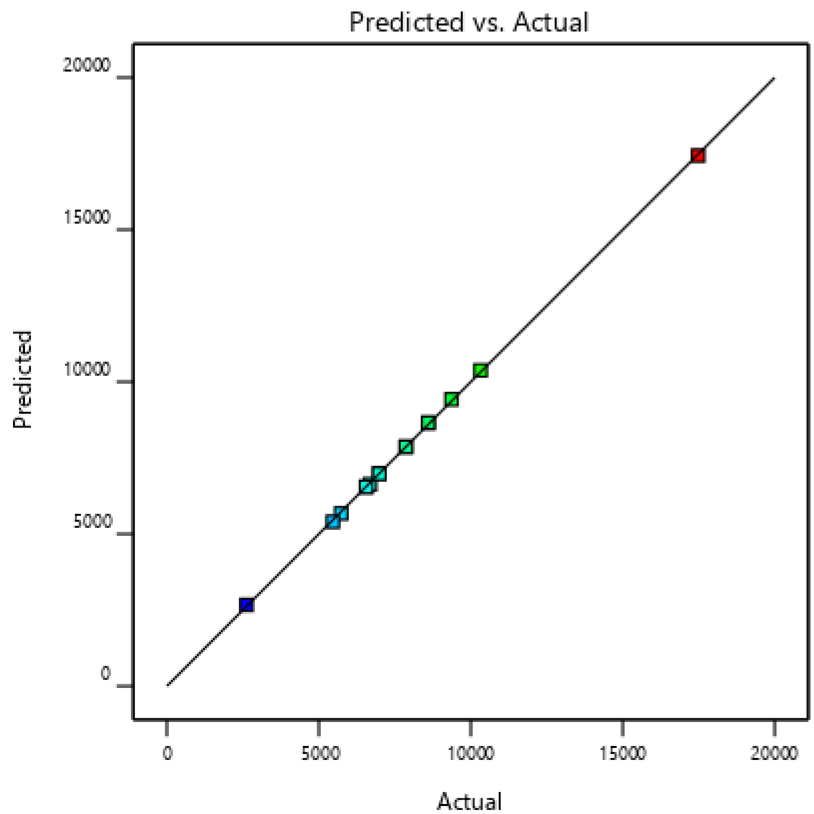


Figure F-15 - Bulbous Bow Displacement Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.5535	4	0.1384	33152.17	< 0.0001	significant
B-Beam	0.2250	1	0.2250	53909.44	< 0.0001	
C-Draft	0.1674	1	0.1674	40093.78	< 0.0001	
B^2	0.0019	1	0.0019	454.48	< 0.0001	
C^2	0.0016	1	0.0016	394.78	< 0.0001	
Residual	0.0000	10	4.174E-06			
Cor Total	0.5536	14				

Figure F-16 - Vertical Bow Stability ANOVA

Std. Dev.	0.0020		**R^2**	0.9999
Mean	0.7711		**Adjusted R^2**	0.9999
C.V. %	0.2650		**Predicted R^2**	0.9999
			Adeq Precision	628.4790

