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AN AUTOMATED APPROACH TO 3D PARAMETRIC SHIP DESIGN

Master's thesis in Naval Architecture

Supervisor: Henrique M. Gasper

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Faculty of Engineering
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ABSTRACT

Digital design tools are commonplace in modern design processes. 3D CAD software helps designers and engineers work with new concepts more easily and conduct efficient simulations. However, this is not always the case when it comes to ship design, where 3D designs are still combined with 2D drawings in conceptual stage. Designing a ship from scratch in full 3D is too complex for a shipbuilder's purposes and would require too much rework if changes were made later on- which is why this is not preferred approach.

However, 3D CAD model can potentially be a good starting point in conceptual design as it helps better visualize the project and helps designer explore more design options, especially when it comes to designing new models. These would be an ideal option for designers if they weren't associated with tedious manual updates every time a design parameter is changed. This brings us to the question- how can we implement 3D models to work as a starting point in conceptual design without having to worry about manually reworking it constantly. In this report, we will be answering this question and how this can be practically achieved on commercial design software.

This report explores the possibility of automating the conceptual ship design process in an effort to reduce cost and time during ship design process. This is done by automating tedious tasks like hull form generation, scantling calculation, weight estimation, performance prediction and initial stability calculations—all of which take a lot of man hours if done manually. The basic idea being that the program would be able to perform repetitive tasks in conceptual ship design that requires minimal supervision or interference, so that human effort can be focused more on the design aspect.

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SYMBOLS AND ABBREVIATIONS

L _{PP}	Length between Perpendiculars
L _{LL}	Freeboard Length
L	Rule Length
B	Moulded Breadth
D	Moulded Depth
V	Maximum Service Speed
T _D	Design Draught
T _{SC}	Scantling Draft
∇	Volume Displacement
Δ	Moulded Displacement
C _B	Block Coefficient
C _M	Midship Coefficient
C _W	Waterplane Coefficient
C _P	Prismatic Coefficient
GZ	Righting lever
LCB	Longitudinal Center of Buoyancy
KB	Vertical Center of Buoyancy
WSA	Wetted Surface Area of Hull
WPA	Waterplane Area
LCF	Longitudinal Center of Floatation
TPC	Tonnes per centimetre immersion
BM _T	Transverse Metacentric Radius
BM _L	Longitudinal Metacentric Radius
KM _T	Vertical distance from Keel to Metacentre
GM _T	Transverse Metacentric Height
Z	Section Modulus
b _{eff}	Effective breadth of attached plating
I _{XX}	Moment of Inertia
R _T	Total Resistance
P _E	Effective Power
P _D	Delivered Power.
CAD	Computer Aided Design
FEA	Finite Element Analysis
CFD	Computational Fluid Dynamics
NURBS	Non-Uniform Rational B-Splines
BREP	Boundary Representation (Surface type)
DNV	Det Norske Veritas (Classification society)
IMO	International Maritime Organisation

1. INTRODUCTION

Shipbuilding industry has a very rich history, is one of the oldest and most traditional manufacturing industries in the world. It which deals with the design, construction, and maintenance of ships along other floating structures. The process of building a ship requires a huge amount of coordination between the various disciplines and trades involved in the construction process. Despite its external appearance, each vessel is unique and is tailored to meet the specific requirements of the project. As a result of this individuality, design process of ships is highly customized and can be highly time-consuming task. Given the time-consuming and unique nature of the design process, even small changes in initial parameters may require large amount of rework or even compromise the entire design. This makes the design process even more expensive and time consuming. (Chaves, 2018) A novel solution to such a context is to automate repetitive processes, so that designers can focus on more creative tasks.

In a very broad perspective, automation can be seen as the process of reducing or eliminating human interaction in redundant and repetitive tasks, with the use of control systems, machinery, or information technology. The basic idea is centred around reducing human effort by automating repetitive and predictable tasks. (Johansson, 2008) In the context of this thesis, automatization refers to areas of ship design, where computational tools and systems shall be used for streamlining and automating repetitive tasks, allowing the designer to focus of creative tasks and explore more design options early in the design phase.

Traditionally, ship design process has been a very laborious process requiring designers to spend a large amount of time in preparing new designs. However, automation has been prevalent in the ship design field for a long time and evolved over years to accommodate more recent technologies. An early example in the field of ship design is the use of templates. Templates were used to create 2D drawings of ships which could then be used to create the physical model. Even though the process was a bit time consuming, it did allow for a degree of accuracy and consistency that was not possible with manual methods.

The field of ship design was revolutionized by the advent of computer and now CAD programs could be used for creating 2D drawings. However, early CAD programs were limited in the capabilities, and allowed the creation of 2D drawings which could be used to create the physical models. These software programs had limitations and were not well-suited for implementing parametric modelling. It was not until the development of 3D parametric modelling software that the true potential for automation in ship design could be realized. Over the years, various software packages have been introduced to the industry to reduce to effort on designers and improve the efficiency of the process, however the design process still involves significant manual input and decision making from the designer.

Automating the ship design process can have numerous benefits. It can help to reduce the amount of time and money spent during the design phase. Automation can help to speed up the design process by eliminating the need for repetitive tasks to be carried out manually. This can free up designers to focus on more creative aspects of the design process. There are many potential areas where automation can be used to improve efficiency and quality in ship design. One such area is the creation of 3D parametric models. Parametric modelling is a type of modelling where geometry is defined by a set of parameters or variables. This allows for easy modification of the geometry as the design evolves. Another potential area for automation in

ship design is the calculation of hydrostatic characteristics. Hydrostatic analysis is a vital part of ship design as it helps determine the stability during operation and ensures that the ship meets all the required safety standards. Structural scantling design which is often carried out in accordance with classification society rules also show good potential for automation. Other possible areas in ship design where automation can be implemented will be explored in detail in the following chapters.

1.1 PROBLEM STATEMENT

The process of ship design is multi-disciplinary, meaning that it draws on the expertise of multiple engineering disciplines. The various disciplines that contribute to ship design include naval architecture, structural engineering, electrical engineering, and more. The most common problem when more than one discipline works together on a project is to find a common platform to integrate individual design. To put things into perspective, a structural engineer is responsible for designing the structural scantlings of the vessel whereas a naval architect handles the general form and stability calculations. Changes in the form of the vessel would directly affect the structure elements of the vessel and would require the scantling calculations to be reworked. When you have engineers working on different platforms, it can be difficult to transfer changes from one platform to the other. This also makes making parameterized models much more difficult.

Ship design is an iterative process which often requires a lot of reworks as the design is manifested to its final state. These iterations in design are extensive manual work and very time-consuming. Especially when working with a 3D model as a starting point in design, iterations during the concept design stage can mean extensive hours of rework. Moreover, new designs usually come with a different mission requirement than previous designs. This means that the use of legacy systems would be to a minimum and the design process would need to be started from the ground up. However, starting a new ship design from scratch can be a daunting task. It requires starting the process over again, which can be time-consuming and expensive. Reusing elements from previous designs can therefore help to save time in the long run.

One of the struggles that many design teams face is bidding on project tenders with their conceptual designs, which often take a lot of time to create. The problem is that even though they put in all this time and effort, they don't always get the project and the time spent on developing the design is wasted. With automating the process of conceptual design, there would be less man-hours spent on developing these designs, giving the team more time to work on other projects and reduce the workload.

While there have been many attempts to develop an autonomous ship design methodology, the current state of the art is that there exists no automated way to design a ship. This is primarily due to the fact that each design is unique in its requirements which makes it very difficult to establish a standard template for a certain type of ship which can be easily parameterized. For the same reason, ship designers must rely on manual methods, which are time-consuming and often result in sub-optimal designs. However, there are still many tasks in the design process that show potential to be automated. This thesis will seek to explore such options.

1.2 MOTIVATION

In the previous section we looked at the problems in conceptual design and the challenges in automation. In this section, we discuss the benefits of automating parametric 3D design during the conceptual stage. The main motivations for exploring automated 3D parametric models in conceptual design stage are explained below:

1) **Savings in Time and Money:** Incorporating parametric design methodology into concept design stage can significantly reduce the time required for overall designing a ship. The traditional method of designing a ship can take weeks or even months, whereas implementing automating tools during concept design can help reduce this timeline to a matter of days. This reduction in design time can lead to considerable cost savings. As the maritime industry looks for ways to reduce costs and speed up production times, parametric design is coming to be an increasingly popular tool. This allows for rapid prototyping and experimentation and can ultimately lead to faster and more efficient ship design.

2) **3D Model as the Starting Point:** Automating concept design provides an opportunity for using 3D model as the starting point in design. This allows for better visualization of the project and allows for identification of possible problems early on in the design stage. The 3D model developed during the concept design stage can make subsequent design phases quicker and more efficient. The model created at this stage can also be used for future analysis and experimentation, to help refine the project.

3) **Explore more Design Options:** Automating concept design process gives more time to the engineer to explore more design options earlier on in the design phase. This provides better opportunities to validate concepts, generate more ideas at the early stages of a project, and identify the best option for different situations. It allows different design options to be studied side by side in order to identify the best possible option for the required problem space.

4) **Checking Rule Compliance:** Marine designs are subjected to number of regulations laid down by classification societies and statutory bodies, especially when it comes to structural design and stability calculations. Typically, lot of man hours are spent on making sure the design prepared is in compliance with these rules, as the designs are required to be checked and approved by these bodies before going into production. Implementing automated methods can make this process much easier.

5) **Reducing Workload:** As discussed in the previous section, design teams often spend many hours developing concept designs for bidding process, which are most often not awarded. By automating the conceptual design methodology, new concept designs can be developed much quicker for bids, reducing the workload on the team and allowing them to concentrate more on live projects.

1.3 OBJECTIVES

The primary objective of the thesis is to develop a methodology for automating the repetitive processes associated with the concept design of ships and implement the same using a computational tool. The basic idea is to streamline the ship design process by creating a set of input parameters that can be quickly modified to generate new designs while repetitive and

time-consuming tasks such as hull form generation, structural scantling modelling, weight estimation and stability analysis will be automated using the proposed parametric tool.

The main objective as explained above can be broken down as stated below:

1. Formulation a standard methodology for automating concept design tasks.
2. Develop a computational tool that implements the established methodology for automating repetitive tasks associated with concept design.
3. Validate the developed design tool against software widely accepted in the industry.

1.4 SCOPE

The purpose of this report is to investigate the potential for using 3D computational tools in automating the conceptual ship design phase. The computational tool developed as part of the thesis is a proof of concept for showcasing the established methodology. It should be noted that the tools is not intended as a comprehensive package that addresses all aspects of design calculation, rather the purpose would be to demonstrate the feasibility of the developed approach for automating concept design tasks. The tool will showcase the potential benefits of using automation in ship design and provide a foundation for further development and refinement in future iterations.

The design tasks explored in the thesis will be limited to parametric hullform generation, structural design, weight estimation, stability, and resistance analysis. The proposed ship design tool aims to automate these tasks and streamline the design process. More advanced calculations such as fatigue, buckling, eigen value, and finite element analysis are excluded from the scope of thesis. The results calculate from the design tool shall be validated against commercial software to ensure accuracy of results.

This thesis tries to combine the principles of ship design, parametric modelling and automation in order to establish a standard methodology for automating concept design phase allowing for rapid virtual prototyping. The scope of this investigation will be limited to conceptual design phase in the ship design process. It is important to note that the focus of this article is on the feasibility of using parametric design tools for ship design, and not on the optimisation or improvement of ship designs.

2. LITERATURE REVIEW

This chapter provides a summary of the theoretical background and state-of-the-art knowledge in the three main domains established within the scope of the thesis: concept design of ships, parametric design methodology, and automation. Chapter begins by introducing the reader to traditional ship design process and isolating concept design from the various design phases. Various tasks carried out in concept design phase will be discussed in detail. The chapter will also discuss most widely used marine engineering tools, their generic features and parametrization and programming options. The third section in the chapter will explore more about which tasks have the potential to be automated and how these can be implemented. Finally, the chapter concludes with a summary of design tasks that will be adopted in the methodology.

2.1 SHIP DESIGN PROCESS

The process of designing a ship is a complex one that involves many different disciplines working together in perfect coordination to achieve a relevant design solution. Design is a complex process that entails cooperation between many individuals with different disciplines. Many like to think of ship design process as a purely technical one, but it is important to also acknowledge the involvement of the non-technical disciplines in the final product such as marketing, procurement, sales etc.

Classical ship design process is often considered to be an iterative one, used to arrive at the best solution for a new project. Typical course of ship design process starts from a set of basic mission requirements, and works its way through function form, performance, and economics of the project. It is a sequential design methodology which primarily consists of an iterative process for arriving at complete ship design. The design loops eventually narrow down and converge into the final stage of detailed design. As it can be seen, each loop consists of a set of tasks such as hydrostatics, structure, powering etc, that need to be completed before moving on to further iterations. The process is repeated until an optimal design is found. This famous design methodology is called the Design Spiral and was first introduced by J.H Evans (Taggart, 1980).

Later over the years, more modern and comprehensive graphical approaches were introduced by several authors such as the one illustrated by Fig 1 (Sen P, 1997), which considers the ship design process to encompass not just the engineering part, but also other aspects of the project such as market study, manufacturing and sales. This approach looks at ship design in a more holistic way, not just stopping at completion of design but seeing the project to its final delivery to client and also encompasses the economic aspect into the picture.

However, there is no one perfect method or a standard approach for designing a ship, as the process highly depends on the type of vessel, its intended purpose, and the preferences of the designer. Despite what method is followed, the ship design process can be generally broken down into four main stages as explained by (Taggart, 1980) as follows:

- 1) Concept design
- 2) Preliminary design
- 3) Contract Design
- 4) Detailed design

In this thesis we will look at the first two phases of ship design, which are often condensed to the term Basic design or often generalized under a common definition as preliminary design.

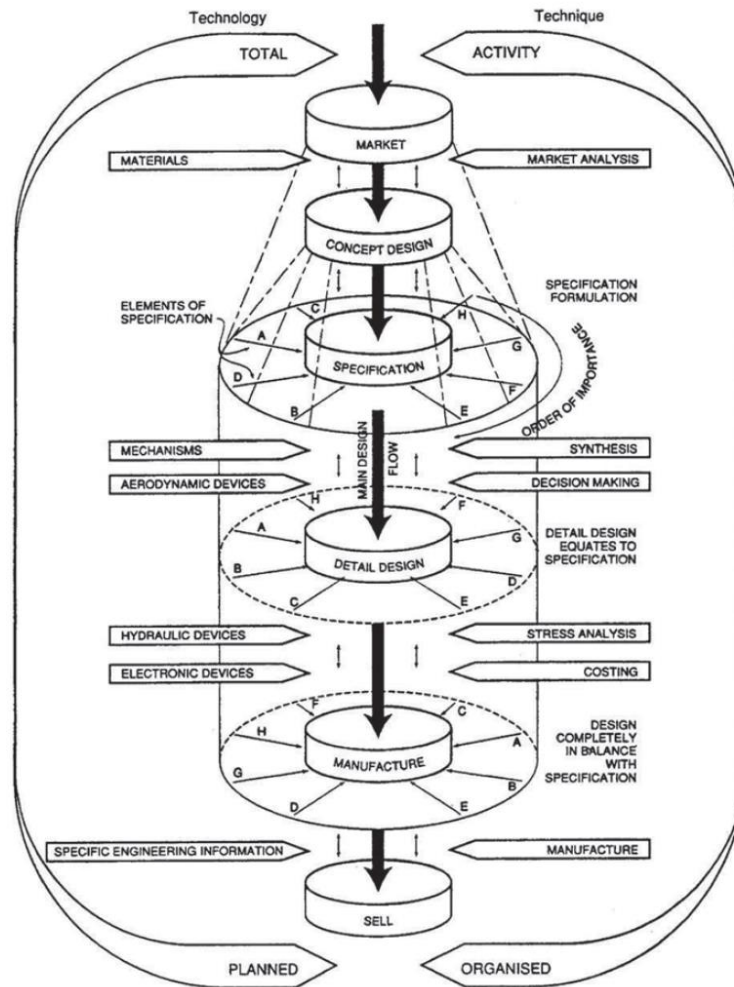


Figure 1 3D Spiral of ship design and construction (Sen P, 1997)

2.2 CONCEPT DESIGN

The initial stage in the inception of new vessel design is called concept design. This involves creating a ship concept that meet the design constraints and functional requirements, such as cargo capacity, speed, range, draft as well as constraints from the builder such as maximum length, width, or height. In this stage, designers carry out an initial analysis of the vessel and ship characteristics, such as the ships performance, structural layout, basic stability characteristics, powering characteristics and so on. Basically, the owner’s requirements are translated into technical specifications considering naval architecture and marine engineering principles.

Preliminary estimations of key ship dimensions and alternative design solutions are explored to identify the most economical option that fulfils the owner's requirements. According to R.K.Kiss (Taggart, 1980) approximately 20 man-days were required to complete a concept design in the 50s, which has been significantly reduced by the advancement in engineering tools in ship design. In present day, an experienced naval architect with the right

tool can design concepts in less than a day's time (Papanikolaou, 2014). The outcome of the thesis hopes to reduce this time even lower to a matter of minutes and having more output in terms of 3D model, structure, stability, weight and powering information at hand, as compared to traditional design calculations.

Now that we have an overview of the concept design process, next we narrow down on the specific tasks carried out during this stage.

2.3 CONCEPT DESIGN TASKS

The following tasks are the main tasks carried out during concept design stage:

1) **Main Dimension Estimation** – the parameters estimated during this stage are Length, Beam, draft, depth, and the hullform coefficients. The criteria used for selecting the overall dimensions of the vessel varies based on the type of the vessel and its intended purpose. According to (Papanikolaou, 2014), there are two major approaches for determining such parameters:

- using statistical data from vessels of similar size and function.
- calculate the optimum hull design specific for the project based on the mission requirements for the project.

2) **Hull form development** - The development of the hull form is a crucial aspect of ship design, as it directly affects the vessel's performance and stability. In this stage, the shape of the hull is determined based on the vessel's main dimensions and hull form coefficients. The objective is to achieve an optimal hull form that minimizes resistance and provides efficient propulsion, while also ensuring stability, floatation, seakeeping performance, and sufficient cargo hold volume. Various parameters, such as displacement distribution, sectional area curves, and longitudinal center of buoyancy, are estimated during this phase. Figure 2 illustrates a typical hull form generated for a cargo ship using the Rhino software, showcasing the initial shape of the vessel's hull.

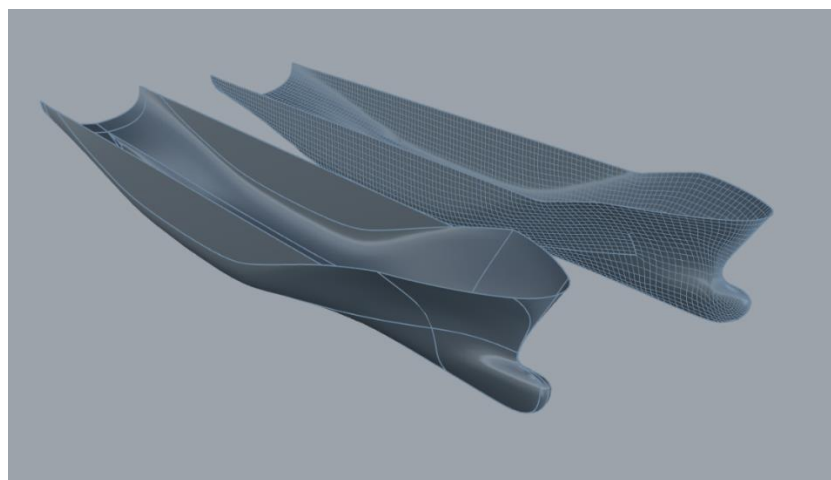


Figure 2 Hullform created on Rhino (author)

3) **General Arrangement Plan** - The general arrangement (GA) plan provides a comprehensive layout of the ship's spaces, ensuring that all functional requirements are met and clear interfaces are established between different areas. This includes the subdivision of the ship's enclosed volume into decks vertically and compartments horizontally through bulkheads or walls, each serving specific functions. Communication routes are also determined, both between decks and within compartments. The general arrangement plan of container ships serves as a typical example of how these spaces are organized, as illustrated below.

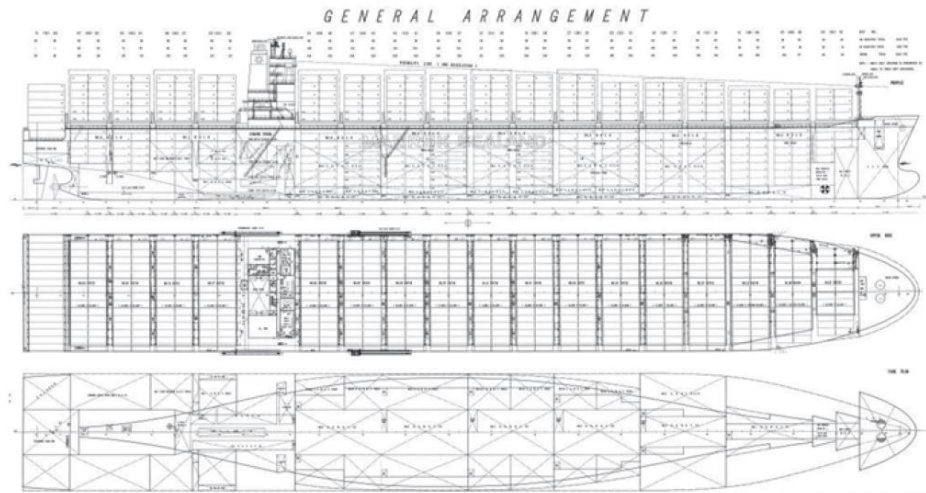


Figure 3 GA of 6300 TEU Containership (Shipyards Hyundai Heavy Industries)

4) **Structural design** – the structural design of the vessel primarily deal with determining the scantlings of plates and stiffeners which support plates. These typically designed to withstand the internal and external loads acting on them during operation from waves, wind, cargo and so on. Structural design also deals with calculation of the global bending strength, buckling and fatigue assessment of the structure. Some of the major structural elements in a vessel are bulkheads, web frames, keel plates, deck plating etc. Moreover, stiffeners can be broadly classified into longitudinal and transverse members. The longitudinal strength members are designed to resist the bending moments induced by external loads whereas transverse structural elements are designed to resist the shear forces and torsional moments induced by the same loads. Fig 4 shows the typical structural arrangement provided at the midship section of a hopper barge, the various longitudinal and transverse members can be seen from the plan.

5) **Hydrostatic analysis** - Hydrostatic analysis is carried out to calculate the ship's intact and damage stability characteristics. This is critical for ensuring the safety of vessel, cargo and crew during operation. This includes calculating the metacentric height, righting moment curve, areas under the curve and so on. The results from calculation are often checked against requirements laid down by regulatory bodies to check compliance. The main inputs that are necessary for hydrostatic calculation is the vessel's hullform, loading conditions and position of down-flooding points. Figure 5 shows an example of righting lever and hydrostatics calculated using Maxsurf for a cargo vessel prepared by the author.

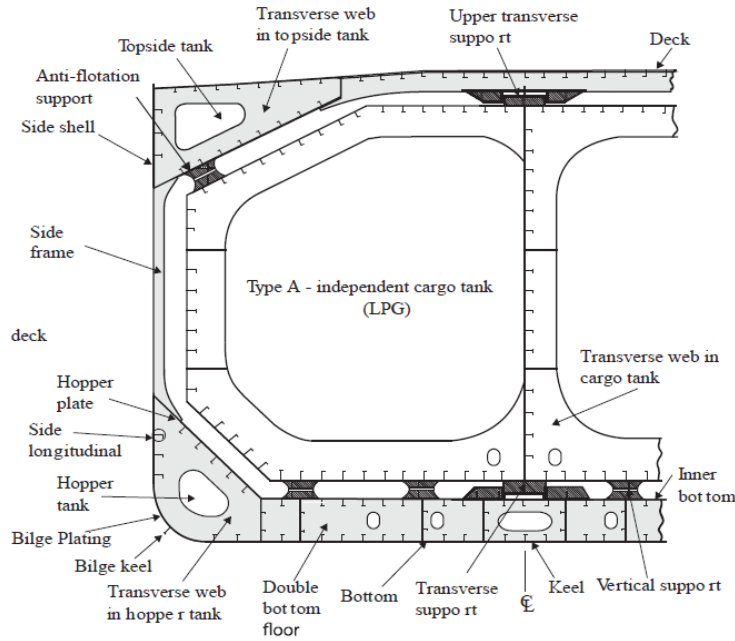


Figure 4 Midship Section of Tanker (DNV, Rules for Classification: Ships (RU-Ship), 2022)

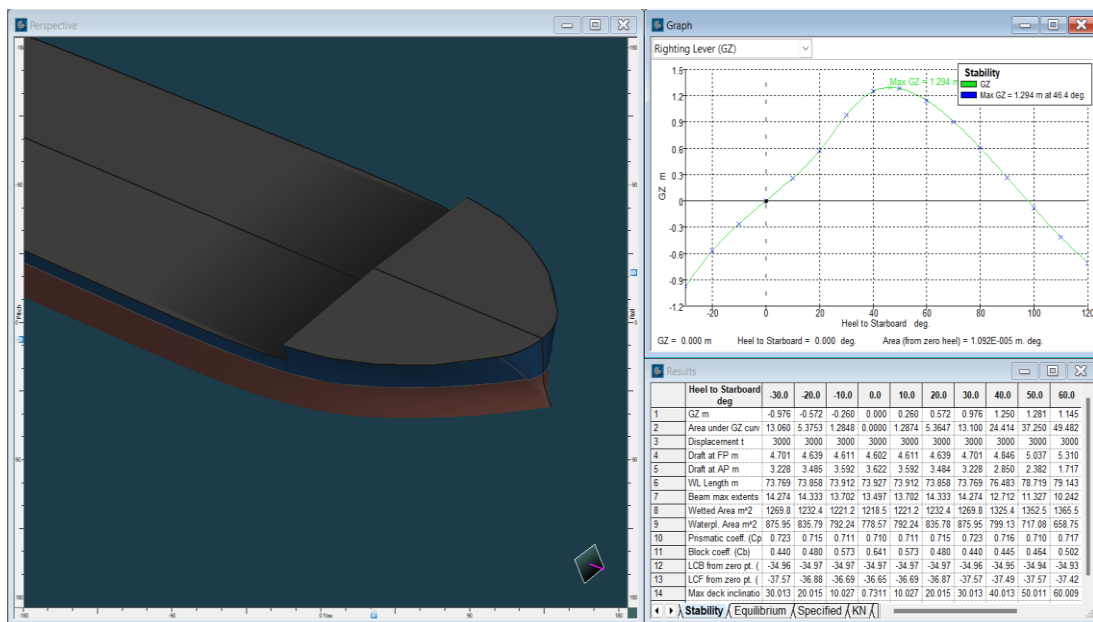


Figure 5 Stability Assessment on Maxsurf (author).

6) **Powering calculation** - determining the power of main propulsion systems and auxiliary machinery. The powering calculation is used to determine the power required for the main propulsion system and auxiliary machinery of the vessel. This includes calculating the resistance of the vessel, propulsive efficiency, fuel consumption, etc. Resistance estimation is typically done using empirical methods or using computational fluid dynamics models. The results of resistance calculation provide the total resistance that the vessel experience when moving forward at a specific speed, this can be directly used to determine the total installed power requirement provided the efficiency losses in the power train are known to us.

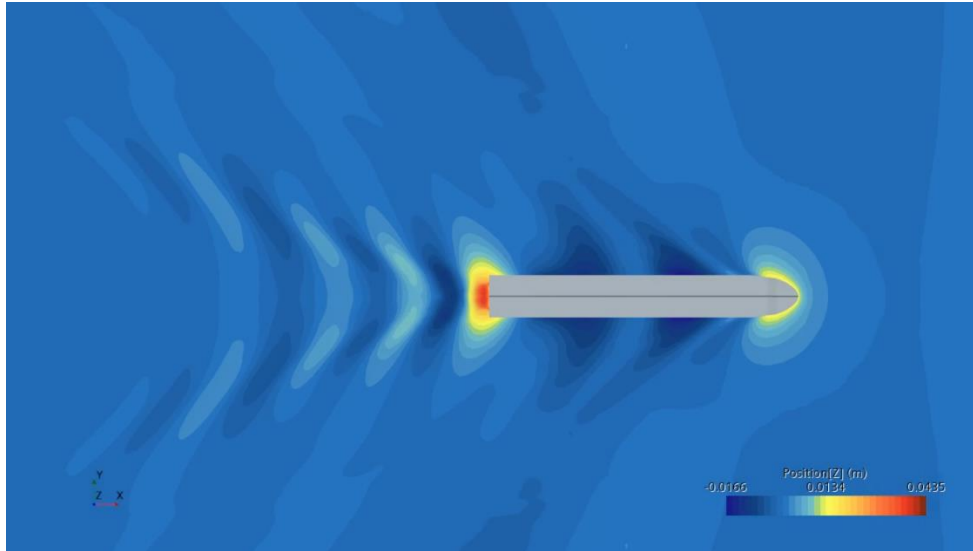


Figure 6 Ship Resistance using StarCCM (author)

2.4 AUTOMATING CONCEPTUAL DESIGN PROCESS

This section will investigate the potential for automating ship concept design tasks. The primary focus will be on identifying the design tasks which are well suited to automation and discussing the benefits that could be achieved from successful automation.

Main Dimension Estimation: Estimation of the main dimension of the vessel is typically the starting point of the design process and is usually provided by the client or limited by the capabilities of the shipyard. The main dimensions of the vessel are also restricted based on route of operation. A typical example is that of container vessel travelling through the Panama Canal (termed as Panamax vessels) would have restrictions to the maximum beam and draft of the vessel. Taking such factors into account, capabilities of automating main dimensions of the vessel is limited. Typically, the parameters that are considered during the onset of a new design are the vessel's length, breadth, depth, draft, service speed and the total cargo carrying capacity. Even if automation of these parameters is limited to a certain extent, boundary values (maximum and minimum) can be assigned to each parameter to try out different combinations that would provide the best results.

Hullform Generation: Generation of hullform for the vessel can be automated once the main dimensions are determined if the hull form is of a particular type. There are several methods for generating hull forms from a set of overall dimensions. One such approach is the rapid hull modelling methodology which defines a set of feature curves matching the overall dimensions of the vessel; the final shape and fairing of the hullforms are based on where and how much each curve was shaped. Generating the hullform based on overall dimensions also will not automatically match coefficients to a specific value, and this process requires iterative work that requires designer decision-making. Once the hullform has been determined, lines plans can be extracted from the 3D model and can be exported or documented. This process also has good potential for automation.

General Arrangement Plan: The GA plan is a drawing of the vessel that provides an overview of the ship and its key features. It provides a representation of the hull, superstructure,

machinery, and equipment. The automated concept design described in this thesis largely focuses on the hullform modelling, and reusing design templates. It would be possible to extract different views and deck plans of the vessel, based on the model. However, in such a case the output would be largely incomplete, as it doesn't account for machinery, equipment, or accommodation layout which is an important aspect in general arrangement plan. Preparation of general arrangement plan largely requires manual work and therefore included in the scope of the automation tool.

Structural Design: Calculation and weight estimation of structural scantlings is one of the most important processes in ship design. It involves calculation the thickness of plates and the size of profiles that are used as stiffeners. The approach for calculating structural scantling is mostly based on classification society of international standard rules, therefore this process shows a good potential for automation. Before carrying out structural scantling calculation, the user would be required to manually define bulkheads and decks where scantlings are to be added. Scantling calculation would require relevant information from the model such as frame spacing, stiffener span etc to calculate the size of structural scantlings required for a particular shell plating. The calculated scantling should be automatically modelled into the hullform to provide a detailed structural model. The calculation would be based on an established classification society rules or international standards. This phase would also be associated with the estimation of the total structural weights. However, one drawback would be that an automated method would not be able to determine the scantling required for areas such as machinery foundations, fore peak etc which are prone to high stress and require additional analysis. Therefore, structural design and modelling of scantling show good potential for automation but does not cover high stresses region that require special consideration. Regions such as equipment foundations cannot be automated since these need further analysis.

Stability Calculation: Like structural scantling calculation, ship stability calculation is also associated with regulations for comparison and validation. Typically, merchant vessels are required to comply with IMO regulations for intact and damage stability. Estimating stability of the vessel is also associated with checking hydrostatic parameters for different drafts and trim conditions of the vessel. The inputs required for stability calculation would be hull model generated in Hull Generation module and the weight estimates from the structural design module. User input will also be required to define the missing weights in terms of deadweight, equipment and outfit weights to establish different load cases. Hydrostatic analysis can be run against these different load cases automatically and can be compared against IMO criteria as a requirement.

Powering Calculation: Powering calculation for vessels can be carried out in two different methods using computer programs- CFD which deals with solving Navier Stokes equation and another using empirical equations which are developed from statistical regression of empirical data. Resistance calculation using empirical methods show good potential for automation since the inputs for such methods are typically hullform parameters, floating draft and the speed of the vessel. The results from powering calculation can help size the powerplant inside the vessel.

Overview of automation capabilities of each design task explored in the above section has been summarized and illustrated in Figure 7. It can be seen that some tasks have better scope for automation while its more difficult to automate other tasks.

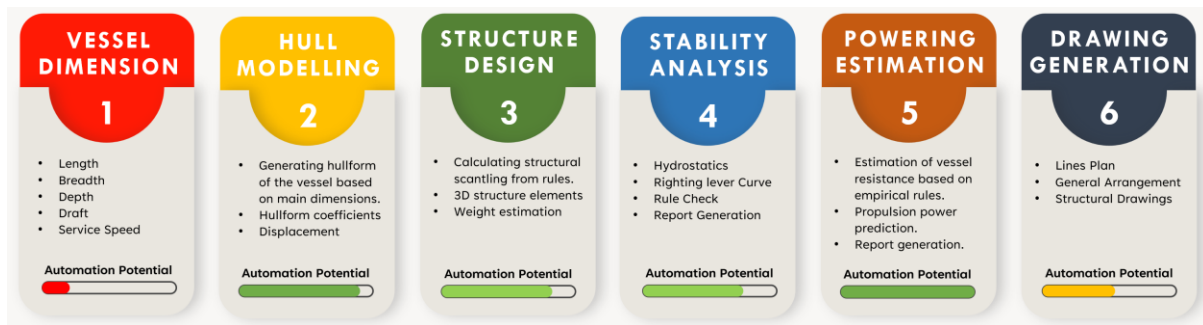


Figure 7 Overview of the author's impression on design task automation capabilities.

From the study, parametric hull generation, structural design, stability and resistance analysis were selected for further investigation and implementation using the design tool.

2.5 3D TOOLS USED IN SHIP DESIGN

This section covers the different design software that are used in marine industry. We will look at the general features of each one - hull form generation, structural design, stability along with the ability to automate and parameterize.

GENERIC FEATURES

Naval architecture is a very broad industry, with many different tasks carried out during the design process. Different software is used in the industry in order to reduce work effort, improve workflow and keep up with the latest advances. Software used in the maritime industry can be broadly grouped based on the purpose for which they are designed for as follows (Menon, 2020).

- 1) **CAD/CAM/CAE Software:** Computer Aided Design (CAD) software usually used for creating 3D models and associated calculations – typically for design of hull surface and offshore structures.
- 2) **Structural Design/ Analysis Software:** Structural design software are used for designing structural members in ships and other offshore structures. Whereas, structural analysis software are used for analysis the strength of the structure designed.
- 3) **Hydrostatics, Hydrodynamics, and Stability Tools:** These programs enable the calculation of a ship's stability in different load conditions, including intact and damaged states. Additionally, they facilitate the development of loading plans and the evaluation of proposed modifications to the vessel's hull, cargo, or ballast.
- 4) **Resistance and Power Prediction Tools:** Such software is used to estimate the resistance of a ship and use this data for predicting the total required engine power. This can be done with an empirical formula or by using advanced techniques such as CFD.
- 5) **Project Planning Tools:** These are essential for managing the tasks and processes involved in a project. These software programs track costs and time spent on each task, enabling efficient management of tasks and budgets even before any expenses are incurred.

6) Integrated suites & workstations: These offer a comprehensive solution by combining various tools and software into a single package. These suites often include plugins and features that enable the entire vessel to be designed and built from start to finish, providing a streamlined and efficient workflow.

Different commercial software packages will be reviewed in the next section to assess their specific features in relation to the capabilities discussed above. It is important to note that there are currently only a limited number of software programs available in the market that encompass all these capabilities, including hull form design, stability analysis, structural design, and power prediction. However, software programs that do offer all these features often lack in terms of parametrization and automation. Therefore, it is crucial to select a program that strikes the right balance between automation and design capabilities to ensure the success of the project.

2.6 SELECTION OF DESIGN SOFTWARE

In this section, we will look at different marine design software packages that are commercially available and look deeper into how well these can be used for automating ship design tasks. We are interested in the design capabilities of these software, their respective pros and cons and most importantly, their capability of providing parametric design and programming options.

1) MAXSURF

Maxsurf is a naval architecture software owned by Bentley Systems, used for design marine vessels. Based on the information available from (Maxsurf - Marine Vessel Analysis and Design Software, 2023) Maxsurf package consists of a suite of programs that provides integrated tools for hull modelling and optimisation, comprehensive stability, motions & resistance prediction, structural modelling, structural analysis, and export to vessel detailing. Maxsurf provides the user with options for modelling complex vessels using dynamically trimmed 3D NURB surfaces, mesh modelling and surface sitting on imported data. It also comes with a structural design module for designing scantlings using steel, aluminium, wood or composites. Maxsurf provides designers, with a number of tools for surface modelling, static stability, resistance and powering calculations, seakeeping analysis, and structural design. However, ship design tools offered by Maxsurf are available as different programs without any provisions for automatically transferring data between these programs, which makes parametrization process difficult.

2) AVEVA MARINE

Aveva provides engineering software solutions for marine and maritime sectors. It offers a variety of solutions, from ship design to digital twin and remote maintenance tools. Some of Aveva's top Marine software include E3D for designing, Aveva Outfitting, Aveva Hull Design, Point Cloud Manager for workflow design and optimization, Aveva ERM for project management, and Unified Operations Centre for operation simulations. (Aveva , 2023)

3) NAPA - INTEGRATED MARINE SOLUTIONS

NAPA is a renowned company in the marine industry offering software solutions for ship design. NAPA provides a wide range of software solutions for ship operations and maintenance. These include the Hydrostatics & Stability Module, the Hydrodynamics Module, Hull Form Design, and Structural Design Module. In addition, NAPA specializes in naval architecture software that includes the following: real-time ship stability and safety, data logging and monitoring, performance optimization and analysing fleet's status. This includes the NAPA Fleet Intelligence solution, ClassNK-NAPA Green solution, NAPA Voyage Optimization Solution, the NAPA Loading Computer solution, and the NAPA Emergency Logger. (NAPA, 2023)

4) CADMATIC

Cadmatic is an engineering solutions provider for offering software packages across various industries. Specifically for marine industry, Cadmatic offers software for the design of ships and offshore structures & related project information management. Design aspects covered by NAPA include hull & structural design, outfitting & piping design, electrical & automation, and information management. Cadmatic even worked with NAPA to integrate many features and ensure cross-platform functionality. As an integrated maritime solution, all aspects of the project can be tracked, and project phases can be recorded right from the design stage until eventual hand-over to the client. However, Cadmatic does not offer modules for stability calculations or powering calculations and come with limited programming capabilities. (Cadmatic- Ship Design, 2023)

5) ANSYS

Ansys is a software provider which offers a diverse range of programs for engineering applications. Ansys Workbench offers a group of modules that can be used for Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), Thermodynamic Analysis, Structural Strength Tests and Hydrodynamic Response Analysis, among others. The most widely-used module is ANSYS Structural, which is used for finite element analysis. Naval architects use Ansys Structural to analyse the structural response under a specific load. This includes loads such as hydrostatic and hydrodynamic pressures, slamming, green water loading, and more. ANSYS also offers Fluent which can be used for CFD and AQWA which can be used for offshore hydrodynamics analysis. ANSYS Workbench offers parametric design optimization between different modules. This feature allows users to create a large number of virtual prototypes than be tested using different modules to determine the best solution. (Ansys - products and services, 2023)

6) RHINOCEROS 3D

Rhino3D, developed by Robert McNeel & Associates, is a CAD software for 3D modelling. Unlike other CAD programs, Rhino3D uses freeform surfaces instead of polygon meshes, allowing users to draw hulls within the boundaries of the NURBS models. In addition to its strong surface modelling capabilities, Rhino also provides users with a visual programming language called Grasshopper, as well as C++ and Python programming capabilities. Among the software discussed in this section, Rhino stands out for its extensive customizability in terms of parameterization and automation. With the help of the built-in programming modules,

Rhino models can be tested for hydrostatics and resistance estimation. (Rhino -3D modelling, 2023)

Table 1 provide an overview of the software discussed above and their supported capabilities.

