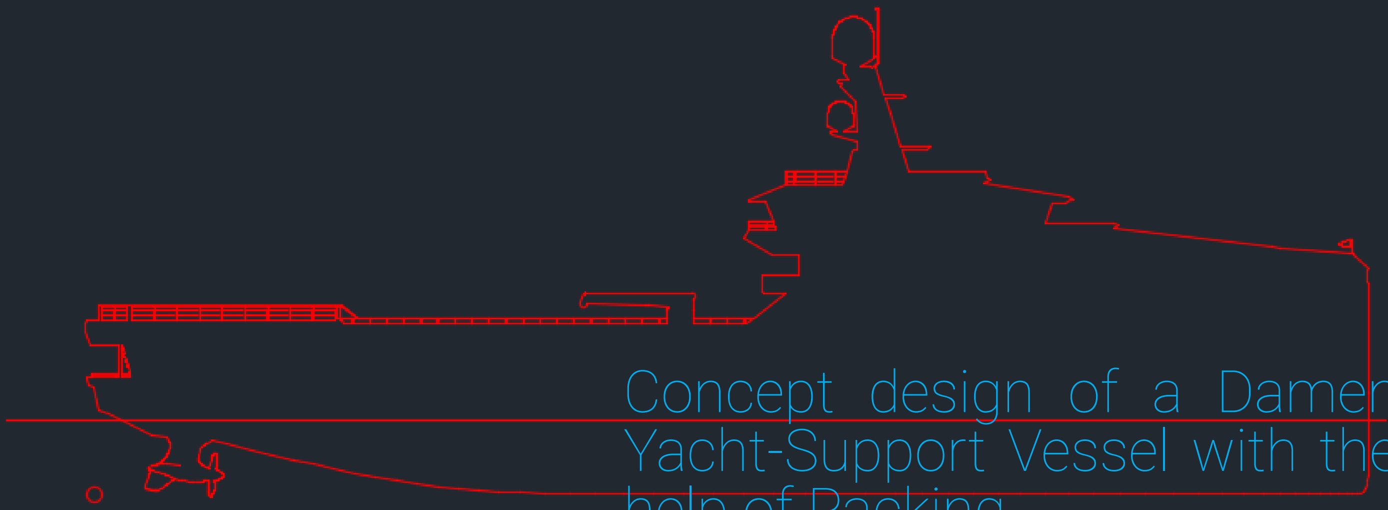

Concept design of a Damen Yacht-Support Vessel with the help of Packing

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by

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Preface

This project concludes two years of stimulating and challenging study, it was written to fulfill the graduation requirements of the Master of Science in Marine Technology at the Technical University of Delft (TU Delft).

The thesis focuses on the concept design of a Yacht Support Vessel. The context in which I was allowed to develop it, Damen shipyards, and in particular the Design and Proposal department of Yacht Support and SeaXplorer, represents the ideal type of work environment in which I would like to find myself in the future. For these reasons I would like to thank all those who made this fantastic experience possible.

Starting from my family, I would like to thank my parents that not only allow me to undertake this great experience but persistently believed in me and supported me in every little step during the course of this study, always with words of motivation and gestures of encouragement.

I also wish to thank all my friends: the old ones, far away but with whom the friendship revealed to be even stronger than before, despite the distance. The relatively new ones, met in this new country, sharing the past two years and always helping each other.

Last but not least, a special thank goes to all the people who directly follow me during this project. Starting from the amazing team at Damen with whom I felt so lucky to collaborate. They shared with me knowledge and gave me suggestions introducing me in the working world, but always having a lot of fun. Thanks to my supervisors: Jaap, Austin and Koen that guided me constantly and patiently to conquer this result.

L. Salvatori
Delft, January 2018

Summary

This thesis discusses the concept development of a 90 meter Yacht Support Vessel (YSV) with the help of TU Delft Ship Synthesis Model (SSM) called packing.

Speed, together with a considerable amount of demanding and conflicting characteristics, such as: the capacity of storing two helicopters and at the same time being able of taking around large and bulky tenders, are crucial aspects of this type of ships. Damen Shipyard, leading this market, collaborated to this study. In particular, the object case-study would ideally represent the flag-ship of the gamma for the shipyard, emphasizing and taking to extreme all this type of ship features. In addition, the vessel should provide storage for spare parts and provisions, accommodations for extra-crew and staff but also have fully dedicated guest areas.

This work discusses the aptitude of the packing approach of dealing with this particular ship design problem. The methodology developed by TU Delft can rapidly generate a large and diverse set of thousands of different feasible low detail ship designs. The dissertation is composed by two main parts: the first one is focused on using this methodology to develop a diverse design space to explore various possibilities before converging on a selected few to further define later in the thesis. The second part provides the elaboration of the most promising design picked up in the first phase.

The packing-based ship description consists of five elements (objects, positioning space, overlap rules, design changes, packing process) representing the Ship Synthesis Model (SSM) that together enable the description and parametric variation of a ship during early stage design. By creating multiple feasible design solutions, the task of the naval architect is focused on analyzing, evaluating and deciding rather than creating different options. Thus, it is proposed to study the feasibility of multiple different options and, by analyzing the more relevant conflicts, it will be possible to drive the choice towards the most promising design. In this work are highlighted the design decisions undertaken by packing on the options modeled, comments and explanations are given on the rationale that helped in cutting the design space represented by thousands of different design concepts. Consequently, it is illustrated how the down-selection from a multitude of options to only few solutions was carried out.

The most promising design is improved through some of the steps typical of the ship design spiral with the aim of satisfying the imposed design requirements. Several rounds of the ship design spiral are undergone bringing gradually to the final outcome. These successive steps led to the fulfillment of all the non-negotiable requirements set in the design brief, successfully developing the 90 meter concept. The description of the main characteristics of the ultimate design closes the second phase of the thesis before conclusions and reflections on the overall project are discussed.

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1 Introduction

1.1. Overview

This master thesis matured with the participation of Damen Shipyard. The collaboration started with the aim of improving one of their concept design: the largest Yacht Support Vessel (YSV) within the range offered by the company (*YS 9016*). As a matter of fact, the firm already proposes a concept of this vessel that extremes all aspects the of Yacht Support series. These are fast luxury service vessels characterized by significant level of complexity which are been developed for demanding super-yacht owners who take these purpose-built vessels all over the world carrying more toys, tenders, personnel, provisions, specialist gear and helicopters.

Paramount characteristic for this kind of vessel is to be able to **sail faster** than the supported mother-yacht. Indeed, a Yacht Support of 90 meters is intended to assist Super yachts of length over 100 meters, which sail at speed between 20 - 22 knots. The existing Damen concept does not meet the 25 knots max speed. A possible solution to this problem, lies in increasing the engine size. However, this increase is expected to be substantial and in turn, will directly affect all the other spaces. Starting from the power installed on the *YS 9016*, the increase in power required to reach the speed is over three times. Therefore the operational requirement to sail fast is a costly affair and must be considered carefully.

Increasing the power will provoke a massive change in the spaces related to the increase in engine dimensions causing inevitably a full-scale redesign layout. The company, already aware of these considerations, manifested the desire of starting from a complete new platform. Yet, the hull form should still be representative of the 'DAMEN *Fast Supply Vessel* style'. Indeed, one of the distinguishing marks of some Damen's vessels is the straight AXE-BOW that they wanted to maintain both from a styling and performance point of view. In addition, the length of the ship should not exceed 100 meters in order of being built under certain classification and be compliant to some regulations.

Naturally, not only speed but also several others features distinguish this type of vessel. Amongst these characteristics, some are highly conflicting. In particular, having the possibility of carrying an incredible amount of tenders and toys, providing an ultimate level of helicopter facilities (both an enclosed hangar and a fully-certified helideck), implies the presence on board of **potentially conflicting aspects** within a constrained design space. The simulation of the 'Interview to the owner's team' and the consequent drawing up of the 'Design brief', will clearly show the mission to satisfy and the aspects causing major problems for this specific design.

The issue related with speed and the necessity of creating a design concept starting from a complete new platform together with strong spatial conflicts due to interaction between huge tenders and extensive spaces associated to helicopter facilities, requires a tool which studies the feasibility of different options with respect to speed performance.

The considerations drawn suggest the approach to the problem with the design of a new ship starting from scratch and particularly this thesis will focus on the early stage (concept) design phase of the vessel.
Van Oers (2011) describes the early stage design of a service vessel as a search, among the many alternatives, for a configuration of relevant systems, which complies with all non-negotiable requirements, and forms a suitable compromise between several negotiable design requirements. These alternatives offer the naval architect the chance to be competitive. The design of a new ship is performed in several stages, during which the level of certainty increases, and, accordingly the design margin decreases. The early concept design al-

ways has a major impact on the final one. Usually, the general design characteristics and dimensions of the vessel are determined in this stage. [38] However, is during this initial phase that ship designers and naval architects often make many determinant design decisions, that considerably affect the final result. Obviously, erroneous choices at this stage will influence the final results with large cost overruns in later stages when it turn out things need to change. [13]

Explore more design concepts with the packing method might result in interesting solutions for approaching this specific design study. The *Packing approach* is a new methodology, developed by the TU Delft, born with the aim of helping the naval architect in the preliminary phase of the ship design. This attitude perfectly fits with the difficulty arose, leading off the option of trying packing to face the ship design problem. Indeed, this thesis will partly follow some steps described by the *IECEM* (*Interactive Evolutionary Concept Design Exploration*), a novel technique to the preliminary phase of ship design that, based on packing methodology, assists the study of main conflicting aspects.

In sum, a new *Ship Synthesis Model (SSM)* will describe the Yacht Support vessel and by analyzing the more relevant conflicts, it will be possible to choose the most promising design.
The second chapter of this dissertation explains all the characteristics of the vessel in details. After that, the model is built and results are produced, the exploration and down-selection amongst thousands designs generated will help in moving towards the most promising design solution. Nonetheless, this process will cover just half of the thesis project: the aim of the second part of the thesis consist in improving the outcome from packing through its development into the well known *Ship Design Spiral* increasing the level of details.

1.2. Problem Statement

Resuming the aspects discussed in the Overview, the capability of arranging all the items requested in the bounded dimensions while still providing feasible design solutions is not a trivial task. Not by chance, here is where packing come in play creating a multitude of design options, making trade offs where necessary and thus permitting the investigation of different concepts. The following two points describe aspects that require a deep analysis and that make this design a real challenge:

- the considerable speed demand largely refers to the increase in power installed. Indeed, excluding radical changes regarding the hull shape, the other 'big player' in achieving speed is power and consequently the power plant configuration of the vessel. It is a matter of fact that the engine room of a ship strongly affects the other spaces on board. In addition the ambitious range (6000 nm at 18 kn) combined with the high power leads to the necessity of reserving a large space for fuel tanks.

- The tough interaction between helicopter-related spaces and the square meters available to store the massive tenders represents the other big challenge. Especially, different combination of helipad and hangar arrangements conflict with the ability of carrying bulky and massive tenders. Of particular interest is the study between two possibilities of hangar location: horizontally or vertically (below) located with respects to the landing area.

1.2.1. Goal of the Research

As previously mentioned, the intention of this master thesis is to find a suitable design for the largest range (over 90 meters) among the Yacht Support vessels offered by Damen with the help of the *packing-tool parametric ship description*.

The process produced satisfactory results in previous applications mostly with the aim of resolving a particular interaction between two or more conflicting aspects in a specific type of ship. In this application, the method will eventually steer the design process through a final most promising design solution.

The picture below represents the well-known ship design spiral. Actually it can be said that the packing approach fall even one level outside this spiral considering the level of detail that it can provide. Of the process illustrated below, some of the phases called for more attention than others in this dissertation. The explanation of this diverse focus is directly linked to the mission the vessel need to satisfy and the problem to be deepen. In particular, on one hand special consideration was reserved to: *arrangements of hull and machinery and powering* due to the strong link of these aspects with speed performance. On the other hand, substantial time was spent on rebuild the light ship weight with the extrapolation of *weight density factors* better describing the overall weight of a Yacht Support compared to the default ones referring to a navy ship. The choice of not using the 'default' weight density factors and generate a set of new ones is linked to the aim of creating a model as faithful as possible increasing the chances of getting a better result.

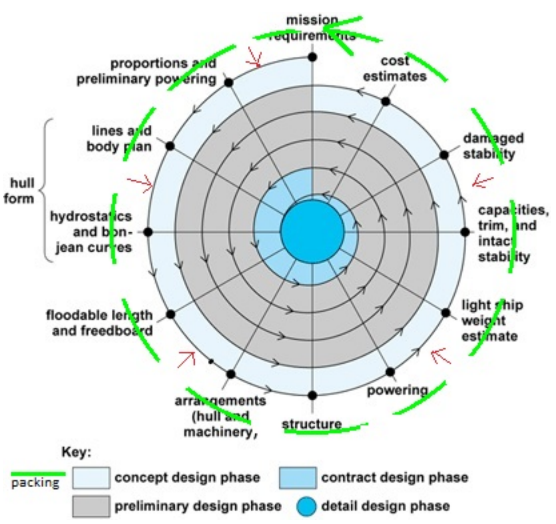


Figure 1.1: Packing in the Ship design spiral

1.2.2. Research Questions

The primary research question is directly tied to the first aim of this thesis consisting in the search of a suitable design for the 90 meters Yacht Support. Thus, first of all:

- Will this study reveal a feasible and even unexpected design solution that satisfactorily meets the requirements of the new 90 meters Yacht Support? Primarily, being able of sailing at a maximum speed of 25 knots while satisfying the spatial conflict?

Secondly, subquestions strictly linked with the packing procedure and its ability to describe the ship:

- Is packing a good tool to study the defined problem?
- Will this study help in defining the limits of the packing-tool ship description thanks to the application on this new kind of vessel?

The general arrangement (GA) appearing directly from this method is still very rough and far from what is widely known as a common Yacht GA. For this reason, the second phase of this thesis will focus on improving such relatively unsatisfactory outcome, and evaluate the consequences on calculations and performances previously obtained from the model. For instance, modification such as: movements or division of blocks and compartments in a more resembling room rationing, besides from the enhancement from the aesthetic point of view, might possibly alter the weight distribution, thus affecting the stability or other relevant performance estimations.

1.3. Description of the Process

The flow-chart in figure 1.2 clearly illustrates the steps characterizing the design process of this thesis. Following in this section, a better explanation of the actions taken will complete the overview of how the work develop.

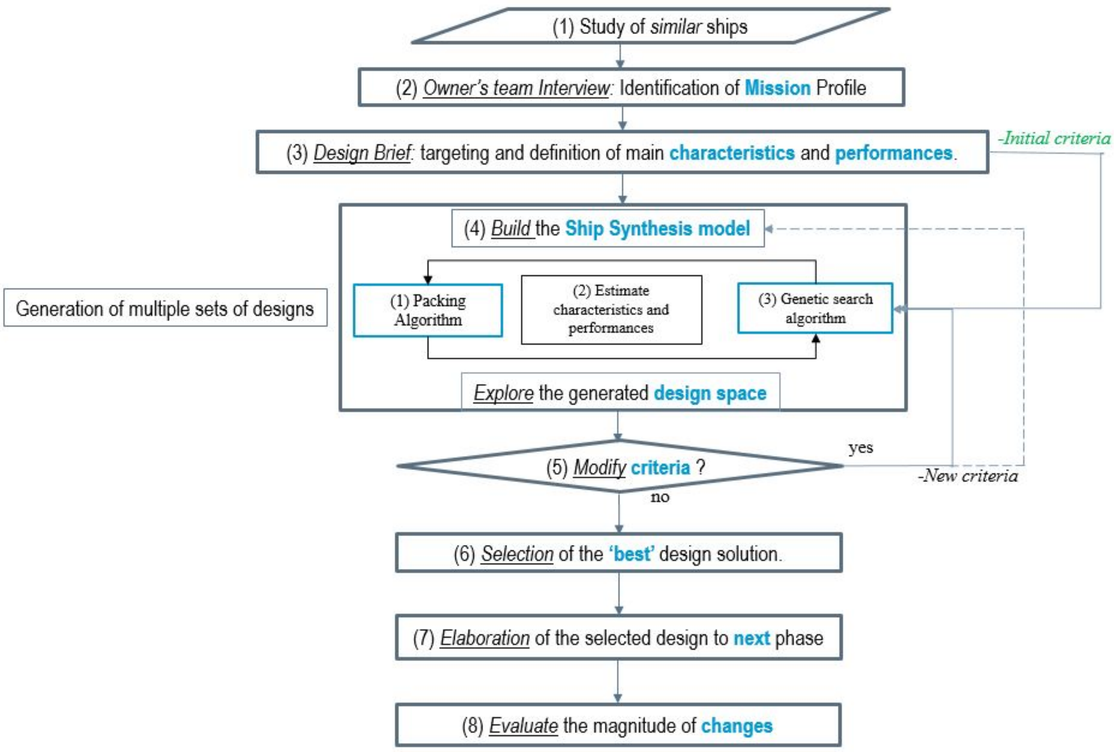


Figure 1.2: Steps in the Design Process

1. **Study of similar ships**
   The first step consisted in the study of similar ship. First with a deep analysis of the smaller ranges designed by Damen and secondly trough a market analysis of competitors.

2. **Identification of mission profile**
   Together with the company the simulation of an *Interview to the Owner's Team* reproduced the initial common step of the design of a ship. Some key questions were prepared in order to identify the mission profile and all the requirements. This is a crucial moment because if the mission definition is not clear, the result might reveal undesirable or the misunderstanding could shows up in a later stage of the design were the required modification will cost significant effort and amount of money.

3. **Targeting of main characteristics and performance**
   Characteristic and performances were further elaborated with the drawing up of a *Design Brief*, typical document of the initial stage of a new design of a ship, that was subjected to revision from the company. At this point terminated the first phase of the thesis in which the question *" What are we looking for? "* was replied.

4. **Build a tailored *Ship Synthesis Model* for the Yacht Support**
   At this stage started the modeling phase. Building the *Ship Synthesis Model (SSM)* creating all the necessary spaces and some mutual relations and relative positions were established. The variations for the most interesting aspects, were also implemented in the code to test design trade-offs.

5. **Explore the results**
   Once the *SSM* is created a design space is generated and its exploration follows. If satisfactory results are found it can be possible to move forward to the next phase, otherwise some modifications need to be done either in the characteristics of the genetic algorithm or to the criteria initially set up, thus modifying the *SSM* itself.

Point 4 and 5 are typical steps of the *IECEM* that uses the packing approach as core methodology. Following, graph 1.3 helps in summarizing the basic principle of the methodology.
It is composed of three main steps:

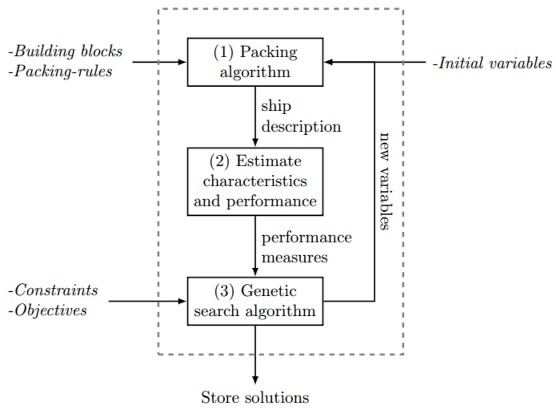


Figure 1.3: Packing approach process [13]

(a) **Packing algorithm**
Combines several elements to produce the packing-based ship description. The elements are: objects, positioning spaces, overlap rules, design changes and overlap management, packing process. All these elements provide a three dimensional ship description, which can be used by performances prediction tools to access various characteristics of the ship.

(b) **Estimate characteristics and performances**
The packing approach uses several tools to access basic feasibility and naval architecture practices.

(c) **Genetic algorithm**
The genetic algorithm, together with constraints and objectives, searches for and generates design solutions. To ensure basic technical feasibility, several non-negotiable requirements are applied as constraints. In particular, constraints ensure basic technical feasibility, while objectives guide the search process.

6. **Select the most promising design option**
   The direct consequence of the exploration phase brings to the selection of the most promising design solution. This preference and choice is driven by the completeness of the options implemented in the model, thus by looking at the 'top' level options ensuring that the most is included in the final design: the most convenient propulsion plant, the highest level of helicopter-related features and the largest amount of toys and tenders required.

7. **Further elaborate the most promising design solution**
   The most promising design will be further developed, bringing it to the next phase of the design process increasing the level of details that packing cannot provide.

8. **Comments on the results**
   First, will be done an analysis of the results coming out from packing. With this knowledge, it will be possible to address the main limitation of the tool. Finally, comments of the resulted design from the overall process will determine the assessment with the requirements.

1.4. Structure of the Thesis

The first chapter gave an overview of the subject of this thesis including the object of the study and of the environment in which it will operate. In addition, the problem statement and the approach that will be applied during the design phase were also introduced. Finally, it was described which are the goals and challenges of the study. The second chapter will specifically states the mission and the requirements the ship needs to satisfy. From this description follows the choice of investigating some conflicting aspects. The following chapter will focus on how the *SSM* was built for the case study, explaining in details some characters describing the ship and the problem to be studied. The fourth chapter will deal with the exploration phase typical of the process applied and the steps made to gradually achieve the most promising design solution. The fifth one will explain why the attention was focused on only two design concepts and the changes generated for improving their general arrangement. The sixth chapter dives into the classical approach that is usually followed during the design of a new ship, with the difference of having as a starting point the most promising design concept selected amongst the ones created by packing. Finally, some conclusions and recommendations will be given in the seventh and final chapter of this thesis.

2

Requirements Setting of the Yacht Support and Design Challenges

Before dealing with the full explanation of all the requirements for the Yacht Support and, among these, the investigation of the most challenging design aspects, the second chapter starts with a market study and a introduction to the Damen Yacht Support concept. The third subsection of this chapter is divided into the interview to the owner's team and the consequent drawing up of the design brief that gives an overview of the demands the vessel need to satisfy. The fourth and fifth subsections will describe in details two majors features of the ship, while the sixth one highlights the challenges of the concept.

2.1. Market Study

2.1.1. Understanding of Competition

Market research generally helps in understand customers, in familiarize with the competition and get to know what people are prepared to pay for your product or service. Whatever sector one is in, understanding the cultural, social and economic context in which one is trading is crucial. Therefore, the exploration of the market in which the Yacht Support Vessel will be involved in gives a first look at the problem. This will mainly lead to the analysis of what the competitors are actually offering comparing to the Damen's Yacht Support vessel production.

The list and description of Damen's main competitors with their relative products is available for consulting in Appendix B. The market study, in the context of this master thesis, serves mainly to draw some conclusions and highlight some aspects of the upcoming design.

Conclusions from the competition analysis

- Damen is leader in the market offering flexible and various solutions through a wide range of vessels from 40 to about 90 meters.
- Decision of the company is not covering the smaller market segment of 15 to 30 meters yacht support vessels, on which, companies such as the Italian *Arcadia yachts* are focusing.
- The highest competition is faced on the ranges of around 50 meters vessels, while for the *YS 6911* some interesting solutions also come from refitting of old-fashion shadow vessels.
- With respect to the case study, looking at the more interesting biggest ranges, only *Ulstein* offers a Yacht Support concept of around 90 meters; the *'PX120'* model coming from the platform Supply Vessel section, might directly compete with the ship case of study.
- An interesting concept that can be considered for the largest range is also an 80 meters Yacht Support vessel from *NEDSHIP group* that shows a nice enclosed hangar into the overall design. In addition, the massive height of the *YSV 63* designed by *PIROU shipyard*, also provide interesting insight on possible

solutions for helicopter-related facilities when thinking back at the design of the largest Yacht Support of the Dutch company.

2.1.2. Analysis of Mother Yachts to be assisted

The study and knowledge about the potential Super-yachts that the vessel should be able to support is crucial for getting familiar with the characteristics that the ship should feature. Therefore, an investigation on the top 10 existing Super-yachts (see Appendix A), especially in terms of speed capability and dimensions, helped in defining the main aspects of the support vessel.

Conclusions from the analysis of mother yachts

- The outcomes from the inspection of the 'top 10' Super-yacht give a first idea on the characteristics to be part of the future design. A Yacht Support vessel should sail at a considerable high speed (above 20 knots), have large spaces for improving the storage capacity of the mother yacht, and being characterized by vast deck area that allow for carrying any kind of tenders and toys.

2.2. The Concept of Damen Yacht Support Vessel

The list below includes all the main features of this type of ship:

- **Bigger Toys**
  Main aim of this concept is to give the owner the opportunity to have everything he desires bringing with him without any compromise or renounce giving a huge capacity available; a yacht support vessel can host all kind of vehicles or tenders one can imagine: 45ft tender, submarines, sailing yacht, to name but a few. All this is possible at a cost that is less compared to the option of including all these options on the Super-yacht itself. Some studies have been carried out which show how the cost of the space on board of a Super-yacht is considerably higher compared to the one on a support vessel; even considering two ships management costs instead of only a larger one. Not to mention the advantage of have the freedom of installing dedicated systems (cranes, davits, slipways) capable of safely deal with these nasty actions.

- **Safer Helideck**
  The opportunity to have a fully certified helideck for day and night operation tells a lot about the safety conditions to which the owner is going to be exposed to. Further ultimate step, is the possibility of also including a fully certified hangar for storing the helicopter safely in every weather conditions.

- **No Waiting**
  Functionality and efficiency are two 'skills' the Yacht Support should necessarily have. It has to do with the installation of proper systems arranged in a coherent ship configuration in order to ensure they work correctly together. Deploying and retrieving water toys is a time-consuming and tedious practice. One of the main characteristics of a yacht support vessel is that it permits the owner of departing and arrive from/at one location whenever it suits him. The aim is indeed to maximize the quality of time this people have. Often, owners who can afford such kind of vessel do not have lot of leisure time. More importantly, the only thing they cannot buy is time; in this perspective optimize their time is extremely relevant. In this way the owner, on board of his Super-yacht, can sail away and leave the Yacht Support to do the hard work. What is more, it should sails faster than its assisted yacht in order to prepare the next destination before the owner arrive.

- **Speed**
  Basic prerequisite of a Yacht Support is having the necessary speed for not lag behind her mother yacht. The ranges provided by Damen can reach speeds up to 25 knots, even in a rough seaway.

- **Luxury**
  One of the intent of the 90-meters YS, is giving the chance to accommodate not only crew but also guests. Thus, should be provided accommodation furnished to the same standard as an interior on a luxury yacht.

- **Aesthetics**
  Because of the environment where it operates, it should look great on side of its mother yacht.

- **Security**
  The concept include the chance of installing proper sensors and weapons on board to sail safe in all kind of waters against eventual piracy or terrorism treat. In this view, it will act also as security patrol with specialized personnel, security equipment and advanced communications systems.
  A further way in which the Super-yacht tenders are used is a scout vessel for its charge the Super-yacht. These scouting missions vary according to the circumstances of the owners' adventure. Locating suitable anchorage for the Super-yacht is a very important task and it is easier as well as safer to send your tender ship ahead rather than the Super-yacht since some ports may not be large enough to handle a mega yacht, so you will need to find the right port.

2.3. Requirements Setting of the 90-meters Yacht Support

The simulation of the interview with owner's team delineates the mission the vessel should perform, while the design brief will clarify and fully describe the Yacht Support vessel giving a detailed and complete definition of requirements and characteristics of the vessel.

2.3.1. *Owner's team Interview* – Individuation of Mission Profile

After a full introduction to the type of vessel, during the first phase of the internship at Damen, the simulation of an interview to the owner's team yielded a more detailed description of the Mission profile proper of the 90-meters Yacht Support. The first part of the interview gave understanding on the mother-yacht to be assisted, which presents the following main characteristics:

Length	140 meters
Beam	22 meters
Draught (Full Load Midships)	6.5 meters
Guests	36 pers.
Crew	50 pers.
Cruise - Maximum speed	18 - 22 knots
Range	6,000 nautical miles

Table 2.1: Mother-yacht characteristics

These values well reflects the first investigation on the 'top 10' Super-yachts (see Appendix A) carried out during the market-analysis phase. The description of the mother yacht consequently brings to the definition of the Yacht Support mission profile and her main characteristics.

- First aim of the Yacht Support is increasing entertainment and leisure capabilities of the assisted Super-yacht.
- This vessel, should allow the owner to bring with him any conceivable water toy or vehicle, still keeping her main feature of being fast enough to anticipate the assisted yacht in reaching the next desired location.
- Crew and staff that are not strictly needed for the operability of the Super-yacht itself but which perform temporary tasks on board of the mother yacht might find more comfortable and spacious accommodation on the Yacht Support.
- The vessel should have advanced helicopter-related features: certified helideck and associated enclosed hangar.
- The vessel should also give the opportunity of hosting on board guests. This implies the presence of luxury spaces of the same level of a Super-yacht.

2.3.2. *Design Brief* - What is Required

This document outlines the requirements of the owner, route, operational profiles, and the constraints that will be imposed on the vessel. However, here only a summarized list will be provided that highlights the aspects relevant for the next analysis, while the whole document can be find in the Appendix C.

Main Dimensions and Persons on board

Length	90-99 meters
Beam	13-22 meters
Draught max.	5 meters
Guests	8 pers.
Crew	46 pers.
Cruise - Maximum speed	18 - 25 knots
Range	6,000 nautical miles

Table 2.2: Yacht Support main characteristics

Hull form
The starting point for the hull form is obtained scaling the fast Yacht Support *YS 6911* provided by Damen. Stretching the length from 69m up to 95m and widening the beam from 11m to 16.

Ambient and Environmental Conditions
The YS will assist her 140-meter mother yacht that will tend to operate in various conditions including Tropical area. The range of weather conditions are thus:

- Outside air: 0 - 45 deg.
- Relative Humidity: 75% at 35 deg.
- Seawater: 0 - 32 deg.

Operational Profile
Analyzing the running hours per year it is possible to identify the following activities:

1. Sailing: 2000 hrs/yr
2. Anchor: 2000 hrs/yr
3. Port: 4700 hrs/yr

By dividing the correspondent sailing hours per year according to the operational profile of the vessel, they can be characterized as follow:

Operation	Time(%)	Speed (knots)
Overtaking	10% time (2000 hrs/yr.)	25 knots
Crossing (i.e. Ocean)	50% time (2000 hrs/yr.)	18 knots
Economic cruising	30% time (2000 hrs/yr.)	15 knots
DP/ Manuovr./ stand-by	10% time (2000 hrs/yr.)	0 knots

Table 2.3: The sailing activity

Helicopter facilities
On the 90 meters yacht support the request consisted in an helideck which can sustain heavy and big helicopters and an enclosed hangar as well that can lodge them to satisfy the most demanding need of fast mobilization. As *nice-to-have* request, the landing area might be used as *tennis court* if there is the possibility. The two helicopters are:

1. Heavy-duty helicopter: H225 - type
2. Medium-duty helicopter: H155 - type

Next section extensively will dive into the regulations required for properly designing a safe and fully certified landing area. The high impact that these helicopter-related spaces have on the overall design together with the high conflict these systems have with the other main characteristic of the vessel, prompts for a careful study on the options that can be considered in later sections.

Toys & Tenders characteristics
The other predominant characteristic of the ship shall be her huge carrying capacity that directly translates in square meters available to store tenders and toys. The list of all the toys and tenders required gives an idea of the immense space required for these and consequently subtracted to accommodations, technical space, stores etc.

No.	Type
1	Hinckley Talaria 55 M/Y
1	Sport fisher Viking 62c
1	Fast Carbon S/Y
1	Newton 36 dive special
3	Cigarette 50' Marauder
3	Ferrari
1	Hummer
6	Volswagen newbeetle
1	mini-sub MIR
1	mini-sub Triton 1000/4
1	SAAB ROV seaeye Jaguar
3	8 meters Ribs
10	Jet-ski
10	Sea-bobs
1	inflatable Island

Table 2.4: List of Tenders and Toys

The area required to store these items will be carefully analyzed in a later stage.

Other relevant spaces
Only a list of some specific spaces required have been reported here for the sake of completeness and information but a more accurate analysis can be found in the Appendix C.

- Large garbage management space
- Extensive spare part stores
- Dedicated workshop
- Hospital
- Ampelmann Access - (*nice to have*)

'Luxury' spaces
As already explained during the concept definition, also some area dedicated to accommodate guests and associated leisure capabilities are listed below:

- Guest accommodation
- Hammam complex
- Large gym
- Guest Lounge
- Boarding Platform
- Swimming pool
- Diving Center

2.4. Helicopter-related Spaces

Helicopters and helipads are becoming increasingly requested features on board Super-yachts but including helicopter facilities is more complex than simply making sure there is space. While helidecks are an attractive feature for any owner, they are complex features that bring with them various challenges. Helicopters are very sensitive to salt air – especially the rotors which are the most complicated and expensive element of a helicopter – and if they are kept aboard on a permanent basis, need to be kept in a pressurised hangar. These are not only complicated but also take up a lot of space. [21]

Helicopter landing area

In order for an *H225* to be able to land on the vessel, the landing area shall have a structural strength that support up to *11 tons MTOW*. The main dimension that determines the landing area size is the *D-value* of the largest helicopter H225: 19.5$metres$. The figure below illustrates dimensions of the heavy duty helicopter, while table 2.5 indicates the dimensions of both of the helicopters requested.

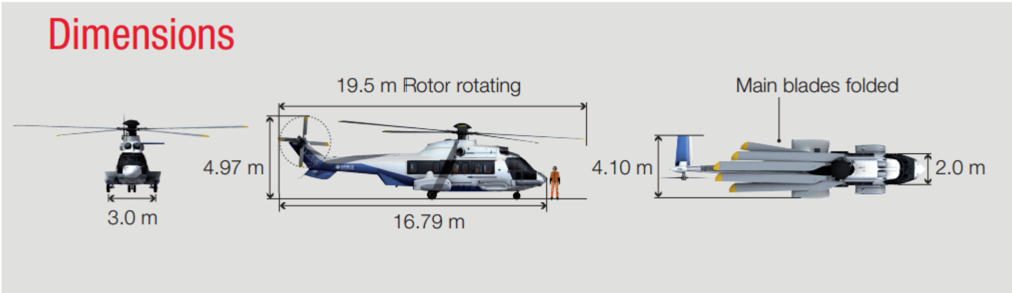


Figure 2.1: H225 characteristics

No.	Type	D[m]	Lf[m]	B[m]	H[m]	m^2	weight (t)
1	H225	19.5	16.79	4.1	4.97	79.95	11
1	H155	14.3	12.71	3.45	4.35	49.33	4.9

Table 2.5: Helicopters specification

Additional wish from the owner's team is the feature of using the landing area also as a *tennis court*. As already explained earlier, this requirement is categorized as *nice to have*. In particular, the length of a tennis court enhances the conflict with other spaces. Around 24m becoming at least 28m by adding a minimum margin of 2m forward and behind the court to allow playing. 28m over 99m represents already the 30% of the length.

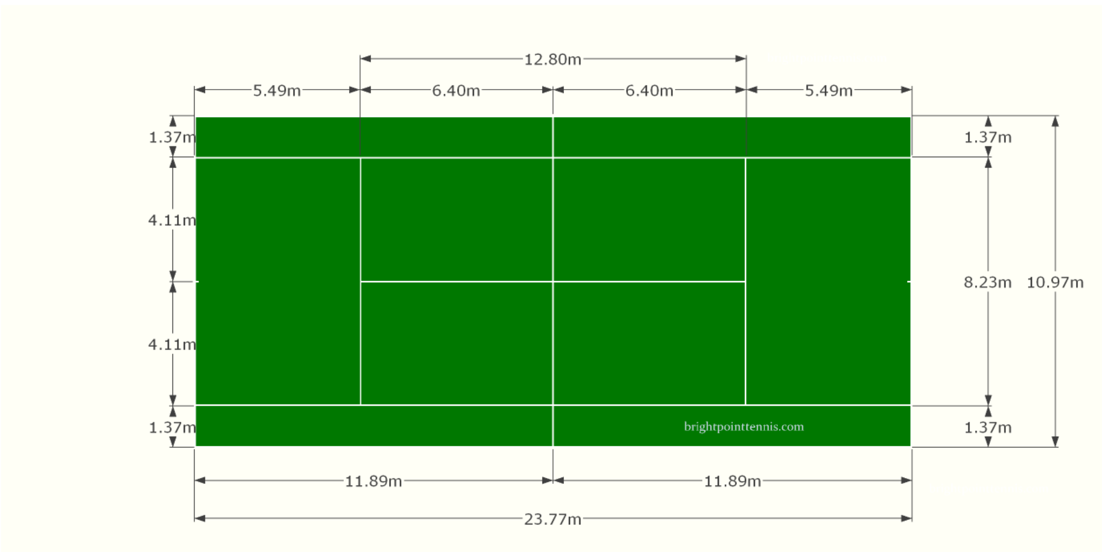


Figure 2.2: Typical tennis court dimensions

Looking at the hull shape of the Yacht Support the aft part of the vessel seems to be the most suitable location for placing the landing area in terms of space available and sensibility to ship motions, for this reason the object was restricted to be placed within the 50% of the length starting from the stern.

Location and size of Operating Area – landing From Cap. 437 *Offshore Heli decks in the section size and obstacle protected surfaces* it is stated that for any particular type of single main rotor helicopter, the helideck should be sufficiently large to contain a circle of diameter *D* equal to the largest dimension of the helicopter when the rotors are turning. This *D-circle* should be totally unobstructed. Due to the actual shape of most offshore and ship helidecks, the *D-circle* will be 'hypothetical' but the helideck shape should be capable of accommodating such a circle within its physical boundaries. For new build helideck designs the minimum landing area size should accommodate a circle encompassed by the outer edge of perimeter marking of at least 1D (based on what just explained).

From the *Appendix H* consultation, the H225 and H155 are both two twin-engine helicopters operating to performance *class 1* or *class 1 equivalent*, or to performance class 2 when taking into account drop down and deck edge miss during the take-off and landing phase. Consequently, applicable in this case is the sub-1D operation.

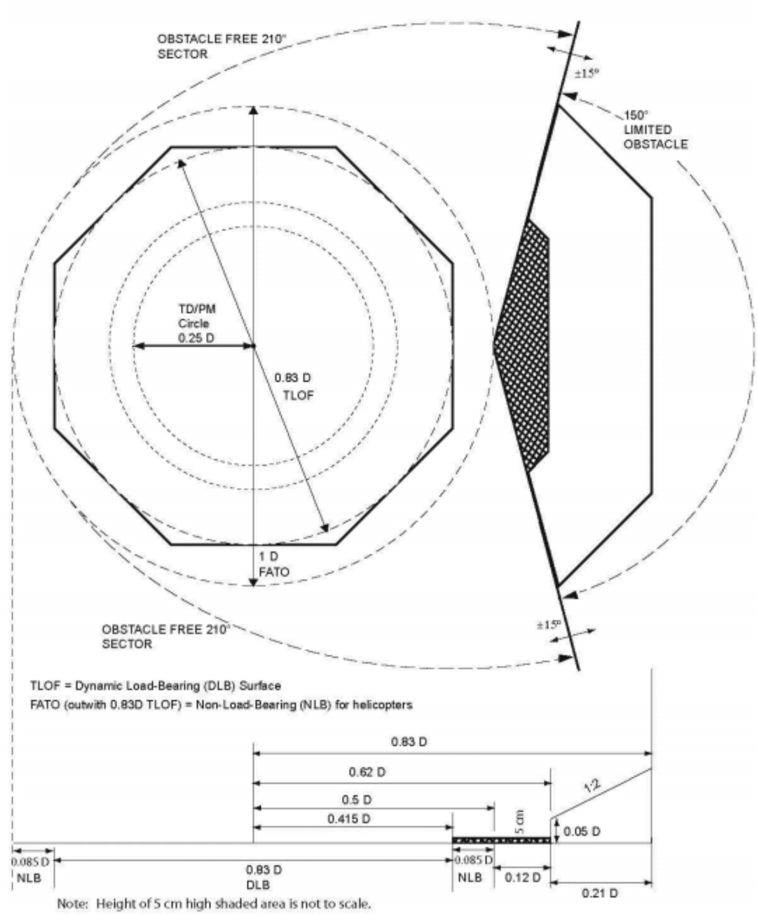


Figure 2.3: Obstacle limitation(single main rotor and side main rotor helicopters) showing position of touchdown/positioning marking circle [2]

Hangar

Regarding the position of the hangar, two main relative positions with respect to the helideck are set up. The first option is the solution endeavored on the *YS 6911*, which provides the hangar just below the landing area with helicopters that will be lifted up and down into the hangar. The second solution expects the hangar at the same deck-level of the helideck; in this case helicopters will be stored and brought in and out thanks to a system of rails.