Figure F-17 - Vertical Bow Stability Model Fit

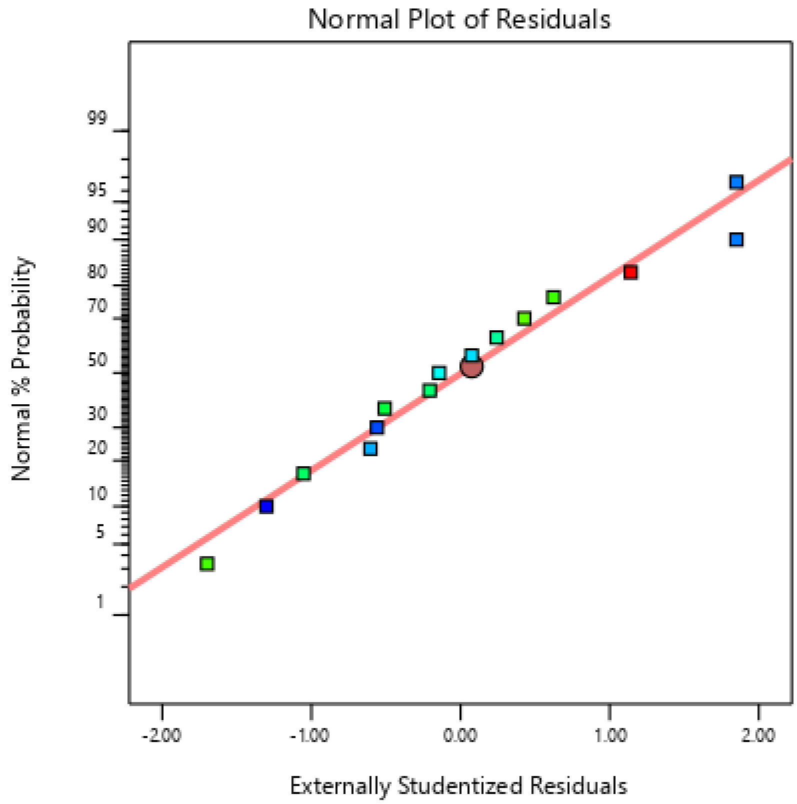


Figure F-18 - Vertical Bow Stability Normal Plot

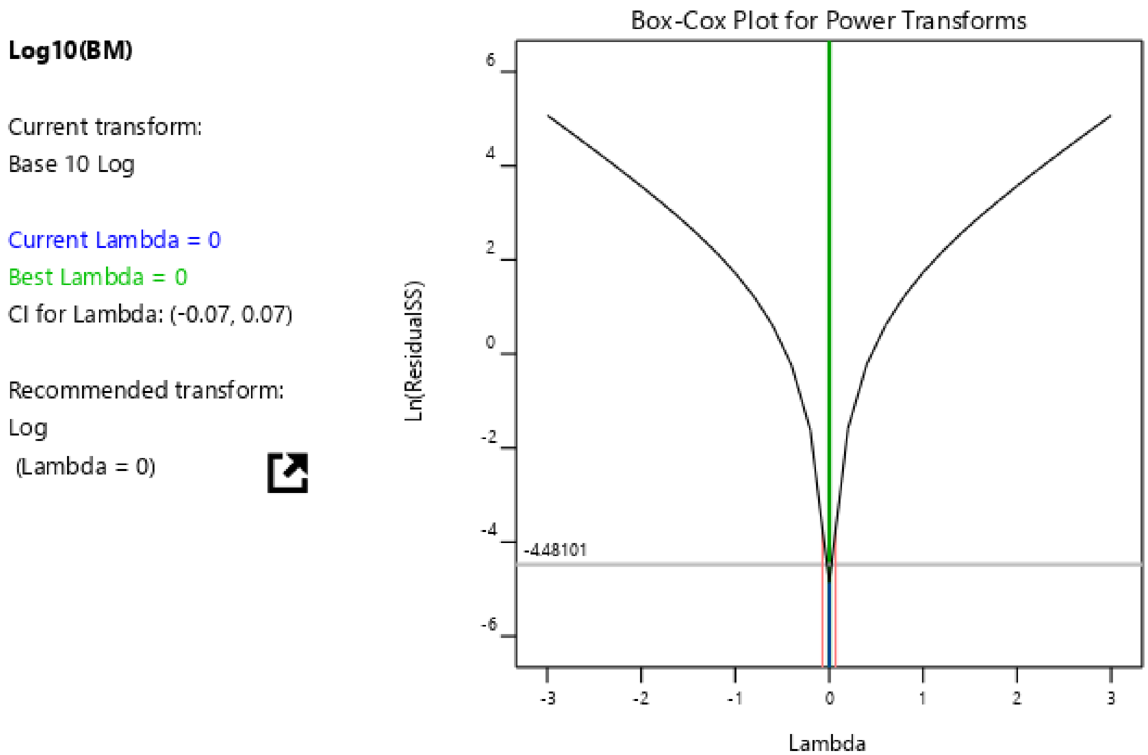


Figure F-19 - Vertical Bow Stability Box-Cox

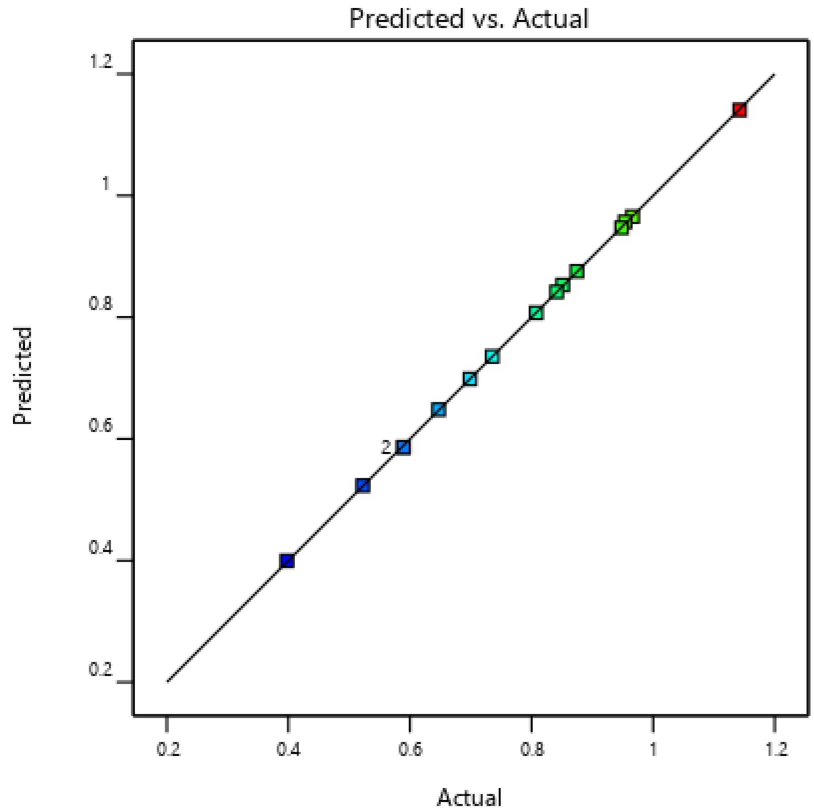


Figure F-20 - Vertical Bow Stability Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.420E+08	6	2.367E+07	7471.69	< 0.0001	significant
A-Length	5.315E+07	1	5.315E+07	16774.80	< 0.0001	
B-Beam	2.961E+07	1	2.961E+07	9344.21	< 0.0001	
C-Draft	5.241E+07	1	5.241E+07	16543.03	< 0.0001	
AB	1.337E+06	1	1.337E+06	422.09	< 0.0001	
AC	2.300E+06	1	2.300E+06	726.00	< 0.0001	
BC	1.289E+06	1	1.289E+06	406.72	< 0.0001	
Residual	25346.38	8	3168.30			
Cor Total	1.421E+08	14				

Figure F-21 - Vertical Bow Displacement ANOVA

Std. Dev.	56.29		**R^2**	0.9998
Mean	7740.07		**Adjusted R^2**	0.9997
C.V. %	0.7272		**Predicted R^2**	0.9984
			Adeq Precision	378.7914