Table 1 Design software Capabilities Summarized

Ship Design Software	Hull Design	Structural Design	Stability Calculation	Powering Calculation	Automation Capability
Maxsurf	✓	✓	✓	✓	✗
Aveva Marine	✓	✓	✗	✗	✗
NAPA	✓	✓	✓	✓	✗
Cadmatic	✓	✓	✗	✗	✗
ANSYS	✗	✗	✓	✓	✓
Rhinoceros 3D	✓	✓	✗	✗	✓

Table 1 summarises the various design software discussed in the previous section. Dedicated marine software like Maxsurf and NAPA were seen to provide specific modules for different aspects of ship design but were found to lack sufficient programming capabilities for effective automation of the design process. Among the software discussed in this section, Ansys and Rhino stood out for their in-built parametrization capabilities, which will be further explored.

Ansys is an engineering and simulation software that provides different modules for a variety of engineering analysis such thermodynamics, fluid motion, structural analysis, optics and so on. Ansys is not a dedicated marine design software but provides a number of different modules that can be used for marine engineering analysis and simulation. Some examples are Ansys Structural module for FEA, Fluent for CFD simulations and AQWA for offshore hydrodynamic analysis and motion response. Ansys brings together, its different modules under a common environment called Ansys Workbench that allows different modules to interact with each other and transfer inter disciplinary data. Workbench also enables users to define design parameters explicitly to create different versions of the same model which can be analysed using its different modules.

However, it should be noted that while Ansys allows parametric design of models, it lacks high degree of automation within the Workbench environment. It does not provide a built-in programming interface that the users can utilize for more customizability, which limits the degree of process automation that can be achieved from the software. Another limitation of Ansys lies in its 3D modelling modules. ANSYS provides two different 3D modelling modules: the older Design Modeller, and the newer Space Claim. While it should be noted that ANSYS has made significant improvements in Space Claim, it is not specifically designed for marine design and lacks many tools that are basic in other design software.

Rhino is a powerful 3D modelling program that is widely used in the ship design industry. Rhino has numerous tools that are specifically designed for surface generation which makes which makes it particularly suitable for hullform design. Rhino is particularly a favourite

among Naval Architects because of the high degree of flexibility in surface generation. Grasshopper is a plugin for Rhino that allows for parametric modelling and programming by leveraging the build-in functions available in Rhino. It is a visual programming language that uses represents functions and code snippets as graphical icons rather than text, making it very user-friendly and easy to use, even for those with no programming experience. Even though Rhino does not provide dedicated stability modules for stability or resistance estimation like Maxsurf or NAPA, the Grasshopper plugin that comes with Rhino can be used for creating these modules and therefore comes overcomes this disadvantage. Moreover, Rhino also comes with dedicated programming interface using Python called 'Rhino Script' and C++ which provides an extra degree of flexibility during modelling.

Due to its high level of customizability, Rhino is chosen as the preferred software for automating concept design in the following sections of the thesis.

2.7 SCOPE OF DESIGN AUTOMATION TOOL

The previous sections described the possibility of automating various concept design tasks and the preferred application for implementation. This information can be directly translated to the functionalities of the automation tool that will be developed and are listed below as follows:

Hull Form Generator - The program at its very core should be able to take a set of input parameters and generate an initial hull form for a ship. The user will be able to modify this hull form by changing the main dimension inputs, which would in real-time modify the dimensions of the hullform. The program could also be used to calculate a set of initial hydrostatics and form coefficients of the designed hullform, so that designers can make informed decision as to whether to continue with the design. An added advantage of using Rhino as a design platform is that, it also allow users to export the hull form as a 3D model that can be used in other programs for rendering, animation and other analyses.

Structural Scantling Calculation - The program shall also be able to calculate the scantling requirements for a ship based on its design parameters according to specific rules and standards; for example, design satisfying structural design rules laid down by classification societies such as DNV or according to international standards such as CSR (Common Structural Rules for Bulk Carriers and Oil Tankers-IACS). Structural design module considers factors such as frame spacing, span and spacing of stiffeners, and environmental loads to calculate the thickness of shell plating, and corresponding size of stiffeners attached to the plating. The program should also be capable of generating a report with details of scantling calculated, dimensions of stiffener profile and also the total weight of the structure that can serve as an input to stability calculation later on. It could also provide information about how much steel is needed for each part of the ship which can be used by the shipyard for an initial cost estimation and budgeting.

Stability Calculation - The program will also have a module for stability calculations based on intact stability requirements laid down by IMO. The calculations will mainly include hydrostatics for different waterline, estimating the floating draft corresponding to the total weight, and GZ calculation with build in rule check against relevant criteria. This module shall a clear picture of how stable the ship will be under different loading conditions and help ensure the vessel is seaworthy enough for its intended use.

Resistance and Powering - The program will also contain a module which calculates the total resistance and installed power requirement for a specific floating draft and service speed. The calculations will be based off on empirical formula for resistance estimation and will help provide the designer with a good idea about the power requirements for the vessel and make estimates about total operating costs.

The scope of the concept design automation tool will be to automate the hull modelling, structural design, stability analysis and resistance estimation against relevant design criteria. The tool also aims to provide a complete concept design at the end of each iteration, which can be modified and evaluated by changing simple main parameters. Figure 8 provides an illustration of scope of the design automation tool, showcasing the functionalities of each module.

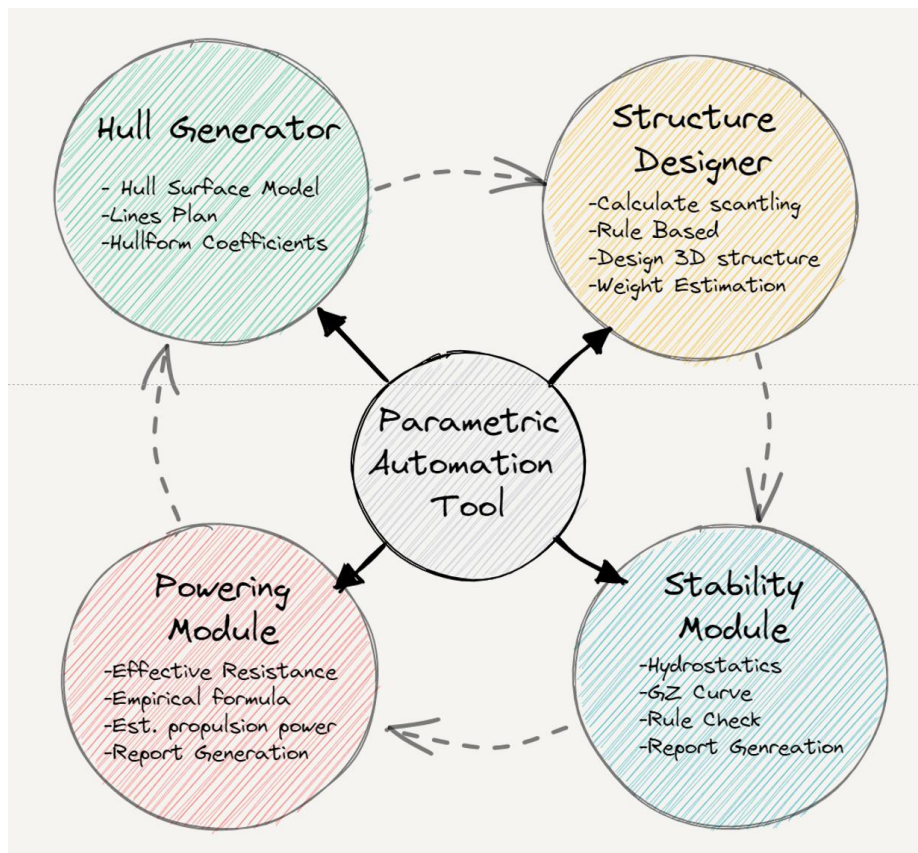


Figure 8 Functional modules of the proposed design automation tool.

3. METHODOLOGY

In the previous chapter we looked at various design tasks that are required to be carried out as a new design is being conceived. We have also looked at the ease of implementation of these tasks and their limitations. In this chapter, we try to establish a logical workflow for automating conceptual design tasks discussed in the previous sections. A generalized methodology will be investigated in this report and a case study which shows the implementation of the developed methodology in a 3D model-based programming language will be showcased in later sections, which shall be demonstrated with a case study.

3.1 ASSUMPTIONS AND LIMITATIONS

The methodology discussed above is implemented in Rhino using an integrated programming module called Grasshopper. Grasshopper is a visual programming language that provides the user to programmatical control over design elements for parametric modelling and design space exploration. The methodology covered and its implementation using Grasshopper has a few limitations as listed below:

LIMITATIONS

- **Design Template** – The application develops designs based on a certain hullform template selected by the user based on ship type. For example, selecting the ship type as ‘container carrier’ would provide the user with a starting hull shape which can be parametrically adjusted to the required main dimensions. Importing hullform from external sources is not supported in the present version.
- **Structural Analysis Type** – Structural scantling calculations carried out by the software covers local and global strength criteria as specified by DNV-RU-Ship. Fatigue and Buckling analysis of the vessel using the selected stiffeners are not included in the application.
- **Load Selection** – Loads selected for scantling calculation is limited to the static and dynamic loads from environment and liquids contained in tanks. Specification of an external load from deck cargo, or additional equipment coming onboard the vessel is presently not included in the software.
- **Stiffener Profiles** – The current version, automatically calculates the sizing of the stiffener profiles based on the shape specified by the user. Providing custom stiffener size input is not possible through the UI. Custom profiles can however be added by defining them with appropriate properties in the stiffener database.
- **Detailed Structural Design** – The present version of the program calculates and draws primary and secondary stiffening members for all plate panels defined in the program. However, structural details like bracket connections, welding scallops and lightening holes in brackets are not modelled. This will be implemented in the later versions. The difference in total weight due to these components are accounted in the weight calculation.

- **Stability Calculation** – Stability estimation of the vessel designs are limited to Intact stability calculations based on IMO Code for Intact Stability (MSC.267(58)). Damage Stability calculations for the designs are not included in the scope in this thesis.

ASSUMPTIONS

- **Structural Scantling Approval** – Structural scantlings for each plate panel is selected from the stiffener database such that it satisfies local strength requirements provided in DNV-RU-SHIP Pt.3 Ch.6 and global girder strength requirements as per DNV-RU-SHIP Pt.3 Ch.5. Rules for structural design from other classification societies are not included.
- **Stability Requirements** – Ship is assumed to be stable if it satisfies IMO Stability Requirements (Resolution MSC.267(85))

3.2 RULES AND APPROVAL

Before the starting the design process, it is important to lay down the rules and criteria against which structural strength and stability of the vessel will be compared against to be deemed approved. Only those designs that satisfy the requirements of the selected rules will be considered as ‘approved’ for further consideration. Rules selected as the baseline for design shall be generally accepted in the shipbuilding industry such as those from a classification society such DNV, LR, ABS etc or an international accredited organization such as International Maritime Organization (IMO) or International Standards Organisation (ISO).

The rules that are incorporated into the program are divided into different groups (Fig.9). These are primarily concerned with the structural strength and stability of the vessel. Structural design rules are based on DNV Rules for classification of ships (Part 3- Chapters 1 to 6) and Stability requirements are adopted from IMO Code for Intact Stability (MSC.267(58)). General equations and thumb rules used in ship design are also included in the program.

STRUCTURAL DESIGN RULES

Primarily, structural design rules play a vital role in establishing a framework that prioritizes the safety of both the ship and its crew. Ship operates in an unpredictable marine environment and are subjected to numerous different external and internal loads. The structural design of the vessel must be sound such that the vessel does not take damage during its normal operation. Damage to the ship structure also puts the safety of the crew and cargo at risk, therefore, it is important to check the strength of ship structural elements against possible loads to ensure safety. This where structural design rules and guidelines show their relevance. These design rules help designers accurately assess the external loads acting on the vessel, selecting suitable structural scantlings, and designing structural arrangements for different parts of the vessel capable of enduring internal and external forces on the vessel during operation. By adhering to these rules, naval architects can mitigate the risks associated with structural failures, collisions, and capsizing.

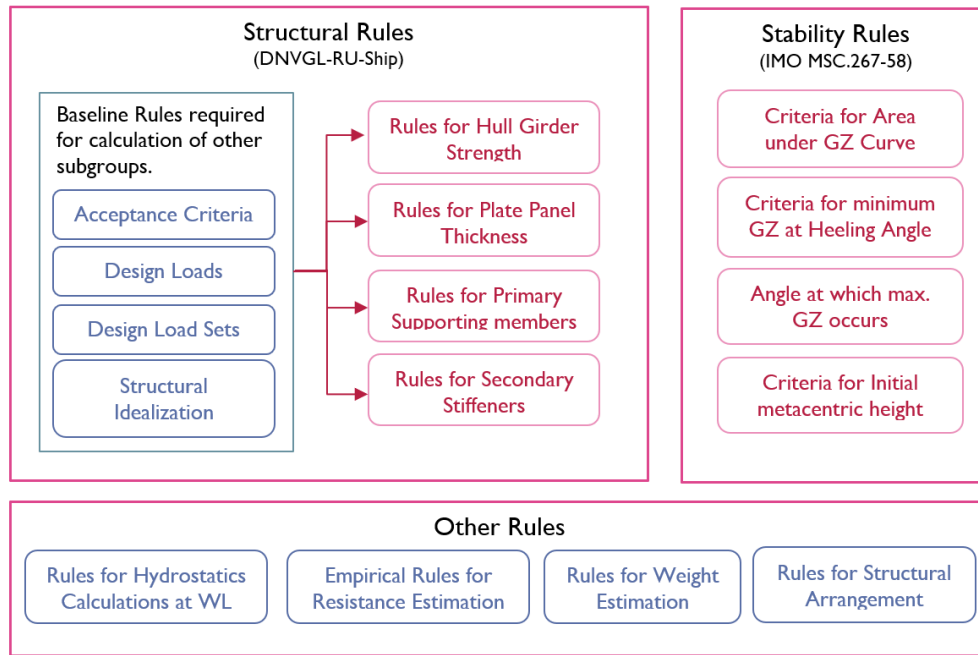


Figure 9 Rules and Criteria for Design Approval

Structural strength rules adopted in the program is based on DNV Rules for Classification of Ships (DNV, Rules for Classification: Ships (RU-Ship), 2022). DNV is a leading independent international organization that offers services for managing risks, quality assurance, and certification across multiple industries, including the maritime sector. DNV also offers a comprehensive set of rules for design and construction of ships. These rules cover a wide range of aspects including materials, structural arrangements, load calculations, and safety considerations which are elaborated in this section.

Design Loads - DNV rules as indicated in (DNV, Rules for Classification: Ships (RU-Ship), 2022) provide comprehensive guidelines for calculating and applying various loads that ships are subjected to during their lifetime. DNV considers a multitude of factors, including environmental conditions, operational profiles, and regulatory requirements, to determine the design loads that a ship must withstand. This encompasses dynamic loads from waves, wind, and other hydrodynamic forces, as well as static loads from cargo, equipment, and machinery. By working through design loads section, it is possible to determine the loads experienced by different plate panels of the vessel such as bottom plates, decks etc along the length of the vessel. These are vital information for calculation of plate thickness and scantling at each location.

Acceptance Criteria and Design Load Sets – Each plate panel in the ship experiences a combination of the design loads mentioned above. For example, the bottom plate of ship sailing, experiences a combination of Static pressure, wave pressure and dynamic pressure from waves. Furthermore, the direction of the incoming wave also exerts an influence on the loads experienced by panel at each location. These combinations of loads are called design load sets and these are specific for different plate panels such as external shell, superstructure sides, exposed decks etc. Acceptance criteria mainly deal with which design load sets are to be used for calculation such that the scantling element is deemed accepted.

Structural idealization – Structural idealization deal with simplifying the complex geometry of a ship's structure into a more manageable representation, allowing for efficient analysis and use in design calculations. For practical purposes, bulb profile can be approximated to an equivalent angle bar for calculations following the criteria stated in the rulebook. (DNV, Rules for Classification: Ships (RU-Ship), 2022)

Hull Girder Loads – Hull girder strength is a critical aspect in establishing the strength of a ship structure. The ship shape typically being long and slender are approximated to girders to estimate the bending and shear properties. Ships during voyage experience hogging and sagging loads from waves which induces high vertical stresses and bending moments in the midship region. Working through the hull girder loads section (chapter 4) helps in determining the total shear force and bending moments at different sections in both still water and wave conditions. These are required to be calculated at:

- at each transverse bulkhead in the cargo area
- at the middle of cargo compartments
- at the collision bulkhead
- at the engine room forward bulkhead
- at the mid-point between the forward and aft engine room bulkheads

Calculated bending moment and shear force values are plotted along the length of the curve and compared against the baseline values from rule. Typical Shear force and bending moment diagram is illustrated below in Fig 10.

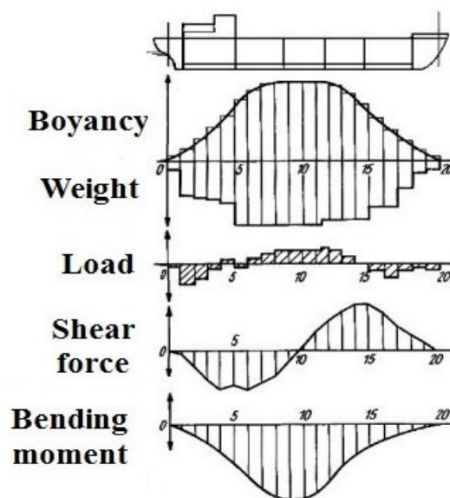


Figure 10 Bending Moment and Shear Force Diagram (Andi Ardiantia, 2018)

Rules for Plate Thickness – these rules meticulously outline the requirements for selecting the appropriate plate thickness for each location along on the vessel such as keel, bilge, side shell etc. These are based on various factors such as yield strength of the steel plate, dimensions of the unsupported plate panel and the load combinations acting on the plate during operation. The calculated thickness is also provided a corrosion addition based on the location. The final calculated thickness is then rounded up to commercially available plate thickness used in shipbuilding.

Rules for Primary Supporting Members - Primary supporting members (PSM) on a ship are the structural components that carry and distribute the external loads throughout the vessel's structure. They provide essential support and stability to the ship's overall framework of the vessel. Some examples of primary supporting members are bottom floors and girders, deck girders and web frames. DNV Rules provide the requirements for minimum section modulus of PSM at different locations. These are governed by factors such as span and spacing of the members, load expected to be carried by the member, and the yield strength of the material along with other empirical coefficients defined in the chapter. (DNV, Rules for Classification: Ships (RU-Ship), 2022)

Rules for Secondary Stiffeners – Secondary supporting members or often called stiffeners are structural components that provide additional support and reinforcement to the primary supporting members. While primary supporting members, such as girders, floors and web frames, bear the primary loads and ensure overall structural integrity, stiffeners run between PSM ensuring that the unsupported plate panel is adequately stiffened. Examples of stiffeners are bottom and side longitudinal, bulkhead vertical stiffeners etc. Selection of stiffener sizes are governed by various factors but primarily depend on the span and spacing of the stiffener, the design load set and material properties of the stiffener. Based on these values, DNV provides rules for calculating the total section modulus and minimum web thickness of the stiffener which can be used for selecting an appropriate profile of the required shape.

STABILITY RULES

The importance of ship stability in maritime operations cannot be overstated. A ship is said to be stable if it can maintain its equilibrium and resist capsizing under normal expected operation conditions and during extreme weather conditions that it might have to navigate through. Stability of the vessel is vital for ensuring the safety of the crew, passengers, and cargo onboard the vessel.

Ship stability can be broadly classified into intact stability and damage stability:

- a) **Intact stability** refers to a ship's ability to resist capsizing and maintain its equilibrium under normal operating conditions. It involves analysing the ship's stability characteristics when fully intact, considering factors such as weight distribution, metacentric height, and righting moments. The goal of intact stability assessment is to ensure that the ship remains stable and safe during regular operations, even when subjected to external forces like waves, wind, and changes in loading conditions.
- b) **Damage stability**, on the other hand, focuses on a ship's ability to withstand flooding or damage caused by accidents, collisions, or hull breaches. It involves assessing the ship's ability to remain afloat and maintain sufficient stability even when compartments are flooded or damaged.

Damage stability calculations are not included in the scope of this thesis. The following sections will outline the intact stability requirements carried out in the application. A ship can be considered to be stable, if it meets the stability criteria and comply with regulatory requirements set by classification societies and maritime authorities. These criteria define minimum stability standards based on factors such as ship type, size, intended service, and operational conditions. The International Maritime Organization (IMO) plays a crucial role in

developing and implementing regulations to ensure the safety and stability of ships at sea. Among these regulations, the IMO Code for Intact Stability (MSC.267(58)) stands as a fundamental framework governing the intact stability requirements for various types of vessels.

The MSC.267(58) Code, also known as the International Maritime Organization (IMO) Code for Intact Stability, is a regulatory framework that establishes requirements and guidelines for ensuring the intact stability of various types of vessels. It outlines minimum stability requirements to ensure that vessels can withstand external forces and maintain equilibrium under normal and extreme operating conditions.

The intact stability criteria according to (IMO, 2008) are specified as follows:

1. **Area Under the Righting Lever Curve:** The code specifies allowable limits for the area under the righting lever curve. This parameter reflects the ship's overall stability and its ability to resist heeling forces.

“ The area under the righting lever curve (GZ curve) shall not be less than 0.055 metre-radians up to $\varphi = 30^\circ$ angle of heel and not less than 0.09 metre-radians up to $\varphi = 40^\circ$ or the angle of down-flooding φ_f if this angle is less than 40° . Additionally, the area under the righting lever curve (GZ curve) between the angles of heel of 30° and 40° or between 30° and φ_r , if this angle is less than 40° , shall not be less than 0.03 metre-radians. “

2. **Righting Lever Curves:** The code provides guidelines for establishing minimum required righting lever curves. These curves depict the ship's ability to resist capsizing and recover its upright position when subjected to external forces.

“ The righting lever GZ shall be at least 0.2 m at an angle of heel equal to or greater than 30° “

3. **Angle of Maximum Stability:** The code defines the angle at which a ship's stability reaches its maximum value, known as the angle of maximum stability. This parameter is crucial in assessing a ship's stability characteristics and ensuring safe operations.

“The maximum righting lever shall occur at an angle of heel not less than 25° . If this is not practicable, alternative criteria, based on an equivalent level of safety, may be applied subject to the approval of the Administration. “

4. **Initial Metacentric Height:** The code defines the initial metacentric height required for the vessel.

“The initial metacentric height G_{Mo} shall not be less than 0.15 m. “

These criteria can be better understood by representation on the righting lever curve of the vessel (Fig 11). Compliance with the MSC.267(58) Code is mandatory for ships falling within its scope and it is enforced by the local maritime authority. Therefore, the program must be

able to validate the stability of the generated designs against the IMO Stability code to ensure its stability in the different loading conditions for which it is designed for.

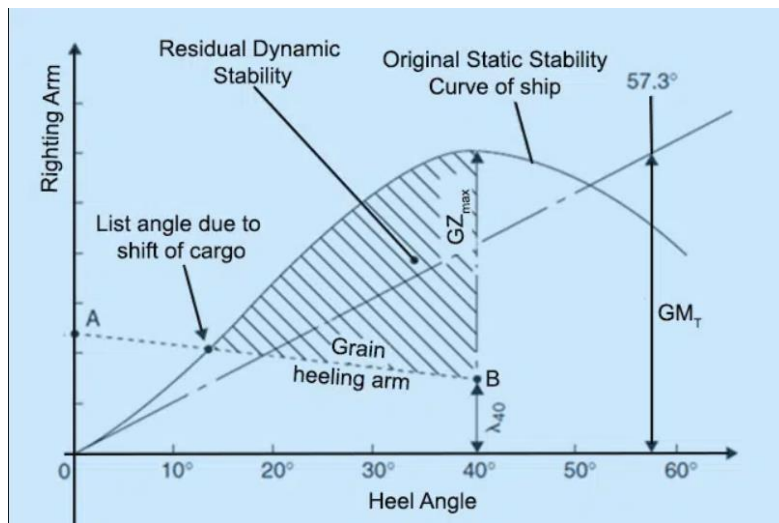


Figure 11 Righting Lever Curve (IMO, 2008)

OTHER RULES

Aside from structural design and stability requirements of the vessel, the program also calculates various other parameters of the design such as the hydrostatics of the vessel, total light weight due to the generated steel panels etc. These are not governed by rules laid down by a maritime authority or a regulatory body, but rather based on general engineering equations. These are described in detail in the coming sections.

3.3 DATABASE

The design tool shall maintain a database of different steel profiles with their associated geometrical properties. As discussed in the previous sections, the application checks the required section modulus of the stiffener element based on DNV Rules. Once the minimum required section modulus is calculated, the program automatically selects the stiffener of the required profile shape having a combined section modulus greater than the calculated minimum. The database maintains a log of different profile shapes. The profile shapes that are typically used in shipbuilding are:

- **Flat Bars (FB):** These are flat, rectangular steel plates typically used as ordinary stiffeners onboard ships. These plates come in various thicknesses and widths, depending on the specific application and structural requirements.
- **Bulb Flats (BP):** Bulb flats are special steel profiles with a unique bulb-shaped cross-section. They are primarily used for the construction of ship's longitudinal stiffeners in areas as such as bottom, inner bottom, sides etc. Bulb flats provide excellent strength and weight distribution characteristics.

- **Angle Bars (EL/UL):** Angle bars, also referred to as L-sections, are commonly used in shipbuilding for various applications, including brackets, stiffeners, and supporting members. They are often used as ordinary stiffeners on ships. These are available in different standards as equal angles have the same dimensions for the web and face plate, and unequal angle bars having different lengths for web and face plate.
- **T-sections (T):** T-sections, also known as tee sections, have a T-shaped cross-section. They are commonly used for primary structural members, including web framing, deck beams, girders and reinforcements.

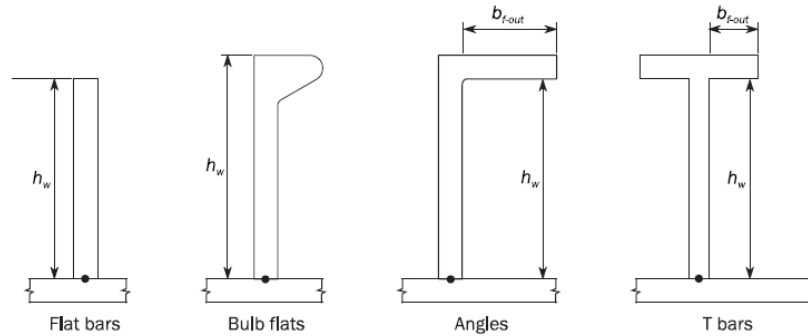


Figure 12 Stiffener Profiles (DNV, Rules for Classification: Ships (RU-Ship), 2022)

The stiffener profiles defined in the database are based on DIN standards. Aside from standard profiles from DIN standards, custom profiles can also be defined in the database in order to account for large section modulus requirement for primary supporting members. In such cases, custom built sections are used instead of standard profiles. The profiles are sorted based on their shape and geometric properties of each profile such as sectional area, height of neutral axis from base and moment of inertia of the section are also recorded along with each entry. Table 2 shows the data recorded for tee-sections from DIN Standard.

Table 2 Tee Section Database

TEE BARS		DIN 1025-5:1994					
Section Name	Height	Breadth	Web Thk	Fl Thk	Sectional	Moment	CG
	mm	mm	mm	mm	Area	of Inertia	Position
1/2 IPE 140	70.00	73.00	4.70	6.90	8.21	33.00	5.38
1/2 IPE 160	80.00	82.00	5.00	7.40	10.00	52.90	6.16
1/2 IPE 180	90.00	91.00	5.30	8.00	12.00	80.30	6.95
1/2 IPE 200	100.00	100.00	5.60	8.50	14.20	117.00	7.75
1/2 IPE 220	110.00	110.00	5.90	9.20	16.70	165.00	8.55
1/2 IPE 240	120.00	120.00	6.20	9.80	19.60	227.00	9.37
1/2 IPE 270	135.00	135.00	6.60	10.20	23.00	346.00	10.53
1/2 IPE 300	150.00	150.00	7.10	10.70	26.90	509.00	11.68
1/2 IPE 330	165.00	160.00	7.50	11.50	31.30	717.00	12.85
1/2 IPE 360	180.00	170.00	8.00	12.70	36.40	992.00	14.01
1/2 IPE 400	200.00	180.00	8.60	13.50	42.20	1450.00	15.48

3.4 METHOD OVERVIEW

As indicated in the previous section, the concept design automation tool can be seen to contain 4 basic functional blocks: Hull generator, scantling calculator, stability module and the powering module. Information passes through successive blocks in a sequential manner for arriving at the final design. If the project team finds that there is room for improvement during the decision-making process, the process can be restarted from initial parameters and the design iterated again. This process helps to easily create virtual prototypes while still in the concept phase. It allows users to explore various design options, so that the best design option can be converged upon. Figure 13 provides an illustration of the proposed workflow methodology.

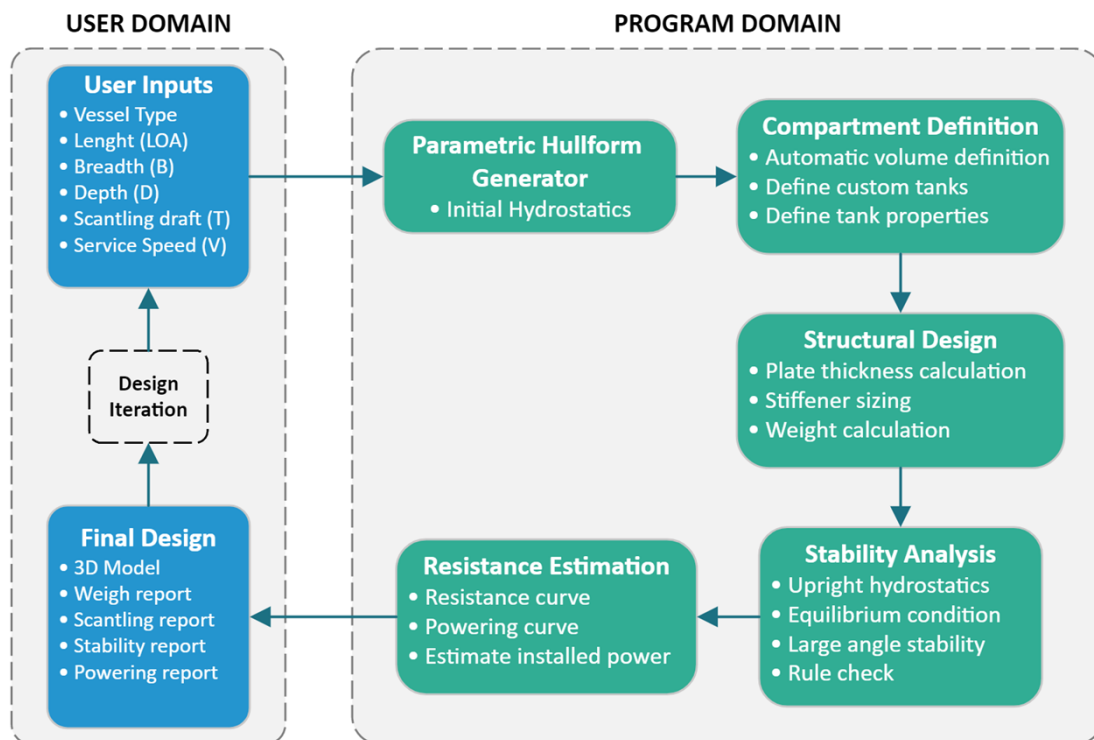


Figure 13 Methodology workflow diagram

The design process begins with definition of the basic parameters of the project by designer. These are namely length overall, maximum beam, hull depth, vessel type, expected draft and service speed of the vessel. These data are typically provided by the client through tender / project specifications. The user inputs in this stage will be used for generating the hullform.

Hullform generator uses the main dimension information provided by the user as input parameters to adjust the basic hullform template to the required scale. The module is provided with default hull templates for different types of vessels. The program selects the corresponding basic hull template based on the vessel type input from the user. This stage will also calculate various initial hydrostatic parameters along with form coefficients to give the designer an early idea about the hullform. If the results are not satisfactory, the hullform can be parametrically updated by changing any of the input parameters.

Once the hull surface is generated, the user manually defines the bulkheads, tanks and other compartment subdivisions in the hullform model. These inputs are provided to the scantling calculator module which extracts relevant information from the model and positions scantlings in the model at appropriate locations. The scantling calculation is carried out as per DNV rules for ship classification (DNV, Rules for Classification: Ships (RU-Ship), 2022). As the calculation is completed, the hull model is updated with 3D representation of the calculated scantlings. The module also calculates the total weight of the ship structure at this stage along with the position of the centre of gravity. The output of scantling calculator is the detailed hull model and the total weight of the hull structure. Additional weight components such as weights of superstructure, machinery, equipment, and deadweight can be provided by the user to define a loading condition.

The hull surface model along with the weight calculated within the loading condition is used by the stability module for carrying out stability calculations. The stability module would calculate the ship loadcase to estimate the hydrostatic particulars of the floating conditions and also check the righting lever curve against IMO criteria for intact stability. Damage stability calculation is excluded from the scope of the thesis. The results of stability calculation is compared against the pass-criteria defined in IMO regulation (IMO, 2008). In case of failure, the user is prompted to update either the hullform or weights to improve stability.

Stability calculation is followed by powering calculation which uses empirical methods to determine the total resistance acting on the hull surface for operation at service speed. The resistance values that are calculated are used for determining the total installed power of the vessel. The module takes as input the hullform, floating draft calculated by the stability module, and service speed of the vessel to calculate the total resistance and corresponding propulsive power requirement for the design. If the total estimated power is higher than what is expected, the model can always be revised by updating the hullform, service speed or draft.

If the results from structure, stability and powering modules are found to be satisfactory, the design iteration is marked as completed and the output is saved. The output is a 3D model in Rhino with complete structural scantlings, weight report, stability analysis report and resistance curves. More iterations can be done by changing the input parameters to the tool, to create a number of other suitable design options which can be compared and contrasted against each other to find the best possible solution for the specific project requirement.

Table 3 provides a summary of the tasks done by each functional block and their expected outcomes.

Table 3 Technical Tasks

Block Description	Tasks	Outcome
Hull Form Generator	<ul style="list-style-type: none"> • Receive the vessel’s main dimension data. • Scale the design template to required dimension. • Calculate hull coefficients and basic hydrostatics based on the generated model. 	<ul style="list-style-type: none"> • Hull model • Hullform parameters
Compartment Definition	<ul style="list-style-type: none"> • Allow definition of bulkhead, tanks and compartments in the hullform. • Automatically identify closed volumes. • Define tank filling, and properties. 	<ul style="list-style-type: none"> • Compartment information
Scantling Calculator	<ul style="list-style-type: none"> • Receives hullform with compartments. • Calculate structural scantling based on DNV rules. • Update 3D model with calculated scantling • Calculate the weight of new structure 	<ul style="list-style-type: none"> • 3D Model with Scantlings • Lightship weight and centroid
Stability Module	<ul style="list-style-type: none"> • Receive loading conditions from user. • Receive weight and hull information from scantling calculator. • Calculate upright hydrostatics. • Estimate equilibrium condition. • Plot Righting lever curve and compare results with IMO criteria. 	<ul style="list-style-type: none"> • Preliminary intact stability report
Powering Calculation	<ul style="list-style-type: none"> • Receive hull surface, draft and speed of design. • Calculate resistance using empirical method. • Calculate total installed power from effective resistance value 	<ul style="list-style-type: none"> • Resistance and powering calculation report

3.5 PROGRAM MODULES

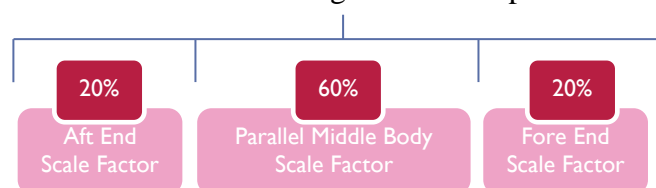
The workflow outlined in the previous section has been implemented in rhino using grasshopper programming interface. Each section in the workflow diagram is implemented as a programming block in grasshopper. Each of which take a certain number of inputs and return a corresponding output, that is either wired to subsequent blocks or provided to the user through GUI. The methodology for the calculations and definition of each block will be explained in the following sections. It should be noted that the grasshopper application has been developed by the author exclusively using grasshopper components. No reference has been made to previous works from others or external sources.

PARAMETRIC HULLFORM GENERATION

Each design process begins with the definition of hullform, which can be parametrically modified to fit the requirements for the specific project. Parametric hullform generation is implemented using a custom user defined module, which provides a versatile approach that allows for the creation of ship hull designs using input parameters such as length, breadth, and depth. These are the fundamental building blocks of the design process. By manipulating these key dimensions, it is possible to explore a wide range of hull configurations and optimize their performance for various objectives. Length determines the overall size of the vessel, while breadth influences stability and cargo capacity. Depth, on the other hand, affects the draft and buoyancy of the hull. By systematically varying these parameters, designers can generate a multitude of hullform variations, considering factors like hydrodynamic efficiency, stability requirements, and structural integrity. This parametric approach streamlines the design process, enabling the evaluation and comparison of multiple designs to identify the most suitable hullform for a given set of requirements.

The program offers users a selection of ship types to choose from. This includes general cargo vessels, container vessels, oil tankers, bulk carriers, offshore supply vessels, passenger vessels, and RORO vessels. Each ship type is associated with a preconfigured default hullform template. When a user specifies a particular ship type, the corresponding default hullform template is imported into the program based on their input. The imported hullform template's dimensions can be adjusted by the user, by providing length, breadth, and depth values as inputs. A scale factor is calculated for each parameter, considering both the user's input and the actual dimensions of the template. This allows the hullform to be scaled accurately to the desired size. Additionally, the hullform template is divided into three sections: aft end, parallel middle body, and fore end. During length scaling, each of these sections is scaled non-uniformly to accommodate increased cargo capacity with longer lengths, prioritizing more on the parallel middle body of the vessel.

$$\text{Length Scale Factor} = \frac{\text{Length overall provided by user}}{\text{Actual Length of the template}}$$



INITIAL HYDROSTATIC CALCULATIONS

Hydrostatic calculations play a vital role during the concept design stage of ship design, providing valuable insights into the vessel's stability, buoyancy, and overall performance characteristics. By accurately analysing the hydrostatics early in the design process, it is possible to make informed decisions that shape the ship's fundamental design features. Accurate hydrostatic calculations lay the foundation for a well-balanced, stable, and seaworthy ship that meets operational objectives and regulatory standards. Therefore, it is important to consider the hydrostatic and hullform parameters of the vessel early on in the design phase.

