Scale-To-Order

An engineering lead time reduction strategy for yachts

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C-JOB

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An engineering lead time reduction strategy for yachts

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Summary

In the super-yacht industry, value is added by customisation of design. From an engineering perspective, standardisation contributes to working more efficiently and effectively and thus less costly. The perspective of naval architecture company C-Job is that standardisation can contribute to engineering lead time reduction. Since customisation (adding value) and standardisation (reducing costs) are counterparts, a conflict arises when both are aimed for. C-Job naval architects found that a solution to provide more standardisation while not decreasing the customisation of super-yachts may be achieved by disconnecting the engineering of the lower part and that of the upper part of the vessel. The lower part of the vessel, housing more of the technical and crew areas, is expected to provide potential for standardisation while the upper part of the vessel, housing more of the owner related areas, is expected to contribute more to customisation. Moreover, C-Job's vision is that making the standardised lower part of the vessel adjustable between a range of main dimensions can also contribute to customisation of the yacht; a concept which is referred to as the 'dynamic platform'. This leads to the main research question of this thesis: *How can reuse of design of the non-owner spaces on super-yachts, support reduction of engineering lead time?*

To provide a substantiated answer to this question three topics are studied. These topics are the design process within C-Job, principles of design reuse and commonalities within existing super-yacht designs. The design process at C-Job is studied regarding the concept and basic design phase routines of the three main engineering disciplines: naval architecture, structural engineering and mechanical engineering. The goal with this is to find which aspects in the design process seem the most effective to achieve time reduction in. Principles of design reuse are studied with the emphasis on platforming and while the aim of the thesis is to accommodate engineering lead time reduction, also ship design optimisation algorithms are discussed. Commonalities in existing super-yacht designs are studied by looking at general arrangement plans, structural drawings and mechanical diagrams.

The results of studying the pillars of this thesis substantiate the proposed solution called the Scale-To-Order strategy. Analysing the design process at C-Job shows that a great portion is consumed by iterating the design to solve all space claim clashes and grid mismatches. Space claim is exerted by all three disciplines to get the right space reservation in the final design. A grid mismatch is where a load and a support are not aligned. Omitting space claim clashes and grid mismatches in an early stage of design would therefore eliminate a significant part of the design process. Reviewing literature on design reuse leads to suggesting the underlying principles of design standardisation, modular design and parametric design for application in the S-T-O strategy. The proposal of using these three principles is based on the commonalities that are found in existing yacht designs. The resulting strategy consists of three stages that follow the kick-off meeting with the future yacht owner. In stage one, principle solutions are chosen, based on the greatest commonalities in existing yachts, that include a typical arrange-

ment below the main deck and a corresponding structural global model and HVAC and sewage principles and routing. In stage two, modifications to the solution chosen in stage one are made if desired. Anticipated modifications can be made modular on beforehand and new modifications can be introduced as modular in the future. Stage three is the scaling of the global model to the desired dimensions and serves as a compliance check for integrity of the model.

The ultimate goal of the S-T-O strategy is to accommodate engineering lead time reduction in the design phase of super-yachts at C-Job. The expected amount of time saved by employing the strategy is roughly fifty percent of the original concept and basic design phases, meaning around four-and-a-half month per project. This result, and the result of this thesis as a whole, are accepted as feasible by the experts at C-Job and also by experts from classification society DNV GL.

Preface

Many influences during my childhood made me choose the path of the naval architect. For one, I spent a great part of my youth on salt water as the product of two joint sailor families. As a boy my mind was set to sail the high seas, but as I grew older I gained a drive to explore and innovate technology that led me to where I am today. Studying in Delft has been a blast and also with my current outlook on the future, I am thankful that this path was open to me.

The subject of this thesis allowed me to actively study the ins and outs of the shipbuilding industry from a naval architecture company perspective. Studying the design process at C-Job had me interact with many of the employees. The lessons I learned and the knowledge I gained go far beyond what I could express in this thesis. It was a valuable year to my personal development and for that I am grateful.

First of all I would like to thank my supervisor from C-Job, Ir. T. Velner for his guidance, for sharing his thoughts and expertise and his moral support. I would also like to thank Prof. ir. J.J. Hopman and later on also Dr. ir. Hekkenberg for the fruitful meetings and steering me in the right direction. I want to thank the people at C-Job for taking the time to help me where needed and I want to thank Dr. ir. W.W.A. Beelaerts van Blokland for joining to assess my work.

Last but not least, I want to express my gratefulness to my parents and my girlfriend for their unconditional support and understanding. Because of you I trust myself with tough challenges.

I hope you will enjoy reading this report.

S. van der Harst
Delft, March 2020

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1 Introduction

This introduction starts with describing the initial problem statement related to engineering lead time. Then the forthcoming research objective is portrayed and translated into research (sub-)questions. The initial scope of the thesis is then described, after which the chapter concludes by presenting the outline of this thesis.

1.1 Engineering lead time reduction

Efficiency and effectiveness, the future of engineering is (still) all about them. Companies and institutes continuously develop tools and methods to work faster, cheaper, safer and greener. The complexity of ships requires naval architects and engineers to be sharp and creative in order to develop these tools. Standardisation in engineering processes contributes to working more efficiently and effectively, but in shipbuilding no vessel is the same. Moreover, in the super-yacht industry, value is added to a vessel by having it designed more custom. Still, many commonalities can be found between different super-yacht designs. Just as in other industries, in the super-yacht industry time and money are of the essence. Therefore super-yacht design becomes a trade-off between standardisation and customisation. But how and where to find the perfect balance?

C-Job Naval Architects has found that the super-yacht industry is booming, and shipyards have full order books. The current design phase of custom-built super-yachts, however, is time consuming and inefficient. A reason for this is the incompleteness and developing of the client's wishes. Another reason is the fact that for many vessels a great part of the design is reinvented repeatedly. These reinvented design plans are then to be approved again by class, which is also time consuming. In the meanwhile, C-Job has developed the 'Accelerated Concept Design' program, that allows for dynamic hull designing of commercial vessels. C-Job's vision now is that a shorter engineering lead time and less total engineering costs can be achieved in yacht-building as well by creating a 'dynamic platform' based on existing class-approved designs that can be scaled through parametric models or fit to the wishes of the client by means of modular design. In these parametric models or modules, it would be beneficial if systems lay-out and technical space reservations are integrated for the main requirements on board as well as structural, safety and stability requirements. C-Job's first estimation based on a market study is that such a dynamic platform for motorised super-yachts would be most effective in the range of length between 60 and 80 meters and a range of beam between 10 and 17 meters. Only the lower parts of the vessel should be part of the dynamic platform, leaving the exterior shape above the waterline more flexible for the designers and the clients' wishes.

The ultimate goal of having a dynamic platform is to shorten the total engineering lead time by allowing shipyards to start production of the hull and its compartments early on, while the design of the remainder of the vessel still needs finishing. The remainder meaning the design and engineering of the superstructure and and the interior design. Figure 1.1 schematically shows how the common engineering process at C-Job would be changed by the availability of a dynamic platform. It shows that the shipyard, the designer, the naval architect and the engineer should collaborate closely to save time, given a dynamic platform to support this collaboration.

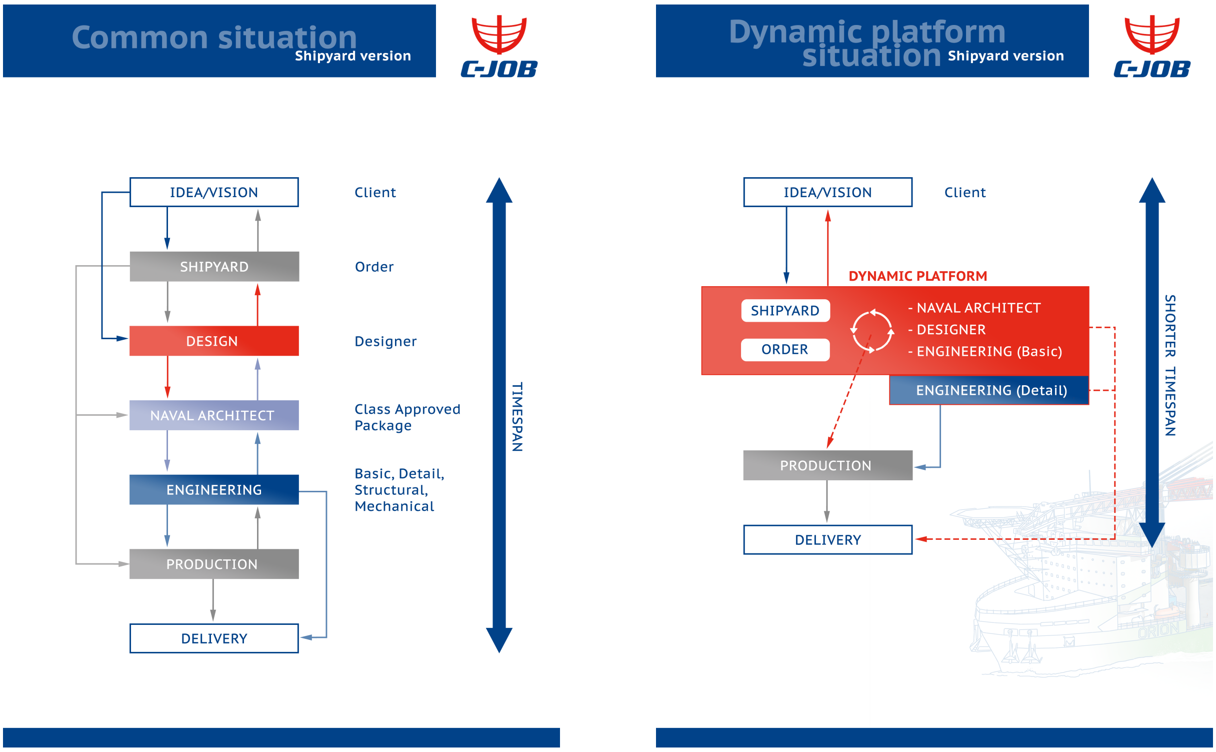


Figure 1.1: Shorter engineering lead time by implementing dynamic platform as envisioned by C-Job

1.2 Thesis objective

The ultimate achievement that this thesis is meant to support, is to reduce engineering lead time for super-yachts in the design phase. In super-yacht design, the owner often has extensive desires regarding the arrangement, the interior, the appearance and the features of the vessel. A lot of value in super-yachts therefore comes from custom design to the wishes of the client. However, a great part of the yacht's engineering consists of technical solutions for the support of the desired functions. The owner of the yacht is assumed to have no direct requirements for this. This leads to the idea that some standardisation can be achieved in the design of the non-owner spaces, meaning the technical spaces and crew areas. As the clients' wishes for the functionalities and appearance of his yacht do indirectly influence the design of technical solutions, a conflict arises. In other words, optimising both standardisation and customisation is conflicting. Still, the philosophy of this thesis is that engineering lead time reduction in the design phase of super-yachts can be effectively achieved by applying standardisation; the only question is how. The main research question is therefore formulated as follows.

How can reuse of design of the non-owner spaces on super-yachts, support reduction of engineering lead time at C-Job?

The main research question implies design reuse. Design reuse methods in shipbuilding have been studied thoroughly before. Therefore a literature study is performed to find the most effective way of design reuse in super-yachts. However, in order to state anything meaningful about a suitable method of design reuse in super-yachts, it should be known where in the design process to apply it most efficiently. To get an idea of the potential of standardisation in super-yachts, the major commonalities and differences in existing super yacht designs will be identified using a sample set of yachts with varying dimensions and built at different shipyards. This will show the conceptual similarities in topology of main systems and compartment functionalities. Standardising the conceptual general arrangement is expected to make scaling of more detailed design aspects feasible. Therefore sub-questions one to three are formulated.

1. Which aspects of design seem the most effective to seek time reduction in?
2. What type(s) of design reuse seem(s) the most effective to apply?
3. What are the major commonalities and differences in existing super-yacht designs?

These first three sub-question have a scoping tendency. The first sub-question will be answered by analysing the current engineering process at C-Job. Answering the first sub-question should point out the greatest bottlenecks in the design process. The second sub-question is answered by reviewing relevant scientific research and more practical applications of design reuse in ship design. Once a chosen design reuse method is at hand, the feasibility of standardisation is further substantiated by answering the third sub-question.

Since the goal is also to make the dynamic platform adjustable for any dimension between certain ranges of length and breadth, sub-question four arises. The answer to sub-question four is not expected to go without consequences. Since the dynamic platform only covers the non-owner spaces below the main deck, it should become clear what the effects are on the design of the owner spaces and the exterior design, because this will influence the design routine. Therefore sub-questions five and six also become relevant.

4. How can the relevant parts of super-yacht design be made scalable?
5. What constraints to the design of the owner spaces and the superstructure are expected?
6. How would the dynamic platform change the design routine for super-yachts?

Although the research questions are meant to steer the research towards answering the main research question, they may still have a wide range of interpretations. Therefore the next section states the delimitation to this thesis.

1.3 Thesis delimitation

This thesis compasses the mapping of engineering efforts at C-Job naval architects with regard to super-yacht design, the mapping of commonalities in existing super-yacht designs that substantiate potential design reuse, and the description of a suggested way to use the acquired knowledge to reduce the super-yacht engineering lead time in the design phase. Research in this thesis is done with regard to standardisation of super-yachts and parametric modelling, but no actual implementation of a computerised model is included. Validation is therefore achieved only based on qualitative estimations and not on statistical data. To use the words of validation expert R.G. Sargent [16]; this thesis presents a conceptual model and not the corresponding computerised model for the problem entity.

In order to preserve freedom of design and custom client wishes, the platform focuses merely on the areas below the main deck, highlighted by the dark area in figure 1.2. This part in super-yachts is commonly used for technical spaces, crew spaces and the engine room, which are further referred to in this thesis as the non-owner spaces. The owner spaces thus also include the guest cabins and the tender bay and beach club area. Pre-designing these parts of the ship will result in constraints to the remaining parts, like topology, total weight and weight distribution. This thesis therefore includes qualitative prognoses, again not based on statistical representation, with regard to the impact of standardisation.

A market study previously performed at C-Job showed that market-wise the most interesting range of super-yachts to be included in the scope of the dynamic platform is between 50 to 80 meters of length. First conclusions from looking at existing vessels in this range shows that the most common type of yacht has a displacement hull. Therefore the scope of the dynamic platform embraces this type of yacht as a starting point. In later stages of research with regard to this topic, less common yacht types and yachts with dimension beyond the range 50 to 80 meters may also be included.

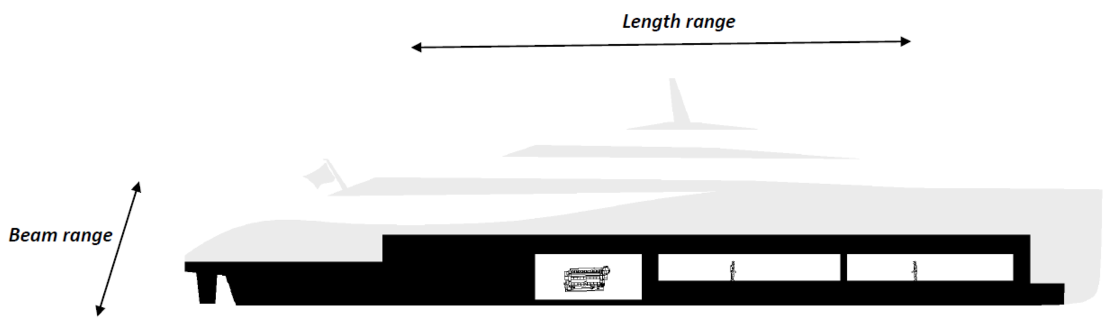


Figure 1.2: Technical parts below main deck

The idea with the dynamic platform is to enable production of the vessel to start soon after the main design requirements have been agreed upon. Design and engineering of the custom superstructure is then performed simultaneously to production of the hull and outfitting. To make this possible, class approval of the dynamic platform design is required in a very early stage too. The timeline in figure 1.3 visualises this. With this relevance of class rules and guidelines, the scope of this thesis also includes class approval related considerations. However, class approval is not among the main goals of this thesis.

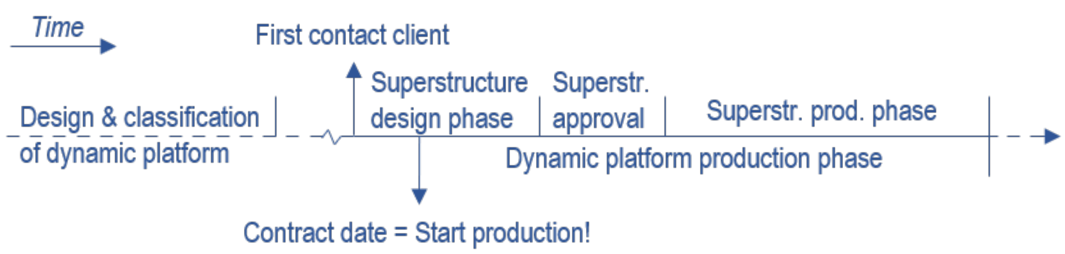


Figure 1.3: Schematic engineering timeline

1.4 Outline

The structure of this thesis is as follows. Chapter two, which is the chapter after this introduction, elaborates on the engineering as currently performed at C-Job. It describes how the design process takes place and how it is experienced by employees within different design disciplines. Together with an analyses of which pillars in the design process are registered to be the most time consuming this study points out the greatest bottlenecks in the design process. Chapter three is a review of relevant literature from scientific research and known applications of standardisation in the industry. It concludes with a statement on which type of standardisation, or design reuse, to deepen out and incorporate in the dynamic platform. Chapter four is based on a study into the design plans of a set of reference vessels built by different shipyards. It elaborates on the major commonalities and differences that substantiate the feasibility of standardisation and it contributes to choosing which form of design reuse seems the most effective to apply. Therefore, chapter four forms the basis for the dynamic platform that is described in chapter five. Chapter five describes a strategy called Scale-To-Order, with which engineering lead time reduction is expected to become achievable. Chapter six describes how the Scale-To-Order strategy is expected to impact the design process of super-yachts at C-Job. Throughout the chapters of this thesis the sub-questions are answered one by one. Figure 1.4 shows the links between each chapter and the sub-questions.