Figure F-22 - Vertical Bow Displacement Model Fit

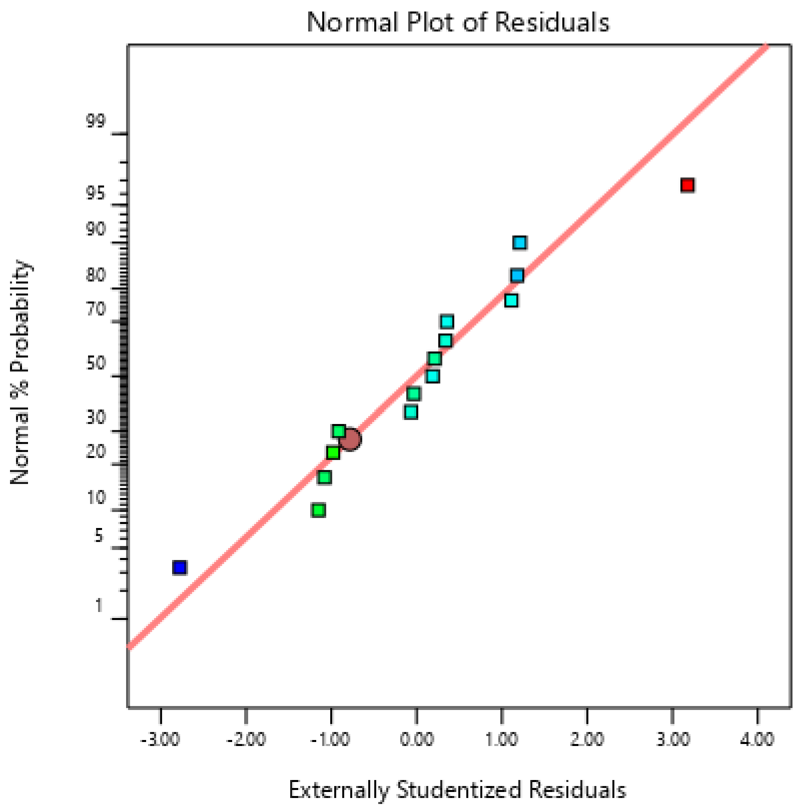


Figure F-23 - Vertical Bow Displacement Normal Plot

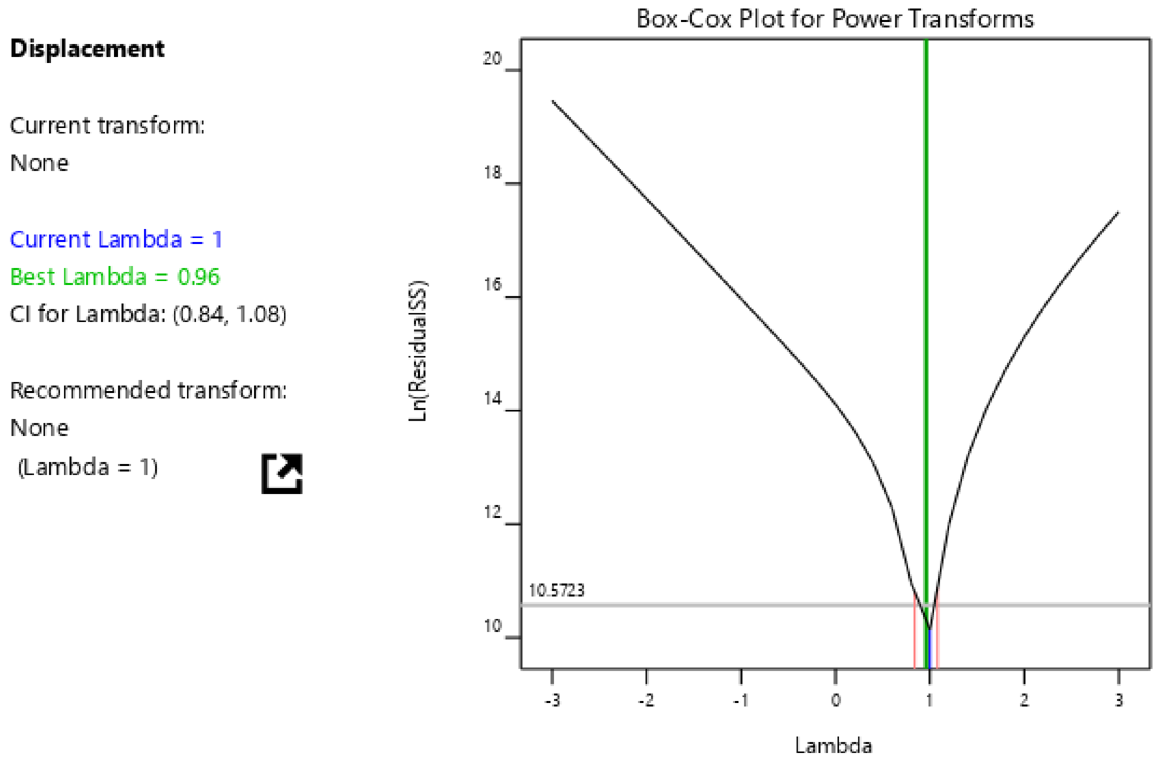


Figure F-24 - Vertical Bow Displacement Box-Cox

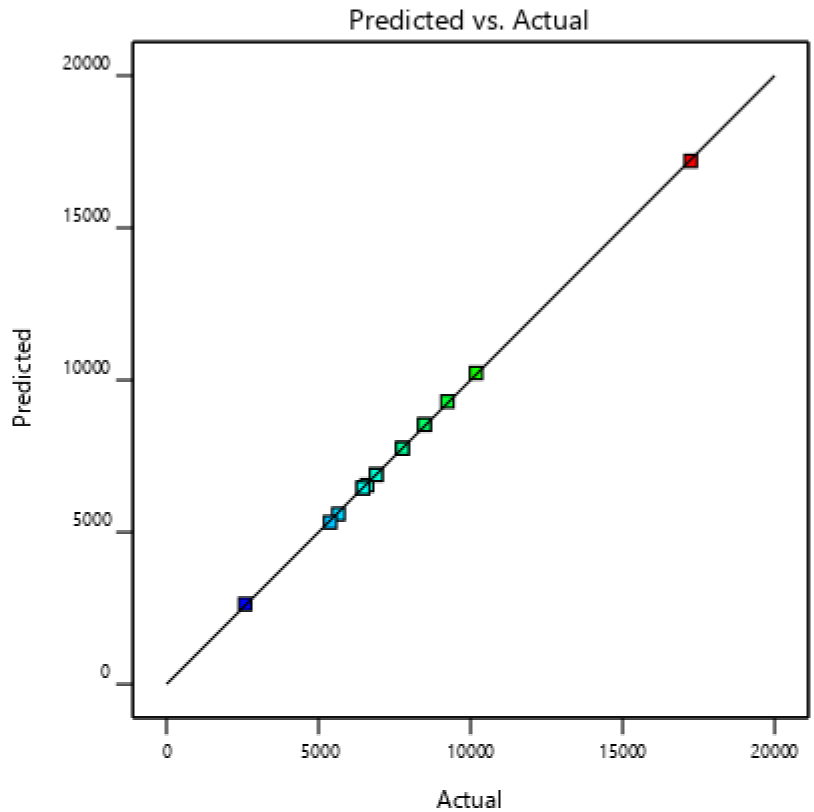


Figure F-25 - Vertical Bow Displacement Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.5534	4	0.1384	33210.03	< 0.0001	significant
B-Beam	0.2250	1	0.2250	54009.65	< 0.0001	
C-Draft	0.1673	1	0.1673	40169.42	< 0.0001	
B^2	0.0019	1	0.0019	453.90	< 0.0001	
C^2	0.0016	1	0.0016	393.98	< 0.0001	
Residual	0.0000	10	4.166E-06			
Cor Total	0.5535	14				

Figure F-26 - X-Bow Stability ANOVA

Std. Dev.	0.0020		**R^2**	0.9999
Mean	0.7733		**Adjusted R^2**	0.9999
C.V. %	0.2639		**Predicted R^2**	0.9999
			Adeq Precision	629.0370

Figure F-0-27 - X-Bow Stability Model Fit

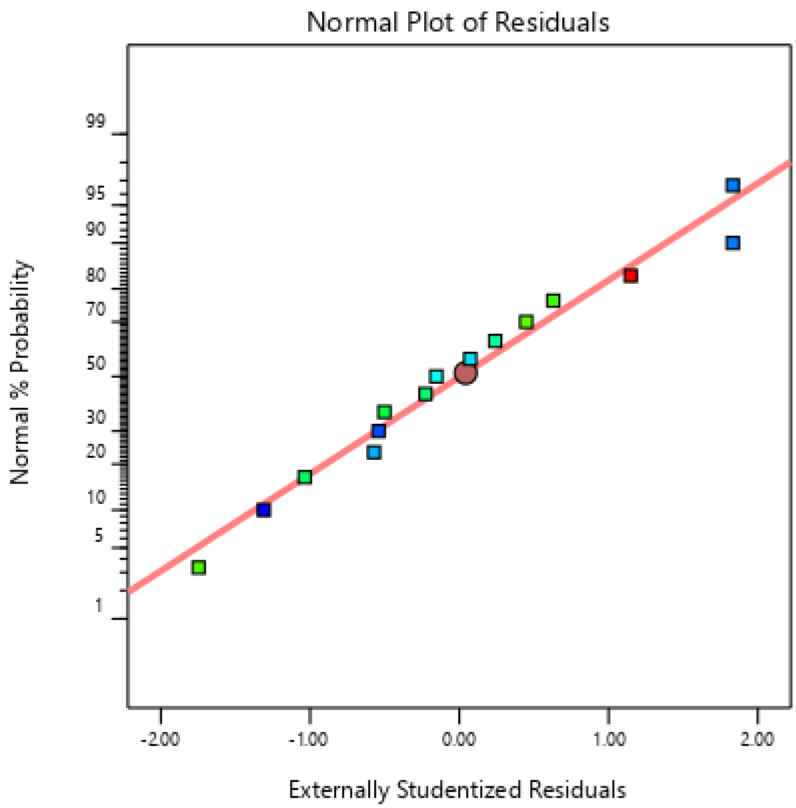


Figure F-28 - X-Bow Stability Normal Plot

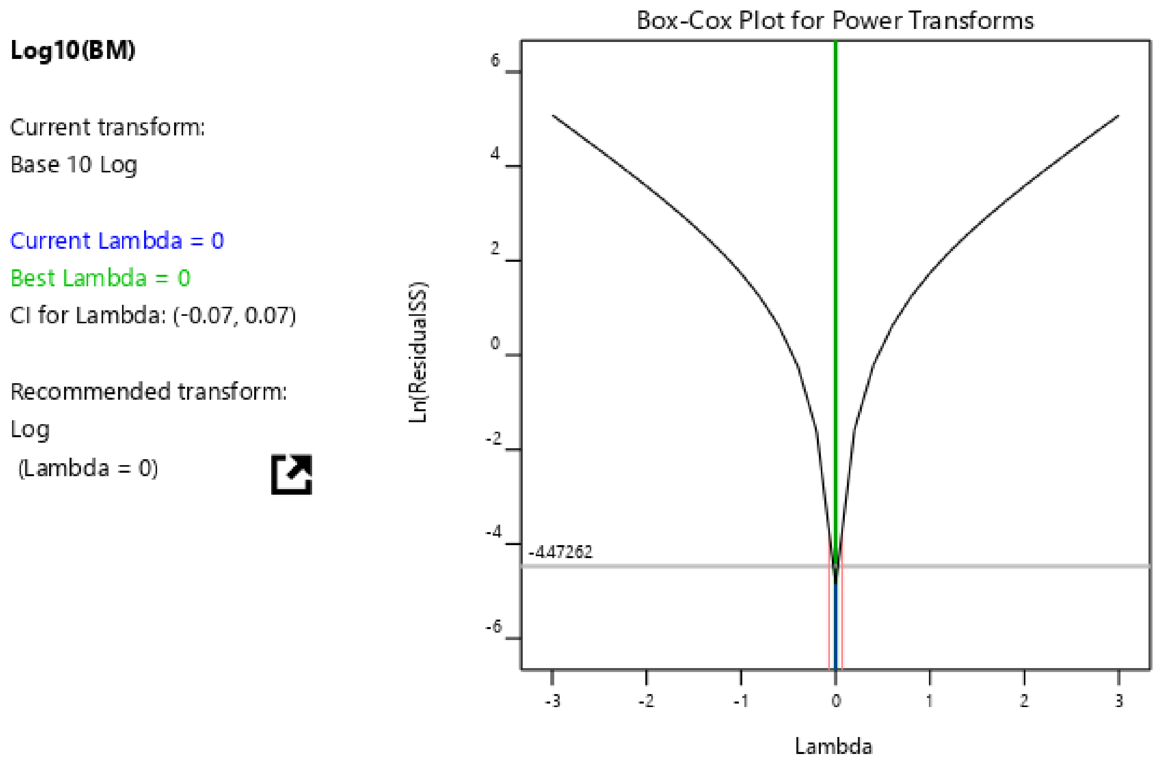


Figure F-29 - X-Bow Stability Box-Cox

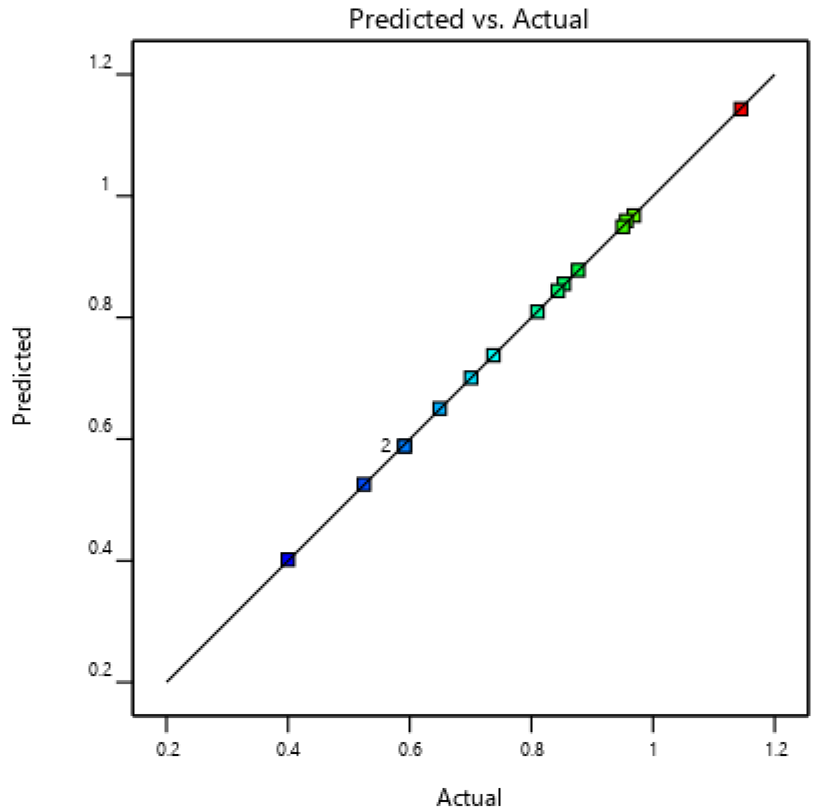


Figure F-30 - X-Bow Stability Prediction Accuracy

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.355E+08	6	2.258E+07	7495.13	< 0.0001	significant
A-Length	5.068E+07	1	5.068E+07	16826.28	< 0.0001	
B-Beam	2.824E+07	1	2.824E+07	9374.91	< 0.0001	
C-Draft	4.998E+07	1	4.998E+07	16592.69	< 0.0001	
AB	1.275E+06	1	1.275E+06	423.22	< 0.0001	
AC	2.197E+06	1	2.197E+06	729.28	< 0.0001	
BC	1.229E+06	1	1.229E+06	407.87	< 0.0001	
Residual	24096.04	8	3012.00			
Cor Total	1.355E+08	14				