The hangar will follow the design guidelines according to SOLAS *chapter II-2: construction – Fire protection, fire detection and fire extinction Part G: Special requirements.* Thus, the hangar, refueling and maintenance facilities shall be treated as *category A machinery spaces* with regard to structural fire protection, fixed fire-extinguishing and detection system requirements.

The enclosed hangar should be sized accordingly to both the helicopter's dimensions. The helicopter's storage can develop along the length of the vessel or transversally considering of storing them either along side-by-side or along one behind the other as shown by fig.2.4. The latter solution it is less convenient from the storing logistic perspective since one should move always first the helicopter that is closer to the opening, but still considered as possible in order to increase the *variety* of solutions.

To conclude considerations on the hangar, it needs to be mentioned that it requires an overall area of $180m^2$ with a minimum width of $6m$ to host at least the H225. Regarding the height of this volume, this is also a crucial aspect, indeed, it extends vertically over two decks since the minimum height for the H225 is $5.5m$ while the space between two decks is $3m$ involving inevitably two-decks encumbrance.

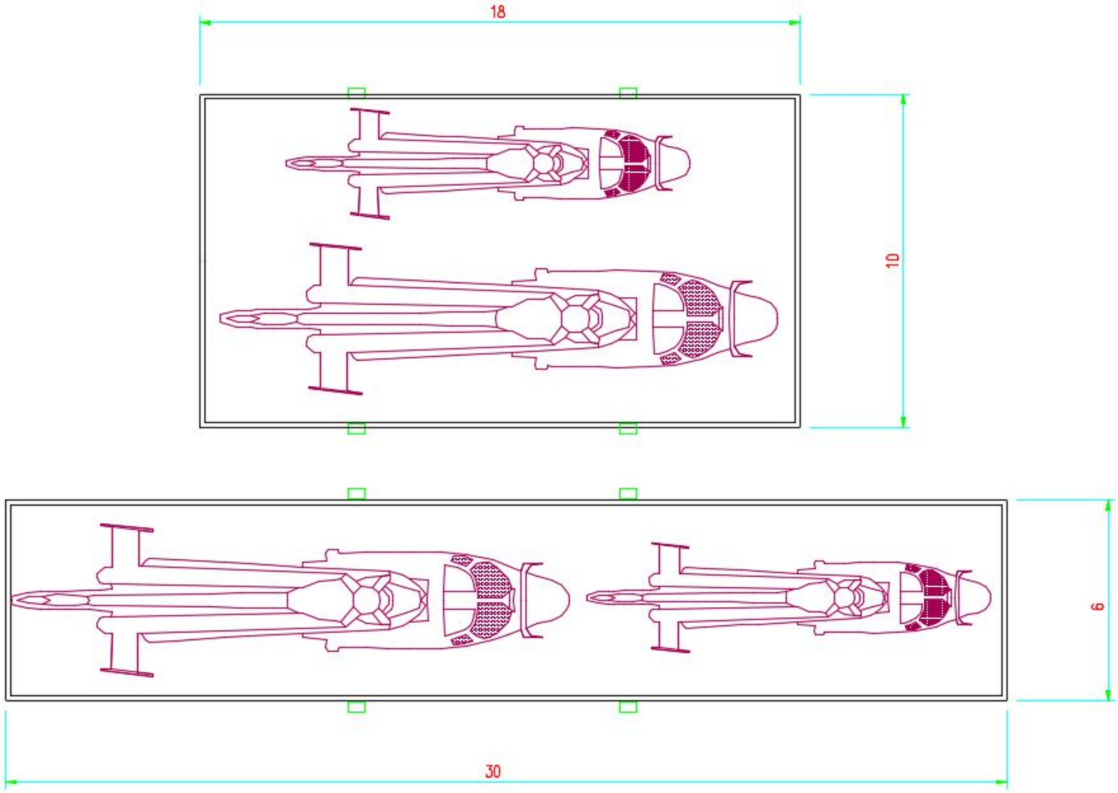


Figure 2.4: Two different hangar shapes

2.5. Toys and Tenders Characteristics

Table 2.6 resumes the list given in section 2.3 adding all the toys and tenders dimensions and weights in order to help in quantify the amount of square meters required on board of the ship:

No.	Type	L [m]	B[m]	H[m]	[m^2]	Weight [t]
1	Hinckley Talaria 55 M/Y	17.0	5.5	5.0	93.5	25.0
1	Sport fisher Viking 62c	19.2	5.8	7.7	111.4	43.0
1	Fast Carbon S/Y	18.0	5.4	29.0	97.2	8.0
1	Newton 36 dive special	10.6	4.5	3.0	47.7	9.0
3	Cigarette 50' Marauder	16.0	2.5	2.0	120.0	24.0
3	Ferrari	4.5	2.0	1.2	27.0	4.5
1	Hummer	4.7	2.3	2.0	10.8	3.0
6	Volswagen newbeetle	4.0	1.8	1.4	43.2	8.4
1	mini-sub MIR	7.5	3.6	3.0	27.0	18.0
1	mini-sub Triton 1000/4	4.0	3.0	2.5	12.0	8.0
1	SAAB ROIV seaeye Jaguar	2.2	1.3	1.5	2.9	2.1
3	8 meters Ribs	8.0	2.7	1.0	64.8	2.4
10	Jet-ski	3.3	1.2	1.2	36.9	4.0
10	Sea-bobs	1.2	0.5	0.4	5.8	0.4
1	inflatable Island	2.0	2.0	1.0	4.0	0.2
Tot.					707	160.0

Table 2.6: Tenders and Toys size and weight

Toys and tenders above listed will be restricted to some areas within the vessel based on a rationale that looks primarily at their size. In addition, their weight is going to decisively affect the relative deploying system and stability of the ship particularly during such operations.

The height of some of the toys, highlighted in red in the table above (i.e. the mast of the *IMOCA 60* or the hard top of the Sport Fisher) is critical for the interaction with other spaces (especially helicopter-related ones) and limits the longitudinal extent of decks coming above. On the other hand, locating these bulky tenders above the main deck is not recommendable because it would compromise the stability of the vessel and making the deploying activities nastier and impracticable. The height between two decks is normally 3 meters, some of tenders exceed by far this vertical available space. Therefore, they will hardly find any place in an enclosed store between two decks, unless a significant stash will shape the main deck, for instance. The total area of 707 m^2, increased with a 10% margin for taking into account the passageway, was reserved for a total of 777 m^2. This value represent the space needed if all the items would be spread on a deck side by side, obviously in reality, it is common practice to maximize the vertical space between two decks while storing toys. Indeed, the arrangement of the smallest toys (i.e. Jet-ski, sea-bobs and the others highlighted in yellow) expects of disposing the latter one on top of the other creating a *'Toys garage'* that accounts for their disposition in one unique room. Same holds for the 10 cars, which in packing are going to be considered as a unique block creating a proper *'Garage'*.

The heaviest tenders and toys are also the ones that have the greater overall height and this might conflict with the position of helicopter's landing area, further explanation and demonstration will be provided afterwards.

2.6. Design Challenges

The analysis of the design brief and the information gained from the owner's team interview brought the attention to the two main issues previously mentioned in section 1.1 : speed and spatial conflict.

First, the attention is focused on the speed problem. Why making the desired speed is a challenge, where the difficulty comes from and how it will be tackled is explained in subsection 2.6.1. The same paragraph serves also for the validation of the accuracy with which packing is able to make the resistance estimation.
The latter will be analyzed based on the description given by sections 2.5 and 2.4 that highlights the two main attributes causing the conflict; namely the spaces related to helicopter operations and the ones required to host toys and tenders. As expected, the engine room, with her variations, also will take part in the interaction, making the conflict even more marked.

2.6.1. Speed - Power

'There is no reason of having a Yacht Support vessel that lags behind'. [47]

The sentence is representative of the philosophy of this type of ship. For this reason, special attention was paid on the aspects related to this performance. It is possible to distinguish two main aspects influencing the speed: the *hull form* and the *power installed*. In this application, varying the hull form is not the main factor subjected to changes. Indeed, this choice is the result of a company decision of keeping a hull-design similar to the other products provided by them. From the beginning, indeed, was manifested the preference in avoiding the use of substantially different hull shapes (bulbous-bow, catamaran etc.). Being the straight AXE BOW a distinctive sign of the company, especially true for the *Yacht Support* and *SeaXplorer* series, the wish of maintaining this styling aspect was claimed.

Resistance comparison

As already mentioned, one of the leading factors determining the speed of a ship is the power installed. *Holtrop & Mennen* approximation method was used for the resistance estimation being aware of the fact that, at maximum speed, the vessel should sail to a regime that lies on the limits of its applicability. The resistance was evaluated with packing and the with software *Maxsurf* on models of equal main dimensions, prevalently to check how good was the table of offsets obtained from the reference hull.

On one side, the resistance and power, on the 3dm. file of the hull provided by Damen, was estimated through the software *Maxsurf*. On the other hand, a dedicated file called *'Run settings for comparison'* was created 'ad-hoc' in the packing model, constraining length and beam to $L = 95m$ and $B = 16m$ respectively, assuring thus similarity with the provided hull. In both the environments, the starting point for setting the draft was carefully placed at the baseline (the very lowest point of the hull), and was set the same $3.5m$ of draft.

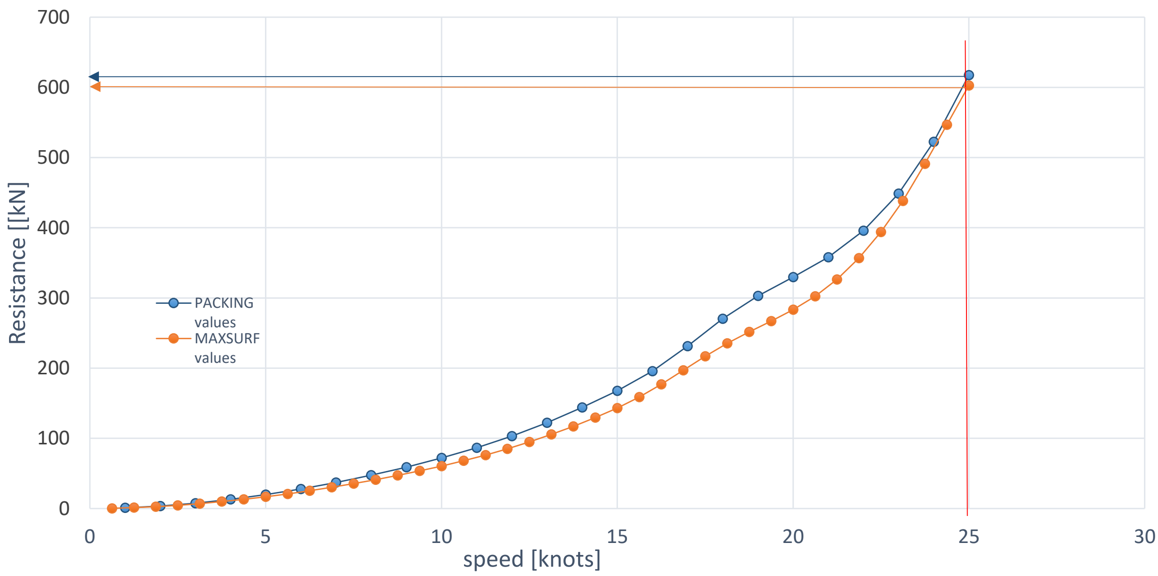


Figure 2.5: Resistance in Maxsurf and Packing

Figure 2.5 plots together on the same graph both the resistance calculated through *Maxsurf* and the one estimated by packing.

From these value of resistance it is possible to go back to the correspondents values of power remembering of taking into account the chain of efficiencies which brings the *Effective Power* to the *Break Power*. The efficiencies are included in the following two values:

- *Propulsive Efficiency*: it is common practice to define the total propulsive efficiency to embrace all effects concerning hull and propeller.[44] Hull efficiency, open water propeller efficiency and relative rotative efficiency contribute to bring the total propulsive to 0.7.

- *Transmission Efficiency*: takes into account shafting and gearbox that are still found between the propulsor and the prime mover. Consequently, gearbox efficiency and shaft efficiency leads to 0.97.

The larger gap between the two curves can be appreciated within the range from 16 to 22 knots, where a maximum of 10% is registered. Around 617.4kN of total resistance are estimated by packing, which compared to 602.8kN well reflects the estimation obtained in *Maxsurf*. To conclude, the validation accounts for a divergence of less than 3% discrepancy at top speed, representing an acceptable level of accuracy. This error is due to small differences in the hull due to the grid used for the extrapolation of points and possibly also to the fact that packing requires the presence of a default engine room to let the program run. As consequence, some of the values of hydrostatics might be slightly altered compared to only a bare-hull.

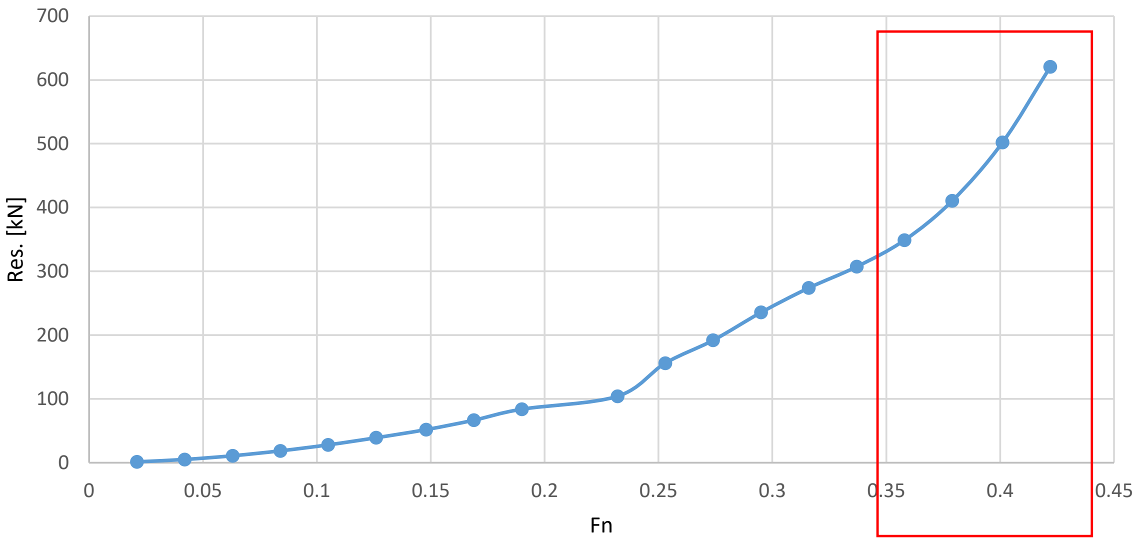


Figure 2.6: Relation between Resistance values and Froude number

Despite the comparison between the two resistance curves and the two different tools used, it is clearly visible, by plotting the resistance versus the Froude number in fig.2.6, that there is a sharp increase for the former starting from $Fn = 0.35$ and even more markedly at around $Fn = 0.4$ which represents exactly the working point of the Yacht Support when sailing at maximum speed.

2.6.2. The Spatial Conflict

From a quick look at the design brief an experienced naval architect should already get the feeling of which might be the most conflicting aspects. However, an effective way to demonstrate which the critical elements are, was by simply showing the space they require in comparison with the space available on average on one-deck level. Figure 2.7 depicts a pie chart illustrating some of the fundamental area characterizing the Yacht Support in comparison to the square meters on one-deck level.

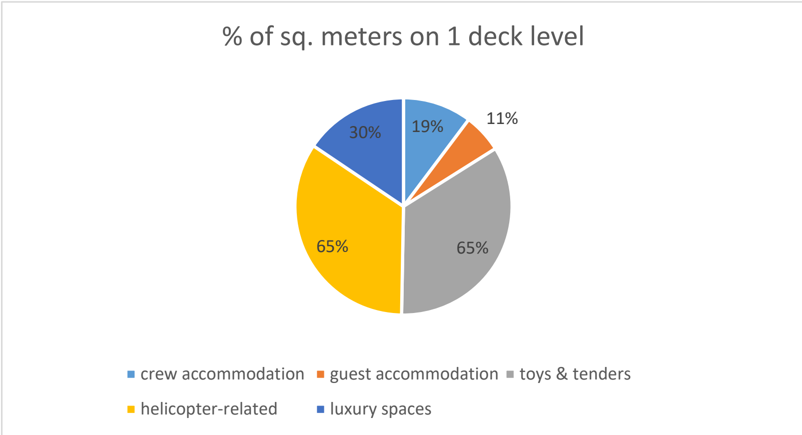


Figure 2.7: Relevance of components over one-deck area

The dimensions of the area analyzed are the ones described within the design brief while the available area on one deck level refers to the hull of reference: 16m wide and 95m long. From the analysis, emerged that both helicopter-related spaces and toys & tenders occupy 65% of the area available on one deck, making them the most conflicting elements on board. All the toys and tenders have been reported, both in the numbers and graphically (below), as spread all over the deck to emphasize their massive dimensions and thus the conflict. However, as previously already mentioned, the smallest toys, will be obviously arranged one on top of the other to profit by the vertical space. Guest accommodations and luxury spaces account together for just less than half of a deck area, but being distributed between separated levels on the vessel, will not represent a serious issue.

The pictures below, further demonstrates the opposing nature of the two elements above. On one side, huge carrying capacity that translates in m^2 available for storage on deck. On the other hand, ultimate helicopter characteristics implying two helicopters to be stored in enclosed hangar and a landing area to serve as a tennis-court as well (as *nice to have* request). The decks reported are two since all the items required did not fit on one deck space, but they are not representative of any potential arrangement.

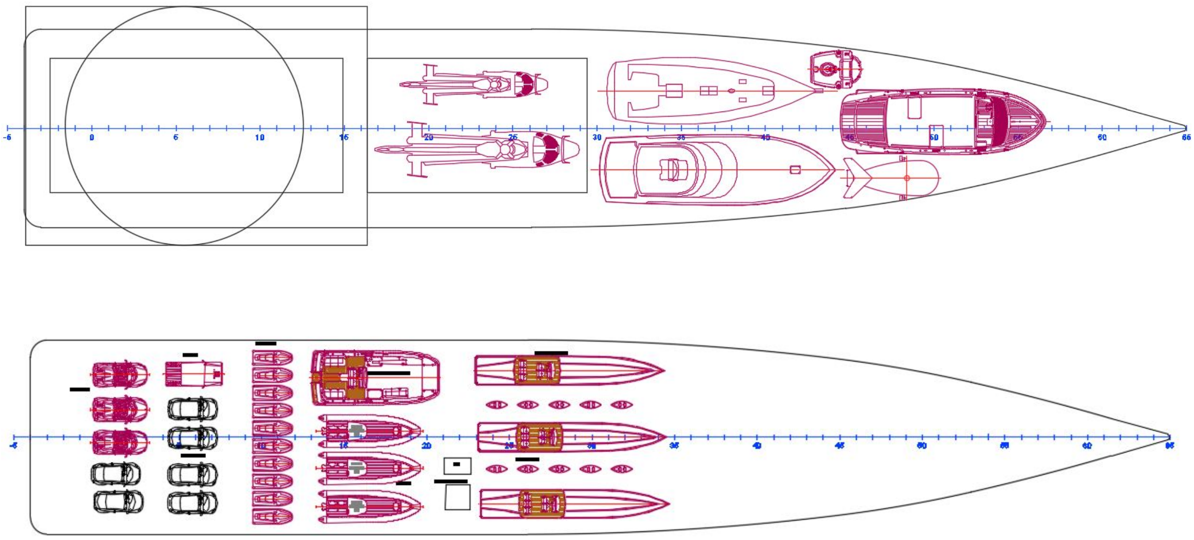


Figure 2.8: Area occupied by the two main conflicting aspects

Not only in terms of square meters, but also on the vertical encumbrance these two aspects are rather critical. Both the hangar and some of the tenders far exceed the height between two decks, making the interactions in this direction even more complicated.

To prove and emphasize the conflict that holds also vertically some runs of the algorithm were performed. The first (on the left in fig.2.9) only with the helicopter-related spaces (helipad and hangar) and the other one (on the right in fig.2.9) with the largest tenders discussed.

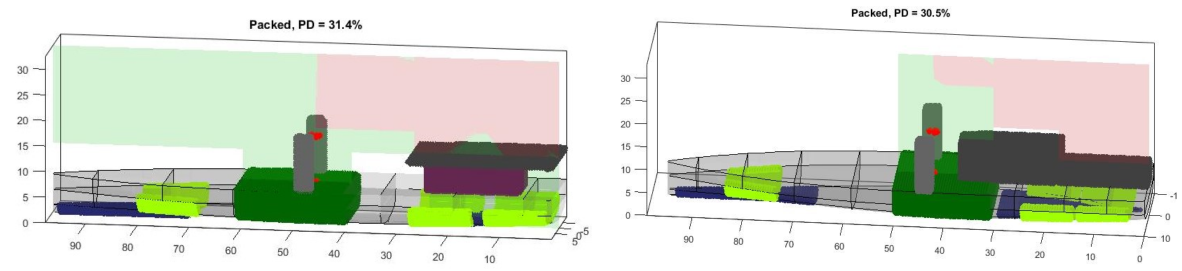


Figure 2.9: Conflict in the vertical encumbrance

On the left it is visible the helipad and below the associated hangar. On the other hand, on the right the grey blocks represent the *Hinckley*, the *Viking* and the *Sailing Yacht*. All these tenders need to be stored on the main deck for practical reasons due to their size and weight, similarly the hangar with the associated helipad also needs to be located around the main deck level for making the helicopter activities safer.

2.7. Recap

To sum up, the 90-meters Yacht Support need to satisfy the following non-negotiable requirements:

- The limitations on the main dimensions are $L < 100m$ and $T < 5m$.
- The ship should be able to reach a maximum speed of 25 knots and have a range of 6000 nm at 18 knots.
- Each mentioned space requires a certain amount of square meters that can be found in the design brief (Appendix C)
- Two helicopters, of the type specified, need to be stored into an enclosed hangar.
- All the toys and tenders mentioned above should be carried on board (the full list is available in section 2.5 and in appendix C).

On the other hand, only the following two points were treated as negotiable (nice to have) requirements:

- A landing area which serves also as tennis court, implying larger dimensions compared to the ones necessary for a certified helideck.
- The space for installing an Ampelmann access.

3

Building the *Ship Synthesis Model*

3.1. Introduction

The *Ship Synthesis Model* (SSM), which will describe the vessel within the *IECEM*, requires as inputs, all necessary information about spaces on board. The design brief (see Appendix C and section 2.3) provided a general overview of which are the exact characteristics of the Yacht Support. All these features and requirements represent the basic set of information necessary to create the desired design space. This chapter will explain how the elements needed to describe the YSV are synthesized in the SSM. Initially, will be given a general overview of what is meant with *basic feasibility* of a certain design solution, following will be provided a list of objects representing the entire YSV. And later in this chapter, those spaces and characteristics of the vessel considered as more relevant for the design study, will be explained in more details.

3.2. Feasible Design and Optimization Process

During the initial stage of a design process, and similarly also within the packing model, there is a distinction between negotiable and non-negotiable requirements.

Until this stage the discussion on negotiable and non-negotiable requirements concerned the aspects and elements requested during the interview to the owner's team. From this discussion, came up that only the following two requests were considered as negotiable:

- landing area to be used as tennis court.
- Installation of an Ampelman access.

As a result, the design space happen to be considerably constrained. Nonetheless, because of eventual non-feasibility of some highly conflicting aspects for the packing capabilities, part of these requirements will be also modeled as negotiable. To give an example, even if two helicopter are required, the possibility of carrying only one is also considered. As consequence, this will lead to the creation of trade-offs between some of the components.On the other hand, an example of non-negotiable requirement that will not be subjected to any compromise is represented by the limitation on the draft allowed, which cannot exceed 5 meters. This chapter will analyze different design options for those elements highlighted in chapter 2 and identified as the 'most interesting' for this case study.

However, in packing the definition of non-negotiable requirements refers to the fact that those requisites need to be met otherwise the safety or workability of the ship will be compromised. The packing algorithm takes into account those requisites in form of constraints. Generally, it is possible to identify a set of performances which cover the basic naval architectural capability considered during a feasibility assessment. van Oers ([35]) highlights the following which are included in the packing model used in this application:

- **Space constraint**: assures that the space reserved by the model is big enough to include all the systems defined in the SSM, taking also into account the space required to satisfy the relations between them.
- **Draft/Buoyancy constraint**: ensures that the *actual* draft, is lower or equal to the *design* one. In this way, the buoyancy is enough to carry the weight of the vessel. This is also directly linked to the capability of meeting the right propulsion power to meet the speed.

- **Stability constraint**: in order to satisfy the basic intact stability, the value of the meta-centric height (GM_t) is imposed to be within a minimum and maximum values.
- **Trim constraint**: limiting the distance between the Longitudinal Center of Gravity (LCG) and the Longitudinal Center of Buoyancy (LCB), the weight distribution is regulated so that the trim of the vessel is kept within a certain limited range.
- **Reserve buoyancy constraint**: a damage length defined by the user will indirectly determine the value for which this constraint will be met or not. Indeed, this requirements is strictly linked to the position of the bulkhead which in turn depend on the value of floodable length allowed. Thus, if the bulkheads are placed correctly, the actual design will meet this requirement and proceed with the packing process.
- **Speed, Endurance and Range constraint**: finally, the speed and power prediction are used to size the engines, the engine room and the fuel-tanks.

With respect to some of the constraints just mentioned, the mathematical model used for the Yacht Support had the following values set, ensuring for the feasibility:

1. GM_{tmin} / GM_{tmax} = 0.75 - 3.5 m
2. Minimum Freeboard = 2 m
3. Delta CoG_x = 2 m
4. Damage Length (%) = 10 % of the overall length
5. Min. Packing Density = 0.3 (30%)
6. Max. speed = 25 knots
7. Range @ 18 knots = 6000 nm

Because the approach presented in this thesis is, based on mathematical packing problems, it is aimed at optimizing based on a certain *objective function*. A characteristic that distinguish the packing approach and the *IECEM* itself, is the fact that the designer does not define the best design up-front. In contrast, as Duchateau (2016) mentioned, the naval architect can gradually determine which are the main aspects of the type of ship in question, thanks to insights and knowledge gradually gained from the process.

At the current state, the starting point of the packing process, expects one initial *objective function* that minimize the *Packing Density*. Both Duchateau (2016) and Droste (2016) highlight the fact that, after the first run, more requirements can be added as additional *objectives* during further iterations of the process. The reason behind this is twofold: first, when adding requirements as an objective, a design will not fail but can only be better or worse depending on its compliance with the objective. Second, it narrows the search during the process, but ensures that a good overview of the design and solution space is kept.[12]

In the case study, several so-called *steering runs* have been conducted after the first one, with the aim of improving the design space with shorter design solutions. From time to time, a different objective function was added alongside the maximization of the packing density trying to find shorter designs.

3.3. The *Ship Synthesis Model*

The *SSM* includes all the elements required to describe the YSV. Within packing these elements are represented by systems, which in turn are made of objects, and a system can include one or more objects. These objects can represent either a space or a discrete object such as an engine or a tender. What is more, to describe the relationship between these spaces and discrete objects, also other type of objects exist; a complete list of them is given following as described by van Oers (2011).

1. *Envelope object*, comprising both the hull and the superstructure.
2. *Subdivision object*, namely bulkheads and decks subdividing the above-mentioned space.
3. *Hard objects*, that can be engines, tenders or lifeboats, but also a working deck.

4. *Soft objects*, most commonly spaces such as accommodation or tanks.
5. *Free Space objects*, to model the free space required for the landing area above an heli-deck or the free view of a guest lounge or of a wheel house.
6. *Connection objects*, may represent the connection between the engine room and the stacks above or a route connecting flying deck to hangar. They were barely used in the case study because of their consistent required effort in modeling them.
7. *Logical objects*, to give the rationale to both *Soft* and *Hard objects* not only for their relative position but also for giving them a location within the envelope.

Based on these objects types, all the systems which represent the SSM are built. Generally, the order in which all the systems are placed and the SSM is built, depends on the order in which they are modeled and put sequentially in the packing model. Previous studies proved that the best way of arranging these systems is based on the number of constraints for that system, the size of the objects in the system itself, the hard objects before the soft ones as the soft objects can form themselves around the hard ones (Zandstra, 2014).

3.3.1. Systems of the Yacht Support Vessel

This subsection lists and explains how the systems described above are specifically created for the case study. The order in which the systems are listed is not casual as it represents the order in which they are gradually created in the mathematical model, representing the packing process.

1. Envelope (hull and superstructure space)
2. Decks
3. Engine Room
4. Bulkheads
5. Bow-thruster Room
6. Working Deck (including largest tenders)
7. Helideck and Hangar
8. Bridge
9. Cigarette (3)
10. Ribs (3)
11. Ampelmann Access
12. Garage
13. Toys Garage
14. Technical Room
15. Garbage Space
16. Freezer Storages (2)
17. Heli-fuel Store
18. Toys and Tenders-fuel Store
19. Diving Center
20. Boarding Area
21. Bosun Store (2)
22. Galley
23. Crew Mess and Lounge (2)
24. Crew Cabins
25. Laundry
26. Hospital
27. Hammam complex
28. Guest Gym
29. Crew Gym
30. Workshop
31. Staff Cabins
32. Spare Parts Stores (5)
33. Emergency Generator Room
34. Helicopters pilots Cabin
35. Officers and Engineers Cabins
36. Captain Cabin
37. Lifeboats
38. Guest Cabins
39. Guest Lounge
40. Office
41. Muster Room
42. Fuel Tanks (3)

43. Ballast Tanks (4)
44. Lube oil Tank
45. Fresh Water Tank
46. Black and Grey Water Tanks
47. Bilge Water Tank

The numbers next to some of the systems state that a specific element is equally reproduced that number of times. A system can be composed by one or more objects.

- *Envelope*: includes hull and space for the decks above. The shape of the hull was obtained from a table of offsets extrapolated from a CAD file while the space reserved for the superstructure is given all the way up starting from the uppermost part of the hull.
- *Decks*: described by three parameters. The first one decides the minimum and maximum value assigned to the tank top, the second is used to determine the height between decks and finally the last one sets the position of the bulkhead deck. Within the model representing the Yacht Support, these information are provided in table 3.1 showing that both the double bottom height and the mean deck height are fixed to 1.5 and 3 meters respectively, while the bulkhead deck can be assigned by the algorithm at the third or fourth deck starting from the bottom line.
- *Engine Room*: is built by three objects. The space of the engine room itself which is modeled as hard object as well as the discrete engines. The third one is a logical one that permits the connection with the up- and down- takes. Regarding the overall position of this system within the envelope, it was restricted to be within 33% and 75% of the hull length and vertically located at the above the tank top.
- *Bulkheads*: as Droste (2016) explains the objects used to define this system are of the type subdivision and are located with a different placement function as the other objects. Three variables are used from the genetic algorithm to place them; the first one is to determine the number of bulkheads, the second one to define the position of the first bulkhead and the last one calculates the minimal distance between each bulkheads.
- *Working Deck*: two are the main objects created to synthesize the working deck strictly in itself: an hard object representing the portion of deck reserved to store the largest tenders and a free-space object to secure that any objects other than tenders will be located on top of it. Its position was assigned to the deck representing the bulkheads deck (the third or fourth) and any restriction along the length was imposed.
- *Helideck and Hangar*: represented by two hard objects, one for the hangar and the other one for the landing area. A free-space object was also modeled from the top of the landing area and upward. Overall, the system is globally restricted to the first 50% of the length and it is allowed to be placed from the bulkhead deck (main deck) up.
- *Accommodation*: are modeled as soft objects. The locations within which they can vary depends on their type: for crew/staff are assigned the lower decks, higher-rating officers and guest ones occupy the higher levels.
- *Bridge*: also composed by three different objects. An hard object representing the space of the room itself, a free-space object that guarantees a view free of obstacles in front, and a logical one assuring the relation with high officers and captain accommodation. The system was restricted longitudinally between 40% and 80% of the length and vertically to two or three decks above the main one.
- Larger tenders and toys are included in the system 'working deck' while the smaller ones are included in a toys garage as well as cars in a garage. On the other hand, *Cigarette* and *Ribs* are modeled singularly both as hard objects. *Cigarette* are allowed to be located in the first 50% of the length between the main and the lower deck. Indeed, thanks to their relatively low height, a possible enclosed storage, between two decks could also be considered. *Ribs* have more freedom because of their smaller dimensions.
- *Garage* and *Toys Garage*: modeled as soft objects with a minimum width for operations. The position of the former was conceded to occupy either the main or the upper deck, for the latter made sense to restrict it to the lower deck since the deployment of the relative toys would have resulted easier. The garage, on the other hand, could provide an opening to one of the side of the ship and connected to the ground through a side ramp.

- *Technical Room* and *Garbage Space*: are characterized both from a soft object which represent the space dedicated to respectively technical equipment and garbage, and from a second logical object assuring 'adjacency'. Both the system are meant to be adjacent to the engine room.
- Similar discussion can be done for system such as *Heli-fuel Store* and *Toys and Tenders-fuel store* which are restricted to be close to helideck and hangar and working deck respectively.
- The *Diving Center* acts as the reference system for the *Boarding Area*. Indeed, the first one is composed by two objects: a soft one describing the space and a second one that allow for the adjacency with the *Boarding Area*.

This type of reasoning and way of modeling the systems repeats itself very similarly for the other objects left in the list.

3.3.2. Variations

In this subsection is proposed an overview of the variations allowed and implemented in the code. Due to the highly constrained case study, some of those were implemented to see how packing was dealing with the creation of potential trade-offs. However, these compromises amongst the requirements, might affect the feasibility with respect to the design brief. Examples are: the larger maximum value of length, the possibility to carry only one helicopter and the lower number of tenders compared to what is required.

Name	Variation (step)	Number
Length	95 - 140 (+0.5)	86
Beam	14 - 24 m	contin.
Draft	2 - 5 m	contin.
Decks in the hull	3 - 4 (+1)	2
Double bottom height	1.5 m	fixed
Deck height	3 m	fixed
Name	Variation (step)	Number
Engine Room	4xDE - 3xDE - F&S	3
Working Deck	1,2,3 largest tenders	3
Heli-config.	1,2 helicopters - vert., horiz. hangar - row, side dispos.	8
Cigarette rotation	long. - transv. disposition	2
Cigarette	1-3 (+1)	3
Ribs	1-3 (+1)	3
Ampelmann Access	Yes, No	2
Garage	10 -7 - 4 cars	3

Table 3.1: Variations implemented in the code

The first set of variations regards the changes affecting the ship in her main dimensions and structure. On the other hand, the second set of variations characterizes more specifically the main features of the Yacht Support, in particular the first three, and those will be further explained in their dedicated subsection. The remaining items of this second list show that the Cigarettes can assume a transverse position with respect to the length of the ship, that both Cigarettes and ribs can be selected in a number of 1,2 or 3, the Ampelmann access can be included or not in the current concept, and finally the garage can assume dimensions such as to contain 4, 7 or 10 cars. Both for ribs and Cigarettes, each of the three single tenders is modeled as single entity.

Each design variable can have a certain limit or range through which it can vary either in discrete steps (e.g., type of hull shape or number of helicopters) or continuously (e.g. length, beam, draft). A combination of variables trough synthesis, produces a design with measurable performance attributes (e.g., speed, range, stability, etc.). An essential goal of concept exploration is to determine the useful and feasible limits of these design and performance spaces as well as the underlying relations between these two domains, which determine these limits. In addition, the design space is not only constricted by the limits of each design variable, not all combination of variables will produce a technically feasible design solution. What is more, even when such technically feasible design solution can be found, additional requirements on performance can still render a combination of design variables as unwanted. [13]

The model representing the Yacht Support changed concurrently: 3 types of engine room layouts (considering different number of engines and their power distribution), diverse helipad-hangar configurations, available deck area and size of enclosed storages for parking tenders (depending on which and how many tenders and toys). However, such a model led to a smaller number of successfully packed designs, compared to a model without variations. This is explained by the fact that the program has to search for multiple compact configurations for many combinations of design options rather than for one combination of design options. In few words the increase in problem dimensionality reflects on the performance of the search algorithm. [13]

3.3.3. Engine Room Arrangements

The actual settings of the packing tool for the 'resistance & propulsion' calculation, reckon on assigning values for transmission efficiency η_{TRM} (0.97) and propulsive efficiency η_D (0.7). Prime movers are selected only based on a required power per component (MCR). No specific attention was further given to the matching of components based on *rpms* and delivered or consumed power. Nonetheless, the simple propulsion plant model gives an initial estimate of the gross component and plant sizes and weights.[13]

The need of creating concepts of diverse engine room layouts arises considering speed as one of the main aspects in this ship design problem. When designing a power plant for a given ship, determining the optimum propulsion system depends on many interconnected factors: missions, operating profile, power, efficiency and fuel consumption, weight, dimensions, maintenance and repair costs, to name but a few.

The location of the machinery spaces also depends strongly on the complexity and the extent of the plant and the overall ship design.[44] Multiple-engine and multiple-shaft configurations with a mechanical transmission require that the propulsion machinery spaces are low in the hull in order to connect the drive to the propeller and usually that the spaces are wider than the aftermost compartment. Consequently, the propulsion machinery spaces are located more forward than the aftermost compartment; for instance at one third or half the ship's length from the aft.[44] One important consideration regarding the position of the engines, is the shafts length that tends to be kept as short as possible.

The algorithm, based on the relationship with the other systems, determines which one of the arrangement created is the most suitable through a *switch* between the correspondent three cases following described.

4xDE configuration The first type of power plant modeled looks like the one in fig. 3.1

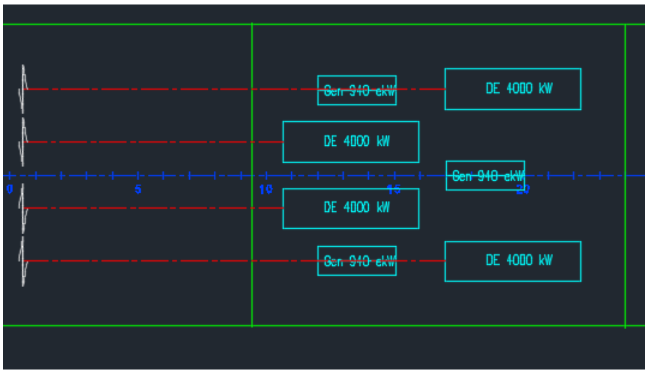


Figure 3.1: 4xDE configuration

How the algorithm proceed when approaching the modeling of this system is explained here.
First of all, it need to be mentioned how the engine selection is carried out. The database of engines is loaded and all the informations of the engines are named and stored. Next, in this specific case, 4 engines are set as input and the power required is divided amongst the number of engines. At this point, the algorithm selects the smallest engine in the database which is able to satisfy the power demand. Finally, the MCR of the engines is calculated and stored with also the total *Specific Fuel Consumption (SFC)* and the other characteristics (size, mass, CoG and name). All these informations are necessary for dimensioning the engine room. In the case of four diesel engines, indeed, the following relations hold:

- $L_{EngineRoom} = 2 \cdot L_{Engine} + 4m$

- $H_{Engine Room}$ = 2 · Mean Decks Height

- $W_{Engine Room}$ = Entire width of the ship

The formulas above together with the help of fig. 3.1 illustrate the dimensions of the room. The 4 meters in addition to the length are took into account to give some clearance aft (2 m) and forward (2 m) of the engine itself. Regarding the height, two times the mean deck height was assigned because in any case the engines considered were exceeding 3 meters (1 deck height).