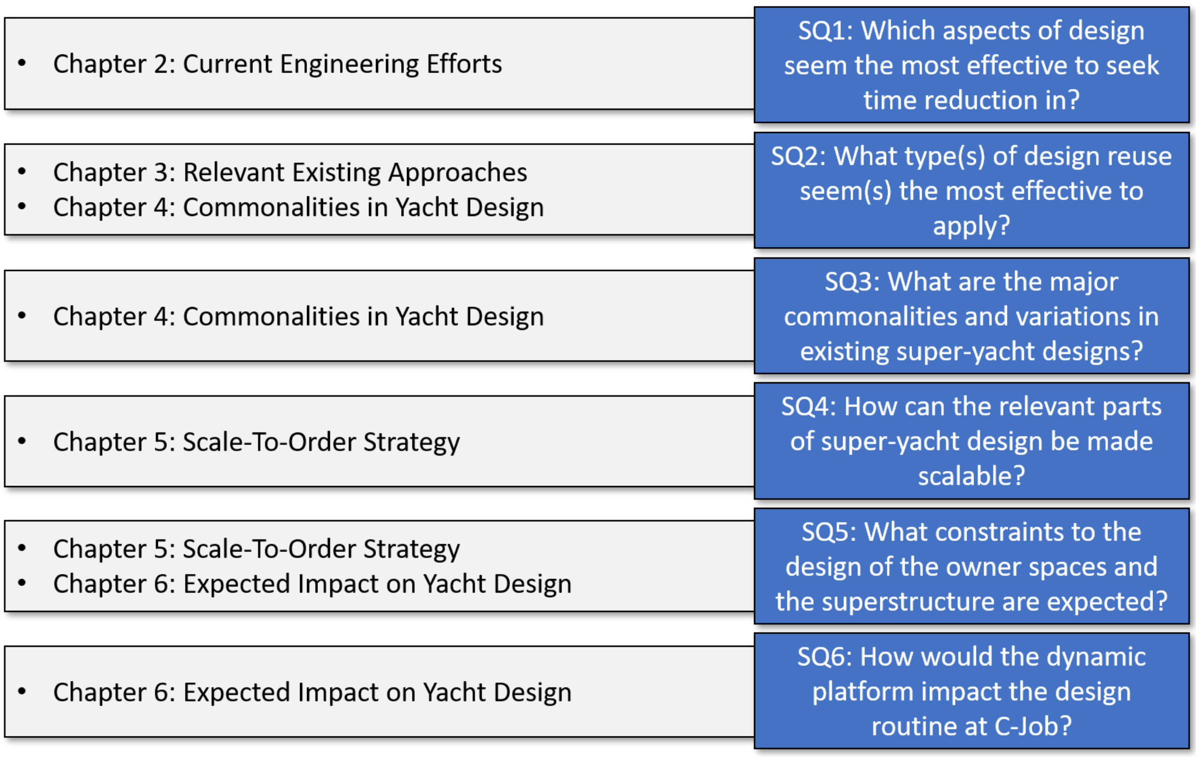


Figure 1.4: Thesis outline

2 Current Engineering Efforts

This chapter elaborates on the engineering as currently performed at C-Job. The goal is to determine which aspects of the engineering process seem the most effective to seek lead time reduction in and therefore to provide an answer to the first sub-question; Which aspects of design seem the most effective to seek time reduction in? The chapter first describes how the design process takes place and how it is experienced by employees within different design disciplines. By asking people from each discipline about their experience, the frictional aspects of design between the disciplines that typically result in extra iterations will come forward. After that, from a project management perspective, an investigation is done to find out which deliverables in the design process are registered to be the most time consuming. The last part of this chapter briefly discusses the transition from the design phase to production and the deliverables valued most by class bureau DNV-GL, as they showed interest in further developing the dynamic platform.

2.1 Design Process

The current design process at C-Job goes through multiple stages that are named as shown in figure 2.1. The process starts with receiving documents stating problems to be solved and wishes to be fulfilled. Then, either the client (being the shipyard or the designer), a third party, or C-Job itself generates a concept design, with tender documents as input for basic design. In basic design, a 3D model is developed in continuous compliance with the classification society. Construction plans are derived from this model and by the end of the basic design stage, all the components in the ship until and including the level of detail where components still have a nameplate are known and included in the design. After class approval of the basic design, it is taken further to detailed design, via an information package in functional design if necessary. This information package contains drawings adapted for the shipyard to have more guidance into detail design. The detail design consists of construction drawings and logistical production information that is matched to the work processes and standards of the shipyard so production can be initiated.

2.1.1 Start of design

The input parameters for a design order as experienced by C-Job often come through receiving a technical specification, or a tender document, from a client typically being a shipyard or a designer. This specification is as unique as the yacht to be built. The information provided in the tender documents can vary greatly in level of detail. Their contents can vary between a functional description and a full package including arrangement drawings, diagrams, renderings and makers lists. This depends on the type of project; if the tender documents are extensive

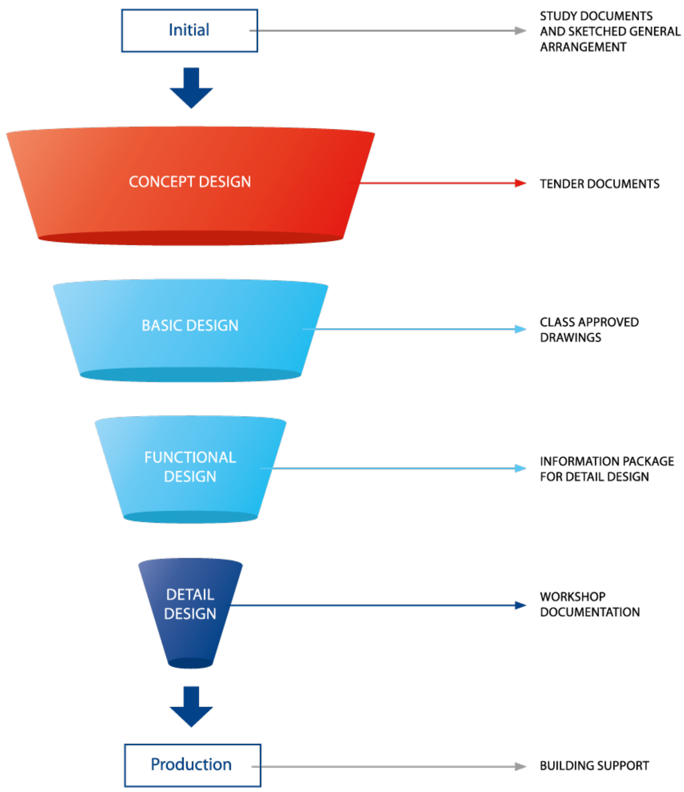


Figure 2.1: C-Job's design pyramid structure

and include much detail, then C-Job's role is probably to work only in the detail design stage. When tender documents include only a functional description; then C-Job is likely to be involved with the early stages of design. The dynamic platform is expected to be most effective when it reaches out to the basic design phase. Changes to the design that are made in this phase are global enough to be addressed by a scaling tool, whereas an attempt to effectively apply scaling in detail design would be too cumbersome. Since the dynamic platform is intended to be valuable from the earlier stages of design on, tender specifications as a lead to concept and basic design projects are examined further.

Usually the tender specifications from shipyards include all information based on which a price indication can be made, so it lists all the systems, their components and their make. The documents are built on agreements on quality between the client and the contractor; the latter being the shipyard or an external designer. Two ways of listing the components are common; structured by system description or by area composition. Systems described in a system-based tender specification include cooling water systems, fuel systems, HVAC systems, electrical distribution systems. This kind of document tends to be more technical than the area composition based document. A fragment from a tender specification based on area composition is given in table 2.1. Typically these kind of tender specifications do not include diagrams yet, but stick merely to the summation of components. In such a case, in the preliminary design phase (before contract), C-Job already performs some hand calculations and sets up a single line diagram and an initial general arrangement.

After a bid is won and a contract signed, based on this kind of layout description, the naval architect will commence setting up arrangement plans and a mainframe, together with the first buoyancy, power, weight and stability calculations.

• Safety flooring	• Emergency escape
• Access door and stairs	• Engine room soundproofed
• Air extraction fans	• Air intakes
• Inspection lamp	• Basic toolbox
• Fluorescent lights	• Emergency lighting
• AC/DC electrical outlets	• Power management system panel
• Engine exhaust silencers and water cooled exhausts	• Engines flexible mounted
• Power steering - electro hydraulic control unit	• Emergency steering - manual pump
• Passerelle hydraulic	• Water maker
• Fire alarm systems	• Fire hydrant system
• Engine room fire extinguishing system	• AC fire pump
• AC bilge pump	• Portable CO2 fire extinguisher

Table 2.1: Example of an engine room specification

2.2 Design Disciplines

The in-house disciplines at C-Job include naval architecture, structural engineering, mechanical engineering, interior design and building supervision. Electrical engineering is not an in-house discipline yet and therefore not analysed in this thesis. For this thesis the disciplines interior design and building supervision are not assumed relevant, so only the three remaining disciplines, naval, structural and mechanical are investigated for their routines. The disciplines naval, structural and mechanical often work simultaneously. Therefore there is constant communication between them to reach the desired feasible integrated design. Firstly the different disciplines are examined separately and then this section closes with a schematic timeline combining them.

2.2.1 Naval Architecture

Ship design is generally initiated by the naval architect. The naval discipline takes care of the the first iterations resulting in a concept design. Based on this concept design, the work is spread over the different disciplines, who all have their expert input to the design spiral. The accuracy and level of detail in the concept design, can contribute to making the next steps in the design process smoother. The routine of a naval architect in the concept design phase can be summarised down to the following steps.

1. Setting up a general arrangement with deck-plans and a mainframe;
2. Making the first lightship weight estimation using the LSW-tool[1]. This requires first input, acquired in a kick-off meeting, from the structural and mechanical disciplines as well;
3. Making a fist assumption of the hull dimensions. A draft and stability estimation is done in Excel or with hand-calculations, based on reference vessels;
4. Setting up a watertight layout and a tanks-plan. The watertight layout is based on class guidelines while the tanks-plan is based on the required specifications such as endurance, power and fresh water capacity;
5. Drawing the initial hull shape and estimating the resistance, required power and engine dimensions.

[1]The LSW-tool is a tool developed by C-Job in which an estimation of the lightship weight of a concept is made based on key figures and reference vessels

In other words, one could state that the naval architect delivers a first set of interdisciplinary information. This means that the first iteration is as good as the interdisciplinary knowledge of the naval architect, or his direct access to relevant sources of information. For example if the naval architect also has some expertise in HVAC principles, he will be able to reserve space and locations in the arrangement for AC units and ducting more accurately.

During the basic design stage, the naval architect takes on more of a controller function. He delivers periodic updates of the general arrangement, tanks-plan, layouts and the lightship weight based on system diagrams. A standardised platform in which these system diagrams are already available in an early stage would contribute to the accuracy with which the naval architect can perform his work, and thus to the iterations to be made with other disciplines as well. The naval discipline works towards delivering a set of documents to the other parties in the project. In the basic design stage, most of these deliverables are arrangement drawings. Table 2.2 lists the standard naval deliverables of the basic design stage in random order.

• Compartment plan	• Tank arrangement
• Room numbering plan	• Cathodic protection plan
• Deck arrangement main deck	• Deck arrangement wheelhouse deck
• Propellorshaft assembly	• Sterntube
• Navigation light arrangement	• Mooring arrangement
• Detail mooring arrangement	• Anchor pocket arrangement
• Freeing port arrangement	• Name, home port registry IMO mark
• Wheelhouse visibility arrangement	• Stairs and ladder plan
• Draught marks fore and aft and bowmarks	• Equipment numeral calculation

Table 2.2: Basic Naval deliverables

The naval architect starts a discussion with the structural engineer about the margins on weights in the design. After the naval architect delivers the concept design, more accurate construction is designed by the structural engineer over the next iterations. Likewise, as the concept design is also a start for the mechanical engineer to start fitting the required equipment configurations, the naval architect starts a discussion about the margins on the engine and technical room dimensions (read: positioning major equipment in general arrangement). The main space claim exerted by the naval architect consists of tank volumes, double bottom height, cabin dimensions and hull shape of the vessel.

2.2.2 Structural Engineering

The structural discipline focuses on solutions that match the naval plans, while optimising structural integrity for environmental and physical requirements. Such requirements can be the operational areas of the vessel and the structural resistance to the wave patterns in these areas. As the naval architect drew an initial mainframe setup, the structural engineer will go in more detail by setting up the mainframe conform applicable loads, being shear and bending moment, and class rules. Then he will work out the construction by setting up typical frames, webframes, and bulkheads to work towards a 3D midship section. The steps that the structural engineer goes by can be summarised in the following points.

1. Gathering information on the materials to be used, the class bureau to go by, the main dimensions and the operational profile;

2. Create a 3D beam package between two or more frames, based on one or more main-cross-sections as defined according to class rules and the maximum bending moments

and pressures. This serves as preparation for the next step, which is the start of basic design;

3. Extruding the 3D beam package to the front and aft of the vessel. This visualises the grid mismatches between arrangements and construction;

4. Performing a steel weight update;

5. Solving the grid mismatches by setting up more cross-sections and 3D beam packages. The result is a global model of the ship with a complete construction 'philosophy' plan.

The construction philosophy plan is an intermediate feasible solution, but it is expected to be subject to alterations still because of iterations in the design process. The philosophy plan will lead to the final structural basic design deliverables through solving space claim issues found by the naval and mechanical disciplines. The basic design deliverables of the structural engineering discipline are listed in table 2.3. Most of them are construction plans, arrangements or foundations.

• Structural Loading Plan	• Main Cross Section
• Construction Plan Aft ship	• Construction Plan fore ship
• Construction Plan superstructure	• Bilge Keel Arrangement
• Welding Table	• Ice Belt Arrangement
• Construction Plan Decks	• Construction plan longitudinal section
• Construction Plan Transverse Sections	• Shell Expansion
• Docking arrangement	• Foundations Hatch Covers
• Foundations Engine Room	• Foundations Masts
• Foundations Mooring Equipment	• Shell connections aft ship
• Material Take Off	• Manhole arrangement
• Doors and hatch arrangement	• Windows and portholes arrangement
• Mast arrangement	

Table 2.3: Structural engineering deliverables

A typical discussion that a structural engineer would start with a naval architect is about the grid mismatches between the arrangement and the construction. An example of a grid mismatch is when a heavy load is designed to be located at a point where it is not directly transferred to a deck-girder. In such a case, the naval architect and the structural engineer will have to agree on a solution in which extra foundation to the construction is added, in which the load is arranged differently, or a compromise. An example of this is shown in figure 2.2, which is a screenshot of a 3D model of a vessel designed by C-Job. It shows that the girder spacing in the double bottom does not align with the right pillar and the left longitudinal bulkhead on the tank deck. Extra girders are therefore added to the construction in the tank top to compensate for this mismatch. The location of pillars is often subject of discussion between all three disciplines. It is also common for a structural engineer to highlight parts in construction drawings where a preliminary decision is made that is expected to change later due to space claim conflicts. Early agreement on the definition of pillar positions with contribute to a more efficient design process.

A structural engineer's argument with a mechanical engineer is likely to be about which girders or members can be penetrated for routing of pipes, ducts and cable trays. In super-yachts, since routing through girders is less common, this discussion is more about the height mapping of the routing on top of the construction. The majority of space claimed by the structural engineer

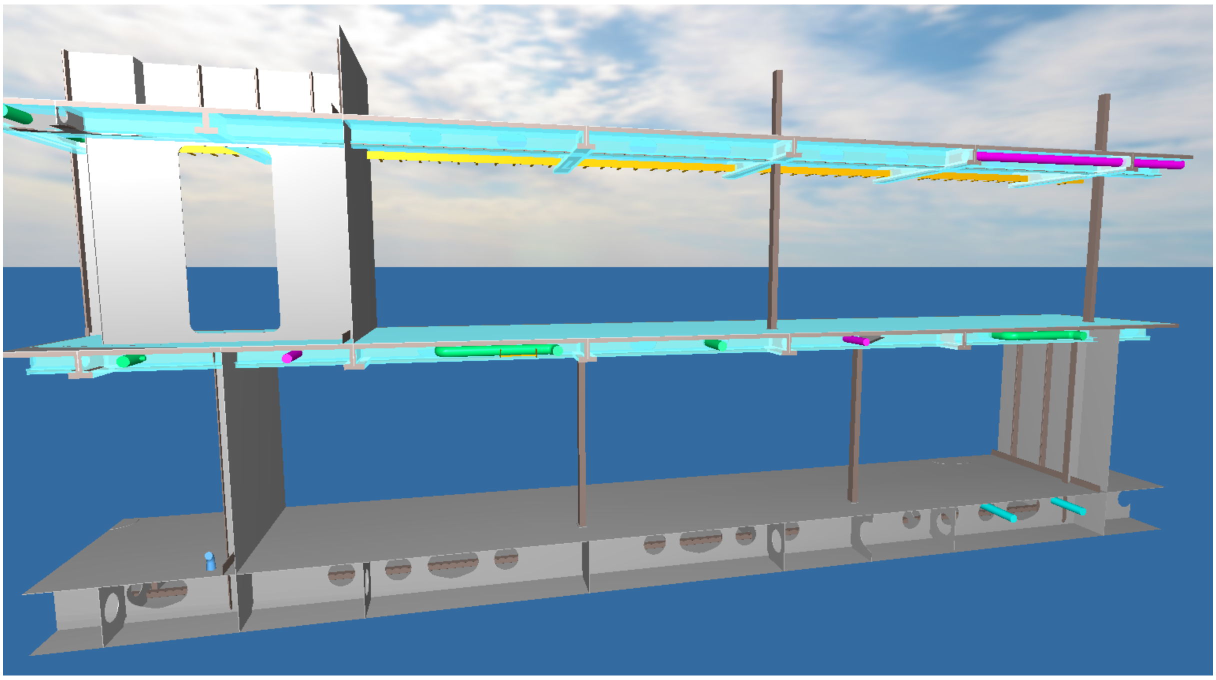


Figure 2.2: Arrangement and construction grid mismatch

is due to girder heights. Figure 2.3 shows an example from a vessel where there is a clear space claim conflict including all disciplines. A green box shaped air duct is running diagonally through a deck girder covered in light blue isolation material and through a yellow cable tray. The cable tray itself runs right through an open hole in the deck where a staircase is located. All the involved disciplines will have to iterate this part of the design to find a feasible integrated solution.