Figure F-31 - X-Bow Displacement ANOVA

	Std. Dev.	54.88		**R^2**	0.9998
	Mean	7558.80		**Adjusted R^2**	0.9997
	C.V. %	0.7261		**Predicted R^2**	0.9984
				Adeq Precision	379.3808

Figure F-32 - X-Bow Displacement Model Fit

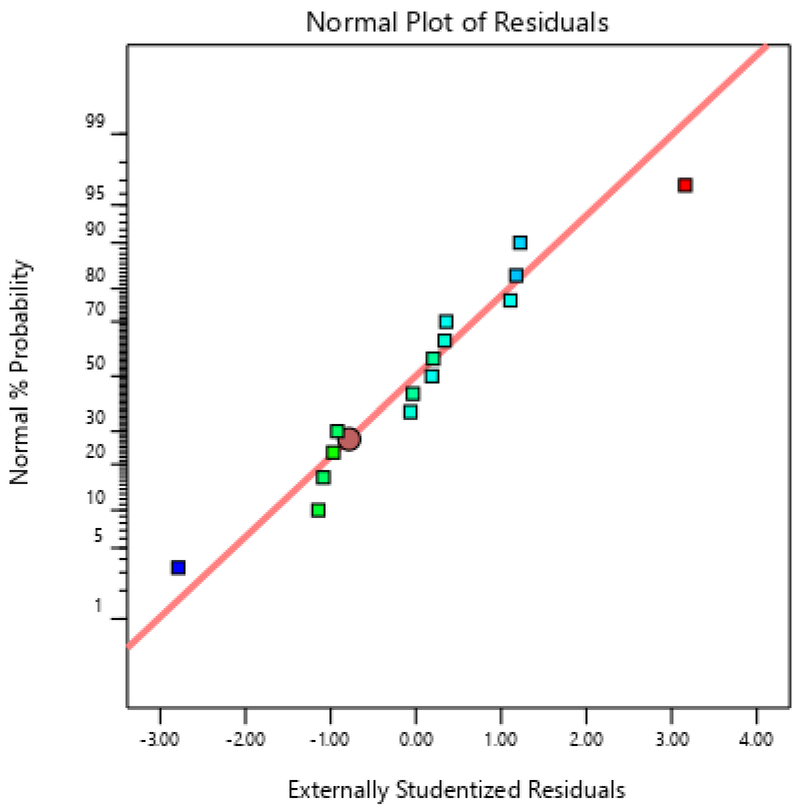


Figure F-33 - X-Bow Displacement Normal Plot

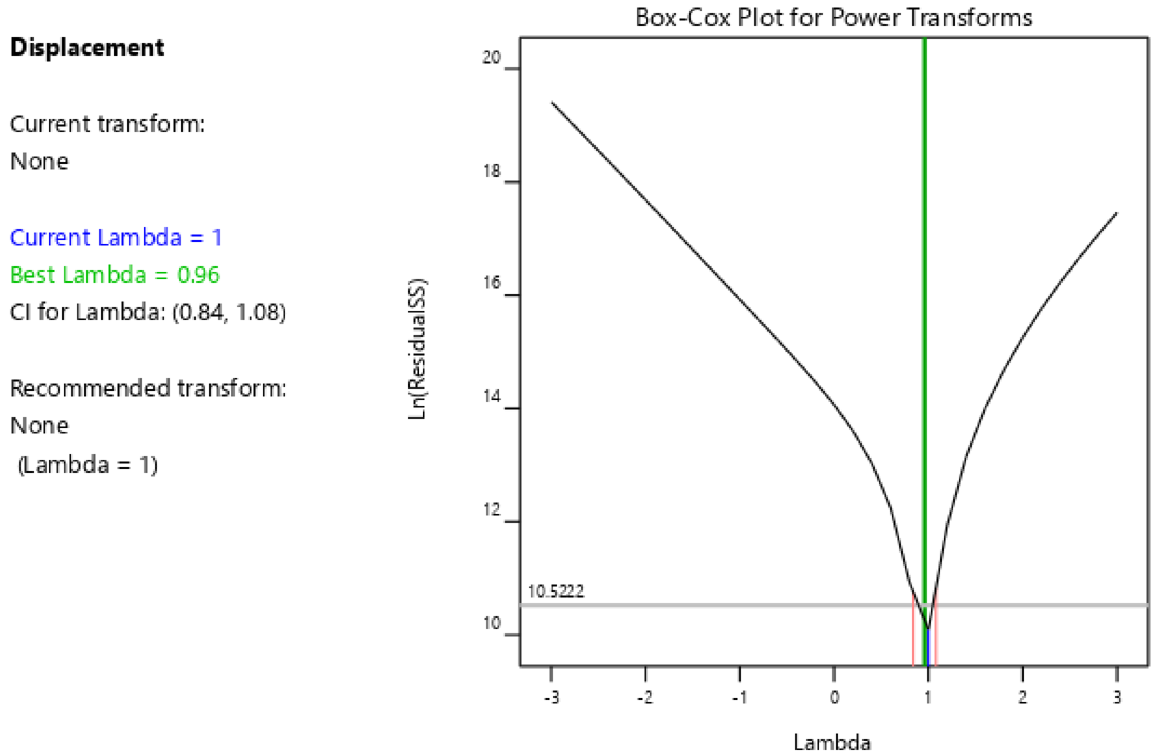


Figure F-34 - X-Bow Displacement Box-Cox

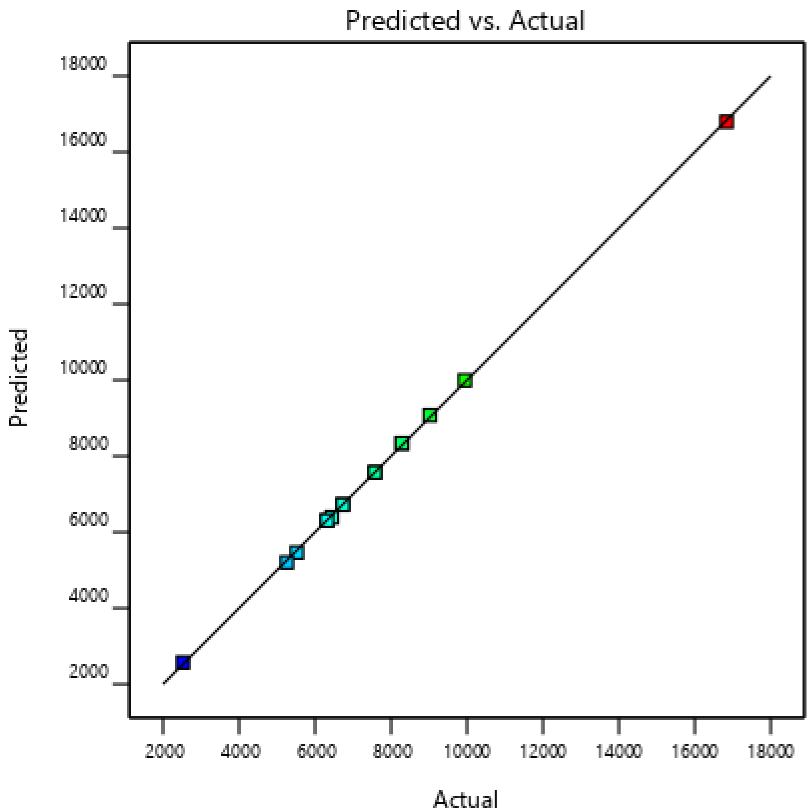
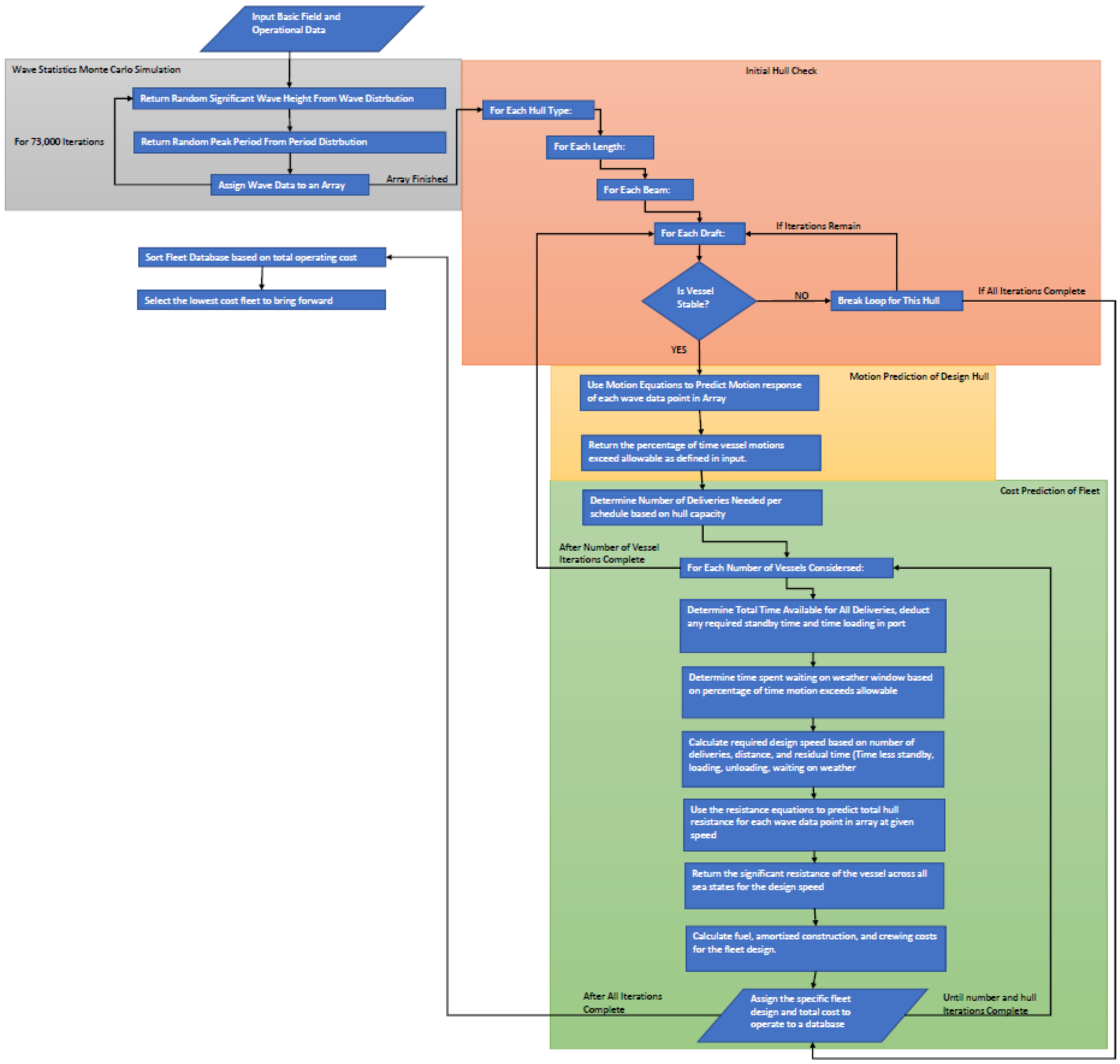


Figure F-35 - X-Bow Displacement Prediction Accuracy

Appendix G: Logic Flow Chart for Optimization Algorithm



Appendix H: Python Source Code

NOTE: This Code Requires the Anaconda Operating Environment for Library Dependencies

ShipDesigners.py

```
#Declare required components
import numpy as np
import math
import MotionFunctions as MF
import CostCalculator as CC
import StabilityCheck as STB

def CalculateRuns(hulltypes,lmin,lmax,lstep,bmin,bmax,bstep,tmin,tmax,tstep,nmin,nmax): #calculate all the runs we need so we can initialize an appropriate numpy array, add 1 to account for the first value
    lruns = math.floor((lmax-lmin)/lstep)+1
    bruns = math.floor((bmax-bmin)/bstep)+1
    truns = math.floor((tmax-tmin)/tstep)+1
    hullruns = len(hulltypes)
    nruns = nmax - nmin + 1
    return lruns*bruns*truns*hullruns*nruns

#Enter Sea Parameters
mu = 2.458 #Gumbel Mu Parameter for Wave Height
beta = 1.101 #Gumbel Beta Parameter for Wave Height
tmean = 10.05 #mean wave period
tdeviation = 2.008 #wave period standard deviation

h = np.zeros([73000,1]) #Intialize a numpy array for wave heights
t = np.zeros([73000,1]) #Initialize a numpy array for periods

for i in range(73000): #Generates a random significant wave height for 25 years of 3 hour seas
    h[i] = np.random.gumbel(mu, beta)
    t[i] = np.random.normal(tmean,tdeviation)
    while h[i] > t[i] - 2: #If We have an impossible sea state keep generating numbers till it works
        h[i] = np.random.gumbel(mu, beta)
        t[i] = np.random.normal(tmean,tdeviation)

h = np.where(h < 0, 0, h)

t = np.where(t<0,0,t)

Waves = np.hstack((h,t)) #Builds an array for each sea, each row is a significant wave height and peak period

#Enter Operational Parameters
field_distance = 250.0 #Distance in nautical miles
area_cargo = 1006.0 #Total deck area of cargo delivered per cycle m^2
volume_cargo = 2071.0 #Total bulk volument of cargo per cycle m^3
max_vert_velocity = 0.6 #Maximum tolerable vertical velocity for which the cargo operations can occur m/s
cycle_length = 72 #Length of a cargo cycle in hours
StandbyShipRequired = True #Is a ship required for standby
fuel_cost = 423 #Fuel cost is dollars/mt
engine_efficiency = 190 #Engine fuel efficiency in g/kwh

#Enter Design Limits
```

```
l_min = 60 #minimum length considered in m
l_max = 120 #maximum length considered in m
l_step = 5 #length stepping for design cases in m
b_min = 15 #minimum beam considered in m