The in- and out-air flow intakes size their dimension accordingly with the maximum of the total power (*MCR*) requested from the previous calculations. The airflow for inlet and exhaust is proportional to the power installed. Approximately, up and down flows require 0.5 m^2 per MW for both, considering 6.8m^3/hr. with a flow speed of 10 m/sec (ISO 061). This setting will hold for every other engine-room arrangement.
The graph below summarizes and gives an overview of the operational profile of the 95 meters Yacht Support.

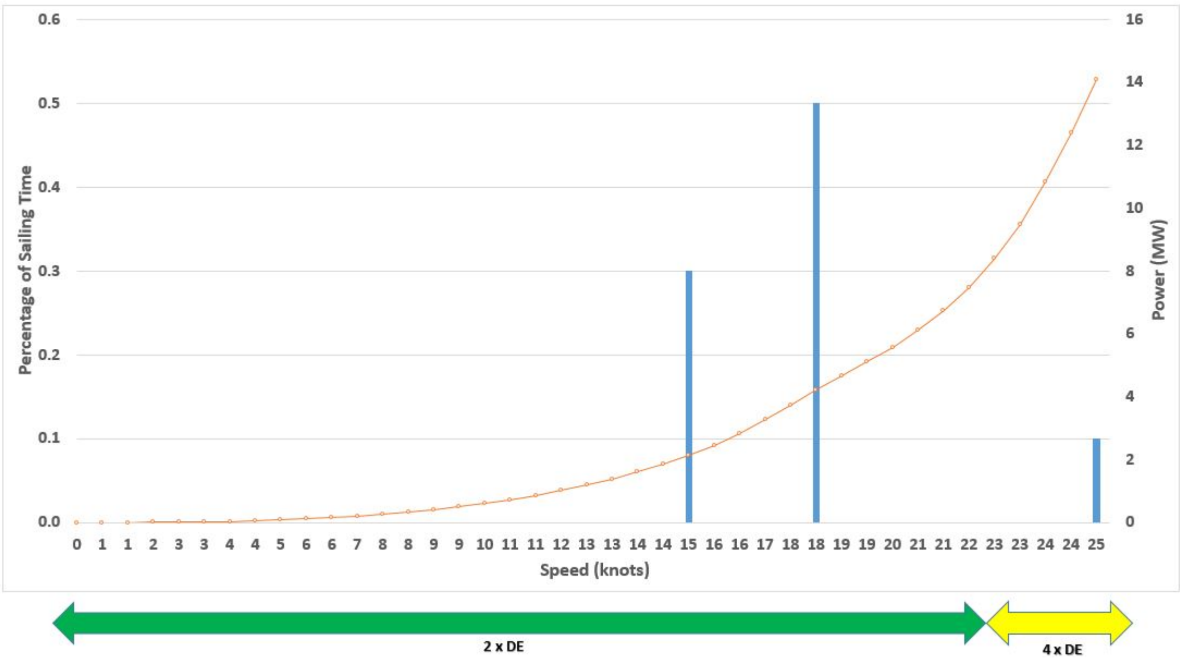


Figure 3.2: operational profile case: 4 x DE

The orange line shows the trend of power against velocity referring to the hull-shape of the starting point (L=95 m, B= 16 m). In reality in the model, this curve will always be substantially different according to how the algorithm is going to stretch the hull. The blue bars display the percentage of the sailing operation time. Indeed, most of the time the ship will be in crossing mode at a speed of *18 knots*. It can be noticed that the large part of the operational mode would be dealt with two engines running which can push the vessel up to *~ 20 knots*, while to reach the top speed for the overtaking mode, also the other 2 engines need to be turned on.

3xDE configuration In this case the engine selection is based on the subdivision of power amongst 3 equal medium-speed diesel engines (DE), probably resulting in heavier and larger engines compare to the previous case. The procedure of selection and storing of the information is identical to the previous case. Fig. 3.3 illustrates the option considered:

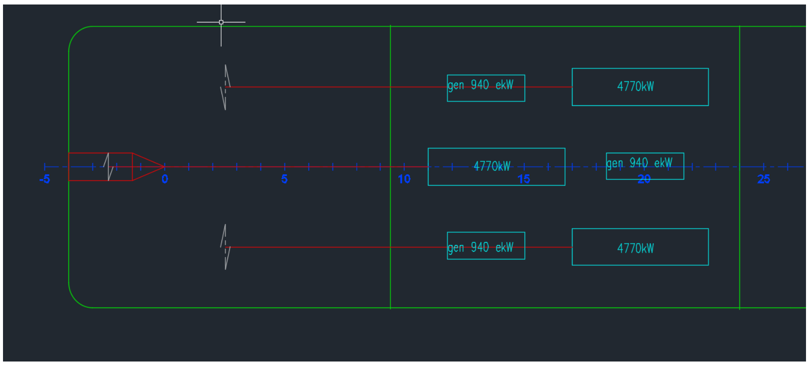


Figure 3.3: operational profile case: 3 x DE

The dimensions of the engine room are:

- $L_{EngineRoom} = 2 \cdot L_{Engine} + 4m$
- $H_{EngineRoom}$ = 2 · Mean Decks Height
- $W_{EngineRoom}$ = Entire width of the ship

As can be noticed from the above list, the relations between the engine room size and the engine dimensions are the same of the 4xDE case. The decision of taking such a generous longitudinal space also in this case, it refers to the fact that this space might, be used to place the generators and other technical equipment. It could be argued that such decision might be too conservative, resulting in a too large engine room, and that the space for the generators could have been found in the technical rooms or with a transverse arrangement instead of longitudinal. However, such rationale was only gained gradually in a later stage compared to the one reserved for the modeling phase. Some comments can already be done once this observation is understood. Indeed, the discussion between the two arrangements described reduces itself to how beneficial it is to have four smaller engines rather than three larger ones with the relative comparison on the total weight.

Regarding the choice of propeller for a future stage, the options are:

- three propellers.
- two wing propellers and a central water-jet.
- three water-jets.

The advantage of the first case is that propellers are the most common means of propulsion and thus less complex compared to a jet installation, with the benefits of being cheaper and lighter. A limitation for this configuration can be represented by the size of propellers and the transom area. This issue is often solved by the installation of jets that thanks to their higher power density due to pressure built-up in water-jet inlet, allow smaller dimensions. On the other hand, the efficiency of water-jets decreases considerably at low speed. The second solution might be interesting for taking benefit from both the two type of propellers.

Father & Sons configuration In order to save space and weight, the configuration proposed along gives a different power distribution among the engines than before. Indeed, the power is not equally assigned to three equal engines. The power is divided in the following two shares percentage:

- P_1 = 70% of the total MCR
- P_2 = 30% of the total MCR

The code in this case presents an additional section through which occurs the allocation of the power to the engines. Indeed, having, in this case, two different value of power to satisfy, two different engine's selections are required by the model. One satisfying P_1 that will be absorbed by the main central engine, and the second one P_2, that need to be satisfied by the two wing-engines. The reason why the total power was distributed in such percentages refers to the fact that the jump in power demand to gain the last few knots is considerably high, even if it only provides few knots more. The other considerable difference of this configuration compared to the previous two, is the way the engine room is sized.

- $L_{EngineRoom} = L_{CentralEngine} + 4m$
- $H_{EngineRoom} = 2 \cdot$ Mean Decks Height
- $W_{EngineRoom} =$ Entire width of the ship

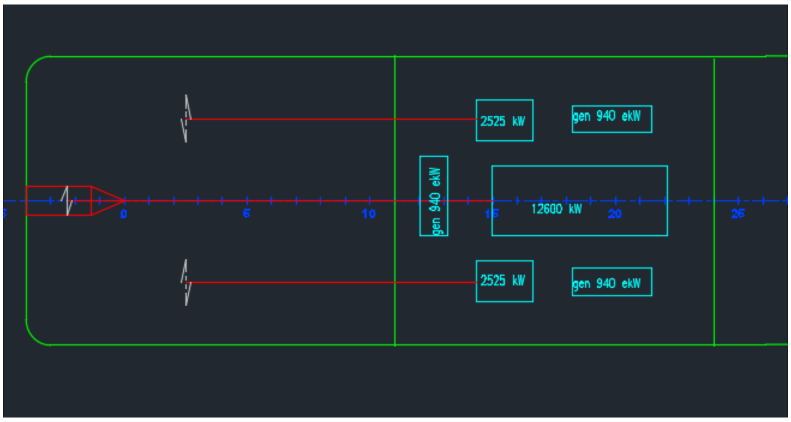


Figure 3.4: Father and Sons configuration

The primary difference is in the definition of the length of the room. In this case, the driving factor is the length of the main central engine and although this dimension will be probably larger than the one of the diesel chosen in the two previous cases, it will never be larger than the double of them, resulting in a more compact global configuration. Considering the main central engine longer that the two wing-engines, no further longitudinal space was took out at the side of it for the location of the generators. Indeed, was assumed that the space resulted from the difference between the length of the main engine and the length of the wing ones, was sufficient for placing other items.

With this configuration, in the best scenario, two smaller high-speed diesels will satisfy the power demand at the lower speeds and a larger medium-speed one will bring the vessel to the required maximum speed. In the *SSM* the database of engines also includes a gas turbine. The introduction of such powerful prime mover was necessary in order to cover also cases in which the power required, during the packing process was extremely high. Indeed, it is wise to remember that the main dimensions of the model can vary between wide ranges of beam and length. As consequence, considerably 'beammy' concepts or heavier ones, will most likely require a huge amount of power to reach the desired speed. Figure 3.4 represents the arrangement in question.

3.3.4. Helicopter-related Alternatives

The problem of the strong interaction between helicopter-related features and the capacity of carrying massive tenders led to the creation of multiple combinations of different helidecks and hangars, creating in total 8 possible different combinations.

It is possible and convenient to distinguish between two principal alternatives: the one that has the hangar below the helideck, and the one that provides the hangar in front of the helideck. Benefits and disadvantages of both the solutions from a practical point of view will be explained at the end of this subsection while, at this stage, are given explanations regarding the *SSM* of these systems.

First of all, the *macro-system Helideck and Hangar* is characterized by 8 variations as can be seen from table 3.1. The packing model can choose amongst these thanks to a *switch* function. Here are reported all the options:

1. Helicopters: H225 and H155 (stored side by side) - hangar below + tennis court
2. Helicopters: H225 and H155 (stored side by side) - hangar in front + tennis court
3. Helicopters: H225 and H155 (Stored in a row) - hangar below + tennis court
4. Helicopters: H225 and H155 (Stored in a row) - hangar in front + tennis court

5. Helicopter: H225 - hangar below + tennis court

6. Helicopter: H225 - hangar in front + tennis court

7. Helicopter: H155 - hangar below

8. Helicopter: H155 - hangar in front

For each of these 8 variations, the system *Helideck and Hangar* is always composed by three objects: two hard ones, representing the helideck and the hangar, and a free-space object for a safe landing area above the helideck. The relative position of the latter is always the same in all the possible combinations starting from the upper surface of the landig area. The only difference is its dimension which, time by time, changes accordingly to the dimensions of the helideck itself. The relative position of the hangar, with respect ot the landing area, is determined by assigning to it a relative longitudinal and vertical position. In case of the hangar below the helideck, as relative longitudinal position is given the same starting point of the Helideck, while for the vertical one the coordinate of the point just below the helideck. On the other hand, with a Hangar in front of the helideck the relative vertical position will be the same as the system helideck (zero) and the longitudinal one will be given by the length of the helideck itself.

Table 3.2 resumes the variations disposed and next are described these alternatives.

No.	Type	Variations
1	H225	*yes, no*
1	H155	*yes, no*
1	Landing area	*tennis-court, no tennis-court*

Table 3.2: Helicopter options

Both H225 and H155 This option represents the ultimate level of helicopter characteristics, giving the opportunity of land on the Yacht Support vessel with a heavy-duty one and having an hangar which can host not only the H225 but also a medium-duty (H155). The table below shows the spaces required for both the helideck and the hangar in this configuration.

No.	Type	L[m]	B[m]	H[m]	m^2	m^3
1	Landing area	28	19.5	-	546.0	-
1	fuel storage	-	-	3.0	50.0	150.0
1	Hangar long	30	6.0	5.5	180.0	990.0
1	Hangar short	18	10.0	5.5	180.0	990.0

Table 3.3: Helicopter-related spaces - case: 'both helicopters'

In this case the length required by a playable tennis court dictated the longitudinal dimension of the Helideck. Two alternatives of hangar show what explained earlier about the two possibilities of having the two helicopters stored side by side or one behind the other. The two pictures below are representative; obviously the shorter hangar compensate for the space lost in the longitudinal direction with a wider transversal encumbrance, which unfortunately cannot be clearly appreciated in fig. 3.5.

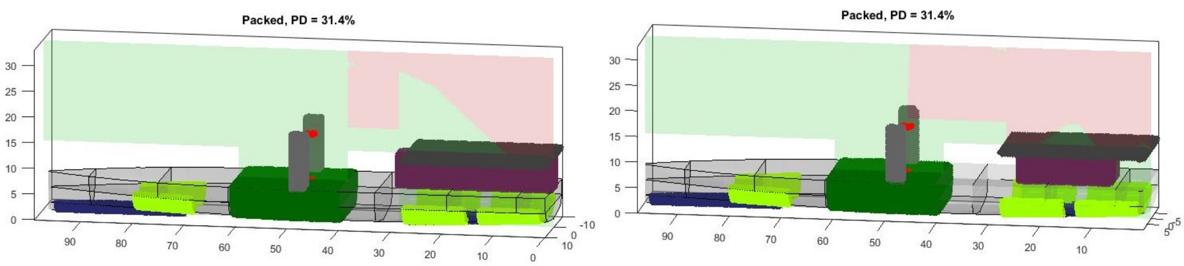


Figure 3.5: Long and short hangar for the case: 'both helicopters'

Only H225-type The following table shows the option of storing only the H225 in the enclosed hangar while the helideck dimensions determine the presence or not of the tennis court.

No.	Type	L[m]	B[m]	H[m]	m^2	m^3
1	Landing area (tennis)	28.0	19.5	-	546.0	-
1	Landing area	22.6	19.5	0.2	441.1	88.2
1	Fuel storage	-	-	3.0	50.0	150.0
1	Hangar	18.0	6.0	5.5	108.0	594.0

Table 3.4: Helicopter-related spaces - case: 'only H225-type'

Comparing these values with the one of table 3.3, looking at the square meters required by the hangar, around 60% less meter squares are required. Regarding the helideck space, when renouncing at the tennis court it is possible to save around 100 m^2.
Figure 3.6 illustrates the smaller helideck in combination with the hangar that can store the H225.

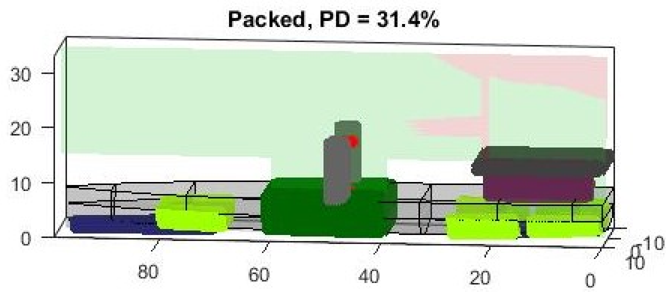


Figure 3.6: Hangar-helipad combination - case:'only H225-type'

Only H155-type Similarly as the analysis done for the H225 only, the same follows for the medium-duty helicopter (H155) with the picture that illustrates the smaller overall space needed.

No.	Type	L[m]	B[m]	H[m]	m^2	m^3
1	Landing area	16.6	14.3	0.2	237.2	47.5
1	Fuel storage	-	-	3.0	50.0	150.0
1	Hangar	13.5	5.0	5.5	74.3	371.3

Table 3.5: Helicopter-related spaces - case: 'only H155-type'

Figure 3.7: Hangar-helipad combination - case:'only H155-type'

It is clearly visible from the collection of pictures how the space related to this feature will influence the overall design, occupying large part of the aft deck in case of the ultimate level (*no compromises*: both H225 and H155 to be stored and helideck serving as tennis court as well).

Example of hangar in front of the landing area The alternatives just showed vary in the model, not only when the hangar is supposed to be below the helideck, but also in the configuration that provides the hangar to be located in front of the landing area. Figure 3.8 reports only the most critical case in the horizontal option.

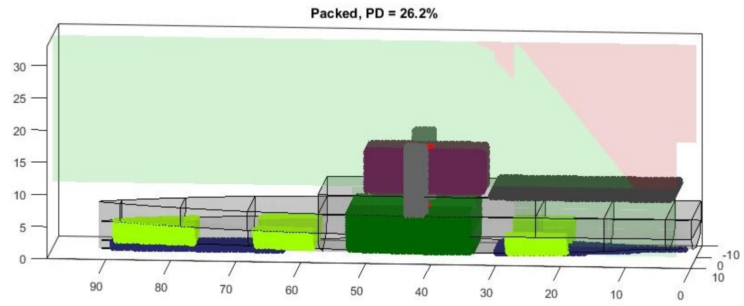


Figure 3.8: Hangar-helipad combination - case: horizontal hangar'

The advantage of having the hangar below the landing area is the huge saving in space longitudinally that strongly conflicts with the location of the working deck. On the other hand, this design solution is less attractive from an economic and functional point of view due to the complexity that lifting devices and opening system bring. Indeed, for example, to make this hangar watertight is not an easy task.

The hangar in front of the landing area is preferred for the simplicity with which the helicopters can be directly brought inside and because avoids the use of complicate lifting system. The big disadvantage, especially when including the option of considering the helipad as a tennis court, is that the overall system (helipad + hangar) covers almost half-length of the vessel (46 meters).

3.3.5. Toys and Tenders Alternatives

Subsection 2.5 listed and described all tenders and toys requested. As extensively reported in the previous chapter, the area required to store the massive tenders will likely conflict especially with the helideck and the hangar.

In this section, arrangements and variations regarding this aspect will be provided with the aim of investigate which trade-offs packing will be able to find when necessary. The criteria of selection might be named as the *'level of fun'* the vessel can provide. The alternatives shown in table 3.6 directly associate how well the vessel complies with its main function: increase the leisure capability of the assisted mother yacht. As can be noticed form the same table, not every single entity is allowed to vary. This is because only some of them cause consistent interaction with other spaces and thus are deemed relevant for the study.

Toys and Tenders			level of fun		
No.	Type	Variations	Ultimate[m^2]	Medium [m^2]	Scarce[m^2]
1	Hinckley Talaria 55 M/Y	*yes,no*			
1	Sport fisher Viking 62c	*yes,no*			
1	mini-sub MIR	*yes,no*			
1	Fast Carbon S/Y	-			
1	Newton 36 dive special	-	415	280	160
3	Ferrari	*1,2,3*			
1	Hummer	-			
6	Volswagen newbeetle	*2,4,6*	100	65	40
1	mini-sub Triton 1000/4	-			
1	SAAB ROV seaeye Jaguar	-			
10	Jet-ski	-			
10	Sea-bobs	-			
1	inflatable Island	-	65		
3	Cigarette 50' Marauder	*1,2,3*			
3	8 meters Ribs	*1,2,3*			

Table 3.6: Tenders and Toys variations

From a modeling perspective, several phases were crossed starting from the creation of each single seabob to building a *Toys garage* (including all the items in orange). The same goes for the *Garage* in which cars (green items) are parked. The working deck, born with the intent of hosting the major tenders and toys highlighted in red. The choice of modeling a working deck instead of having the largest toys as single entities free to be moved, matured with the awareness of the level of detail that it is possible to achieve. More explicitly, placing manually the boats in a specific available area, as is commonly done in a CAD environment, permits to make the most of the space, while in packing, this level of detail is harder to achieve, implying an advanced used of overlap rules within the code.

It is interesting to notice the difficulty of packing when dealing with large *hard objects*. Once created the systems representing the largest tenders, it was assigned to them the same longitudinal position with the aim of storing all of them side by side. Even though no other system was in the game yet, the algorithm hardly tended to place the elements all at the same frame. What is more, the overall beam of the provided design was 18.62 meters, which could actually contain all three boats. The top view of fig. 3.9 shows what just explained:

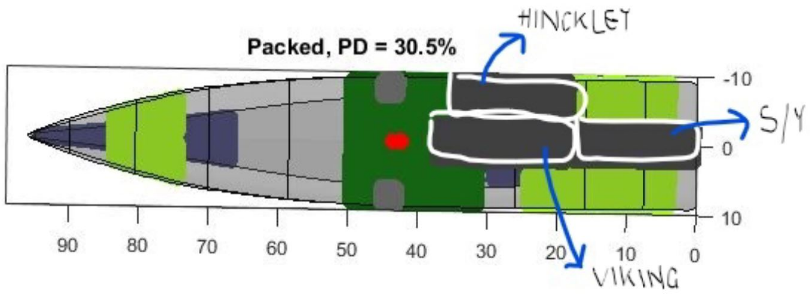


Figure 3.9: Transverse object location

This tendency of the algorithm gradually brought to the choice of modeling only a working deck characterized by the required area simplifying the packing process. Indeed, modeling the working deck with the toys on top resulted in a much easier packing process, where later the tenders were assigned.

On the other hand, the choice of leaving out the bulky tenders and not allowing packing to investigate 'unexpected' solutions brings the consequence of not being able to study results which arrange them in 'unusual' positions. The Super-yacht *Ulysses* provides a clear example of what want to be pointed. Picture 3.10 illustrates the solution adopted for the Norwegian yacht, which actually presents a complete forward-working deck representing a not commonly seen choice. In the same fashion, one of the largest tenders, subjected to the randomness of the algorithm, might found location in the bow.

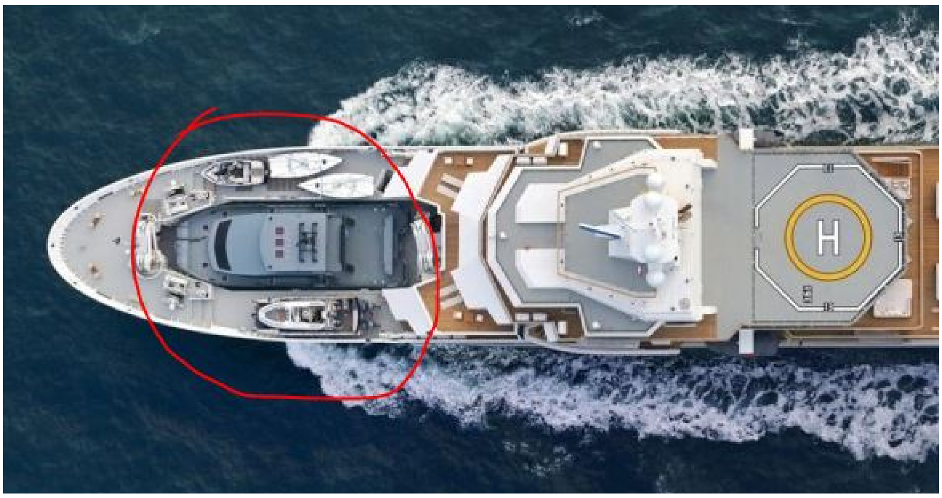


Figure 3.10: Example of large tender-store

A further analysis on the working deck modeled is that its length will not be really affected (or only slightly) by the variations considered. Indeed, as *sailing boat* (18 m), *Hinckley* (17 m) and *Viking* (19.2 m) are never excluded all together, the longitudinal encumbrance of the working deck must never be less than 20 meters. This implied that the working deck dimensions will not really varying accordingly to the 'levels of fun' but rather the model is set up in such a way that will host different toys and tenders conforming to the ones every time excluded.

Table 3.7 summarizes the the items included for each 'level of fun'.

Type	Ultimate	Medium	Scarce
Hinckley Talaria 55 M/Y	✓	✓	-
Sport fisher Viking 62c	✓	-	-
Fast Carbon S/Y	✓	✓	✓
Newton 36 dive special	✓	✓	✓
mini-sub MIR	✓	-	-
Ferrari	3	2	1
Hammer	✓	✓	✓
Volswagen	6	4	2
mini-sub Triton 1000/4	✓	✓	✓
SAAB ROV seaeye Jaguar	✓	✓	✓
Jet-ski	✓	✓	✓
Sea-bobs	✓	✓	✓
Inflatable Island	✓	✓	✓
Cigarette 50' Marauder	3	2	1
Ribs	3	2	1

Table 3.7: Toys and tenders included in each 'level of fun'

3.4. Weight Density Factors

The lightweight and the determination of the center of gravity of the ship is calculated by assigning to each block/system its own weight. Therefore, in order to have a performance estimation which reflects as close as possible the ones of the Yacht Support, an extrapolation of some more specific density factors was carried out, with the addition of two more systems groups compared to the default one, already present in the model. The approach followed in order to get out the weight density factors from the correspondent Damen spreadsheet, is briefly described. The groups representing the SWBS (*Ship Work Breakdown Structure*) as described by Damen divides as following:

1. Group 100 – shipbuilding (hull and outfitting)
2. Group 200 – Main machinery (propulsion)
3. Group 300 – Primary ship systems
4. Group 400 – Electrical systems
5. Group 500 – Deck equipment
6. Group 600 – Machinery (secondary elements)
7. Group 700 - Joinery and Arrangement Accommodation
8. Group 800 – Nautical, navigation and communication equipment
9. Group 900 – Special equipment

These weights groups are translated to the *SSM* thanks to a dedicated piece of code, that characterize each system, which recall to a dedicated spreadsheet created on purpose. An idea of how this spreadsheet is built is given.

The weight density factors have been extrapolated distributing these weight groups between the systems characterizing the model. These can be volume based or area based accordingly to their proper nature, i.e. structural weights are volume based while electrical are area based. In this way each of the 47 systems listed in 3.3.1 has its own weight and all together recreate the lightweight ship. Each of the group was analyzed to a high level of detail in order to reproduce a weight distribution that well matches with the similar ship provided.

For example, group (110), representing the hull weight and accounting for a total of 1776.9 $tons$, is assigned to all the systems included in the hull, taking care of adjusting the value of the density factors accordingly to the vertical position of the system within the envelope. More specifically, a higher density factor compared to 'crew accommodation' (which belong to one deck higher) will multiply systems such as tanks and the technical spaces occupying the lowest part of the hull. During the extrapolation, another difference was also taken into account. Indeed, considering group (370), representing natural and mechanical ventilation systems, this is distributed between the spaces taking care of the type of system, if it is a simple store will have a lower density factor compared to the engine room or accommodation spaces. Lastly, another relation is respected during the determination of these factors. The dimension of the system is obviously considered: same type of system having very different dimension should keep the same density factor value.

As Droste explains, in addition to a weight based on volume or area, the option of adding discrete weights with their own specific *CoG (Center of Gravity)* is also included. Examples are the lifeboats as well as tenders and toys, or cars in the garage similarly to the diesel engines in the engine room. To obtain a CoG of the volume and area based weights, the volumetric CoG of the object is used in case of a volume based object or the CoG of the area in case of an area based weight. The individual weights and CoGs are then combined to a lightweight and a ship center of gravity. [12]

Finally the resulted total weight of the lightship was found to be around 20% lower than the ship of reference that was reasonably heavier due to substantial differences. Indeed, the weights of reference were related to a *'SeaXplorer'* of 95 meters, characterized by quite different features. The company agreed that this value represented a good starting point for the weight estimation, being the value founded slightly higher than expected but naturally conservative.

4

Exploration phase and Analysis of outcomes from the Model

4.1. Introduction

In this chapter will be explained the approach to the exploration phase, with the aim of illustrating how the down selection to most interesting solutions was carried out. Two different ways of proceeding can be distinguished, one mainly looking at the 'top-level' options of the variations and the other one scanning the shortest designs. Both the methods have been applied to all the runs conducted, but only the major points will be presented, taking as a reference one of them. This tendency of cutting the design space is in line with the aim of the study of finding the most promising design solution hence justifying the necessary massive reduction in number of the designs to compare.

However, the first run will be presented first, in order to have a general overview of how the design space is generated and which are the principal modifications that were needed for proceeding with the next runs. In addition, the other reason why it comes before the two methods of selection, is because it was not subjected to them. Final sections of the chapter will present some comments and considerations on the outcomes of the packing model built for this application, highlighting the major conclusions from the exploration.

4.2. 1^{st} Run

The first run of the model was characterized by 200000 attempts and the number of feasible designs coming up accounted for 7 % of the total (15512). This first run helped mainly in understanding some inconsistency in the model by revealing undesired features of some design solutions. However these results still served for some analysis on characteristics of the model and in gaining first general insights on systems and performances.

Graph 4.1 illustrates how the design space is distributed with respect to main dimensions (Length, Beam, Displacement). It is already recognizable the strong limitation on the length. Despite the assigned given range from 95 to 140 meters, only one design reached a minimum length of $109m$. The average displacement of the design space is more dense around the value of $5000t$ meeting the expectations. The considerably high beam allowed, did not help significantly in reducing the length of the vessel, probably because the *L/B* ratio needs to be conserved in order to push the boat up to *25 knots*.

A possible analysis that can already be carried out in this data set, regarded the influence of the three different engine rooms modeled. Indeed, fig. 4.2 draws the area around those designs characterized by the correspondent choice. It is possible to highlight how different engine room layouts did mainly influence displacement (restricted to $\geq 5000t$) and length (*4xDE* and *3xDE* options are restricted to a length $\geq 126m$) of a concept, while not very strong is the effect on beam. In particular almost all the designs generated (98%), were characterized by the 3^{rd} configuration. This is clearly linked to the fact that the *Father & Sons* configuration is by far the most compact option.

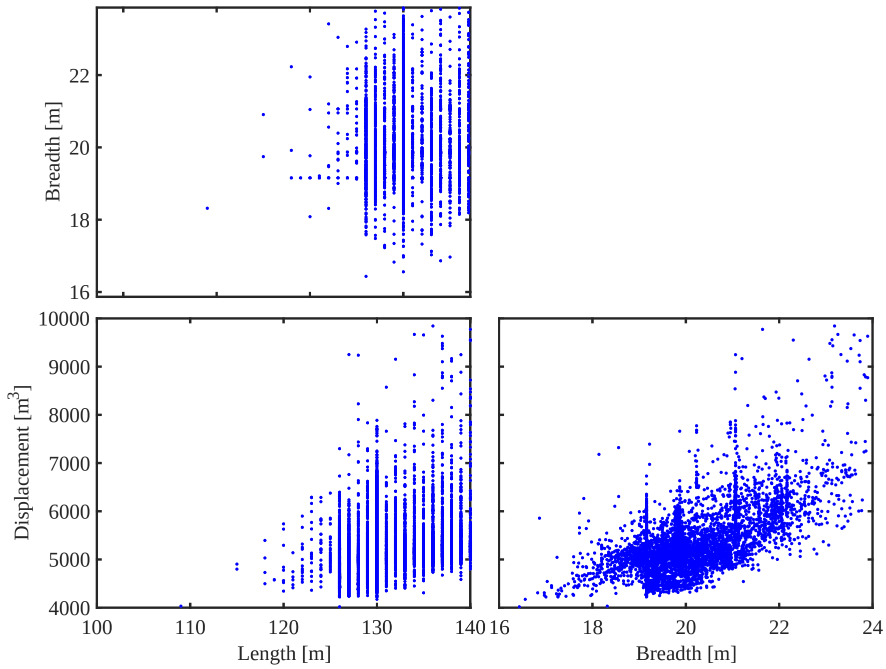


Figure 4.1: Length,Beam and Displacement relation for the first run

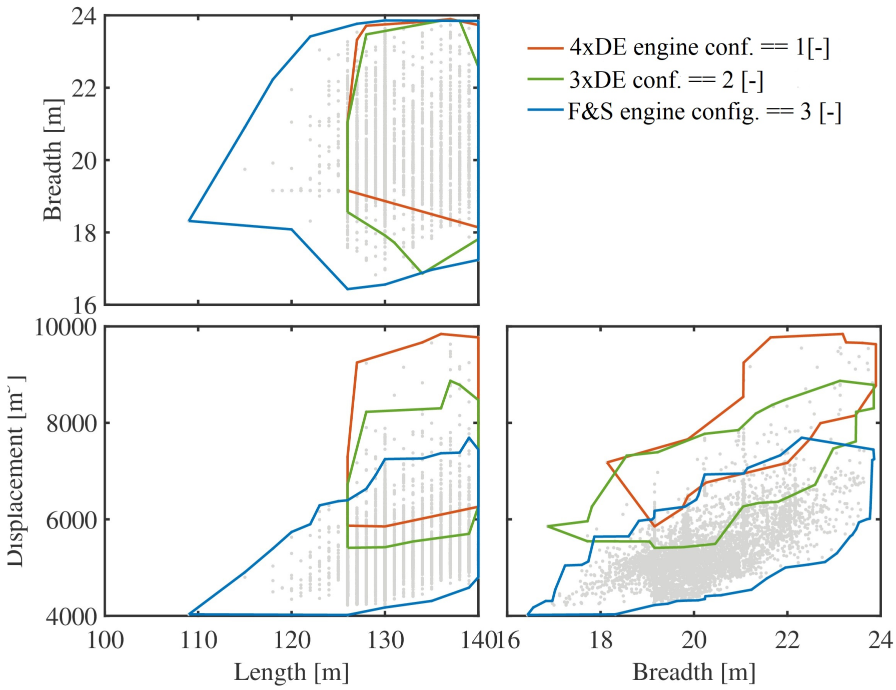


Figure 4.2: Influence of different engine room configurations on mian dimensions

4.3. First Method for Down-selection

The search focused on vessels which provide the *ultimate* 'level of fun' and that can host 2 helicopters. Then, the study shifted to the research of similarities between the designs selected and last step consisted in changing the position in the *system criteria* options to eventually find out different interesting solutions.

4.3.1. 2^{nd} Run

With the intent of finding shorter designs, the changes on the model from the previous run consisted in:

- implementation of the working deck variations,
- Cigarette might be placed transversally to the ship length.

A *Draft feasibility*, shown by equation 4.1, was introduced and used as additional filter.

$$T_{des} - T \geq 0 \tag{4.1}$$

By imposing this relation, designs which fail of satisfying this equation might still be feasible for the hard constraint of falling within the 5 meters draft, but the calculations done upfront from packing, first of all the resistance estimation, will not be valid anymore. The power might not be enough if the engines selected according to the *design draft* were not sufficiently exceeding the power requested. Thus, there might still be interest in investigate these designs which, although incurring in this failure might be re-elaborated, namely repeating the resistance and estimate if those engines are still powerful enough or looking for other ones that could satisfy the new power request.

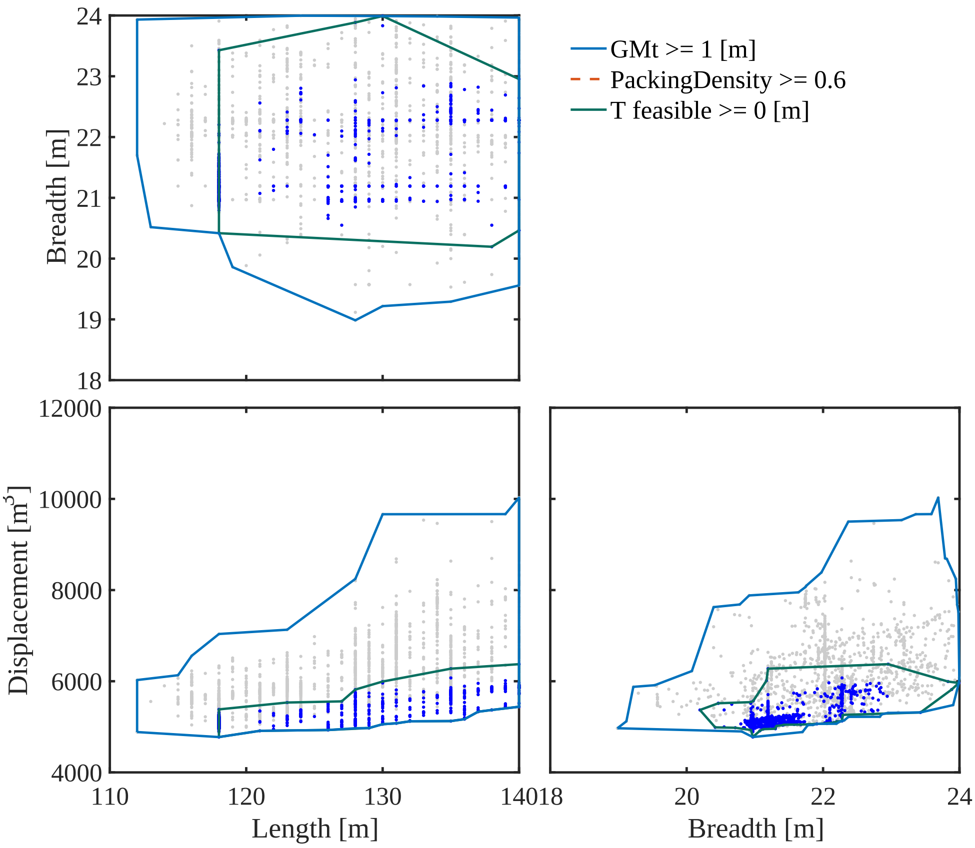


Figure 4.3: Design space of the second run

The second run gave less feasible designs: 4409 overall compared to 15512 of the first one. This can be explained with the slightly more constrained model that characterized the second run and by the adding the restriction of equation 4.1 . Investigating the design space generated from the second run (fig. 4.3) and comparing it with the first one (fig.4.1), it is possible to notice that more designs were generated in the 112 - 125 length range.

What is strongly limiting the wide generation of solutions is the *Draft feasibility* (4.1) (green line) that has a dramatic impact on all the heaviest designs (roughly above 6000t). The exploration of the second run started by selecting all the 'top level' variations. The aim was to look which characteristics the 'ultimate-design' concept had. Hence, first, regarding helicopter-related features, almost 100% of the feasible options had both the helicopters stored in an hangar which can host them side by side. Secondly, the design space was filtered by selecting the *'ultimate' level* of working deck housing all the three largest toys.

By applying the filters just mentioned, the design space did not result to be significantly ruled out, probably thanks to the larger length allowed. However, also for this run, none of the design generated featured the option of having the hangar in front of the landing area proving, thus, the space optimization.

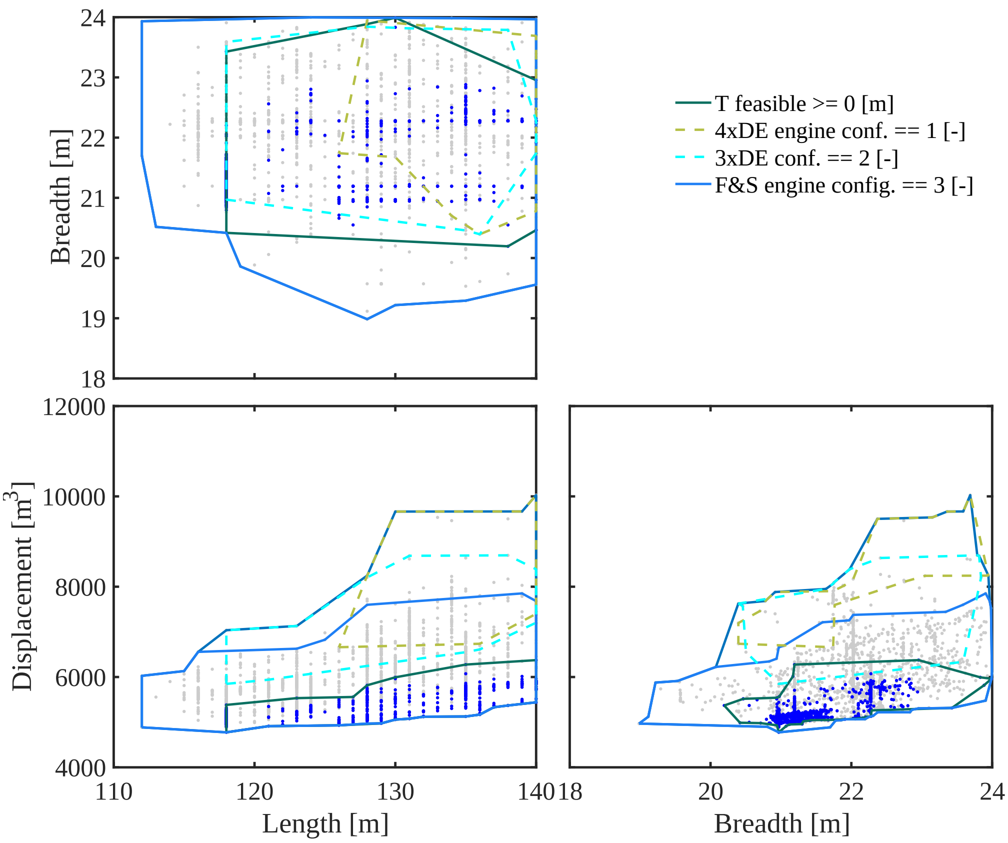


Figure 4.4: Engine room layouts with respect to L,B and Displacement

Regarding the engine room arrangements, fig.4.4 is explicative of the effect the three different options produced. As can be noticed diverse engine room layouts largely affected the displacement of concepts. Indeed, the option of four diesel engines (green line) or the one of three (light blue line) are restricted to the higher part of the two graphs at the bottom. This is due to the fact that the medium speed diesels coming from the database refer to engines that could reach more than 100 $tons$ each. In addition, what considerably influence this behavior, are the considerations made on the different size the three engine rooms are characterized by. (see subsection 3.3.3).