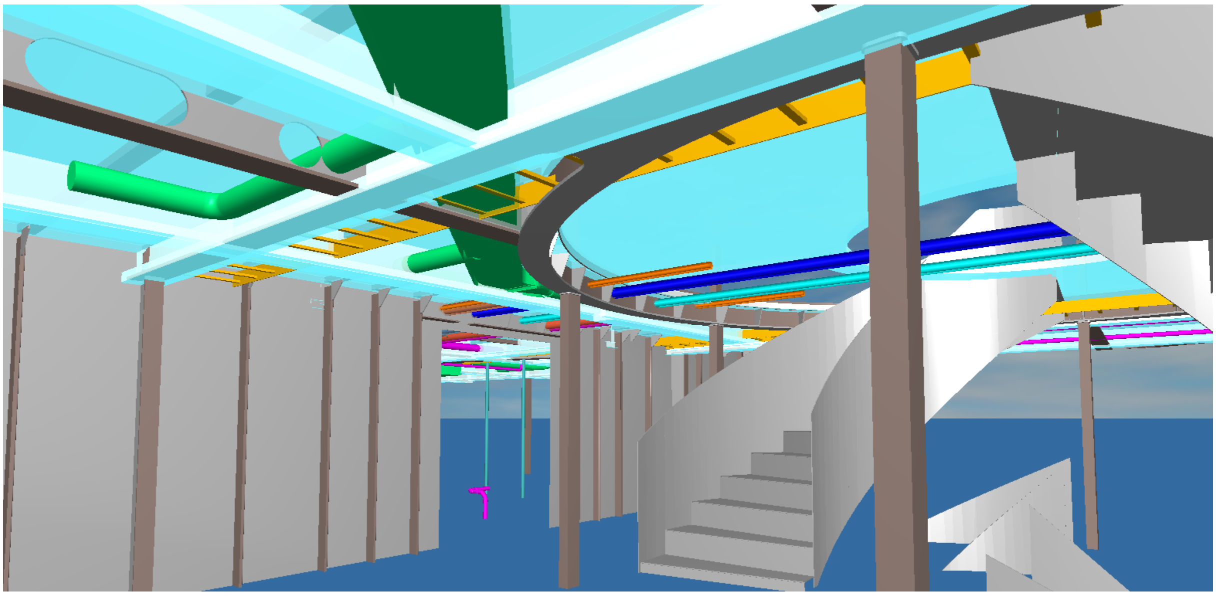


Figure 2.3: Structural and mechanical space claim conflict

To illustrate the seriousness of the situation; The screenshots shown in figures 2.2 and 2.3 are of the design at the state it was in when the shipyard already started production.

2.2.3 Mechanical Engineering

The focus of the mechanical discipline is mainly on setting up the schematics for cabling, piping, ducting, and specifying the components for HVAC, power generation and pumps. When the mechanical engineer starts his work, he always looks at earlier made diagrams to see if parts of it can be used again. He often gets involved with meeting the client to talk about layouts, the propulsion train and HVAC requirements in the very beginning, but then his actual work usually starts only after the naval architect and the structural engineer have delivered their first setups. The steps that a mechanical engineer takes in his work can be summarised as follows.

1. Setting up system functional diagrams, based on the naval architect's concept design;
2. Defining the main mechanical components;
3. Setting up the main ducting and rough routing schematics;
4. Checking whether the first ducting and routing setup fits with construction within the height map;
5. At the end of basic design, all schematics and layouts are done, including every component that has a label with type and capacity.

Most of the deliverables that the mechanical engineer produces in the basic design stage are system diagrams, but also arrangements of the technical spaces including the engine room. Table 2.4 lists the standard mechanical deliverables of the basic design stage in random order.

• Arrangement Engine Room	• Arrangement Paintstore
• Arrangement Pipe Tunnel	• Controlroom arrangement
• Arrangement Steering Gear Room	• Seachest/boxcooler arrangement
• Anti heeling system arrangement	• Technical space
• Arrangement AC Room	• Equipment list
• Fitting List	• Shaft brackets
• Rudder and rudder stock arrangement	• Diagram Bilge/Ballast/Firefighting/Deckwash System
• Diagram cooling water system	• Diagram water ballast system
• Fresh water system	• Air, fill and sounding arrangement
• Diagram lubrication oil system	• Diagram dirty oil system
• Ventilationplan	• Equipment

Table 2.4: Mechanical deliverables

In yachts, HVAC is, next to the propulsion train, the greatest power consumer and so it is also in terms of space claim. First of all the air-conditioning units require technical spaces that have to be taken into the arrangement with certain topological restrictions that are discussed in chapter 4. Not less challenging, however, is the ducting through the vessel to bring the conditioned air from the unit to the air-conditioned rooms for example. This is where the major space claim conflict arises between mechanical and the other disciplines. Other typical items that contribute to mechanical space claim are the engine room ventilation duct, the galley duct and the larger cable trays. The foundations for the engines and the watertight and soundproof requirements for the engine room cause for the main cross-section extruded through the vessel by the structural engineer to require a lot of extra attention at the engine room.

The mechanical engineer indicates that he often has discussions with the interior designer on how to find solutions for so-called domes, staircases, lifts and balconies. A dome being an elevation in the ceiling to fit lights for example. These items are considered real 'height eaters and a dead end to routing. However, these kind of interior designs are typically applied in owner space on and above the main deck and therefore not assumed relevant for this thesis.

2.2.4 Discipline routines combined

As stated at the beginning of section 2.2, the disciplines naval architecture, structural engineering and mechanical engineering work simultaneously. Therefore, there is constant communication between them to reach the desired feasible integrated design. The routines investigated per discipline in this section are put together and visualised in the timeline in figure 2.4. The figure schematically shows how the design process at C-Job regarding the three disciplines naval, structural and mechanical runs. It is not up to scale, but the bigger blocks show the larger efforts. For the naval architect, to update the deliverables in basic design, is not as effort intensive as the tasks for the other disciplines are, but it runs all the way through basic design because of the iterative nature of the design process. Therefore, this block is marked with a dotted line. The figure does not directly point out when and where the iterations are, but typically they run back and forth between and within the disciplines during the whole design phase. The sizes of the blocks marked with A and B are greatly influenced by the vast amount of iterations in this stage due to incorrect space reservations and grid mismatches and are therefore typically this long.

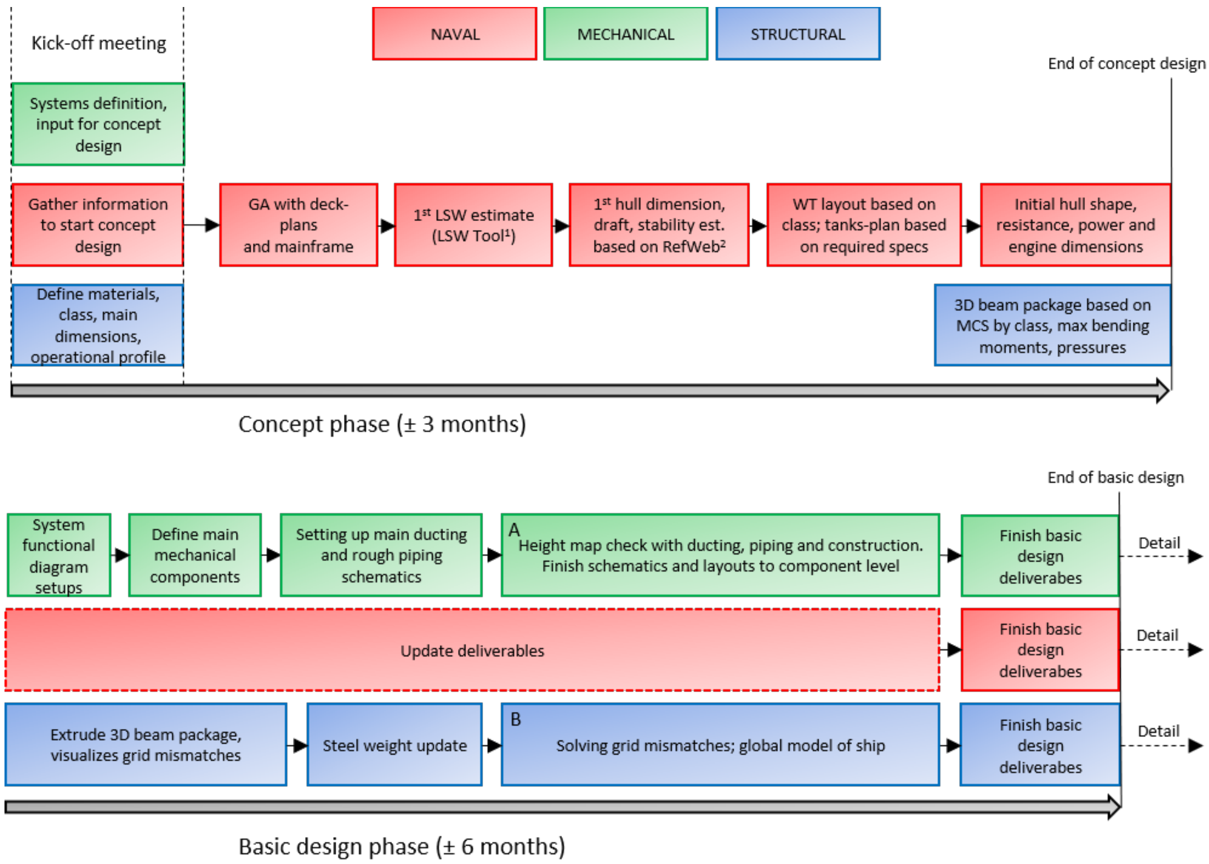


Figure 2.4: Schematic timeline of the disciplines in concept and basic design

The critical path of the concept phase mainly follows the path of the naval architect. Basic design starts after the concept design stage is finished. Within basic design, the critical path depends on the amount of grid mismatches and space claim clashes encountered after the initial iterations in setting up the arrangements, schematics and construction have been done. The structural discipline can only finish a global structural model to base the final deliverables to start detail design after it is assured that no more modifications must be made due to incorrect or missing information from the other disciplines. Likewise, the mechanical discipline must know that no more adjustments to the arrangement are coming. This interdependency is inherent to ship design and the foundations of it are displayed in the famous ship design spiral.

2.3 Engineering hours allocation

After speaking with the different disciplines about their experience with the design process, the engineering time is looked at from a project management point of view. To support the target of engineering lead time reduction, registration of hours spent on each deliverable within basic design scopes of past super-yacht projects at C-Job are investigated. This investigation shows which deliverables are the most significant in terms of effort intensity. The conclusions drawn from the investigation of the registered hours, however, cannot be taken strictly as there may be inaccuracies. Moreover, no yacht projects in C-Jobs database were found in which a full basic basic design scope was fulfilled. Still, the outcome of this investigation is deemed a useful estimation.

Basic design hour registrations of two super-yacht projects of similar ship lengths were analysed. For one of the vessels C-Job was assigned with a mechanical scope and for the other a structural scope. From the hours registration analysis of both vessels together it was concluded that setting up the main construction plans consumes the most time by far. In the structural design scope, 80% of the time was spent on making the main construction plans. The greatest time consumer in the mechanical design turned out to be project coordination with 23.1%, closely followed up by making the arrangements of the engine room and technical spaces with 22.8% of the total time spent on the scope. The outcome of the two deliverable types, construction plans and arrangements of engine room and technical spaces, being the most time consuming adds up to earlier conclusions. The main construction plans are updated with every grid mismatch solved and the arrangements are updated with every change due to iterations in space reservations.

Effective application of a dynamic platform should enable the structural engineer to pull forward in time the main construction plans. Standard solutions to specific construction hot-spots like funnels and shell-doors integration are expected to significantly contribute to the effectiveness of the dynamic platform. Many of the items in the main construction plans are directly derived from a 3D global ship model.

Decisions on construction go hand in hand with decisions on arrangements. The hour registration analysis has shown that the arrangements of the engine room and technical spaces have been among the most time consuming basic design deliverables for C-Job on super-yachts in the past. A structural scope would seem the most effective for application of the dynamic platform since the main construction plans consume the most time within C-Job. Further relevance of the main construction plans as an important deliverable from a dynamic platform tool is supported by looking at what a shipyard requires to start production.

2.4 Start of Production

The aim with shortening the engineering lead time in the design phase is to allow for earlier start of production. Production of super-yachts usually start with construction of the hull while the full engineering of the vessel is not finished yet, according to the experts at C-Job. During production, detailed engineering deliverables comes in packages. Production and detail engineering are therefore overlapping processes as shown in figure 2.5. It shows a schematic timeline that is simplified to a distinction between the design and production phases for the hull and the superstructure.

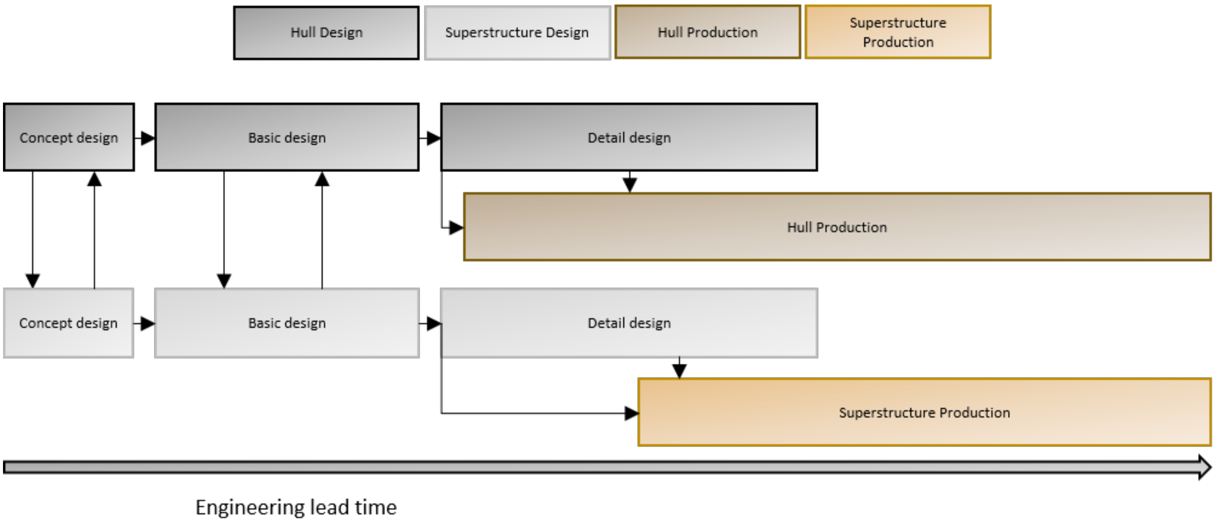


Figure 2.5: Overlap of detail engineering and production

To start, the most important documents a shipyard requires are first of all the material take-offs and secondly the finished construction plans and the steel weight calculations. These three items therefore deserve a high level of priority in the implementation of a dynamic platform. Before the shipyard starts production, the required documents should be approved by class. The next section shortly describes what classification society DNV-GL prioritises in terms of importance for approval.

2.5 Class approval

To make the dynamic platform approach more effective in reducing engineering lead time, early approval by class should be striven for. Classification society DNV-GL has shown willingness to cooperate and consider 'approval in principle'. Approval in principle meaning approval of a platform with clear predefined expectations or constraints for the remaining parts of the vessel. According DNV-GL, the deliverables for this approval in principle include a naval, a mechanical and a construction scope in which stability, watertight integrity, fire integrity and the power plant between and including the fuel supply and the exhaust are important. For the dynamic platform this implies that the funnel design above the main deck is to be incorporated and will therefore be a fixed constraint to the design of the superstructure.

Modelling a construction into a 3D beam package is a developing concept as class societies are working towards an approval mechanism of this kind of 3D models as opposed to 2D construction plan drawings. Ship engineering companies like C-Job derive their 2D drawings that are up for approval directly from their 3D models. At this stage tools like the structural optimisation tool 'NAPA Steel' [18] are available that check a 3D model on class guidelines. For the future it is also foreseen that concept optimal structures will be generated by software, based on input of the main particulars and class guideline constraints. This enhances feasibility of a dynamic platform in which engineering lead time is further reduced by this accelerated way of design. However, these tools do not yet consider interdisciplinary coherency in height mapping and grid matching. So far, every discipline is optimising only for itself.