b_max = 25 #maximum beam considered in m
b_step = 2 #beam stepping for design cases in m
t_min = 4 #minimum draft considered in m
t_max = 8 #maximum draft considered in m
t_step = 1 #draft stepping for design cases in m
n_max = 6 #Maximum fleet size considered
stabcriteria = 1.0 #Minimum GM value to be considered stable
designlife = 25 #Design Life of Ship in Years

if (StandbyShipRequired): #If a ship is required to be on standby we cannot have less than 2 ships
    n_min = 2
else:
    n_min = 1

hull_types = ["Axe", "X", "Vertical", "Bulbous"]

runs = CalculateRuns(hull_types,l_min,l_max,l_step,b_min,b_max,b_step,t_min,t_max,t_step,n_min,n_max)

results_table = np.zeros([runs,8]) #Initialize Array

cycle = 0 #For iterating steps

for hulltype in hull_types: #Check Every Type of Hull

    for length in range(l_min,l_max+1,l_step): #Check all possible design lengths

        for beam in range(b_min, b_max+1, b_step): #check all possible beams

            for draft in range(t_min,t_max+1,t_step): #check all possible drafts

                stable, displacement = STB.CheckStability(hulltype,length,beam,draft,stabcriteria) #Performs a check
of the stability and freeboard for this specific hull design and calculates its displacement

                if(not stable): #if we find an unstable or not loadline compliant hull, don't proceed, skip to the next hull
design
                    continue

                Downtime, SailingConditions = MF.CalculateMotions(hulltype,length,draft,Waves,max_vert_velocity)
#Find the percentage of time the vessel is down and the conditions under which it would be allowed to sail

                for n in range(n_min,n_max+1,1): #for all possible fleet sizes
                    #Find the cost, average speed, and installed power required for this vessel arrangement
                    cost, designspeed, power, possible =
CC.CalculateCost(hulltype,length,beam,draft,displacement,n,Downtime,SailingConditions,StandbyShipRequired
,field_distance,area_cargo,volume_cargo,cycle_length,fuel_cost,engine_efficiency,designlife, Waves)
                    if (not possible): #If this is an impossible design, break the current iteration
                        continue
                    print(cycle) #Feedback on result progress

                    results_table[cycle,:] = [hull_types.index(hulltype),n,length,beam,draft,designspeed,power,cost]
#Reassign the results storage array to current result
```

```
        cycle += 1

results_table = np.delete(results_table,range(cycle,runs),axis=0) #Remove empty rows

results_table = results_table[np.argsort(results_table[:,7])] #Sort by the total annual cost

np.savetxt('FleetDesigns.csv',results_table,fmt = '%f', delimiter = ',', header = 
'HullType,Number,Length,Beam,Draft,Speed,Power,AnnualCost') #Write the datatable to a csv file
print("Calculation Complete - View FleetDesigns.csv for table of results")
```