Initial hydrostatics and hullform parameters are determined using a separate module in grasshopper which takes as inputs, the hullform of the required dimensions and the scantling draft of the vessel. Hydrostatics are calculated for the corresponding scantling draft provided as input. Various hydrostatic parameters calculated by the program are as follows:

- Rule Length (L) - The rule length L is the distance, in m, measured on the waterline at the scantling draught T_{SC} from the forward side of the stem to the centre of the rudder stock. L shall not be less than 96% and need not exceed 97% of the extreme length on the waterline at the scantling draught TSC. (DNV, Rules for Classification: Ships (RU-Ship), 2022)
- Length between Perpendiculars (L_{BP}) - The length between perpendiculars (L_{BP}) of a vessel refers to the horizontal distance between the forward and aft perpendiculars.
- Length of Waterline (L_{WL}) – Length of Waterline refers to the horizontal distance measured along the waterline of the vessel, where the ship's hull makes contact with the water at floating draft. It is an important parameter for the design of the vessel's design and hydrostatic parameters.
- Volume Displacement (∇) – The volume displacement of a vessel refers to the total volume of water displaced by the submerged portion of the ship's hull when it is floating or in equilibrium. The unit of measurement is cubic meters.
- Moulded Displacement (Δ) – Moulded displacement, in tons, corresponds to the underwater volume of the ship, at a draught, in seawater with a density of 1.025 t/m³. This represents the total weight of water that is displaced by the hullform at a specific floating draft.
- Longitudinal Center of Buoyancy (LCB) - LCB refers to the longitudinal location of the center of buoyancy, which represents the horizontal point along the ship's length where the buoyant force acts. It indicates the balance between the weight and buoyancy forces along the vessel's longitudinal axis. The position of the LCB affects the ship's stability, particularly in terms of longitudinal stability.
- Vertical Center of Buoyancy (KB) – KB is the height of the center of buoyancy above the baseline or keel. It is expressed in meters.
- Area of Waterplane (WPA) – the waterplane area as the name suggests, represents the area of the floating waterplane. It is required to determine the change in mean draft during loading and unloading of weights. It is expressed as square meters.
- Longitudinal Center of Flotation (LCF) – LCF refers to the longitudinal position of the center of flotation. The center of flotation is the point along the ship's length where the total underwater volume can be considered to act. It represents the balance between the submerged volume forward and aft of the LCF.

In addition to the hydrostatic parameters mentioned above, the program also calculates the following form coefficients. These coefficients serve as valuable indicators for estimating the ship's resistance, power requirements, and performance during sea voyages in the initial stages

of ship design. The following form coefficients are commonly utilized, and their definitions as per (DNV,2022) are provided below. It's important to note that these coefficients specifically apply to the submerged part of the hull.

- Block Coefficient (C_B) is a measure of the proportion between the volume of the submerged hull and the volume of a rectangular block with dimensions equal to the ship's length, breadth, and depth. It provides an indication of the ship's load-carrying capacity relative to other vessels of similar dimensions. The Block Coefficient varies depending on the type of ship, with values ranging from 0.45 for high-speed ships to 0.85 or higher for very large crude oil tankers. The calculation for the Block Coefficient is represented by the following equation:

$$C_B = \frac{\nabla}{LBT}$$

- Waterplane Area Coefficient (C_{WP}) evaluates the degree of completeness or fitness of the waterplane when the ship is afloat. It is determined by dividing the area of the waterplane (A_w) by the area of the rectangle that encloses it. Typical values for CWP typically fall within the range of 0.67 to 0.92.

$$C_w = \frac{A_w}{LB}$$

- Midship coefficient (C_M) characterizes the fullness of the midship section of a ship's hull. It is determined by comparing the area of the immersed midship section to the area of the circumscribing rectangle. For extremely sleek hulls, the C_M can be 0.75 or even lower. However, in the case of larger merchant vessels, the midship section typically features vertical flat sides and a flat bottom, deviating from a rectangle only due to rounded bilges. Consequently, their midship section coefficients fall within the range of 0.95 to 0.99.

$$C_M = \frac{A_M}{BT}$$

- Prismatic Coefficient (C_P) characterizes the sleekness of a ship's hull ends independently of the midship section. It is determined by comparing the volume of displacement to the volume of a prism with a cross-section resembling the immersed midship section and a length equivalent to the ship's overall length.

$$C_p = \frac{\nabla}{A_M L}$$

Within the Grasshopper software, the hydrostatic parameters mentioned above are calculated based on inputs provided by the user. These inputs include the hullform generated in a previous module and the user-specified scantling draft. To facilitate further calculations, the hullform is adjusted by trimming and capping it at a height equal to the scantling draft above the baseline. This creates a closed underwater volume that can be utilized for subsequent computations. The volume and mass displacement are determined by analysing this closed underwater volume. Additionally, the estimation of the centroid of this volume provides values for the Longitudinal Center of Buoyancy (LCB) and the Vertical Center of Buoyancy (KB) of the vessel. By extracting the surface that forms the upper boundary of the underwater volume, the floating waterplane is obtained, which can be utilized to calculate the waterplane area (A_{wp}) and the Longitudinal Center of Flotation (LCF). The distance corresponding to the midpoint of the

Length Between Perpendiculars (LBP) marks the midship section. Midship area value is obtained by computing the area of this section. The volume of displacement, midship area, waterplane area, and the main dimensions of the vessel are utilized to calculate various form coefficients. Implementation in grasshopper is represented using the following figure:

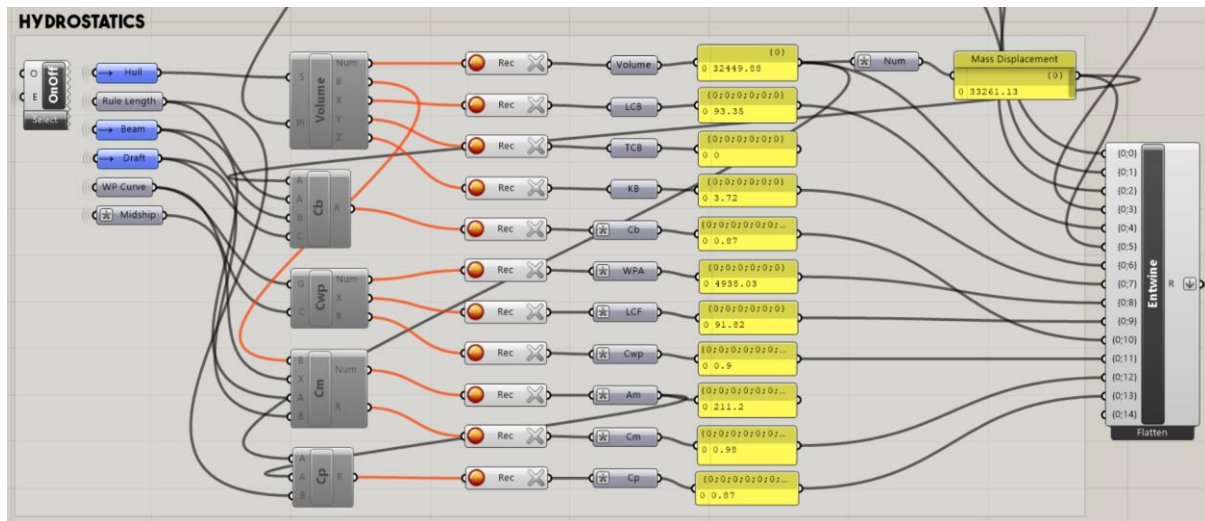


Figure 14 Hydrostatics calculation using Rhino Grasshopper

For each newly generated hullform, the primary dimensions of the vessel can be modified, and hydrostatic calculations can be performed. This iterative process allows for adjustments until a hullform is achieved that meets satisfactory hydrostatic values. Once this optimal hullform is obtained, it is saved and utilized for subsequent computations and analyses.

COMPARTMENT DEFINITION

This section deals with definition of structural components in the vessel which divides the ship into compartments. For further reference, tanks are those compartments which are used for carrying fluids. Compartments in ships play a crucial role in enhancing safety, structural integrity, and functionality. Compartments subdivide the vessel into cargo carrying space, machinery spaces, tanks and accommodation/control spaces.

One important feature of compartmentalization is the use of transverse watertight bulkheads. These vertical partitions extend from the ship's bottom to its main deck, dividing the interior space into separate compartments. Transverse watertight bulkheads provide structural strength and enhance the ship's ability to withstand flooding or damage. They restrict the spread of water in the event of a breach, thereby preserving the ship's stability and preventing excessive flooding. Certain default transverse watertight bulkheads such as aft peak, fore peak, cargo hold fore and aft bulkheads are provided as default with new design, the location of these can be modified by the user. Additional transverse bulkheads can be added by providing the location at which these need to be inserted. A transverse plane is added at the location specified by the user and trimmed using the hull model in order to generate transverse bulkheads. The newly generated bulkheads are sorted based on their longitudinal location and stored for further computation.

Another integral aspect of compartmentalization is the inclusion of wing tanks. Wing tanks are located outboard of the ship's hull and are positioned along the sides of the vessel. These tanks serve multiple purposes, such as improving damage stability and providing additional space for ballast or fuel storage. Wing tanks also contribute to reducing the ship's free surface effect, which can impact stability during operations. For the design templates, wing tanks are created between fore and aft cargo hold bulkheads. The vertical extend of the wing tanks are between double bottom and the main deck. The offset of wing tank from the centerline can be adjusted by the user to determine the position and overall capacity of the wing tanks.

The double bottom is a vital component of ship compartments, especially in larger vessels. It provides an additional layer of watertight compartments constructed beneath the cargo holds or spaces in the ship's bottom structure. The double bottom enhances the ship's longitudinal strength, increases buoyancy, and provides space for ballast water, fuel, or other necessary equipment. Double bottom tanks extend between fore and aft peak bulkheads. Height of double bottom tanks can be defined by the user.

Finally, the main deck of a ship is an essential structural component that serves as the uppermost continuous deck covering the hull. It provides a platform for various operations, including cargo handling, accommodation, and machinery placement. The main deck also contributes to the structural strength of the ship and plays a role in distributing loads across the hull. Figure 15 shows different structural components defined by the component definition module.

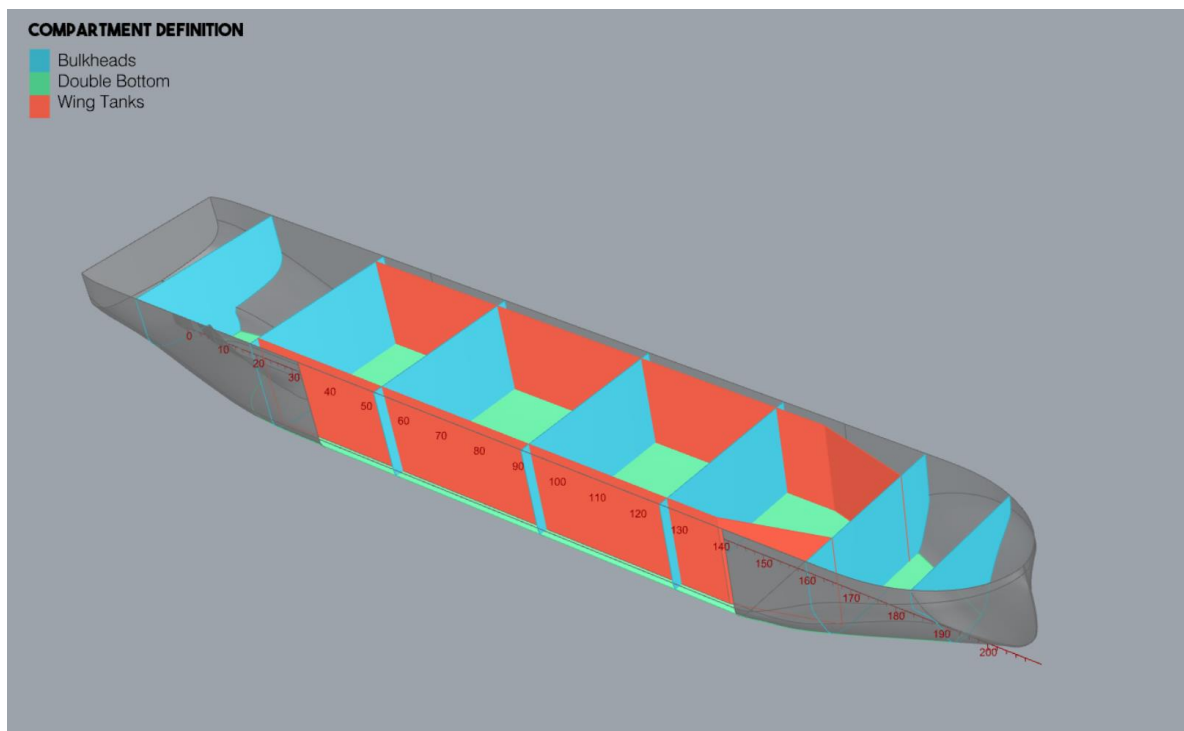


Figure 15 Compartment Definition Module Output

AUTOMATION VOLUME COMPUTATION AND TANK DEFINITIONS

After defining the bulkheads, double bottom, and main deck, the program includes an automated volume calculation tool to simplify the process of defining compartments and tanks for the user. The tool takes as inputs, the locations of previously defined partition elements (double bottom, wing tanks and main deck) and generates enclosed volumes automatically. These computed volumes can then be used for further analysis and design considerations. By automating the volume computation process, the program eliminates the need for manual calculations, saving valuable time and reducing the potential for error.

The process of volume computation involved in the program can be comprehensively explained through several sequential steps:

- In step 1, the program utilizes the generated hullform and main deck surface to construct a closed hull volume. By incorporating the shape of the hull and the main deck, the program defines the boundaries of the hull volume, enclosing the space within the ship's structure.
- Moving on to step 2, the software takes into account the positions of the previously defined transverse bulkheads. It proceeds to create rectangular boxes that extend between each pair of bulkheads, effectively spanning the designated spaces. The program then calculates the intersecting volumes resulting from the intersection of each box with the hullform. This step enables the determination of the hull volume between the bulkheads, considering the specific compartments and spaces within the ship.
- In step 3, the program further refines the volume computation process. It identifies and extracts the fore peak and aft peak tanks from the overall list of closed volumes. These tanks are distinct compartments located at the forward and aft ends of the ship, respectively. Subsequently, the program divides the remaining volume using the double bottom surface, generating double bottom tanks and overhead compartments.
- Lastly, the program focuses on the overhead compartments located between the cargo hold forward and aft bulkheads. These compartments are split using the wing tank surface, resulting in the creation of wing tanks and cargo hold spaces. This division accurately reflects the organization and functional allocation of compartments within the ship.

Throughout the process, the generated compartments are sorted based on their longitudinal position, ensuring logical and systematic arrangement. The resulting compartments are stored in brep format, which is a boundary representation format commonly used in computer-aided design (CAD) systems. This format enables further computations, analyses, and design-related tasks to be performed efficiently and effectively. Overall, the step-by-step volume computation process employed by the program ensures the accurate and comprehensive definition of compartments and tanks within the ship's structure. By utilizing the generated hullform, bulkhead positions, and other design elements, the program enables precise volume calculations, enhancing the overall integrity and functionality of the ship design program.

In addition to the volume computation, the application incorporates automatic sorting functionality for the wing tanks and double bottom tanks based on their intended use for

carrying fluids. These tanks are categorized separately from the remaining compartments, which can be utilized for carrying cargo, machinery, or other items based on the user's requirements. Furthermore, the program provides users with the flexibility to define names for each tank or compartment, allowing for clear identification and organization of the different spaces within the ship. The program also offers the user the option to specify the type of liquid that will be carried in each tank. By allowing the user to define the contents of the tanks, the program takes into account the specific requirements and characteristics associated with different types of fluids such as fluid density. This information is valuable for subsequent analyses and considerations, such as weight distribution, stability calculations, and operational planning. Figure 16 shows the workflow employed for automatic computation of compartments.

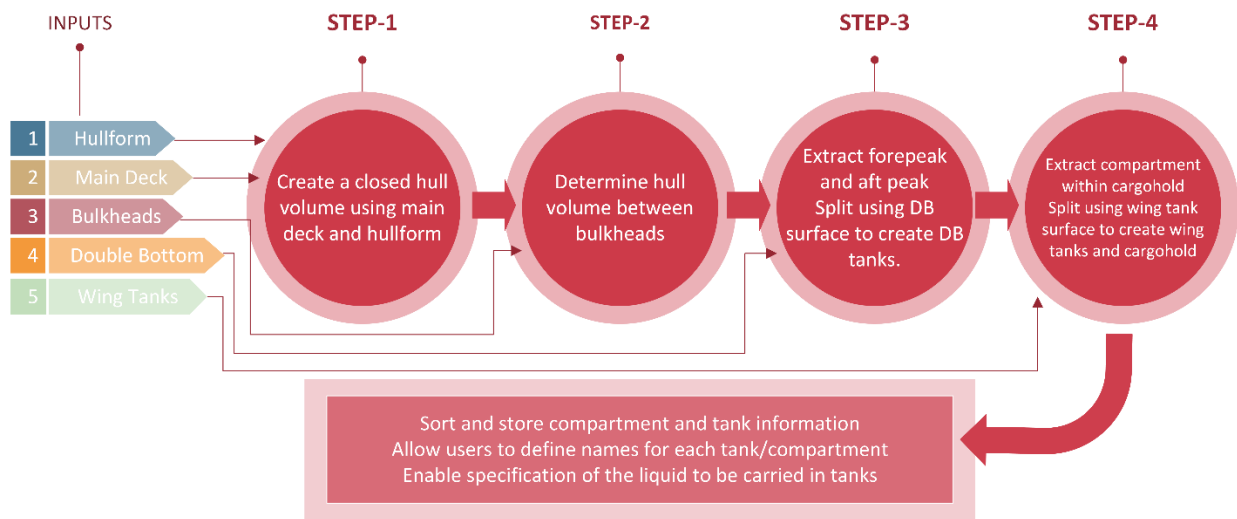


Figure 16 Automatic Compartment generation workflow

Additionally, the program offers users the flexibility to define custom tanks within the existing hullform. Users can specify the desired location and dimensions of these tanks using adjustable sliders, allowing for precise customization according to their requirements. The program ensures that tanks placed in intersecting positions with the hull are appropriately trimmed over the sides, aligning with the overall shape of the hullform. This feature enables users to create tailored tank configurations that cater to specific needs, such as additional storage or specialized functionality. By providing this option, the program empowers users to further refine the design and optimize the use of space within the ship's structure. Figure 18 shows custom tank definition using the application.

After the generation of compartments and tanks, the program presents the user with a dedicated window for further customization. Within this window, the user can conveniently assign names to each compartment or tank, facilitating easy identification and organization of the different spaces within the ship. Moreover, the program provides the user with the option to classify the volume as either a compartment or a tank, allowing for clear differentiation between storage areas and functional spaces. If the user designates the volume as a tank, the program offers an additional feature to specify the type of liquid stored within. By selecting the appropriate liquid from a predefined list or inputting a custom liquid, the user can accurately define the contents of the tank. Furthermore, the program displays the density of the selected liquid alongside the tank volume. Figure 18 provides the UI window for definition of tanks.

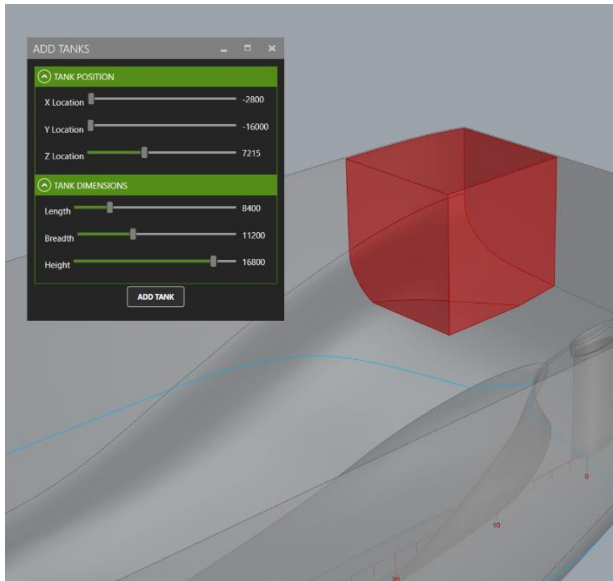


Figure 18 Custom Tank Definition

The image shows a software interface titled 'EDIT TANK PROPERTIES' displaying a table of tank definitions. The table has columns for SI, Name, Type, Fluid Type, Specific Gravity, and Volume m3. The data is as follows:

SI	Name	Type	Fluid Type	Specific Gravity	Volume m3
1	Aft Peak Tank	Tank	Water Ball	1.025	2343.27
2	SG Room	Comp	None	0.000	1142
3	Engine Room	Comp	None	0.000	6872.49
4	Cargo Hold FR40-70	Comp	None	0.000	6773.54
5	Cargo Hold FR71-100	Comp	None	0.000	7620.23
6	Cargo Hold FR101-130	Comp	None	0.000	6773.54
7	Cargo Hold FR131-170	Comp	None	0.000	6159.3
8	DB Tank 1P	Tank	Fuel Oil	0.943	3868.15
9	DB Tank 1S	Tank	Fuel Oil	0.943	219.31
10	Wing Tank 2P	Tank	Water Ball	1.025	555.57
11	Wing Tank 2S	Tank	Water Ball	1.025	629.3
12	Wing Tank 3P	Tank	Fresh Water	1.000	559.41
13	Wing Tank 3S	Tank	Fresh Water	1.000	517.5

Figure 17 Definition Tank Properties

AUTOMATED PLATE THICKNESS GENERATION

After the completion of compartment subdivisions, it becomes necessary to estimate the appropriate net thickness for the steel plates to be used in the construction. For this purpose, the 3D model is meticulously analysed and divided into plate panels. Each plate panel's thickness is then individually calculated, adhering to the guidelines and regulations specified by DNV. These calculated thickness values are then incorporated into the Rhino model.

In this section, we will delve into the comprehensive process of determining the thickness for each plate panel, as well as explore the workflow implemented through Rhino Grasshopper. The use of Rhino Grasshopper, along with its spreadsheet capabilities, enables efficient management and manipulation of the data involved in the calculation process. By integrating the computational power of Rhino Grasshopper and leveraging its spreadsheet capabilities, a streamlined method is adopted where precise plate thickness calculations can be achieved, resulting in accurate representation and compliance with DNV Rules.

CALCULATION OF PLATE THICKNESS

Before initiating the calculation of plate thickness, it is imperative to identify the distinct plate panels across the vessel. This step is crucial due to the varying loads experienced by different regions of the vessel during marine operations. For instance, the forward bottom plating encounters significantly higher loads compared to the plates forming the sides of the superstructure. This is primarily due to the hydrostatic pressure from water, hydrodynamic pressure from waves, and the additional impact of slamming loads during rough seas. Consequently, the forward bottom plating necessitates stronger reinforcement to ensure the structural strength and integrity of the vessel. In contrast, the plates forming the sides of the superstructure are mainly subjected to weather loads and do not require extensive reinforcement. As a result, identifying the different plate panels on the vessel becomes crucial in creating an efficient design that appropriately addresses the specific load requirements of each region.

Hence, to effectively construct the structural components of a vessel, the panels within the hullform are categorized into distinct regions and further organized into plate panels. Shipbuilding encompasses a diverse range of plate sizes, which are available in various grades, thicknesses, and panel dimensions. For this particular application, we have chosen plate dimensions of 10m x 2m, aligned along the length of the vessel. These plates are then sorted into different plate panels that correspond to specific areas of the ship's structure, including the keel, bottom, bilge, sides, exposed deck, bulkheads, and inner bottom plating. By employing this systematic approach, we can efficiently manage the construction process and ensure that each plate panel is appropriately positioned and tailored to meet the structural requirements of the vessel.

With the hullform successfully organized into plate panels and segmented into regions, the next step is to calculate the appropriate thickness for each individual plate. This calculation is performed in accordance with the DNV Rules for classification of ships (DNV–RU-SHIP-Part3). The criteria and guidelines for determining plate thickness are outlined in Chapter 5 of the rulebook, specifically in sections 3 and 4.

Section 3, titled "Minimum thickness" provides the minimum thickness requirements for each plate panel based on various factors such as the panel's function, length of vessel and the yield strength in order to anticipated loads it will experience. These requirements ensure that the plate panels possess the necessary strength and structural integrity to withstand the expected operational conditions. The minimum required thickness in mm calculated as per (DNV, Rules for Classification: Ships (RU-Ship), 2022), is not to be taken less than:

$$t = a + bL_2\sqrt{k}$$

where:

a and b are coefficients defined based on type of plate panel. (Table 1 in Ref.1)

L₂ is the rule length, but not taken greater than 300m.

and k is the material factor defined in chapter 3 section 1.

Section 4, titled "Plating subjected to lateral pressure" addresses the specific requirements for plate thickness based on the lateral pressure that it is subjected to, such as those located on the hull sides or the bottom of the vessel. This section defines the additional considerations and calculations necessary to determine the appropriate thickness for these plates, taking into account factors such as pressure acting on the plate, unsupported length and breadth of the plate panel, yield strength of the materials and bending effects acting on the hullform. The net required thickness in mm, is not to be taken less than:

$$t = 0.0158\alpha_p b \sqrt{\frac{|P|}{c_\alpha R}}$$

where:

α_p - correction factor for plate panel aspect ratio based on length and breadth of plate.

b - unsupported breadth of the plate panel in mm.

P - cumulative pressure acting on plate panel from external and internal loads.

R - yield strength of the steel plate in N/mm².

c_α - permissible bending stress coefficient.

The maximum of the thickness calculated in the above equations are selected as the thickness of the plate panel. The thickness value calculated from the equations are provided an additional corrosion allowance and rounded up to the nearest commercially available standard plate thickness. Standard plate thickness often used in shipbuilding include 6mm, 8mm, 10mm, 12mm, 14mm, 16mm, 20mm and 25mm. The inputs required for calculation are summarised in the figure 19.

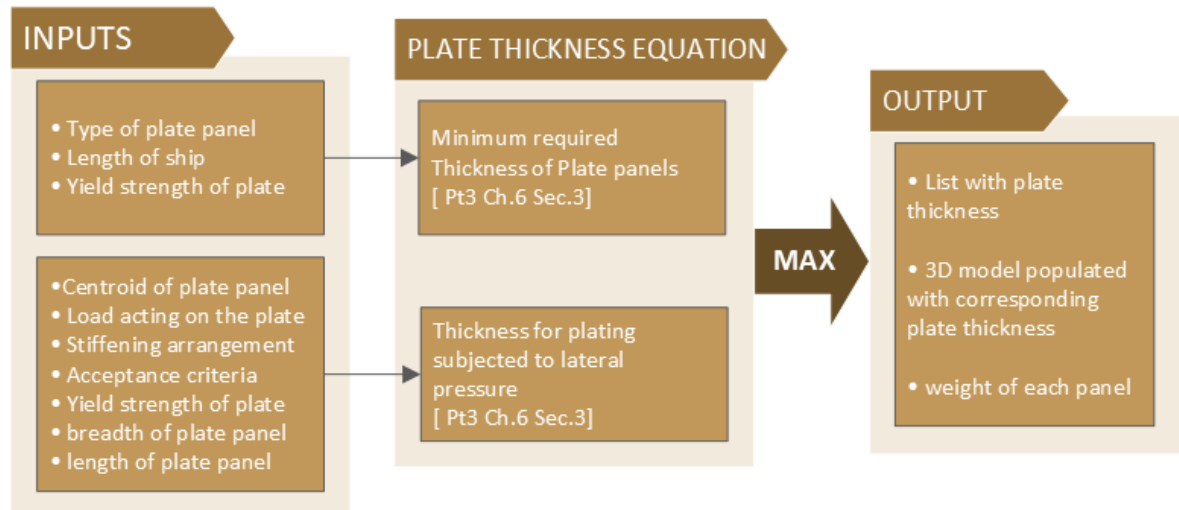


Figure 19 Plate Thickness Calculation

THICKNESS CALCULATION WORKFLOW

The process of calculating plate thickness involves several stages, taking into consideration the limitations and capabilities of the Grasshopper visual programming language integrated with Rhino. Due to Grasshopper's limitations for intensive calculations and repetitive tasks, the thickness calculation is performed using an Excel spreadsheet and VBA scripting.

To initiate the thickness estimation, the required inputs outlined in Figure 17 are obtained from Grasshopper and exported to an Excel sheet. These values are then utilized by a VBA script within Excel to iteratively calculate the thickness for each plate panel. The calculated thickness values are sorted based on the type of panel and subsequently read back into Grasshopper.

The obtained thickness values are rounded to the nearest available commercial thickness of shipbuilding steel plates. These values are then applied to the corresponding nested plates displayed within the 3D model through the Rhino 3D interface. The result is a plate thickness plot, as depicted in Figure 20, which provides a visual representation of the thickness distribution across the vessel. As it can be seen from the thickness plot, plating in high stress regions such as forward and bottom have been provided with a higher thickness as compared to less stressed regions.

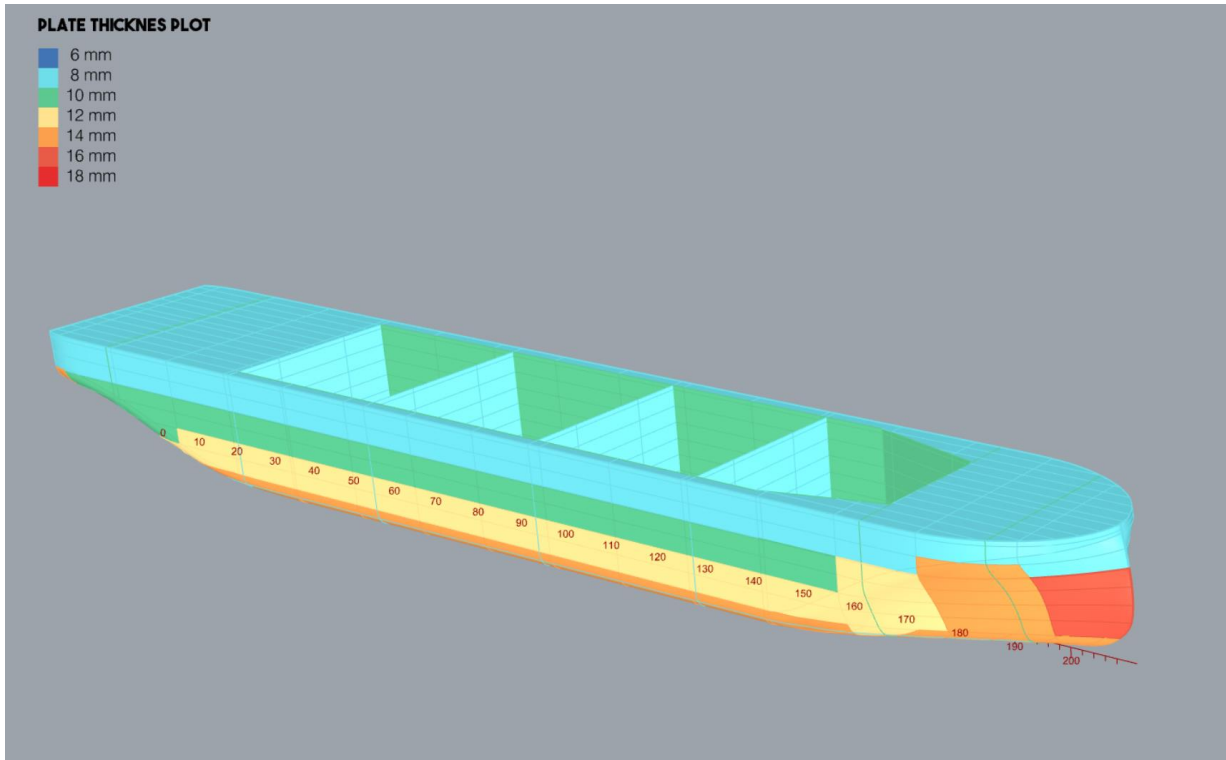


Figure 20 Calculated Plate thickness visualized using Rhino

Furthermore, based on the area of each nested plate and its assigned thickness, the weight and centroid values for each individual plate, as well as the plate group, are generated. These values are presented to the user through an interactive GUI, allowing for comprehensive analysis and evaluation of the structural characteristics of the ship's plates. GUI representation of results are provided in Figure 21.

PLATE PANEL DETAILS											
PLATE PANEL PROPERTIES:											
Total Weight: 1352.130 tons			Total Number of Plates: 1120								
LCG: 75.53 m		TCG: 0.01 m		VCG: 5.84 m							
KEEL	BOTTOM	BILGE	SIDE(L)	SIDE(U)	DECK	DB(O)	DB(C)	WING.TK	FPBHD	APBHD	WTBHD
WEIGHT(t)	LCG(m)	TCG(m)	VCG(m)	NUMBER	GRADE						
19.475	75.812	0	0.134	30	A						
PANEL NAME	THK(MM)	AREA(M2)	WEIGHT(T)	LCG(M)	TCG(M)	VCG(M)					
KeelPt 001	12.00	6.950	0.655	6.272	0.362	0.588					
KeelPt 002	12.00	6.950	0.655	15.000	0.352	0.000					
KeelPt 003	12.00	6.950	0.655	25.000	0.353	0.000					
KeelPt 004	12.00	7.072	0.666	35.000	0.352	0.000					
KeelPt 005	12.00	5.213	0.491	45.000	0.352	0.000					
KeelPt 006	12.00	6.950	0.655	55.000	0.352	0.000					
KeelPt 007	12.00	6.950	0.655	65.000	0.352	0.000					
KeelPt 008	12.00	6.950	0.655	75.000	0.352	0.000					
KeelPt 009	12.00	6.950	0.655	85.000	0.352	0.000					
KeelPt 010	12.00	6.950	0.655	95.000	0.352	0.000					

Figure 21 Plate Panel weight results

The implementation of the plate thickness calculation workflow involves three interconnected layers: the graphical user interface (GUI), the Grasshopper programming module, and the computational layer utilizing Excel VBA. This layered approach enables efficient data flow and interaction between the user, Grasshopper, and Excel VBA, resulting in accurate and automated plate thickness calculations for ship design.

At the top layer, the GUI serves as the interface between the user and the workflow. It allows the user to input relevant parameters, such as panel dimensions, load requirements, and other design specifications. The GUI also displays the output, including the calculated plate thicknesses and other relevant information. The user interacts with the GUI to provide inputs and view the results.

The Grasshopper programming module operates in the middle layer and acts as the bridge between the GUI and the computational layer. It collects the input data from the user through the GUI and populates the necessary variables and parameters required for the plate thickness calculation. The Grasshopper module utilizes the collected data and implements the necessary logic and calculations to generate the plate thickness values.

The computational layer, implemented using Excel VBA, resides at the bottom layer. It performs the intensive calculations required for plate thickness estimation based on the provided inputs. The Excel VBA script iterates through each plate panel, applies the relevant rules and guidelines (such as DNV Rules), and computes the minimum required thickness for each panel. The calculated thickness values are then passed back to Grasshopper for further processing and visualization. The flow of information between the layers is represented in Figure 22, illustrating the seamless interaction and data transfer from the GUI to the Grasshopper module and then to the computational layer.

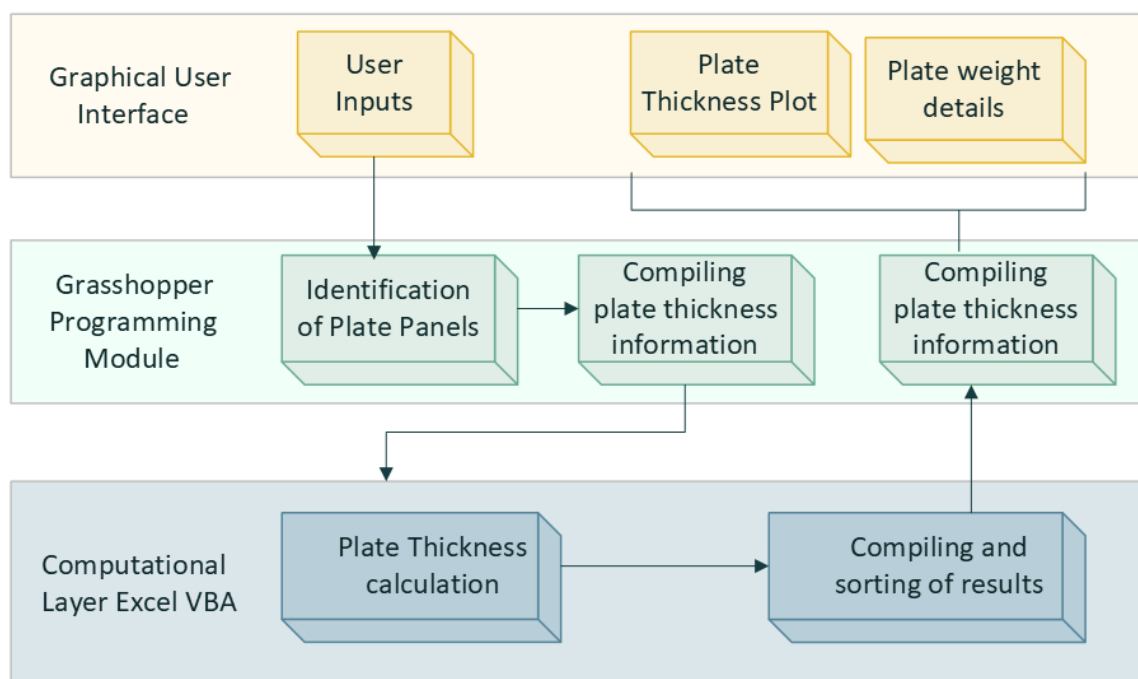


Figure 22 Plate Thickness Workflow Diagram

AUTOMATED STIFFENER GENERATION

After generating the plates with the required thickness according to DNV Rules, the next step in ship construction is to reinforce the plate panels by adding stiffeners. Stiffeners are classified into two main categories: primary supporting members (PSM) and secondary stiffeners, which are commonly referred to as stiffeners in subsequent sections.

Primary supporting members (PSM) are the main load bearing members in a ship. These structural elements that provide significant strength and stiffness to the ship's hull structure. These members are typically larger and have higher load-carrying capacities compared to secondary stiffeners. Common types of PSM include transverse bulkheads, girders, web frames and floors. These primary members are strategically placed in critical areas of the ship's structure to ensure structural integrity and resistance to various loads and stresses.

On the other hand, secondary stiffeners, also known as stiffeners in subsequent sections, are smaller structural elements that assist in distributing the loads acting on the plate and enhancing the overall stiffness of the plate panels. They are usually attached to the plate panels to reinforce and increase the resistance of the plate against local bending, buckling and fatigue loads. Examples of secondary stiffeners include longitudinal, bulkhead verticals etc. These stiffeners work in conjunction with the plate panels to withstand the bending, shear, and torsional forces experienced by the ship during operation. A typical example of stiffened panel is illustrated in Figure 23. Here, the primary supporting members are the longitudinal girders and transverse frames which act as the main load bearing elements. The unsupported plate panels between the girders and frames are stiffened using longitudinal stiffeners.

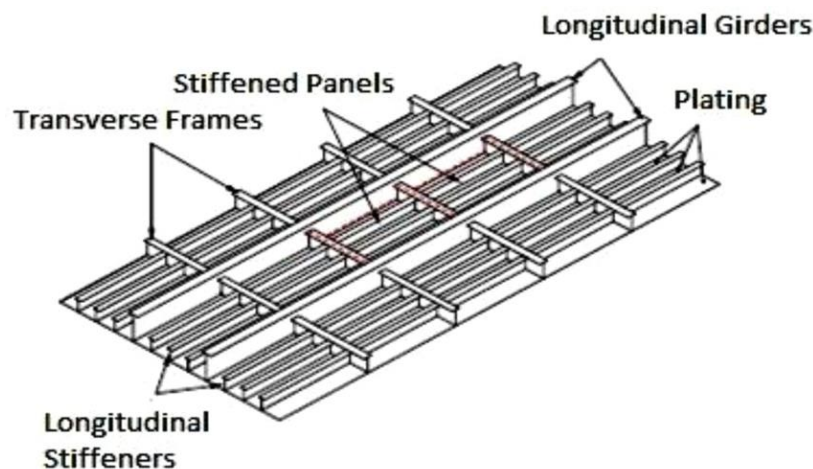


Figure 23 PSM and Stiffeners in a stiffened panel (Khosrow Ghavami, 2006)

The integration of structural stiffeners into the 3D ship model is a crucial step in ship design as it ensures the structural integrity and strength of the vessel. Traditionally, this process involved manual calculations and tedious iterations to determine the appropriate size and placement of stiffeners. This module greatly simplifies and streamlines the process by automating the calculation and incorporation of the necessary stiffeners according to the regulations specified by DNV Rules.