2.6 Conclusion

Several aspects of design have come forward in this chapter that seem effective to achieve time reduction in. First of all, the different disciplines naval architecture, structural engineering and mechanical engineering regard space claim as the most significant source of effort and time consumption. The inaccuracy of space reservations in an early stage of design result in the need for design iterations. Particularly the space claim in vertical orientation throughout the ship, called the height map, is critical in super-yachts. Also mismatches between the naval and structural grids lead to the need for iterations.

In the basic design phase, setting up the construction plans seems to be the most time consuming based on hour registration in a relevant yacht project. Also setting up the arrangements for the engine room and technical spaces is time consuming. The foundations for the engines and the watertight and soundproof requirements for the engine room cause for the main cross-section extruded trough the vessel to require a lot of extra attention at the engine room.

Deliverables with the highest priority for the shipyard to start production are the material take-offs, the construction plans and steelweight calculations. The main construction plan deliverables were also the most time consuming and they are only finished after the last iteration of solving grid mismatches. Class bureau DNV-GL notes that in order to grant approval in principle, stability, fire integrity, watertight integrity and the power plant between and including the fuel supply and the exhaust are particularly important.

The design deliverables required for production are dependent on the duration of the iterative concept and basic design process. The conclusion on which aspects of the design phase seem the most effective to seek time reduction in is therefore the iterations due to space claim, in particular of the technical systems and construction. High accuracy of space reservations in an early design stage is expected to contribute to engineering lead time reduction.

3 Relevant Existing Approaches

Standardisation in ship building, as one of many product industries, has been a topic of research for decades. Literature deemed relevant for this thesis has been studied to substantiate the purpose of the dynamic platform philosophy and to partially answer the second subquestion; What type(s) of design reuse seem(s) the most effective to apply? Since the ultimate goal of this research is to accommodate reduction of engineering lead time, the varying existing theories to achieve this are laid out in this chapter. A distinction is made between design reuse, often associated with platform-based design, in section 3.1 and optimisation techniques in section 3.2. Optimisation algorithms in itself are not part of design reuse principles. However, their objectives and parametric formulation may be relevant. This chapter elaborates on scientific literature first and then focuses more on known application of standardisation in ship design in section 3.3. The chapter closes with an evaluation and a conclusion in section 3.4.

3.1 Design Reuse and platforms

Standardisation and design reuse are effective methods to reduce costs and lead-time in shipbuilding according to Nieuwenhuis [12]. Design reuse in ship-building is thought to be feasible through the use of product platforms, Nieuwhuis states as he studies the appropriateness of product platforms in design reuse for ships. Nieuwenhuis mentions research done by Simpson [19] on Platform-based product development, which is further elaborated upon in section 3.1.1. This section then continuous to discuss modular platforms as studied by Erikstad [3] and Navais [10].

According to Nieuwenhuis [12], a product platform is a common set of parameters, features, or components that remain constant within a product family. Researching parametric ship design is driven by the competitive nature of the shipbuilding industry. Designing 'engineered-to-order ships' is often knowledge intensive and requires highly skilled engineers. This makes these special ships expensive to design and produce, and so their market is sensitive to competitiveness. Western-European shipbuilders continuously strive to reduce costs, effort and throughput time, while keeping the quality of their customised orders as high as possible, to improve their market position. An approach to achieve this is to apply "design reuse". Design reuse can be interpreted as standardisation of for example payload modules or complete designs and engineering packages. It can also be interpreted as the use of yard standards for smaller construction parts, or as the use of reference vessels as starting points for new ships or ship's systems. An example of design reuse in shipbuilding within early design is reuse of a complete design, using a reference ship based design method, using algorithms based on previous designs. During Basic engineering design reuse may be applied using expert systems and working with frame contracts. During detailed engineering design reuse may include applying yard standards or ad-hoc reuse of detailed engineering design solutions.

Nieuwenhuis mentions the western European shipbuilder 'ICON yachts' as an example of a user of the design reuse principle. In his words, Nieuwenhuis describes the practice of design reuse at ICON yachts as a product composed by preconceived, planned and embedded design reuse within the process, across several product domains, based on previously developed design solutions. This basically means that ICON prepares new designs to be reusable. The level of detail in standardisation is complementary to the level of customisation. Standardisation can be achieved at the level of product features, parts, components (including interfaces), systems, arrangements and design, production and assembly processes. For any design reuse strategy to be successful in super-yacht building however, the high degree of customisation should not be affected, or it should be sufficiently compensated, to retain the value of the yacht.

Nieuwenhuis describes three approaches of product platforms; the modular, the integral and the scalable approach. The modular approach is the most widely known platforming approach. According to Simpson [19], with a modular approach, product family members are derived by substituting and/or removing modules, possibly complemented with individually designed product portions. Three years earlier, Simpson described the scalable approach [20] as one that uses a platform that has a number of scaling variables that be used to “stretch” or “shrink” the platform in one or more dimensions. The integral approach, according to Gonzalez-Zugasti and Otto [6], is based on a platform that is a single predefined assembly shared by all the products in a family. Individually designed portions are added to the platform to create a finished product.

Integral, modular and scalable platforms in this description all sound like promising solutions when it comes to developing a dynamic platform based on design reuse, with a high perception level of custom and with adaptable dimensions.

3.1.1 Platform-based product development

As mentioned, Simpson [20] distinguished module-based and scale-based product families. In his paper, Simpson states that platform-based product development offers a multitude of benefits including reduced development time and system complexity, reduced development and production costs, and improved ability to upgrade products. Further Simpson implies that platforms promote better learning across products and can reduce testing and certification of complex products such as aircraft, spacecraft, and aircraft engines. A reduction in product lead times of as much as 30% is said to be achieved in the automotive industry where platforms enable greater flexibility between plants and can increase plant usage. A reduction of 50% in capital investment can be yielded by sharing underbodies between models, especially in welding equipment. An example of two different cars sharing the same underbody design are the Ford Ka and the Fiat 500 (figure 3.1). These cars, from different brands, share the same production facility.

Within module-based product families, the architecture is either classified as modular, if the mapping of functional elements to physical structures is one to one or many to one, or integral, if this mapping is complex or coupled. Scale-based platforms are used to create product families by stretching or shrinking it. As an example, Boeing developed many of its commercial airplanes by “stretching” the aircraft to accommodate more passengers, carry more cargo, or increase flight range.

Figure 3.1: Ford Ka (left) and Fiat 500 (right) sharing the same underbody

According to Simpson, some consider scale-based product families to be a subset of module-based product families. Platform based design is often supported by multi-objective optimisation to determine the optimal platform variables within the family. This is often based on the assumptions that maximising each product's performance maximises it's demand and that maximising commonality among products minimises production costs.

3.1.2 The configure-to-order strategy

Recently, more research was performed on the use of modularity in service vessels by Choi et al., [3]. Their paper focusses on modularity in service vessels, while handling a configure-to-order strategy. They call this type of vessel the 'modular adaptable ship' or 'MAS'. The major advantages are seen as the possibility to postpone investment decisions until the need for particular modules is realised. For yachts this could be interpreted as the ability to adapt to the clients' developing functional wishes. The model created for the concept introduced by Choi is based on maximising revenue rather than minimising costs and it is modelled as a multi-objective optimisation problem regarding capability and economic aspects. The packing approach by Van Oers is mentioned as an available MAS design synthesis approach for applying the configure-to-order strategy.

3.1.3 NAVAIS

Quite similar to the configure-to-order strategy, the ongoing European joint industry project, called NAVAIS [10], for New Advanced Value Added Innovative Ships, is developing a platform-based modular product family approach to support the 'assemble-to-order' business strategy. This strategy allows shorter lead times and reduced design and production costs. The approach is supported by the '3DEXPERIENCE' integrated business platform created by d'Assault systems. One of the main focusses of the Navais project is passenger/road ferries. An example of such a concept is shown in figure 3.2.

Navais' objective with implementing platform-based product families is to define groups of related products that share common features, components, subsystems, interfaces and manufacturing processes that comply with a broad range of requirements. NAVAIS claims that 30% higher efficiency in ship design development, production lead-times and cost, testing and approval times for customised vessels and in reduction of rework during the warranty period can be achieved.

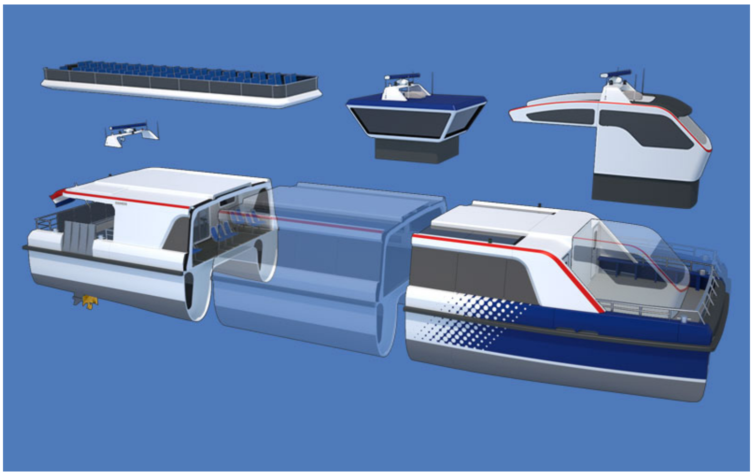


Figure 3.2: Platform-based modular product family design and production

Modularisation and platform-based development look quite promising when it comes to reduction of lead times and costs in shipbuilding. The next section elaborates on a technique less focused on standardisation to achieve this goal.

3.2 Algorithms to Reduce Time and Effort

The first aim with standardisation is to reduce time and effort. Design reuse in ship-building is thought to be feasible through the use of product platforms. Another way to achieve this for engineered-to-order ships is by speeding up the design phase as a whole in a holistic manner. This has been subject of study related to service ships by Pawling [14], Van Oers [13] and Nick [11] and related to trailing suction hopper dredgers by De Winter [21].

3.2.1 The building block approach

First ship layouts and arrangements are made in the early stages of design. Finding a multitude of feasible designs in an early stage may be time and effort consuming. A result according to Van Oers is that sub-optimal compromises are accepted. Pawling, Nick and Van Oers use similar definitions that ship design is based on optimising the configuration of spaces within the physical boundaries of vessels. Out of the three, Pawling [14] was the first to research the possibility to effectively computerise ship concept design, by dividing the arrangement into building blocks. In her approach, each 'Design Building Block' is a three-dimensional space reservation for a specific function. The approach of assigning functions to space reservations in a vessel seems useful for the current thesis.

3.2.2 Zone-Deck Arrangement Optimisation

An arrangement optimisation tool derived from the design building block approach is suggested by E.K. Nick [11]. Assuming a fixed hull form with fixed structural members, she suggests a model that optimises arrangement per deck. The model takes continuous longitudinal passages and a list of ship spaces with constraints for location, adjacency and shape given by the user as input. The spaces are positioned on the zone-decks in two steps. First the spaces are allocated to a zone-deck. A zone-deck is one of the areas 1 to 17, being the intersections between the longitudinal subdivisions and the decks, as denoted in figure 3.3.

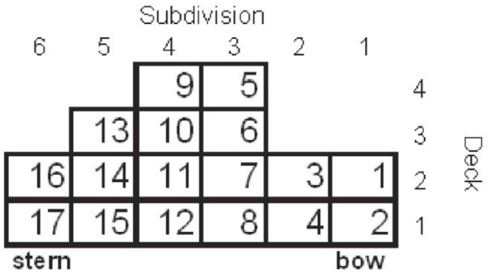


Figure 3.3: Zone-deck representation of a ship

Second, the spaces are arranged into a coherent layout that complies with the given constraints. This is illustrated in figure 3.4.

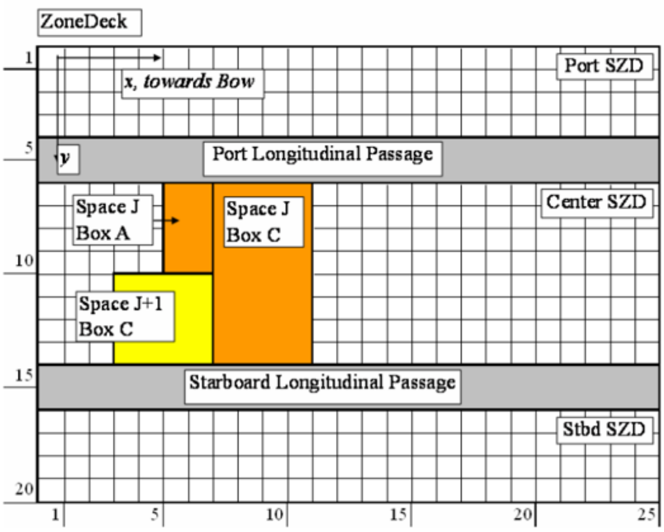


Figure 3.4: Zone-Deck arrangement

The constraining of decks, bulkhead positions and main passageways seems an interesting way of standardising in a platform that is to achieve the goals the current thesis.

3.2.3 Packing Approach

Another approach derived from Pawling's design building block approach is the packing approach by Van Oers [13]. It consists of three elements: a parametric ship description, a search algorithm and a selection approach. For proper use of the packing approach a set of ship systems and design requirements are assumed available. Identifying this input for the packing approach can be built upon existing approaches like a functional decomposition. The parametric ship description uses the set of given ship systems and design requirements and geometrically describes and alters the ship's systems and their configuration. The parametric description then forms an input for the search algorithm NSGA-II, which searches for feasible ship designs. The algorithm has one objective; packing density. It is constraint to several non-negotiable requirements. Trade-off decisions are made by naval architects in the design selection part, where the feasible designs are identified to extract the most promising ones. The selection is supported by studying the relevant aspects, filtering and visualising the general arrangement plans. Selection decisions may be revised if the resulting solutions turn out non-compliant.

A knowledge gap his dissertation pointed out by Van Oers is that no attempt was made to implement rules-based objectives and constraints as it was considered prohibitive. According to experts at C-Job naval architects, rule-basedness could be valuable in reduction of engineering lead time as a significant amount of time is lost while waiting for re-approvals after alterations to the design are made.

The arrangement optimisation oriented approaches now discussed have in common that they are based on the desire to generate a multitude of feasible designs fast. This is a different perspective on achieving reduction of lead times and effort than envisioned by the platform-based design approaches discussed earlier. Design reuse by platforming seems more effective to achieve reduction of lead times in the design of yachts, since yachts are expected to show more commonalities than service vessels. At C-Job, however, a tool was developed based on optimisation algorithms and not on platforming. Before the subject of optimisation is closed, research on this tool is reviewed.

3.2.4 Accelerated Concept Design

An algorithm that incorporates scaling in the concept design phase, called Accelerated Concept Design (ACD), is developed at C-Job. De Winter [21] developed an algorithm that optimises the concept design of trailing suction hopper dredgers. The driving philosophy behind this is that a computational method can significantly speed up the design process compared to the original iterative design spiral way of concept design. The algorithm uses as decision variables the main dimensions, length and breadth of the ship, the dimensions, length, width and height of the hopper and the foreship length. Figure 3.5 illustrates this.

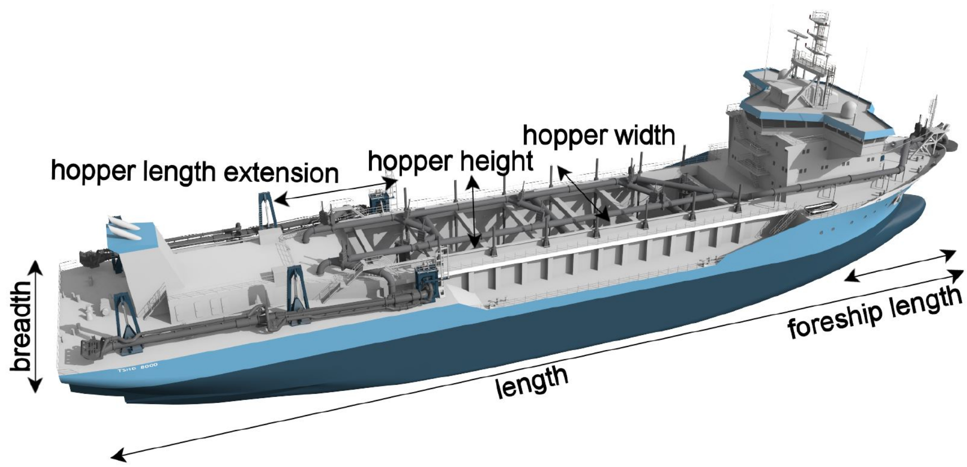


Figure 3.5: ACD decision variables on a trailing suction hopper dredger

The constraints are divided into two categories; practical constraints and domain constraints. The practical constraints are the space reservations for payload, fuel tanks, engine room, pump room and accommodation. The domain constraints are mainly based on classification rules and regulation. The objectives of the algorithm are maximising performance and minimising building costs. This is simplified to minimising the hull resistance and the steel weight. The accelerated concept design approach in the way described, is very conceptual and needs much pre- and post-engineering. Since the aim in the current thesis to standardise technical parts of the vessel to more detail than the accelerated concept design approach proposes, the method suggested in the current thesis may connect to ACD by adding detail. For now, however, the objectives of the ACD algorithm do not match with the objectives of this thesis; the dynamic platform is not a design optimisation tool but a design reuse tool.