StabilityCheck.py

```
import math

def CheckStability(hull_type, length, beam, draft, stabcriteria):
    if (hull_type == "Axe"):
        BM = 10**(0.49 + 0.088*beam -0.15*draft - 0.0011*beam**2 + 0.0065*draft**2)
        KB = 0.81725 * draft
        KG = 0.8 * draft * 1.839
        if (KB + BM - KG < stabcriteria):
            return False, 0.0
        displacement = math.floor(1860.05 - 22.78*length - 97.21*beam - 325.45*draft + 1.11*length*beam + 
3.70*length*draft + 16.61*beam*draft)
        tabular_freeboard = 0.0000849*length**2 + 0.00352*length + 0.06108 #Formula approximating loadling 
table
        if (displacement/1.025 > 0.68*length*beam*draft): #correction for displacement
            tabular_freeboard *= ((displacement/1.025)/(length*beam*draft) + 0.68)/1.36
        depth = draft*1.838
        if (depth > length/15):
            tabular_freeboard += ((depth - length/15)*length/0.48)/1000
        if (depth - draft < tabular_freeboard):
            return False, displacement
        return True, displacement

    elif (hull_type == "X"):
        BM = 10**(0.13 + 0.088*beam -0.15*draft - 0.0011*beam**2 + 0.0064*draft**2)
        KB = 0.5505 * draft
        KG = 0.8 * draft * 1.333333
        if (KB + BM - KG < stabcriteria):
            return False, 0.0
        displacement = math.floor(7086.32 - 83.04*length - 369.82*beam - 1239.96*draft + 4.22*length*beam + 
14.09*length*draft + 63.23*beam*draft)
        tabular_freeboard = 0.0000849*length**2 + 0.00352*length + 0.06108 #Formula approximating loadling 
table
        if (displacement/1.025 > 0.68*length*beam*draft): #correction for displacement
            tabular_freeboard *= ((displacement/1.025)/(length*beam*draft) + 0.68)/1.36
        depth = draft*1.333
        if (depth > length/15):
            tabular_freeboard += ((depth - length/15)*length/0.48)/1000
        if (depth - draft < tabular_freeboard):
            return False, displacement
        return True, displacement

    elif (hull_type == "Vertical"):
        BM = 10**(0.13 + 0.088*beam -0.15*draft - 0.0011*beam**2 + 0.0064*draft**2)
        KB = 0.55225 * draft
        KG = 0.8 * draft * 1.333333
        if (KB + BM - KG < stabcriteria):
            return False, 0.0
        displacement = math.floor(7253.76 - 84.99*length - 378.88*beam - 1268.95*draft + 4.32*length*beam + 
14.42*length*draft + 64.75*beam*draft)
        tabular_freeboard = 0.0000849*length**2 + 0.00352*length + 0.06108 #Formula approximating loadling 
table
        if (displacement/1.025 > 0.68*length*beam*draft): #correction for displacement
            tabular_freeboard *= ((displacement/1.025)/(length*beam*draft) + 0.68)/1.36
```

```
        depth = draft*1.333
        if (depth > length/15):
            tabular_freeboard += ((depth - length/15)*length/0.48)/1000
        if (depth - draft < tabular_freeboard):
            return False, displacement
        return True, displacement

    elif (hull_type == "Bulbous"):
        BM = 10**(0.12 + 0.088*beam -0.15*draft - 0.0011*beam**2 + 0.0064*draft**2)
        KB = 0.5584 * draft
        KG = 0.8 * draft * 1.333333
        if (KB + BM - KG < stabcriteria):
            return False, 0.0
        displacement = math.floor(7358.70 - 86.22*length - 384.20*beam - 1287.21*draft + 4.39*length*beam + 
14.63*length*draft + 65.66*beam*draft)
        tabular_freeboard = 0.0000849*length**2 + 0.00352*length + 0.06108 #Formula approximating loadling 
table
        if (displacement/1.025 > 0.68*length*beam*draft): #correction for displacement
            tabular_freeboard *= ((displacement/1.025)/(length*beam*draft) + 0.68)/1.36
        depth = draft*1.333
        if (depth > length/15):
            tabular_freeboard += ((depth - length/15)*length/0.48)/1000
        if (depth - draft < tabular_freeboard):
            return False, displacement
        return True, displacement
    else:
        return False, 0.0
```

MotionFunctions.py

```
import numpy as np

def CalculateMotions(hull_type, Length, Draft, Seas, MaxVelocity):
    if (hull_type == "Axe"):
        Motions = (0.24 - 0.0080*Length - 0.025*Draft + 0.12*Seas[:,0] + 0.11*Seas[:,1] - 
0.00043*Length*Seas[:,0] + 0.0024*Draft*Seas[:,1] + 0.0075*Seas[:,0]*Seas[:,1] + 0.000032*Length**2 - 
0.0071*Seas[:,0]**2 - 0.0063*Seas[:,1]**2)**2
        DownTime = np.size(Motions[Motions>MaxVelocity],0)/np.size(Seas,0)
        DownTime = round(DownTime,3)
        SailingIndices = Motions < MaxVelocity
        SailingConditions = Seas[SailingIndices,:]
        return DownTime, SailingConditions

    elif (hull_type == "X"):
        Motions = (-1.20 - 0.0036*Length + 0.093*Seas[:,0] + 0.68*Seas[:,1] - 0.002 * Length * Seas[:,1] + 0.0068 
* Seas[:,0] * Seas[:,1] + 0.000036 * Length**2 - 0.0073*Seas[:,0]**2 - 0.064 * Seas[:,1]**2 + 0.00012 * Length 
* Seas[:,1]**2 + 0.0018 * Seas[:,1]**3)**2
        DownTime = np.size(Motions[Motions>MaxVelocity],0)/np.size(Seas,0)
        DownTime = round(DownTime,3)
        SailingIndices = Motions < MaxVelocity
        SailingConditions = Seas[SailingIndices,:]
        return DownTime, SailingConditions

    elif (hull_type == "Vertical"):
        Motions = (-1.11 + 0.0035 * Length + 0.031 * Seas[:,0] + 0.58 * Seas[:,1] - 0.0022 * Length * Seas[:,1] + 
0.0072 * Seas[:,0] * Seas[:,1] - 0.053 * Seas[:,1]**2 + 0.00014 * Length * Seas[:,1]**2 + 0.0014 * 
Seas[:,1]**3)**2
        DownTime = np.size(Motions[Motions>MaxVelocity],0)/np.size(Seas,0)
        DownTime = round(DownTime,3)
        SailingIndices = Motions < MaxVelocity
        SailingConditions = Seas[SailingIndices,:]
        return DownTime, SailingConditions

    elif (hull_type == "Bulbous"):
        Motions = (0.58 - 0.014*Length - 0.12*Draft + 0.039 * Seas[:,0] + 0.25*Seas[:,1] - 
0.000012*Length*Seas[:,1] + 0.033*Draft*Seas[:,1] + 0.0068*Seas[:,0]*Seas[:,1] + 0.000056*Length**2 - 
0.037*Seas[:,1]**2 - 0.0019*Draft*Seas[:,1]**2 + 0.0018*Seas[:,1]**3)**2
        DownTime = np.size(Motions[Motions>MaxVelocity],0)/np.size(Seas,0)
        DownTime = round(DownTime,3)
        SailingIndices = Motions < MaxVelocity
        SailingConditions = Seas[SailingIndices,:]
        return DownTime, SailingConditions

    else:
        DownTime = 1.0
        SailingConditions = np.zeros((1,2))
    return DownTime, SailingConditions
```