Making this consideration helps in understanding why the first two options are barely chosen by the algorithm and also why most of the designs characterized by those engine room arrangements are likely to fail on the draft requirement. Hence not surprisingly, the region rounded up by the *Draft feasibility* is included in the one of the 3rd engine room configuration area (blue line). Some influence can be appreciated on the beam, with a form of designs clustering around 21.5m; on the other hand, for this run, the length was not affected at all.

By gradually adding the more demanding requirements one could gain insights on how those influenced the generated design space. Obviously, not all the effects related to the variations will be accounted with the same importance. This statement will become more clear going through them.

The *ultimate* levels of helicopter-related spaces and working deck did not affect any of the area of the design space. The quantity of Cigarette carried on board, as well as the number of ribs, seemed to exclude a significant portion of the design space. However, this outcome might be carefully evaluated because of the struggle the algorithm manifested with such 'free' hard objects (Cigarette) might overestimates the realistic non-feasibility of designs. This might be addressed to some inappropriate modeling choices or to limitations of the algorithm. When combining and summing the multitude of requirements together, this behavior (regarding the Cigarette) will actually have some influence for further analysis, because the space required to store these crafts is not irrelevant, however it need critical considerations. On the other hand, the same will not holds for ribs, since they are not considered so determinant for the global design.

Combining all the 'top-level' features, the design space resulted finally truncated to 26 designs. After an analysis of the design layouts characterizing this selection of solutions, the arrangement was generally characterized by:

- the helicopter-related spaces in the aftermost part of the vessel
- the working deck occupies the mid-ship
- the accommodations confined in the bow

The minimum length allowed by all the variations set, as explained, accounted for 123m, suggesting that starting from such dimensions, apparently no trade-off is necessary.

4.3.2. Looking for Different Solutions

Before investigating some possible diverse solutions, that could emerge by switching the position through the *system criteria* option, it might be interesting to look and verify the high conflict between helicopter-related spaces and working deck. Figure 4.5 shows that the longitudinal positions of the two systems is indeed almost the same between 10% and 50% of the length. The center of gravity of Helipad system, represented by red dots, including the hangar below, implies that the system overall ends up on almost one deck below the dots as suggested by the relative dashed box. Regarding the working deck a similar analysis can be considered because the system itself was modeled including the objects representing the largest tenders. This also means that the ultimate end of the physical system is corresponding, in reality, at least at one deck above. The preferred working deck position is between 38% – 57% of the length.

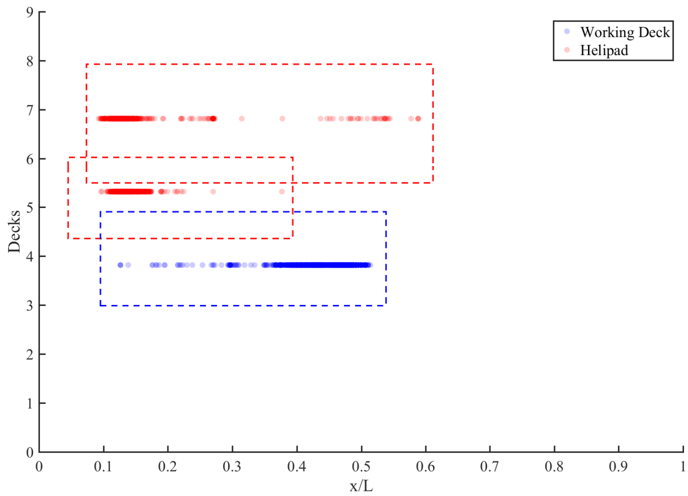


Figure 4.5: Interaction between helicopter-related spaces and working deck

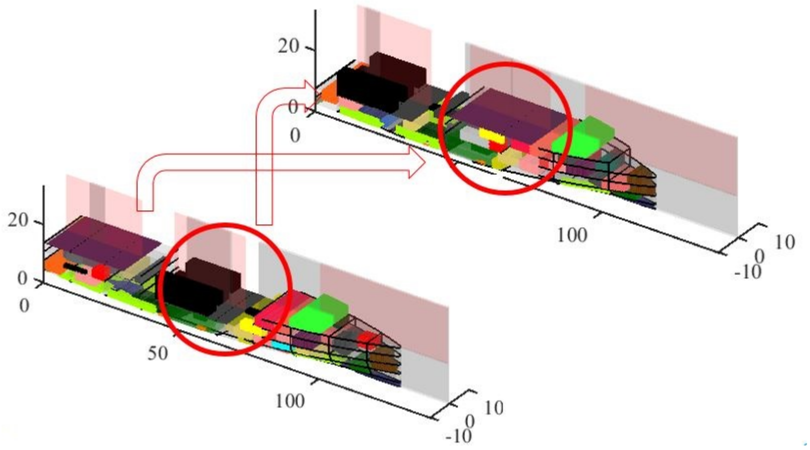


Figure 4.6: Change position of Working deck - Helipad

Figure 4.6 represents the next step during the exploration process that consisted in looking for some different architectural options changing the relative disposition of these two more relevant systems. The search found only one feasible solution characterized by a position for the *working deck - system criteria* confined to 35% of the length from aft perpendicular, confirming the 'preference' of packing in placing the former system at mid-ship.

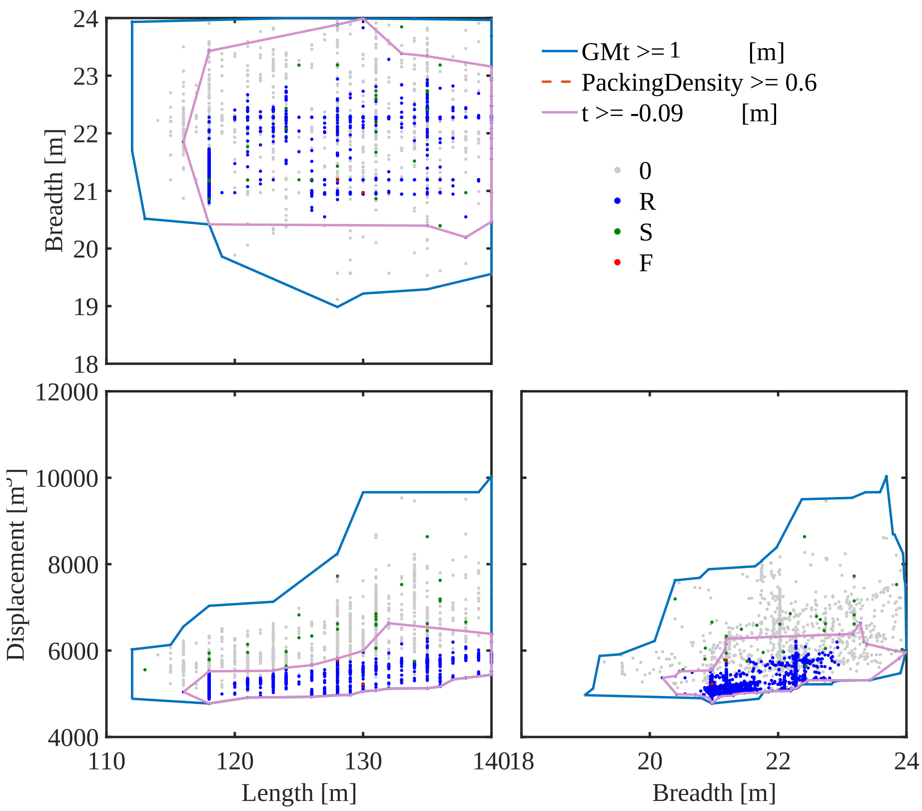


Figure 4.7: Main dimensions referring to helicopter-related areas at mid-ship

Figure 4.7 illustrates the same design space of fig.4.4 but providing different informations. Looking carefully at fig. 4.7 the blue dots indicate that the *requirement criteria* are satisfied, in this case only the $GM_t \geq 1$ and the *Draft feasibility* set to be $\geq -0.09m$, thus designs exceeding the constraint of about $9cm$. Indeed, since only one design was complying with the *Draft feasibility* ≥ 0 this value (-0.09 m) was chosen to investigate which characteristics had the next design satisfying a slightly released constraint.

On the other hand, green dots represent those design solutions which satisfy the *system criteria* of the helicopter spaces to be between 25% and 60% of the length (the central body). Lastly, the red dots indicate designs which are compliant to both the above mentioned criteria (only two designs). Looking at the two bottom graphs of fig. 4.7, the majority of green dots fall above the area identified by eq. 4.1 and thus not matching with the *requirement criteria* (*Draft feasibility* ,GM_t).

The study of general arrangements of these designs showed some interesting solution such as the vicinity of the landing area with the guests accommodation, feature that might be preferred from a 'luxury' prospective, compare to the solution that provide a long working deck to cross before reaching the guest accommodations.

4.3.3. Successive 'Steering' Runs With the Aim of Reducing the Length

3^{rd} Run As well as the other successive runs, also the third one was conducted with the aim of minimizing the length of the generated concepts. In this perspective, a second objective function (f_2) was added to the algorithm.

$$\begin{array}{lll} \min\limits_{x} & f_1 & -PD(x) \\ \min & f_2 & \dfrac{L_{design}}{L_{max}} \end{array} \tag{4.2}$$

The same procedure was adopted to look for the similarities and differences and eventually gaining new insights. Due to the fact that the process will repeat similarly as done in the previous run, the analysis will be synthesized from now on, and only some more relevant comments will highlight the differences between previous results.

First of all, was noticed that fewer designs were generated in the lowest range length. As consequence, it was registered a reduction in beam values for these solutions when comparing this design space with fig. 4.3. The search brought to the down-selection to three designs that presented the following main characteristics:

- $L \cong 129m$
- $B \cong 19.7m$
- $Displ \cong 4997tons$

A substantial difference from the set of designs investigated before can be appreciated by looking at the GAs of these concepts. Examining 'Lower Deck' and 'Main Deck' was noticed that the crew accommodation together with their relative mess and lounge and the galley were located in the aft part of the ship, around 20-30 m, separating thus the guest area from the crew one.

This aspect might have some benefits such as: more privacy for guests but also a better logistic for crew and staff in managing the working deck and the helicopter operations. On the other hand, having accommodation spaces far away one from the others implies a less optimized and more complicated service routing.

The 4^{th} run was conducted with the goal of finding designs providing a solution of hangar in front of the landing area. The 5^{th} one included one deck more within the hull for placing the systems, aimed in reducing the length. Unfortunately, both did not produce the hoped results.

6^{th}Run This paragraph reports a new attempt to find shorter designs with slightly differently defined objective functions.

$$\begin{aligned} \min_{x} \quad & f_1 \quad -PD(x) \\ \min \quad & f_2 \quad \frac{L_{design} - L_{min}}{L_{max} - L_{min}} \end{aligned} \tag{4.3}$$

In this case, at the second objective, was added: $L_{min} = 95m$. The penalty value in the genetic algorithm for $f(2)$ was set at 2 in case of failure. To improve the yield of the designs, the helicopter configuration was fixed on the vertical solution only. Unfortunately no shorter designs were found, however the distribution appeared to be closer to the one of the 2^{nd} Run, where a large quantity of solutions was found in the $118-125m$ length range. The designs resulting from the selection (explained in sec 4.3) are all long about 123 meters.

It is interesting, for sake of notification and with respect to find 'diverse' solutions, that only for this set of calculations there were a couple of designs which provide a forward working deck. One of these two measured 140 m in length while the other one was 124 m long. Unfortunately was found that both failed on the *Draft feasibility*.

4.4. Second Method for Down-selection

Initially, the search aimed for ruling out all the longer options, imposing a limit on the *Length* to the design space. The second filter applied, consisted in increasing the *Packing Density*. The reason behind this choice is to be borne back to the possibility of bringing the eventual selected design to the next phase. Indeed, in view of the next step of increasing the level of details of one of the design generated, choosing a more densely packed design, should mean, slightly less future modifications.

2^{nd} Run By following the reasoning explained in the Introduction of this section, these two filters were applied to the first run:

- L ≤ 120 m
- PD ≥ 75 %

The restriction on the length (120 m) was assigned based on a trade-off between the exaggerate value given upfront (140 m) and the maximum initial constraint (100 m) with the aim of trying to have a good variety level. The application of these restrictions gave a bunch of around 200 similar designs characterized by the following main specifications:

- L ≅ 118 m
- B ≅ 21 m
- Displ. ≅ 4960 tons

A possible interesting design solution suggested by this concept, regarding the storage of Cigarette, is the location at extreme stern where those might be placed transversally. Their deployment could be done through a big opening on the stern and overhead cranes if it is going to be placed on the lower deck, only a overhead crane if from the main deck and above.

Since the investigation on the other set of calculations did not bring any relevant outcome, they are not reported.

4.5. 7^{th} Run - Different Length Constraints

A final set of calculation was executed in order to investigate if the algorithm was able to find feasible shorter designs, but in this case just setting more tight constraints on the length:

- 95 -110 m

Unfortunately any fully feasible design was generated. A critical analysis of these results showed that those designs were failing on the *Draft feasibility*. Indeed, the minimum value found for this constraint was:

$$T_{des} - T \geq -0.15m \tag{4.4}$$

valid only for one of the generated concept. Eq. 4.4 states that this design failed the *Draft feasibility* by 15 cm. However, there might still be interest in investigate designs which, although incurring in this failure might be re-elaborated, namely repeating the resistance and estimating if the power installed is still enough to provide the required speed.

When filtering the design space with a restriction on the length (looking for solution below 100m) only one design was found below 100 m and this exceeded the *Draft feasibility* of 1.10 m, which is a huge difference for the resistance and power estimation and thus, definitely subjected to changes regarding the power to be installed. The concept is reported below in fig.4.9 and several changes might be applied to improve that design; these are described in section 4.8.

In fig. 4.8 is reported the design space generated also for this run. It is wise to remember that here no *Draft feasibility* was imposed because otherwise any feasible design would have been represented in the graph. Designs are more concentrated on the part of the graph were length ad beam are larger than 107 m and 22 m respectively. Predictably, also for this group of designs, the engine layouts preferred was the third one confirming the trend shown for the other set of calculations.

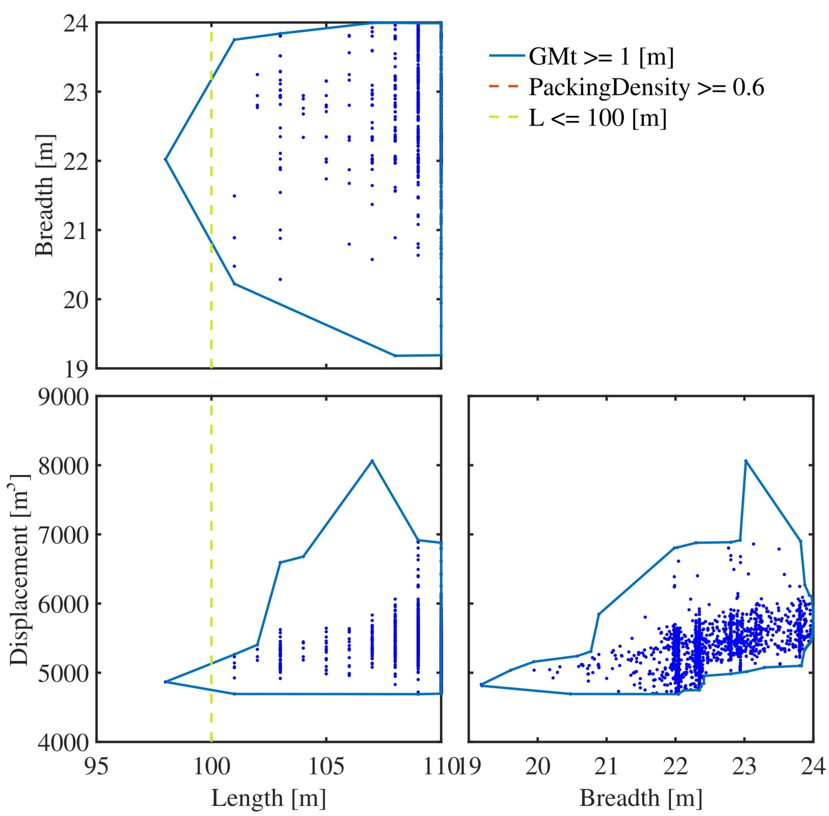


Figure 4.8: Design space - run 27-06

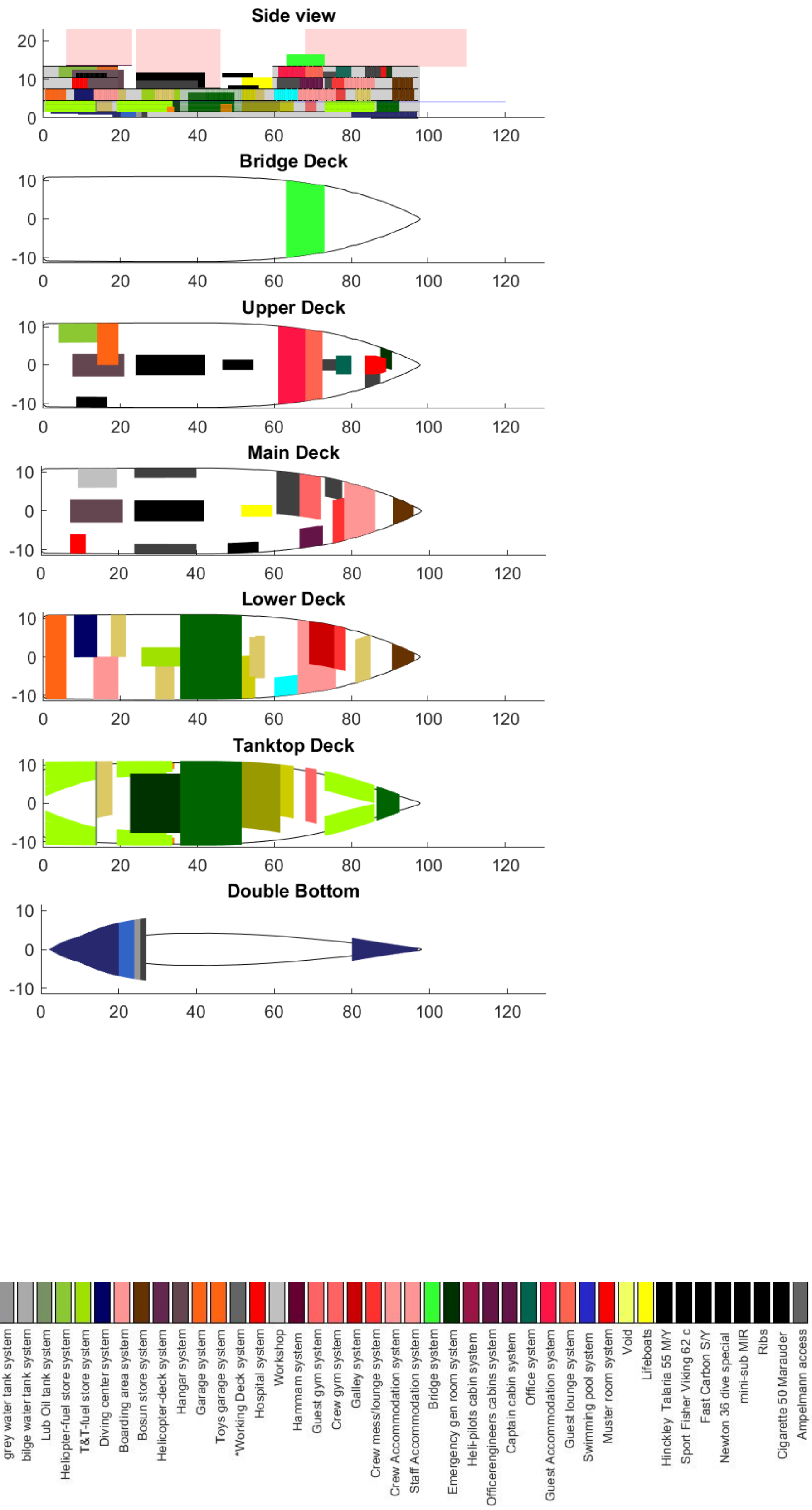


Figure 4.9: Design within 98 m in length, 27-06

4.6. Runs Analysis - Minimizing Power Installed

A new search was carried out on the multitude of results generated, primarily looking at the power installed. The reason of this investigation is to be brought back to all the benefits of having less power. Each set of calculations was filtered with the aim of minimizing this aspect.

Applying the usual feasibility condition (4.1) here reported:

- $T_{des} - T \geq 0 \longrightarrow$ *Draft Feasibility*

the minimum value of *MCR* found was, for almost all the Runs, about 22 MW. A remarkable outcome regarded the 5^{th} Run for which was found a minimum value of power of 17.8 MW belonging to one design with the following main characteristics:

- L = 140 m
- B = 18 m
- T = 3.97 m

This result showed that a long and slender solution endorsed the installation of less power in order to reach the desired speed, underlying the well-know aspect of the naval architecture that lengthening the ship helps in reduce the resistance.

4.7. Observations from the Analysis

This section will go through the analysis of some results from the exploration phase, highlighting the principal results.

4.7.1. Effects of Different Engine Room Layouts

The first outstanding result, was that all the feasible designs were characterized by the *F&S* engine room layout, meaning that, predictably, the space saving is primarily relevant. Furthermore, also the weight of the vessel might be affected by the size of the engine room and, for a certain extend, by number of engines. Is not a case, indeed, that all the feasible solutions (compliant with the *Draft Feasibility*) are characterized by the *F&S* configuration. In this respect, talking about medium speed diesel engines, their weight is considerably high, reaching in some cases more than 100 $tons$. Consequently, options that provide 4 or 3 of these massive engines can have a big influence on the displacement and thus probably contributed in causing the failure of draft constraint. On the other hand, it is reasonable to recognize that such conclusion might overestimate the influence of the number of engines on the *Draft feasibility* failure.

A more careful look at the way the engine rooms are modeled, can give a more complete and critical interpretation of the outcome. Remembering, indeed, the way the engine rooms are sized in the mathematical model (subsection 3.3.3), it can be realized that the four and three diesel engine configurations are characterized by a significant longer engine room compared to Father & Sons one. This way of modeling the engine rooms is probably limiting the selection of different engine room layouts. Would be interesting to modify the arrangements of engines in the first two cases in order to have an overall length comparable with the *F&S* one.

Analyzing some graphs will help in understanding how the diverse engine room arrangements affected main dimensions of the ship.

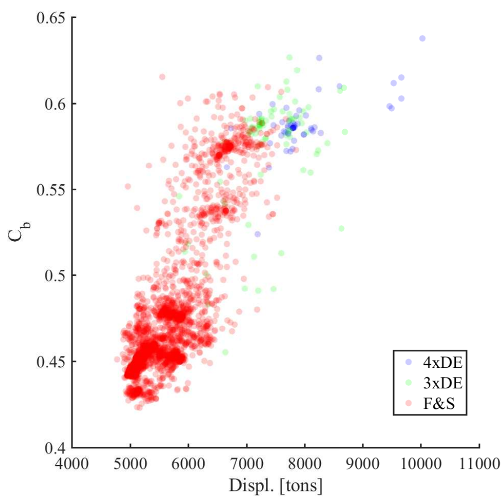
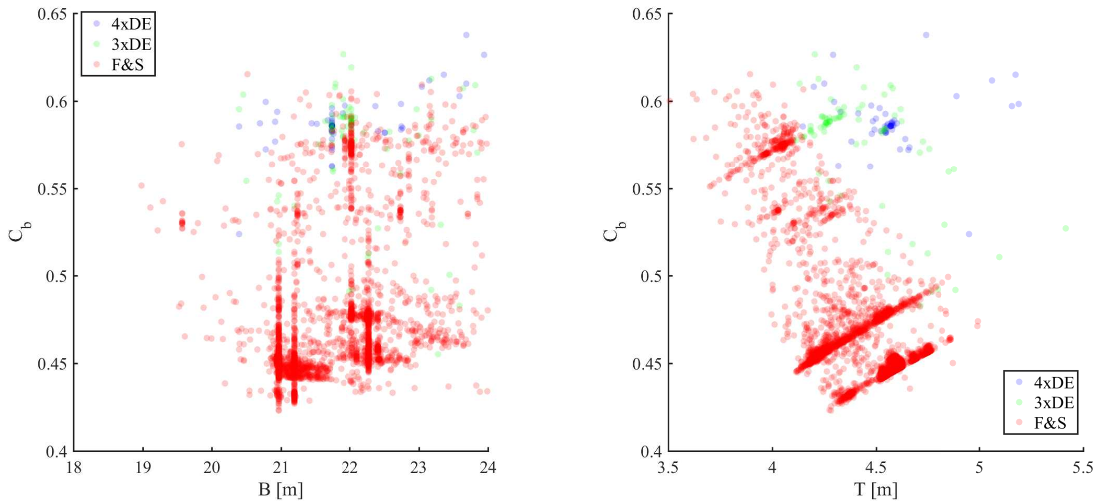


Figure 4.10: Effect of Engine room layouts on C_b and Displ., 27-06

First, it is reported the influence that the three distinct engine rooms have on *Displacement* and *Block Coefficient (C_b)*: despite the predominance of the *F&S* arrangement, the graph illustrates a substantial clustering of designs around a $C_b = 0.45$ and a $Displ. = 5000 - 5500\ tons$. The *3xDE* (green dots) layout resulted quite spread out on the design space while the *4xDE* (blue dots) remains concentrated in the region above a $C_b = 0.6$, only one or two occasional dots can be identified below.

Fig. 4.11 reports the same design space highlighting the direct effect on *Beam* and *Draft*. As fig. 4.10, these other two graphs illustrate that designs with a lower C_b, provided all the *F&S* arrangement (red dots). The tendency for the other two engine room types reflected the trend illustrated above with higher values of C_b and generally higher drafts.

When examining these parameters it is interesting looking at the forms of clusters created. Two main groups of designs disposed around a value of C_b of ~ 0.45 and ~ 0.47, showing quite clearly a jump when crossing a value of $B = 22m$. Investigating the reason why designs were clustering in this fashion, for this specific run, the step in beam had to be responded to the number of Cigarette when passing from 2 to 3. An aggregation of designs (green and blue dots) starting from $C_b \simeq 0.57$ suggested that higher C_b values allowed the *4xDE* and *3xDE* engine room configurations. Similar clusters can be recognized in graph 4.11b where the C_b is reported against the draft. The combination of these two graph, especially looking at the red region, highlights an increasing trend of C_b with lower values of draft indicating that the volume is increasing thanks to a beam or length growth.



(a) Effect of Engine room layouts on C_b and Beam

(b) Effect of Engine room layouts on C_b and Draft

Figure 4.11: Effect of Engine room layouts on C_b Beam and Draft

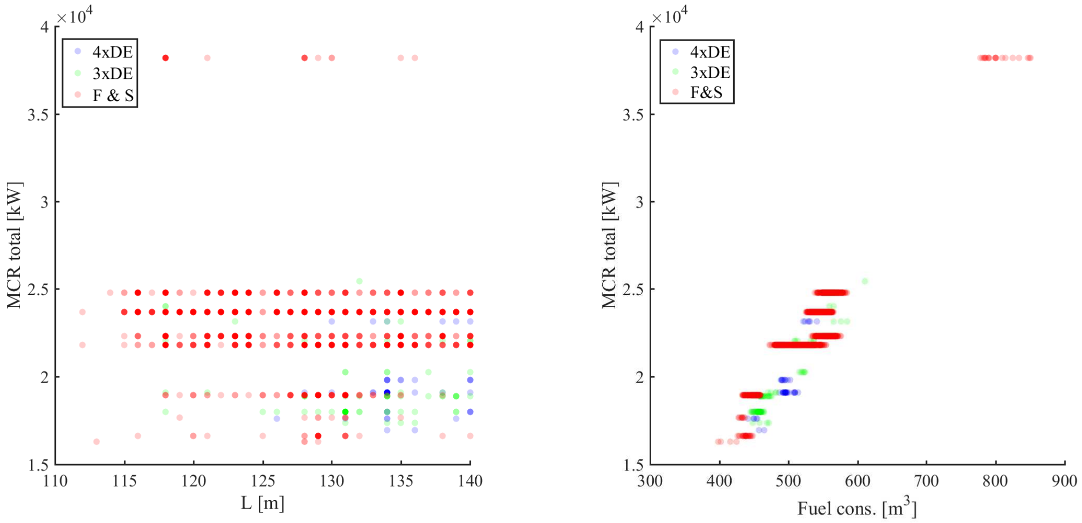
4.7.2. Influence of Power Installed

This subsection underlines the consequences of amount of power installed on ship dimensions.

First of all, fig. 4.12a shows which range of power the three engines layouts can provide and how they affected the length of the ship. The *F&S* configuration covered all ranges of lengths and there is a predominance of designs with a total *MCR* between 22 and 25 MW. The *F&S* engine room layout also offers a incredible powerful solution providing around 38 MW thanks to the presence in the *Engine Database* of a Gas Turbine (type: *LM2500+*) capable of delivering alone 30.2 MW. By looking more carefully at graph 4.12a, blue dots position confirms that the *4xDE* was only present in the region of designs identified by a length value above 126 m. Keeping always in mind the type of engines available in the database and the tendency of the model of choosing the engines with the minimum *MCR* capable of satisfying the power requested, this remark sets a limit on the application of this engine room layout for shorter designs.

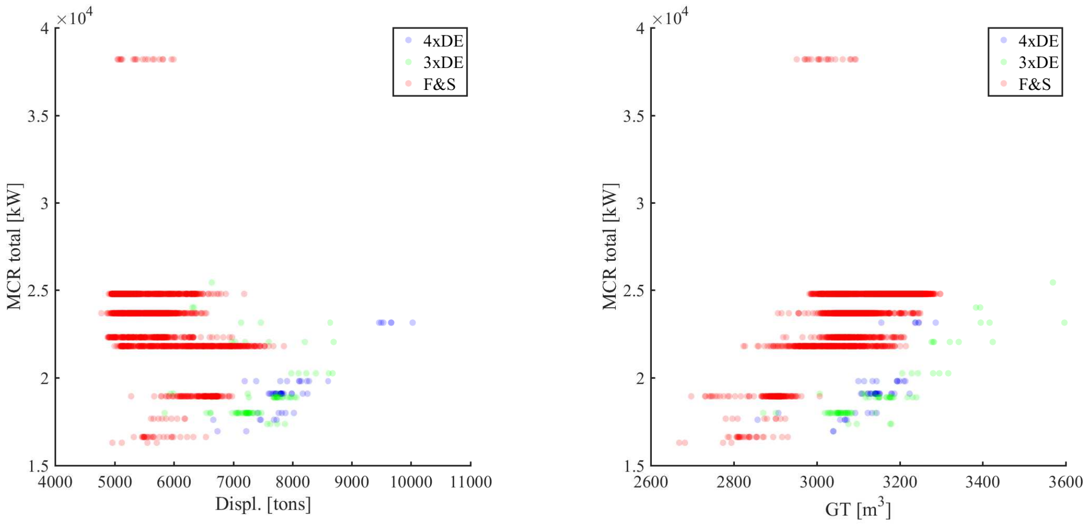
On the other hand, image 4.12b illustrates the huge jump in amount of fuel required for the group of concepts characterized by the gas turbine: almost double of the fuel required for the layouts of diesel engines is necessary.

Next, are reported the same information but now with respect to *Displacement* and *Gross tonnage*. Figures 4.13a and 4.13b show how equipping the vessel with more power, affected the weight and the total volume of the ships. The comparison between the two graphs in fig. 4.13 proves that when choosing the *F&S* engine room layout, a more marked beneficial effect can be appreciated on the overall weight of designs rather than on the final volume. This means that when looking at designs with the *F&S* configuration, increasing the power does not necessarily means increasing the weight. Once again the isolated group of designs characterized by the gas turbine stood out clearly from both the images. As predictable, this small cluster is characterized by the lowest range of displacement.



(a) (b)

Figure 4.12: Influence of Power installed on length and fuel consumption



(a) (b)

Figure 4.13: Influence of Power installed on Displacement and GT

4.7.3. Comments on Helicopter-related Spaces and Working Deck

A further notable result regarded the choice of helicopter related spaces. The entire set of calculations went for the solution of both helicopters stored in an hangar *below* the landing area. Indeed, generally none of the designs created from the diverse runs chose for the solution of hangar *in front* of the landing area. Even when the settings were restricted to this specific relative position of the hangar, any successful solution was found.

When looking at the ultimate level of helicopter facilities (at the dimensions reported in table 3.3) simply summing the length of the landing area, of the hangar and the working deck together, they already reach 75% of the maximum entire length (100 m). With these characteristics the conflict and the unsuccessful outcome is understandable. However, the same reasoning cannot be given to the cases where either the helicopter-related spaces are less demanding or when the range of length was relaxed up to 140 m. During this analysis it is also wise to remember that the model included *free space* objects describing the *system Helipad* which interact directly with the envelope space and also with other systems possibly limiting the choice.

Below it is reported an overview of the preferred longitudinal and vertical locations of the main systems characterizing the ship.

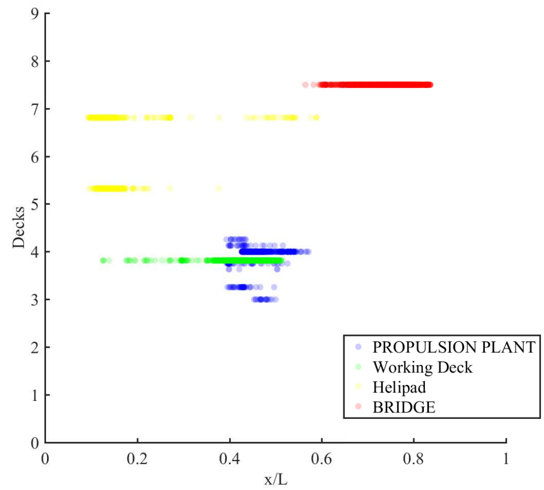
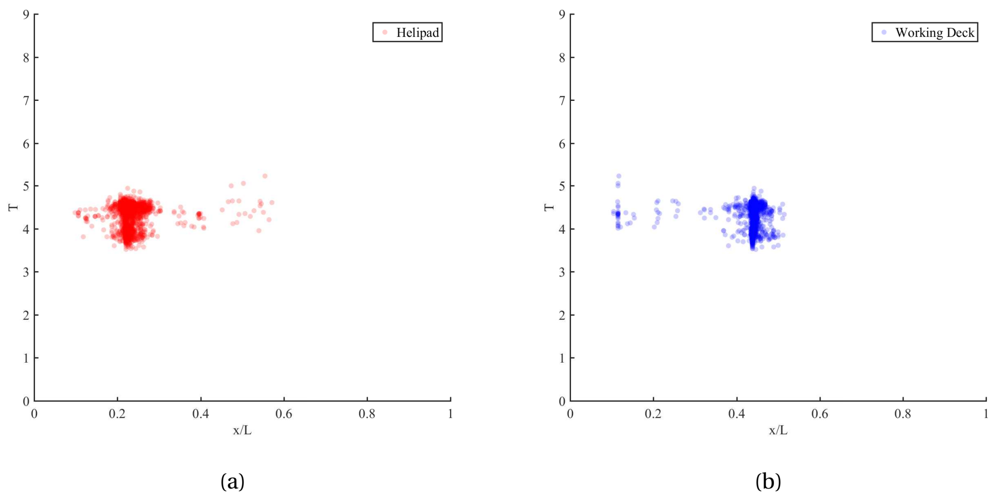


Figure 4.14: Interaction between main *Systems*

From fig. 4.14 can be understood the position of these systems and the overlap between them. The *Bridge* is reported together with the other main systems because it is linked with the higher rating accommodation including the captain room and guest spaces. It is important to remember the *constraints* assigned to these modules that were described in section 3.3.1.

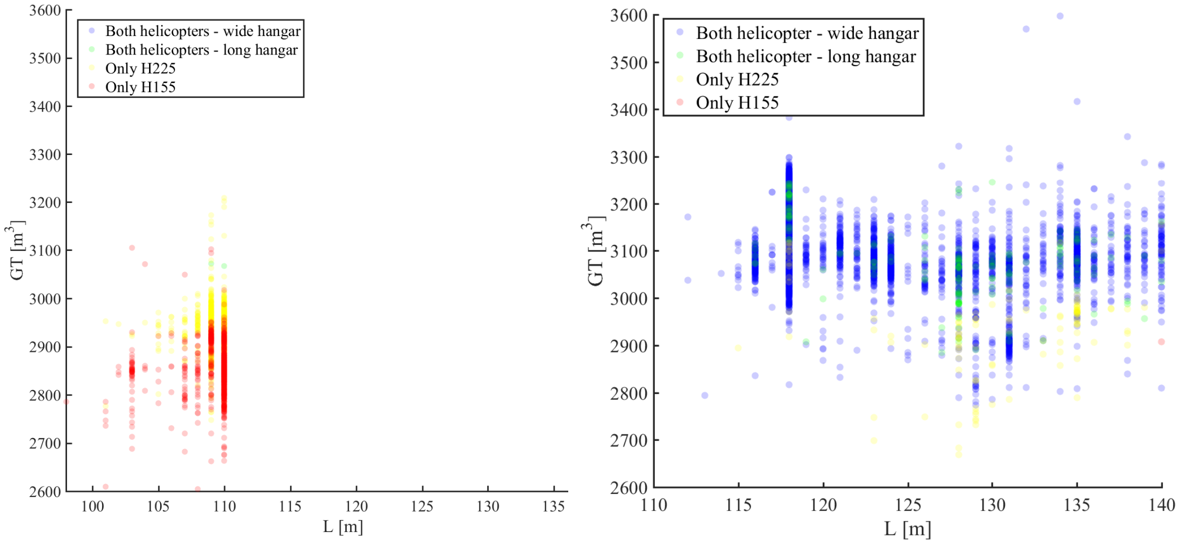
Interesting observation can be done on the tendency of the algorithm to assign the helicopter-related spaces to the aftermost part of the ship. Still some feasible results were found for the option of those spaces assigned to mid-ship, but the majority of solutions went for the former. Figure 4.15 well illustrates the tendency of packing for the second run case. The clustering of designs characterized by the the helipad system at 25% of the length is evident. In addition, with this plot the intention was also to evaluate if the position of the system helipad was influencing somehow the draft of concepts. What can be highlighted is that, although there is no evident correlation between an higher draft and the position of the helipad system, those few designs which exceeded the draft of 5 meters are exactly those that have the helipad more forward in the ship. Opposite and complementary discourse can be done for the system working deck, and fig.4.15b illustrates the correspondent behavior.