3.3 Product Platform Approaches in super-yachts

Several existing approaches to achieve reduction of lead times and effort in shipbuilding have been reviewed, but in academic literature little is said about applications in yachts. Since industries have been striving to enhance revenue and reduce costs, effort and time spent, design standardisation is a common subject to research and development for yacht-builders too. Varying super-yacht shipyards have been applying standardisation in various ways. This section describes what little information on these yacht standardisation applications is publicly available.

3.3.1 Amels

Amels-Holland [1] has a series called the limited editions and they call it the perfect balance between semi-custom and full custom. The series consists of six exterior designs ranging from 55 to 83 meters of length. More than thirty limited edition yachts had been delivered until September 2018. The limited edition approach is based on the use of a standardised technical platform in combination with a full custom interior. With this technique, Amels claims to be able to provide yachts with shorter delivery time, greater quality and reliability and better service. Amels keeps track of their delivered yachts in a database with all encountered problems plus the solutions applied and therefore the limited edition yachts are based on proven solutions. Technical reliability and the opportunity for the client to personalise his yacht are both very important. Research and development at Amels came up with new designs and ideas, in cooperation with Marin and the TU Delft.

Aspects like the breadth of the bridge, the position of the jacuzzi, the helideck, features on the outer decks and appearance of the vessel can be altered in various ways while the base platform remains the same. The drawback of the Amels concept relevant to the current research is that the main particulars of the yachts in the limited edition series cannot be changed. Therefore the yachts in this series seem to incline more towards standard yachts than custom.

3.3.2 Heesen

At Heesen yachts, an existing design is sometimes re-used in a completely standardised way. For example they have a series called the 55m steel [7], of which three sister ships are built with only minor changes in the interior arrangement.

3.3.3 ICON

ICON yachts [22] has the ICON vision line in which they aim to save time and money by employing a number of tried and tested hull platforms which share a common technical backbone. ICON also applies a modular construction technique in combination with pre-planning to reduce the time to delivery [23]. This is supported by Nieuwenhuis's statement in section 3.1 about embedded design reuse at ICON yachts. Unfortunately the company is not publicly transparent concerning their modular approach. Another yacht builder that, based on what is publicly available, uses a quite similar technique to reduce engineering lead time is Royal Huisman.

3.3.4 Royal Huisman

Royal Huisman handles an approach in which they have a fixed platform including all the technical aspects and hull shape of the vessel. The project is called PURA [8] and, unlike the previously discussed yacht-builders, concerns a sailing yacht concept. The goal of this concept is to achieve shorter delivery times by saving time and effort. The platform consists of standardised operating systems including propulsion, power generation and management, hotel and security systems, HVAC, hydraulics, mast, rig, sail plan, sail handling, hull structure and keel. The exterior and interior design of this concept can be selected from a pre-engineered design database. This makes the PURA concept have a modular nature. The modularity in the concept is not functional, but focused on style and appearance. Figure 3.6 gives an impression of this concept.

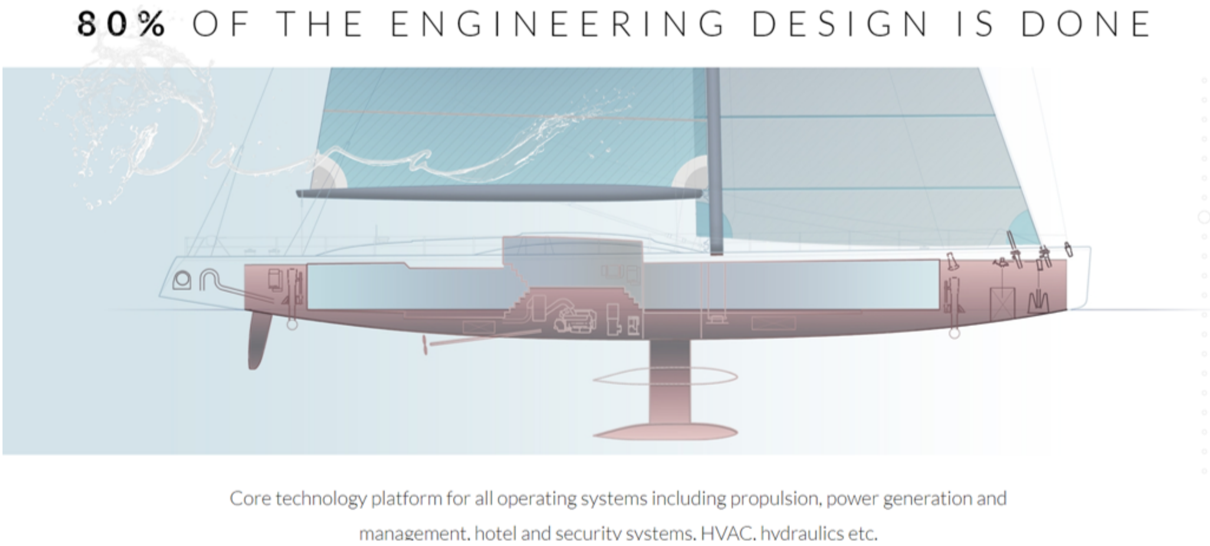


Figure 3.6: Royal Huisman's PURA concept

Royal Huisman also provides maintenance following a pre-planned schedule at a fixed cost while the ship systems are monitored in real time. The platform also enables the company to ensure more reliability of the ship systems as they are taken from proven concepts. Just as with the limited edition from Amels, the downside of the PURA concept is that it has fixed main particulars. The PURA concept comes close to what is aimed for in this thesis, but the level of customisation of PURA is not satisfactory.

3.4 Evaluation

Concluding the literature review, it appeals that modularity is a popular innovative way to go when it comes to reducing engineering lead time in the more complex maritime industries. The main goal with modularity, however, is to achieve a broader functional applicability of a single base-platform. In a way modularity is thus a way of standardising parts of the ship that can be re-used to support multiple purposes. For super-yachts more specifically, standardisation is often applied in such a manner that only parts of the owner spaces can be made custom. Comparing the modular approach and the current standardisation in super-yachts, it looks like modularity leaves more space for customisation. This is applied in the PURA concept by Royal Huisman, where modularity is used to provide multiple solutions for the exterior and interior design whereas the technical parts of the ship are standardised. For the yachting industry the main functions of the vessels do not differ as much as they do for service vessels for example, as they are all there to provide luxury and hotel functions. A modular approach could be interesting to apply for the design of the owner spaces like tender bays, beach clubs, helicopter decks, cinemas, cabins etc. However, for the technical parts of the ship, which are the parts that the owner usually does not visit, a more standardised solution like an integral platform seems more effective. Current applications of standardisation in super-yacht design implies strongly limiting the main particulars of the vessel. The novel approach aims to lose the constraining of the main particulars by making the dynamic platform scalable, while integrating the different design disciplines from the previous chapter.

To avoid strong limitation of the level of customisation of the owner spaces, which for now are left engineered-to-order, the type of design reuse most effective to apply for the design of the non-owner spaces in super-yachts will lie somewhere between fully standard, modular and scalable. Figure 3.7 shows a plot of the examined existing lead time reduction approaches. The ideal desired solution is one with a higher sum of engineering lead time reduction and perception of custom compared to the existing approaches.

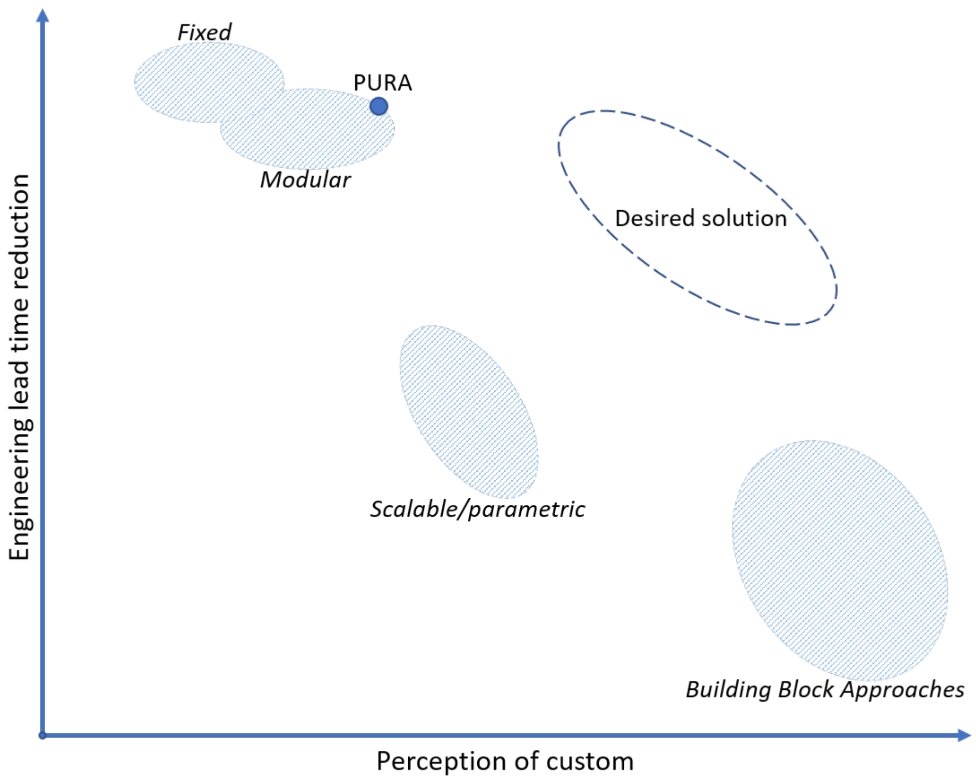


Figure 3.7: Desired solution compared to existing approaches

The upper left corner of the graph contains the current standardisation application in yachts and the modular platform approaches. A modular platform is regarded as slightly more custom than the standardised yachts because of their potential to swap functionalities and appearances. Still, the modular platforms are built up of fully standard parts. The Pura platform by Royal Huisman is considered more custom than most of the modular platforms because it basically is modularity applied in yachts. This means that the modularity in Pura is specifically meant to impact the appearance of the vessel and thus the perception of custom to the yacht owner. The arrangement optimisation researchers are found in the lower right part of the graph. With their goal to provide a large database of feasible designs comes a high perception level of custom. However, since the optimisation is applied only in the concept design phase, engineering lead time reduction is limited. The scalable approaches by Simpson and De Winter are both quite conceptual and are used to scale an existing design.

4 Commonalities in Yacht Design

So far in this thesis, studies of the design process at C-Job and relevant existing approaches have shown potential application of design reuse in the non-owner spaces of super-yachts below the main deck. Design reuse, however, can only be effective if enough commonalities and few enough significant differences in existing yacht designs can be found. This chapter elaborates on the feasibility of reusing parts of yacht design, based on the existing commonalities and differences found in sets of reference vessels and therefore provides an answer to sub-question three; What are the major commonalities and variations in existing super-yacht designs?

The topics of the commonality studies in this chapter again reflect on the three disciplines naval architecture, structural engineering and mechanical engineering, as these are the targeted design disciplines. To limit the available data to examine, for each discipline the documents deemed most relevant, having a higher information density on a concept and basic design level, are studied. From a naval architecture perspective, the reference vessels are compared based on their general arrangement. The construction principles are compared mainly by looking at main cross-sections and construction plans. The mechanical principles are narrowed down to the aspects exerting the most space claim, being HVAC and black/grey water. Other important mechanical aspects like firefighting, fresh water supply and electric cabling as discussed in section 2.2.3 are disregarded for now as their role in space claim is lesser than that of HVAC and the grey and black water systems. Also they have been pointed out as less time consuming. After analysing the commonalities and differences between the yachts in the reference selection, an attempt is made to define a typical arrangement and typical construction and mechanical principles.

4.1 Reference vessel selection

Designing every possible super-yacht within the range of fifty to eighty meters using a standardised 'dynamic' platform intuitively seems impossible. Therefore, to help the feasibility of the platform approach, a suitable set of reference yachts is selected that live up to some common characteristics. After a first look at existing yachts with lengths between fifty and eighty meters, as also briefly stated in section 1.3, the scope of the reference yachts, is narrowed down to yachts with a twin-screw diesel-powered propulsion. Diesel-powered meaning either diesel-direct or electric propelled through diesel generators. The vessels are also selected based on their overall 'conventional' appearance. This means that no 'unconventional' yachts, like the Damen SeaXplorer, were selected, but rather yachts with a pyramid shape as depicted in figure 4.1. Bow configuration was deliberately left free as this part may contribute significantly to specific wishes of the client and a changing market towards steep vertical bows. For most of the reference vessels though, the bow turned out to be bulbous.

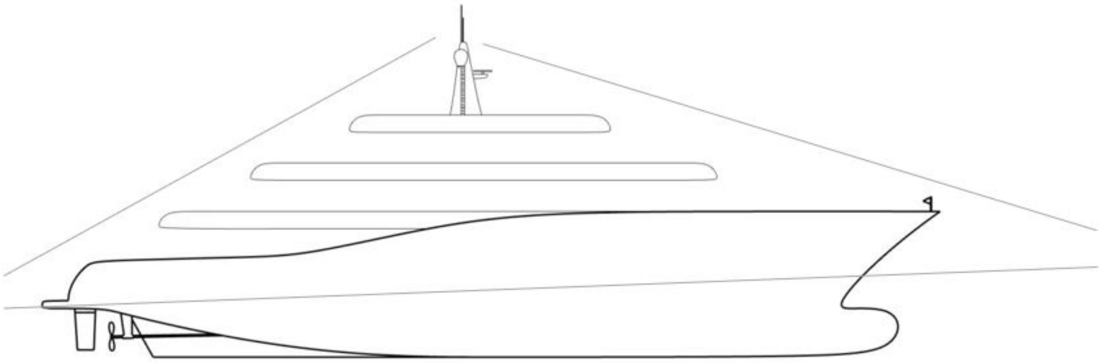


Figure 4.1: Pyramid shape yachts

For the analysis of general arrangements, twelve yachts ranging from 50 to 81 meters were selected. reference vessels are analysed on their general arrangement to find the commonalities and differences. The motorised displacement yachts were selected from varying shipyards to show that they all have similar ideas about arrangements.

For the construction principles, eight reference vessels were used ranging between 40 and 109 meters of length. Regarding the scope of 50 to 80 meters, one of the eight vessels is shorter and two of them are longer. Only two of the eight vessels are also used for their general arrangement because of lack of information. Just as the with the selection of the first twelve vessels, the eight for construction are chosen based on the same characteristics.

The mechanical diagrams are taken mainly from the two vessels that were both in the arrangement and the construction selection. This leaves a very narrow database, but the reason for doing this is that for these vessels the available information was quite complete. Moreover, this is done because mechanical engineering in current yacht design is chronologically prioritised after arrangements and construction have undergone some iterations. It is therefore expected that for a typical arrangement with a typical construction principle, a typical mechanical solution is also likely to be found.

4.2 Trends in main particulars

The first simple check to find out commonalities in super-yachts between 50 and 80 meters of length was to collect their most common shape. Based on the set of reference vessels with a pyramid shape, a second simple check is to compare their main particulars. The amount of decks, the cruising speed, the gross tonnage, the main dimensions, the number of crew and the number of passengers are available for most of the vessels and therefore compared in this section. The corresponding trend lines can be found in appendix A.

An interesting conclusion is that throughout the whole range of 50 to 80 meters, the vessels generally have room for 12 guests. This is easily explained as this number is the maximum allowed number of passengers on a ship for it to not have to comply with the SOLAS (Safety Of Life At Sea) code for passenger vessels. The amount of crew appears to increase with length. As rule of thumb it seems that from 50 meters onward an additional crew member is added with every 3 meters of additional length. The cruising speed for all vessels lies between 12 and 16 knots. Although there is a slight correlation between length increase and speed increase, the data points are rather spread out, as shown in figure 4.2. The conclusion from this data is therefore that there is a general spread of speeds for vessels with lengths between 50 and 80 meters rather than a trend.

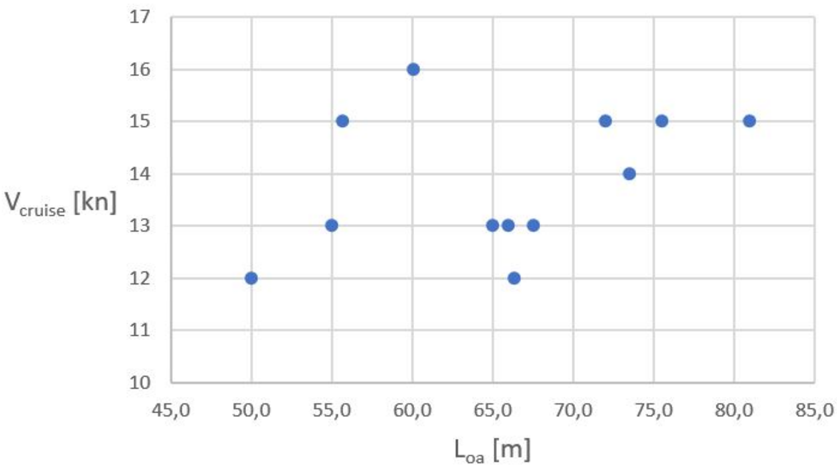


Figure 4.2: Trend: Length over all versus cruising speed

The number of decks in the reference vessels varies between four and six, while seven out of the twelve vessels have five. The vessels with six decks are more towards the longer end of the selection, but their gross tonnage does not tend to be significantly higher than other vessel close in the range. This is probably because the extra deck is a small one added on top of the vessel. In the lower en of the selection however, the vessels with only four decks, which are also the shortest two vessels with lengths of 50 and 55 meters, clearly end up with a lower gross tonnage as well. This is probably because the missing deck compared to the other vessels here is the tank deck.