CostCalculator.py

```
import math
import numpy as np

def CalculateCost(hull_type, length, beam, draft, displacement, n, downtime, sailingconditions, standby,
distance, area, volume, cycle_length, fuel_cost,efficiency,designlife,seastates):
    runs = CalculateNumberDeliveries(length,beam,displacement,area,volume) #Find the number of required
delivery runs

    designspeed, possible = CalculateRequiredSpeed(cycle_length,runs,downtime,distance,n,standby) #Determine
the speed and if this vessel isn't impossibly fast
    if(not possible):
        return 0.0, designspeed, 0.0, possible

    power, fuel_annual_cost =
CalculateFuelCost(hull_type,length,beam,draft,designspeed,sailingconditions,runs,distance,cycle_length,fuel_co
st,efficiency) #Determine the total required engine power and fleet fuel costs

    Operating_Cost = CalculateOperatingCost(displacement, n) #Determine the cost of crewing required for this
vessel

    buildcost, possible = CalculateBuildCost(hull_type, displacement, power) #Determine the cost to build and if
this vessel's power plant and equipment are too heavy to be possible
    if(not possible):
        return 0.0, designspeed, 0.0, possible

    apr = 0.05 #Annual mortgage rate APR
    amortization = 12 * buildcost * n * (apr/12*(1+apr/12)**(designlife*12))/((1+apr/12)**(designlife*12)-1)
#Amortize the build cost of the fleet over their life based on the interest rate

    station_keeping_cost =
CalculateRequiredPositionKeeping(seastates,sailingconditions,beam,draft,standby,n,runs,cycle_length,fuel_cost,
efficiency, displacement, length)

    cost = fuel_annual_cost + Operating_Cost + amortization + station_keeping_cost

    return cost, designspeed, power, possible

def CalculateOperatingCost(displacement, n): #Function To Find the Crewing Cost of each vessel
    officers = 12 #Number of Officers Per Ship
    ratings = 25 #Number of Non Officers Per Ship
    officer_rate = 105773 #Average Officer Salary
    rating_rate = 84288 #Average Crew Salary
    allowances = 706236 #Additional Crew Allowances

    crew_cost_per_ship = officers * officer_rate + ratings * rating_rate + allowances #Assign Crew Costs
    crew_cost = crew_cost_per_ship * n

    insurance_per_ship = (85.99 * (0.471 * displacement / 1000) ** 0.6942) * 365 * 2.57 #Calculate Insurance
Costs
    insurance_costs = insurance_per_ship * n

    repair_per_ship = (105.4 * (0.471 * displacement / 1000) ** 0.6942) * 365 * 2.57 #Calculate Repair Costs
    repair_costs = repair_per_ship * n
```

```
    victuals_cost = 421480 #Assign Victuals Cost

    operating_cost = crew_cost + insurance_costs + repair_costs + victuals_cost

    return round(operating_cost,0)

def CalculateBuildCost(hull_type, displacement, power): #function to find the build cost of each vessel
    if (hull_type == "Axe"):
        lightship = 0.529 * displacement
        equip_weight = lightship * 0.128
        plant_weight = 0.0376 * power - 24.491
        if (plant_weight < 7.2):
            plant_weight = 7.2
        hull_weight = lightship - equip_weight - plant_weight
        if hull_weight < 0.29 * displacement: #If our other weights are too high then we should reject this vessel
            possible = False
            qs = 1994.663
            hull_weight = 0
        else:
            qs = 1994.663 + 0.015549 * hull_weight - 154.0222 * (hull_weight ** 0.2471932)
            possible = True
        qe = 9749.0427 + 14.66748 * equip_weight - 16.71265 * equip_weight ** 0.9963722
        qp = 16720.374 + 0.7839685 * plant_weight - 221.3641 * plant_weight ** 0.510682
        cost = round(qe * equip_weight + qp * plant_weight + qs * hull_weight,0)
        return cost, possible

    elif (hull_type == "X"):
        lightship = 0.529 * displacement
        equip_weight = lightship * 0.128
        plant_weight = 0.0376 * power -24.491
        if (plant_weight < 7.2):
            plant_weight = 7.2
        hull_weight = lightship - equip_weight - plant_weight
        if hull_weight < 0.29 * displacement: #If our other weights are too high then we should reject this vessel
            possible = False
            qs = 1994.663
            hull_weight = 0
        else:
            qs = 1994.663 + 0.015549 * hull_weight - 154.0222 * (hull_weight ** 0.2471932)
            possible = True
        qe = 9749.0427 + 14.66748 * equip_weight - 16.71265 * equip_weight ** 0.9963722
        qp = 16720.374 + 0.7839685 * plant_weight - 221.3641 * plant_weight ** 0.510682
        labour_cost_per_ton = qs - 500 #subtract the steel cost from the hull cost
        labour_costs = labour_cost_per_ton * hull_weight
        labour_costs *= 0.85
        cost = round(qe * equip_weight + qp * plant_weight + 500 * hull_weight + labour_costs,0)
        return cost, possible

    elif (hull_type == "Vertical"):
        lightship = 0.529 * displacement
        equip_weight = lightship * 0.128
        plant_weight = 0.0376 * power -24.491
        if (plant_weight < 7.2):
            plant_weight = 7.2
        hull_weight = lightship - equip_weight - plant_weight
```

```
        if hull_weight < 0.29 * displacement: #If our other weights are too high then we should reject this vessel
            possible = False
            qs = 1994.663
            hull_weight = 0
        else:
            qs = 1994.663 + 0.015549 * hull_weight - 154.0222 * (hull_weight ** 0.2471932)
            possible = True
        qe = 9749.0427 + 14.66748 * equip_weight - 16.71265 * equip_weight ** 0.9963722
        qp = 16720.374 + 0.7839685 * plant_weight - 221.3641 * plant_weight ** 0.510682
        cost = round(qe * equip_weight + qp * plant_weight + qs * hull_weight,0)
        return cost, possible

    elif (hull_type == "Bulbous"):
        lightship = 0.529 * displacement
        equip_weight = lightship * 0.128
        plant_weight = 0.0376 * power -24.491
        if (plant_weight < 7.2):
            plant_weight = 7.2
        hull_weight = lightship - equip_weight - plant_weight
        if hull_weight < 0.29 * displacement: #If our other weights are too high then we should reject this vessel
            possible = False
            qs = 1994.663
            hull_weight = 0
        else:
            qs = 1994.663 + 0.015549 * hull_weight - 154.0222 * (hull_weight ** 0.2471932)
            possible = True
        qe = 9749.0427 + 14.66748 * equip_weight - 16.71265 * equip_weight ** 0.9963722
        qp = 16720.374 + 0.7839685 * plant_weight - 221.3641 * plant_weight ** 0.510682
        cost = qe * equip_weight + qp * plant_weight + qs * hull_weight
        bulb_weight = displacement * 0.0138
        bulb_cost = (0.03395 * 0.55 * 2.292 * bulb_weight ** 0.772) * 1000000
        cost += bulb_cost
        cost = round(cost,0)
        return cost, possible

    else:
        return 0,False

def CalculateNumberDeliveries(length, beam, displacement, area, volume): #function to find the number of deliveries that need to be completed in a given cycle
    Area_Ratio = 0.41 #Ratio between vessel block area and usable cargo area
    Volume_Ratio = 0.376 #Ratio between the displacement and the bulk volume capacity
    Area_Capacity = length * beam * Area_Ratio
    Volume_Capacity = displacement * Volume_Ratio
    runs = max(area/Area_Capacity,volume/Volume_Capacity)
    runs = math.ceil(runs)
    return runs

def CalculateRequiredPositionKeeping(seastates, sailingconditions, beam, draft, standby, n, runs, cycle_length, fuel_cost, efficiency, displacement, length): #calculate the total fuel consumption holding position

    StandbyWind = 6.5327*seastates[:,0]**0.6549 #Finds wind speeds corresponding to sea states

    UnloadWind = 6.5327*sailingconditions[:,0]**0.6549 #Finds wind speeds corresponding to seas during unloading
```

```
    #Assign Currents based on waves
    StandbyCurrent = seastates[:,0]
    StandbyCurrent = np.where(StandbyCurrent<0.4,0.25,StandbyCurrent)
    StandbyCurrent = np.where((StandbyCurrent>=0.4) & (StandbyCurrent<0.8),0.5,StandbyCurrent)
    StandbyCurrent = np.where(StandbyCurrent>=0.8,0.75,StandbyCurrent)

    UnloadCurrent = sailingconditions[:,0]
    UnloadCurrent = np.where(UnloadCurrent<0.4,0.25,UnloadCurrent)
    UnloadCurrent = np.where((UnloadCurrent>=0.4) & (UnloadCurrent<0.8),0.5,UnloadCurrent)
    UnloadCurrent = np.where(UnloadCurrent>=0.8,0.75,UnloadCurrent)

    #Wind assumed to be bow on
    WindCoefficient = 0.423

    Depth = 1.333*draft + 9 #Hull depth at the bow, to account for a 2 deck forecastle structure and breakwater