(a) (b)

Figure 4.15: Longitudinal position of Working Deck adn Helicopter related spaces

The two plots in fig. 4.16 illustrate the helicopter related spaces characterizing the design space of one of the run with ’relaxed’ length constraint (2^{nd} one) and the set of calculation characterized by the more restricted length values (7^{th}). It is rather evident how the different lengths constraints influenced the selection of the level of helicopter characteristics. Indeed, the 7^{th} run showed a predominance of options: *’Only H225’* (yellow dots) and *’Only H155’*(red dots). In strong contrast, the 2^{nd} illustrates how the majority of designs is characterized by the option: *’Both helicopters - wide Hangar’* (blue dots) showing that for such relaxed length constraints the model was less sensible in creating trade offs regarding this variation.



(a) 7^{th} run: length range (95-110m)

(b) 2^{nd} run: length range (95-140m)

Figure 4.16: Different choice of helicopter -related spaces for run with different length setting

Obviously, designs with the capacity of storing only one helicopter featured a smaller GT (red dots). On the other hand, the different shape of the hangar was not really affecting the GT neither the length of the vessel. Indeed, green dots (representing the long hangar) were distributed all around the design space with an even significant clustering on 118 m length.

This outcome is probably explained with the fact that the hangar was always below the landing area and, with these options, the latter was characterized by a length of 28 m that equaled the size of the longest hangar. Thus, when the space for the landing area was found, a different shape of the hangar below was not significantly determinant.

4.8. Reflections after Packing

To summarize the findings after the exploration phase, here are reported the main points from which gaining insights for the next step:

- First of all, it was recognizable the strong limitation in finding short ships within all the sets of calculations conducted. The considerably high beam allowed (24 m), did not help significantly in reducing the length of the vessels; probably the reason can be found in the fact that the *L/B* ratio needs to be conserved in order to have sufficient power to push the boat up to *25 knots*.
  Several attempts were done after the first results with the intent of finding shorter solutions:
  1. Implementation of options for dealing with the tenders and toys (i.e substitution of tenders on the working deck according to variations, rotation of Cigarette storing them transversally).
  2. Adding a second objective function:

  $$min \;\; f_2 \qquad \frac{L_{design}}{L_{max}} \tag{4.5}$$

     In the second objective, L_{design} indicates the length of the current design generated by the algorithm and L_{max} represents the maximum value of length in the constraint settings.

The second objective should minimize the length obtaining a theoretical minimum of 0.67, represented by $L_{min} = 95m$ (lower bound) divided by the $L_{max} = 140m$ (upper bound). Instead, the minimum sticked at 0.9 which, on the other hand, referred to roughly $L_{design} = 126m$.

3. Allowing the main deck to be placed to an additional level: the aim was trying to develop the systems more 'vertically' rather than along the length.

4. Adding a different second objective:

$$min \ \ f_2 \qquad \frac{L_{design} - L_{min}}{L_{max} - L_{min}} \tag{4.6}$$

   The difference with the previous case, is that the range of values that can be assumed by the packing density (first objective) and by this second objective, is the same (both from 0 to 1). While in the previous case, the second objective function could have assumed only values from 0.67 to 1.

5. In addition, an investigation was carried out regarding the number of bulkheads and the minimum distance between them. This aspect might represent a limitation to the desired shorter length. The feeling that some settings of the algorithm related to this feature might impede the generation of shorter designs is still present but due to the complexity of the code no evident answer was found in this direction to fully demonstrate the outcome.

Despite multiple changes to the initial settings of the model, in both, systems definition and setting of the genetic algorithm, the hoped result was not found. This first conclusion confirms what was already found in previous packing applications revealing the tendency of software in producing larger ships compared to the desired dimensions, partly due to the presence of void spaces. Thus, looking back at the hard requirement on length, it seems that the tool did not give entirely satisfactory results. The struggle of packing with hard objects appeared to be a substantial limitation for the way the model was set up. Indeed, the most numerous causes of failure were due to systems characterized by hard objects. Naturally, systems that occupy a significant amount of space on the overall layout, together with the ones that have strong interaction between each others, also contributes notably to the difficulties in finding feasible solutions.

- Regarding the influence of the three different engine rooms modeled, it was possible to highlight how these drove displacement and length of a concept, while not very strong was the effect on beam. In particular almost all the designs generated, were characterized by the 3^{rd} configuration. Choosing the *F&S* engine room layout brought a more marked beneficial effect on the overall weight of designs rather than on the final volume. Meaning that when looking at designs with the *F&S* configuration, increasing the power does not necessarily means increasing the weight.

- The investigation for the helicopter-related spaces led to the conclusion that none of the designs generated got the option of the hangar *horizontally* placed to the landing area. The exact reason why an hangar in front of the landing area did not give any feasible solution is still not clear but some thoughts were made when thinking at the dimensions involved, at the relations between other spaces and at the way this system was modeled.

- *Working deck* and *Heli-related* spaces confirmed the supposed potential conflict manifesting a tendency of occupying similar areas. However, the tendency of the former system was to be located in the mid-ship position, while for the latter the preference was at the aft.

- At first the modeling phase started exactly from the creation of toys and tenders in order to get familiar with the creation of *system/blocks.* Subsequently, thanks to the understanding of the program and acknowledging the limitations of packing, the decision of creating a *working deck* as done for the creation of the two garage, where later placing the tenders, started to gain more credits and was considered more appropriate. In the specific case of the largest toys and tenders the benefits of creating a *working deck* and later constraining their position to be exactly on top of it, made the packing process significantly easier and successful.

- The concept illustrated in fig. 4.9 represents a potential solution to move forward because of her small length. However, according to the model settings, this concept showed strong compromises between heli-related spaces and working-deck. Several changes might be applied to improve the design, such as trying to enlarge the hangar to host both the helicopters or to 'manually' fit the toys that were excluded. For example, storing two Cigarette at the side of the hangar, making free space on the working deck an thus giving the chance of carrying the others larger toys. Finally, regarding the estimation of the resistance and of the power installed, this will not be valid, due to the non feasibility of draft.

- In contrast with the previous point, if the choice would fall on a 120 meters concept, no compromises would have been considered. In addition, due to the higher packing density compared to the shortest model, less modifications would be needed.

Overall from the packing process it was confirmed the conclusion drawn in [13] that finding a correct balance between the number and type of constraints and/or logical relations versus the desired diversity of the resulting solutions, is not an easy task. In this perspective, on one hand there is a high risk of over-constraining the model, which will result in only a limited exploration. However, on the other hand, the concern of avoiding eventual non-sense in final results pushes the designer to create links between spaces in the natural process of imagining the proper design. It is important thus, to distinguish between the *necessary* connections from the *possible* ones.

5

Selection and GAs Improvement

5.1. Selection

After the analysis on all the collection of results, a discussion with the company suggested to focus on two general arrangements in particular. Since the company wanted to keep in strong consideration the length constraint, the next step will consist in improving the layout of the only concept within the 100 m length (98m) and another one to be chosen within 120 meters to evaluate the added value offered by these larger dimensions.

5.2. Improvement of the 120 m Concept *YS 11820*

The reason of focusing the attention on a larger vessel lies in evaluating the advantages of having about 20 meter in excess. Two very similar concepts where selected of about 120 meters length. Both were characterized by no significant trade-offs regarding the variations, thus including all the *non-negotiable* requirements.

The best attributes from both designs were selected and moved forward to further study. The main dimensions of only one of the two is represented (the one related to the 2^{dn} run) since they are almost the same; table 5.1 reports the specifications of one of them.

	2^{nd} run concept
Length overall	118.00 m
Beam overall	20.97 m
Draught	4.54 m
Displacement	4974 tons
Maximum speed	25 knots
Range @ 18 knots	6,000 nautical miles
Packing density	75%

Table 5.1: main characteristics: 120 m concept

Both the design solutions are characterized by the third engine room configuration. Several small expected modifications were done in *CAD* environment but here are only reported the additional features given by the 'extra' space provided.

- The main deck is characterized by a surplus of around $50m^2$ that can be used for additional accommodation/storages/others.
- The working deck offered more than $100m^2$ in excess compared to the previous design, giving the opportunity of placing also the Ampelmann access (*nice-to-have* request).
- The helipad serving also as *tennis-court*, was included thanks to the larger overall length. (*nice-to-have* request).

5.3. Improvement of the 98 m Concept - *YS 9822*

Only one concept satisfied the requirement of the design brief about the length restriction (< 100 m) but it was unfortunately failing on the *Draft feasibility*. In particular:

- $T_{des} \simeq 3m$
- $T_{actual} = 4.11m$

highlighting a substantial difference ($\sim 1.10m$) and implying that the total power installed ($MCR = 22320\,kW$) will most likely be insufficient when considering the *actual Draft*.

For this design solution a more detailed explanation on the changes will be provided since it was decided to focus the attention on this shorter concept. In addition, the room for potential improvement, both in terms of more clever space arrangement and of space savings, was large. Some main characteristics of the concept, as was created from packing, are reported here:

Length overall	98.00 metres
Beam overall	22.02 metres
Draught	4.11 metres
Displacement	4867 tons
Maximum speed	25 knots
Range @ 18 knots	6,000 nautical miles
Packing density	58%

Table 5.2: YS 9822 Specifications

- First of all, the *beam* was reduced from 22 to 20 meters.

Several modifications have been done when 'translating' the general arrangement produced by packing into a *CAD* environment (*AUTOCAD software*). The following list briefly reports the major changes. These adjustments are highlighted in fig. 5.1 and need to be compared to the initial GA of fig.4.9 representing the *YS 9822* (outcome from packing).

- *Engine room (dark green)*: in the packing concept the position of the engine room was at around 50% of the overall length. However, a more aft position of the engine room is often preferred due to the reduction in length of the shaft line. Thus, the engine room position was shifted backwards with the re-arrangement of watertight bulkheads taking care of maintaining a similar spacing.
- *Fuel storages (light green)*: two rooms assigned to the storage of the fuel, both for the helicopters and for toys, were joined together and moved down to the tank deck level close to fuel tanks. Joining them in one area seemed to be more logical due to the restrictions and further precautions that fuel storages require.
- *Galley (red)/ Crew accommodation (rose)/ Crew recreational areas(purple)*: at the lower deck, the galley has been brought a little behind its packing position and the more forward space have been tapped by 'Crew Accommodation'. This choice reflected the fact that accommodation spaces are more easily squeezed in narrower volumes (extreme bow) while a more spacious area is more appropriate for the galley and recreational areas. In the model, both the type of systems were modeled as *soft objects* and thus packing does not really recognize a significant difference.
- *Helipad-Hangar (violet)*: the helipad dimensions were increased from the ones allowing to land with the H155 helicopter to the ones for the H225. The hangar was upgraded from being capable of hosting only the medium duty helicopter to store both of them. The change required an increase from 108 m^2 to 180 m^2. This change was made possible thanks to the void spaces left from packing.
- *Working Deck (black)*: was also subjected to an 'upgrade'. In this case, however, the significant change does not regards the 4 meters added to the length of the system but rather it lies on the change in toys hosted. Indeed, by moving the two Cigarette (firstly assigned on the working deck) at the sides of the hangar, it was possible to include the two big toys (Viking and Hinckley) on the working deck itself.

- *Ribs and Cigarette (black)*: four ribs were located at the same manner of the Cigarette, but one deck below. The choice of having the ribs at the main deck and the Cigarette at the upper deck resides in the will of creating a nice enclosed block around the hangar. Locating four 8-meters ribs in an enclosed storage was considered more appropriate. Additionally, a Cigarette was placed at the extreme aft, at the upper-deck level transversally to the ship length.
- *Garage and Toys Garage (orange)*: a clever use of space allowed to increase the dimension of the garage as well. It was located at the main deck, when the superstructure rise, between the open working deck and the accommodations. it was separated in two rooms, allowing a central passageway. The dimensions of toys garage were reduced making use of the vertical space, considering that jet-ski and sea-bobs were disposed one on top of the other.
- *Bridge (green)/ High officers accommodation/ Guest areas(purple)*: all these three systems, occupied in the final GA approximately the same location set by packing, they were only slightly re-arranged in order to find the most appropriate rationale but maintaining the same overall zone assigned by the algorithm.

5.4. Conclusions from GA Improvement

The beam reduction and the more efficient and clever use of voids created by packing, suggested that, according to the model settings, the tool overestimated the need of creating trade-offs between the variations set up.

Generally, it can be concluded that with the increasing level of details during this phase, the following two actions might be pursued, thanks to the making use of the voids created by the tool by better arranging the systems:

1. Reducing the vessel dimensions,
2. improving the vessel features.

In addition, it can be concluded that the position of the macro-spaces (heli-related ones, working deck, accommodation) were kept the same, while the position of smaller systems was corrected due to the higher level of details.

The improvement of the *YS 9822* into the *YS 9820* already represents the first step of the next phase: the development of the most promising concept into the ship design spiral.

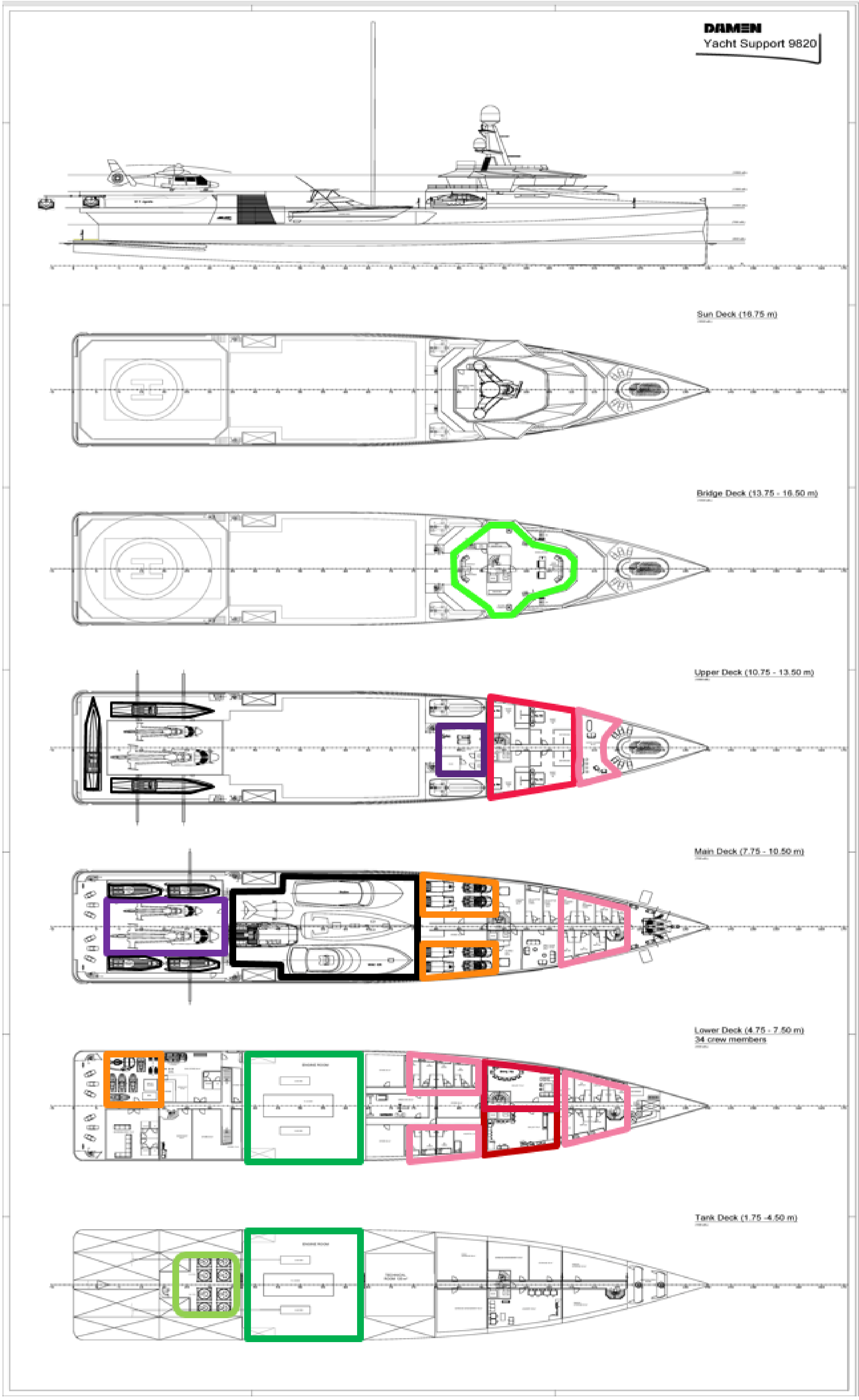


Figure 5.1: GA of the YS 9820

6
The Classical Approach

Chapter 5 concluded the process of improving the general arrangement of the 'most promising' design, generating what it has been called *Yacht Support 9820* identified with the acronym *YS 9820*. This chapter, on the other hand, works to refine the selected concept to one integrated design.

The well-known design spiral conceived by J.H. Evans constitutes an undiscussed excellent way of proceeding during the design of a vessel. Fig. 6.1 is an attempt, by means of a model, to display a rational over-all design procedure as applied to an hypothetical but typical, surface cargo ship problem. The purpose is to assist in organizing the thought process, having in mind particularly the use for such, so as to enable ship design problems to be solved most efficiently, and by means of automatic computers, if desired. The radial lines of the diagram represent the salient considerations of the designer arranged, it is believed, in the logical order most conducive of rapid convergence on the ultimate, refined and balanced solution indicated by the inner closed circle. [16]

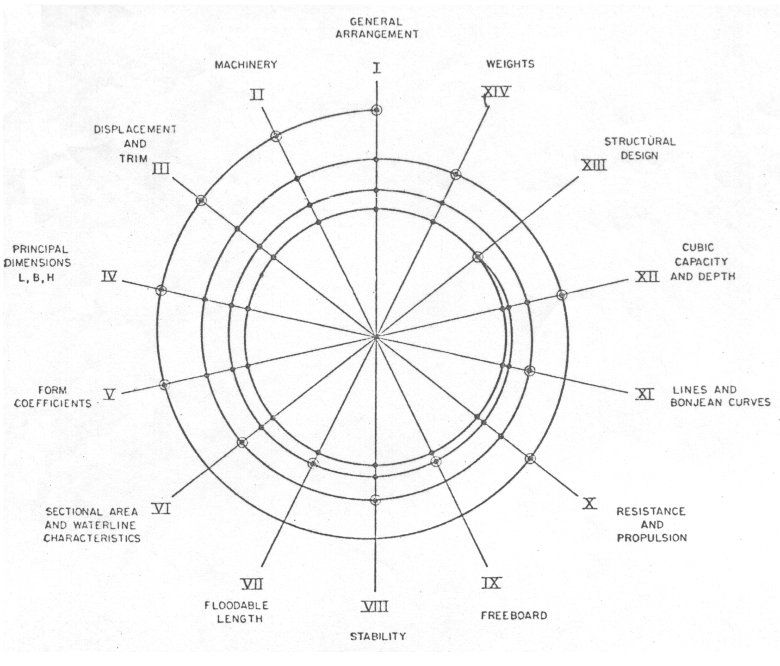


Figure 6.1: Ship Design Spiral - J.H. Evans

The *Design Spiral* describes the above-mentioned iteration and this concept will be applied for approaching the preliminary design of the *YS 9820*. In this chapter the steps characterizing the design process of the case study will be illustrated. The first aspect was the elaboration of the general arrangement, already started in chapter 5, the following list describes the remaining subjects faced in the preferred order.

- Weights
  - Light Ship Weight - LSW
  - Dead Weight - DW
- Hull Shape - Lines Plan
- Tank Arrangement
- Resistance, Propulsion and Range
- Stability
- Construction - Main Frame
- Design Check calculation
  - Form coefficients
  - Principal dimensions
  - Displacement and trim
  - Machinery

This list represents a guideline to help the process of designing the new *YS 9820* and being able of developing an **integrated design** as stated in the proposal of this master thesis.

6.1. Weights

6.1.1. Light Ship Weight - LSW

Introduction

Before defining the weights for the *YS 9820*, it was necessary to research similar ships built in house (within Damen) providing reliable data from which the correct factors could have been extrapolated.

First, the *LSW* was initially approached taking as reference the *SeaExplorer 95* (*SX 95*). Unfortunately this type of ship turn out to be not exactly suitable, especially for the estimation of *Shipbuilding and Outfitting*. Indeed, the *SX 95* is an expedition yacht compliant with the polar code, implying a special strength for making the hull ice-breaking. As consequence, with the use of factors relative to this ship, the *YS 9820* resulted to be excessively heavy leading to the need of looking at other ship types.

The production sector of the *Patrol Vessels* of Damen was considered as the most opportune for finding proper ships of comparison. In particular the *Offshore Patrol Vessel OPV DN 2200* was taken as reference for the determination of the weight density factors constituting the weight of hull and superstructure. To determine the weight of the ship, a *Ship Work Breakdown Structure (SWBS)* was followed. However many approximations and assumptions are made during this stage while estimating these weights.

1^{st} **round - Design Spiral**

Group 100: The first group represent *Shipbuilding and Outfitting*. In order to determine the weight relative to this group two CAD drawings where made to help in dividing properly the ship and to approach the estimation as realistically as possible. Indeed, a *Section Plan* was executed in order to create a certain number of *Patches* or *Blocks* that, built separately, will be welded together forming the entire ship. Each of these *Patches* was characterized by a certain density factor referring to similar ships. Thus, for example, to a block representing one part of the hull was assigned an higher density factor ($90 kg/m^3$) compared to the block representing a part of the superstructure (made of aluminum, $30 kg/m^3$). The shape of the *Patches* was assigned taking into account the position of the watertight bulkheads. Additionally to the *Section Plan* the other drawing that supported the definition on volumes and construction details, was the *Centerline Elevation Plan* showing the height of each deck and of the ceiling.

Group 200: This group called *Main Machinery* represents the weight related to engines, propeller, and all the items related to the connection between prime mover and propeller. The weight of the engines represented in the GA were taken into account for this first round of the spiral. Regarding propellers, the weight of a three-meter CPPs (mounted on the *DN 2000*) was taken as reference. By roughly locating the propellers, based on a comparison with both the *YS 6911* and the *DN 2000*, an initial weight was assigned to: shaft, stern tube, seals and bearing and rudders, stocks and tubes.

Group 300: Regarding this weight group (*Primary Ship Systems*), the value of the *SX95* was scaled based on LxB.

Group 400: All the *Electrical Systems*, were conveniently adjusted comparing both the *SX95* and the *YS6911*.

group 500: Some items of the *Deck Equipment* were taken from the *SX95* while some others were calculated according to the tenders toys to deploy and retrieve.

Group 600: for the *Secondary Ship Systems*, the weight of the *SX 95* was considered acceptable at this stage.

Group 700: This weight group representing all the *Joinery and Accommodations*, was calculated according to different area based weight density factors depending on the type of space considered.

Group 800: *Navigation/Communication* items were taken the same as the *SX 95* taking care of adjusting the relative Vertical Center of Gravity and Longitudinal Center of Gravity according to the position of the relative GA.

Group 900: *Special Equipment*, such as elevators, dumbwaiter and hangar with the relative equipment were taken from the *SX 95* with proper adjustments.

The outcome of the evaluation of the LSW is summarized in the following table:

	LSW [t]	VCG [m]	LCG [m]	TCG [m]
Total Lightship incl. margin	3692.1	6.20	44.94	0.00

2^{nd} **round - Design Spiral**

The weight group 200 was the one that determined the major changes for the LSW during next rounds of the spiral. In particular, the power estimation from the 1^{st} round revealed that with the diesel engine installed from packing, was not possible to fill the gap of power to reach the top speed. Thus, the huge main central diesel engine (*CAT 16M 43C*) was replaced with a much more powerful Gas turbine (GT) (*LM 2500*). Gas turbines are particularly sensitive to pressure losses due to installation and the required volume for the inlet and exhaust ducts, "up- and down-takes" installation, is quite large. This argumentation, when talking about yachts, affects the available interior space and layout and are always a spacial area of attention regarding styling. [22] In case of the *YS 9820*, the extra space required for exhaust of the gas turbine will sacrifice some working deck area coming up straight above the engine room.

Together with the introduction of the GT also the weight and the position of potentially feasible gearboxes were added to the LSW. Two gearboxes were considered connecting the two *CPPs* from the wing diesels and one central for completing the propulsion train between gas turbine and water-jet. These changes brought the following new values of LSW and position of center of gravity.

	LSW [t]	VCG [m]	LCG [m]	TCG [m]
Total Lightship incl. margin	3536.7	6.26	45.28	0.00

As expected, by placing a prime mover which weights about 200 tons less, the overall value of LSW was reduced of about *100 tons* and because of the aft position of the engine compared to the midship section, the LCG resulted moved forward of a little more than *0.3 m* while the VCG rose of *0.6 m*. No relevant further changes were done in successive runs of the spiral.

6.1.2. Dead Weight - DW

The other 'big player' in the determination of weights is the *Dead Weight* including all the consumables, the spaces dedicated to spare stores, the amount of garbage that can be handled and the applicable load on deck.

The vast majority of volume dedicated for the fuel tanks will contribute decisively to the total dead weight. An initial estimate of the m^3 useful for meeting the range, was taken from the outcome of packing. The net total storage capacity of diesel tanks is based on the transit range (6000 nm), transit speed (18 kn). An extra 10% margin should be taken into account as the tanks cannot be filled nor drained completely. Regarding the lube oil tanks 0.001 m^3 per installed kW of power was taken into account. 20 m^3 plus 0.6 m^3 per person of fresh water capacity are reserved. For gray and black waters, approximately 90 m^3 are included for the former and 20 m^3 for the black ones. Additional fuel need to be brought on board for refueling both the helicopters and toys and tenders, approximately 40 m^3 of aviation fuel and the same amount of additional fuel for toys and tenders. Finally, the bilge tanks calculated as the 5% of the sum of all the fuel oil carried. The DW includes also variable loadings, the weight of which is area based: waste handling area calculated as 0.1 t/m^2 and dry stores weighting 0.35 t/m^2. Other components are all the toys and tenders represented as *Deck Load*, and the weight of the two helicopters.

The following table summarizes the items characterizing the DW in the first run of the spiral.

Table 6.1: DW first round

TANKAGE	Departure	[t]
Fuel Oil	98%	553
Fresh Water	98%	58
Grey & Black Water	98%	110
Lube Oil	98%	24
Bilge Water	98%	32
Crew Affects	98%	3.5
Garbege Stores	98%	15
Spare Part Stores	98%	70
DECK LOAD	Departure	[t]
Vicking	-	43
Hinckley	-	25
S/Y	-	8
Newton 36	-	9
MIR Sunbmarine	-	18
Ribs	-	3.2
Cigarettes	-	24
Garage	-	13
Toys's Garage	-	15
Helicopters	-	15.5
Helicoper Fuel	98%	40
T&T's Fuel	98%	40

Once determined all the elements constituting the DW, four different loading conditions were investigated as it is common practice in shipbuilding.

- *Trial (or Design)* condition (50% consumables).
- *Departure (or Full)* condition (98% consumables).
- *Arrival* condition (10% consumables)

- *Summer* loading condition (98% consumables plus a margin of 9% of the total DW plus a 3% for future growth)

A first comparison between the 'Classical approach' and packing can be done by comparing the displacement calculated in the two situations. During such correlation it is important to remember the differences that characterize the two different situations. Comparing the value of displacement of the first round of the spiral in trial loading condition with the correspondent one of packing, a 8% divergence it was revealed. In particular *4471 tons* was the weight coming out from the first iteration of the design spiral, while *4867 tons* was outcome from packing. The divergence (8%) was considered acceptable taking into account that the packing design is 2 meters wider compared to the *YS 9820* and that the LSW during the 'Classical Approach' was done more accurately through the comparison with other similar ships.

During the second run of the spiral, the DW of the ship was subjected to an increase in fuel oil tanks capacity reaching a value of around 690 $tons$ useful for hopefully meeting the range. Indeed, the power estimated during the first round of the spiral, was higher compared to the outcome from packing, thus also the range resulted to be insufficient. The third round of the spiral was only focused on evaluating the changes on the lines-plan, and consequently no changes to the DW were made. During the fourth run of the spiral, due to a more accurate resistance estimation, the DW needed a further increase of fuel tanks of about 60 $tons$.

6.2. Lines-Plan

Before making the Resistance-Power estimation and checking the stability, is convenient to have a clear picture of the hull shape by means of drawing a proper *Lines Plan*. The complete drawing of the lines-plan is reported in Appendix F. The hull, was modified during the third round by reducing the beam on the waterline (B_{WL}) of about 1 meter: green lines in fig.6.2 represents the wider vessel while red ones the narrower.

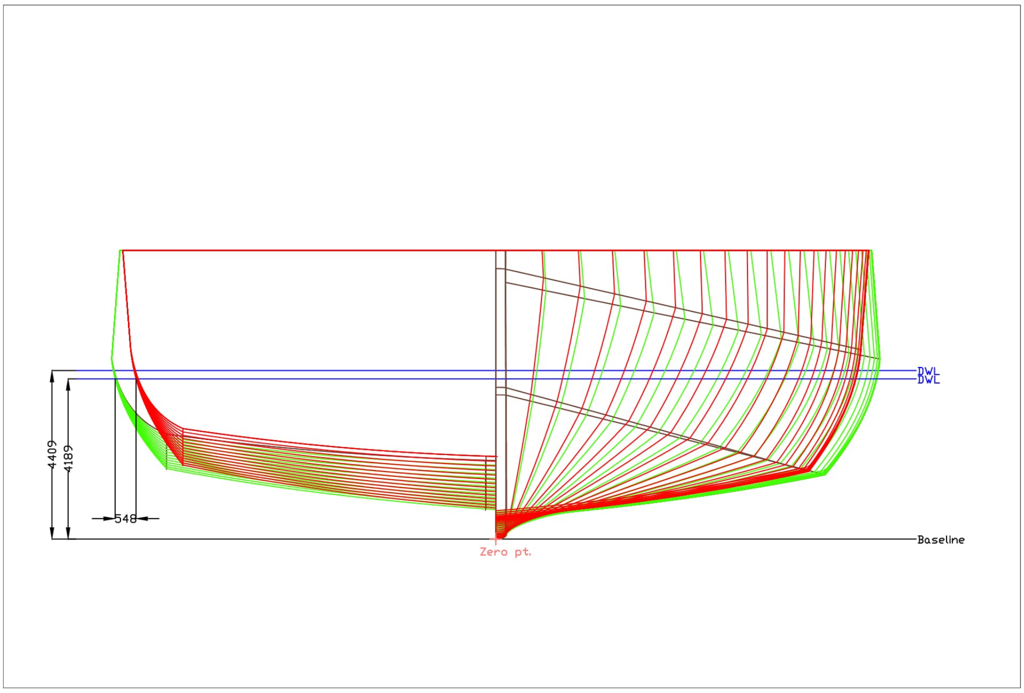


Figure 6.2: Comparison lines-plan

Both the LSW and the DW of the two models were kept the same in order to be able to compare only the impact of the mentioned hull modification. The reason for investigating this hull change, was to improve her efficiency; however the differences in resistance between the two hull-shapes (*YS 9819* and *YS 9820*) was tiny. In fig. 6.3 the two resistance curves show very little discrepancy one from the other especially in the speed range up to 18 knots. From this value until about 23 knots, a larger gap is revealed with 3% higher values for the wider ship. Finally, the difference between the resistances seemed reducing again from 23 knots up to the maximum speed with only 1% discrepancy. From this analysis can be concluded that striving for a 1 meter narrower ship will not significantly change the power to be installed and consequently the focus will be kept on the wider concept.

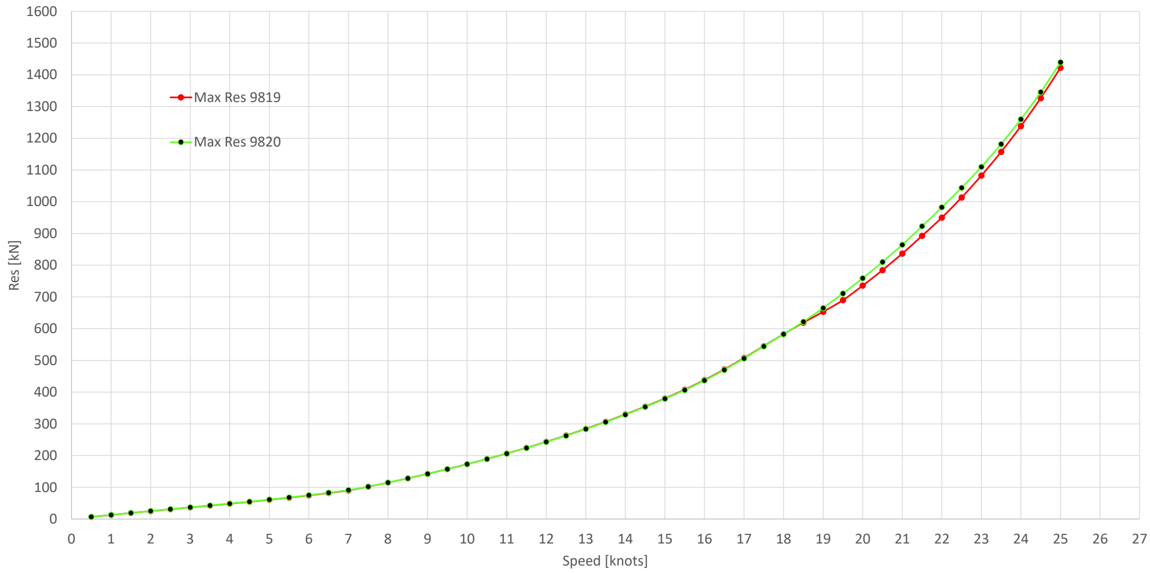


Figure 6.3: Comparison between resistance estimation of YS 9820 and YS 9819

6.3. Tank Arrangement

Once the DW has been defined for each loading condition, a *Tank Plan* can be arranged in order to be able of doing some initial stability calculations with the values of hydrostatics.

The way this step has been approached was by means of the software *Maxsurf*. Initially, the way of proceeding consisted in trying to first fill the lowest part of the hull in order to keep the *Vertical Center of Gravity (VCG)* as low as possible. Thus, a first revision of the initial GA was already possible, because all the double bottom was used for making tanks where storing fuel oil, while in packing, these were not allowed to be located in such a position. The double bottom characteristics were defined following *Regulation 9* of SOLAS *PART B - 2 Subdivision, watertight and weather-tight integrity*.

During the second round, fuel oil tanks were slightly rearranged. In addition, the tank top level rose from 1.5 m above the base line up to 1.8 m due to the need of substantially increasing the fuel volume.
Since the third round looked only at a smaller beam, in oder to have the same DW of the previous round, the tank arrangement was subjected to some changes to maintain the same value of fluids in the narrower hull.

The last increase of about 90 *tons* of fuel tanks volume was applied with the resulted final tank arrangement (see Appendix D). The additional fuel was added by means of restoring the two wing tanks around the midship.

6.4. Stability

The *LSW* with the position of the *CoG* and the set of all the items composing the *DW* determined the four different loading conditions. These constituted the necessary information to check the stability of the vessel under different situations.

To avoid confusion, it is assumed as *zero point* for measurement is located on the symmetry plane at the intersection of the *Aft Perpendicular (AP)* with the *Base-line*. Thus, when the vessel is trimmed by the stern, she is supposed to have a positive angle of trim.

Equilibrium

First of all, the equilibrium of the *YS 9820* was investigated for all the 4 different loading conditions (Arrival, Trial, Departure, Summer). The *trim*, which is one of the most important and critical parameter for the resistance of the ship, was kept around a favorable value by gradually filling the tanks due to the distribution of *Tank Arrangement*.

Large Angle Stability

The next characteristic that needs to be check was the *Large Angle Stability*. A dedicated set of calculation can be found in *Maxsurf* that determines all the values required by the IMO *International Codes - 2008 IS Code – International Code on Intact Stability, 2008 - Part A – Mandatory Criteria - Chapter 2 – General Criteria*.

When considering the *LSW*, the *Departure* and *Summer* loading conditions, all the criteria related to the above-mentioned regulation, were satisfied. In contrast, the other two loading conditions were causing the failure of the *267(85) Ch2 - General Criteria 2.2.3: Angle of maximum GZ*. In *Arrival* and *Trial* conditions the maximum *righting lever GZ* was occurring at an angle of heel = 23.6° ≤ 25°, causing thus the failure of meeting the criteria. For explaining this behavior, the different loads constituting the DW were varied to understand which one were the most incisive items causing the undesired behavior. The outcome was that the *Effect of free surfaces of liquid in tanks* was contributing considerably.

During the next round, the actions were aimed at solving the issues arose.

- First, was made a longitudinal subdivision of tanks in order to reduce the *Free-surface effect*. Indeed, during the investigation of the failure of the ship on the maximum *righting lever GZ*, was noticed that fluids in the tanks were the ones most influencing the unwanted behavior.

- A modification to the upper part of the hull was created for helping in satisfying the above-mentioned criteria. It was created a step in the uppermost watertight deck (main deck) in the forward part (from 53 meters fwd the Aft Perpendicular), where the superstructure starts rising. Fig. 6.4 shows the change. Together with the creation of this step, a *waterplane* was modeled in Maxsurf Modeler, representing the *watertight deck* at 7.5 meters above the base line, with the same purpose of making the simulation more realistic.

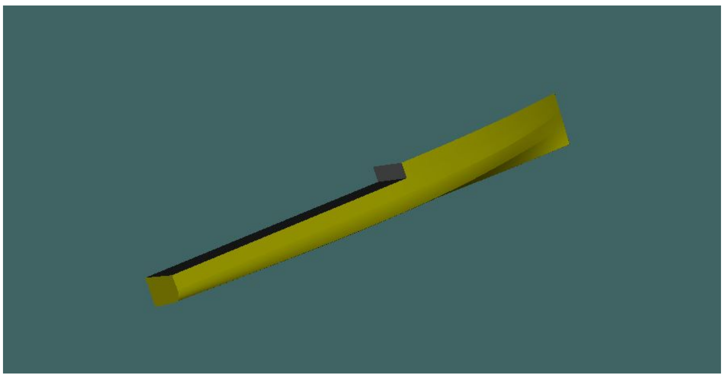


Figure 6.4: hull model YS 9820 with deck step

The values of Hydrostatics at different loading conditions are shown in 6.2 for the fourth and last iteration.

Table 6.2: Hydrostatics YS 9820 - fourth round

	LSW	Arrival	Trial	Departure	Summer
Draft Amidships [m]	3.7	3.9	4.2	4.48	4.55
Displacement [t]	3537	4004	4401	4881	4988
Heel [deg]	0	0	0	0	0
Draft at FP [m]	3.9	4.0	4.2	4.3	4.4
Draft at AP [m]	3.5	3.9	4.2	4.6	4.7
Draft at LCF [m]	3.7	3.9	4.2	4.50	4.57
Trim (+ve by stern) [m]	-0.3	-0.1	0.06	0.28	0.25
WL Length m	98	98	98	98	98
Beam max extents on WL [m]	19.6	19.8	19.9	20	20
Wetted Area [m^2]	1829.1	1884.6	1931.4	1986.4	1999.8
Waterpl. Area[m^2]	1593.3	1613.8	1628.3	1641.9	1645.2
Prismatic coeff. (Cp)	0.714	0.731	0.741	0.751	0.752
Block coeff. (Cb)	0.457	0.498	0.526	0.558	0.558
Max Sect. area coeff. (Cm)	0.788	0.798	0.806	0.816	0.818
Waterpl. area coeff. (Cwp)	0.827	0.831	0.833	0.835	0.836
LCB from zero pt. (+ve fwd) [m]	45.3	44.1	43.5	42.8	42.9
LCF from zero pt. (+ve fwd) [m]	41.7	41.6	41.7	41.75	41.8
KB [m]	2.5	2.6	2.8	2.93	2.97
KG fluid [m]	6.26	6.28	5.9	5.72	5.73
BMt [m]	12.8	11.7	10.9	10.1	9.9
BML [m]	284.2	255.1	234.8	214.2	210.4
GMt corrected [m]	9.05	8.12	7.75	7.32	7.17
GML [m]	280.4	251.5	231.6	211.4	207.6
KMt [m]	15.3	14.4	13.7	13.0	12.9
KML [m]	286.6	257.7	237.624	217.2	213.3
Immersion (TPc) [tonne/cm]	16.331	16.5	16.7	16.8	16.9
MTc [tonne.m]	101.2	102.7	104.0	105.3	105.7
RM at 1deg = GMt.Disp.sin(1) [tonne.m]	558.9	567.6	595.3	623.4	623.7
Max deck inclination [deg]	0.23	0.06	0.04	0.17	0.15
Trim angle (+ve by stern) [deg]	-0.23	-0.06	0.04	0.17	0.15

Apparently, with the new arrangement of tanks and the modification of the hull shape in the fore part, the vessel was complying with all the requirements of the IMO *International Codes - 2008 IS Code – International Code on Intact Stability, 2008 - Part A – Mandatory Criteria - Chapter 2 – General Criteria*, included the *267(85) Ch2 - General Criteria 2.2.3: Angle of maximum GZ.*

Figure 6.5 and the correspondent associated values for the angles of the maximum *righting lever GZ* are reported below.