Another interesting statistic is that the length over beam ratio of the selected reference vessels for the general arrangement varies between 5.04 and 6.21 with one outlier of 6.98. The lowest in this range having a beam of 13.1 meters and a length of 66 while the beams of all reference yachts vary between 9.5 and 13.5 meters. This one relatively wide vessel also has an exceptionally high gross tonnage and an extra deck on top. Another related statistic of this single yacht is that it has relatively many crew members on board. Therefore it seems that the added beam in this yacht has a causality with the added crew cabins.

4.3 General arrangement

The potential of design reuse in the non-owner parts below the main deck of super-yachts is explored by comparing the general arrangements of the twelve yachts in the range of 50 to 81 meters of length. The aim with this is to find commonalities in the topology of systems and compartment functionalities that can be used as a base for the dynamic platform. First of all, the watertight bulkhead positions are determined and with this also the amount of watertight compartments. Generally in yacht design, as few watertight bulkheads as allowed are used in order to make the perception of open space as large as possible. The next step is to document the compartmentalisation of functionalities. This is done by going through each of the general arrangements from aft to front and compartment by compartment state the rooms or big components that are inside the compartment. Figure 4.3 shows how the yachts are divided into compartments schematically. Most of the reference vessels turn out to have five or six watertight compartments. The minimum number of watertight compartments according to class is defined by the minimum number of bulkheads [5]. In the vessel range studied in this thesis, the minimum number of watertight bulkheads is four, one aftpeak bulkhead, two engine room bulkheads and one collision bulkhead, plus the amount of bulkheads required for damage stability in case of one compartment damage.

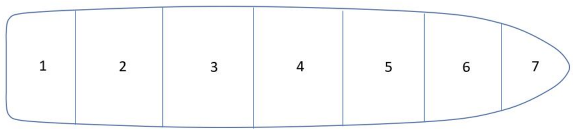


Figure 4.3: Yacht compartmentalisation

4.3.1 Functional compartment topology

Given the compartmentalisation defined in figure 4.3, functions of the enclosed compartments are defined. Per deck, below the main deck, the different types of areas encountered throughout the reference vessel range and their position in the compartmentalisation are noted. This way commonalities in the arrangement become visible in number of occurrence. An excerpt from this method is shown in figure 4.4. The numbers in the table represent the compartment numbers in which the concerning area is located on the concerning vessel. The full table containing the results of this study are given in appendix B.

Ship name	Beatrix	Vida	Taiba	Andreas L
Builder	Cantieri na	Heesen	Columbus	Benetti
GT [t]	651	740	1013	971
B [m]	9,5	9,6	10,2	10,4
Loa [m]	50,0	55,0	55,7	60,0
Lower deck				
Beach club/spa/gym	-	1	-	-
Tender garage	1	-	1	1
Engine room	2	2	2	2
Guest cabins	3	3	3	3,4
Crew mess	5	4	4	-
Crew cabins	4,5	4,5	4,5	5,6
Main staircase	3	3	3	3
Galley	-	-	-	-
Crew Lounge	-	-	-	-
Laundry	?	4	4	-

Figure 4.4: Functional areas per deck, allocated to compartments (excerpt)

For the lower deck for example, which is the first deck below the main deck, the encountered functional areas are an owners area with a beach club, spa and/or gym, a tender garage, the engine room, guest cabins, crew mess room, crew cabins, main staircase, the galley, crew lounge and laundry. The technical spaces on the tank deck consist of pump rooms, generator rooms, stabiliser rooms and thruster rooms.

4.3.2 Crossing multiple compartments

A general arrangement shows locations of major ventilation ducts, staircases, elevators, means of escape and corridors. At this low level of detail it is already clear that both structural and mechanical solutions have to be applied specifically at these locations as these components are crossing compartment boundaries. In order to apply standard solutions for construction and mechanical outfitting it is therefore important to give the concerning items a fixed location in the platform. As for the main staircases for example; most of them are situated right in the transverse middle of the vessels, so routing will not be able to go neatly through the corridors, but around the staircase and in most cases over guest cabins.

4.3.3 Functional arrangements

The whole range of vessels between 50 and 80 meters of length cannot be committed to one single arrangement. To enlarge the commonality rate, the set of reference vessels is split up into narrower selections. The first clear cut in the selection is made between 60 and 65 meters of length. At this transition, there is a step where the longer vessels both have a beach club/spa/gym and a tender bay in the aft whereas the shorter vessels have only either one. With the knowledge gained about the general arrangements, example functional arrangements are set up. The result of this method is that two arrangements were drawn based on compartment functionalities. One arrangement including the lower deck and tank deck for yachts in the range of 60 to 81 meters is shown in figure 4.5. Another arrangement, for yachts in the range of 50 to 65 meters is shown in figure 4.6.

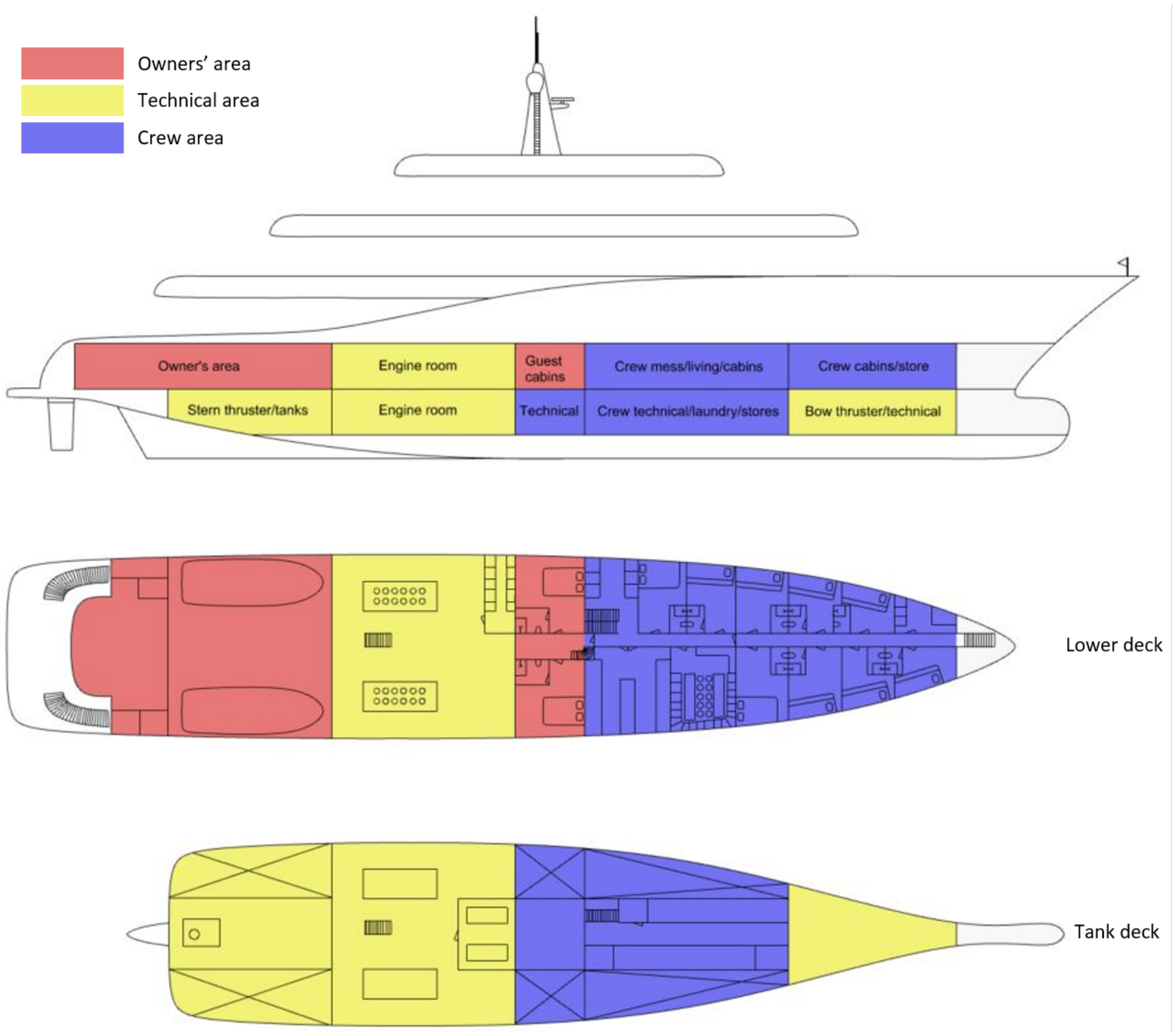


Figure 4.5: Extracted arrangement for yachts between 60 and 81 meters

The arrangement in figure 4.5 has on the lower deck the areas: engine room, guest cabins, crew cabins, crew mess, galley and storage rooms. This arrangement also has two compartments for owner spaces like a beach club, spa and/or gym and a tender bay. The rooms on the tank deck are as low as possible to save height in the vessel. The arrangement in figure 4.6 has only one deck with at least 1.9 meter headspace below the main deck. The areas depicted below the lower deck in this arrangement are small rooms, accessible via a hatch. The technical space below the lower deck can be seen as a corridor between the tanks, with a height lower than minimum standing height, like a crawl space. This area can be a pump room for example.

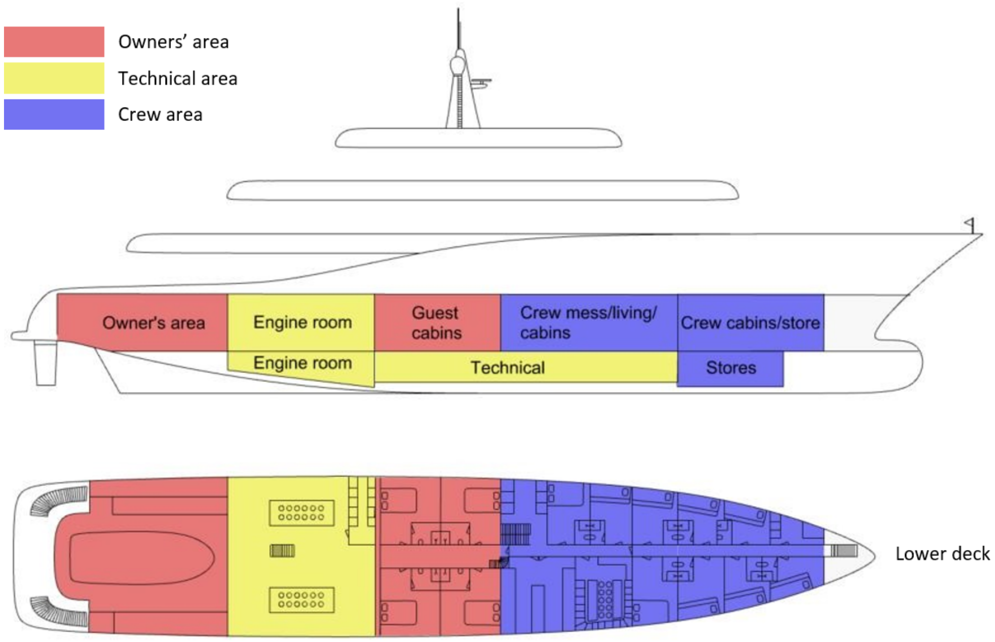


Figure 4.6: Extracted arrangement for yachts between 50 and 65 meters

The amount of available general arrangements for the dynamic platform should increase over time, based on evolving experience. In other words, more reference vessels can continue to be added to the selection either from in-house work at C-Job or from publicly available information on chartered super-yachts as was also done for this thesis. The result shows that, from a general arrangement point of view, design reuse in the non-owner spaces below the main deck of super-yachts seems feasible. However, the arrangements shown are still in very low level of detail. The expectation is that in further development of a dynamic platform more detail can be included.

An important part of the arrangement is also the tanks plan, which is not drawn into the arrangement yet. The tanks plan is one of the first things the naval architect starts working on, as this is directly based on the operational profile including endurance and speed requirements stated in the tender document. Fresh water and fuel capacities are determined in an early stage of design and therefore the required tank volumes. Looking at a couple of tank plans puts forward that the gross of all the tanks are always positioned in the centre of the vessel. This is mainly for stability purposes. There are no ballast tanks, but rather there is a fuel tank in the front and the aft. The fuel can be pumped back and forth between all the fuel tanks to counter for static stability and trim. Also interesting is that grey water tanks are separated between the different regions of the vessel to avoid unintentional cross-flooding in damaged conditions through the grey water system. The tanks plan is also quite dependent on the hull shape. However, for the set of reference vessels was chosen for a rough similar appearance, it is assumed that the underwater hull shape does not significantly differ.

4.3.4 Main conceptual variations

The two arrangements derived in the previous section are not valid for all the vessels in the reference selection. Figure 4.7 shows the commonality percentages for the arrangement derived for yachts in the range of 60 to 80 meters and figure 4.8 shows them for the 50 to 65 meter range.

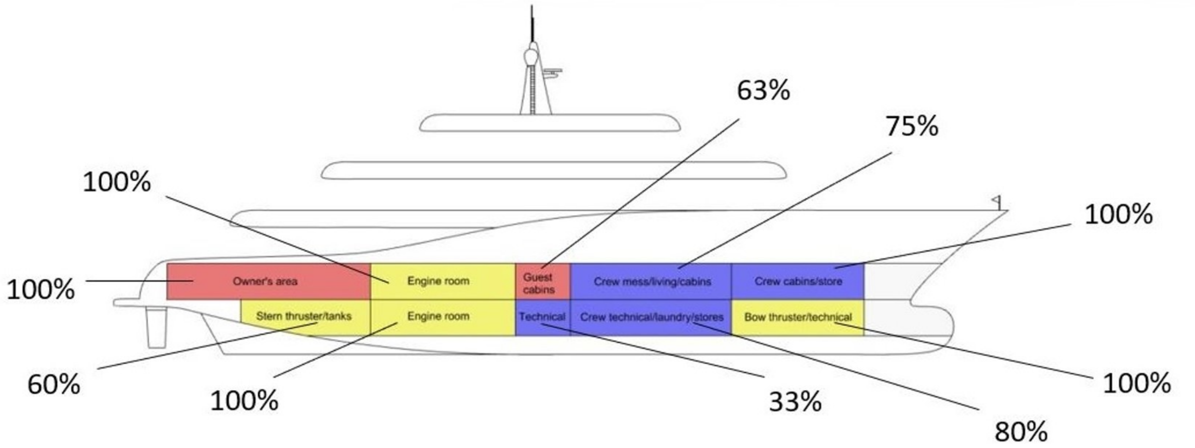


Figure 4.7: Commonality percentages arrangement 60 - 80 m

It is clear that some of the functions have a 100 percent topological similarity, these functions therefore show great potential for standardisation. Some other function-locations however, are less common. Especially those with a commonality percentage under 70 percent demand for a more flexible solution than full standardisation to keep the promise of a high level of customisation in yacht design based on design reuse. For these areas with lower commonality percentages a modular approach may be effective.

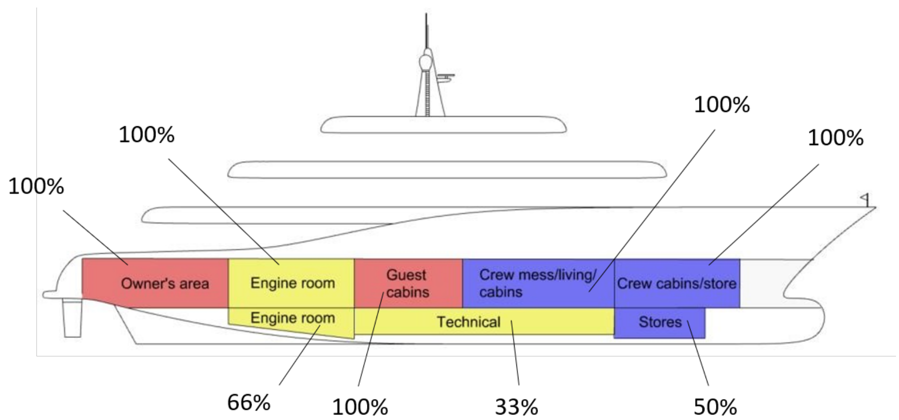


Figure 4.8: Commonality percentages arrangement 50 - 65 m

4.4 Construction plans

Shipyards often have their own standards for constructing their yachts. This statement implies quite a challenge for a comprehensive yacht platform strategy suggested in this thesis. Just as for the arrangements, a study regarding the commonalities and major differences in construction plans points is performed to substantiate the feasibility of design reuse in super-yachts. This is done by looking at main cross-sections. Main cross-sections tell a lot about the vessel's construction principles that are used throughout the vessel. They do so especially on the level of detail that is aimed for in this thesis because as the detailed construction based on extrusions of the main cross-sections. Local modifications to the construction are only done where grid mismatches or space claim issues arise.

4.4.1 Main cross-sections

Important aspects that are shown clearly in the main cross-sections are the number of decks, bulkheads, side girders and scantlings. Important units are found in the frame spacing and the web frame height. Based on the set of reference vessels discussed in section 4.1, main cross-sections were studied. Figure 4.9 and 4.10 show examples of a frame drawings of a 55 meter and a 71.5 meter yacht respectively. Both have longitudinal secondary stiffeners and low web frames. Figure 4.10 shows nicely how a space claim compromise was found between required standing height on the tank top and required tank capacity. On the centerline in this vessel people can walk on the tank-deck while the bilges are used for tank volume.