    HullArea = (Depth-draft) * beam

    DeckhouseBeam = beam
    DeckhouseHeight = 9 #Accounts for normal of 3 decks above the top of focsle

    DeckhouseArea = DeckhouseBeam * DeckhouseHeight

    StandbyWindLoads = 0.5 * 0.001225 * StandbyWind **2 * WindCoefficient * HullArea #IMCA Hull Wind
    StandbyWindLoads += 0.000615 * 1 * 1.18 * DeckhouseArea * StandbyWind **2 #IMCA Deckhouse Wind

    UnloadWindLoads = 0.5 * 0.001225 * UnloadWind **2 * WindCoefficient * HullArea
    UnloadWindLoads += 0.000615 * 1 * 1.18 * DeckhouseArea * UnloadWind **2

    CurrentFactor = 0.07 #Current coefficient for supply ships at 0 deg incidence current

    StandbyCurrentLoads = 0.5 * 1.025 * StandbyCurrent ** 2 * beam * draft * CurrentFactor #Formula to derive
the loading acting due to current in all cases
    UnloadCurrentLoads = 0.5 * 1.025 * UnloadCurrent ** 2 * beam * draft * CurrentFactor

    StandbyTsurge = seastates[:,1] / (0.9 * length ** (1/3)) #From DNV calculation for dynamic positioning loads
    UnloadTSurge = sailingconditions[:,1] / (0.9 * length ** (1/3))

    FStandbyTSurge = np.where(StandbyTsurge < 1, 1, StandbyTsurge ** (-3) * np.exp(1 - StandbyTsurge ** (-
3))) #From DNV Calculation
    FUnloadTSurge = np.where(UnloadTSurge < 1, 1, UnloadTSurge ** (-3) * np.exp(1 - UnloadTSurge ** (-3)))

    StandbyWaveLoads = 0.5 * 1.025 * 9.81 * seastates[:,0] ** 2 * beam * 0.0628 * FStandbyTSurge #From
DNV Calculation
    UnloadWaveLoads = 0.5 * 1.025 * 9.81 * sailingconditions[:,0] ** 2 * beam * 0.0628 * FUnloadTSurge

    StandbyTotalLoads = StandbyWindLoads + StandbyCurrentLoads +  StandbyWaveLoads #Combine all
station keepign loads
    UnloadTotalLoads = UnloadWindLoads + UnloadCurrentLoads + UnloadWaveLoads

    StandbyAverageLoad = np.mean(StandbyTotalLoads) #Find the average requirement across all sea states
    UnloadAverageLoad = np.mean(UnloadTotalLoads)

    ThrusterEfficiency = 0.10 #Efficiency of propellor to thrust in kN/kw power including mechanical losses and
flow losses
```

```
    StandbyPower = StandbyAverageLoad / ThrusterEfficiency #Get the power requirements to maintain this position
    UnloadPower = UnloadAverageLoad / ThrusterEfficiency

    StandbyFuel = StandbyPower * cycle_length * efficiency / 1000000
    UnloadFuel = UnloadPower * runs * 8 * efficiency/ 1000000

    StandbyCost = StandbyFuel * fuel_cost
    UnloadCost = UnloadFuel * fuel_cost

    if (standby):
        return round((StandbyCost + UnloadCost) * 8760 / cycle_length,0)
    else:
        return round(UnloadCost * 8760 / cycle_length,0)

def CalculateRequiredSpeed(cycle_length,number_deliveries,downtime,distance,n,standby): #calculate the required speed for delivery
    time_to_load = 8 #time required to load up the vessel in hours
    time_to_unload = 8 #time required to unload cargo offshore
    total_time = cycle_length * n

    if standby:
        available_time = total_time - cycle_length
    else:
        available_time = total_time

    loading_time = number_deliveries * time_to_load
    net_time = available_time - loading_time
    sailing_time = (1-downtime) * net_time
    voyage_time = sailing_time - number_deliveries * time_to_unload #Unloading is only done if we are in the weather window
    hours_per_sail = voyage_time / number_deliveries

    if hours_per_sail <= 0:
        possible = False
        speed = 0.0

    else:
        speed = 2 * distance / hours_per_sail #Speed needs to be doubled to allow time for ship to return to port
        possible = True
        if speed < 10.0: #If lots of time is available, the speed doesnt need to be fast, but we still would not design a vessel for less than 10 knots, ships would simply spend more time in port
            speed = 10.0
        if speed > 30.0: #Reject vessels that require impossibly fast designs
            possible = False
        speed = math.ceil(speed)

    return speed, possible

def CalculateFuelCost(hull_type,length,beam,draft,speed,sailing_conditions,runs,distance,cycle_length,fuel_cost,efficiency): #Calculates the fuel cost for the vessel
    if (hull_type == "Axe"):
```

```
        all_resistance = 10 ** (-0.085 - 0.0087*length + 0.021*beam + 0.25*draft + 0.14 * sailing_conditions[:,0] +
0.094 * speed - 0.0019*length*draft + 0.000096 * length ** 2 - 0.017 * sailing_conditions[:,0] ** 2 - 0.00091 *
speed ** 2)
        average_resistance = np.mean(all_resistance)
        power = round(average_resistance * speed * 0.5144,0) #Effective Power

        # Power Efficiency Losses
        QPC = 0.55 #Quasi Propulsive Coefficient accounts for and propellor efficiency
        Eta_g = 0.95 #Gearbox Losses
        Eta_s = 0.98 #Shaft Losses
        Eta_sw = 0.998 #Switchboard Losses
        Eta_fc = 0.985 #Frequency Convertor Losses
        Eta_motor = 0.97 #Electric Motor Efficiency

        power = power / (QPC * Eta_g * Eta_s * Eta_sw * Eta_fc * Eta_motor) #Required Generator Power

        fuel_cost_per_run = power * 2 * distance/speed * efficiency * fuel_cost / 1000000
        cost_per_cycle = runs * fuel_cost_per_run
        fuel_annual_cost = round(8760 / cycle_length * cost_per_cycle,0)
        return power, fuel_annual_cost

    elif (hull_type == "X"):
        all_resistance = 10 ** (-2.32 - 0.0029*length + 0.027*beam + 0.65*draft + 0.036*sailing_conditions[:,0] +
0.59*sailing_conditions[:,1] + 0.070*speed - 0.00015 * length * speed - 0.098*draft*sailing_conditions[:,1] -
0.025 * sailing_conditions[:,1]**2 + 0.0042*draft*sailing_conditions[:,1]**2)
        average_resistance = np.mean(all_resistance)
        power = round(average_resistance * speed * 0.5144,0)

        # Power Efficiency Losses
        QPC = 0.55 #Quasi Propulsive Coefficient accounts for and propellor efficiency
        Eta_g = 0.95 #Gearbox Losses
        Eta_s = 0.98 #Shaft Losses
        Eta_sw = 0.998 #Switchboard Losses
        Eta_fc = 0.985 #Frequency Convertor Losses
        Eta_motor = 0.97 #Electric Motor Efficiency

        power = power / (QPC * Eta_g * Eta_s * Eta_sw * Eta_fc * Eta_motor) #Required Generator Power

        fuel_cost_per_run = power * 2*distance/speed * efficiency * fuel_cost / 1000000
        cost_per_cycle = runs * fuel_cost_per_run
        fuel_annual_cost = round(8760 / cycle_length * cost_per_cycle,0)
        return power, fuel_annual_cost

    elif (hull_type == "Vertical"):
        all_resistance = 10 ** (-4.16 - 0.012*length - 0.087*beam + 1.19*draft + 0.10*sailing_conditions[:,0] +
1.19*sailing_conditions[:,1] + 0.054 * speed + 0.00024*length*beam - 0.19*draft*sailing_conditions[:,1] -
0.0049*sailing_conditions[:,0]*sailing_conditions[:,1] + 0.0023*beam**2 - 0.049*sailing_conditions[:,1]**2 +
0.0080*draft*sailing_conditions[:,1]**2)
        average_resistance = np.mean(all_resistance)
        power = round(average_resistance * speed * 0.5144,0)

        # Power Efficiency Losses
        QPC = 0.55 #Quasi Propulsive Coefficient accounts for and propellor efficiency
        Eta_g = 0.95 #Gearbox Losses
        Eta_s = 0.98 #Shaft Losses
        Eta_sw = 0.998 #Switchboard Losses
```

```
        Eta_fc = 0.985 #Frequency Convertor Losses
        Eta_motor = 0.97 #Electric Motor Efficiency

        fuel_cost_per_run = power * 2 * distance/speed * efficiency * fuel_cost / 1000000
        cost_per_cycle = runs * fuel_cost_per_run
        fuel_annual_cost = round(8760 / cycle_length * cost_per_cycle,0)
        return power, fuel_annual_cost

    elif (hull_type == "Bulbous"):
        all_resistance = 10 ** (-0.94 + 0.01*length + 0.025*beam + 0.19*draft + 0.032*sailing_conditions[:,0] +
0.14*speed - 0.0013 * length * draft - 0.00035 * length * speed - 0.00069 * speed ** 2)
        average_resistance = np.mean(all_resistance)
        power = round(average_resistance * speed * 0.5144,0)

        # Power Efficiency Losses
        QPC = 0.55 #Quasi Propulsive Coefficient accounts for and propellor efficiency
        Eta_g = 0.95 #Gearbox Losses
        Eta_s = 0.98 #Shaft Losses
        Eta_sw = 0.998 #Switchboard Losses
        Eta_fc = 0.985 #Frequency Convertor Losses
        Eta_motor = 0.97 #Electric Motor Efficiency

        fuel_cost_per_run = power * 2 * distance/speed * efficiency * fuel_cost / 1000000
        cost_per_cycle = runs * fuel_cost_per_run
        fuel_annual_cost = round(8760 / cycle_length * cost_per_cycle,0)
        return power, fuel_annual_cost

    else:
        power = 0.0
        fuel_annual_cost = 0.0
        return power, fuel_annual_cost
```