- *LSW* = 2.68 m at 30°
- *Arrival* = 2.525 m at 29.1°
- *Trial* = 2.516 m at 30°
- *Departure* = 2.45 m at 30°
- *Summer* = 2.4 m at 30°

During this set of calculation a check of the criteria to be satisfied was done on the slightly slender hull and on the final settings for the last round.

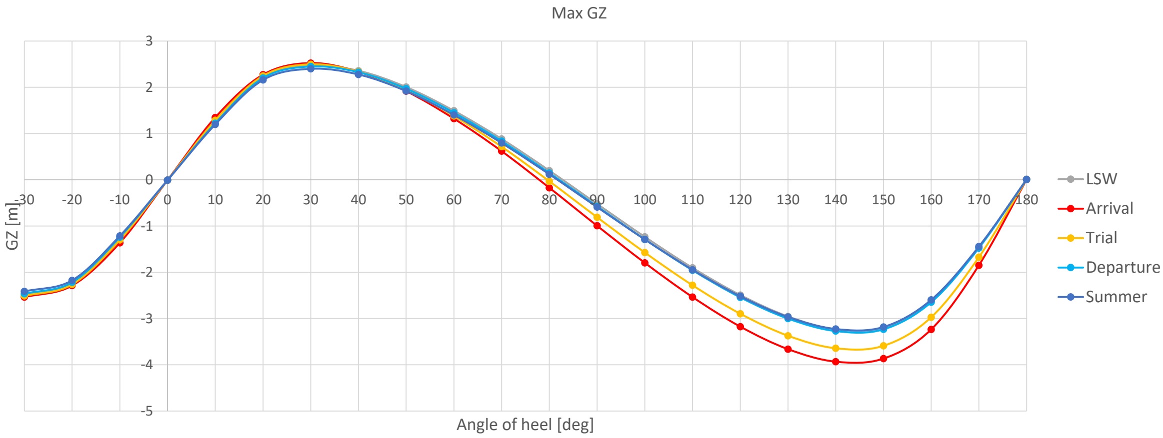


Figure 6.5: maximum lever GZ at different loading condition

6.5. Resistance, Power and Range

The resistance estimation needs a careful look for two reasons. First, because the ship is characterized by a relatively recent hull shape (axe-bow concept) and secondly because her top speed is distinguished by a critical Froude number. In addition, a good resistance and power prediction is crucial for a balanced and effective propulsion plant (see sec.6.6).

The resistance estimation was initially carried out with *Holtrop & Mennen (H&M)* and subsequently will be gradually improved proceeding with the next iterations. In a first stage, the power estimation was carried out with two tools, *Maxsurf* and a dedicated *spreadsheet*, using the same methodology: *Holtrop & Mennen (H&M)*. It need to be highlighted that, in the packing concept of reference, the design draft was exceeding the one for which the power was estimated initially. As consequence, most probably, the engines selected in the first estimation of the *LSW* will not be sufficient to push the vessel up the maximum speed.

The values of Hydrostatics, have been directly used in *Maxsurf Stability* likewise as input in the dedicated *spreadsheet*. To compare the outcomes of the two tools, the value of *Effective Power* need to be checked. From *Maxsurf Resistance*, 20185 kW are required for reaching maximum speed without taking into account the chain of efficiencies that brings up to the *Break Power*. From the spreadsheet calculation, the same value stands to 19834 kW (less than 2% discrepancy) probably linked to the fact that in the *spreadsheet* were used some parameters accounting for appendages while in *Maxsurf* not.

However, considering the following values of efficiencies:

- $\eta_H = 0.95$
- $\eta_R = 1.00$
- $\eta_O = 0.6$
- $\eta_{GB} = 0.95$
- $\eta_S = 0.98$

these correspond to the equivalent *Propulsive efficiency* of 0.57 (packing = 0.7) and a *Transmission efficiency* of 0.93 (packing = 0.97). The overall *Break Power* resulted significantly higher compared to the one coming out from packing (22 MW), where the chain of efficiencies was simplified and more optimistic, not to mention the fact that the latter was referring to a much lower design draft compared to the actual one. The following picture shows the curve of the *Break Power* related to the speed, and it is visible that at 25 knots the required output is about 40 MW.

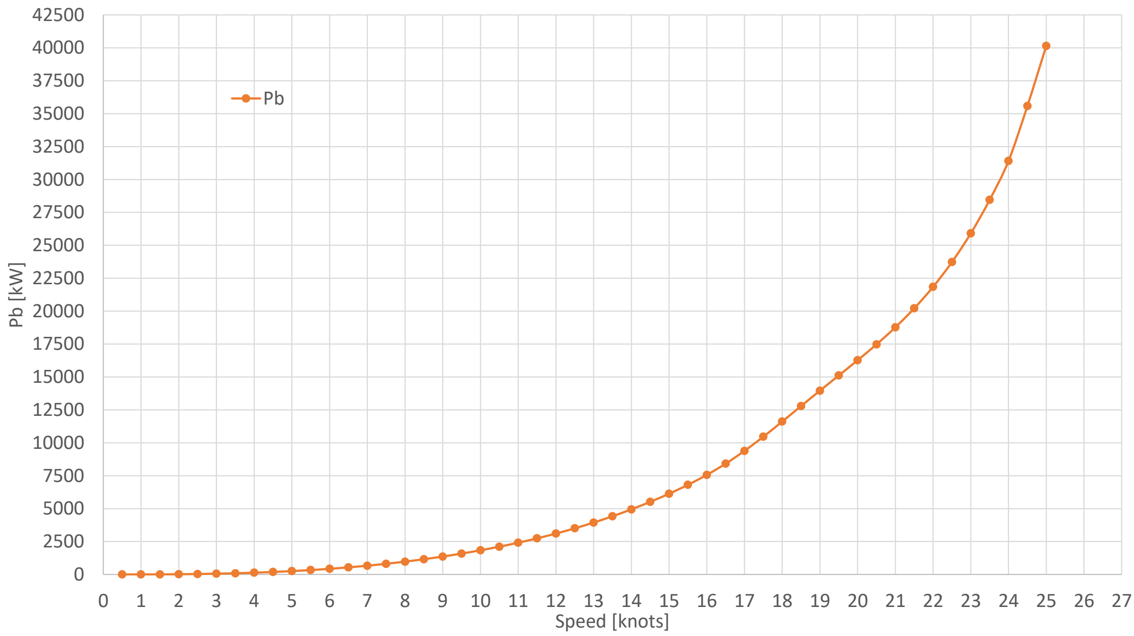


Figure 6.6: *Break Power* after 1^{st} round of the spiral

The chain of efficiencies was considered here with an higher level of details, especially the *open water propeller efficiency* = η_O was set to a more realistic value (0.6) compared to what was assigned in the mathematical model (0.7). In addition, a 15% of sea-margin was included in the calculation.

Finally, calculating the *Range* correspondent to that power request at 18 knots, the maximum that could have been reached with the fuel stored in the actual tank arrangement, was about 4000 nm. The range was calculated starting from the value of break power required at the correspondent speed and taking into account the specific fuel consumption of the engines. In the calculation a 10% of fuel reserve is taken into account together with an additional 3% of range margin. At the actual stage, the desired range of 6000 nm can only be reached at the speed of 15 knots. The range calculation takes into account also an *Auxiliary Engine Power* of *400 kW* as it is supposed that only one of the three generators is running while sailing.

The more recent power estimation revealed that with the diesel engine installed from packing, was not possible to fill the gap of power to reach the top speed, thus the changes done in the LSW and DW were reflected during the second iteration. As consequence of the general overall weight, the power estimation resulted significantly lower compared to the first round; the total power required for the top speed went down to about 33.6 MW.

Also a range calculation was carried out to check if the current state of the design was able to meet the one set in the design brief. The ship was able to fully meet the range of 6000 nm and more at 17 knots while at 18 knots 400 nm were missed from the desired goal and the total fuel volume was around 800 m^3 for these settings.

The third round of the spiral aimed to reduce the resistance opposed by the ship. Yet, in this prospective, it seemed wise to check the resistance prediction more accurately with the help of the *R&D* department of the company. Indeed, the application of *Holtrop & Mennen* methodology, as already stated previously in this dissertation, is on the limit of its application for the case study.

A more accurate resistance was calculated by a software developed in-house by the company (*HSC Resistance*), based specifically on tests carried out on *axe-bow* concept. In particular, the hull used as starting point in the software is an *Axe-bow concept* 65 meters long and 11 meters wide. The methodology assumes the length/displacement ratio to be dominant for the basic resistance level. The 'new' resistance will be then based on the estimation of this developed software, but still two correction factors needed to be taken into account.

- The first correction factor (*b*) is necessary due to the fact that the resistance calculated with *HSC Resistance* is based on towing tank tests. Thus, because the company had already calculated the resistance for an analogous ship (*YS 6711*), it was suggested a 7% correction factor to be added to the *Residuary* component of the resistance.
- The second correction factor (*a*) regarded the different *L/B* ratio of the *YS 9820* compared to the reference hull (*Axe bow 6511*). The correction for taking into account this aspect came by calculating the resistance with *Bailey* method on two different set of hull dimensions. The first one was done on a 'fictitious' *YS 9816.6* created scaling the *L/B* ratio of the *6511-hull* on the length of 98 meters. Secondly, the same measure was done for the *YS 9820* hull. Finally, the ratio between these two values of resistance gave the second correction factor (*a*) to be added to the final one.

To conclude, the resistance of the *YS 9820* was be given by the following formula.

$$Total\ Resistance_{YS9820} = Resistance\ Axebow\ of\ YS9820_b + a \tag{6.1}$$

where:

- $Resistance\ Axebow\ of\ YS9820_b$: is the value of resistance estimated on the basis of the Axebow concept with the increased 7% on its *Residuary* component.

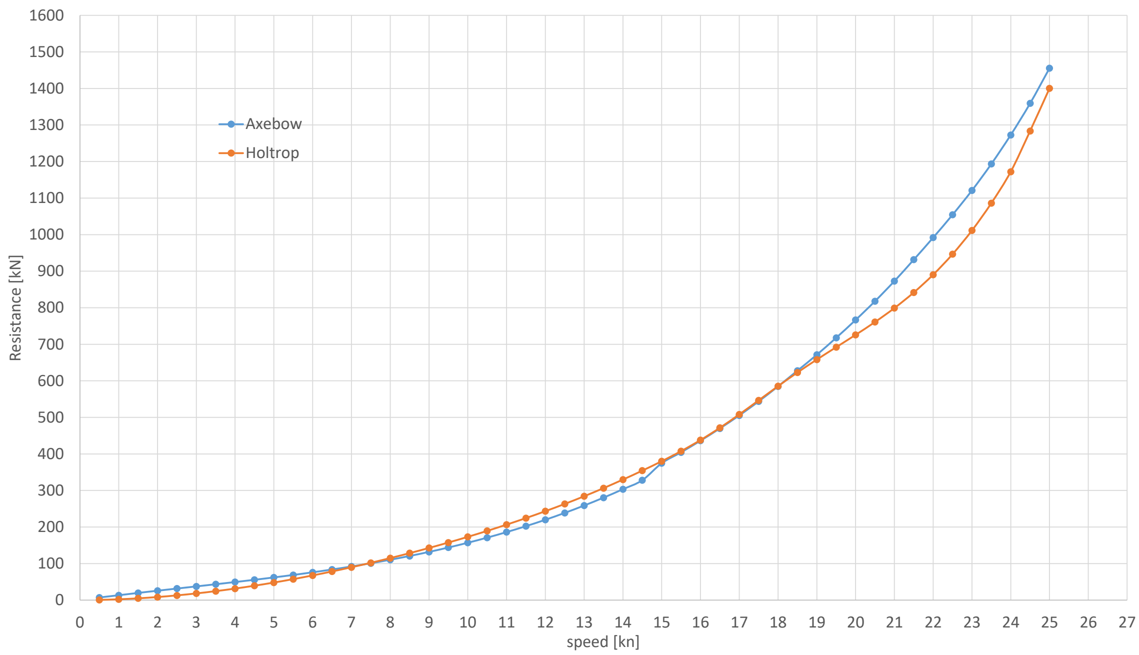


Figure 6.7: Resistance comparison: Holtrop and Mennen vs Axebow

Above, it is reported a graph (fig.6.7) where a clear comparison between *Holtrop & Mennen* and the explained *Axebow* estimation is shown. The comparison is reported for the *Trial* condition only, but the same testing was done also for arrival and full loading condition and the trend reported gave similar results. In particular, the *Axe-bow* analysis gave a slightly more severe estimation (4% more) at top speed (25 knots). Generally, between 7.5 and 19 knots *Holtrop & Mennen* (orange line) assumes higher values while from 19 to 25 knots the *Axe-bow* (blue line) estimation is again more severe with values up to 9% higher.

Also the correspondent values of power required in both cases are reported in graph 6.8 when adding the efficiencies mentioned in section 6.5. As expected, using the same efficiencies, the difference in power installed accounted for the 4% as well, with values of 33935 kW for Holtrop and 35274 kW for the 'Axebow' method.

Overall, it seems that *Holtrop & Mennen* prediction method, approximated rather well the resistance of the vessel and the consequent power required to reach the maximum speed, especially considering the stage of the design this dissertation is focusing on (Preliminary design phase). However, from now on, for next calculation purposes the maximum value of power required between the two method proposed will be chosen in order to be conservative.

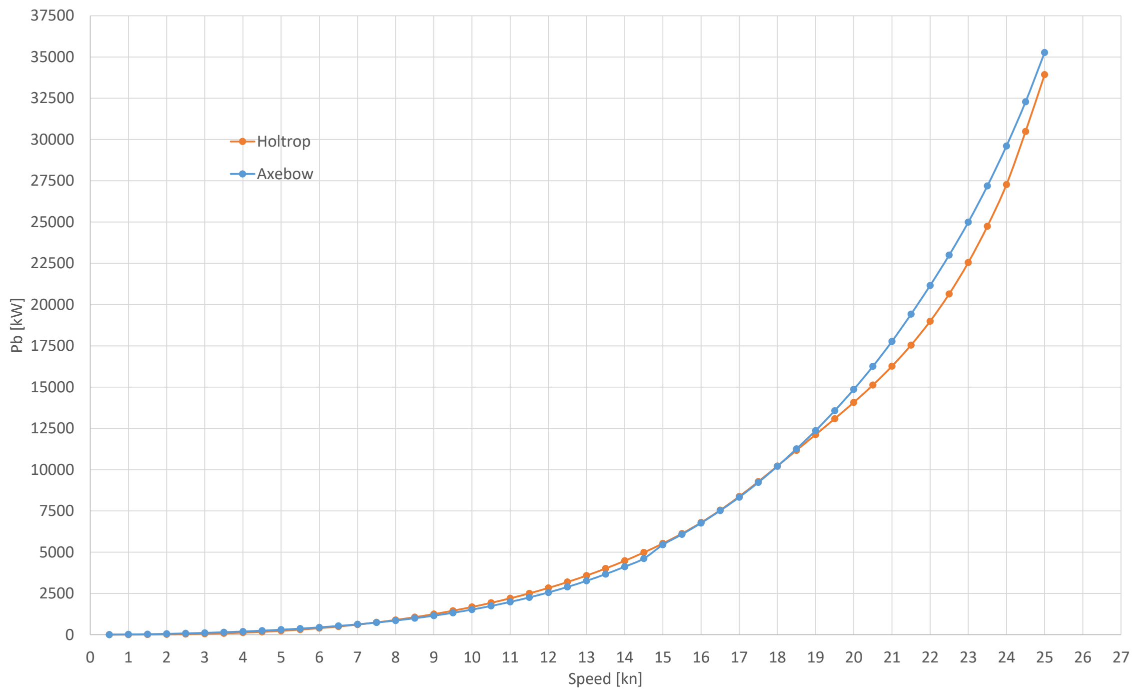


Figure 6.8: Power comparison: Holtrop and Mennen vs Axebow

Similarly as for previous rounds, the range calculation was carried out in order to check if the vessel, after the modification of the lines-plan was still keeping the same capabilities in terms of endurance. Fig. 6.9.

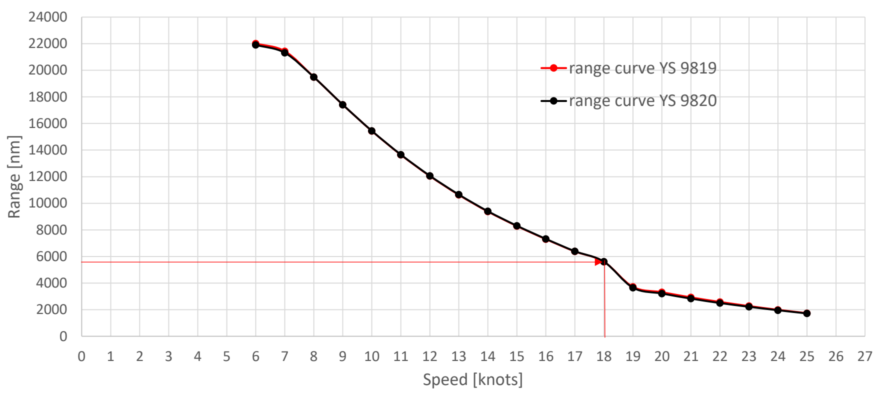


Figure 6.9: Range calculation for the third round

In graph 6.9 was added the line representing the range capability of the *YS 9819* (red line hardly visible). The difference between the curve range of the *YS 9820* is almost imperceptible. This is due to the fact that the differences in resistance between the two concept is also very small. Regarding the resistance for this round, the relative graph was reported in 6.3.

For the last round, the range calculation will be reported here, while the power and the resistance considerations will be implicitly treated in section 6.6. The primary reason that made this further round necessary was the increase in fuel tanks in order to meet the desired range. Indeed, evaluating the consideration about range capability of previous section, it is possible to move forward in two directions: the speed of 17 (even 17.5) knots it is accepted by the client for sailing 6000 nm with no need of increasing the tank capacity or, on the other hand, it is not acknowledged to meet the range at a slightly lower speed and if there is space available, the fuel tanks volume should be increased. The case study followed the second option and thus the new graph shows the achieved capacity in fig. 6.10.

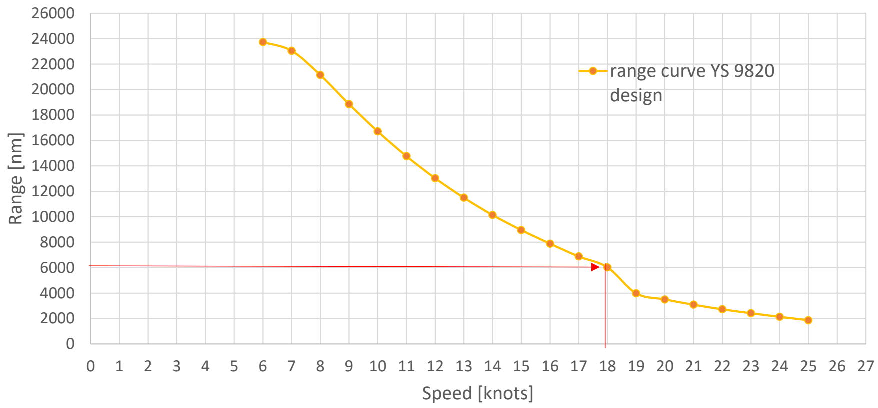


Figure 6.10: Range YS 9820 after 4th iteration

6.6. An Hybrid Propulsion System

The propulsion plant designed for this vessel provides a combination of two different types of propulsion means, two *Controllable Pitch Propellers (CPPs)* linked to two wing-engines and one *Water-Jet (WJ)* run by the main central engine, creating the so-called *WARP* configuration (*Water-jet and Refined Propellers*). [26]

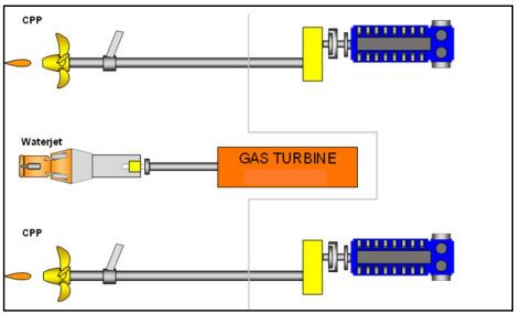


Figure 6.11: WARP configuration [26]

The primary situation where WARP is an interesting alternative is when a mix of operational parameters needs to be fulfilled, typically the requirement to achieve a high top speed, and at the same time have a moderate cruising speed combined with long range. [26] The scope of the vessel and its operational profile has crucial importance and it is represented in fig. 6.12.

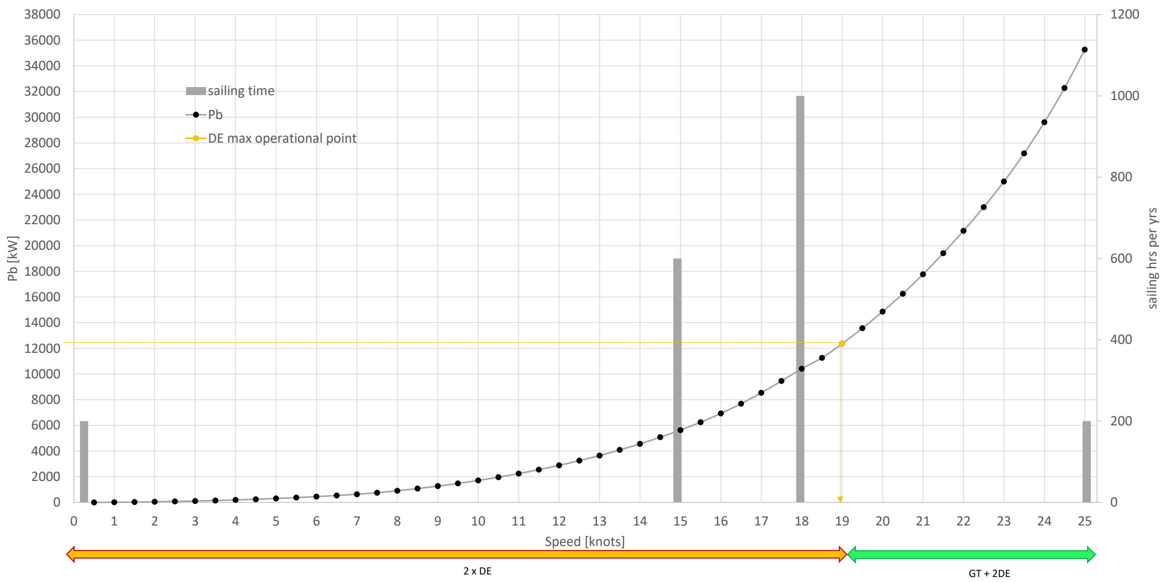


Figure 6.12: Operational Profile

The choice of types of engines to be applied highly depends on whether or not there is a long-distance range requirement besides the high-speed requirement. That would require a well balanced fuel efficient design covering the whole speed range. [22]

Two diesel engines *CAT VM 32 C* (of 6363 kW each) were initially selected to satisfy the cruising speed condition which represents the larger portion of sailing time (50%). To sail at top speed, the gas turbine is triggered together with the two diesels. In this condition, it is crucial that the propellers will be able to still produce enough thrust in the range of speed above the cruising one (18 to 25 kn). This situation might be achieved if the variable pitch of CPPs can be sufficiently increased during the boosting mode.

Indeed, the main problem is that with the increase in ship speed due to the boosting mode, a FPP will become under loaded (thrust decreases at higher ship speed) due to the high inflow speed while the power is not increased. Increasing rpm means the rotational speed will be really high in the booster mode, the cavitation number will decrease which leads, in turn, to more cavitation.[26] This effect is partially compensated by the higher pitch but will also occur in the CPP case; however, the big advantage is that the cavitation number will not decrease because the rotational speed would be kept the same. On the other hand, a FPP type might also be installed if a 2-speed gearbox is used as connection between engine and propeller in the power train. Indeed, with a reduction gear that allow to operate also in the highest speed range the feasibility might be obtained.

A limit that holds for both the options (CPP and FPP) is the *tip speed* that should not exceed $49m/sec$ for the type of ship considered. This value can be checked with the calculation of the *critical rate of rotation* (n_{cr}):

$$n_{cr} = \frac{15.92}{D} \quad [sec^{-1}] \quad [36] \tag{6.2}$$

With D diameter of the propeller.

The best way to proceed for the determination of the WARP configuration is if the following approach could be taken:

1. Define the size and powering of the propellers required for the cruising speed;
2. Match the booster size and powering to meet the desired top speed.

6.6.1. Define the size and Powering of the Propellers Required for the Cruising Speed

In order to find suitable propeller characteristics for the two CPPs a software of the company was used. First, was found the design point at 18 knots (cruising speed) and maximum engine rpm (750 rpm) and secondly, was checked if, increasing the pitch, was still possible to produce an effective sufficient thrust at the top speed of 25 knots.

The outcomes in terms of power train parameters, propeller characteristics and total effective thrust, are reported in table 6.3 at the two speeds of interest. During the testing also a 5% reduction on the speed is accounted for the difference between *theoretical* and *actual* values, implying that 26.3 knots of theoretical speed correspond to 25 and the cruising speed of 18 knots is represented theoretically by 19 knots.

Parameters	dim.	*Design conditions*	*Off-design conditions: boosting*
Gearbox red.	[-]	3.02	3.02
Engine speed	[rpm]	750	750
Eng. Power	[kW]	6363	6363
Eng. mech. losses	[-]	5%	5%
D	[m]	3.1	3.1
P	[m]	3.489	4.012
P/D	[-]	1.126	1.294
# of blades		4	4
η_O	[-]	0.62	0.7
n_p	[rpm]	248.3	248.3
tip speed	[m/s]	40.3	40.3
V_s (theoretical)	[knots]	19	26.3
eff. Thrust	[kN]	363.31	293.15
P_D	[kW]	6044.9	6044.9
Propell. load	$[P_b/D^2]$	662.12	662.12
TOTALS			
tot. eff. Thrust	[kN]	726.62	598.31
tot. engine Power	[kW]	12726	12726

Table 6.3: Desing and Off-design (boosting mode) conditions with change in pitch

With these information, the Water-jet should be chosen in the way that the overall thrust produced at 25 knots should be sufficient to compensate the gap of 'remaining resistance'. Analyzing the values in table 6.3, the efficiency of the propeller is increasing with the increase of pitch and the eff. thrust is decreasing as shown in fig. 6.13.

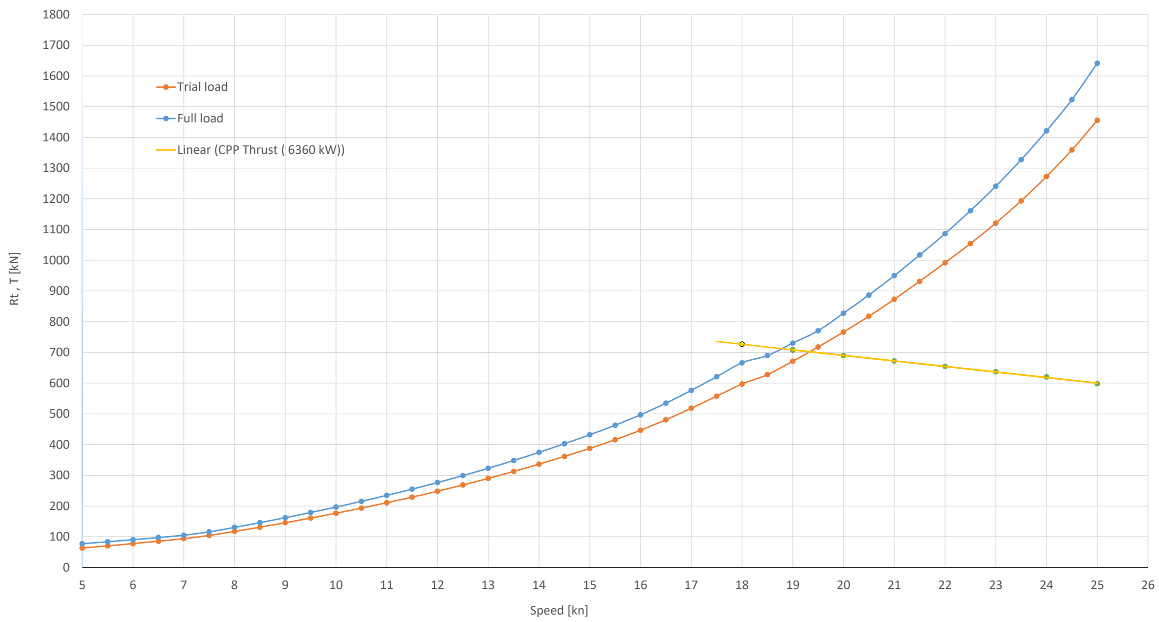


Figure 6.13: 'Remaining resistance'

To satisfy the gap of speed created by the boosting mode, another solution was also analyzed in order to be more critical on the options available and give the chance to decide on the best solution. The alternative method consist in using a *2-speed gearbox* connecting the two diesel engines with two FPPs, that would help in covering the difference by allowing an higher shaft speed. A similar investigation suggested that the values of effective total thrust is nearly the same regarding both *design* and *boosting* operations.

Overall, it is noticeable how the propellers still provide quite substantial portion of the total resistance; about 40% of the total resistance is produced by the two wing propellers even though the total power of the two side engines account for 35% over the total. In the end the choice fell on CPPs because of the improved maneuverability of the ship especially at low speeds.

6.6.2. Match the Booster Size and Powering to Meet the Desired top Speed

The next step consists in estimating the required thrust (and consequently the waterjet size) accordingly to the 'remaining resistance' or effective power. The difference between the resistance of the ship and the thrust produced by the propellers, visible also in fig. 6.13, should be compensated by the thrust of the waterjet when the gas turbine is activated.

In this analysis is crucial the discussion with the manufacturer providing the waterjet which should furnish the product information including thrust graphs for different waterjet sizes. Indeed, the potential supplier of the jet (Wartsila) was also involved in the estimation of performances. Initially, with the informations available in a very first stage of the design, the collaboration with the water-jet supplier suggested the use of a certain booster size: *LJX 2020B*. With the development of the project, the increase in level of details and the accuracy of the informations, the jet initially considered was no longer suitable to meet the desired maximum speed. The reason for the non-feasibility needs to be traced back to the optimal working conditions of the jet: the limitation is linked to the excessive power density installed for the jet dimensions. The maximum thrust produced by that waterjet at 25 knots was about 600-650 kN, while the *'remaining resistance'*, resulted by the difference between the overall resistance (at full loading condition) and the thrust generated by the CPPs at

25 knots, was accounting for 1040 kN. At this point three solutions might be investigated to solve the problem and meet the requirement.

1. The first solution could be installing a larger jet; however with the largest waterjet available from the manufacturer (*LJX 2180B* limited at 20 MW of installed power) the vessel would reach about 24 knots, thus still not enough.

2. The second option would consists in using two "smaller" boosters with 13 MW limitation each, size *LJX 1880B*. This would then lead to 25+ knots, due to the smaller power density per jet, their efficiency is indeed higher. However, the changes due to this solution would result to be excessive for the time left until the end of the project.

3. The third solution consist in increasing the power on the CPPs to increment their overall thrust and leave the last 600-650 kN to the *LJX 2020B* booster or about 800 kN if the *LJX 2180B* would be chosen.

The last option was considered the most suitable for the stage of the design and the time left until the end of the project realization. To increase the power, was chosen a different medium speed diesel engine between Warstila products, type *W 14V31*, characterized by 8540 kW. Even if still some power could have been absorbed by the actual propellers size (the loading on them is actually $662.12 kW/m^2$ and the limit for the type of ship in question should be: $850-900 kW/m^2$), the diameter of propellers was increased from 3.1 to 3.3 meters in order to keep the loading on them around a more favorable value. The same reduction ratio of the initial case was then considered and the results are provided by table 6.4.

With a power increase of 26% the gain in total effective thrust at 25 knots accounted for 18%. Increasing the propeller diameter implied that more pronounced tunnel stern should be created. This is necessary in order to reduce the shaft inclination affecting resistance, running trim and propulsive quality.

Parameters	dim.	*Design conditions*	*Off-design conditions: boosting*
Gearbox red.	[-]	3.02	3.02
Engine speed	[rpm]	750	750
Eng. Power	[kW]	8540	8540
Eng. mech. losses	[-]	5%	5%
D	[m]	3.3	3.3
P	[m]	3.654	4.188
P/D	[-]	1.107	1.269
# of blades		4	4
η_O	[-]	0.6	0.69
n_p	[rpm]	248.3	248.3
tip speed	[m/s]	42.9	42.9
V_s (theoretical)	[knots]	19	26.3
eff. Thrust	[kN]	458.67	363.40
P_D	[kW]	8113.0	8113.0
Propell. load	$[P_b/D^2]$	784.21	784.21
TOTALS			
tot. eff. Thrust	[kN]	917.34	726.80
tot. engine Power	[kW]	17080.0	17080.0

Table 6.4: Desing and Off-design (boosting mode) conditions with 8540 kW and 3.3 m propeller diameter

Another aspect which cannot be disregarded when considering the propeller design, is the source of vibrations it involves. The occurrence of vibrations due to the working propeller and due the propulsor hull interactions can have a great impact on the design of the propulsor and the appendage elements. Vibrations are caused by pressure fluctuations as well by thrust and torque fluctuations. The effect of the propeller pressure field on hull plating and appendage elements, as struts and rudders, increases with: thrust loading, extend of cavitation and declining propeller tip clearance, shaft inclination.

The clearance between the blade tip and the hull was kept as 25% of the diameter in case of $D = 3.1\ m$, in order to keep the level of vibration down. However, the enlargement of the propeller was deemed advisable but to not exceed the immersion of the propeller of more than *40 cm* below the baseline, and to not cut out too much space in the hull by creating too pronounced tunnel sterns, the clearance was reduced to 20% of *D*. In fig. 6.14, is represented the propeller arrangement for the *3.3 m diameter case*.

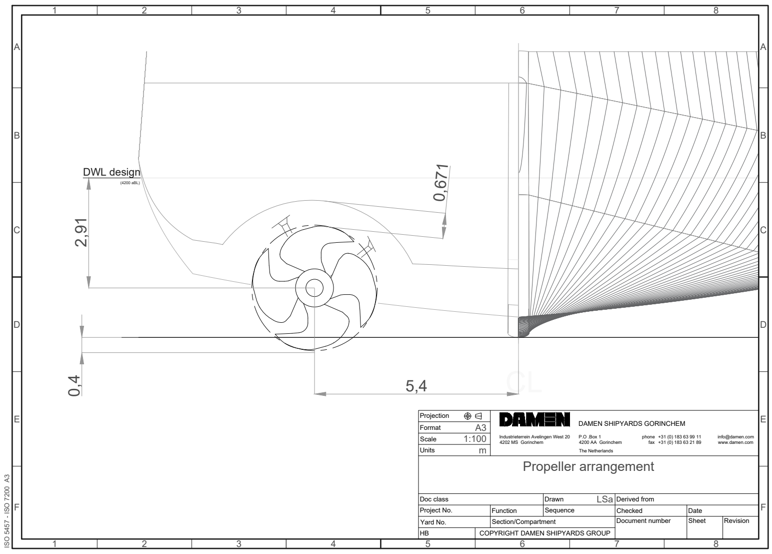


Figure 6.14: 'Propeller arrangement for 3.3 m diameter'

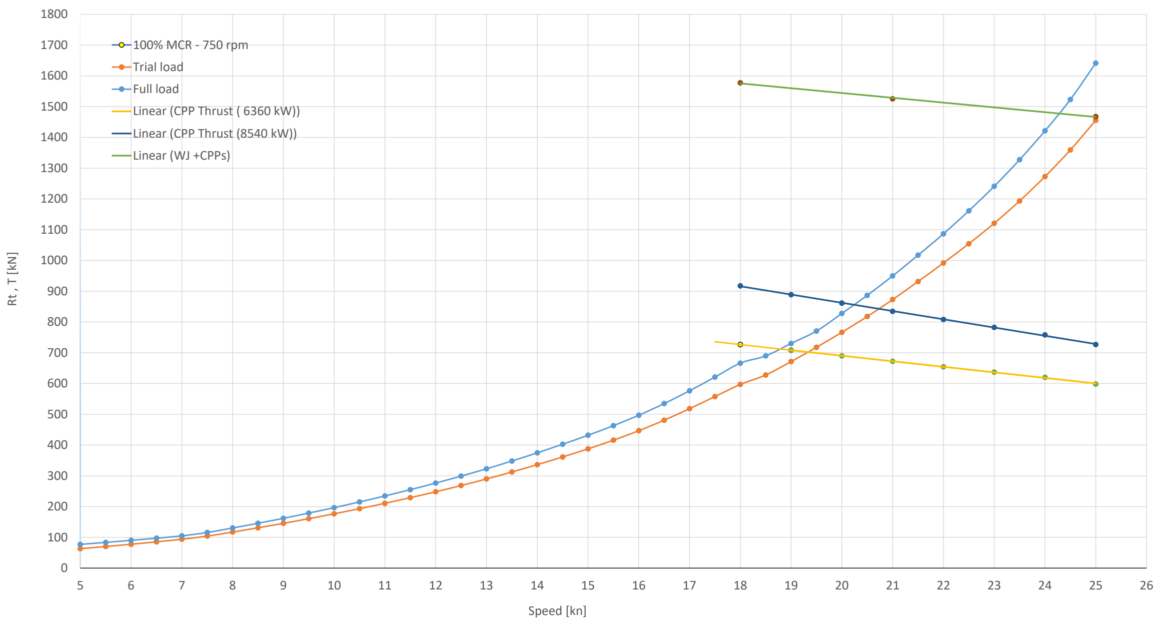


Figure 6.15: 'Remaining resistance with increase in propeller power'

The value of thrust produced by the CPPs due to the power change at the cruising speed of 18 knots, resulted, in excess compared to the value of resistance at that speed. This behavior can be appreciated in fig.6.15 (blue line). As consequence, at 18 knots would be necessary a reduction of pitch (compared to the value proposed in table 6.4) or a reduction in throttle, or a combination of the two actions to sail efficiently.

Considering the solution of increasing the power on the propellers with 8540 kW for each ’wing-engine’, the vessel could reach the maximum speed with a booster jet type *LJX 2180B* driven by 20 MW gas turbine. Indeed, the ’remaining resistance’ accounted for about 900 kN in full loading condition and about 730 kN in the design one. By adding the thrust contribution of the above mentioned jet to the propellers one, the green line in fig. 6.15 can be drawn, showing that the ship is able to meet the desired speed when sailing in *Trial* load condition. On the other hand, need to be specified that, considering the *Departure* one, the ship lose about half knot.