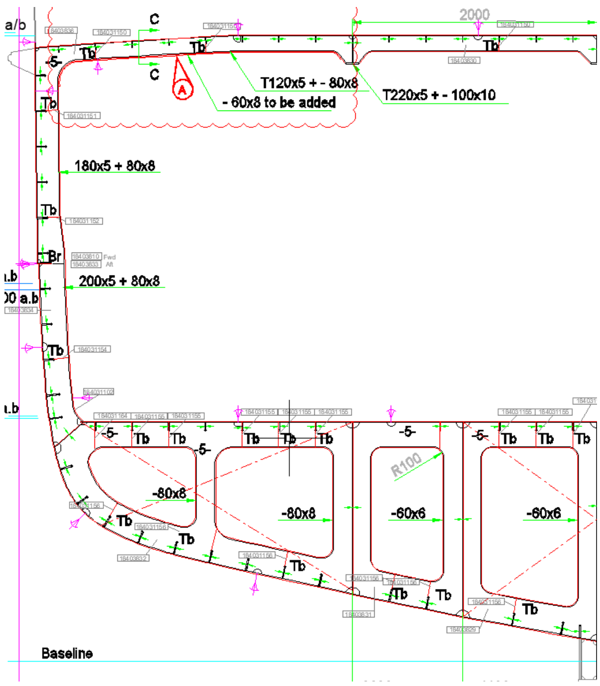


Figure 4.9: Frame 16 in a 55 m yacht

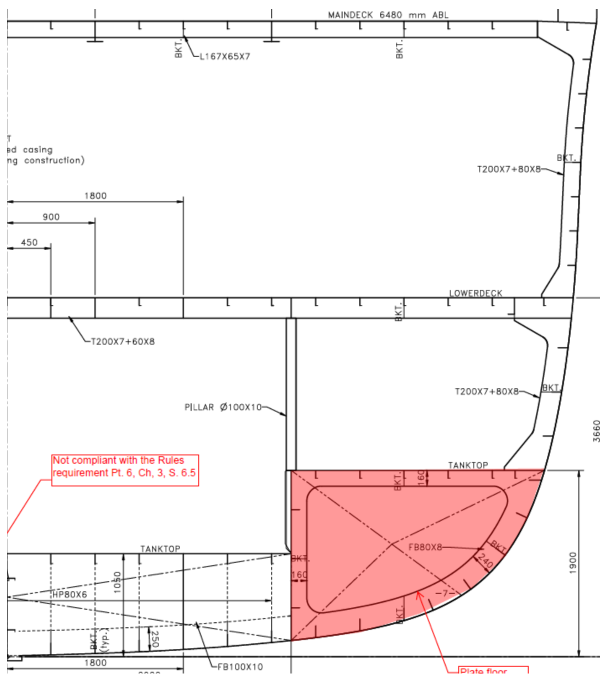


Figure 4.10: Frame 47 in a 71.5 m yacht

Remarkable is the low height of the web frames throughout the reference vessel selection, leaving the space for piping and ducting mainly below this in stacking height instead of through the girders. This is done in current yacht design because it saves time in solving multidisciplinary space claim problems in the design stage and because shipyards are often not equipped to perform pre-outfitting. With web frames constructed like this, the thickness of deck constructions are often pushed towards the minimum in order to win millimetres of space for interior.

Although the range of lengths in the vessels studied for construction is large, the difference in frame spacings seems not so significant. Ship size seems to have a direct effect on stiffener scantlings but not so much on frame spacings. Table 4.1 shows the frame spacings of the studied vessels according to their overall length. T denotes that the vessel is transversely stiffened. Striking is that the longitudinal frame spacing increases a bit with increasing ship length, whereas the web frame spacing decreases.

Ship length [m]	41.0	50.0	55.0	55.0	66.25	71.5	87.0	109.0
s [mm]	300	300	300	300	550(T)	450	495	500
S [mm]	1200	1200	1200	1200	1650	750	750	600

Table 4.1: Secondary (s) and primary (S) frame spacings

An interesting commonality found in the main cross-sections is that throughout the whole range of studies vessel between 40 and 109 meters, all but one are longitudinally stiffened. The one transversely stiffened yacht shows two other striking features; the ability to host 14 passengers (owner and guests), whereas most of the other vessel can host 12 passengers, and a slow cruising speed of only 12 knots. Next to these other features the vessel does not show more peculiar characteristics; it stays right in the middle of the trends found in other main particulars including the length over beam ratio. Since this is the only vessel in the reference selection to be transversely stiffened while it shows no other major design differences, it does not make sense to include transverse stiffening into the scope of the dynamic platform. For the dynamic platform only longitudinal stiffened design is therefore considered.

Although this is also shown in the arrangement drawings, the cross-sections show more clearly that in the vessels studied for construction principles ranging from 60 to 109 meters long, there are two decks below the main deck. These are the lower deck and the tank deck. In the range of 40 to 56 meters, there is only one deck below the main deck, but some compartments in the double bottom are also used for stores and technical spaces. All the yachts studied for their construction plans are designed with a double bottom in which the fuel, water, oil and bilge tanks are situated. Main cross-sections also nicely show how deck-penetrating objects like staircases are supported by structural solutions.

4.5 Mechanical schematics

The design for routing of ducts and pipes is generally done after construction and arrangements have been designed, as seen in section 2.2.3. The solutions for mechanical design are therefore studied by discussing routing with engineers at C-Job on the basis of plans for one of the vessels in the reference selection. The relevant mechanical components for space claim in the basic design phase according to the experts at C-Job are the grey/black water systems and especially the HVAC plans. As found in chapter 2, the HVAC systems on board of superyachts use up a significant amount of the available space both in arrangements as well as in deck heights. As the size of grey and black water piping is also assumed significantly large, this also taken into the scope. The other important mechanical aspects like firefighting, fresh water supply and electric cabling are not elaborated upon as stated in the beginning of this chapter.

4.5.1 HVAC principles

For superyachts, the heating, ventilation and air conditioning (HVAC) systems are the major power consumers next to propulsion. Regarding space claim these systems are extremely influential. The functions of HVAC on board of yachts are mainly to create a desirable atmosphere for living and to maintain environmental conditions in which equipment is able to function well. The space claim of HVAC systems depends on their installation principle. In super-yachts two HVAC principles are common; the central heating principle as depicted in figure 4.11 and the fan-coil principle as depicted in figure 4.12. Both figures were acquired from CEDengineering.com [2].

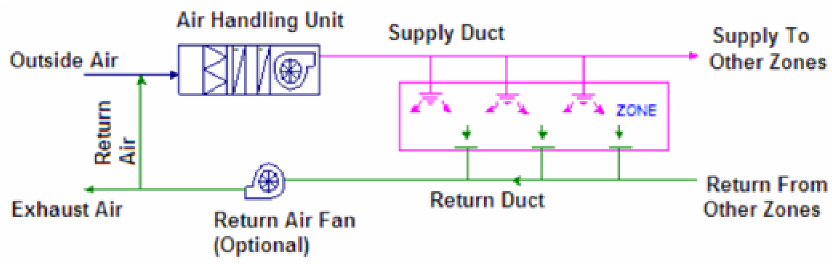


Figure 4.11: Central heating principle

There is a significant difference in space claim between the two principles. The space claim of the fan-coil principle is lower, because the cross-sectional area of the required piping for water is less than that of air distribution ducting. Although the central heating principle requires significantly more space in the height mapping of yachts, there are still reasons to choose for this principle. One of the reasons is the fact that the air-conditioning unit may be centralised and therefore more accessible for maintenance. Moreover, with central heating it may be easier to ensure better air quality and to avoid noise in the conditioned space.

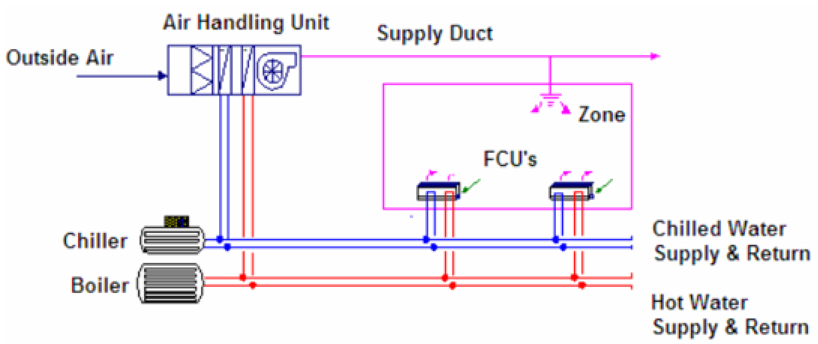


Figure 4.12: Fan-coil principle

Specific characteristics of HVAC that occur for both principles are that the ducting never crosses from one watertight zone to another. The air-conditioning units, also with the central heating principle, are designed either above or next to the conditioned room, to avoid unnecessary extra ducting and thus space claim. Some areas like the galley are directly ventilated to comply with fire integrity. The galley therefore has its dedicated air-conditioning and ventilation system.

4.5.2 Grey and black water principles

After the HVAC systems and routing, waster water systems and routing for grey and black water are the most space consuming mechanical aspects in the height mapping of super-yachts. Grey water is the collective name for return water from sink and shower drains and from other systems that use fresh water, like laundry. Where possible, the grey water layout is often gravity based, meaning that the water is drained towards the tanks using the potential energy from gravity of the water. Black water is the waste that is drained from toilets. This water is treated differently than grey water, often using vacuum pumps and a sewage system. Figure 4.13 shows a simplified diagram of how a common grey and black water system on board of yachts is set up.

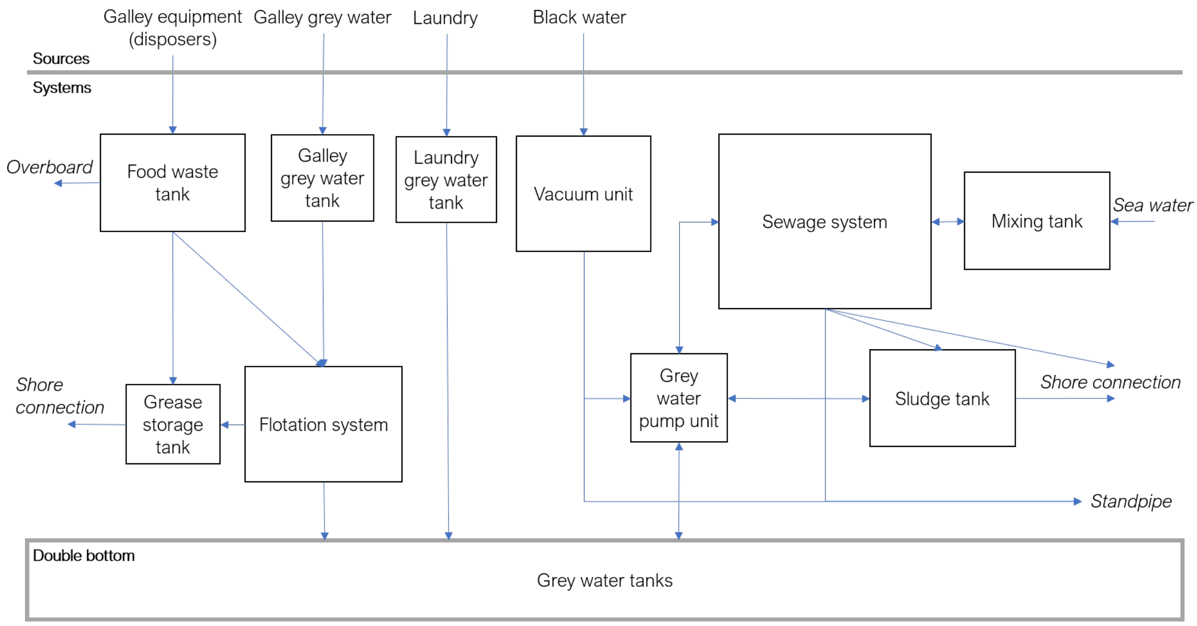


Figure 4.13: Simplified schematic grey and black water systems layout

Since grey water systems are often gravity-based, the routing of the pipes is done in the most vertical possible way. Tanks for grey water are therefore located as close as possible to the drains in the horizontal plane. While omitting the installation of extra pumps, wastewater pipes in yachts are often designed to go through watertight bulkheads using close-off valves to maintain watertight integrity. Sewage from guest, owner and crew areas are separated into different diagrams towards different tanks to avoid any pressure interface. This way the owner, the guests and the crew will not be able to notice the activation of each others grey and black water systems.

4.6 Conclusion

The results of studying the reference vessels enhance the feasibility of design reuse in the non-owner spaces below the main deck. Major commonalities are found in the functional arrangement of technical spaces and crew spaces. Although the rooms themselves may be arranged inside the watertight compartments a little differently, the topology of the compartment functionalities stays quite intact throughout the reference vessel range. Major variations found in the arrangement are related to what is referred to in this thesis as owner spaces, such as the guest cabins. More global variations are found in a transition between ship lengths of sixty to sixty-five meters. Above this transition yachts tend to have an extra deck and an extra watertight compartment compared to yachts under the transition.

Great commonality throughout the reference vessels is found in the construction principles. The vast majority of the studied vessels have longitudinal secondary stiffeners. Commonalities are also the number and position of watertight bulkheads, and the fact that the ducts and pipes are routed under and not through girders. Lastly all the studied yachts have in common that they have a tanktop on a double bottom in which tanks for fuel, fresh water and waste water are constructed.

The HVAC principles are mainly common on arrangement level, where the air-conditioning systems are split over different areas in the vessel. Owner areas, guest areas and crew areas therefore have their own HVAC systems. The same applies for the grey/black water systems. The grey/black water routing collects in the double bottom, where each separate system has their separate disposal tank. Major variations in HVAC systems is the execution principle. HVAC based on central heating or fan-coil units is a significant difference, but both are common. For grey/black water, the principle may vary between gravitational or vacuum pumped.

With the acquired knowledge so far gained in this thesis about the bottlenecks in the yacht design process at C-Job, the available design reuse methods and the commonalities in existing yacht designs, a suggestion can be made for an effective engineering lead time reduction strategy. The commonalities found in the non-owner arrangement allow for great standardisation under the main deck of yachts. Therefore, a standard, or integral, platform is expected to be effective. However, with the varying high-value wishes of the client, flexibility should be incorporated and therefore a modular platform may also be effective. Lastly, C-Job's initial desire was to find an ideal solution that could be scalable for any ship size desired by the client within the range of fifty to eighty meters. For this, a scalable, or parametric, platform would be effective. The next chapter describes the proposed solution, incorporating all three suggestions.

5 Scale-To-Order Strategy

The goal of reducing engineering lead time is expected to be effectively achieved by tackling the 'space claim' problem in super-yacht design, where much time is spent on iterating towards a satisfactory integration of all ship design disciplines. The strategy to achieve effective design reuse that will reduce time required to properly integrate all disciplines involves finding principle solutions to arrangements, construction and routing of ducts, pipes and trays. To serve the lions' share of yacht designs within the range of fifty to eighty meters of length, the innovative part of the strategy is to make these principle solutions scalable throughout the range. This chapter provides an answer to sub-question four; How can the relevant parts of super-yacht designs be made scalable? It also partially provides an answer to sub-question five; What constraints to the design of the superstructure are expected? This chapter starts with recalling the space claim problem as described in the previous chapters and then proposes a solution method, called Scale-To-Order, based on conclusions drawn in the previous chapters. This chapter then continues by sketching how the different parts of the solution are built-up by going through the different stages of the solution method between the start of design and the finishing of the basic design stage.

5.1 The space claim problem

The duration of yacht design in the concept stage and mainly the basic stage can be attributed primarily to the iterative nature of ship design. Iterations are made between the disciplines naval, mechanical and structural mainly because of inaccurate space reservations and mismatches between the naval arrangement grid and the structural grid. These uncertainties make for the different disciplines to start iterating the design towards an integrated feasible design, including the main construction plans and the arrangements of the engine room and technical spaces. During these iterations, conclusions are drawn that too little space was reserved for some aspects; this results in the need to make changes to the design. Moreover, the disciplines tend to nibble from each other's space during the earlier design iterations, resulting in a lack of space reserved for some aspects again. Especially the stacking of space reservations in vertical orientation, called the height map, is delicate. In yachts, there is a strong urge to maximise the headroom for interior aesthetics while minimising the space between decks, for exterior aesthetic reasons. This optimisation conflict results in squeezing the engineering of the decks, meaning the height map of construction and piping, ducting and cable trays, as much as possible. This struggle for space is further referred to as the space claim problem. Omitting the space claim problem will allow for earlier finishing of the basic design stage and therefore reduce the total engineering lead time.

5.2 The solution

The proposed solution is called the Scale-To-Order (S-T-O) strategy. This strategy suggests the use of a platform based on the available design reuse principles of modular, parametric and standard design. The more accurate these space reservations are made at an early stage of design, the fewer iterations need to be made to integrate everything properly. So, the solution to the space claim problem is to collect yacht designs and to reuse them. The most trivial manner to omit the space claim problem is by fixing the whole design. However, the goal of this thesis is to find a solution with a high perception level of customisation and therefore scalable based on the main dimensions. The solution presented in this report applies the three design reuse principles (standard, modular and parametric) in the part of the ship below the main deck and is further referred to as a tool called the 'dynamic platform'. The part above the main deck is then left to be Engineered-To-Order (E-T-O) as much as possible according to the clients' wishes, but within the constraints imposed by the dynamic platform. Figure 5.1 depicts this concept.