To begin, the program accepts user inputs that specify the desired type of stiffener, the required span and spacing of the stiffeners at specific locations within the ship structure. Additionally, it considers the previously calculated plate thickness for accurate estimation of the stiffener section modulus. Using this information, the module calculates the appropriate size and dimensions of the stiffeners, ensuring they meet the regulatory requirements set forth by DNV Rules. By automating this process, it saves significant time and effort for designers, eliminating the need for manual calculations and potential errors. With the stiffener data calculated, the program incorporates them into the 3D ship model, accurately positioning and attaching them to the corresponding plate panels. This integration provides a comprehensive representation of the ship's structural elements, allowing designers to visualize and analyse the overall strength and stability of the vessel.

The ability to automate the calculation and population of stiffeners provides numerous benefits. Firstly, it streamlines the design process, eliminating the need for manual calculations and reducing the risk of errors. Secondly, it allows for quick iterations and modifications, enabling designers to refine the structural configuration efficiently. This automated approach also improves the accuracy of weight details, which is crucial for stability calculations, structural analysis, and estimating material costs.

By utilizing this module, designers can focus more on the creative aspects of ship design while relying on the program to handle the complex calculations and generation of the stiffeners. The integration of the stiffeners into the 3D model ensures a comprehensive visualization of the vessel's structural framework, facilitating a thorough evaluation of its strength and integrity. Overall, the module significantly reduced the time taken in structural calculations and enhances the efficiency and of the ship design process by automating the calculation and population of stiffeners as required by DNV Rules.

STIFFENER SIZING

DNV rule requirements for the sizing of both primary supporting members and secondary supporting members are different, and the process of calculation is described below.

DNV Rules provide specific criteria for the primary supporting members (PSM) in terms of the minimum required section modulus and minimum shear area of the stiffeners. To meet these requirements, the program utilizes a stiffener database containing a range of pre-defined stiffener profiles. The program selects the appropriate stiffener from this database based on the minimum section modulus and minimum shear area criteria specified by the rulebook.

In addition to these criteria, the calculation of the section modulus of the PSM also considers the moment of inertia of the attached plating. The effective width of the plating is taken into account in this calculation, which accounts for the contribution of the attached plating to the overall stiffness and strength of the PSM. Effective width of the attached plating is calculated based on the equation 1.

By considering these factors and performing the necessary calculations, the program identifies the suitable stiffener from the stiffener database that satisfies the minimum section modulus and minimum web thickness requirements. This ensures that the selected stiffener is capable of providing the required structural support and meets the regulatory standards set by DNV rulebook.

Equation 1 Effective width of attached plating

$$b_{eff} = S \cdot \min \left[\frac{1.12}{1 + \frac{1.75}{\left(\frac{\ell_{bdg}}{S\sqrt{3}}\right)^{1.6}}}; 1.0 \right] \text{ for } \frac{\ell_{bdg}}{S\sqrt{3}} \geq 1.0$$

$$b_{eff} = 0.407 \left(\frac{\ell_{bdg}}{\sqrt{3}} \right) \text{ for } \frac{\ell_{bdg}}{S\sqrt{3}} < 1.0$$

where,

S - spacing of the stiffener in m.

ℓ_{bdg} - bending span of the stiffener in m.

The minimum section modulus of the stiffener according to (DNV, Rules for Classification: Ships (RU-Ship), 2022), considering the moment of inertia of the attached with an effective width as described above are as follows:

$$Z = 1000 \cdot \frac{P S \ell_{bdg}^2}{f_{bdg} C_s R_{eH}}$$

where,

f_{bdg} - bending moment distribution factor, as given in Pt.3 Ch.6 Sec.6

P - total load acting on the plate panel in N/mm².

C_s - permissible stress coefficient taken as 0.70 for AC-I, 0.85 for AC-II and AC-III.

R_{eH} - yield strength of the material in N/mm²

The shear area, in cm², of primary supporting members subjected to lateral pressure, calculated in accordance with Ch.3 Sec.7 [1.4.6], shall not be taken less than the greatest value for all applicable design load sets defined in Sec.2 [2], given by:

$$A_{shr} = 10 \frac{f_{shr} P S \ell_{shr}}{C_t \tau_{eH}}$$

where,

f_{shr} - shear force distribution factor, as given in Pt.3 Ch.6 Sec.6

ℓ_{shr} - shear length of the stiffener in m.

C_t - permissible shear stress coefficient taken 0.70 for AC-I, 0.85 for AC-II and AC-III.

τ_{eH} - specific yield stress of the material.

In case of secondary stiffeners, the criteria specified by DNV deals with minimum section modulus and minimum web thickness of the stiffener. Like as for primary supporting members, the attached plating is also included in the calculation of section modulus, the width of which is defined by the following equation.

- Where plating extends on both sides of the stiffener:

$$b_{eff} = 200 \cdot l \text{ or}$$

$$b_{eff} = s$$

whichever is lesser.

- where the plating extends on one side of the stiffener, i.e., stiffeners bounding openings
 $b_{eff} = 100.l$ or
 $b_{eff} = 0.5.s$
 whichever is lesser.

The minimum web thickness of the stiffener subjected to lateral pressure is calculated according to (DNV, Rules for Classification: Ships (RU-Ship), 2022) based on the following equation,

$$t_w = \frac{C_m f_{shr} |P| s \ell_{shr}}{d_{shr} C_t \tau_{eH}}$$

where,

C_m - coefficient for combined axial stress as defined in Pt.3 Ch.6 Sec.5.

d_{shr} - shear depth of the stiffener in mm.

Similarly, the minimum section modulus for the stiffener including the moment of inertia of the attached plating as per (DNV,2022) is given by the equation.

$$Z = \frac{f_u |P| s \ell_{bdg}^2}{f_{bdg} C_s R_{eH}}$$

where,

f_u - factor of symmetrical profiles as per Ch.6 Sec.5 [1.1.2]

In the program's stiffener database, various profiles of stiffeners with different shapes and sizes are stored along with their corresponding sectional area, moment of inertia, and vertical center of gravity position. Using the calculated thickness of the attached plating and the effective breadth obtained from the formula mentioned earlier, the program determines the vertical position of the neutral axis and calculates the combined moment of inertia of the selected stiffener profile.

To obtain the section modulus of the stiffener, the program divides the combined moment of inertia by the distance from the top and bottom of the plate to the neutral axis. This calculation provides the section modulus, which represents the ability of the stiffener to resist bending stresses. The program ensures that the calculated section modulus of the selected stiffener exceeds the minimum required section modulus specified for primary supporting members and other stiffeners. (Tupper, 2013) explains calculation of section modulus as

$$h_{NA} = \frac{\sum Ay}{\sum A} \quad \text{-- height of neutral axis from sectional area (A) and centroid (y)}$$

$$I_{xx} = \sum \frac{b d^3}{12} + \sum Ay^2 - (\sum A) h_{NA}^2 \quad \text{-- combined moment of Inertia.}$$

$$z_{xx} = \frac{I_{xx}}{h_{NA}} \quad \text{-- combined section modulus of stiffener.}$$

STIFFNER CALCULATION WORKFLOW

The workflow for calculating and populating stiffener sizes in the 3D model follows a multi-level process. At the top level, the user interacts with the graphical user interface (GUI) to provide inputs such as the desired shape of the stiffener profile and the span and spacing values for the stiffeners. The options available for the stiffener profiles include flat bars, bulb flats, equal and unequal angle bars, and tee bars. The user can iterate through different parameter values to find the optimal solution that meets the strength requirements specified by the classification society while minimizing the weight of the design.

The user inputs, along with the location of the stiffeners along the length of the vessel, are tabulated and consolidated in grasshopper. This data is then passed to an Excel-based Visual Basic code that performs iterative calculations to determine the criteria for each stiffener and selects an appropriate stiffener from the database which meets the corresponding requirements. The calculations for primary supporting members (PSM) and secondary stiffeners are carried out separately, and the results are recorded in the Excel spreadsheet.

The results which includes the selected stiffener shape, dimensions, and location, are then passed back to the grasshopper interface. Based on this information, the grasshopper module models the stiffeners at their corresponding locations in the 3D model for visualization. Rhino interface is used to display the populated stiffeners to the user.

This multi-level workflow allows for efficient exploration of the design space by iteratively adjusting parameters such as span, spacing, and material grades until the optimal solution is achieved. The integration of grasshopper, Excel, VBA scripting, and Rhino 3D enables interaction and visualization, saving time and ensuring compliance with classification society requirements while offering design flexibility and accuracy. The flow of information for calculating stiffener profiles are outlined below.

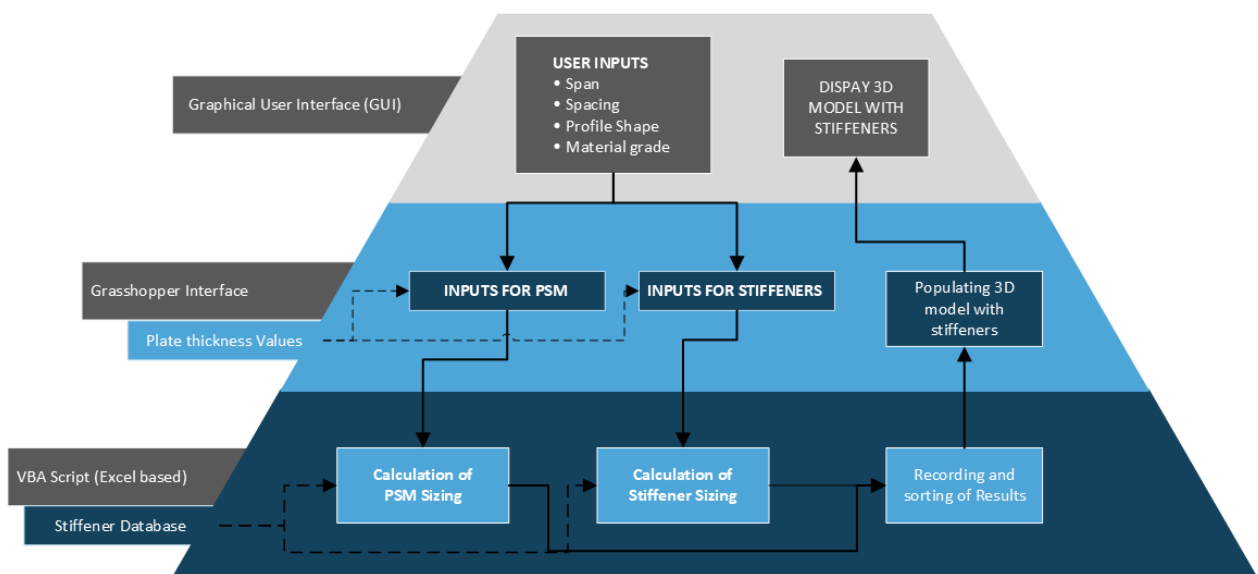


Figure 24 Stiffness calculation Workflow Diagram

WEIGHT ESTIMATION

Once the plate thickness and stiffener sizes have been calculated and populated in the 3D model using the previous modules, the next step is to determine the weight of these components. The total steel weight can be estimated by adding the total weight of plate panels to the total weight of stiffeners, which is an important parametric in estimating the stability of the vessel.

To calculate the weight of the plates, the program utilizes the area of the plate panel, and thickness. The program then multiplies the area of the plate panel by the density of the specific steel grade used in the construction, typically provided by the classification society or based on industry standards. The resulting product gives the weight of each plate panel. (Tupper, 2013)

$$\text{Total plate weight} = \sum A_i \cdot \rho_i$$

where,

A - area of the plate panel in m².

ρ - density of the plate panel in t/m³.

Similarly, for the stiffeners, the program considers the specific stiffener profile, such as flat bars, bulb flats, angle bars, or tee bars. Each stiffener profile has predefined dimensions and sectional properties, including its area, moment of inertia, and weight per unit length. By multiplying the length of each stiffener by its weight per unit length, the program can determine the weight of each stiffener. (Tupper, 2013)

$$\text{Total Stiffener Weight} = \sum W_i \cdot l_i$$

where,

W - weight per unit length of the stiffener in t/m³.

l - length of the stiffener in m.

The calculated weights of the plates and stiffeners are then summed up to obtain the total weight of the hull structure. This information are provided to the user through the graphical user interface (GUI) or displayed in a separate output window. The weight details can include the individual weights of each plate panel and stiffener, as well as the overall weight of the vessel's hull.

Accurate weight calculations are crucial for various aspects of ship design and operation, such as stability analysis, load distribution, and determining power requirements. By automating the weight calculation process, the program ensures efficiency and consistency in determining the structural weight, enabling designers to make informed decisions and optimize the vessel's design.

STABILITY CALCULATION

Stability estimation is a fundamental element in ship design, playing a critical role in ensuring the stability and overall safety of a vessel at sea. This process can be divided into three key steps: upright hydrostatics, equilibrium condition, and the calculation of the righting lever curve also known as GZ curve. These steps are of utmost importance as they enable the evaluation of the vessel's adherence to the stability criteria mandated by the International Maritime Organization (IMO) for cargo vessels. A comprehensive understanding of these steps is essential to ensure the vessel's stability and overall safety. The following sections will explain, these different types of stability analysis in detail.

UPRIGHT HYDROSTATICS

Upright hydrostatics for ships deals with the estimation of hydrostatic parameters when the vessel is in an upright position, i.e. free from list or trim and operating in calm waters. The hydrostatic parameters calculated by the software include displacement, LCB, KB, BM, KM, GM, MTC and TPC among others. These parameters are calculated by the software at various waterlines in increments of 1m, starting from the baseline and progressing up to the main deck. The resulting data is recorded for subsequent analysis and calculation. This process enables a comprehensive understanding of the vessel's hydrostatic behaviour and is valuable data for subsequent stability analysis and estimation of the equilibrium condition of the vessel. The hydrostatic parameters calculated and reported by the software are as follows:

- Mass Displacement (Δ) – refers to the weight of seawater displaced by the vessel in its floating condition. It is also a measure of the total weight of the vessel including deadweight and is expressed in tonnes. The software calculates mass displacement by trimming the hull surface at waterline in order to get the underwater volume of the vessel. Grasshopper provides inbuilt tool for estimating the volume of closed brep surfaces. Multiplying the volume obtained in such manner by the density of sea water gives the mass displacement of the vessel.
- Longitudinal Center of Buoyancy (LCB) – the center of buoyancy represents the point through which the vertical buoyant force acts on the ship. The longitudinal coordinate of buoyancy is called LCB. It is expressed in meters and is an important parametric for estimating trim of the vessel. Software calculates LCB by the extracting the longitudinal coordinate of the centroid of underwater volume calculated in previous step.
- Vertical Center of Buoyancy (KB)- KB refers to the vertical coordinate of the center of buoyancy measured from the baseline of the vessel. It is expressed in meters and is calculated in similar method as to how LCB is calculated.
- Waterplane Area (WPA) – refers to the area of the floating waterplane of the vessel. It is expressed in meter square and is calculated using the software by trimming the floating waterplane using the hull surface. The area function in grasshopper provides the total area of the extracted surface along with its centroid.

- Longitudinal center of floatation (LCF) – LCF is the longitudinal coordinate of the centroid of waterplane area. It is calculated by extracting the x-coordinate of the centroid calculated in the previous step for waterplane area.
- Tons per centimetre Immersion (TPC) – TPC represents the weight capacity of the ship per unit immersion, or in other words, the amount of weight that is required to bring about a change in floating draft by 1cm. According to (Barass & D.R.Derett), TPC expressed using the following formula:

$$TPC = \frac{WPA}{100} \times \rho$$

- Metacentric Radius (BM) – BM refers to the vertical distance between the center of buoyancy and the metacenter of the vessel and gives the location of the metacenter with respect to the COB. BM can be calculated as (Barass & D.R.Derett):

$$BM = \frac{I_{xx}}{\nabla}$$

where,

I_{xx} - volume displacement of the vessel (m^3)

∇ - second moment of inertia of the waterplane along x-axis (m^4)

The second moment of inertia can be directly calculated in grasshopper by using the area moments function which provides the moments along X and Y axis, which is used for calculating the transverse and longitudinal metacentric radii respectively.

- Metacentre height above Keel (KM)- is the vertical distance between the keel and the metacenter determined in the above step. It is expressed in meters and is an important parameter in establishing the transverse stability of the vessel. KM is determined easily by adding KM to KB.

$$KM = KB + BM$$

- Metacentric Height (GM) – GM is the most fundamental stability parameter and represents the static stability of the vessel. In physical sense, it gives the vertical distance between the centre of gravity and the metacenter of the vessel. The vertical coordinate of centre of gravity (KG) is obtained from weight calculation, and location of metacenter is defined by KM calculated in the previous step. GM value also provides an indication of whether the floating body has a stable or unstable equilibrium condition. A vessel with positive initial GM is said to have stable equilibrium and tends to return to its initial position when inclined. In similar way, a vessel with negative GM would heel further when inclined by a small angle and is said to have unstable equilibrium. Therefore, calculation of GM is an important step in stability assessment of vessel. It is expressed as:

$$GM = KM - KG$$

- Moment to change trim (MCT) – MCT is the moment that is required to change the trim of the vessel by 1cm. It is an important parameter for estimating the change in trim of vessel due to adding/removing weight or shift of cargo. Moment to change trim is expressed as follows (Barass & D.R.Derett):

$$MCT_{1cm} = \frac{\Delta \times GM_L}{100L}$$

where,

GML - longitudinal metacentric height (m)

L - length of the vessel (m)

Figure 25 illustrates the hydrostatic parameters calculated and reported by the program.

DRAFT(M)	MASS(T)	LCB(M)	TCB(M)	KB(M)	WSA(M2)	WPA(M2)	LCF(M)	TPC(T/CM)	BMT(M)	BML(M)	KMT(M)	GMT(M)	MTC(TM)
2	6609	76.39	0	1.05	3803	3555	76.08	36.44	37.04	678.93	38.09	30.3	267.37
3	10320	76.19	0	1.57	4177	3675	75.59	37.67	24.94	473.78	26.51	18.72	291.35
4	14133	75.97	0	2.09	4541	3764	75.17	38.58	18.88	368.63	20.97	13.18	310.44
5	18037	75.74	0	2.61	4906	3855	74.64	39.51	15.3	308.66	17.91	10.12	331.74
6	22041	75.47	0	3.14	5283	3962	73.84	40.61	12.95	273.11	16.09	8.3	358.69
7	26173	75.11	0	3.67	5708	4116	72.25	42.19	11.34	257.32	15.01	7.22	401.31
8	30495	74.53	0	4.21	6163	4286	70.43	43.93	10.22	248.45	14.43	6.64	451.46
9	34921	74.01	0	4.76	6529	4344	70.5	44.53	9.18	225.11	13.94	6.15	468.42
10	39395	73.64	0	5.3	6887	4383	70.87	44.93	8.27	204.45	13.57	5.78	479.94
11	43903	73.37	0	5.83	7243	4412	71.32	45.22	7.49	186.87	13.32	5.53	488.87
12	48438	73.2	0	6.36	7598	4435	71.69	45.46	6.84	171.89	13.2	5.41	496.13
13	52992	73.08	0	6.89	7950	4448	71.91	45.59	6.28	158.47	13.17	5.38	500.4
14	57554	72.99	0	7.41	8299	4451	71.94	45.62	5.78	146.15	13.19	5.4	501.22

Figure 25 Upright Hydrostatic parameters generated by program.

EQUILIBRIUM CONDITION

The second step in stability assessment is determining floating equilibrium condition of the vessel. This effectively means calculating the final draft in which the vessel floats for a specific total weight, acting through its centroid along with the trim and heel of the vessel in this final configuration. The software also calculates the hydrostatic parameters described in the previous section for equilibrium condition as well.

In this calculation, external forces from environmental factors like waves, current, and wind are not taken into account. Instead, the focus is on the static forces resulting from the buoyancy of the vessel, acting through the center of buoyancy (COB), and the total weight of the vessel, acting through the center of gravity (COG). When the center of gravity (COG) and center of buoyancy (COB) do not align vertically, it creates a moment that causes the vessel to tilt or heel along either the transverse or longitudinal axis. Static equilibrium refers to a state in which the forces and moments acting on the vessel are balanced, as a result of which the vessel assumes a new floating condition with trim and/or heel.

Practically, there are two ways in which this can be implemented in the program:

Method-1: The floating draft of the vessel can be interpolated from the upright hydrostatics data based on the mass displacement which equals the total weight of the vessel. Subsequently, the trim and heel can be calculated by physically rotating the vessel about the center of flotation by predetermined increment, until the COG and COB are aligned along the same vertical axis. The displacement of the vessel would also need to be iterated during each increment.

Method-2: The vessel is assumed to have an initial floating draft of 1m in the upright condition, with a corresponding weight acting through its COB. The remainder of the weight calculated is added to the vessel as an additional weight such the combined COG of the total weight acts through the COG calculated by the software. The next step would be to calculate the total bodily sinkage or rise due to the extra added weight, which can be estimated according to (Young, 2001) using the following formula:

$$\text{Bodily Sinkage} = \frac{\text{Weight loaded}}{TPC}$$

Adding the bodily sinkage to the initial draft gives us the new floating draft of the vessel. The next step in estimating the floating draft is to calculate the trim and heel of the vessel. For calculating the trim, the weight moment of the added weight with respect to LCF is estimated and used in the following formula (Young, 2001):

$$\text{Change of Trim} = \frac{\sum(w \times d)}{MCT\ 1cm}$$

Taking the distance between the forward and aft perpendicular to the LCF, the trim ratio for the same can be estimated as follows:

$$\text{Trim Ratio} = \frac{\text{Distance to LCF}}{LBP} \times \text{Change of trim}$$

The same calculation for trim ratio is carried out for both forward and aft perpendiculars. Using the above equations, the final draft of the vessel at both forward and aft perpendiculars can be determined as follows (Young, 2001):

$$\text{Final draft} = \text{Original Draft} + \text{Mean Bodily Sinkage/Rise} + \text{Fwd. or aft trim ratio}$$

When comparing the two methods, it is evident that method-1 is more computationally intensive. It involves rotating the geometry in each iteration and computing the underwater volume and its centroid properties. Due to its complexity, the software opts for method-2 to calculate the equilibrium condition of the vessel. Method-2 relies on mathematical formulas based on ship hydrostatics for the calculations.

Using method 2, the drafts at the forward and aft perpendiculars are estimated. Subsequently, the ship's 3D model is translated to the calculated waterline and rotated about the new center of flotation to simulate the equilibrium floating condition with the correct trim and heel angles. The hydrostatic parameters, as explained in the previous section, are also calculated for this equilibrium condition, and presented to the user through the user interface (UI).

RIGHTING LEVER CURVE AND STABILITY CRITERIA CHECK

Before delving into the implementation of the rule check in the methodology, it is crucial to grasp the concept of the righting lever curve and its significance in statical stability.

In the equilibrium condition, the weight acting through the center of gravity and the buoyancy force acting through the center of buoyancy align vertically. However, when external forces cause the ship to tilt or incline, the center of buoyancy shifts towards the inclined side. In this scenario, the buoyancy force acting upwards through the center of buoyancy and the weight acting downwards through the center of gravity create a couple or moment. This moment is known as the moment of statical stability, which strives to restore the vessel to its initial configuration. In the inclined condition, the perpendicular distance between the line of action of these forces is referred to as the righting lever. In such a case, moment of statical stability is the product of mass displacement and the righting lever, expressed as:

$$\text{Moment of Statical Stability} = \Delta \times GZ$$

Figure 27 illustrates the development of the righting lever as the vessel undergoes inclination.

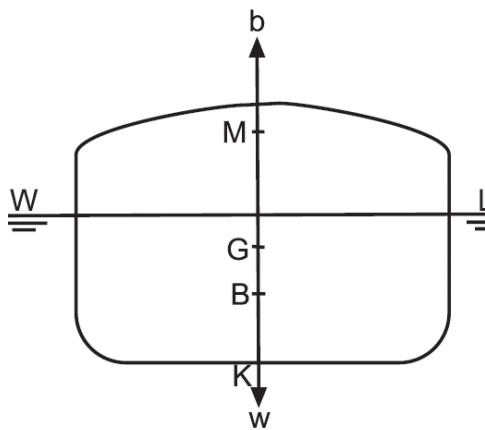


Figure 26 Upright Position
(Barass & D.R.Derett)

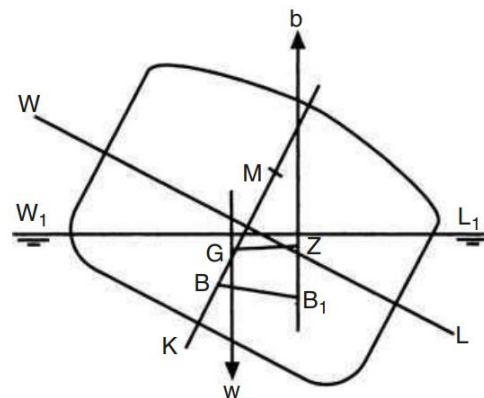


Figure 27 Righting lever in inclined condition
(Barass & D.R.Derett)

For small angles of heel, the buoyancy force is considered to act vertically through the vessel's initial metacentre. This is illustrated quite well by (Barass & D.R.Derett) in Fig 27.

$$GZ = GM \sin\theta$$

However, for large angles of heel typically above 15 degrees, the buoyancy force is no longer considered to act vertically upwards through the initial metacentre (M) as illustrated in figure 20(b). In such cases, GZ is estimated using a formula known as the wall sided formula as (Barass & D.R.Derett):

$$GZ = (GM + 0.5BM \tan^2\theta) \sin\theta$$

Using the above formula, the program calculates the GZ values for different angles of inclination starting from 0 degree up to down flooding point explicitly defined by the user or deck immersion condition, whichever occurs first. The angles for calculation can be explicitly provided by the user or taken as default by the program if no input is provided.

Fig 28 illustrates the GZ curve generated by the program, showing the relationship between righting lever (GZ) and the angle of inclination (Θ).

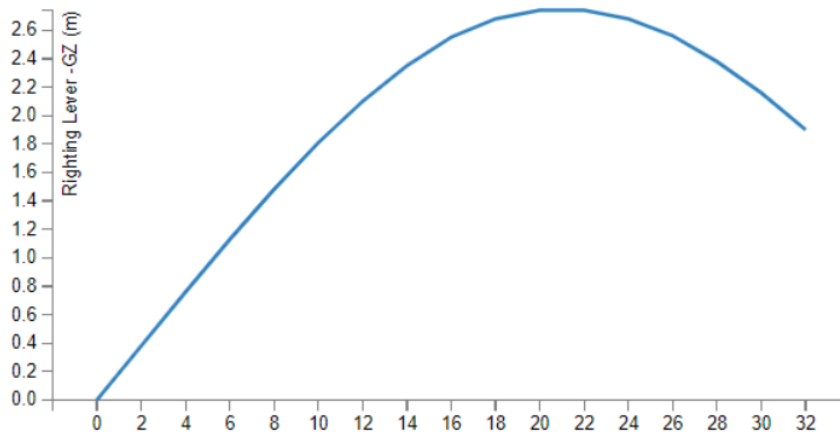


Figure 28 Righting lever curve generated by the program.

The GZ values generated by the program can be used to assess the stability requirements set by the International Maritime Organization (IMO) MSC.267(58). These stability criteria are outlined in detail in the "Rules and Approval" section of chapter 3. The criteria specified in the IMO guidelines are primarily applicable to cargo vessels, and vessels that meet these criteria are considered to be approved in terms of stability. Intact stability criteria laid down by (IMO, 2008) can be briefly summarized as follows:

1. Area under the Righting Lever Curve: This criterion sets a minimum value for the area under the righting lever curve. It ensures that the vessel has sufficient stability throughout its range of inclinations.
2. Righting Lever at 30 Degrees or Higher: This criterion specifies a minimum value for the righting lever at a specific angle of inclination (30 degrees or higher). It ensures that the vessel maintains adequate stability even at significant angles of heel.
3. Angle of Maximum Righting Lever: This criterion determines the angle at which the maximum righting lever is generated. It sets limits on this angle to ensure that the vessel achieves its maximum stability at a suitable inclination.
4. Initial Metacentric Height: This criterion relates to the initial metacentric height (GM), which is a measure of a vessel's initial stability. It sets a minimum value for the GM to ensure that the vessel has sufficient initial stability.

The program checks each of these criteria against the calculated GZ values for the vessel. If the vessel meets all the stability criteria, it is classified as passing the stability assessment. However, if any of the criteria are not met, the vessel is classified as failing to meet the stability requirements. By applying these stability criteria, the program helps determine whether the vessel complies with the regulations established by the IMO. Fig 29 illustrates the stability criteria assessment by the program.

IMO MSC 267(58) CODE				
CRI	CRITERIA	REQ	ACTUAL	STATUS
CR1	Area under GZ Curve upto 30deg.	0.055	0.79	PASS
CR1	Area under curve upto 40deg or DF angle	0.09	0.863	PASS
CR1	Area under curve between 30deg and 40deg	0.03	0.073	PASS
CR2	Righting lever at 30deg or greater	0.2	2.16	PASS
CR3	Angle of Maximum Righting Lever	25	20	FAIL
CR4	Initial Metacentric Height	0.15	0.19	PASS


DISPLAY RIGHTING LEVER CURVE 

Figure 29 Stability criteria assessment by program

RESISTANCE CALCULATION

Resistance and powering estimation for the design is carried as empirical formulae. These formulae are based on established relationships and observations from previous designs, making them convenient for quick calculations. The primary goal of the application is to facilitate the exploration of various design options during the initial design phase while minimizing the effort required by the designer.

By utilizing empirical formulae, the application allows designers to rapidly assess different design alternatives and make informed decisions. Implementing more advanced methods, such as computational fluid dynamics (CFD) solvers, would be time-consuming and may not align with the application's objective of efficiency in the initial design stage. The use of empirical formulae strikes a balance between accuracy and computational speed, providing designers with reasonable estimates of resistance and powering. While these methods may not capture all intricacies of fluid dynamics, they serve the purpose of quickly evaluating design options and narrowing down choices for further refinement.

The empirical formulae used for calculation is an approximate power prediction method proposed by J. Holtrop and G.G.J. Mennen. The method proposed by (Mennen, 1982) is based on regression analysis of propulsion and resistance data gathered by from various model ships and full-scale data. Regression analysis allows for the development of mathematical equations that represent these relationships. These equations can then be used to estimate propulsion and resistance characteristics for new ship designs based on their specific hull form parameters.

Total resistance according to (Mennen, 1982) is defined as follows:

$$R_{total} = R_F(1 + k_1) + R_{APP} + R_w + R_B + R_{TR} + R_A$$

where,

- R_F - frictional resistance according to ITTC 1957 friction formulae
- $1 + k_1$ - form factor describing the viscous resistance of the hull in relation to R_F
- R_{APP} - resistance of appendages
- R_w - wave making and wave breaking resistance
- R_B - additional pressure resistance of bulbous bow near the water surface
- R_{TR} - additional pressure resistance of immersed transom
- R_A - model ship correlation resistance

The different components of resistance mentioned in the above formula can be estimated empirically based on fundamental design parameters of the vessel such as length of waterline, wetted surface area, displacement, floating draft etc. These parameters serve as inputs for the calculation and are kept constant for a design, with the exception of speed which is iterated to determine the corresponding resistance values for each speed increment. The effective power required to overcome the resistance in a function of speed and is expressed as:

$$P_E = R_{total} \times V_s$$

Resistance and power curves calculated by the software are illustrated in Fig 30.

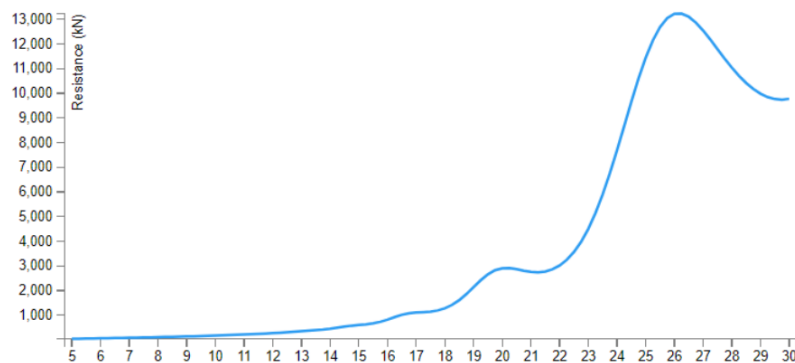


Figure 30 (a) Resistance Curve generated by program.

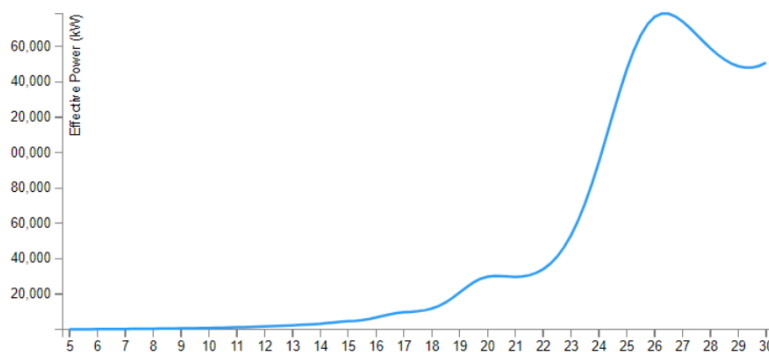


Figure 30 (b) Power curve generated by program.

However, delivered power (P_D) which is the actual power output of the propulsion system, is greater than the estimated effective power output. This is because of the propulsion efficiency and power losses within the propulsion system and are characterized by efficiency losses. The efficiency components considered in delivered power calculation according to (K.J. Rawson, 2001) are hull efficiency, gearbox efficiency, mechanical efficiency of the shaft and the open water efficiency of the propeller. The equation for delivered power is formulated as follows:

$$P_D = \frac{P_E}{\eta_{hull} \eta_{gear} \eta_{shaft} \eta_{propeller}}$$

It's important to note that this method is based on empirical relationships and may have limitations when applied to unconventional ship designs or extreme operating conditions. However, for typical ship designs within the range of the data used in the regression analysis, this approach provides a practical and efficient estimation of resistance and powering requirements during the initial design phase.

DESIGN SPACE ITERATION

The primary goal of the application is to enable designers to easily explore and evaluate different design options using just a few basic inputs during concept design stage. By automating various ship design tasks, the application aims to minimize the designer's effort in navigating through multiple design alternatives during the concept stage.

The program requires the designer to provide several key inputs that establish the design basis for the vessel being designed. These inputs are essential parameters of the vessel that should remain constant throughout the design space exploration. For instance, if the designer is tasked with creating a 100m container vessel, the program will ensure that the length and hull form type of the vessel remain unchanged during the search for the optimal design option. The user-defined inputs that establish the design basis include the main dimensions of the vessel, the chosen hull form type, the expected scantling draft, the desired service speed, and the definitions of compartments within the vessel. These inputs serve as the foundation for the design exploration process.

By specifying these design basis parameters, the designer sets the fundamental characteristics and constraints of the vessel. The program then utilizes these inputs as fixed parameters while exploring different design options. This approach allows the designer to focus on the exploration and evaluation of design variations within the established design basis, ensuring consistency and control throughout the process.

Once the inputs are received from the user, these parameters are fixed and a design basis is established. The program aims to achieve two main objectives through design exploration:

- Minimize the structural weight of the design while satisfying DNV rules (DNV, Rules for Classification: Ships (RU-Ship), 2022)
- Identify the solution that provides maximum stability while having the satisfying IMO rules as per (IMO, 2008).

The design parameters that can be changed by the program to find the optimal solution are mainly pertaining to variables in structural design. In case of stiffeners and primary supporting members, (DNV, Rules for Classification: Ships (RU-Ship), 2022) provides rules for the

minimum required section modulus for the structural member along with the attached plate. A number of different acceptable stiffener profiles can be selected by procedurally iterating through the following design parameters:

1. Frame spacing – distance between primary supporting members (PSM).
2. Stiffener spacing - distance between secondary stiffeners.
3. Stiffener profile shape – flat bar, bulb flats, angle bars or tee bars.
4. Material grade used for the stiffener.

Different combinations of these design parameters can be iteratively explored to find the stiffener for a specific region that satisfies the strength requirements while offering the least weight. Similarly, thickness of the shell plates used in ship structures are primarily governed by the dimensions of the un-supported plate panels, which are the distance between PSM and stiffeners. Therefore, thickness of plate panels can also iteratively optimized by controlling the following design parameters:

1. Frame spacing – distance between primary supporting members (PSM).
2. Stiffener spacing - distance between secondary stiffeners.
3. Material grade used for the plating.

By iterating through these design parameters, the program can explore various combinations and configurations to find the optimal solution for the design of stiffeners and shell plates. The goal is to achieve the required structural strength while minimizing weight, thus contributing to the overall efficiency of the vessel design.

3.6 OVERVIEW OF GRAPHICAL USER INTERFACE

The design tool is integrated with Rhino's 3D modelling interface, providing an efficient workflow for creating, modifying, and analysing 3D vessel geometry using Rhino. It enhances the functionality of Rhino by adding features and capabilities tailored specifically for ship design. The tool is used in conjunction with Rhino's 3D modelling interface for creating and analysing new concept design. The 3D modelling interface from Rhino is used for visualization and navigation of the 3D model prepared by the program, whereas the program GUI is used for accepting inputs from the user and displaying results. The split between Rhino interface and design program GUI is represented in Fig 24.

The Graphical User Interface (GUI) of the program is categorized into different tabs, indicating the different tasks in the development of a concept design. The different tasks in concept design covered are parametric hull generation, compartment subdivision, structural design, intact stability analysis and resistance estimation. It is recommended to follow the tabs in a sequential manner for achieving proper results.

HULLFORM TAB

Upon launching the program, the user is presented with the parametric hullform tab, which serves as the initial interface for defining the project parameters. This tab has two expanders. The first expander within the parametric hullform tab enables the user to specify essential information such as the project name, type of vessel, and the main dimensions of the vessel. Additionally, the user can also define the scantling draft and service speed of the vessel as well.

The program incorporates a collection of pre-defined hullform templates that correspond to each vessel type chosen by the user. These templates serve as starting points for the design process, providing a foundation upon which further modifications and refinements can be made. By selecting the desired vessel type, the program initializes the design using the corresponding hullform template. To facilitate user interaction, sliders are provided for adjusting the main dimensions, draft, and speed. The 3D model published in Rhino is updated in real-time based on the slider inputs from user.

Once the user is satisfied with the main particulars of the vessel, pressing the calculate button generates the preliminary hydrostatics data of the generated hullform to the user. This data provides the designer with essential information about vessel based on its scantling draft, allowing the user to make informed decision as to continue with the design or not. The data provided to the user include information about the dimensions of the vessel, displacement, center of flotation and buoyancy, along with form coefficients of the hullform. If the user is not satisfied with the results, the process can be repeated by changing the dimensions or draft.

Results from preliminary hydrostatics can be visualized in Fig 31.