It is clear from al the subject discussion, that a WARP propulsion configuration is challenging to design properly and the main parameters of the propellers should be carefully considered for each separate case. Also, it is stated in [26] that the detailed design of propeller will be challenging and will require an experienced designer.

6.7. Longitudinal Strength

The purpose of incorporating Structural Design in the preliminary study of the *YS9820* lies with the final scope of drawing the main frame of the vessel in her details and check her longitudinal strength.

The overall load on a craft consists of three components, namely *primary*, *secondary* and *tertiary* loads. The classification of loads as primary loads, which affect the hull as a whole, secondary loads, which affects large components of the hull such as bulkheads, and tertiary or local loads, which have a local effect only, has been made for convenience in relation to structural considerations.[18]

The *Rules and Regulation for the Classification of Special Service Craft* were applied to the case study. *Pt.5 Ch.5 Global Load and Design Criteria* of this regulation gives the guideline for the determination of *primary* or *global* loads considered for the scope of this exercise aiming at verify the *Hull Girder Strength.* The global loads and design criteria applicable are the followings:

- Still water bending moments (M_S) and associated shear forces (Q_S) arising from mass distribution and buoyancy forces.

- Vertical wave bending moments (M_W) and associated shear forces (Q_W) arising from low frequency hydrodynamic forces.

According to *Pt.5 Ch.5 sec. 5 - Design criteria and load combinations* the Rule bending moment, M_R, and associated shear forces, Q_R, for non-displacement craft are to be determined as the maximum value calculated along the vessel with equations 6.3 and 6.4.

$$M_R = M_S + M_W \qquad [kNm] \tag{6.3}$$

$$Q_R = Q_S + Q_W \qquad [kN] \tag{6.4}$$

6.7.1. Still Water Bending Moments and Associated Shear Forces

Still Water Bending Moments The still water bending moment, M_S, hogging and sagging is the maximum moment calculated from the loading conditions. Indeed, the calculations of still water shear forces and bending moments are to cover both departure, trial and arrival conditions. As stated in *Pt.5 Ch.5 sec.2.3*, still water bending moments are to be calculated along the craft length. For these calculations, downward loads are to be taken as positive values and are to be integrated in the forward direction from the aft end of L_R. Hogging bending moments are positive.

Still Water Shear Forces The still water shear force, Q_S, at each transverse section along the hull is to be taken as the maximum positive and negative value found from the longitudinal strength calculations. Still water shear forces are to be calculated at each section along the craft length. For these calculations, downward loads are to be taken as positive values and are to be integrated in a forward direction from the aft end of L_R. The shear force is positive when the algebraic sum of all vertical forces aft of the section is positive. Motor yachts generally show distinct hogging bending moments in still water. The calculations for still water contribution (max. values) are shown in table 6.5.

Following are reported the weight distributions (fig.6.16) and the resulted calculations of shear forces (fig.6.17) and the associated still water bending moments (fig.6.18) for the three usual loading conditions: departure, trial and arrival.

Table 6.5: Values of max shear, momentum and their longitudinal position of occurrence

	Shear			**Moment**		
	[t]	[kN]	location [m]	[t m]	[kN m]	location [m]
Arrival	164	1608.3	38.5	3617	35470.7	56
Trial	-149	-1461.2	81.2	3632	35617.8	54.6
Departure	-144	-1412.2	81.2	3975	38981.4	44.8

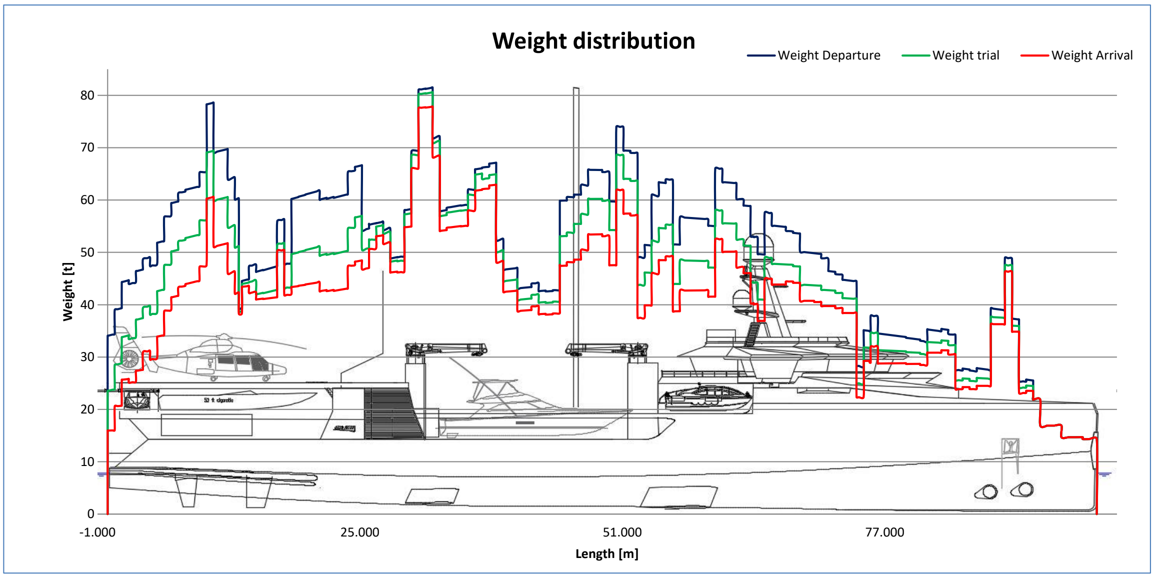


Figure 6.16: Weight distribution for each loading condition

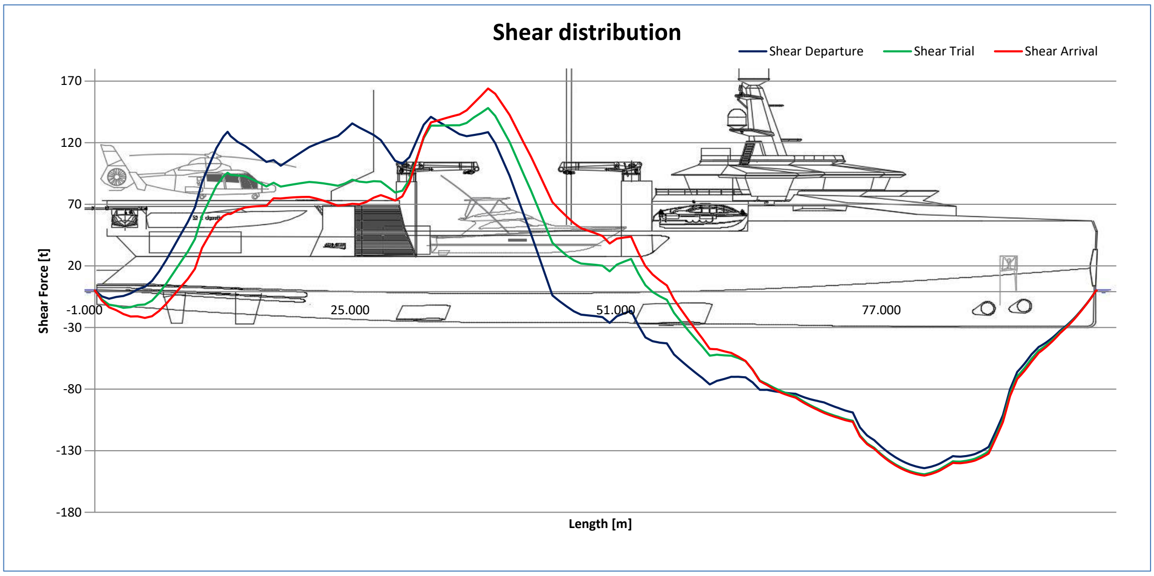


Figure 6.17: Shear distribution for each loading condition

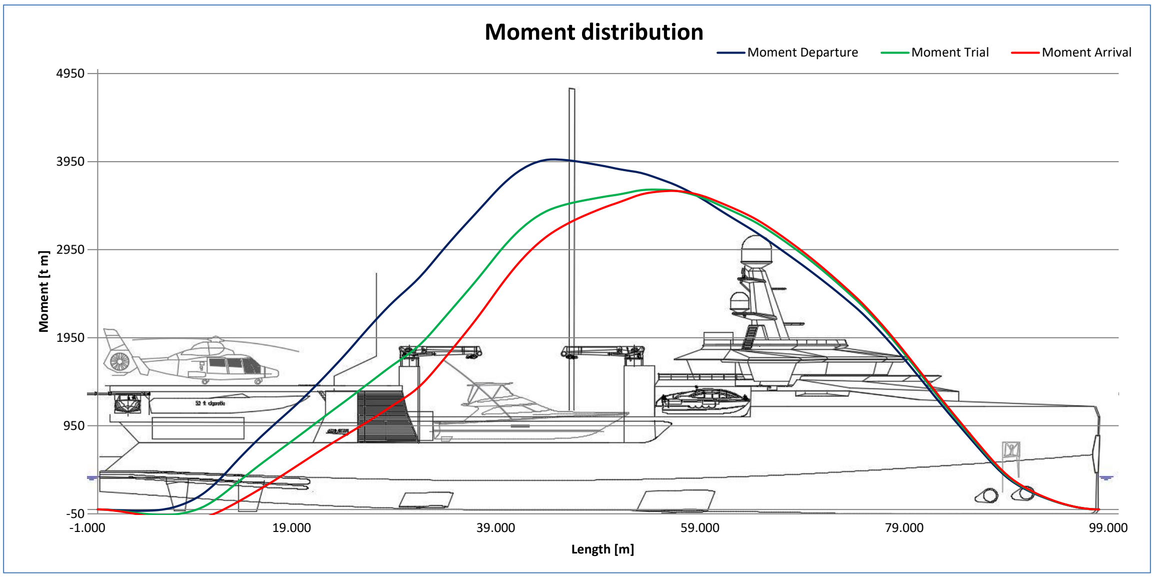


Figure 6.18: Moment distribution for each loading condition

Generally, due to the increase in weight, from arrival to departure loading condition, the location of occurrence of the maximum value of bending moment experiences a gradual backward shift. Both from table 6.5 and figures from 6.16 to 6.18 it is possible to notice that is the departure condition, the location where the shear force is null and thus the maximum moment is registered, is quite different compared to the other two cases. For this reason, it was investigated the contribution of the additional weight due to the dead weight items and the one relative to the tanks separately. Dead weight items include:

- **Crew affects/ Garbage stores/ Spare-part stores**: these are subjected to changes accordingly to the load-case.
- **Deck load**: including the largest tenders and fixed independently from the specific load-case.
- **Cigarettes**
- **Ribs**
- **Garages**: one relative to cars, the other to small toys.
- **Helicopters**
- **Fuel for helicopters and toys**: also changing accordingly to load-case.

On the other hand, for tanks, their filling level changes depending on arrival, trial and departure conditions. The increase in weight (%) due to these items was investigated along the length of the vessel, that was divided in three parts: main central body (0.4 L) and the aft and for extremes. The outcome are listed in table 6.6:

Table 6.6: Weight increase to LSW due to Tanks and DW Items

	0 - 29 [m]		29 - 69 [m]		69 - 98 [m]	
	Tanks	DW Items	Tanks	DW Items	Tanks	DW Items
Arrival	6.4%	6.6%	9.2%	5.5%	1.2%	0.0%
Trial	16.0%	8.1%	15.2%	6.5%	5.9%	0.0%
Departure	23.5%	9.9%	21.3%	7.4%	11.0%	0.2%

The increase due to the fluids into the tanks is substantially higher compared to the one linked to the DW items, and the increase appears to be higher in the aft part of the vessel. The values of still water bending moment and associated shear forces referring to the most critical case (departure) are listed in table 6.7.

Table 6.7: Still Water Bending moment and Shear Forces for Departure condition

	[m]	M_{sw} [t.m]	M_{sw} [kNm]	Q_{sw} [t]	Q_{sw} [kN]
APP	0	0	0	0	0
$0.1L_R$	9.4	114.1	1174.5	60.6	624.2
$0.2L_R$	18.8	1118.5	11517.2	104.4	1074.6
$0.3L_R$	28.2	2268.6	23359.9	119.9	1234.8
$0.4L_R$	37.6	3431.6	35334.8	126.7	1304.4
0.5LR	47.0	3951.7	40690.5	-17.3	-178.2
$0.65L_R$	61.1	3390.2	34909.1	-72.8	-749.3
$0.7L_R$	65.8	3045.3	31357.4	-81.0	-834.1
$0.8L_R$	75.2	2196.1	22613.3	-113.5	-1169.0
$0.85L_R$	79.8	1588.9	16360.7	-141.1	-1453.3
$0.9L_R$	84.5	929.6	9571.7	-135.2	-1392.3
Fore	93.9	83.2	856.4	-37.0	-380.9

The highest value of bending moment is occurring around the half of the length (red). The values of beinding moment and shear were also increased by 5% for taking into account a design margin for possible future changes.

6.7.2. Vertical Wave Bending Moments and Associated Shear Forces

Wave Bending Moments Since the Yacht Support is supposed to operate in unrestricted service area with the exception for polar regions, it falls into the category of **service group G6** for which the vertical bending moment is calculated by the following formula:

$$M_W = F_f D_f M_O \qquad [kNm] \tag{6.5}$$

Where F_f is the hogging, F_{fH}, or sagging, F_{fS}, correction factor based on the amount of bow flare, length and effective buoyancy of the aft end of the craft above the waterline.

For relatively slow mono-hull motor yachts, the longitudinal wave induced bending moments are the most important loading, being most severe in head seas.[18]

Wave Shear Forces The wave shear force, Q_W, at any position of the craft is calculated by the following formula:

$$Q_W = \frac{3K_f M_O}{L_R} \qquad [kN] \tag{6.6}$$

Where K_f is a factor that change depending on the positive and negative value of the shear force and on the position along the length of the ship.

Table 6.8 and table 6.9 summarize all the calculation done for obtaining the value of vertical wave bending moment and associated shear forces for both hogging and sagging conditions. The tables also include the same values of tab.6.7 and the resulted maximum values of *Rule bending moment (M_R)*, eq.6.3, and associated *shear forces (Q_R)*, eq. 6.4.

Table 6.8: vertical wave bending moment and associated shear forces (hogging)

	[m]	M_w [kNm]	M_{sw} [kNm]	M_R [kNm]	Q_w [kN]	Q_{sw} [kN]	Q_R [kN]
APP	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$0.1L_R$	9.4	39771.2	1174.5	40945.7	2832.3	624.2	3456.5
$0.2L_R$	18.8	79542.3	11517.2	91059.5	4248.4	1074.6	5323.0
$0.3L_R$	28.2	119313.5	23359.9	142673.4	4248.4	1234.8	5483.2
$0.4L_R$	37.6	159084.7	35334.8	194419.5	4055.0	1304.4	5359.4
$0.5\ L_R$	47.0	159084.7	40690.5	199775.2	-4055.0	-178.2	-4233.2
$0.65L_R$	61.1	159084.7	34909.1	193993.7	-4055.0	-749.3	-4804.3
$0.7L_R$	65.8	159084.7	31357.4	190442.1	-4617.4	-834.1	-5451.4
$0.8L_R$	75.2	119313.5	22613.3	141926.8	-4617.4	-1169.0	-5786.4
$0.85L_R$	79.8	79542.3	16360.7	95903.0	-4617.4	-1453.3	-6070.7
$0.9L_R$	84.5	39771.2	9571.7	49342.8	-3551.8	-1392.3	-4944.2
fore	93.9	0.0	856.4	856.4	0.0	-380.9	-380.9

Table 6.9: vertical wave bending moment and associated shear forces (sagging)

	[m]	M_w [kNm]	M_{sw} [kNm]	M_R [kNm]	Q_w [kN]	Q_{sw} [kN]	Q_R [kN]
APP	0	0	0	0	0	0	0
$0.1L_R$	9.4	-57457.3	1174.5	-56282.8	2832.3	624.2	3456.5
$0.2L_R$	18.8	-114914.6	11517.2	-103397.5	4248.4	1074.6	5323.0
$0.3L_R$	28.2	-172372.0	23359.9	-149012.1	4248.4	1234.8	5483.2
$0.4L_R$	37.6	-229829.3	35334.8	-194494.5	4055.0	1304.4	5359.4
$0.5\ L_R$	47.0	-229829.3	40690.5	-189138.8	-4055.0	-178.2	-4233.2
$0.65L_R$	61.1	-229829.3	34909.1	-194920.2	-4055.0	-749.3	-4804.3
$0.7L_R$	65.8	-229829.3	31357.4	-198471.8	-4617.4	-834.1	-5451.4
$0.8L_R$	75.2	-172372.0	22613.3	-149758.7	-4617.4	-1169.0	-5786.4
$0.85L_R$	79.8	-114914.6	16360.7	-98554.0	-4617.4	-1453.3	-6070.7
$0.9L_R$	84.5	-57457.3	9571.7	-47885.7	-3551.8	-1392.3	-4944.2
fore	93.9	0.0	856.4	856.4	0.0	-380.9	-380.9

As expected the combination of hogging condition of the ship with the correspondent one from the wave, resulted in the maximum value of moment, occurring at about midship. Equations 6.7 and 6.8 summarize the maximum value of moment and the correspondent value of shear at that section. The hogging condition of the ship combined with the sagging one of the wave, was reported for completeness.

$$M_R = M_S + M_W = 199775.2 \qquad [kNm] \tag{6.7}$$

$$Q_R = Q_S + Q_W = -4233.2 \qquad [kN] \tag{6.8}$$

Even though the combination of the still water bending moment (hogging) with the vertical wave sagging one resulted to be less critical compared to the combination of the former with the vertical wave moment of the hogging type, the values resulted comparable. This outcome can be explained with the analysis on the value assumed by the correction factor F_{fS}. Since the *YS 9820* fall on the category of service group G6, for these types of vessel, the factor F_{fS} depends on the the amount of bow flare, length and effective buoyancy of the aft end of the craft above the waterline. Accordingly to *Pt.5, Ch.5, sec. 2* of the regulation in question, the value of the correction factor F_{fS}, depends on an *area ratio factor* R_A as it follows:

$$F_{fS} = -1.10 \cdot R_A^{0.3} \quad for\ values\ of\ R_A \geq 1.0 \tag{6.9}$$

$$F_{fS} = -1.10 \quad for\ values\ of\ R_A < 1.0 \tag{6.10}$$

R_A was calculated for the vessel and was estimated a value of 1.6, falling on the case shown in eq. 6.9 with a final value for F_{fS} of -1.267. Multiplying this number with the other terms of eq. 6.5, resulted in a significantly increased contribution compared to the case of eq.6.10.

6.7.3. Main Frame Description

The selection of a structural framing system in any vessel must be made from a consideration of weight, production matters, suitability to resist global load and vibration. [25] As the size of a vessel increases the significance of hull girder loads increase dramatically. Usually, the change occurs at a length between 50 and 90 meters depending on the vessel type; in general longitudinal stiffening of the decks is preferred when the length of the yacht is in excess of 50 meters.[18] The hybrid combination framing employs both transverse and longitudinal framing within the same section. Typically, this would entail longitudinally framing for some or all of the decks, with the reminder of the structure being transversally framed. For the *YS 9820* was assumed that the vessel features a steel hull and main deck and aluminum superstructure which do not contribute significantly to the vessel's global strength. Due to the consideration done above, an hybrid framing system was chosen combining longitudinally framed decks and double bottom with a transversally framed side shell characterized by a primary stiffener spacing of 1400 mm.

The principal characteristics and midship section geometry are presented in fig. 6.19. The section is characterized by a double bottom height of 1800 mm above base line, a lower deck at 4500 mm above base and the main deck at 7500 mm. Primary girder were spaced in such a way that the last one, starting from the center-line, was aligned with the step of the side-fuel tanks in order to create a connection with a pillar between the two heights. This resulted in an offset of the first girder of 2500 mm from the center-line and the second one of 5700 mm.

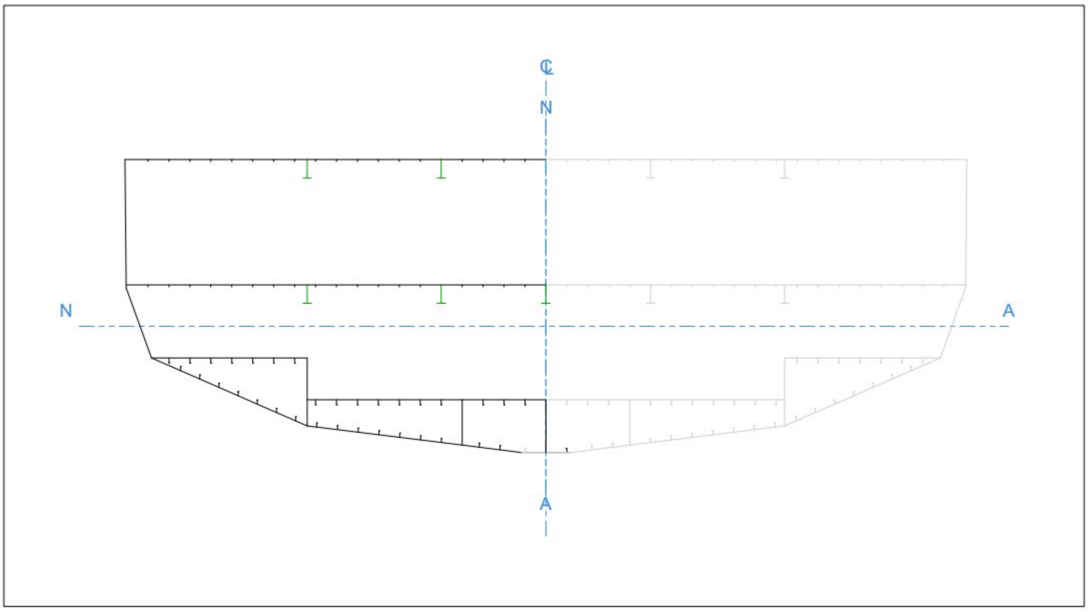


Figure 6.19: Sketch of midship section

Mild steel was considered throughout with the use of HP and fabricated steel sections.

Properties	units	*Value*
Frame number	[-]	67
distance forward of AP	[m]	47
Fraction of rule length (x/LRule)	[-]	0.532
Section modulus at deck	$[m^3]$	1.306
Section modulus at keel	$[m^3]$	1.727
Shear Area	$[m^2]$	0.150
Inertia YY	$[m^4]$	5.215
Inertia ZZ	$[m^4]$	34.261
Total area	$[m^2]$	0.950
Total effective area	$[m^2]$	0.950
Neutral Axis	[m-AB]	3.557
Weight unit length	[kg/m]	7458.589

Table 6.10: Midship section properties

Plating and stiffeners The following tables helps in summarizing the plates characteristics and the distribution of the longitudinal stiffeners per plate.

Shell and double bottom

	thickness [m]	**width** [m]	**long. stiff**
keel plate	12	1200	1 x HP 100x7
from keel to 2 m from CL	10	1411.2	2 x HP 100x7
from 2 to 5.7 m from CL	10	3728.1	7 x HP 100x7
from 5.7 to 9.416 m from CL	10	4056.9	7 x HP 100x7
side shell-bilge	13	1781.8	-
side shell	10	3074.1	transverse
inner bottom CL to 2m	9	2000	3 x HP 120x7
inner bottom 2m to 5.7m	9	3700	7 x HP 120x7
inner bottom 5.7m to 9.416m	8.5	3716	7 x HP 120x6

Table 6.11: plating and stiffners for sheel and double bottom

The HP profiles listed in the table for each panel are all equally spaced one from the other of 500 mm. (fig.6.19). Three double bottom girders of 8 mm each, are located delimiting the tanks as can be seen from fig. 6.19 and in more details in fig.6.20.

Lower Deck

	thickness [m]	**width** [m]	**long. stiff**
from CL to 2.5m	6	2500	4 x FB 50x6
from 2.5m to 5.7m	6	3200	6 x FB 50x6
from 5.7m to side-shell	6	4321	8 x FB 50x6

Table 6.12: plating and stiffners for sheel and lower deck

The longitudinal girders, at the lower deck, are located at center-line (CL), at 2500 mm form CL and at 5700 mm from CL. They are of the 'T-bar' type and characterized by the following dimensions: *T 440x10/200x20*.

Main Deck

	thickness [m]	**width** [m]	**long. stiff**
from CL to 2.5m	6	2500	4 x FB 50x6
from 2.5m to 5.7m	6	3200	6 x FB 50x6
from 5.7m to side-shell	6	4321	8 x FB 50x6

Table 6.13: plating and stiffners for sheel and main deck

The longitudinal girders, at the main deck, are located at the same positions of the ones at the lower deck with the same properties. The transverse side web with a space framing of 700 mm is a *HP-profile 200x10*, while both at lower and main deck the web frames are *HP-profile 100x7*.

6.7.4. Hull-Girder Strength

To check the **bending strength**, the effective geometric properties of the midship section are to be calculated directly from the dimensions of the section using only the effective material elements which contribute to the global longitudinal strength irrespective of the grades of steel incorporated in the construction. For the purpose of this analysis an element may be of deck plating, longitudinal girder, inner bottom, etc. or other continuous member. Since the vessel is considered sailing in displacement mode,

$$\Gamma = \frac{V}{\sqrt{L_{WL}}} = 2.53 < 3 \tag{6.11}$$

The longitudinal strength of the vessel is to satisfy both the following criteria:

$$\sigma_k < \sigma_p \tag{6.12}$$

$$\sigma_d < \sigma_p \tag{6.13}$$

Where σ_p is the maximum permissible hull vertical stress, in N/mm^2:

$$\sigma_p = f_{\sigma gH}\sigma_s = 0.72 \cdot 235 = 169.2 \qquad \left[\frac{kN}{m^2}\right] \tag{6.14}$$

with $f_{\sigma gH}$, limiting hull bending stress coefficient that for bending is equal to: $0.72 \cdot \eta_{HTS}$.

Since from the analysis of previous subsection it came up that the departure (full) loading condition was the one characterized by the maximum value of *Still Water Bending Moment*, that one was taken as reference for proceeding with the calculation. From eq. 6.3 it is possible to find the value of Rule Bending Moment (eq. 6.7). Here below definitions of the hull girder bending stress at strength *deck amidship* (σ_d) and at the *keel* (σ_k) form the Regulation:

$$\sigma_d = \frac{M_R}{1000 Z_d} \tag{6.15}$$

$$\sigma_k = \frac{M_R}{1000 Z_k} \tag{6.16}$$

In which the *actual section modulus* at the main deck (Z_k) and at the keel (Z_k), was calculated based on the following:

$$Z_d = \Phi_Z \frac{psl_e^2 Ks}{f_\sigma 235} = 1,306 \;\; [m^3] \tag{6.17}$$

$$Z_k = \Phi_Z \frac{psl_e^2 Ks}{f_\sigma 235} = 1,727 \;\; [m^3] \tag{6.18}$$

Thus, by combining eq. 6.17 and eq. 6.18 with eq. 6.15 and eq. 6.16, by substituting the value of M_R found in eq. 6.7, both the criteria result fulfilled:

$$\sigma_d = 152.97\left[\frac{kN}{m^2}\right] < \sigma_s = 169.2\left[\frac{kN}{m^2}\right] \tag{6.19}$$

$$\sigma_k = 115.68\left[\frac{kN}{m^2}\right] < \sigma_s = 169.2\left[\frac{kN}{m^2}\right] \tag{6.20}$$

Additionally, *sec.2.3* of the same regulation, defines a **minimum hull section modulus** given by equation 6.21.

$$Z_{min} = \eta_{HTS} L_f L_R^2 B_{WL}(C_b + 0.7) \cdot 10^{-6} = 1.814 \;\; [m^3] \tag{6.21}$$

with which the vessel should be compliant. Indeed, considering the overall section modulus (at deck and keel), the requirement is achieved as illustrated below:

$$Z_{min} = 1.814 \; [m^3] < Z_d + Z_k = 3.033 \; [m^3] \tag{6.22}$$

Finally, the criteria regarding the **shear strength** summarized by equation 6.23:

$$\frac{Q_R}{A_\tau} 10^{-3} \le \tau_p \tag{6.23}$$

Where Q_R is the design hull shear force at any section along the Rule length defined in eq. 6.4. A_τ as stated in the regulation, is the *shear area* of transverse section, in m^2, is to be taken as the effective net sectional area of the shell plating and longitudinal bulkheads after deductions for openings. For longitudinal strength members which are inclined to the vertical, the area of the member to be included in the calculation is to be based on the area projected onto the vertical plane. Finally, τ_p is the maximum permissible shear stress and similarly to the maximum permissible *hull vertical stress* is defined as:

$$\tau_p = f_{\tau gH}\tau_s = 0.72 \cdot \frac{\sigma_s}{\sqrt{3}} = \frac{235}{\sqrt{3}} = 97.69 \quad \left[\frac{kN}{m^2}\right] \tag{6.24}$$

with $f_{\tau gH} = 0.72 \cdot \eta_{HTS}$.

The check of the shear force is done at the main frame, where the maximum moment occurs but also with the maximum shear force registered for a further check.

The value of A_τ was found equal to 0.150 m^2, thus at midship:

$$\frac{Q_R}{A_\tau}10^{-3} \leq \tau_p = \frac{4233.2}{0.150}10^{-3} \leq 97.69\left[\frac{kN}{m^2}\right] = 28.22\left[\frac{kN}{m^2}\right] \leq 97.69\left[\frac{kN}{m^2}\right] \tag{6.25}$$

and with the maximum value of Q_R occurring:

$$\frac{Q_R}{A_\tau}10^{-3} \leq \tau_p = \frac{6070.7}{0.150}10^{-3} \leq 97.69\left[\frac{kN}{m^2}\right] = 40.47\left[\frac{kN}{m^2}\right] \leq 97.69\left[\frac{kN}{m^2}\right] \tag{6.26}$$

Due to a failure on the buckling assessment, the initial plate thickness of the main deck was increased from 6 to 8 mm, even if the longitudinally framed structure increases the ability to resist globally induced buckling. The detailed drawing of the main frame is shown in fig. 6.20.

The vessel type is of primary importance when choosing the kind of frame. The routing of services, particularly large diameter horizontal HVAC ducting in deck heads, can be very challenging on yachts. This can drive the scantlings of the structure, particularly on longitudinal framed decks, well above those required from a pure strength perspective.

On the other hand, one advantage of a transversally framed side shell is the ability to route larger services vertically within the hull side linings. The side shell is one area where transverse framing can offer advantages. The deep web frames required for longitudinal framing can impact the accommodation, reducing internal space, and increasing recess depths in way of hull windows etc. In addition, since the transverse hull side frames only have to support a modest plate area, it is easier to incorporate and manage late design changes in window and port light positions which seems an inevitable part of the stylist's GA development.[25]

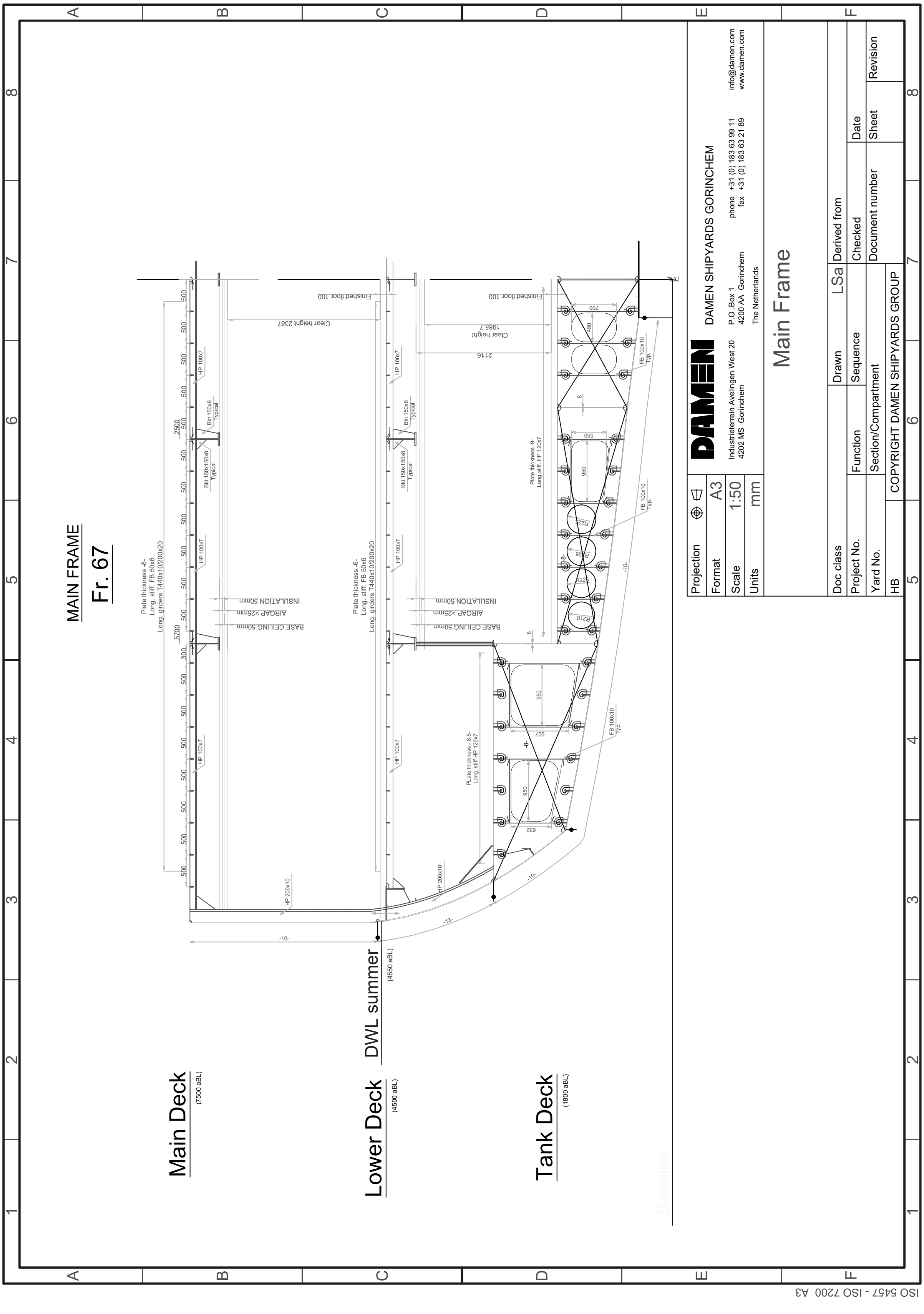


Figure 6.20: Main Frame details

6.8. General Specifications of *YS 9820*

It goes without saying that the level of details of the actual design is not comparable with a complete concept proposal and there is obviously room for improvements especially regarding some aspects such as: more accurate stability checks, including a damage stability calculation and an inclining test for the tenders deployment, or a sea-keeping assessment, to name but a few. However, the essential points for the feasibility of the preliminary design were examined, seeking to achieve the requirements listed in the Design Brief.

Basic function Yacht Support Vessel

Description The Damen Yacht Support 9820 is meant to represent the ultimate level of this vessel type, emphasizing and taking to extremes and all her typical features.
The vessel can be operated as a means to assist the largest 'top-ten' type existing Mega-yachts, but might also operate independently since is characterized by several Superyachts virtues (i.e. sauna, swimming pool, Guest accommodation).
The nature of the ship is summarized by the following list of qualities and capabilities:

- Transportation of tenders, toys, spares, fuel, food supplies
- Transportation of on and off-watch crew/ supernumeraries/ staff/ guests
- Considerable waste handling capabilities
- Fully certified helicopter operations with dedicated helicopter hangar
- Transportation of guests from helicopter deck to/ from mother yacht
- Supporting diving operations through a dedicated diving center, equipped with normal breathing air, Nitrox, mixed gas and decompression chamber. In addition, to further assist diving activities it can carry as a tender a purposeful boat: *Newton 36 dive special*.
- Guarantee ultimate submersible operations with two type of submarines.
- Greatest refueling facilities for all tenders, toys and helicopter operations.
- Advance deployment of water toys so that they are ready before guests arrive and no waiting before guests depart

Classification Society The vessel will be built under supervision of and according to the class notations of Lloyd's Register with the following notation:

Notation ✤100 A1, SSC, Support Yacht Craft, Mono, G6, ✤LMC, UMS, ECO.

Flag state authorities Marshall Islands - LY3 certified Helicopter landing Area

Main dimensions

Properties	*Value*
Length overall	98.00 m
Length over waterline	98.00 m
Beam Moulded	20.00 m
Depth at Side	7.50 m
Draught (Full Load Midship)	4.50 m
Gross Tonnage	app. 4100 GT
Speed (maximum)	25 kn
Speed (cruising)	18 kn
Range @ 18 kn	6000 Nm

Table 6.14: Main Dimensions

Capacity

Items	*Value*
Crew	25 persons + Captain
Staff	20 persons
Guests	8 persons
Fuel Capacity	app. 740000 Liters
Fresh Water Capacity	app. 70 Liters
Dead Weight Cargo	app. 1300 tonnes
Free Outside Deck Space	780 square meters
Tenders & toys fuel	app. 40 Liters
Crane Capacity	15.680 tones @ 13.00 meters
Helicopter MTOW	11000 kg
Aviation Fuel	app. 40 Liters

Table 6.15: Capacity

Environmental Conditions The Yacht's machinery and equipment are capable of safe operation under the following conditions:

- Seawater temperature: +5 up to +32 $°C$
- Outside air temperature: +0 up to +35 $°C$

Construction The hull is constructed from marine marine grade A steel. The first tier superstructure is built from marine grade A steel. The second and third tier superstructure are built from marine grade aluminum.

Propulsion and technical Installation The Yacht is propelled by a WARP (Water-jet and Refined Propellers) configuration. Two bow thruster are fitted to improve maneuverability:

Items	*Type*	*Value*
Wing Engines x 2	W 14V31	8450 kW
Propellers x 2	CP	3.3 m
Main Central Engine x 1	LM 2500	22000 kW
Water-jet x 1	LJX 2180B	Transom Flange 2.790 m
Bow-thruster x 2	BU50	315 kW

Table 6.16: Propulsion characteristics

Electrical Installation For the electrical generation the following generator sets are provided:

Items	*Type*	*Value*
Main Generator Sets	3 x C18	3 x 465 bkW
Emergency Generator Set	1 x C18	599 bkW

Table 6.17: Electrical Installation

Deck Hoisting Equipment Two main cranes installed on a supporting structure provided by rails that allow a flexible use. Overhead cranes for ribs and cigarettes located in their dedicated spots. Two lifeboats with specific davits.

Items	*Type*	*Value*
Main Cranes x 2	AKC 290 LHE2	15680 kg @ 12.98 m
Overhead cranes x 7	SL-18691 DEX	5000 kg @ 7.6 m

Table 6.18: Deck Hoisting Equipment

Helicopter Operations An LY3 certified helicopter landing deck is positioned in the aftermost part of the ship. By means of a lift platform and sliding covers on the helideck, the helicopters can be lowered into a weather-tight hangar on main deck.

Properties	*Value*
Max Take-off weight	11000 kg
Max helicopter D value	19.5 m

Table 6.19: Helicopter Operations

Accommodation The list of spaces included at each deck level.