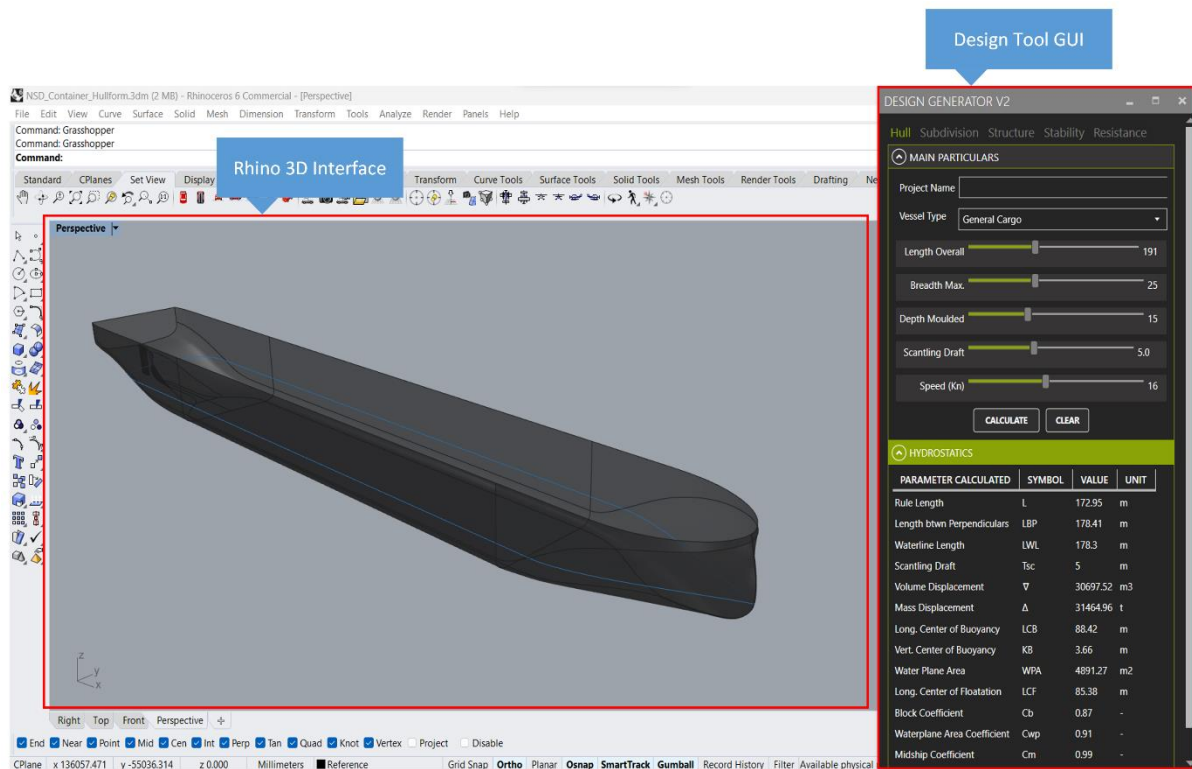


Figure 31 Integration of Rhino interface with design too

COMPARTMENTS TAB

Once the main particulars for the vessel are defined in the hullform definition, the design basis has been established and the next step is to subdivide the hullform into compartments and tanks. Subdivision tab is further categorized into three different expanders as compartments definition, addition of transverse bulkheads, and tank definition sections. Based on the ship type provided in Hull tab, the software identifies basic structural elements typically present in similar ship type such as peak bulkheads, cargo hold bulkheads, double bottom, wing tank and

main deck. The position of these elements can be adjusted using sliders and toggles are provided for visualization in Rhino interface. This section also provides the user with the option to adjust frame spacing of the vessel which is one of the design parameters that is optimized by the application. Fig 32 illustrates the compartments defined by the program.

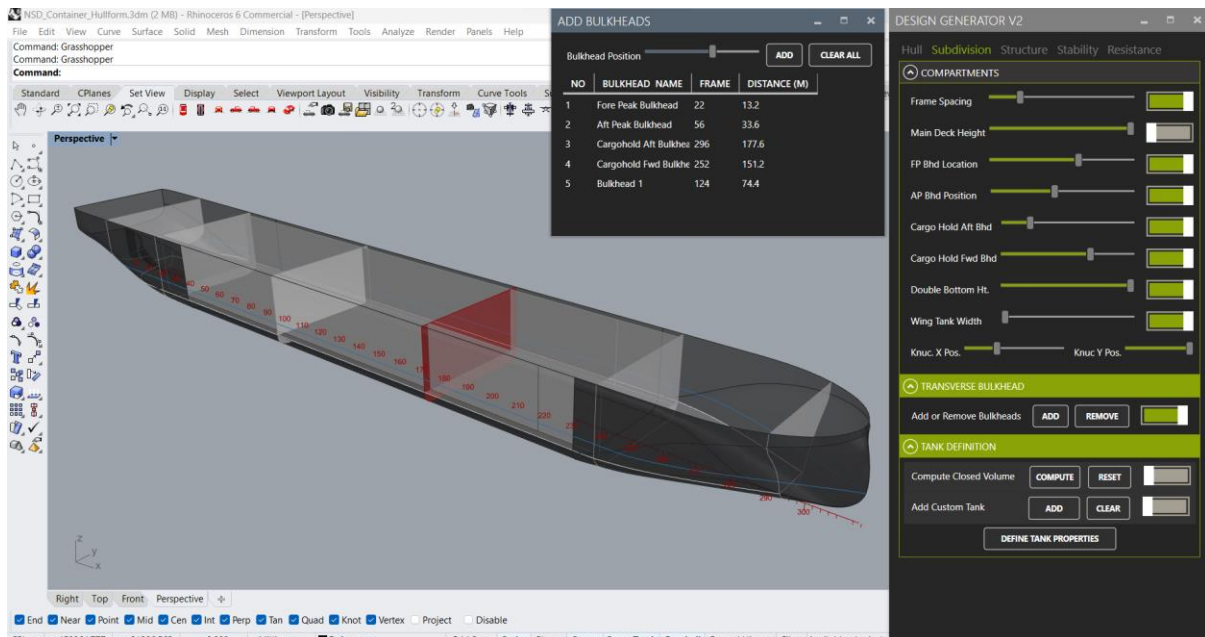


Figure 32 Bulkhead definition under compartments tab

The program offers the functionality to add user-defined bulkheads along the length of the vessel. By pressing the 'Add' button under the 'Transverse Bulkhead' section, a prompt window is displayed, allowing the user to define and add their own bulkheads. This feature allows the user to incorporate specific bulkhead configurations based on their requirements. Fig 31 illustrates the prompt window for adding user-defined bulkheads.

Furthermore, the program automatically identifies the compartments and tanks generated by the defined bulkheads. By pressing the 'compute' button under the 'Tank Definition' expander, the algorithm determines the closed volumes created by the bulkheads and categorizes them as tanks and compartments. This automated process saves time and effort for the user. This can be changed by the user later using 'Define Tank Properties' window under the same section. In addition to this, the window also allows the user to rename tanks and assign the fluid stored in tanks. The results from automatic volume calculation are illustrated in Fig 33 and tank properties in Fig 34(b). This visualization provides the user with a clear overview of the generated volumes and their respective categorizations.

In addition to the automatic identification of tanks and compartments, the program also offers the option to add custom tanks. By pressing the 'Add' button next to the 'Add custom tanks' label, the user can define and incorporate their own custom tanks into the design. This feature enables further customization and tailoring of the vessel's tank arrangement to specific requirements. The 'Add custom tank' window, as depicted in Fig 34(a), allows the user to specify the location and dimensions of the custom tank.

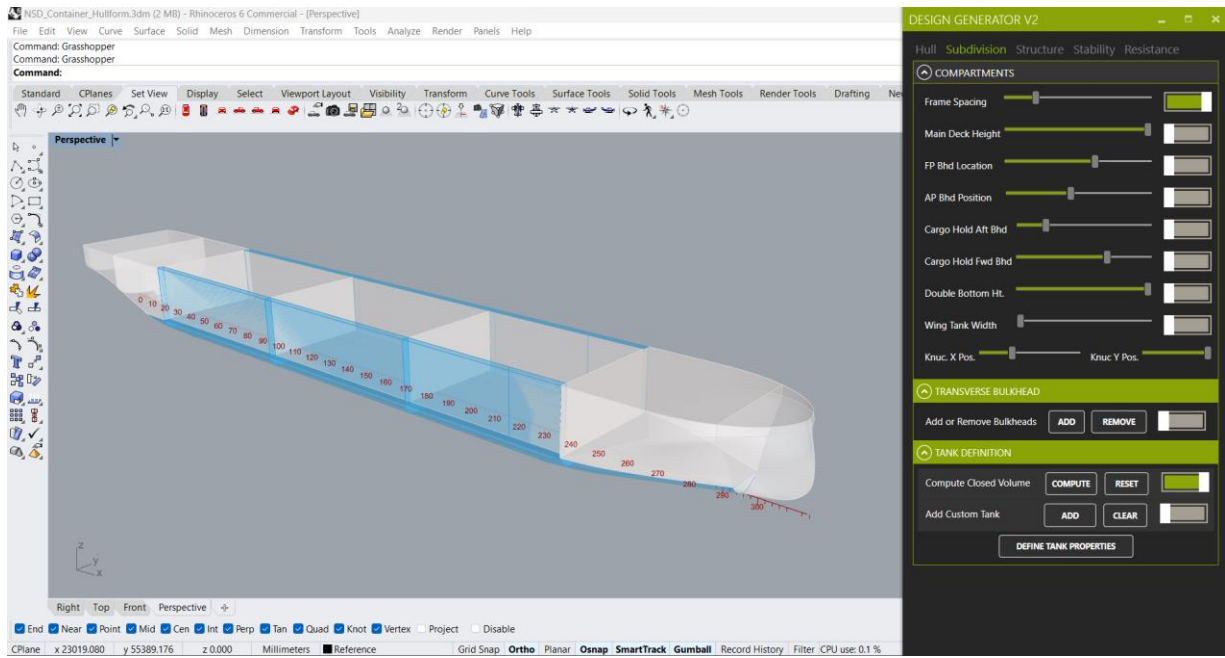


Figure 33 Automatic Compartment identification by program.

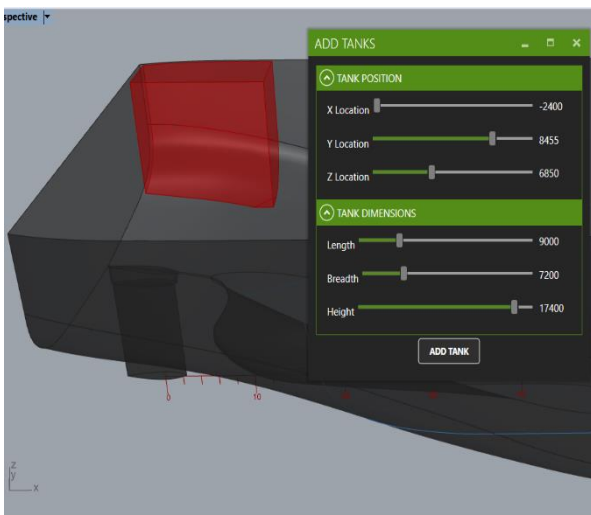


Figure 34(a) Add Custom Tanks Window



Figure 34(b) Edit tank properties window.

STRUCTURE TAB

Design process is continued in the structure tab after compartments. Like the previous tab, the structure tab is also divided into different expanders as shell plate generator, stiffener generator and weight details which summarises the total weight of the vessel. It is advised to follow the sequential order of execution from top down for proper results.

Within the shell plate generator expander, the user is provided with the option to specify the grade and yield strength of the steel used for calculation. The identify plate panels button categorizes and nests the plate panels generated in the previous section as keel, bilge, bottom etc. This is critical for subsequent calculation as the loads differ based on plate location. The results from 'Identify plate panels' function is illustrated in Fig 35.

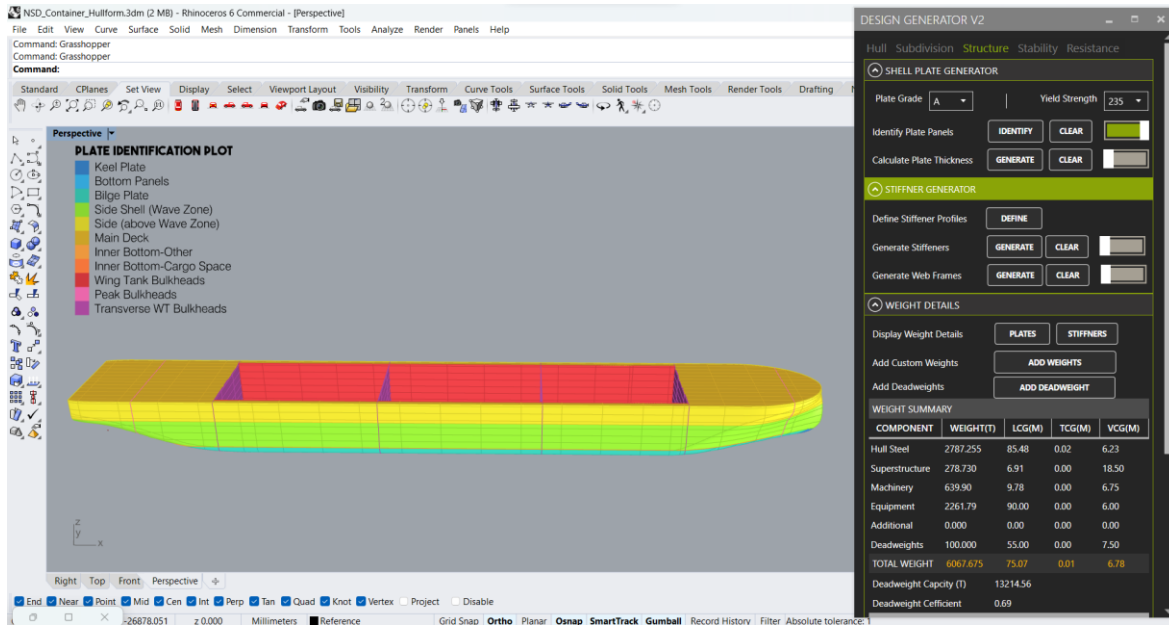


Figure 35 Results from identify plate panel function

Once the plate panels have been identified, the program offers a functionality to calculate the thickness for each individual plate panel. By toggling the "calculate plate thickness" function and pressing the "calculate" button, the program sends the plate details generated in the Identify section to a spreadsheet for calculation. The spreadsheet performs the necessary calculations based on the provided parameters and returns the thickness values for all plate panels. The results from thickness generation function are visualized in the Rhino environment and is illustrated in Fig 36.

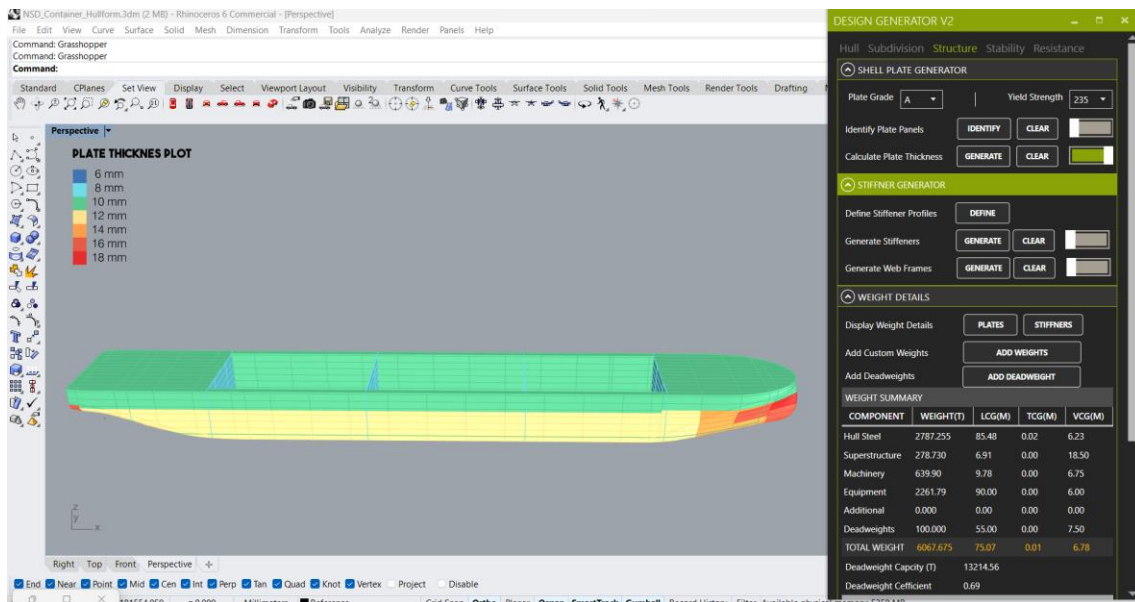


Figure 36 Results from plate thickness calculation

The plate thickness values generated are used for section modulus calculation of stiffeners and it is now possible to populate primary supporting members and stiffeners on the plating. The program also provides the user the option to define the stiffeners profiles to be used at different

locations. Stiffeners and PSM can be generated by clicking the Generate button against corresponding labels. 3D model with stiffeners as generated by the model is shown in Fig 37.

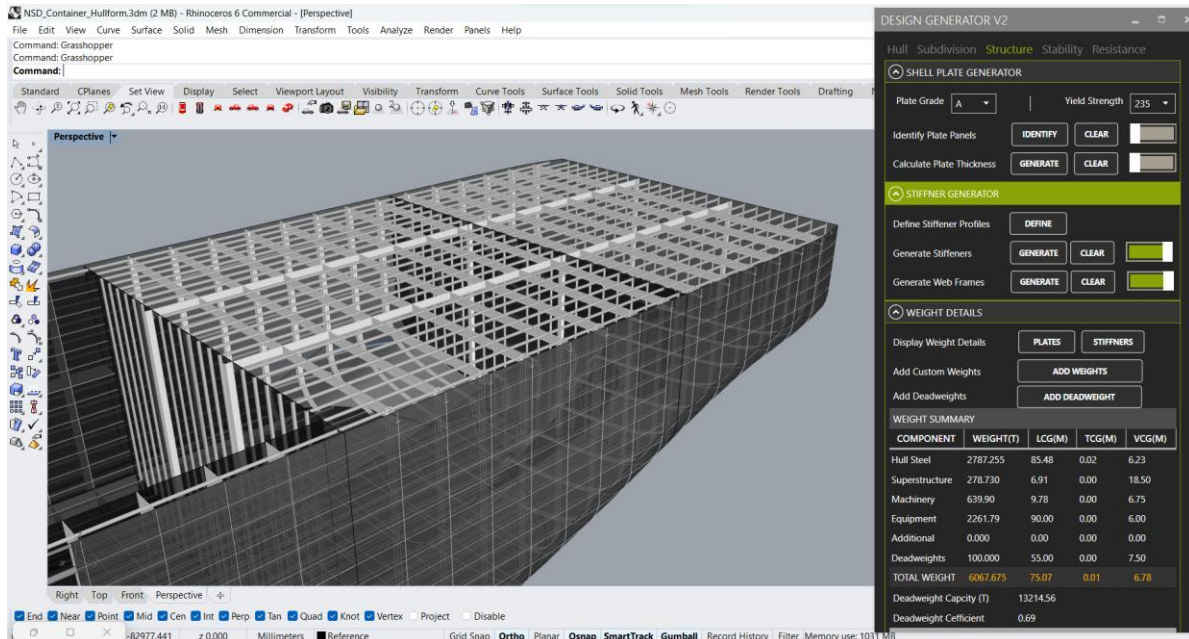


Figure 37 Stiffeners generated using program

The weights of both plates and stiffeners are tabulated and provided to the user for reference. These can be viewed separately by pressing ‘Plates’ and ‘Stiffeners’ button against the label ‘Display weight details’. The weights reporting for panels is shown in Fig 38. In addition to the total weight of the panel, the program also reports the total weight of the plate group as well as individual plate panels.

PLATE PANEL DETAILS											
PLATE PANEL PROPERTIES:											
Total Weight: 1565.159 tons				Total Number of Plates: 1315							
LCG: 92.58 m		TCG: 0.04 m		VCG: 6.82 m							
KEEL	BOTTOM	BILGE	SIDE(L)	SIDE(U)	DECK	DB(O)	DB(C)	WING.TK	FPBHD	APBHD	WTBHD
WEIGHT(T)	LCG(m)	TCG(m)	VCG(m)	NUMBER	GRADE						
32.726	95.716	0	0.104	38	A						
PANEL NAME	THK(MM)	AREA(M2)	WEIGHT(T)	LCG(M)	TCG(M)	VCG(M)					
KeelPt 001	14.00	6.252	0.687	6.468	0.418	0.672					
KeelPt 002	14.00	7.950	0.874	15.000	0.402	0.000					
KeelPt 003	14.00	7.950	0.874	25.000	0.403	0.000					
KeelPt 004	14.00	7.950	0.874	35.000	0.402	0.000					
KeelPt 005	14.00	7.950	0.874	45.000	0.402	0.000					
KeelPt 006	14.00	7.950	0.874	55.000	0.402	0.000					
KeelPt 007	14.00	7.950	0.874	65.000	0.402	0.000					
KeelPt 008	14.00	7.950	0.874	75.000	0.402	0.000					
KeelPt 009	14.00	7.950	0.874	85.000	0.402	0.000					
KeelPt 010	14.00	7.950	0.874	95.000	0.402	0.000					
KeelPt 011	14.00	7.950	0.874	105.000	0.402	0.000					

Figure 38 Plate panels weight details generated by program.

In addition to the structural weight calculations, the program also allows the user to define and estimate other weight groups such as superstructure, machinery, equipment, and additional

custom weights. The user can provide explicit inputs for these weight groups, or in the absence of user-defined inputs, the program automatically calculates them using empirical equations for approximate weight estimation, as described by (Cudina & Zanic, 2010). The program provides an option to add custom weights, allowing the user to account for any additional equipment or loads that may be present in the design. Furthermore, the deadweight and cargo carried by the vessel can be specified using the ‘Add Deadweight’ option. Once all the weight groups are available, the weights are summarized by the program as show in Fig 39. The same total weight is used for stability calculation in further steps. The program provides information about the total weight of the vessel along with its centroid, while also highlighting the deadweight capacity with respect to scantling draft for the loading condition.

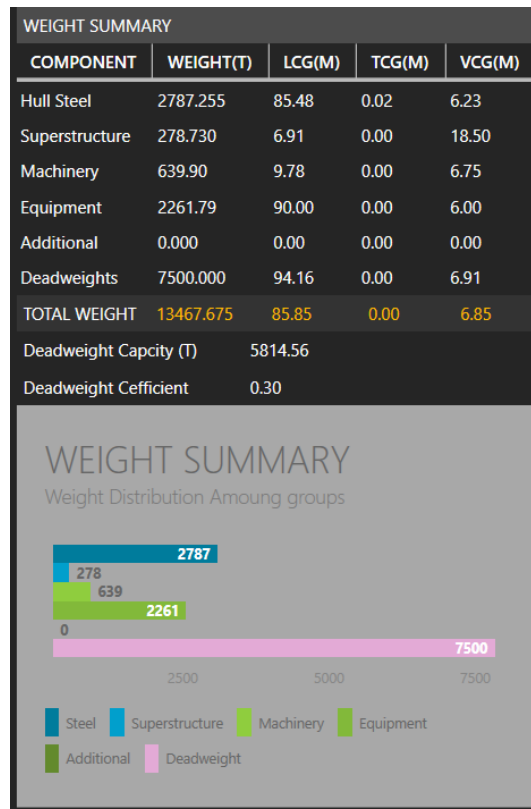


Figure 39 Weight Summary generated by program.

STABILTY TAB

As explained in the previous section, stability analysis within the program is broken down into three stages namely upright hydrostatics, equilibrium condition and large angle stability. These calculations are separated into different expanders and are expected to be carried out in sequential order.

Upright hydrostatics calculate the hydrostatic parameters of different floating drafts up till main deck. This can be done by toggling on the function and hitting the calculate button. This provides the user with a table report with hydrostatic parameters of different draft condition as shown in Fig 40.

UPRIGHT HYDROSTATICS													
DRAFT(M)	MASS(T)	LCB(M)	TCB(M)	KB(M)	WSA(M2)	WPA(M2)	LCF(M)	TPC(T/CM)	BMT(M)	BML(M)	KMT(M)	GMT(M)	MTC(TM)
2	7130	94.72	0	1.04	4142	3805	94.38	39	25.94	1096.48	26.98	20.13	465.85
3	11092	94.5	0	1.57	4576	3915	93.85	40.13	17.4	759.71	18.97	12.12	502.13
4	15146	94.27	0	2.08	5001	3995	93.4	40.95	13.14	588.02	15.22	8.37	530.7
5	19282	94.02	0	2.6	5428	4078	92.83	41.8	10.62	489.29	13.22	6.37	562.18
6	23510	93.74	0	3.12	5864	4175	91.97	42.79	8.96	429.45	12.08	5.23	601.62
7	27854	93.35	0	3.65	6345	4315	90.25	44.23	7.82	399.54	11.47	4.62	663.14
8	32371	92.74	0	4.19	6853	4469	88.29	45.81	7.02	380.98	11.21	4.36	734.88
9	36982	92.18	0	4.73	7282	4523	88.37	46.36	6.3	344.56	11.03	4.18	759.3
10	41637	91.78	0	5.26	7703	4558	88.78	46.72	5.67	312.72	10.93	4.08	775.87
11	46323	91.5	0	5.79	8124	4585	89.27	47	5.14	285.73	10.93	4.08	788.69
12	51034	91.31	0	6.32	8543	4606	89.68	47.21	4.7	262.77	11.02	4.17	799.08
13	55762	91.19	0	6.84	8959	4618	89.92	47.33	4.31	242.33	11.15	4.3	805.2
14	60498	91.09	0	7.36	9374	4620	89.96	47.36	3.98	223.68	11.34	4.49	806.35

Figure 40 Upright hydrostatics table generated by program.

After estimating the upright hydrostatic parameters and calculating the weight in the Structure module, it becomes possible to determine the equilibrium floating draft of the vessel. This module provides the user with information about the floating draft of the vessel with corresponding hydrostatic particulars for the same. The visualization in Rhino also adjusts the vessel to correct floating waterline to give the user a better idea of the draft forward and aft.

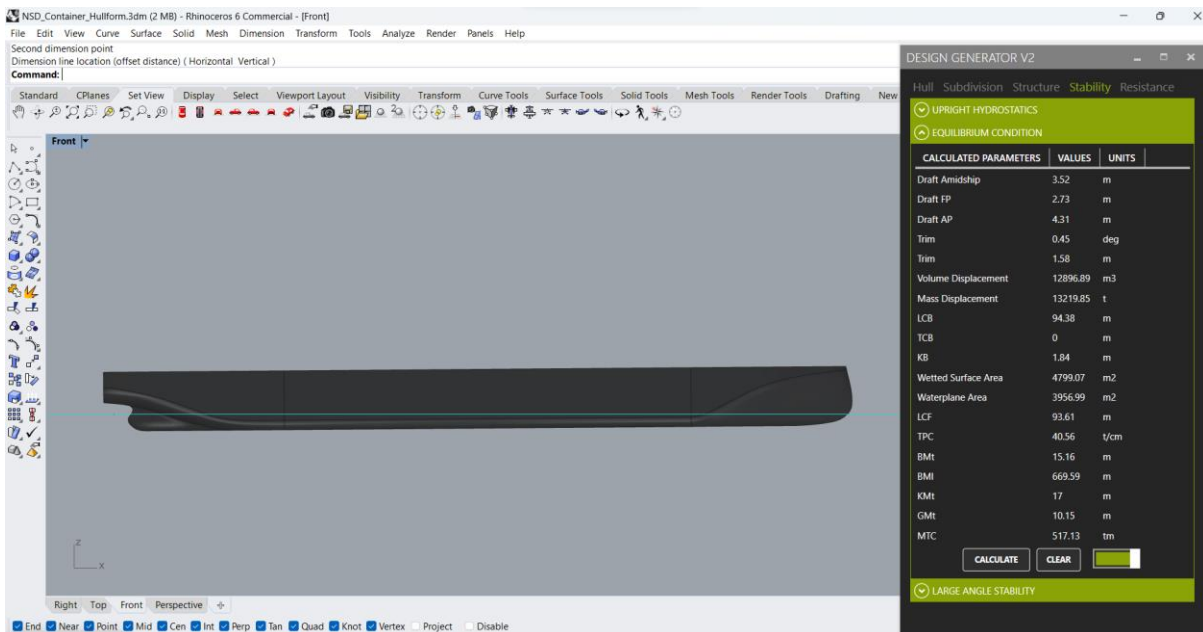


Figure 41 Equilibrium condition assessment using program.

After completing both upright hydrostatics and equilibrium analysis, the program can now calculate the righting lever curve and check the compliance of the ship against stability criteria laid down by (IMO, 2008). Righting lever curve can be generated by toggling the function under 'Large angle stability' expander and pressing the 'calculate' button. The generated GZ curve can be viewed by toggling the 'Display righting lever curve' option as shown in Fig 42(a)

Pressing the ‘Check Rules’ button compares the generated righting lever curve against IMO rules, and the results are displayed in a tabular format as illustrated in Fig 42(b). Criteria that don’t pass IMO rule check are marked as FAIL against the relevant entries. Designs that do not pass stability check and prompted to be recalculated with different inputs. The change in inputs that can be done to improve stability are as follows:

- Changing the main dimensions of the vessel and re-iterating the design process.
- Increasing freeboard of the vessel.
- Change the total weight of the vessel or loading condition.

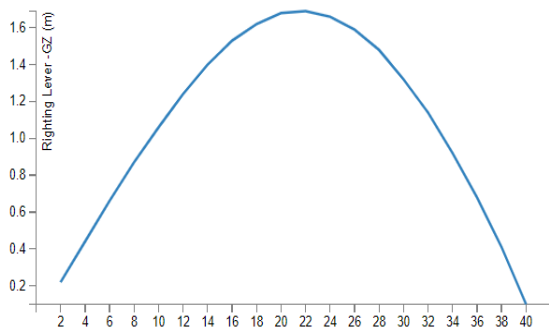


Figure 42(a) Righting Lever Curve generated by program.



Figure 42(b) Rule check against IMO Criteria

RESISTANCE TAB

As described in the previous sections, resistance calculation in the program is carried out using empirical method for approximate power prediction as described by (Mennen, 1982). The program takes as input data such as stern shape, wetted appendage area, immersed transom area and bulb characteristics, and calculates the resistance and powering data for the service speed provided as input in Hullform Tab. Resistance tab along with resistance and powering plots calculated by the program are shown below in Fig 43.

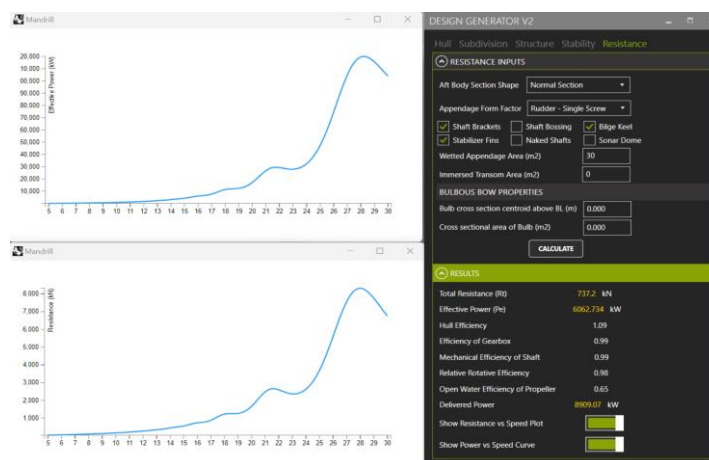


Figure 43 Resistance window and plots generated by program.

4. CASE STUDY

In this chapter, a concept study will be carried out to check and assess the performance of the developed application. In this case study, a new concept design of a general cargo vessel will be generated using the application. The structural scantling and stability results obtained from the application are summarized and validated against industry-approved design applications to ensure their accuracy. However, it should be noted that the resistance data from the application is not validated as it relies on empirical methods for estimation.

The main objective of this thesis is to establish a methodology that facilitates the concept development of vessels by automating various ship design tasks, thereby reducing the burden on designers. For the purposes of this case study, a new design with arbitrary project requirements is chosen instead of validating an existing design. This choice aligns with the primary focus of the application, which aims to facilitate the create and explore various design options for new designs, rather than validation and examination of existing designs.

In the following sections, we will be looking at preparing a concept design of a general cargo vessel as indicated by the mission requirements from table 4. The main requirements listed below are suggest the main dimensions, cargo capacity, operational area and the service speed of the vessel. Other requirements such as endurance, seakeeping, navigational and operational capabilities of the vessel are not explored in this study.

Table 4 Mission requirements for the case study.

Requirement	Value	Units
Length Overall	150	m
Moulded Beam	25	m
Maximum Depth	15	m
Service Speed	18	kn
Scantling Draft	8	m
Cargo carrying capacity	19000	t
Service Area Notation	R0	--

The information provided in the above table represent the essential information that are required for initiating a design process using the application and are typically provided by the client at the outset of a new design. Using this information, a design basis can be established which can then be automatically populated with plate panels and stiffeners. Based on this information, a design basis is established, and the program automatically generates the required plate panels and stiffeners. Subsequently, the software estimates the lightship weight, which is crucial for calculating the overall weight of the ship, an essential component of stability assessment. By utilizing the estimated floating draft obtained from the design, the program can perform resistance and powering calculations to determine the total power necessary for the vessel. These steps are explained in detail in the following sections.

To initiate the design, the main dimensions, vessel type, scantling draft and service speed of the vessel are fed into the main particulars expander under the hullform tab. Hitting the

calculate button generates hullform of the specified dimensions and provides the initial hydrostatics along with form parameters for the specific design, illustrated in Fig 44.

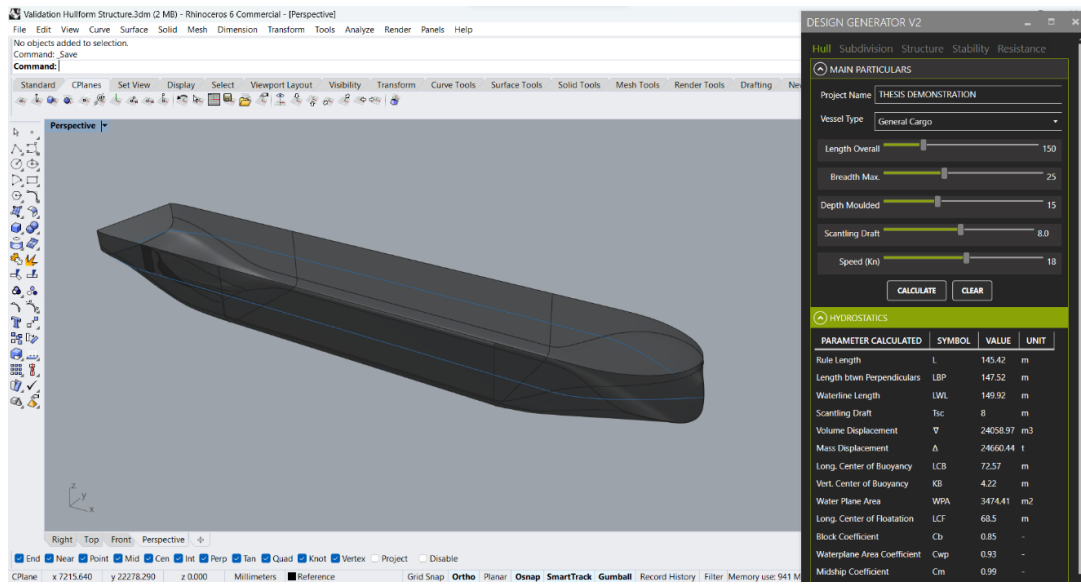


Figure 44 Hullform and initial hydrostatics developed from main particulars.

Next step in the process is to define the frame spacing of the vessel, frame spacing for this specific design was taken to be 600mm, and web frames are arranged every 4-frame spacing along the length of the vessel. Sliders under subdivision tab can be used for arranging the position of default structural elements in the design. Position of forepeak bulkhead is automatically recommended based on the Rule requirements (DNV, Rules for Classification: Ships (RU-Ship), 2022) and was chosen to be 9.6m aft of forward perpendicular. The location of remaining transverse watertight bulkheads is not strictly mandated by classification society rules, but recommended total number is suggested for damage stability. Transverse watertight bulkheads were provided at the following locations. These help in ensuring the stability of the vessel in case of damage and also help in segregating the machinery and tanks from cargo spaces.

Table 5 Bulkhead Positions

Bulkhead Name	Frame No.	Distance from AP.
Fore peak bulkhead	230	138
Aft peak bulkhead	12	7.2
Cargo hold aft bulkhead	48	28.8
Cargo hold forward bulkhead	200	120
Bulkhead FR#84	84	50.4
Bulkhead FR#120	120	72
Bulkhead FR#180	160	96

In addition to transverse bulkheads, wing tanks were added within the cargo spaces between frame 48 and 400, at an offset of 10.8m from CL of the vessel. Inner bottom panels were added between the fore and aft peak bulkheads at a height of 2.5m above the BL. The frame spacing, position of bulkheads, and inner bottom heights are added based on designer input and not

mandated by requirements. Automatic volume computation algorithm was used for determining the closed volumes of compartments and tanks, and these were categorized and named using the ‘define tank properties’ option. Fig 45 shows the hullform subdivided into compartment and tanks.

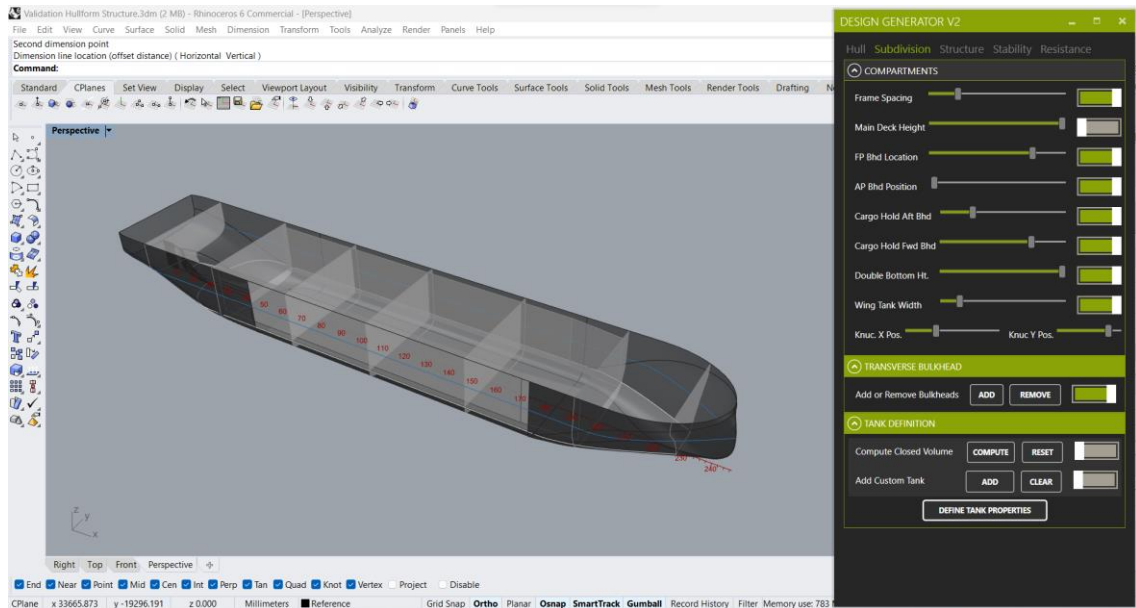


Figure 45 Hullform subdivided into compartments.

Once the compartments and tanks are defined, we move on to structural design module of the program. We begin with defining the grade and yield strength of the steel used in construction. Grade A steel plates having a yield strength of 235 MPa were chose for the case study. ‘Identify plate panels’ option is used for nesting the shell elements to plate panels of size 10m x 2m. These panels are also categorized into plate regions such as keel, bottom, sides etc and their respective area and centroids estimated. This information is used for calculation of the plate thickness. Fig 46 illustrates the thickness plot generated by the program.