Tank deck :

- Technical service space
- Fuel Storage
- Garbage stores
- Freeze stores
- Laundry facilities
- Stores

Lower deck :

- Guest boarding area
- Diving facilities
- Workshop
- Toys garage
- Storage Spare parts
- Crew Gym
- Crew Mess
- Galley
- 15 Cabins
- Hospital

Main deck :

- Garage
- High-ratings office
- 11 Cabins

Upper deck :

- Hammam + Guest Gym
- Guest Lounge
- 4 Guest Cabins

General Arrangement The final General Arrangement of the vessel is drawn below in fig. 6.21:

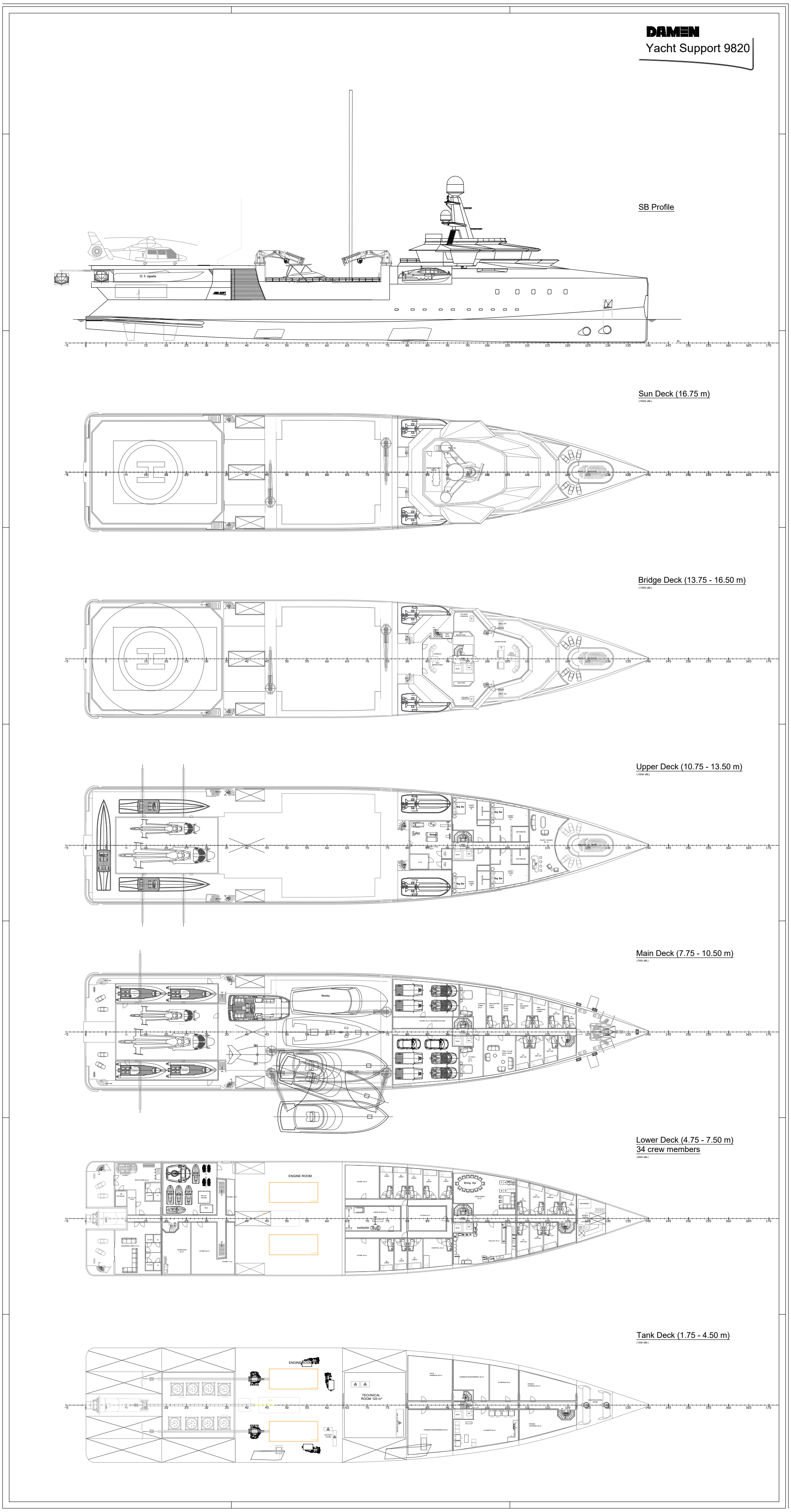


Figure 6.21: General Arrangement *YS* 9820

7 Conclusions

The previous chapter ended with the delineation of characteristics of the *YS 9820* that, being compliant with all the non-negotiable requirements, demonstrates the final reached goal. By including the packing approach within the used design process, limitations and potential problems that might show when using this tool were highlighted. In particular, the performances of packing when facing the specific design problem of the 90 meter yacht support revealed to be not completely adequate. Several are the potential reasons and explanations that brought to this conclusion and this chapter will summarize them.

A way to proceed might consist in gradually answering the research questions stated during the Introduction, starting from the primary one:

- Will this study reveal a feasible and even unexpected design solution that satisfactorily meets the requirements of the new 90 meters Yacht Support? Primarily, being able of sailing at a maximum speed of 25 knots while satisfying the spatial conflict?

  The resulted final design from the overall study (*YS 9820*) represents a satisfactory design solution. All the non-negotiable requirements are, indeed, included in this concept. However, considering the packing model (YS 9822) from which the *YS 9820* was born, the differences between the two are substantial. It needs to be recognized that the packing outcome required considerable changes and improvements before reaching the final result. Thus, for the shortest length (about 100 m), the model expressed a tendency in creating trade-offs which were proved to be not necessary when increasing the level of details. The differences between the two results are partly due to better knowledge gained during the development of the project:

  - Difference in performance parameters, such as different value of the chain of efficiency for power request.
  - Difference position definition for some of the systems modeled (fuel in the double bottom, more freedom to tenders and toys, helicopter-related spaces).

  On the other hand, also aspects more strictly linked to packing limitations contribute to the large gap between the selected packing outcome and the final vessel resulted from the design spiral, such as:

  - The lower level of details that the tool is able to deal with, implying the presence of many void spaces (at least in the concept selected, the YS 9822).
  - The limited capability of packing of handling many *hard* objects free of moving.

  The second group of issues would probably resulted to be less marked if the choice would have fall on a longer, more densely packed, and more complete design (i.e. one of the solutions of about 120 m). Additionally, if that was the case, less differences regarding the design brief assessment would have been registered compared to the packing solution within 100 m.

  About the final general arrangement, it strongly resembles the one of the existing concepts (smallest DAMEN ranges). Indeed, the overall disposition of the three main macro-areas identifying the vessel provides: helicopter features on the stern of the vessel, large open working-deck at midship and accommodation and recreational area mainly in the bow. This outcome, refers partly to a *systems definition*, during the modeling phase, but also to a specific will from the company of not choosing a layout with heli-related spaces at midship and working-deck areas on the extreme aft (see sec. 4.3.2). The presence of only few very different designs can be explained by the fact that the author, while building the model, was considerably influenced by existing layouts. Thus, constraining and driving the multitude of *systems* to certain areas, a large percentage of the mathematical solutions were coming closer to a similar space distribution to previous Damen Yacht Support Vessels, somewhat limiting the possibility of having 'unexpected' or more original solutions. This issue was also highlighted while describing the reflections about packing where was emphasized the conflict between the tendency of already 'designing' the ship while creating the mathematical model and giving to the software the freedom of creating different solutions. The risk consists, indeed, in over-constraining systems constituting the *SSM* with excessive packing rules.

The considerable speed demand of sailing at a maximum speed of 25 knots was achieved by means of a *WARP* propulsion configuration. In this perspective, as expected, the substantial power installed was a crucial requisite in order to satisfy the demand. This need was primarily caused by the hard constraint on the length of the vessel, that forced the ship on being 'locked' at an unfavorable Froude number. Regarding this aspect, packing revealed what is already widely known to ship designers and hydrodynamic specialists, that by enlarging the length of the vessel, less power would be required to meet a high maximum speed (see section 4.6). The model showed that generally lower amount of power where required compared to the final outcome from the design spiral, because of the difference in efficiencies.

- Is packing a good tool to study the defined problem?

  With the actual setting of the *systems* describing the Yacht Support, the tool did not provide a satisfactory result, showing limitations when hard space constraints are combined with demanding requirements.

- Will this study help in defining the limits of the packing-tool ship description thanks to the application on this new kind of vessel?

  The application of packing to this specific case study, proved and confirmed some limitations already known regarding the generation of larger vessels compared to the desired ones. In addition, a limit of packing might be addressed to its capacity of dealing with *hard* objects. The decision of modeling many of this objects (i.e. tenders) singularly, with the intent of finding more different and unusual dispositions, was complicating the packing process of converging to feasible designs. In addition, it also goes against the common sense of having all these items close together in order to later optimize the deploying systems; that is why modeling the total amount of area (i.e working deck, garage) where later storing single items, appears to be beneficial in the end.

Strongly linked with all the consideration drawn until now, is the expertise of the designer/ naval architect who approaches the modeling phase. Their *know-how* about the type of vessel they are going to design, in term of rules and regulations which the vessel need to comply with, or understanding and knowledge of the systems they are going to consider in their concept and that should also be properly modeled in the *SSM*, are crucial for more satisfactory results.

In addition, even if it is recognized that *Matlab* environment is amongst the most intuitive coding language and it is relatively short the time required to get familiar with it, an improvement that might be considered for making the use of the tool handier, would be creating an interface to make the software more user-friendly without the need of coding skills.

Nonetheless, approaching the modeling phase a second time would result to be quicker and easier. In this perspective, would be interesting and attractive to try packing again for the same ship design problem mainly for investigating 'unexpected' results due to more relaxed constraints for the major systems.

Appendices

A

Top-10 Super-yachts

In order to understand which are the potential mother vessels the yacht support should be able to assist, an investigation on the top 10 existing Super-yachts explains their characteristics, pointing the attention on their speed and dimensions.

AZZAM

Figure A.1: AZZAM

Length	180.60 m
Beam	20.80 m
Draft	4.30 m
Speed	30 knots

Table A.1: AZZAM Specs

ECLIPSE

Figure A.2: ECLIPSE

Length	162.50 m
Beam	22.00 m
Draft	5.90 m
Speed	25-22 knots

Table A.2: ECLIPSE Specs

DUBAI

Figure A.3: DUBAI

Length	162.00 m
Beam	22.40 m
Draft	5.00 m
Speed	24-22 knots

Table A.3: DUBAI Specs

DILBAR

Figure A.4: DILBAR

Length	156.00 m
Beam	24.00 m
Draft	6.10 m
Speed	23-18 knots

Table A.4: DILBAR Specs

AL SAID

Figure A.5: AL SAID

Length	155.00 m
Beam	24.00 m
Draft	5.20 m
Speed	22.9-19.5 knots

Table A.5: AL SAID Specs

TOPAZ

Figure A.6: TOPAZ

Length	147.25 m
Beam	21.50 m
Draft	- m
Speed	22.9-19.5 knots

Table A.6: TOPAZ Specs

PRINCE ABDULAZIZ

Figure A.7: PRINCE ABDULAZIZ

Length	147.00 m
Beam	18.30 m
Draft	4.88 m
Speed	22.0-18.2 knots

Table A.7: PRINCE ABDULAZIZ Specs

SAILING YACHT A

Figure A.8: SAILING YACHT A

Length	142.80 m
Beam	24.90 m
Draft	8.00 m
Speed	21 knots

Table A.8: SAILING YACHT A Specs

YAS

Figure A.9: YAS

Length	141.00 m
Beam	15.00 m
Draft	4.30 m
Speed	26 - 20 knots

Table A.9: YAS Specs

OCEAN VICTORY

Figure A.10: OCEAN VICTORY

Length	140.00 m
Beam	18.60 m
Draft	5.56 m
Speed	24 - 18 knots

Table A.10: OCEAN VICTORY Specs

B
Analysis of Competitors

In this appendix are listed the principal competitors found during the market research. For each vessel are reported a representative image together with short specs.

JFA YACHT

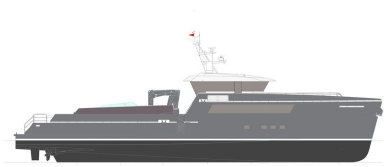


Figure B.1: JFA 40 meters [45]

Length	42.24 m
Beam	8.6 m
Draft	2.5 m
Displacement	285 tons
Engines	2 x 2895 Hp MTU
Gen-set	2 x 80 kW Kohler
Speed (max - cruise)	22.5 - 20.0 knots
Range	4000 nm @ 14 knots

Table B.1: JFA 40 meters

ATLAS

Figure B.2: ATLAS concept

Length	44.00 m
Beam	14 m
Draft	2.8 m
Displacement	550 tons
Engines	2 x 2360 Hp CAT
Gen-set	-
Speed (max - cruise)	20.0 - 17.0 knots
Range	6000 nm @ 17 knots

Table B.2: ATLAS concept

LYNX

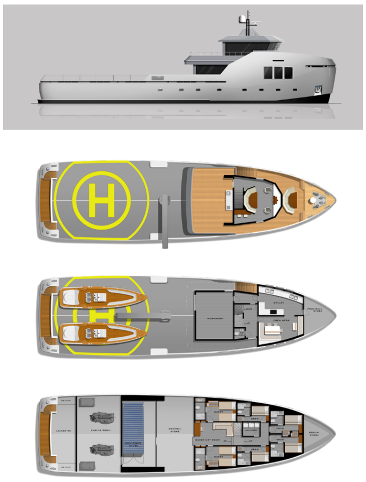


Figure B.3: Lynx 36 [46]

Length	35.50 m
Beam	9.50 m
Draft	2.30 m
Displacement	280 tons
Engines	2 x 1200 kW CAT C32 Acert
Gen-set	2 x 80 kW
Speed (max - cruise)	17.0 - 15.0 knots
Range	1300 nm @ 15 knots

Table B.3: Lynx 36

DORRIES YACHTS

Figure B.4: Dorries 60 - meters conscept [28]

Length	50.00 m
Beam	17.30 m
Draft	2.30 m
Displacement	450 tons
Engines	2 x 1765 bkW + 2 jets kW
Gen-set	2 CAT C9 200 ekW
Speed (max - cruise)	22.0 - 20.0 knots
Range	5000 nm @ 22 knots

Table B.4: Dorries 60 - meters conscept

MARCELLO PENNA YACHT DESIGN

Figure B.5: Marcello Penna - YSV [6]

Length	50.00 m
Beam	17.30 m
Draft	2.30 m
Displacement	450 tons
Engines	2 x 1765 bkW + 2 jets kW
Gen-set	2 CAT C9 200 ekW
Speed (max - cruise)	22.0 - 20.0 knots
Range	5000 nm @ 22 knots

Table B.5: Yacht Shadow Vessel

PIRIOU Shipyard

Figure B.6: PIROU 40 meters YSV [3]

Length	40.00 m
Beam	8.20 m
Draft	2.10 m
Displacement	-
Engines	2 x 1007 kW
Gen-set	2 x 110 kVA
Speed (max - cruise)	25.0 - 18.0 knots
Range	5000 nm @ 14 knots

Table B.6: PIROU 40 meters YSV

Figure B.7: PIROU 53 meters YSV [3]

Length	53.40 m
Beam	10.00 m
Draft	2.50 m
Displacement	-
Engines	2 x 1200 kW
Gen-set	2 x 178 kVA
Speed (max - cruise)	30.0 - 20.0 knots
Range	5000 nm @ 17 knots

Table B.7: PIROU 53 meters YSV

Figure B.8: PIROU 63 meters YSV [3]

Length	62.50 m
Beam	12.50 m
Draft	3.90 m
Displacement	-
Engines	2 x 1200 kW
Gen-set	2 x 178 kVA
Speed (max - cruise)	21.0 knots
Range	5000 nm @ 17 knots

Table B.8: PIROU 63 meters YSV

ULSTEIN

Figure B.9: ULSTEIN PX 129 [40]

Length	63.00 m
Beam	15.00 m
Draft	4.90 m
Displacement	2100 tons
Engines	-
Gen-set	-
Speed (max - cruise)	12.0 knots
Range	5000 nm @ 17 knots

Table B.9: ULSTEIN PX 129

Figure B.10: ULSTEIN PX 130 [40]

Length	73.00 m
Beam	17.50 m
Draft	5.70 m
Displacement	3500 tons
Engines	-
Gen-set	-
Speed (max - cruise)	13.0 knots
Range	5000 nm @ 17 knots

Table B.10: ULSTEIN PX 130

EVOLUTION YACHT & SHIP

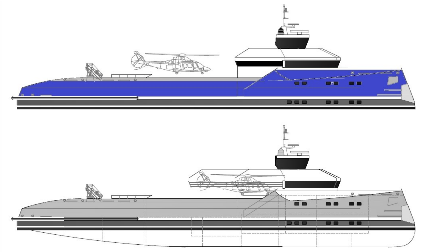


Figure B.11: Indipendence EYS concept

Length	58.00 m
Beam	9.00 m
Draft	-
Displacement	-
Engines	-
Gen-set	-
Speed (max - cruise)	18.0 / 14.0 knots
Range	5000 nm @ 17 knots

Table B.11: Indipendence EYS concept

ARESA Group International

Figure B.12: ARESA Group concept [23]

Length	30.00 m
Beam	7.50 m
Draft	-
Displacement	-
Engines	-
Gen-set	-
Speed (max - cruise)	25.0 / 20.0 knots
Range	-

Table B.12: ARESA Group concept

NEDSHIP GROUP

Figure B.13: NEDSHIP Group concept [19]

Length	79.00 m
Beam	13.40 m
Draft	4.00 m
Displacement	-
Engines	-
Gen-set	-
Speed (max - cruise)	-
Range	-

Table B.13: NEDSHIP Group concept

SOLUTIONS FROM THE REFIT-MARKET

GOLDEN SHADOW

Figure B.14: Golden Shadow [17]

Length	66.70 m
Beam	11.80 m
Draft	4.30 m
Gross Tonnage	1293 GT
Engines	2 x 1500 kW
Gen-set	-
Speed (max - cruise)	16.5/ 15.5 knots
Range	6500 nm @ 15.5 knots

Table B.14: Golden Shadow

Shadow Support Yacht SURI

Figure B.15: SY Suri [43]

Length	63.70 m
Beam	11.58 m
Draft	3.35 m
Gross Tonnage	1500 GT
Engines	2 x 820 kW
Gen-set	-
Speed (max - cruise)	12.0/ 10.0 knots
Range	6500 nm @ 15.5 knots

Table B.15: Suri

SPUTNIK

Figure B.16: Sputnik

Length	60.00 m
Beam	16.80 m
Draft	4.84 m
Gross Tonnage	1620 GT
Engines	-
Gen-set	-
Speed (max - cruise)	-
Range	-

Table B.16: Sputnik [7]

KARINA

Figure B.17: Karina

Length	55.17 m
Beam	9.00 m
Draft	3.10 m
Gross Tonnage	-
Engines	-
Gen-set	-
Speed (max - cruise)	21.3/ -
Range	-

Table B.17: Karina

C
Design Brief

This appendix reports the full document representing the Design Brief.

Main Dimension and Persons on board
The overview of the main dimensions, spaces and other features the Yacht Support needs to have, comes next. Some of the dimensions are given between a range, in view of the nature of 'packing' of varying those while creating different design options. Yet, not all the numbers in the table reflect the set in the calculations because several attempts were carried out with more wide range of values for *Length* and *Beam* due to the tendency of the program of better dealing with less constrained problems.

Length	90-99 meters
Beam	13-20 meters
Draught max.	5 meters
Guest	8 pers.
Crew	46 pers.
Maximum - Cruise speed	25 - 18 knots
Range	6,000 nautical miles

Table C.1: Yacht Support main characteristics

The *Draft* should not exceed 5 meters considering the possibility to closely reach remote and undiscovered bays, compensating for the limitation of the large mother yacht value (Draft max = 6.5 m). Other considerations on main dimensions regarded the maximum length, which should not exceed 100 meters.

Accommodation

No	Type	Occupancy	Total cabins	m^2
1	Captain	1 p	1	17
1	1st officer	1 p	1	9
1	Chief engineer	1 p	1	9
1	2nd Engineer	2 p	1	9
2	Helicopter Pilots	2 p	1	18
20	Crew	2 p	10	90
8	Staff heli	2 p	4	36
12	Staff toys	2 p	6	54
46	tot.		25	242
8	Guests	2 p	4	120

Table C.2: Accommodation

Hull form
The starting point for the algorithm regarding the hull form is obtained scaling the fast Yacht Support *YS 6911* kindly provided by Damen. Stretching the length from 69m up to 95m and widening the beam from 11m to 16.

The *3dm.* file in Rhinoceros gave place to a table of offsets from the centerline representing the distances from the middle plan (beams at different frames) that 'packing' can use to wrap the hull.
The high-speed requested and the will of making some designs as realistic as possible, made the choice to fall on this platform rather than others.

Range and Speed
The maximum speed of the vessel need to be 25 $knots$ exceeding the speed of the assisted Super-yacht (22 $knots$). In addition, being the range of the mother yacht 6000 nm, consequently the Yacht Support need to have the same endurance capability, at a speed of 18 $knots$.

Ambient and Environmental Conditions The YS will assist her 140-meter mother yacht that will tend to operate in various conditions including Tropical area. The range of weather conditions are thus:

- Outside air: 0 - 45 deg.
- Relative Humidity: 75% at 35 deg.
- Seawater: 0 - 32 deg.

A note regarding the climate in which the vessel will operate is that the eventual use of gas turbines could be compromised by the significant high environmental temperature.
The vessel will be designed to be capable of facing worldwide operations except the exploration of Polar Regions.

Operational Profile
Once the average power required from the resistance estimation is known, it is crucial the definition of the operational profile of the Yacht Support before thinking at which power plants configurations may be suitable. The selection of the most appropriate propulsion system depends on the vessel platform and the intended mission profile.
Resuming the correspondent requirements previously defined:

- top speed: 25kn
- range at 18 knots: 6000nm

And analyzing the running hours per year it is possible to identify the following activities:

1. Sailing: 2000 hrs/yr
2. Anchor: 2000 hrs/yr
3. Port: 4700 hrs/yr

By dividing the correspondent sailing hours per year according to the operational profile of the vessel, they can be characterized as follow:

Operation	Time(%)	Speed (knots)
Overtaking	10% time (2000 hrs/yr.)	25 knots
Crossing (i.e. Ocean)	50% time (2000 hrs/yr.)	18 knots
Economic cruising	30% time (2000 hrs/yr.)	15 knots
DP/ Manuovr./ stand-by	10% time (2000 hrs/yr.)	0 knots

Table C.3: The sailing activity

Dynamic Positioning The vessel will have a DP 0 system, it should be counted for the power requirement.

Roll-reduction System Fin stabilizers will provide a better stability while sailing to reduce the risk of accident due to the transport of heavy cargo (toys and tenders) and during the stationing for facilitating the leisure-related activities. The exact type of Fin-stabilizers need to be evaluated based on values of GMt and other stability informations. For this reason, a rough estimate on their dimension and weight was set upfront based on a dimension comparison with the *YS 6911*.

Garbage Management A garbage treatment plant will be included in the design, stores should be included both for standard and cold garbage, based on *IMO Guidelines MEPC.220(63) - ANNEX 25 RESOLUTION MEPC.220(63) Adopted on 2 March 2012 2012 GUIDELINES FOR THE DEVELOPMENT OF GARBAGE MANAGEMENT PLANS*, containing procedures on:

1. garbage minimization
2. garbage collection
3. garbage storage
4. garbage processing
5. garbage disposal
6. equipment used onboard for handling of garbage
7. the designation of the person or persons in charge for implementing the Garbage Management Plan

The area required the garbage store has to be large enough to collect also the garbage of the mother yacht. For this purpose, the basis is the same space of the *Rainbow Fish - RBF* (another DAMEN concept) and it has been further enlarged by 125%, with a total square meter of 150 m^2.

Helicopter facilities
On the over-90 meters Yacht Support the request consisted in an helideck which can sustain heavy and big helicopters. Should be included an enclosed hangar that can lodge them to satisfy the most demanding need of fast mobilization. The two helicopters are:

1. Heavy-duty helicopter: H225
2. Medium-duty helicopter: H155

Section 2.4 extensively dives into the regulations required for properly designing a safe and fully certified landing area. The high impact that these helicopter-related spaces have on the overall design together with the high conflict these systems have with the other main characteristic of the vessel, prompts for a careful study on the options that can be considered in later sections.

Helicopter- Fuel storage: about $50m^3$ of petrol for the helicopter need to be stock in a dedicated space, which should be preferably close to the hangar to facilitate refuelling. The store will be built in compliance with the SOLAS *Chapter II-2: Construction – fire protection, fire detection and fire extinction.*

Toys & Tenders characteristics
The other predominant characteristic of the ship shall be her huge carrying capacity that directly translates in square meters available to store tenders and toys. The list of all the toys and tenders required gives an idea of the immense space required for these and consequently subtracted to accommodations, technical space, stores etc.

No.	Type
1	Hinckley Talaria 55 M/Y
1	Sport fisher Viking 62c
1	Fast Carbon S/Y
1	Newton 36 dive special
3	Cigarette 50' Marauder
3	Ferrari
1	Hummer
6	Volswagen newbeetle
1	mini-sub MIR
1	mini-sub Triton 1000/4
1	SAAB ROV seaeye Jaguar
3	8 meters Ribs
10	Jet-ski
10	Sea-bobs
1	inflatable Island

Table C.4: List of Tenders and Toys

The area required to store these items will be carefully analyzed in section 2.5.

Toys & Tenders - Fuel storage: Having so many vehicles imply the presence of a dedicated space that can contain approximately $50m^3$ of petrol. It shall be located preferably close to the hangar following similar regulation characterizing the helicopter-fuel storage.

Relevant Spaces

Hospital The hospital will have the capacity of two bed (20 m^2), and might be positioned as close as possible to the hangar so that in case of emergency the patient can more easily reach the helicopter to be transferred on the closest hospital ashore. From the *Maritime Labor Convention Standard A3.1 – Accommodation and recreational facilities*, with respect to requirements for hospital accommodation, ships carrying 15 or more seafarers and engaged in a voyage of more than three days' duration shall provide separate hospital accommodation to be used exclusively for medical purposes; the competent authority may relax this requirement for ships engaged in coastal trade; in approving on-board hospital accommodation, the competent authority shall ensure that the accommodation will, in all weathers, be easy of access, provide comfortable housing for the occupants and be conducive to their receiving prompt and proper attention.

Spare-parts store Around 200 m^2 for storing all kind of spare parts related to such a big vessel and the even larger part coming from the mother yacht. This large area, conceived as only one unique entire space is a huge space on board, which hardly will find a good location and logistic. As consequence, this area will most likely be separated into smaller spaces. Some of these rooms will be close to the area of operation, were storing toys and tenders, others will be probably find different location.

Workshop Located between the main and the lower deck, and the aft-mid ship zone in such a way that it will be effective for fixing operation on toys, the space dedicated to the workshop is around 50 m^2.

Ampelman Access Considered as negotiable requirement, an Ampelmann access might be installed on the vessel to facilitate the transferring of persons (crew, staff, guests), directly from Yacht Support to mother yacht, without the need of taking a tender.

Looking at the sea state in which the Yacht Support should operate (the Caribbean sea it has been taken as example), one can decide which type of Ampelmann access installing on board. Indeed, the choice of this device is made based on the significant wave height of the relative sea state. The picture below reports the Wave Height (ft)/ Wind Direction, Smaller wave heights are shown in blue hues and larger wave eights are shown in yellow and red hues. The improved L-type features electro-mechanical actuation of four key axes, is able to transfer personnel up to 2.0 m significant wave height and allowing continuous flow of people 50 pax/5min. [4]

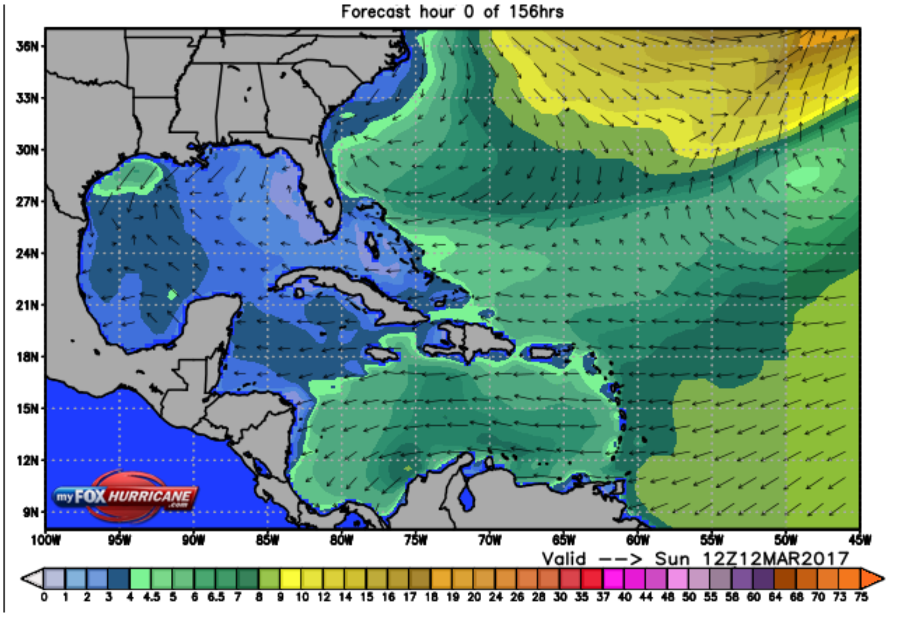


Figure C.1: Diverse engine room layouts rule out the design space [31]

'Luxury' Spaces
Hammam complex The Hammam complex including:

- Massage room
- Steam room
- Sauna

Will be built following the *SOLAS Chapter II-2: Construction – fire protection, fire detection and fire extinction.*

Large Guest-Gym a minimum of 50 m^2 will be accounted for, considering that one machine is 2 x 1 m.

Guest Lounge The guest deck, in addition to the 4 guest rooms, need a deluxe and bright lounge space personalized by a nice 180-degree view either looking at aft or forward ship.

Boarding Platform A comfortable boarding platform will assist the embarkation and disembarkation of guest and eventually owner. To satisfy this need a side or back opening of the hull, already conceived for deployment of one of the heaviest toy, can serves the purpose.

Swimming Pool The 24 m^2 should be placed on the upper deck at the same level of the guest accommodation for both enjoy a nice view while being easily accessible from the person who are going to benefit from it. However, considering 1.5 m depth, the swimming pool will contain around 36 liters of water for a weight of 36 tons. Therefore, the location is critical because a large pool on an upper deck creates a weight issue that can interfere with the boat's stability and center of gravity. Some influence on survivability in case of flooding could be given by draining swimming pools but even if it is a large pool, it will probably not be so relevant on the overall weight contribution. If the swimming pool can be drained out in less than 3 minutes, it should not be taken into account in the stability calculations anyway.

Diving Center Placed on the lower deck in the proximity of the embarkation platform to facilitate the movements of equipment when going for diving. It include:

- Oxygen storage
- Decompression chambers
- Storage area for 10 sets of scuba gear.

Will be build accordingly to IMO – international code - Code of Safety for Diving Systems, 1995. The decompression chamber need to be as close as possible at the embarkation point so that the divers can easily and quickly have access to it.

Lifeboats 2 luxury lifeboats: SEL-T 10.75 with dedicated davits.

D

Tank Arrangement

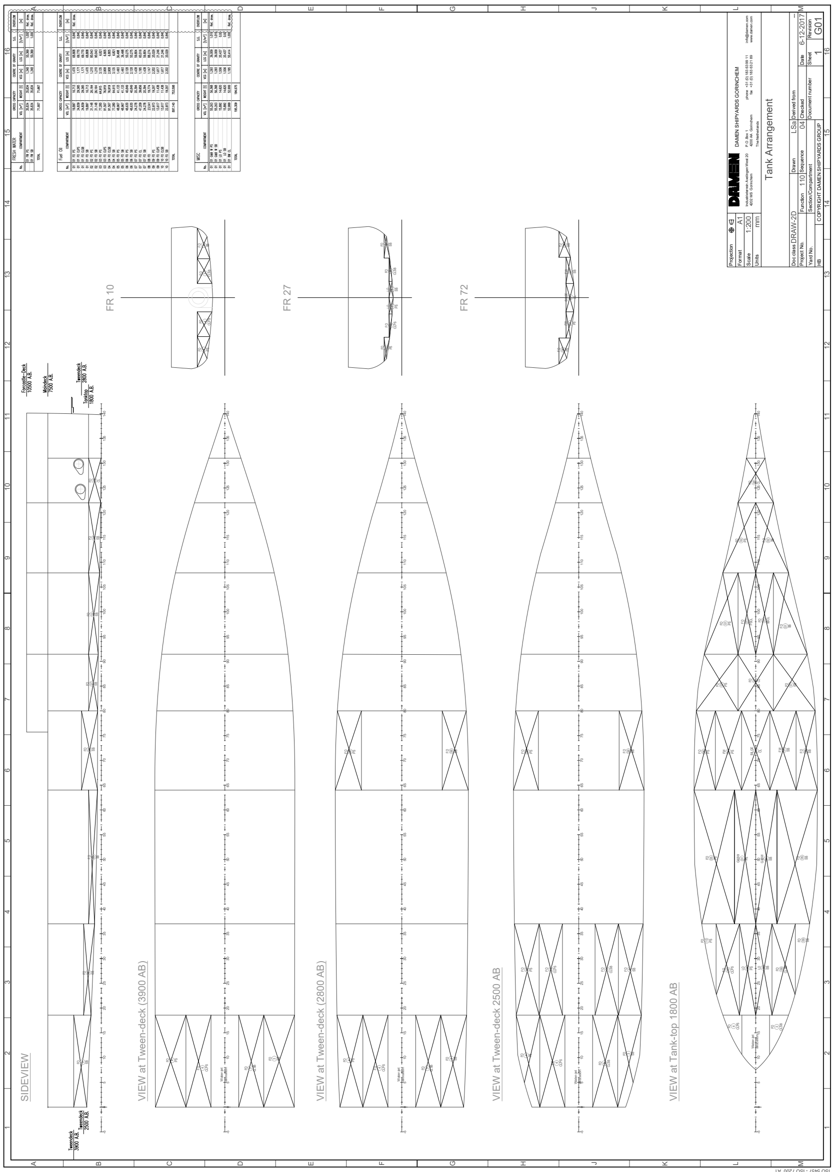


Figure D.1: Tank Arrangement

E

Reference Lines

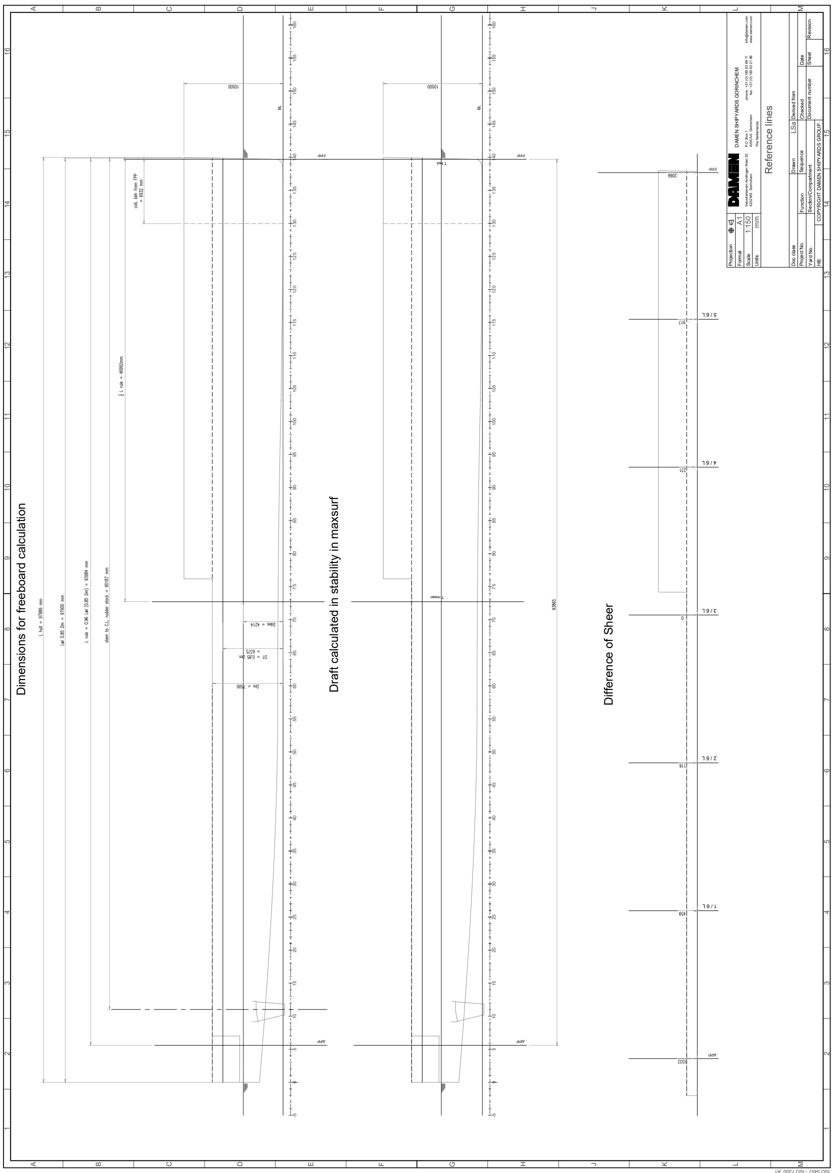


Figure E.1: Reference lines

F

Lines Plan

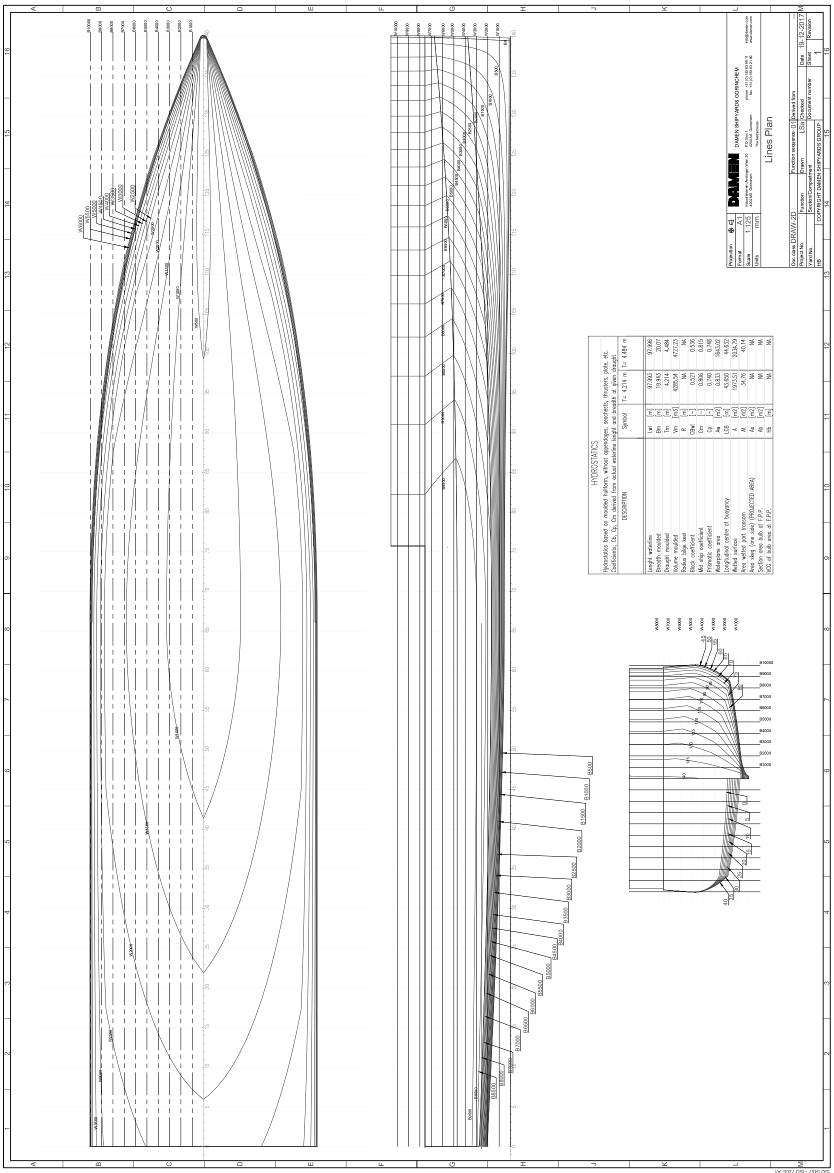


Figure F.1: Lines Plan

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