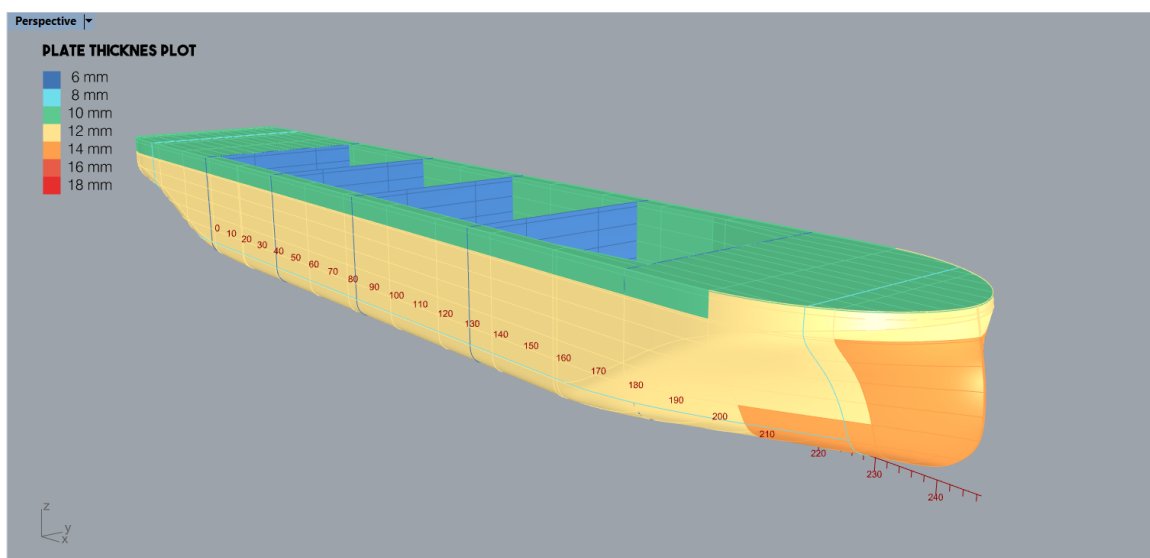


Figure 46 Plate thickness generated by application.

Plate thickness data thus calculated is then used for generating primary supporting members (PSM) and stiffeners. The span for stiffeners is calculated from frame spacing provided as 2400 mm and the spacing between stiffeners is taken to be 700mm. PSM and stiffeners are generated in the hull model, as illustrated in Fig 47.

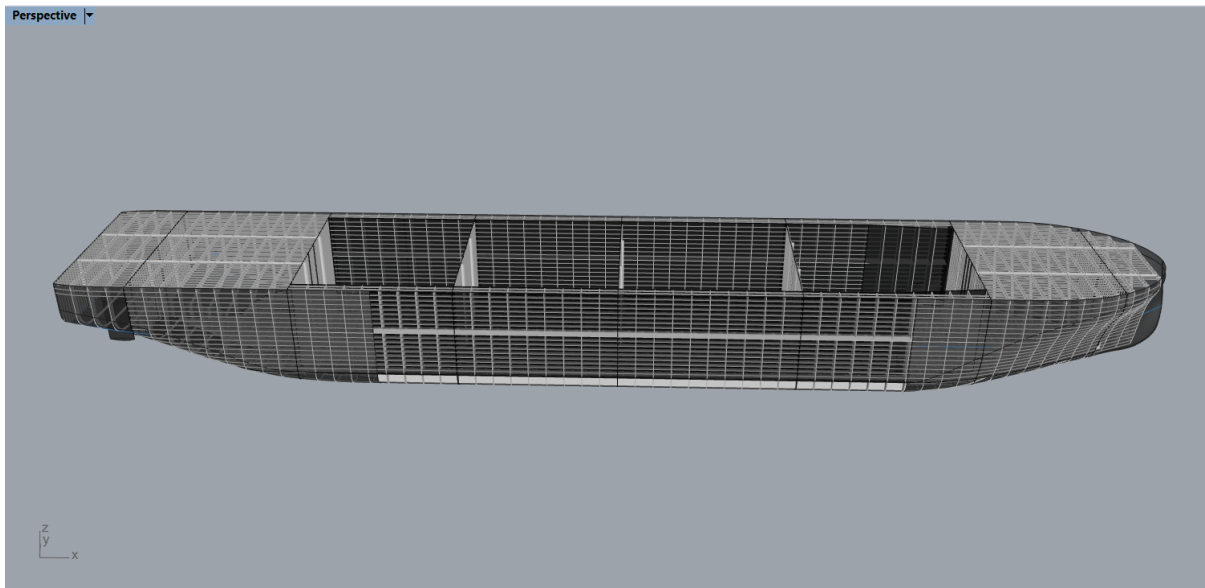


Figure 47 Stiffeners and PSM published to 3D model.

The total steel weight of the hull which includes the weight of all plate panels and stiffeners is automatically calculated by the software. Weight components such as equipment, machinery, and superstructure weight are manually provided. Additionally, cargo holds are loaded as detailed in Fig 48 to a total capacity of 19000 tons. Summary of total weight of the vessel is shown in Fig 49.

ADD DEADWEIGHTS				
Number of Entries (Max : 50) <input type="text" value="4"/>				
COMPONENT NAME	WEIGHT(T)	LCG(M)	TCG(M)	VCG(M)
Cargo hold FR48-84	5000	41.00	0.00	6.50
Cargo hold FR84-120	5500	62.00	0.00	6.25
Cargo hold FR120-160	4500	84.00	0.00	7.00
Cargo hold FR160-200	4000	108.00	0.00	5.85

Figure 48 Deadweight window

WEIGHT SUMMARY				
COMPONENT	WEIGHT(T)	LCG(M)	TCG(M)	VCG(M)
Hull Steel	2299.243	71.92	-0.01	6.36
Superstructure	229.920	6.50	0.00	18.50
Machinery	852.83	8.75	0.00	6.75
Equipment	1886.89	69.50	0.00	6.00
Additional	0.000	0.00	0.00	0.00
Deadweights	19000.000	71.37	0.00	6.41
TOTAL WEIGHT	24268.883	68.46	0.00	6.50
Deadweight Capacity (T)	391.56			
Deadweight Cefficient	0.02			

Figure 49 Weight summarized by application.

The total weight thus calculated serve as the primary input for stability calculation. Stability assessment of the design begins with estimation of upright hydrostatics data of the

vessel. Hydrostatics are calculated from an initial draft of 2m to a final draft of 14m with increments of 1m. The results from hydrostatics are tabulated in Fig 50.

UPRIGHT HYDROSTATICS													
DRAFT(M)	MASS(T)	LCB(M)	TCB(M)	KB(M)	WSA(M2)	WPA(M2)	LCF(M)	TPC(T/CM)	BMT(M)	BML(M)	KMT(M)	GMT(M)	MTC(TM)
2	5332	74.41	0	1.05	3132	2872	74.1	29.44	25.69	639.86	26.74	20.24	203.3
3	8331	74.21	0	1.57	3480	2971	73.61	30.45	17.3	446.96	18.87	12.37	221.88
4	11414	73.99	0	2.09	3821	3043	73.2	31.19	13.1	348	15.19	8.69	236.69
5	14571	73.77	0	2.62	4163	3119	72.67	31.97	10.62	291.64	13.24	6.74	253.22
6	17811	73.5	0	3.14	4514	3207	71.88	32.87	9	258.34	12.14	5.64	274.18
7	21157	73.14	0	3.67	4905	3334	70.3	34.17	7.88	243.83	11.55	5.05	307.4
8	24660	72.57	0	4.22	5323	3474	68.5	35.61	7.11	235.83	11.33	4.83	346.54
9	28249	72.05	0	4.76	5668	3523	68.57	36.11	6.38	213.72	11.14	4.64	359.75
10	31877	71.67	0	5.3	6007	3555	68.94	36.44	5.75	194.12	11.05	4.55	368.73
11	35533	71.41	0	5.84	6345	3579	69.38	36.68	5.21	177.44	11.05	4.55	375.7
12	39212	71.24	0	6.37	6682	3598	69.75	36.88	4.76	163.22	11.13	4.63	381.37
13	42906	71.12	0	6.89	7017	3608	69.96	36.98	4.36	150.48	11.25	4.75	384.73
14	46606	71.03	0	7.42	7350	3610	70	37	4.02	138.75	11.44	4.94	385.33

Figure 50 Upright hydrostatics data calculated by application.

Equilibrium floating condition of the vessel is now estimated using the upright hydrostatics data and total weight of vessel determined previously. Hydrostatics calculated for equilibrium floating condition is shown in Fig 51.

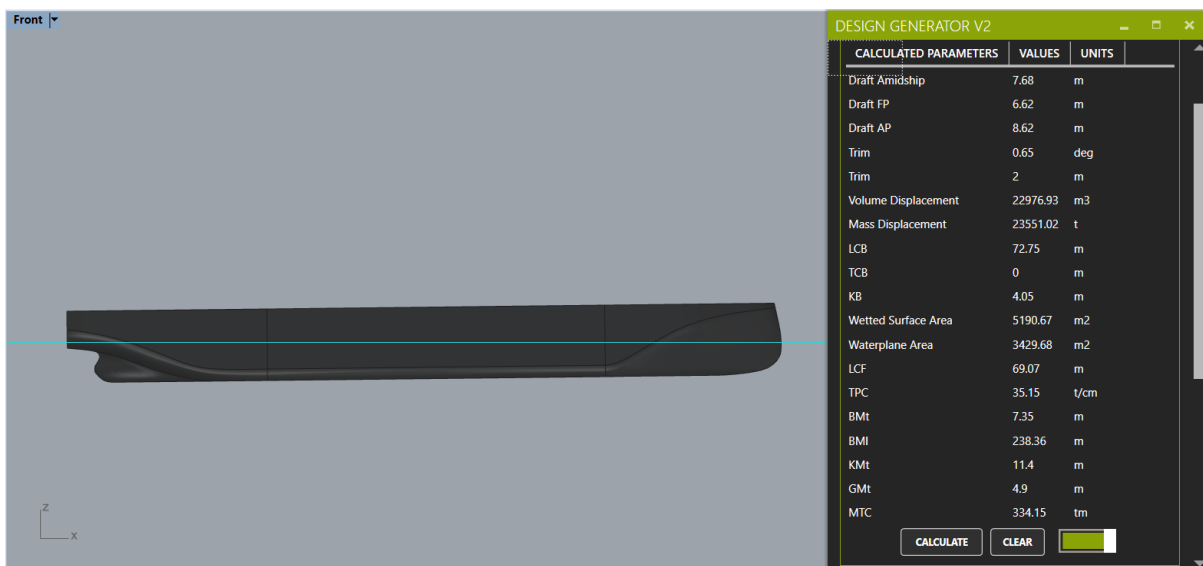


Figure 51 Equilibrium Condition Estimated by Program.

The vessel in equilibrium floating draft is inclined through 0 to 60 degrees in order to calculate the GZ curve for the vessel in the specific floating condition. GZ curve is an important parameter for assessing the static stability of vessels. Criteria for intact stability of vessels as described by (IMO, 2008) is checked based on the GZ values generated and the results are plotted. GZ curve calculated for the floating condition is illustrated in Fig 52 and results for the rule check against IMO stability criteria is shown in Fig 53.

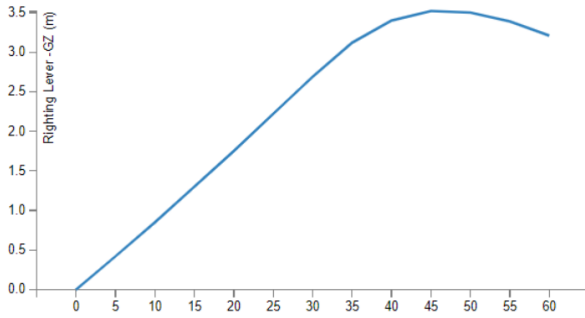


Figure 52 GZ Curve for floating condition

IMO MSC 267(58) CODE				
CR#	CRITERIA	REQ	ACTUAL	STATUS
CR1	Area under GZ Curve upto 30deg.	0.055	0.765	PASS
CR1	Area under curve upto 40deg or DF angle	0.09	1.237	PASS
CR1	Area under curve between 30deg and 40deg	0.03	0.596	PASS
CR2	Righting lever at 30deg or greater	0.2	3.531	PASS
CR3	Angle of Maximum Righting Lever	25	45	PASS
CR4	Initial Metacentric Height	0.15	4.813	PASS

DISPLAY RIGHTING LEVER CURVE

Figure 53 Rule check against IMO Criteria by application.

Since the vessel is found to satisfy the criteria for intact stability, we can now move to resistance and powering calculation. As explained in the previous chapter, resistance estimation is carried out by the application using method for approximate power prediction established by (Mennen, 1982). Inputs for resistance estimation and corresponding results calculation the total resistance and delivered power are illustrated in Fig 54. Resistance and powering curves calculated as illustrated in Fig 55.

RESISTANCE INPUTS

Aft Body Section Shape: Normal Section

Appendage Form Factor: Rudder - Single Screw

Shaft Brackets Shaft Bossing Bilge Keel
 Stabilizer Fins Naked Shafts Sonar Dome

Wetted Appendage Area (m2): 25.00

Immersed Transom Area (m2): 5

BULBOUS BOW PROPERTIES

Bulb cross section centroid above BL (m): 0.000

Cross sectional area of Bulb (m2): 0.000

RESULTS

Total Resistance (Rt): 1180.006 kN

Effective Power (Pe): 10917.416 kW

Hull Efficiency: 1.09

Efficiency of Gearbox: 0.99

Mechanical Efficiency of Shaft: 0.99

Relative Rotative Efficiency: 0.98

Open Water Efficiency of Propeller: 0.65

Delivered Power: 16042.92 kW

Show Resistance vs Speed Plot

Show Power vs Speed Curve

Figure 54 Resistance Calculation Inputs and Results

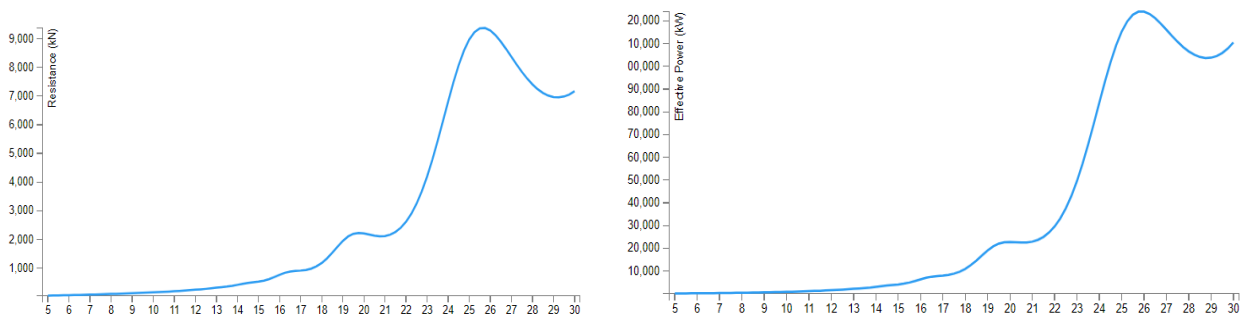


Figure 55 Resistance and Powering Curves generated by application.

5. DISCUSSION AND VALIDATION

The results from the case study in the previous chapter will be examined and discussed in the following sections. These results will also be validated against results from the same test run in widely accepted industrial software. Validation of the application is an important step for ensuring accuracy and assessing reliability of the designs generated by the application. Furthermore, it also helps in identifying potential errors or miscalculations in the application, thereby highlighting areas where the tool can be improved and enhances the precision of the application. Therefore, validation of results is an important step in ensuring the accuracy of the application's output.

Structural scantlings generated by the application and subsequent stability assessment carried out will be scrutinized and validated in the following sections by using established software widely used in the marine industry. Structure and stability modules being the main aspect of the program, it is important to validate these results against reliable sources to ensure the accuracy and reliability of the outputs. As explained in the previous chapter, resistance and powering analysis carried out by the program will not be validated, since this employs an empirical model based on direct equations.

5.1 STRUCTURAL SCANTLING RESULTS VALIDATION

The results from structural scantling calculation can be broadly classified into two main categories: plate thickness calculations and stiffener sizing. These calculations are carried out by the software using DNV Rules for classification of Ships (DNV, Rules for Classification: Ships (RU-Ship), 2022).

To ensure reliability and accuracy of validation process, these results are evaluated using proprietary software provided by DNV called Nauticus Hull. Nauticus Hull is a software package provided by DNV to its clients for strength assessment of hull structures. It offers tools for efficient hull design and verification according to DNV Rules and IACS Common Structural Rules for Bulk Carriers and Oil Tankers (CSR BC & OT). It offers designers tools for detailed calculations of plate thickness, stiffener sizing and other structural components, while considering the design criteria and loading. (DNV, Ship structural analysis and design - Nauticus Hull, 2023) It is widely recognised by naval architects and other classification societies for its capabilities and ensuring compliance of the design with DNV rules. Since the developed application deals with calculation of plate thickness and stiffener scantling according to DNV rules, DNV Nauticus Hull is found to be ideal tool for validation of results.

In order to validate of structural scantling results from the design tool, a test case was created in Nauticus Hull with the same main particulars and scantling results obtained from the design tool. The evaluation process in Nauticus starts with providing the main particulars for the vessel being designed, followed by definition of bulkheads and web frame locations. Additionally, Nauticus also provides the user with option for choosing the material properties of steel and choice for selecting the stiffener profiles used in calculation. In order to assess compliance with DNV rules, Nauticus Hull evaluates 2D sections along the length of the vessel. For the purpose of validation, a midship section (FR.130) from the original design was selected and modelled in Nauticus Hull based on the plate thickness and stiffener scantling calculated by the design tool. Figure 56 and 57, illustrates the comparison between the frame 130 modelled in Rhino using the design tool and the same frame modelled in Nauticus Hull.

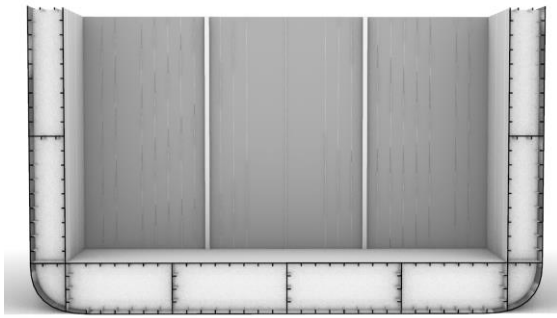


Figure 56 FR130 created in Rhino using design tool

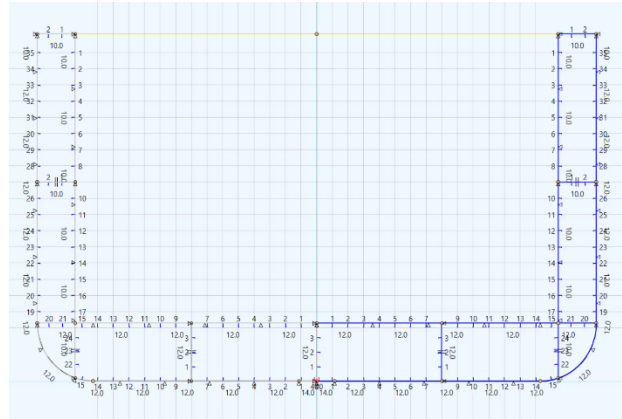


Figure 57 FR130 created in Nauticus using results from Design tool.

Plate thickness calculated from the design tool have been used for modelling the section in Nauticus Hull. Running cross sectional analysis tool to check compliance against DNV rules show that plate thickness satisfies DNV rule requirements. The results comparing plate thickness generated by the design tool against the Nauticus are summarized in Table 6.

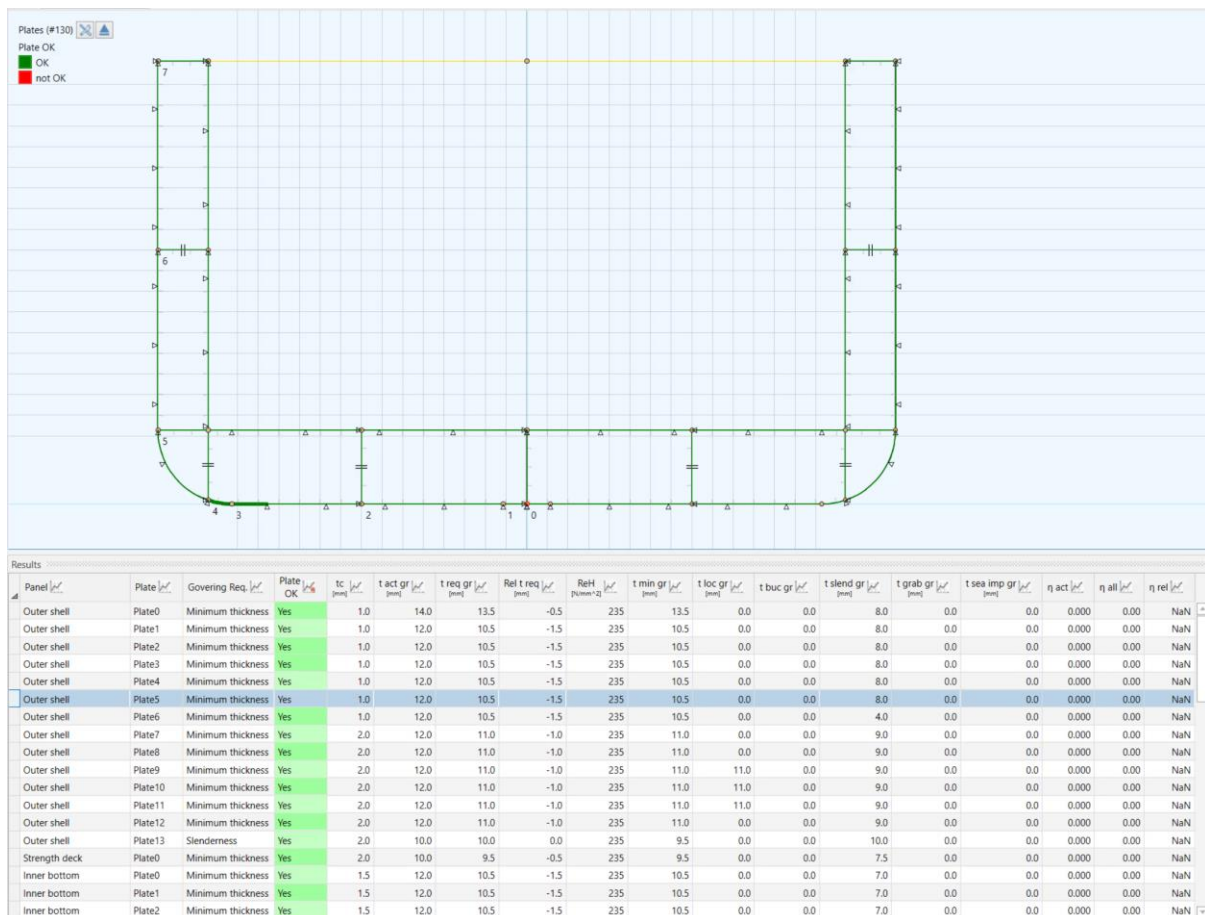


Figure 58 Plate thickness validation using Nauticus Hull

Table 6 Plate thickness calculation compared against Nauticus Results

Plate Group	Thickness Calculated by Design Tool	Thickness Calculated by Nauticus Hull	Status	Margin (%)
Keel	14.00	13.50	PASS	3.57
Bottom	12.00	10.50	PASS	12.50
Bilge	12.00	10.50	PASS	12.50
Side (Lower)	12.00	11.00	PASS	8.33
Side (Upper)	10.00	10.00	PASS	0.00
Strength Deck	10.00	9.50	PASS	5.00
Inner Side	10.00	8.50	PASS	15.00
Inner Bottom	12.00	10.50	PASS	12.50
Stringers	10.00	8.50	PASS	15.00
Girders	12.00	10.00	PASS	16.67

Similarly, stiffeners calculated by the design tool have been modelled in Nauticus hull for checking compliance with DNV rules. Nautical hull identifies the governing criteria for a specific stiffener and analyses compliance of the stiffener with the same automatically. As depicted in Fig 55, the governing criteria has been automatically chosen for most longitudinal is the minimum web thickness. However, for stiffeners on upper side shell the governing criteria is that of minimum section modulus. While the design tool currently checks the stiffeners against minimum web thickness and section modulus requirements specified in Part 3, chapter 6 and section 5 of DNV rule book (DNV, Rules for Classification: Ships (RU-Ship), 2022), the program in its present version does not account for additional section modulus requirements in sides for berthing. Therefore, these even while satisfying minimum web thickness are found to fail the requirements. Correction to section modulus calculation will be added in the further versions of the software. The results are summarized in Table 7.

Table 7 Summary of Stiffener rule check using Nauticus Hull.

Longitudinal Group	Stiffener Selected	Actual Web Thickness	Min. Web Thickness as per Nauticus	STATUS	Margin (%)
Keel	BP 140x7	7.00	6.5	PASS	7.14
Bottom	BP 140x7	7.00	6.5	PASS	7.14
Side (Lower)	BP 140x8	8.00	7.5	PASS	6.25
Side (Upper)	BP 140x8	8.00	7.5	FAIL	6.25
Strength Deck	BP 140x8	8.00	7.5	PASS	6.25
Inner Side	BP 160x8	8.00	7.5	PASS	6.25
Inner Bottom	BP 160x8	8.00	6.5	PASS	18.75
Stringers	BP 140x7	7.00	6.5	PASS	7.14
Girders	BP 140x8	8.00	6.5	PASS	18.75

Longitudinal stiffener calculated for upper side shell fail the criteria check as it does not meet the minimum section modulus requirements as it can be seen from Fig 59.

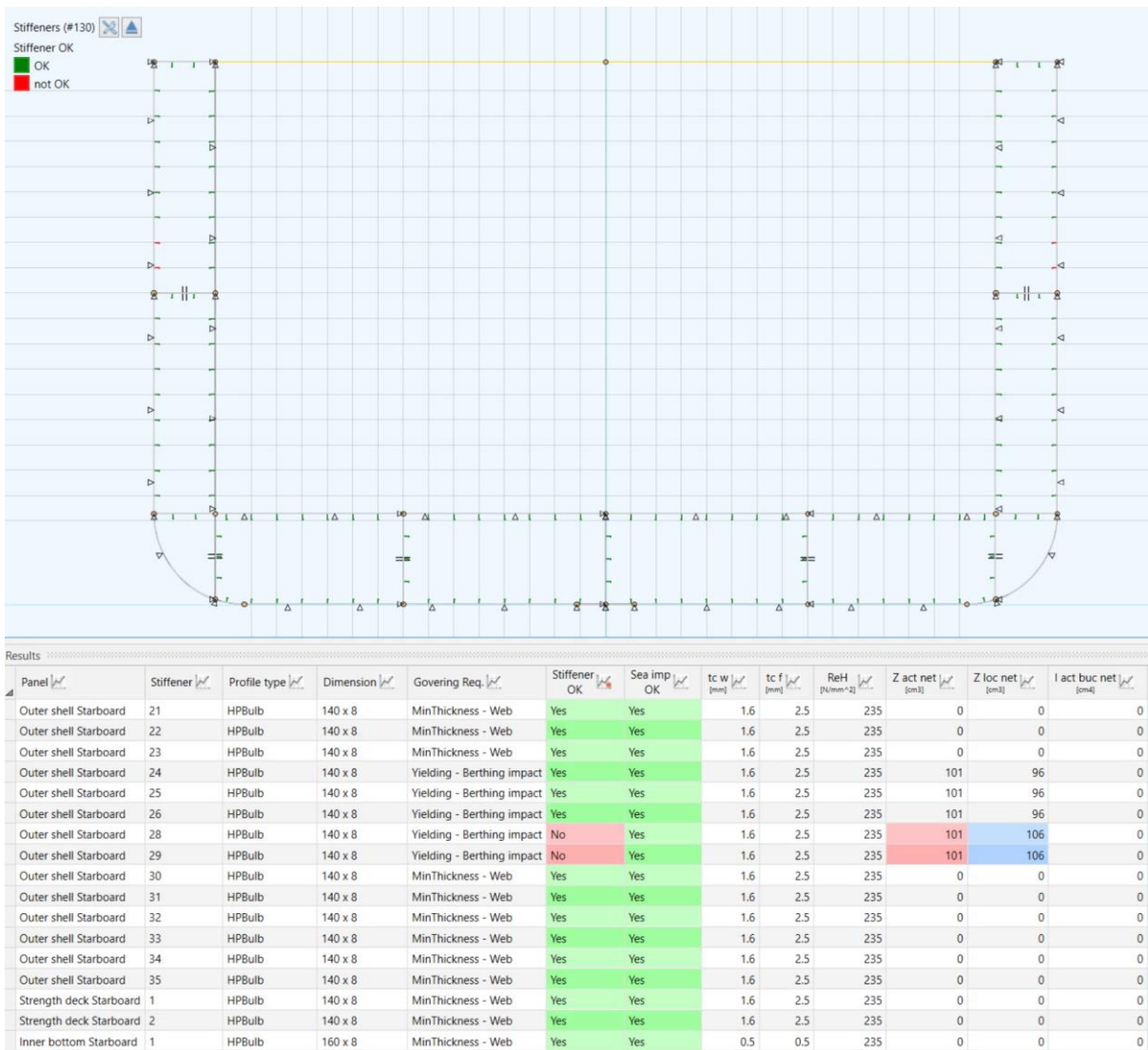


Figure 59 Stiffener sizing validation using Nauticus Hull

The results obtained from the design tool demonstrate that the calculated plate thickness meets the minimum requirements specified by DNV, as confirmed through validation using DNV Nauticus Hull. It is worth noting that the design tool rounds up the calculated plate thickness to the nearest commercially available plate thickness, which may account for the higher margin observed in the plate dimensions.

Regarding stiffener calculations, the design tool generally provides accurate results. However, during the validation process, it was observed that the design tool does not account for the additional section modulus required at berthing locations, as specified by the DNV rules. As a result, stiffeners in proximity to berthing areas may have smaller scantlings than what is mandated and require special attention during the design phase. This error has been identified and will be rectified in future versions of the software to ensure compliance with the complete set of DNV requirements.

5.2 STABILITY CRITERIA VALIDATION

Stability is one of the most importance aspects of ship design and it is also what differentiates the design of floating structures from other civil constructions. Intact stability directly affects the safety of the crew and cargo while at sea and is therefore a crucial element in any concept design. Stability of new designs are assessed based on stability criteria established by regulatory bodies. For this specific application, IMO code for intact stability of ships, specifically that mentioned in (IMO, 2008) has been referred. Validation of stability calculations done by the program help assess the accuracy of the calculation. It also helps to identify potential risk and miscalculations that can affect the overall stability of the vessel, and which could risk the safety of crew, cargo, and passengers onboard. Therefore, validation of the design's stability characteristics using a widely accepted stability software is of utmost importance.

For this case study, the stability results are validated using Bentley Maxsurf. Maxsurf is a ship design package offered by Bentley software solutions and comes with various modules for different aspects of ship design such as hullform modelling, stability calculations, structural modelling, resistance estimation and hydrodynamic analysis. Maxsurf allows definition of hull using trimmed NURBS surfaces without the need for offsets or batch file preparation. It also supports the use of native Rhino 3D files for definition of hull and tanks, which makes the replication of hullform highly efficient and accurate. For the same reason, Maxsurf was found to be ideal choice for validation of stability results.

As mentioned in the previous chapters, stability results are categorized into three sections as: upright hydrostatics, equilibrium condition, and righting lever curve with rule checking. The results from design tool are validated against the results generated by Maxsurf to assess its accuracy and performance. Upright hydrostatics data are calculated in both in design tool and Maxsurf for vessel draft ranging from 2m to 14m above BL, in increments of 1m. Results generated by Maxsurf are tabulated in Table 8.

Table 8 Upright hydrostatics results from Maxsurf

	Draft Amidships m	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000	10.000	11.000	12.000	13.000	14.000
1	Displacement kg	53290	83268	11409	14566	17807	21153	24655	28243	31871	35527	39204	42897	46596
2	Heel deg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	Draft at FP m	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000	10.000	11.000	12.000	13.000	14.000
4	Draft at AP m	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000	10.000	11.000	12.000	13.000	14.000
5	Draft at LCF m	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000	10.000	11.000	12.000	13.000	14.000
6	Trim (+ve by stern) m	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	WL Length m	142.06	143.33	143.48	143.22	143.44	147.51	149.91	149.80	149.64	149.45	149.24	149.02	148.82
8	Beam max extents on WL m	24.957	25.000	25.000	25.000	25.000	25.000	25.000	25.000	25.000	25.000	25.000	25.000	25.000
9	Wetted Area m ²	3120.7	3460.4	3794.8	4125.5	4468.1	4849.5	5260.1	5669.8	5877.9	6184.0	6488.8	6790.4	7089.7
10	Waterpl. Area m ²	2870.1	2969.3	3043.6	3119.3	3207.8	3333.4	3473.9	3522.2	3554.1	3577.9	3596.0	3605.9	3607.1
11	Prismatic coeff. (Cp)	0.767	0.779	0.794	0.808	0.820	0.810	0.811	0.826	0.839	0.850	0.861	0.870	0.878
12	Block coeff. (Cb)	0.733	0.756	0.776	0.794	0.807	0.799	0.802	0.817	0.831	0.843	0.854	0.864	0.873
13	Max Sect. area coeff. (Cm)	0.956	0.970	0.977	0.982	0.985	0.987	0.989	0.990	0.991	0.992	0.992	0.993	0.994
14	Waterpl. area coeff. (Cwp)	0.810	0.829	0.849	0.871	0.895	0.904	0.927	0.940	0.950	0.958	0.964	0.968	0.970
15	LCB from zero pt. (+ve fwd) m	74.413	74.213	73.996	73.769	73.500	73.137	72.566	72.048	71.671	71.412	71.240	71.122	71.035
16	LCF from zero pt. (+ve fwd) m	74.117	73.626	73.185	72.652	71.853	70.311	68.501	68.566	68.927	69.365	69.736	69.951	69.993
17	KB m	1.049	1.572	2.094	2.616	3.141	3.673	4.217	4.761	5.301	5.836	6.367	6.895	7.419
18	KG m	6.500	6.500	6.500	6.500	6.500	6.500	6.500	6.500	6.500	6.500	6.500	6.500	6.500
19	BMT m	25.697	17.311	13.110	10.626	9.000	7.882	7.111	6.382	5.750	5.212	4.757	4.363	4.018
20	BML m	639.11	446.68	348.26	291.99	258.69	243.70	235.79	213.66	194.06	177.33	163.01	150.19	138.41
21	GMt m	20.246	12.383	8.704	6.741	5.641	5.055	4.828	4.644	4.550	4.548	4.624	4.758	4.937
22	GML m	633.66	441.75	343.86	288.10	255.33	240.87	233.51	211.92	192.86	176.67	162.88	150.59	139.33
23	KMt m	26.746	18.883	15.204	13.241	12.141	11.555	11.328	11.144	11.050	11.048	11.124	11.258	11.437
24	KML m	640.16	448.25	350.36	294.60	261.83	247.37	240.01	218.42	199.36	183.17	169.38	157.09	145.83
25	Immersion (TPc) tonne/cm	29.419	30.436	31.198	31.973	32.881	34.168	35.608	36.103	36.430	36.674	36.859	36.961	36.973
26	MTC tonne.m	228.85	249.28	265.87	284.41	308.13	345.30	390.18	405.64	416.57	425.37	432.76	437.79	440.00

Hydrostatics data for WL8 calculated by both Maxsurf and design tool are compared side by side in Table 9 to get a better understanding of data discrepancy.

Table 9 Hydrostatics data comparison at WL8

Parameter	Data from Maxsurf	Data from Design Tool	Margin (%)
Draft Amidship m	8.00	8.00	0.00
Displacement t	24655.90	24660.00	0.02
Wetted Area m²	5260.20	5323.00	1.19
Waterpl. Area m²	3473.93	3474.00	0.00
Prismatic coeff. (Cp)	0.81	0.84	3.58
Block coeff. (Cb)	0.80	0.85	5.99
Max Sect. area coeff. (Cm)	0.99	0.99	0.10
Waterpl. area coeff. (Cwp)	0.93	0.93	0.32
LCB from zero pt. (+ve fwd) m	72.57	72.57	0.01
LCF from zero pt. (+ve fwd) m	68.50	68.50	0.00
KB m	4.22	4.22	0.07
KG m	6.50	6.50	0.00
BMt m	7.11	7.11	0.01
BML m	235.80	235.83	0.01
GMt m	4.83	4.83	0.04
KMt m	11.33	11.33	0.02
Immersion (TPc) tonne/cm	35.61	35.61	0.01
MTc tonne.m	390.19	346.54	11.19

From the result comparison summarized in Table 9, it can be observed that the difference between the hydrostatics data calculated in both Maxsurf and design tool are relatively small, with an average variation less than 1.5%. However, there are larger deviations observed specifically for MCT. These discrepancies are likely attributed to the differences in the computation of GML values by both software. Further analysis is necessary to understand the underlying behaviour and to implement appropriate corrective measures.

Equilibrium analysis allows the user to determine the draft, heel and trim of the vessel as a result of loads applied to it. Equilibrium condition of the vessel is computed on both software using the same weight data calculated within the structure module. Results from both software are summarised and compared in Table 10.

Table 10 Comparison of Equilibrium condition calculated between Software.

Parameter	Results from Maxsurf	Results from Design Tool	Variation (%)
Draft Amidships m	7.79	7.68	1.39
Displacement t	24270.39	23551.02	2.96
Draft at FP m	6.49	6.62	2.07
Draft at AP m	9.09	8.62	5.18
Total Trim m	2.61	2.00	23.22

Comparing the results from both applications indicate a deviation in the estimated floating draft and trim values. There are few possible reasons for such a discrepancy, but primarily this can be attributed to the method in which each software calculates hydrostatics parameters and approximation used in both calculations.

The developed design tool calculates equilibrium floating condition based on the hydrostatic values calculated in the previous step. The program assumes the vessel floats at a minimum draft, subsequently the remaining weight is added to the vessel at the calculated equivalent centroid such that the final weight configuration becomes the loaded condition of the vessel. In this method, the new floating draft is calculated based on the TPC of the initial floating draft and the extra weight being added. However, TPC is variable which changes with the waterplane area and therefore an iterative solution is required as the vessel reaches draft which is not implemented in the software. After estimation of the floating draft, trim of the vessel is estimated based on the moment of the added weight about LCF at floating draft. Both position of LCF and MCT value for the estimated draft is interpolated based on hydrostatic data available for waterplanes at every 1m interval. A linear interpolation scheme is employed, which is also adds to slight inaccuracy in calculations.

Whereas the design tool relies exclusively on the hydrostatic values calculated based on the waterplane surface in Rhino, Maxsurf divides the input geometry into a number of sections and employ integration methods for hydrostatic calculations. This is clearly explained in the manual for Maxsurf Stability module (User Manual, Appendix-A, 2013) along with potential areas for errors in hydrostatic calculations. According to Maxsurf developers (User Manual, Appendix-A, 2013), there are several potential sources of errors when calculating the hydrostatic properties of immersed sections. The main source of error stems from the integration method employed, which typically relies on numerical integration techniques such as Simpson's rule or the Trapezium rule. The accuracy of these methods improves as the step size is reduced, allowing for more precise calculations. These differences in calculation precision become apparent when comparing the results obtained from different hydrostatics packages applied to the same hullform. Generally, variations in basic parameters such as displacement are typically below 0.5%, which is considered good agreement. However, derived form parameters may exhibit more significant variations. Maxsurf developers associated the error in calculation and deviation in results to the following factors:

- Convergence limits when balancing a hull to a specified displacement or centre of gravity.
- Different number of integration stations used, and their distribution. Where there are large changes in shape, such as near the bow and stern, the stations should be more closely spaced. This can be of particular importance if the waterline intersects the stem profile between two sections.
- Differences in the hull definition, and number of interpolation points used to define each section. If the surface is exported as DXF poly-lines then the precision used and he number of straight-line sections used to make up the poly-line are important.
- The integration method used: trapezium, Simpson, or higher order methods.

The variation in equilibrium condition results is noted, and it is acknowledged that further examination and rectification are necessary in future versions of the program. By addressing these variations, the aim is to enhance the accuracy and reliability of the program's calculations for equilibrium conditions.

The third and final step in stability assessment of a new design is calculating the GZ curve at the loaded condition and checking compliance with regulatory requirements. Figure 60 and 61 illustrate the GZ curves generated by both Maxsurf and the design tool for comparison. Table 11 provides a summary and comparison of the corresponding GZ values obtained from both applications. This comparison serves to assess the consistency and accuracy of the stability calculations performed by the design tool, validating its capability to predict the vessel's stability characteristics.

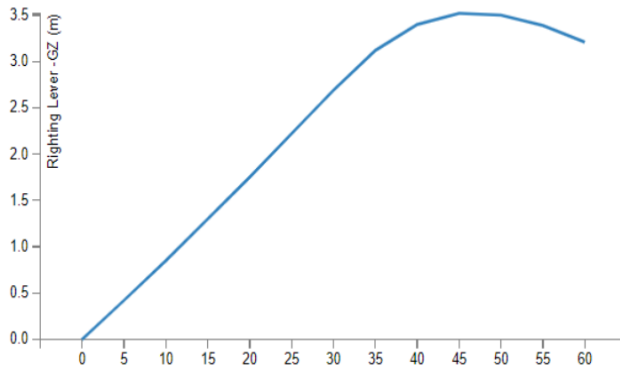


Figure 60 GZ Curve generated by the tool.

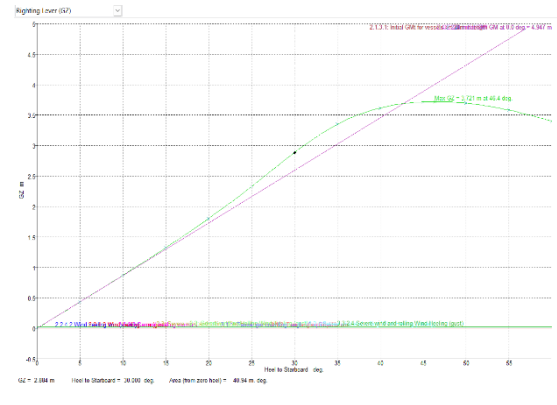


Figure 61 GZ Curve generated by Maxsurf.

Table 11 Comparison of GZ values from both applications

Heeling Angle (deg)	GZ from Maxsurf (m)	GZ from Design Tool (m)	Variation (%)
0	0.00	0.00	0.00
5	0.43	0.42	2.78
10	0.87	0.85	2.30
15	1.32	1.30	1.66
20	1.80	1.75	2.94
25	2.33	2.22	4.60
30	2.88	2.69	6.73
35	3.35	3.12	6.81
40	3.62	3.40	6.00
45	3.72	3.52	5.27
50	3.69	3.50	5.25
55	3.58	3.39	5.33
60	3.40	3.21	5.50

Since GZ data is calculated in the floating condition, the variation in results as observed for equilibrium condition is reflected in GZ calculations as well. GZ data is seen to have an average variation of 4.24% between both applications. Both Maxsurf and the design tool offer automatic check for compliance with IMO Rules for Intact stability. (IMO, 2008). The results of these compliance checks are compiled in Table 12 for reference and further analysis.

Table 12 Rule Check Comparison data from both software.

Criteria	Required	Calculated from Maxsurf	Calculated from Design Tool	Variation (%)
Area under curve from 0 to 30 deg	0.055	0.7145	0.765	7.07
Area under curve from 0 to 40 deg	0.09	1.2929	1.237	4.32
Area between 30 to 40 deg or DF	0.03	0.5784	0.596	3.04
Maximum GZ at 30 deg or greater	0.2	3.721	3.531	5.11
Angle of Maximum GZ	25	46.4	45	3.02
Initial GMt	0.15	4.947	4.813	2.71

Considering that both applications perform the rule check using the generated GZ curve, it is expected to observe similar discrepancies in the stability criteria results presented by each software. The average deviation of 4.21% indicates a variation between the results, with Maxsurf generally showing a higher margin. This deviation could be attributed to differences in the calculation methods and algorithms employed by the two applications. These discrepancies will be analysed in detail to identify the underlying causes and ensure that the stability criteria are accurately assessed and met.

In conclusion, the intact stability results obtained from the design tool were compared and validated against the Maxsurf stability module for the selected test case. The comparison revealed that both software packages yielded similar results with minimal deviation for upright hydrostatics calculations. However, slightly higher discrepancies were observed in the calculations for equilibrium conditions and GZ curve generation. These deviations can be attributed to the different approaches and methods employed by the two applications.

The observed errors in the stability data can be attributed to several factors. Firstly, the discrepancies may arise from differences in the convergence limits used during the hull balancing process. Additionally, inadequate station distribution in representing the hull form could contribute to inaccuracies in the stability calculations. Another contributing factor is the use of approximation methods in the numerical integration techniques employed by both software packages, which can introduce some level of error.

To address these discrepancies and enhance the accuracy of the stability calculations, further analysis and improvements will be carried out in future versions of the design tool. The areas of concern will be thoroughly examined, and corrective measures will be implemented. By addressing these issues, the design tool can provide more reliable and accurate stability results, ensuring the safety and performance of the designed vessels.

6. BEYOND PARAMETRIZATION

Methodology for automating ship design process developed during the course of this thesis, can extend beyond the scope of simple parametric design practice and become a foundation to efficient ship design practice. Automated concept design methodology, implemented with the help of Grasshopper for Rhino was tested to create several designs of different main requirements. The use of design tool was found to have various benefits as explained below:

- **Savings in Time and Money** – Proper implementation of the ship design automation tool can provide significant reductions in time spend by the designer in concept design stage, which in effect leads to cost savings for the design firm in the long run.
- **Better Exploration of Design Space** – Parametrization of concept design process by automating design tasks gives the designer more time for exploring various possible design options early in the development stage and arrive at the best suitable solution for the specific project requirements.
- **Using 3D Model as Starting Point in Design** – The Concept design tool designed based on Rhino allows the use of its inherent 3D modelling capabilities, to visualize the hullform from start to finish during the design process. This also helps the designer identify possible issues in the design and correct these at an early stage.
- **A Comprehensive Design in Minimal Time** – The final output from the tool is in a 3D model format complete with nested plates and stiffeners. Inherent properties of the scantlings such as dimensions, thickness and material are stored as attributes and can be reused on other platforms. The final output also contains consolidated scantling, weight, stability, and resistance report so that the design can be evaluated against other designs more effectively.
- **Check Rule Compliance** - The tool also automatically calculates structural scantlings based on DNV rules, and stability according to IMO criteria without the need for user prompts. Thereby, the process of evaluating the design against regulatory criteria has been made much for efficient, reducing the overall time for validation and workload on the designer.

Asides from the benefits mentioned above, the output from the tool can also be coupled with other applications to greatly increase the scope of design. In this aspect, the design tool has numerous possible applications, some of which are discussed below:

1. **Hullform Optimization** – The tool in its present configuration generates hullform of the required dimensions based on the provided vessel type. It basically modifies the feature curves of the template to scale the vessel to dimensions provided by the user. However, this feature can be further expanded by introducing a hullform optimization script which fairs the generated hullform by smoothing waterlines to ensure a good flow around the hull, thereby reducing resistance and increasing overall performance of the vessel.
2. **Structural Optimization** – Once the hullform and compartments in the vessel are finalized, the tool automatically generates plates and stiffeners based on DNV Rules.

However, there are many different configurations in which plates and stiffeners can be generated. These are controlled by parameters such as span, spacing of stiffeners, profile shape and material properties of steel. These parameters can be iteratively explored using an optimization algorithm to find the best balance between structural strength and weight.

3. **Drawing Generation** – The final output from the design tool at the end of each design iteration is a 3D model of the vessel complete with structural scantlings. This can be used as basis for generating drawings. The 3D model thus generated can be sectioned to 2D curves for creating drawings such as section plans, construction profiles, deck plans, shell expansion, tank plan, general arrangement of the vessel etc. Rhino also has the capability to export designs in .dxf and .dwg formats, making the designs generated compatible with 2D CAD software such as AutoCAD. These plans can be used for design approval or as fabrication drawings which greatly increases the application of the tool.
4. **Finite Element Analysis** – Since the final output is in surface format, the hullform generated by the tool along with complete structural scantlings can be exported to an external 3rd party application such as Ansys, Staad or Siemens NX for finite element analysis. The parametrization capabilities of the design tool linked with FEA capabilities of the mentioned software packages can be a greatly useful implementation.
5. **CFD Analysis** – at present, the tool calculates resistance of the vessel using empirical formulae. However, this can be greatly improved by coupling output from tool to CFD packages such as Openfoam, Ansys Fluent or StarCCM. Since CFD analysis is a time and resource intensive process, checking the resistance of each design created by the tool using CFD methods would not be a efficient method. The parametric capabilities of the design tool can be used to shortlist a few viable design options, which can be run on CFD packages for resistance estimation. The output in such cases would be the hull in surface or mesh format, the floating draft, trim in floating condition and the speed for which the simulation is to be carried out. Domain definition, meshing, boundary, and solver specification can be carried out in chosen CFD software.
6. **Artificial Intelligence** – The marine industry is currently in the process of revolutionizing itself with the application of AI in many domains, a few examples being autonomous navigation, trajectory prediction, route optimization and so on. However, the use of AI in improving the design of vessels are yet to be explored in detail. One possible application of coupling the design tool with neural network is discussed here. Once the design tool has been rigorously tested and validated, the design outputs from the tool can be used to train an artificial neural network. The input parameters for optimization could be main dimensions, type, draft, and speed of the vessel. By leveraging the output from design tool for training AI, new vessel designs can be automatically created and optimized. Naval architects could possibly be replaced by artificial neural networks in future in many aspects of design development.

It should be noted that the application of design tool discussed above are not included in the present version of automation tool, as the thesis is being return. The objective here is to explain how parametrizing concept design by automating design tasks can have more applications by coupling with software packages leading to better ship design process.

7. CONCLUSION

The objective of the thesis work is oriented towards addressing these issues and developing a methodology for streamlining the concept ship design process by automating various ship design tasks. By automating certain aspects of ship design, designers can save valuable time which can be focussed on exploring different design options and narrowing down the best design for the specific requirements.

Throughout the thesis, we have looked at the concept design process in detail and identified the tasks that hold significant potential for automation. We have also looked at various software that are widely used in the marine industry to narrow down on the most suitable package for automating ship design task. From thorough examination, Rhinoceros coupled with its inbuilt programming language called Grasshopper was found to be the best option for the specific application. Subsequently we moved forward to developing a streamlined methodology for automation of the concept design tasks identified previously. The method facilitates the designer to create hullform from few basic input parameters. It also provides the designer with tools to easily compartmentalizing the hullform, while automatically identifying and delineating compartments and tanks from the model. The methodology further facilitates the nesting panels into steel plates of appropriate thickness, and populate stiffeners based on DNV rules. Doing so enables, automatic calculation of steel weight of the hull which is subsequently used in stability analysis of the design. Finally, floating draft from the equilibrium condition will be used for calculating the total resistance of the vessel and thereby, the total required installed power for the vessel. The methodology so formulated was programmed into Grasshopper to create concept design automation tool which works in conjunction with Rhino 3D modelling interface. The tool has a GUI for accepting information from the user and displaying results to the user, while it used the 3D modelling interface of Rhino to provide a real-time 3D model of the vessel being designed.

Working through the various design tasks in a systematic manner completes a design cycle and provides the designer with a concept design of the vessel in Rhino which is a 3D model complete with structural scantling data, weight details, stability, and resistance information. The Rhino 3D model generated by the tool, such as the one illustrated in Fig 40, can be used for a multitude of design applications, such as creating drawings, nesting plate panels or even exported to other applications for FEA and CFD analysis. By visualizing the design, potential issues or shortcomings can be identified promptly, enabling timely rectification and improvements. The concept design tool for Rhino offers designers a valuable advantage by streamlining the generation of a comprehensive 3D model of the hullform. With this tool, designers can create a detailed and accurate representation of the hull, including nested panels and stiffeners, in a significantly reduced timeframe compared to manual methods which can be highly time consuming and labour intensive. The program also increases the efficiency and significantly reduced the time in design process by bringing various aspects of design such as 3D modelling, structural design, stability and powering calculation together one package. Moreover, the program also streamlines the whole process by using the output from one module as the input for the next with minimal inputs from the designer.

With that being said, the present implementation of the automated design methodology using Rhino and grasshopper has a few drawbacks as well. Grasshopper is essentially a visual programming language built into Rhino, which enables the user to make use of functions and

commands available in Rhino in a programming interface. This allows users to parametrically control geometric or automate design process. However, information has a unidirectional flow within Grasshopper meaning that simple programming elements like a global variable or a loop is very difficult to implement within Grasshopper. Having a linear workflow, Grasshopper also struggles with large and complex models. Grasshopper is also known to have performance issues when working with large models resulting in higher processing times, leading to slow performance and potential crashes. During the development of the application, this issue was addressed in 2 ways. First, the program was divided into computational blocks that are only activated when prompted by the user. This way, computational resources are utilized only when necessary, minimizing the strain on the system. Additionally, certain computationally intensive tasks, such as plate thickness calculation and stiffener sizing, were performed outside of the Grasshopper interface using external tools like spreadsheets and VBA. This helps to reduce computational time and improve overall performance.

While the established methodology for ship concept design presented in the thesis has its strengths, it's important to acknowledge its limitations and potential drawbacks. Several aspects of the design process are not addressed within the methodology.

- **Missing Design Tasks:** The methodology does not incorporate tasks such as seakeeping analysis, endurance calculation, drawing generation, and cost estimation.
- **Limited Design Options:** The methodology relies on modifying a design template of a vessel, which may limit the extent to which design options can be explored. It may not provide the flexibility needed to fully explore and optimize different design configurations.
- **Structural Strength Assessment:** While the methodology includes local and global strength assessments according to DNV rules, it does not consider fatigue and buckling failures. These are crucial considerations for ensuring the long-term structural integrity of the vessel.
- **Damage Stability:** The present version of the application does not take into account the assessment of damage stability, which is essential for evaluating a ship's ability to withstand damage and maintain stability.
- **Optimization Capabilities:** The initial idea of incorporating a separate script to iterate through design parameters and identify designs with the best stability characteristics for the least lightship weight has not been implemented. This limits the optimization capabilities of the methodology.

Addressing these limitations and incorporating the missing design tasks would enhance the comprehensiveness and accuracy of the methodology. Further development and refinement of the methodology could involve incorporating seakeeping analysis, endurance calculation, drawing generation, cost estimation, and additional assessments such as fatigue, buckling, and damage stability. Optimization algorithms could be integrated to explore a wider range of design options and identify optimal designs based on stability and weight criteria.

Finally, the design tool developed using the proposed methodology was used to develop the concept design of a 150m long General Cargo vessel. Structural scantling and stability results were validated against widely approved industrial software. The tool demonstrated its capability to generate accurate structural scantling results, with minor discrepancies that can be addressed in future versions. The stability calculations showed good accuracy in upright

hydrostatics but exhibited some variations in equilibrium and large angle stability, which can be attributed to the different approach taken by the application for equilibrium estimation. These discrepancies will also be addressed in future versions of the tool.

It is important to note that the primary objective of the application was to serve as a proof of concept for the formulated methodology, rather than being a fully comprehensive system for concept design. The application successfully demonstrated the feasibility and potential of the methodology, providing a foundation for further development and improvement. Therefore, in that context, the application can be considered successful in fulfilling its purpose.

The development of this design tool highlights the possibilities of automation in ship concept design, streamlining the process and reducing the time and effort required by designers. With future iterations and enhancements, it has the potential to become a valuable tool in the ship design industry, enabling designers to explore design options more efficiently and effectively.

8. FUTURE WORKS

While the design tool developed in this thesis has demonstrated the feasibility of automating certain aspects of ship concept design, there are several avenues for further development and improvement. The following areas can be considered for future works:

- **Enhanced Stability Analysis:** The present version of the design tool focused on upright hydrostatics and basic stability criteria. Future versions can incorporate more comprehensive stability analysis, including damage stability, seakeeping analysis, and advanced stability criteria as per industry standards and regulations. This would provide designers with a more comprehensive understanding of the vessel's stability characteristics.
- **Integration of Additional Design Tasks:** The current methodology primarily focuses on hullform generation, structural scantling, and basic stability analysis. Future iterations can expand the functionality of the design tool to include other design tasks such as endurance calculation, seakeeping analysis, drawing generation, and cost estimation. This would provide a more holistic approach to ship concept design and enable designers to consider multiple factors simultaneously.
- **Optimization and Iteration:** The design tool can be further developed to incorporate optimization algorithms that iteratively modify design parameters to optimize certain objectives, such as minimizing weight while meeting stability requirements. This would allow designers to explore a wider range of design options and identify designs that offer the best trade-offs between various performance parameters.
- **Integration of Fatigue and Buckling Analysis:** The structural strength assessment in the current version of the tool focuses on local and global strength according to DNV rules. Future versions can incorporate fatigue and buckling analysis to account for potential failures due to cyclic loading and structural instability. This would provide a more accurate assessment of the vessel's structural integrity.
- **User Interface and Usability Improvements:** The user interface of the design tool can be further enhanced to improve user experience and ease of use. This includes developing a more intuitive and user-friendly interface, providing clear instructions and guidance for input parameters, and incorporating visualization tools for better understanding and analysis of the design results.
- **Validation and Verification:** Future works should include rigorous validation and verification processes to ensure the accuracy and reliability of the design tool. This can involve comparing the results of the design tool with physical model tests, full-scale measurements, or data from established software packages. This validation process will further enhance the credibility and trustworthiness of the design tool.

In conclusion, there are several areas for future development and improvement of the design tool, ranging from enhancing stability analysis and incorporating additional design tasks to optimizing design parameters and improving the user interface. By addressing these aspects, the design tool can evolve into a more comprehensive and powerful tool for ship concept design, enabling designers to make informed decisions and explore a wide range of design options efficiently and effectively

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APPENDIX-A

GRASSHOPPER SCRIPTING COMPONENTS

The grasshopper tool for automation of concept design process showcased in the thesis has been developed by author during the course of the thesis. The tool has been developed completely from ground up using exclusively grasshopper components. No reference has been made to previous works from others or external sources.

Various modules that are automated are added as tabs in the design automation tool. GUI for each module is shown below.

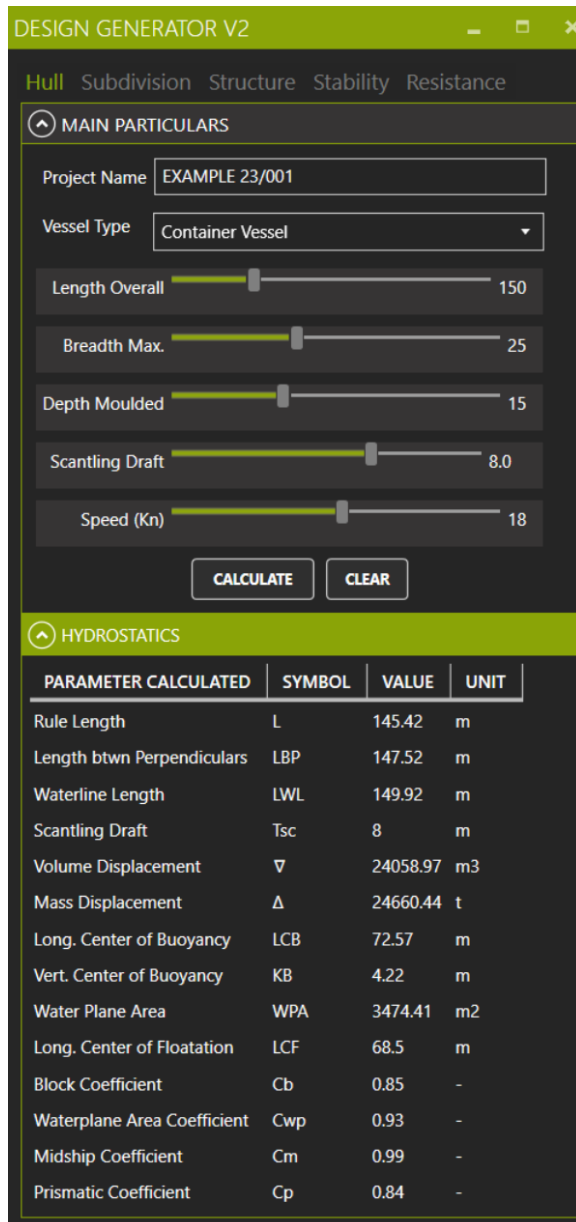


Fig 1 Hullform Parametric Design Module

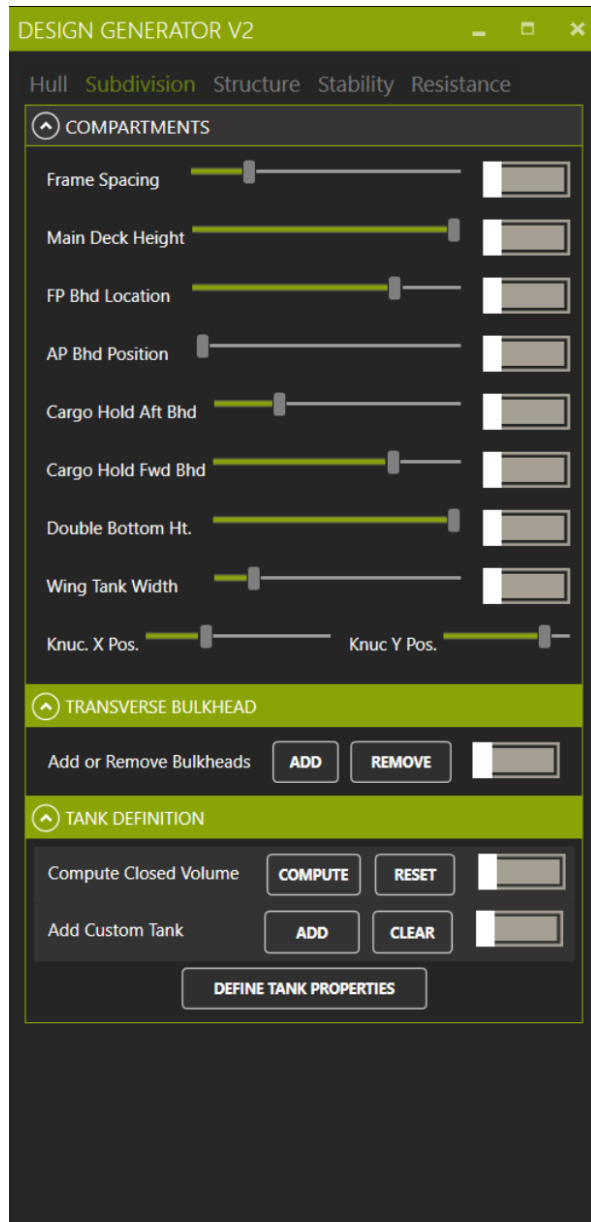


Fig 2 Compartment Subdivision Module

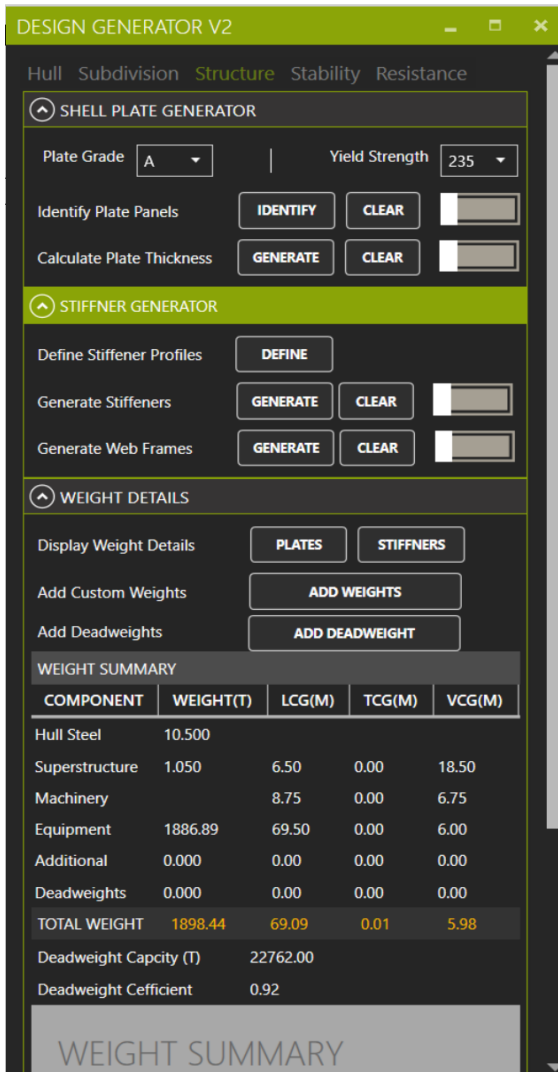


Fig 3 Structure Module

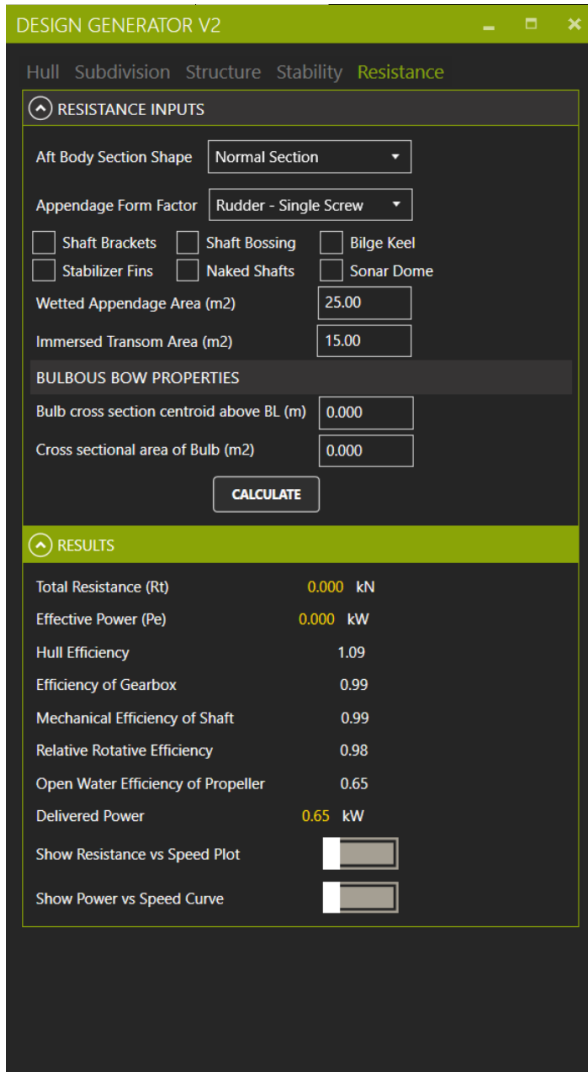


Fig 5 Resistance Module

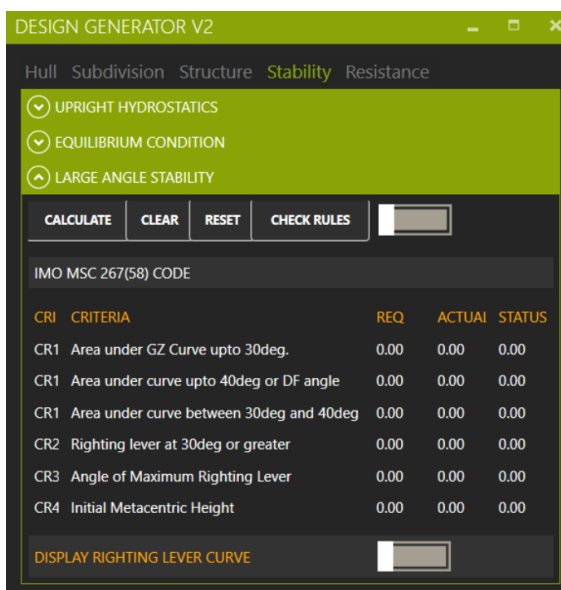


Fig 4 Stability Module

Grasshopper is a programming language that comes with Rhino, which makes use of 3D modelling functionalities of Rhino for creating parametric design models. Within grasshopper, each function is represented as block and the information passing from one block to the next is represented as threads. Within grasshopper, information flows in a linear manner from the left to the right.

Within grasshopper, the entire script can be divided into 2 main sections – the programming modules and the graphical user interface which presents the data calculated by the programming module to the user.

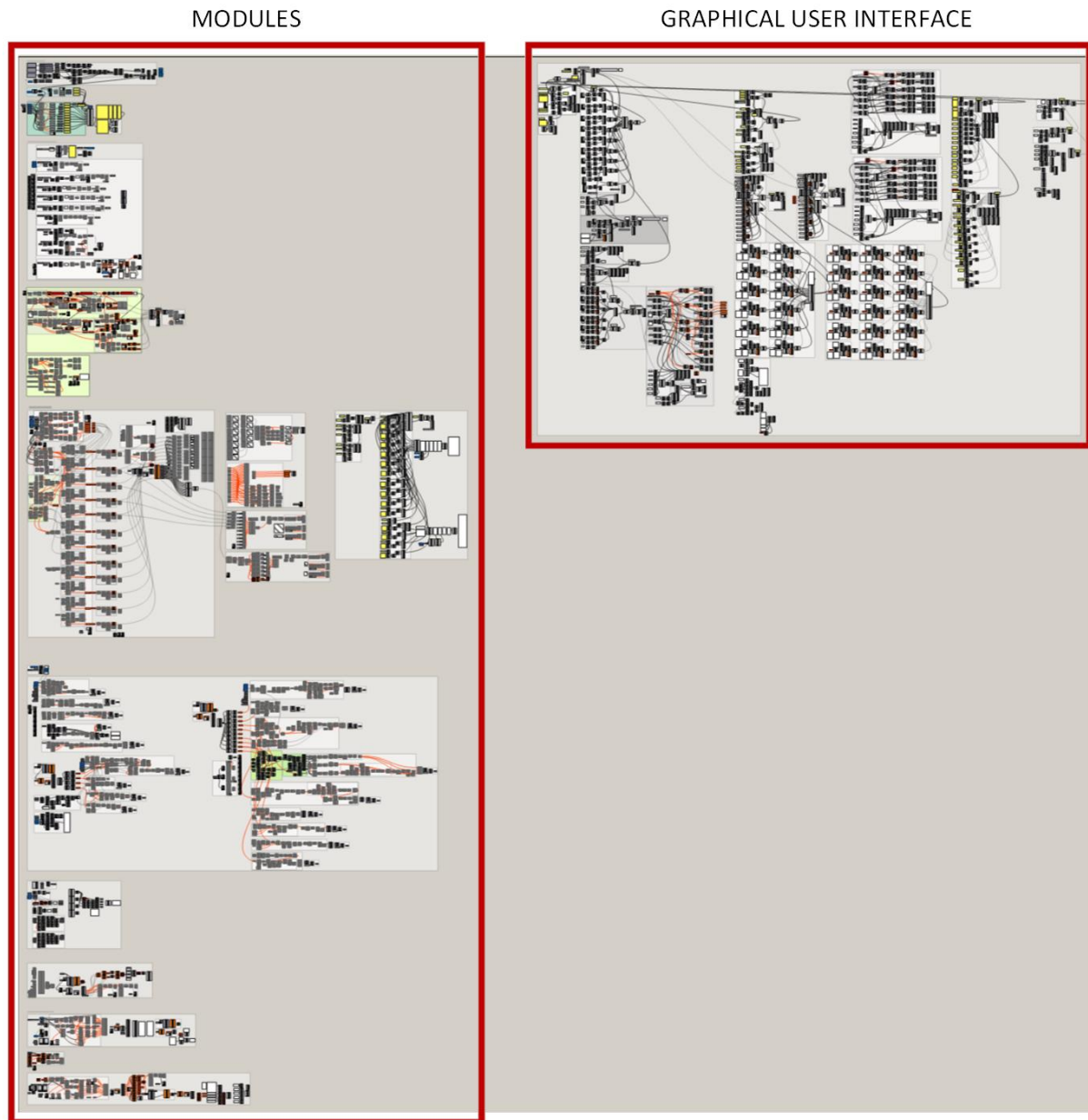


Fig 6 Complete script in Grasshopper

The various programming modules used in the program are illustrated below:

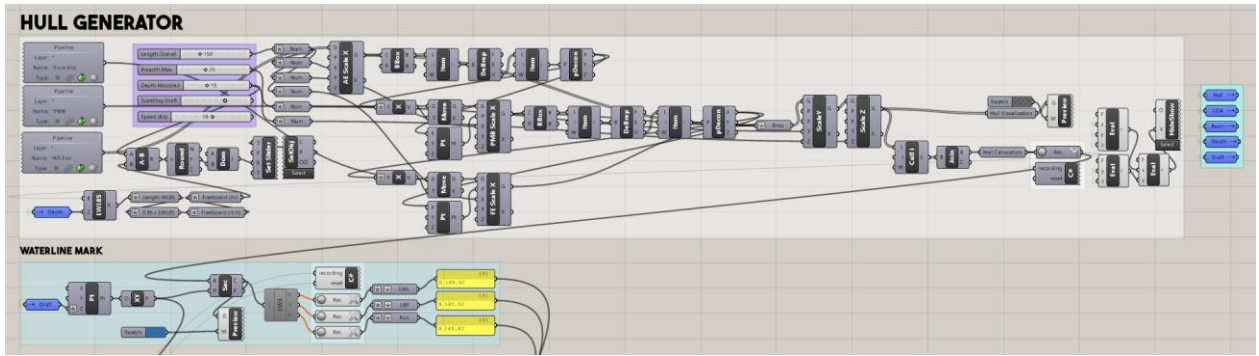


Fig 7 Parametric Hullform Generator

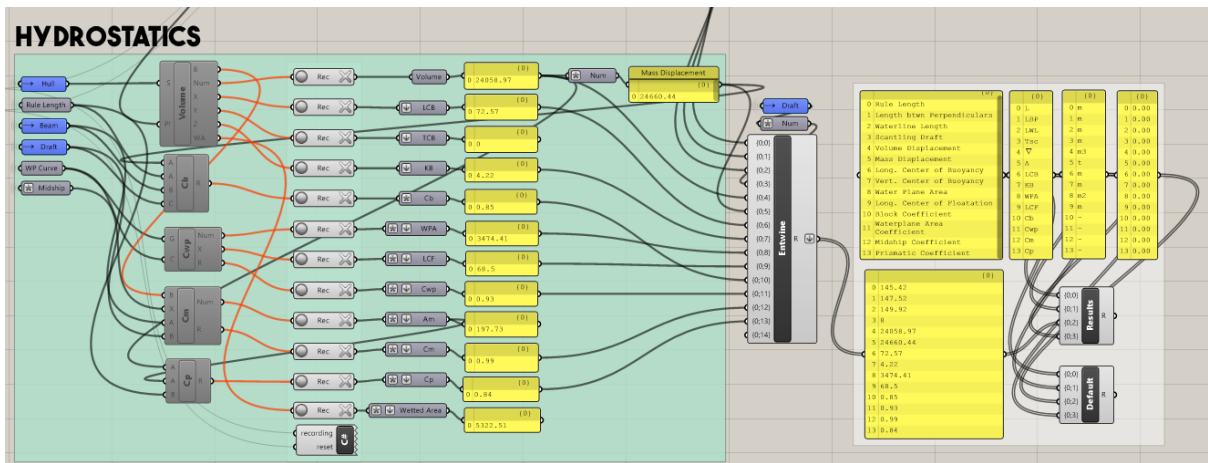


Fig 8 Initial Hydrostatics Calculation

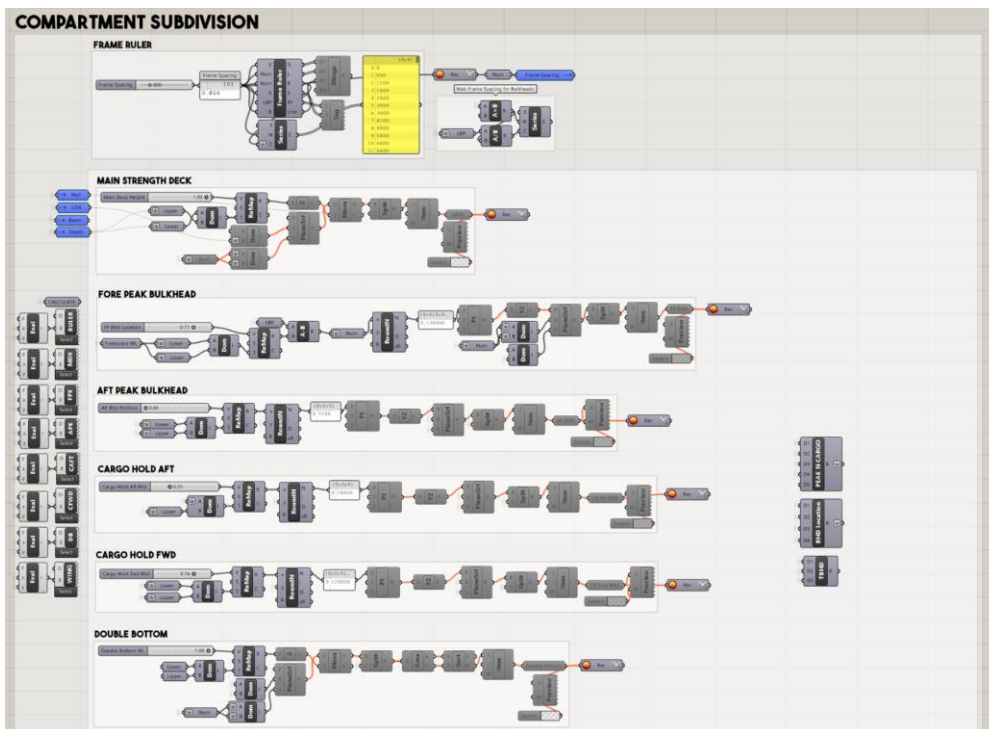


Fig 9 Adding Bulkheads, Main Deck, DB to Model

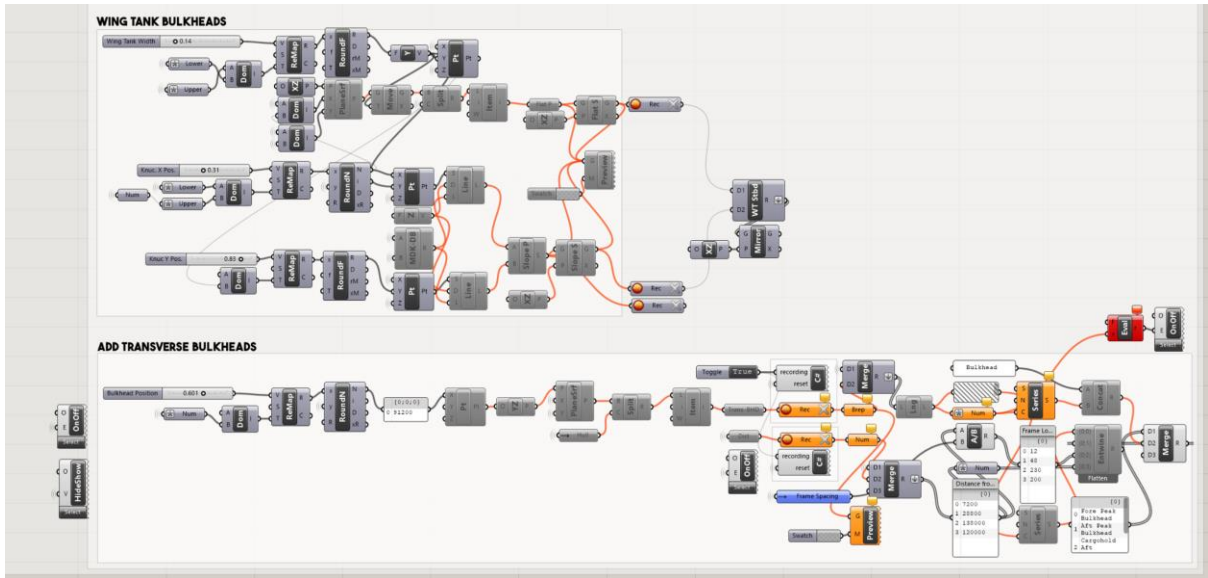


Fig 10 Adding Wing Tanks and Trans. Bulkheads

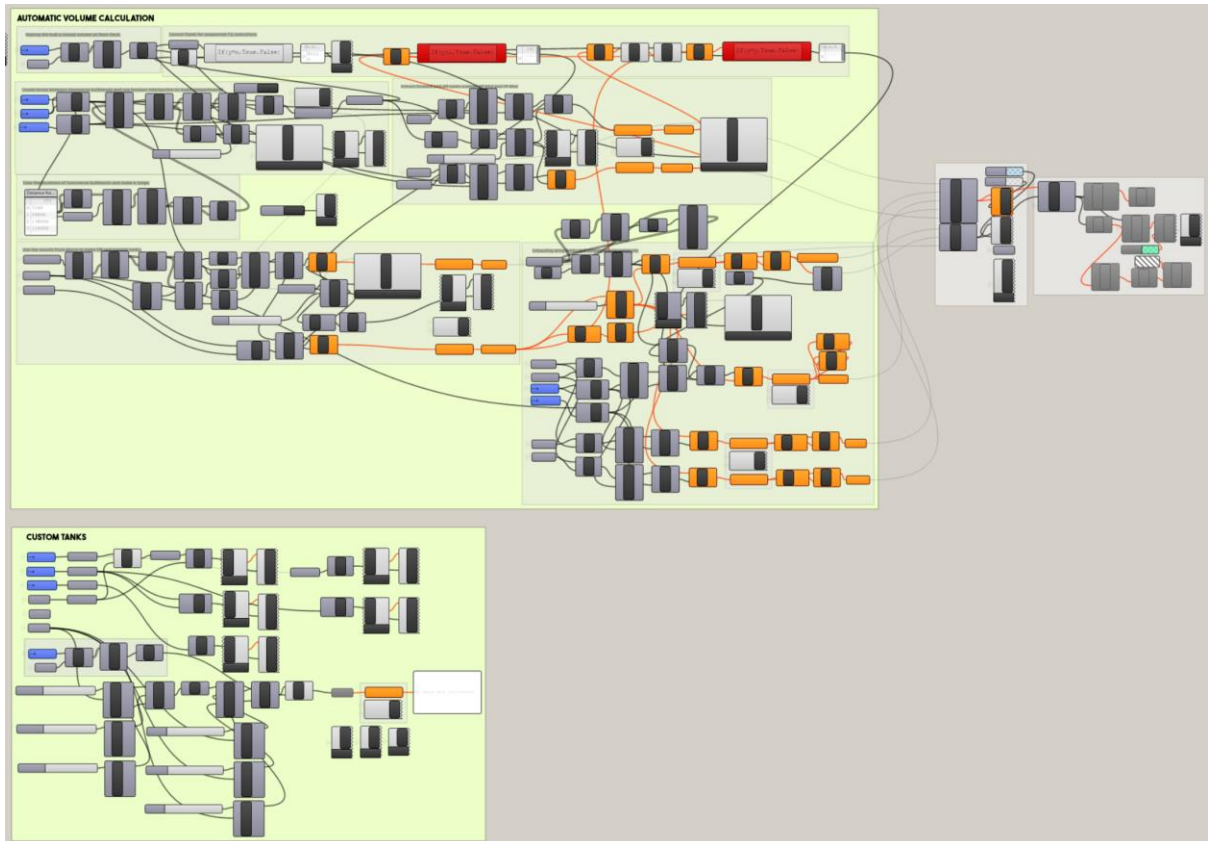


Fig 11 Automation Tank Identification, Definition of custom tanks

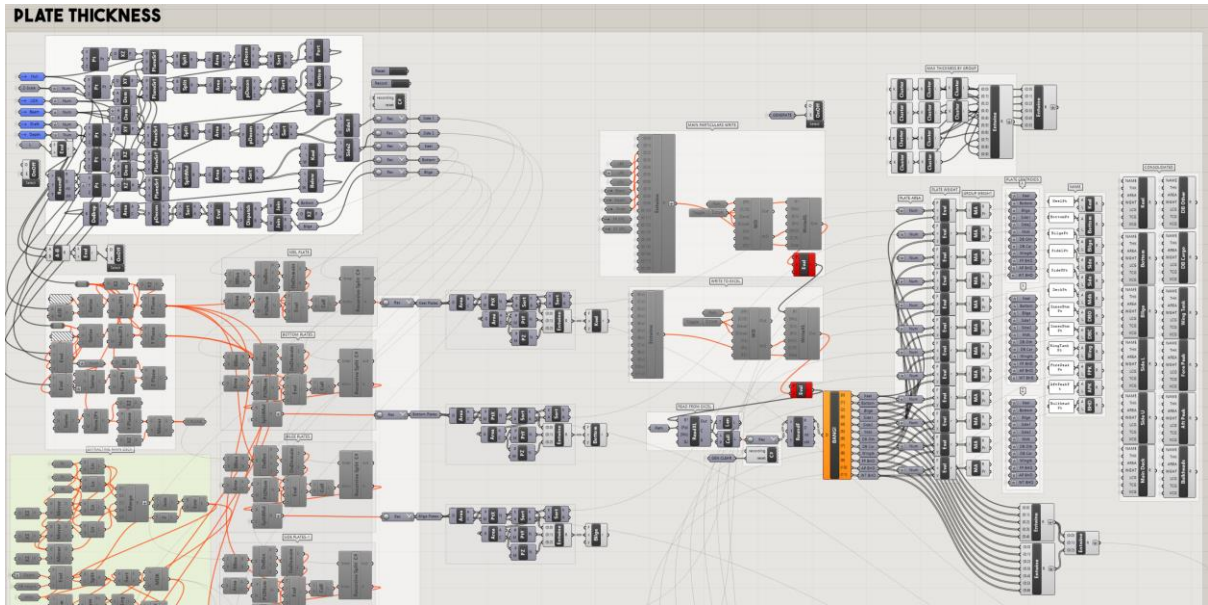


Fig 12 Plate Thickness Calculation

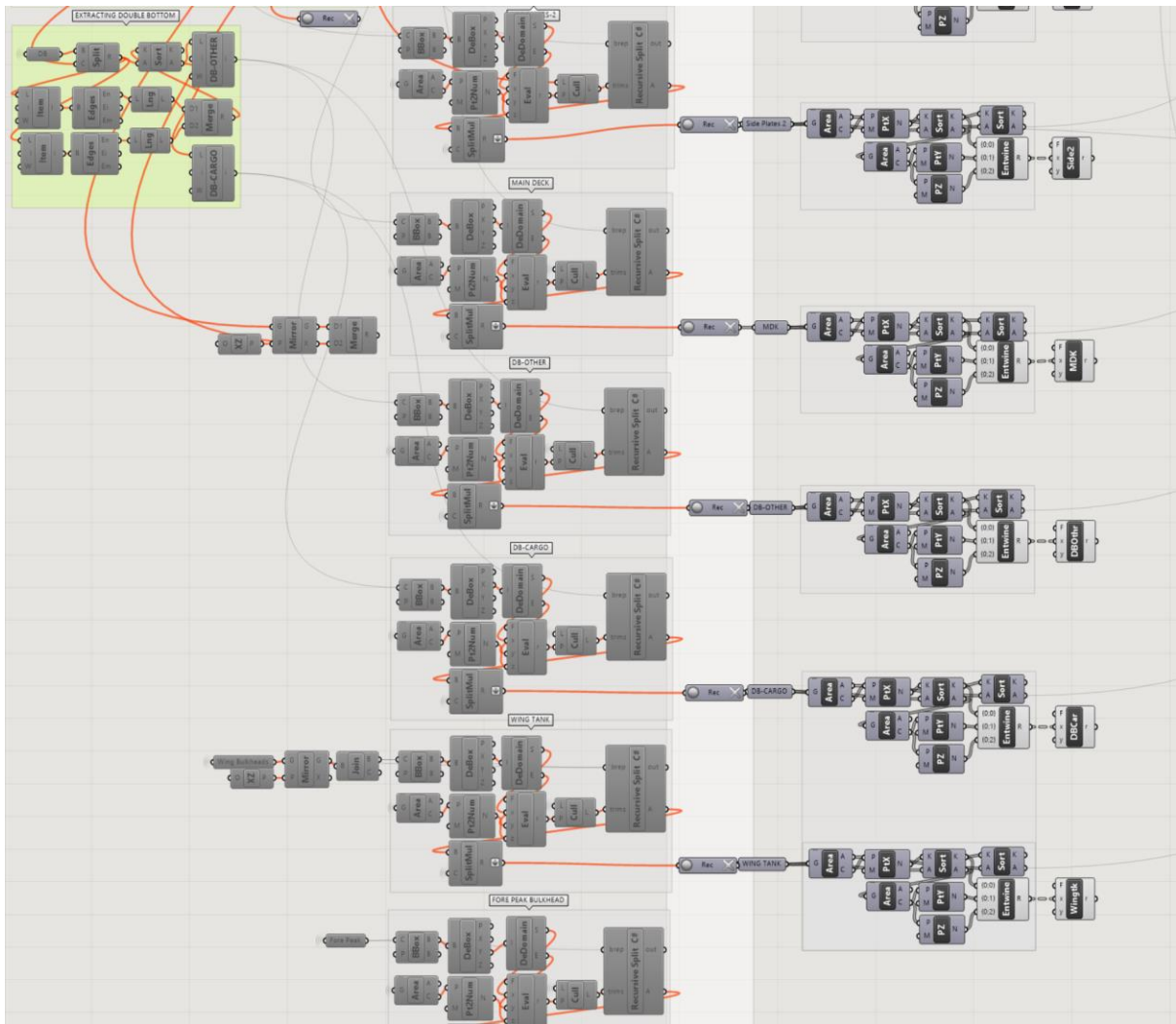


Fig 13 Plate Thickness - Cont.

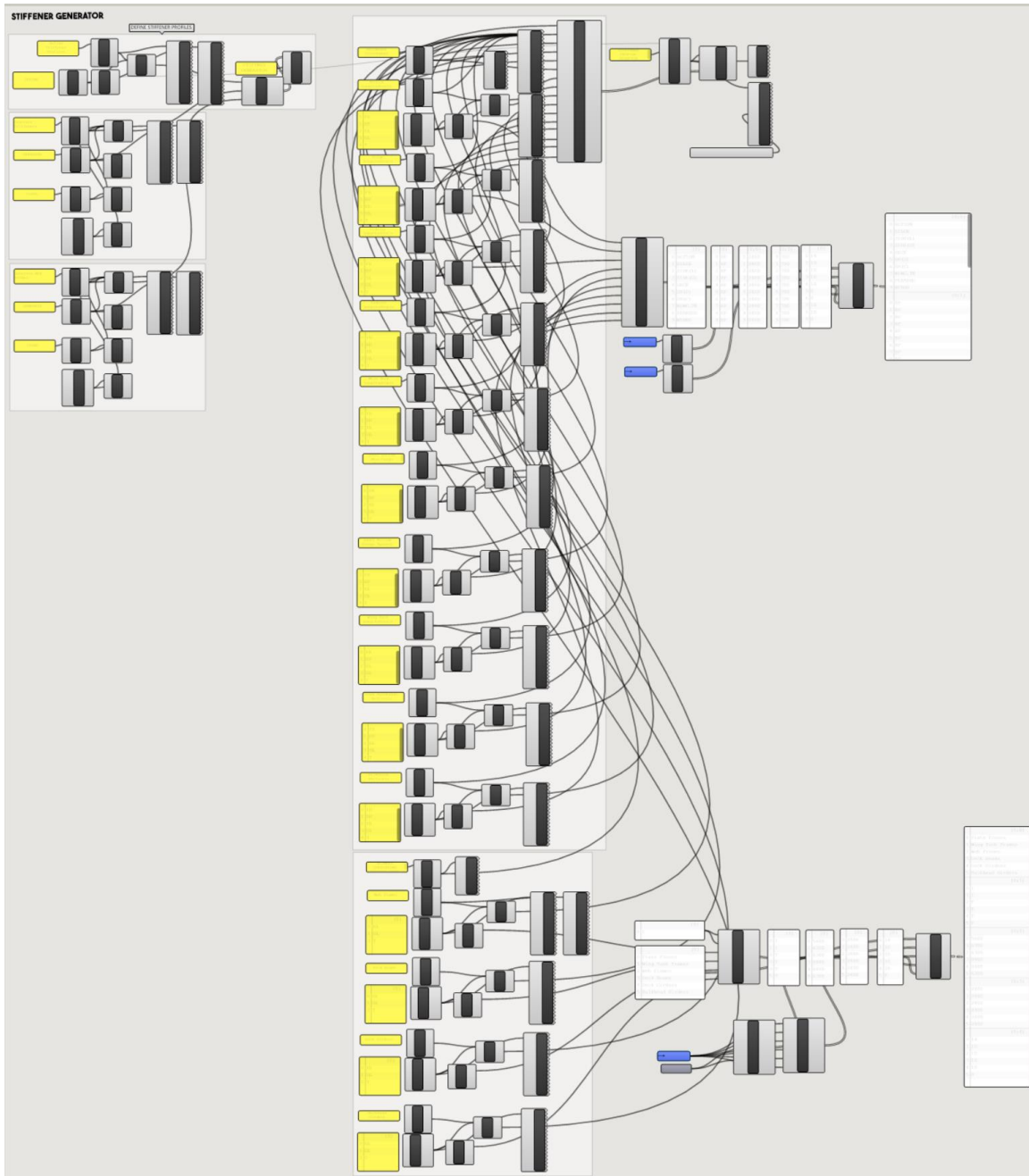


Fig 14 Stiffener Sizing Calculation

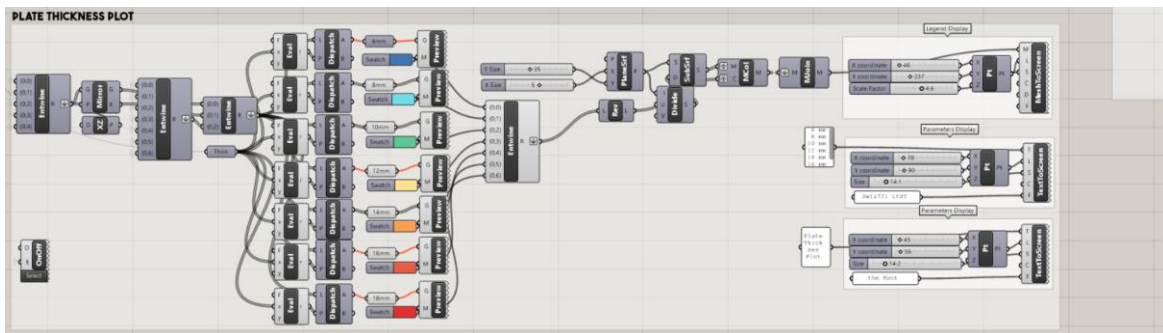


Fig 15 Plate Thickness Plot

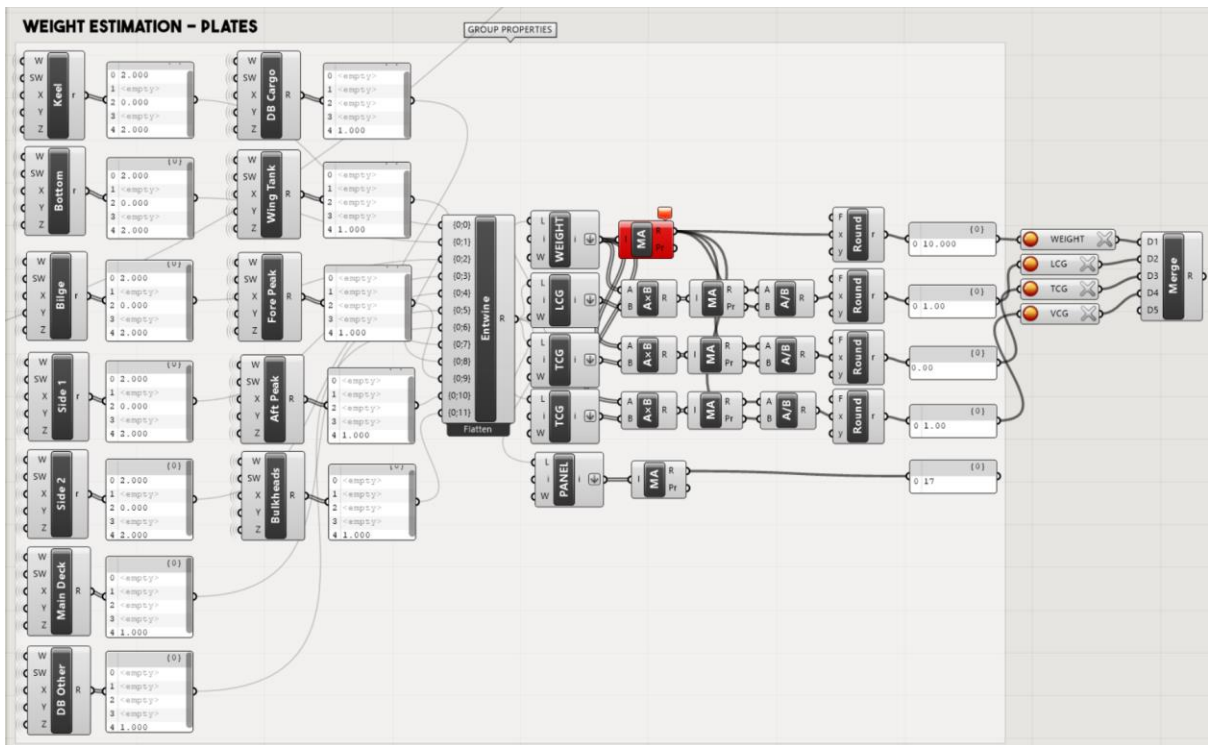


Fig 16 Weight Calculation

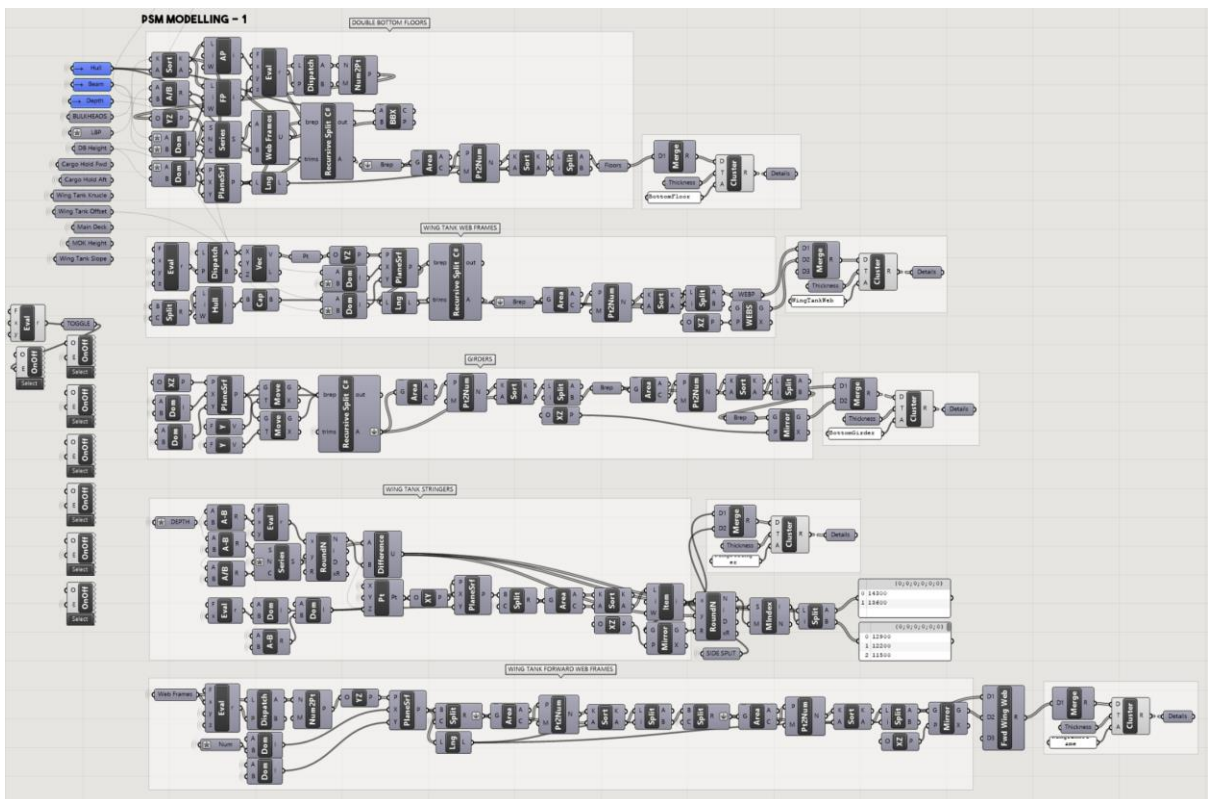


Fig 17 PSM Modelling -1

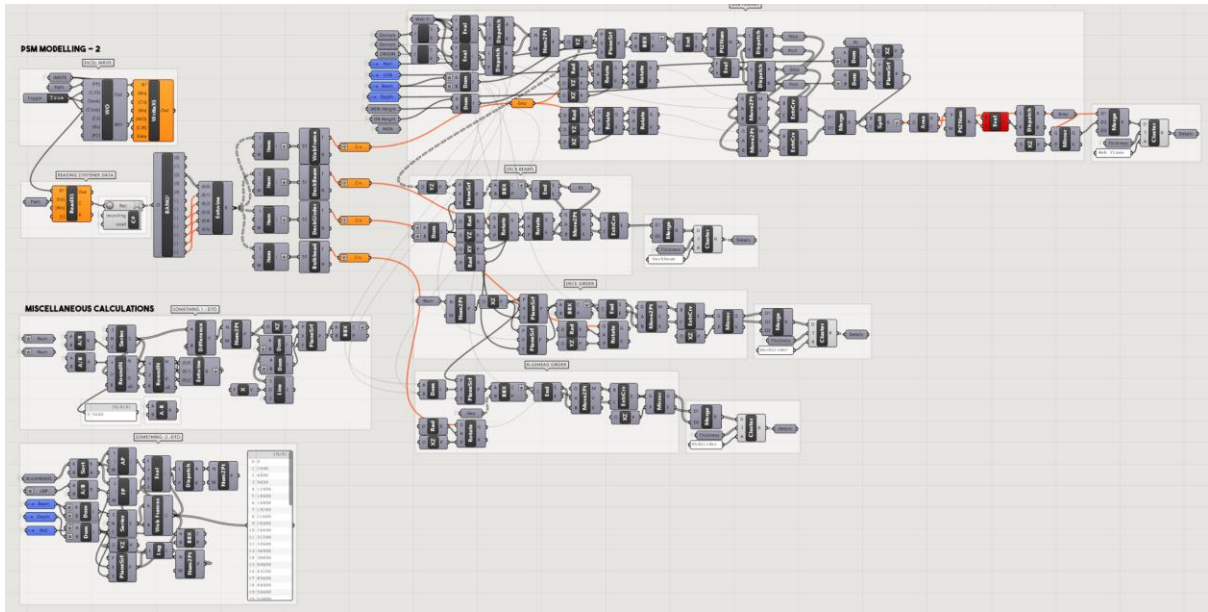


Fig 18 PSM Modelling -2

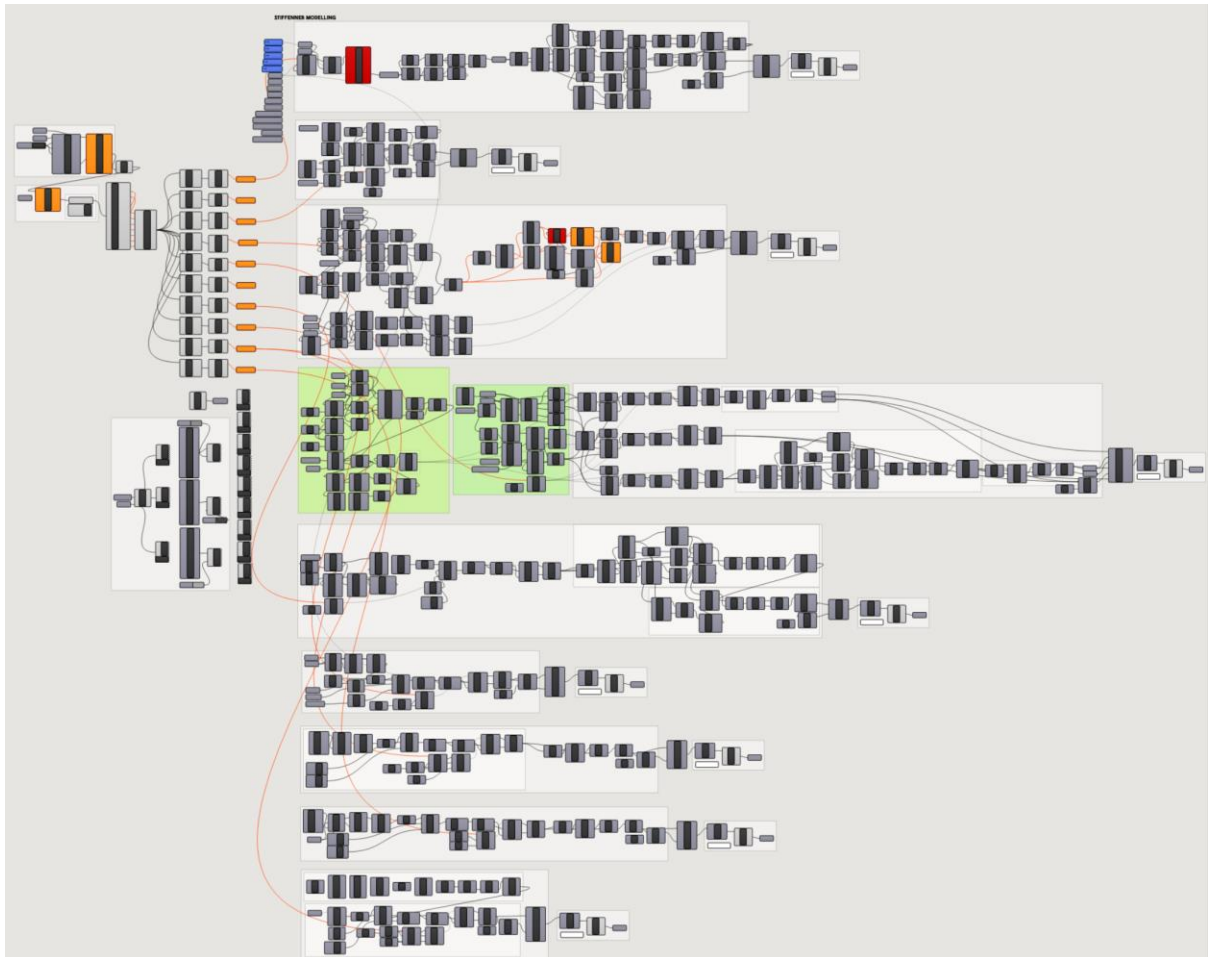


Fig 19 Ordinary Stiffener Modelling

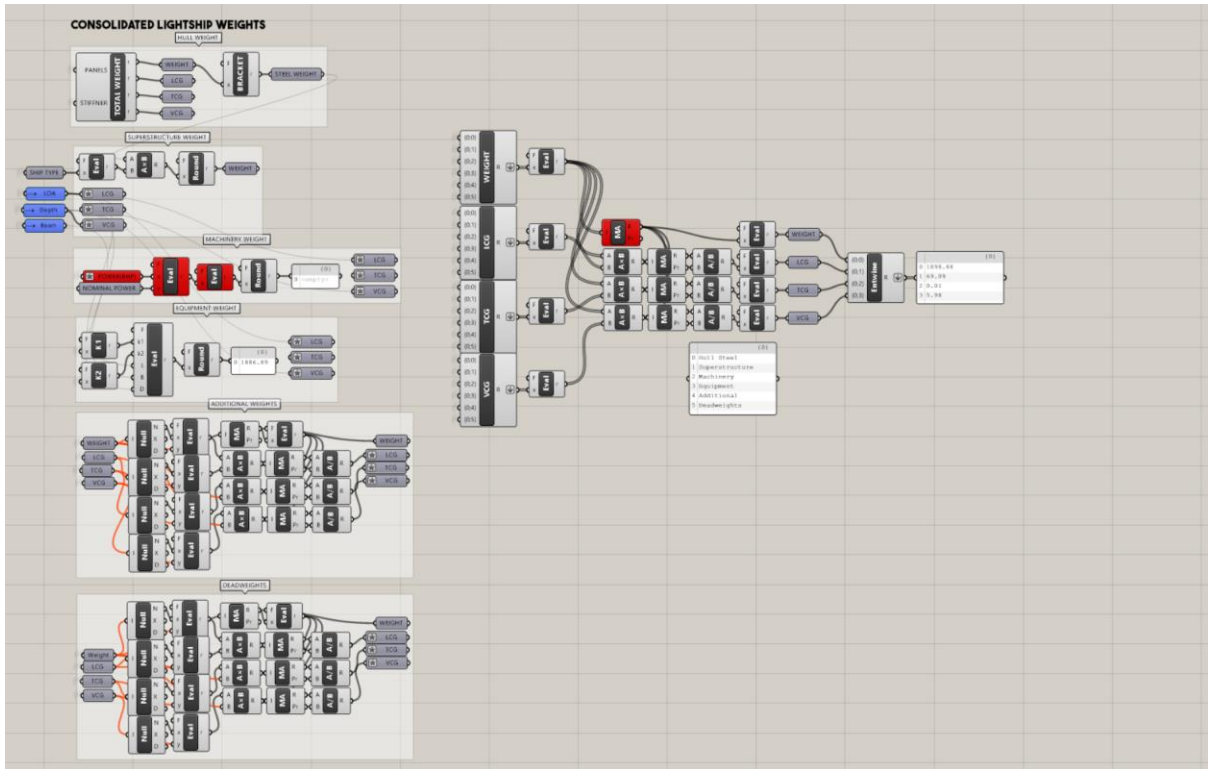


Fig 20 Lightship weight consolidated.

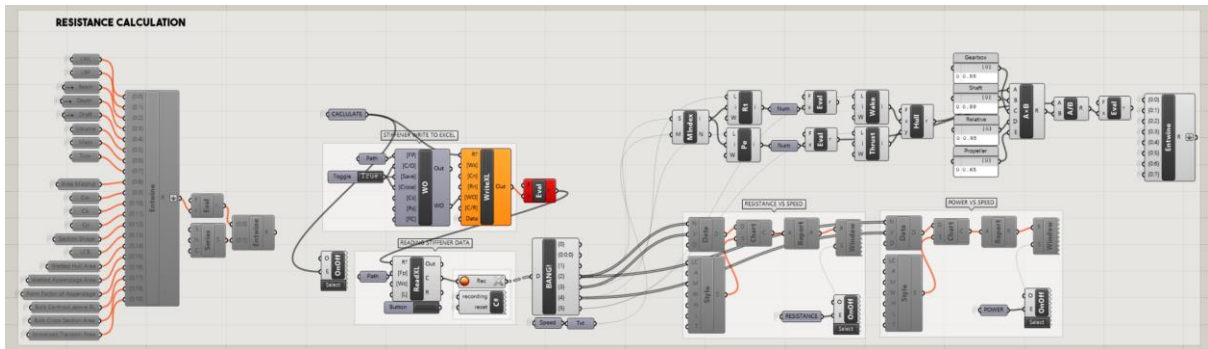


Fig 21 Resistance Calculation

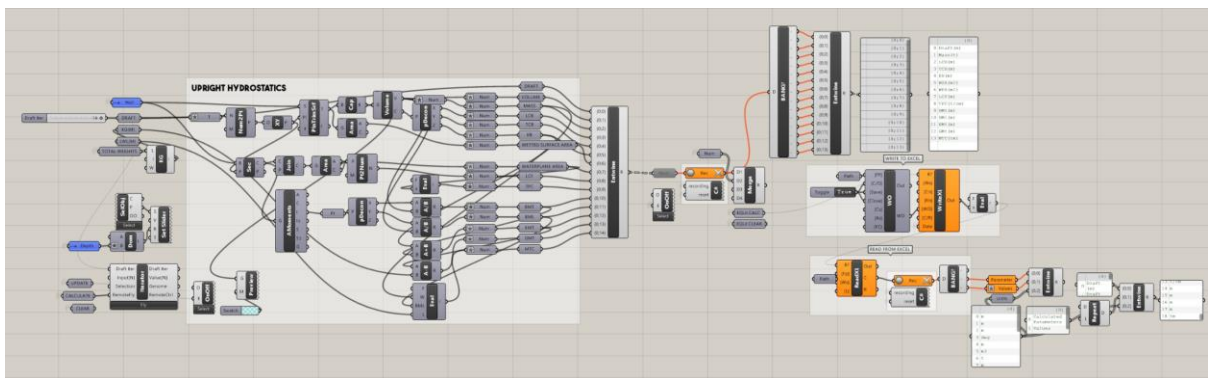


Fig 22 Upright hydrostatics

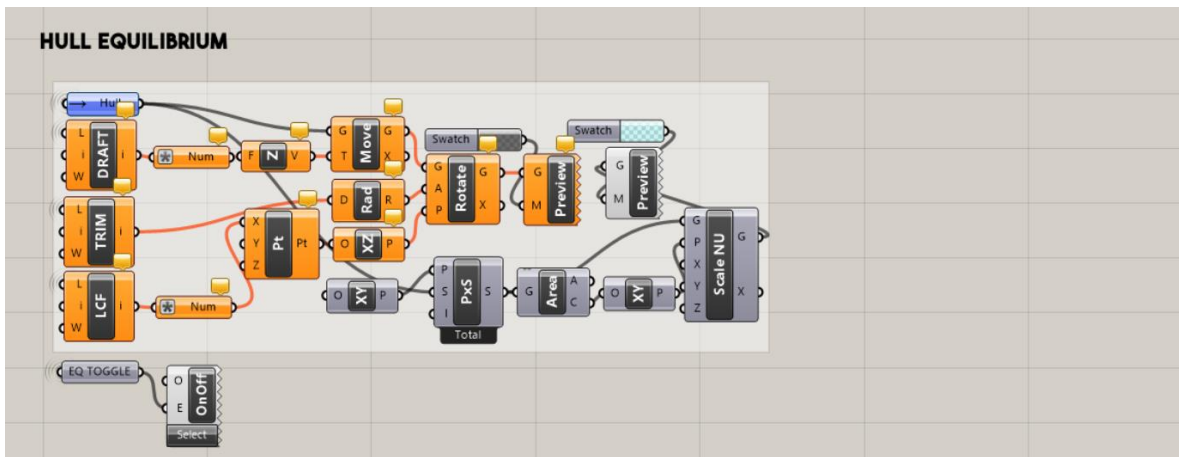


Fig 23 Setting vessel to floating draft.

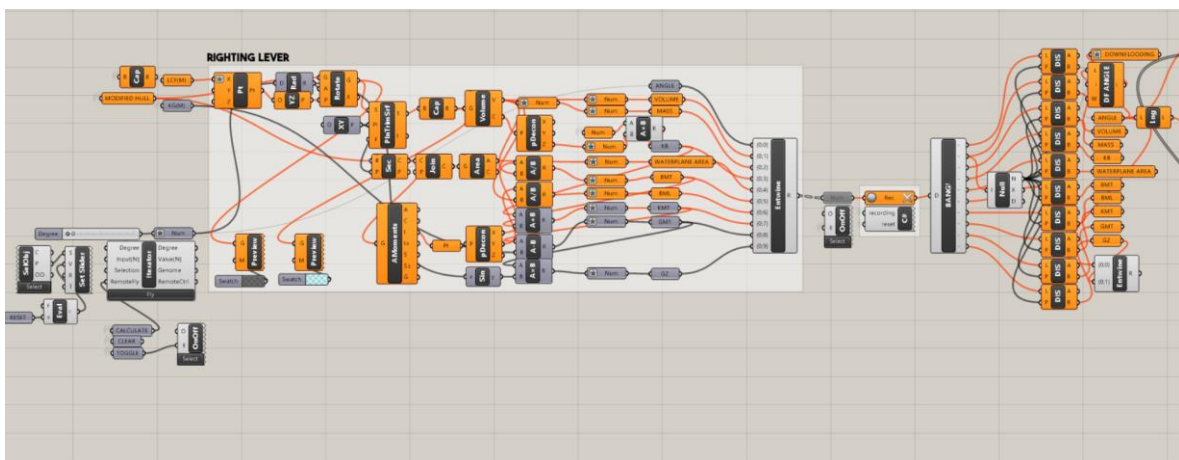


Fig 24 GZ Curve Calculation

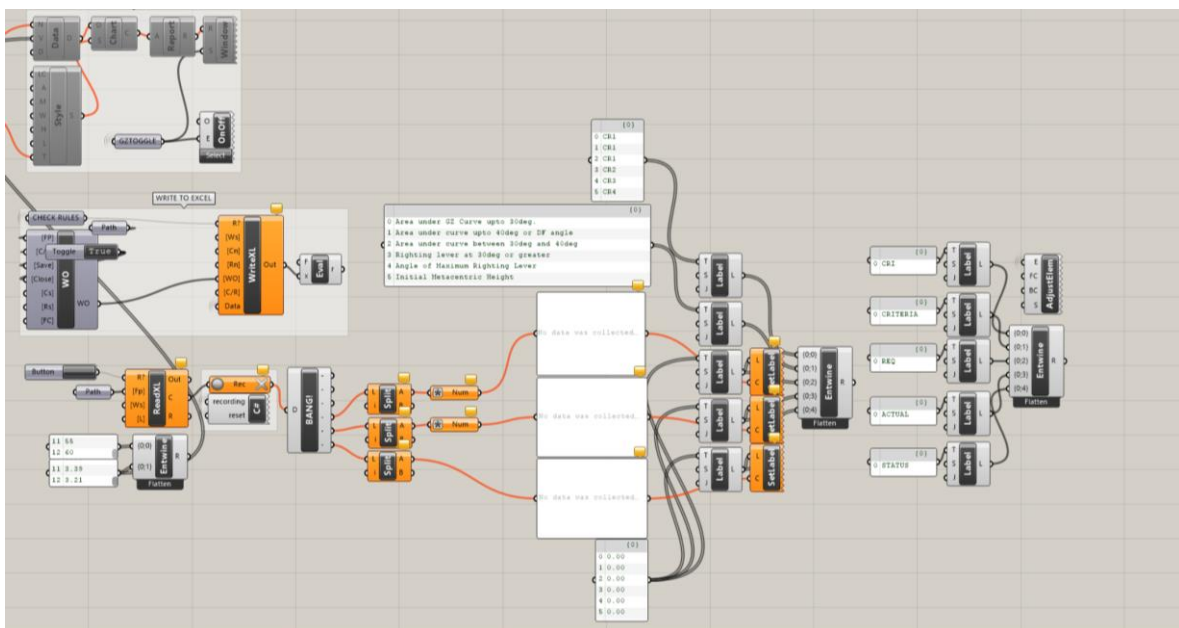
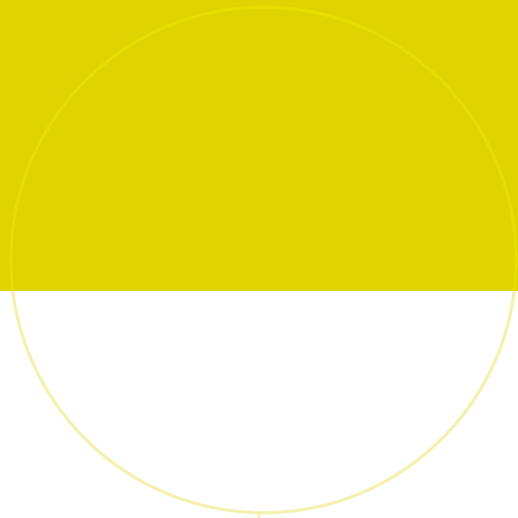


Fig 25 IMO Rule Check



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