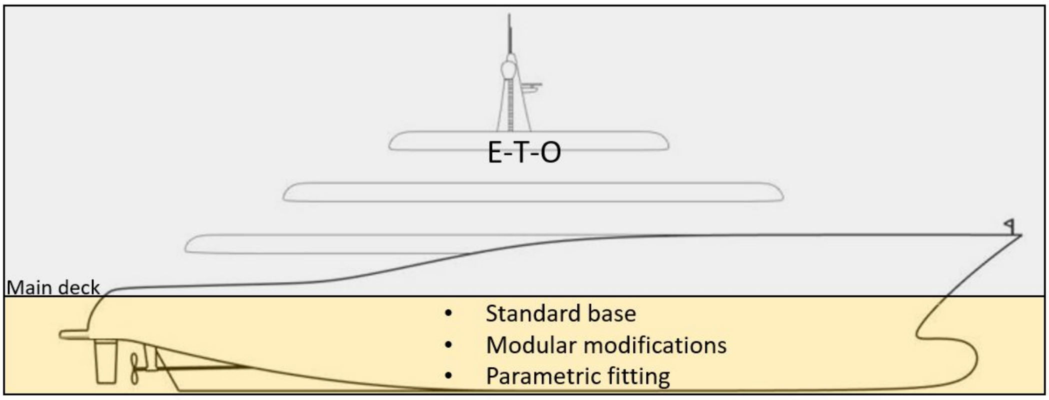


Figure 5.1: Design reuse principles in the dynamic platform

The three design reuse principles are applied in the dynamic platform in steps. Figure 5.2 shows the design flow belonging to this strategy. The first step is to meet with the client to discuss the ideas and vision for their yacht. The result from this meeting should be agreements on the specifications of the yacht to be built and at least fulfil the required input parameters for the dynamic platform.

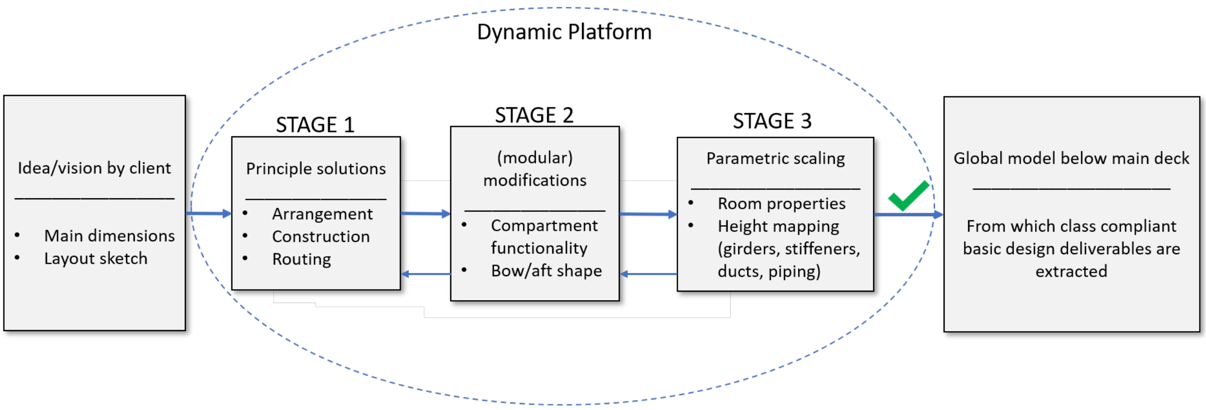


Figure 5.2: Schematic flow of the S-T-O strategy

Based on the main dimensions of the new project, a general arrangement is selected in the first stage of the dynamic platform along with corresponding construction, HVAC and sewage principles. This stage is further discussed in section . The set of chosen 'principle solutions' now functions as a base platform for stage two, where modifications can be applied. These modifications are implemented on a compartment functionality level or at the level of changing the bow and aft shape as discussed in section 5.4. Collectively the information in the dynamic platform tool acquired this far can be called a multidisciplinary global space claim model, or global model. The third and last stage in the dynamic platform, 'parametric scaling' is about scaling the global model based on room properties. The parametric scaling stage also serves as a check for the integrity of the dynamic platform after scaling and undergoing modifications. This stage is described in section 5.5. The outcome of the dynamic platform tool is a global model, from which the basic design deliverables for the non-owner spaces below the main deck of the specific super-yacht can be derived.

5.3 Stage 1: Principle Solutions

The arrangement of the dynamic platform is based on commonalities in a set of reference vessels discussed in the previous chapter. Significant differences in their arrangements were found in a transition area of yachts between 60 and 65 meters of length. Therefore, an example default arrangement for the dynamic platform is derived for the range of 60 to 80 meters. This is arrangement A as shown in figure 5.3, or figure 4.5. The yachts in the range of 60 to 80 meters will have a length over breadth ratio of 5.6 to support geometric scaling. The standard amount of crew members on board is 15 plus one for every 3 meters of length above 60 meters, for who space is reserved in the crew accommodation compartment. The cruise speed can be chosen between either twelve or 15 knots. This results in a choice between two engine types. A yacht with arrangement A will have two decks below the main deck and two watertight compartments aft of the engine room. The dynamic platform arrangement could in the future be broken down into more subdivisions as illustrated in figure 5.3. The discrete breakdown and limited amount of principle solutions is important because each variation brings complexity to the parametric scaling stage. Still, with C-Job's desire to stay shipyard-independent, there is a tendency to account for the variations found in HVAC principles for example.

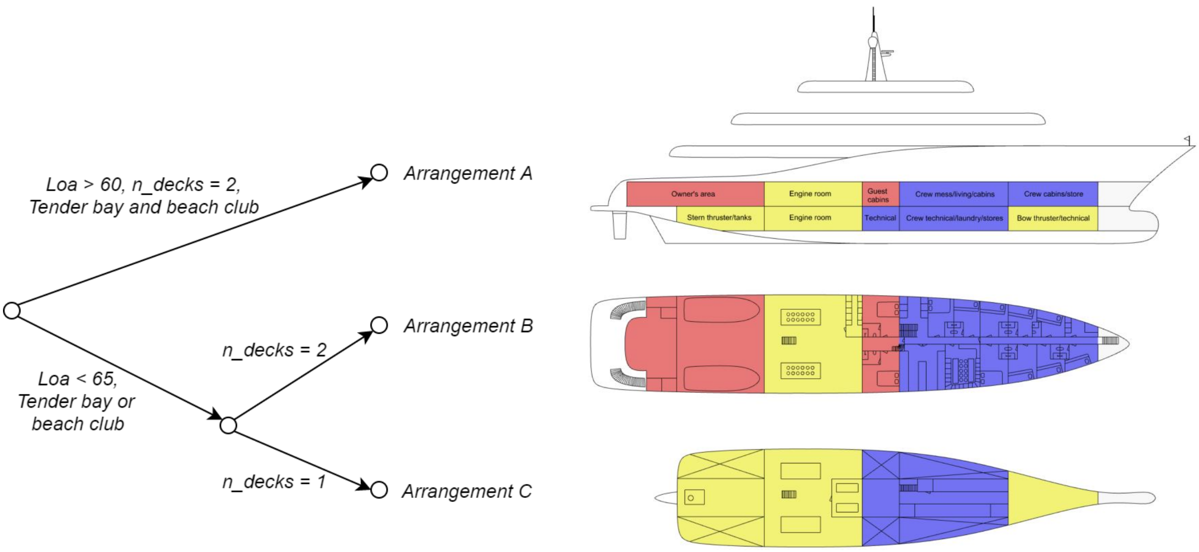


Figure 5.3: Left: Arrangement selection based on overall length; Right: Arrangement A

In the design process at C-Job, the three disciplines naval, structural and mechanical work simultaneously. At the end of each design stage, they have to finish their own set of deliverables. For the S-T-O strategy to be effective, the critical path of the design process must be shortened, meaning that all disciplines have to benefit. By standardising the arrangement, also the global model for the construction and the main routing diagrams based on standard principle solutions for HVAC and grey/black water sewage can be standardised to complete the height map and to match the grid. Also space reservations for the main technical components should come from a supplier database for accuracy. With the selected arrangement therefore also construction and mechanical principles are selected. With arrangement A, the construction is longitudinally stiffened, the bulkhead positions are known and the web-frame spacing is fixed. Girder and stiffener dimensions are then to be scalable via rule-based relations and they are integrated in the height map with the mechanical discipline. For example, the HVAC systems principle layout can be selected from two possible scenarios being a 'fan-coil' solution and a central heating solution as depicted in figures 4.12 and 4.11. Either solution results in a corresponding integrated height map with construction. To make the height map complete, also the main piping and cable tray routes are standardised in a similar manner.

To make scaling feasible, a secondary frame spacing is defined in stage one. It is important to keep in mind that any scaling, be it geometric or not, is done discretely based on frame spacing. Table 4.1 showed that the secondary frame spacing in a wide range of main ship dimensions changes very little. To come close to the known data and given the distinction made between arrangement A, B and C, two fixed frame spacings are chosen. For arrangement A the frame spacing is 500 mm and for arrangement B and C it is 300 mm.

5.3.1 Interface to the superstructure

The last part of stage one is the definition of the platform interface to the superstructure. Standardising the non-owner spaces, below the main deck, of the yacht imposes physical and regulatory restrictions to the main deck and upwards. On a global level the superstructure is constraint to maximum dimensions in order to fit the dynamic platform both physically and aesthetically, a maximum power consumption, total weight and centre of gravity. The superstructure should be close to a predefined total weight to prevent changes to the draft of the vessel and to the stability requirements. The longitudinal, transverse and vertical centre of gravity are constrained to ensure the stability characteristics of the yacht based on the dynamic platform do not change.

On a local, topological level, the upper part of the vessel should fit like Lego on top of the lower part. The interface is at main deck level. Therefore, the interface items become the main structural members, the staircases, elevators and escape hatches, the funnels, the galley duct, the location of HVAC units and the main mechanical routing. The AC units should be close to the corresponding air-conditioned rooms to avoid unnecessary complex routing of ducts and thus extra space claim. The galley requires a dedicated fire-proof ventilation shaft, which always ends above the watertight bulkhead deck. Figure 5.4 schematically visualises this.

The principle solutions and especially the platform interface have a limiting effect on the freedom of design for the superstructure and the owner spaces. In yacht design, custom changes are very common. Especially when using a fixed arrangement as a starting point also flexibility should therefore be incorporated. This is done in stage two of the dynamic platform.

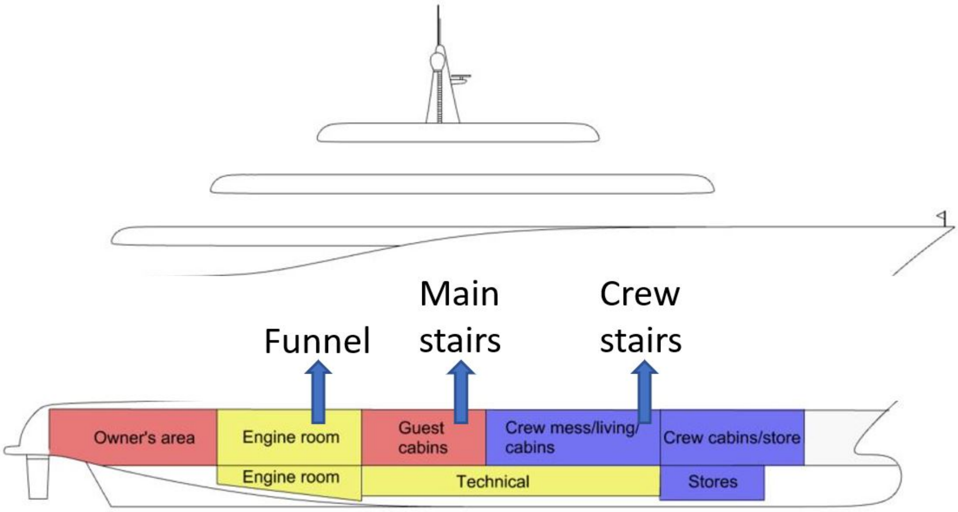


Figure 5.4: Interface to the superstructure

5.4 Stage 2: (modular) Modifications

The arrangement from stage one is almost certain to require local modifications to fit the wishes of the future yacht owner. Each modification also implies added lead time; this is then part of the bargain. However, from the arrangement commonality study the most likely modifications can be anticipated. For example, the guest cabins in arrangement A, which have a commonality percentage of 63% as shown on the left side of figure 4.7, may be replaced by a block hosting the galley. This likeliness may trigger to make a modular design where the galley and the guest cabins are interchangeable within the same default arrangement. Rooms can be interchangeable while fitting the boundaries to the adjacent rooms of the initial space reservation. This modular concept is illustrated on the right side of figure 4.7. Another driver for making modifications modular is that it may verify integrity of the design towards classification societies. With this modular approach also the default bow and aft shape of the dynamic platform can be modified. This allows for the selection of a straight bow over a bulbous bow for example.

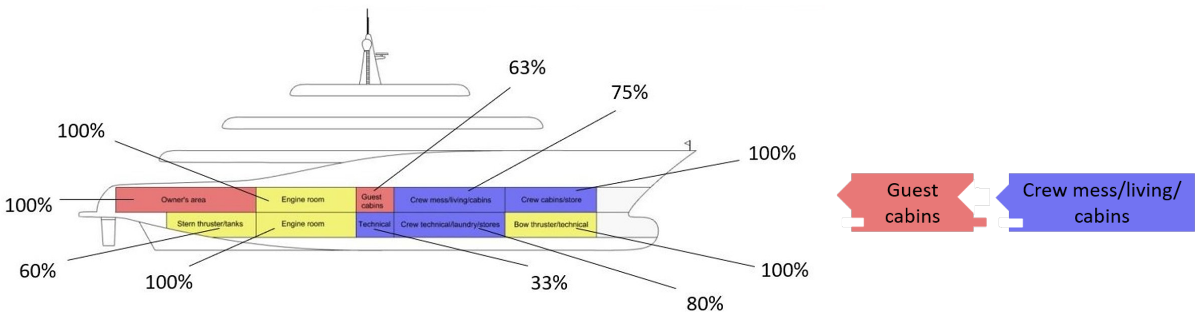


Figure 5.5: Left: Commonality percentages in arrangement A; Right: Modularity

Implementing modularity to capture the most likely modifications does not directly mean that custom modifications can not be made. Custom modifications should also be possible within the dynamic platform if they are treated with the same mentality as modular modifications. If the functionality of the guest cabin compartment should be changed to any other functionality that is not a pre-engineered module, then the modular interface to the adjacent compartments should still be utilised to keep the rest of the arrangement selected in stage one intact. The engine room also is a nice example of where modifications can be made and saved as a module if an alternative power plant configuration is desired. A custom modification designed to meet the modular interface to adjacent compartments can be saved as a new standard modular block for possible future reuse.

5.5 Stage 3: Parametric Scaling

The dynamic platform is meant to be scalable to fit the main dimensions that match the client's vision about his future yacht. This scaling is achieved through parametric models for the construction, arrangement and routing. To ensure integrity of the scaled global model and to simplify parametric formulation, scaling is done using discrete steps in duct and stiffener dimensions and based on discrete system capacities like that of the power plant and HVAC units. While the overall length of the vessel is used as the main input parameter for the dynamic platform, it goes in discrete steps. The secondary stiffener of frame spacing is defined in stage one and the overall length is scaled in steps of this frame spacing.

A great part of the parametric formulation of the structural design can be derived from rules and regulation, which in itself often consist of parametric formulations. The scaling of the arrangement is based mainly on geometric proportions while the topology remains fixed. Crew cabins for example scale geometrically, but the total number of crew cabins increases discretely with the length of the ship. The engine room scales with the size of the main engine and generators. These sizes are also discrete, but engine sizes for yachts in the range of fifty to eighty meters does not differ drastically. The power requirements of all the studied vessels could be served with engines from the MTU 4000 series [15] for example. The concerning engines would differ in the order of magnitude of around one meter in length and less so in the other directions.

Stage three of the S-T-O strategy also serves as a check for the integrity of the dynamic platform after scaling and undergoing modifications. It is a compliance check for mechanical and structural properties and their space claim and combined height map as well as stability, watertight integrity, fire integrity and for the power plant between the fuel supply and the exhaust. If compliance is not met somewhere in the dynamic platform, the algorithm steering the parametric model will notify the user so that he can solve the issue locally in the global model. An example of this is the re-routing of a local duct as a result of blowing up the local height map.

5.5.1 Rule-based Construction

The scaling of construction can be mainly based on classification guidelines. Since the construction principles were selected based on the chosen arrangement and the vessel's main particulars in stage one, just as in traditional ship design, the assumption is made that the construction is already optimised for steel weight and structural strength. Therefore it is also assumed that scaling the construction based on rules and regulation is feasible.

DNV GL, Bureau Veritas and Lloyd's register are known for their parametric formulations of rules and regulations. Well-known applications for this are DNV GL's Nauticus hull and Bureau Veritas' Mars2000. Engineers at C-Job have implemented these rules in tools that make for example setting up a class compliant mainframe quicker and easier. For example, AuTOM [4] is being developed, which is a tool that forms input to Mars2000 through parametric formulas based on a vessel's main particulars. Software developer NAPA [18], in cooperation with class bureau DNV GL, has put some effort in making their CAD software suitable for making ship 3D models ready for class approval. The fact that different parties are working on an integrated solution for design and class approval allows for the assumption that parametric ship design based on class rules and regulations is feasible for implementation in the dynamic platform.

5.5.2 Room properties

Like construction, scaling of mechanical systems cannot be done strictly geometric. Scaling of mechanical systems can be done based on room properties. Rooms are the blocks inside the watertight compartments that have a specific function; like the engine room, the galley and a crew cabin. The scaling of piping and ducting is based on the required capacities derived for each room and its thermodynamic properties. After going through the previous stages of the dynamic platform, expressions for the dimensions, weight and centre of gravity of each room can be expressed as well as their required capacities in terms of electricity, air and fluids. Figure 5.6 shows a schematic representation of room in general.

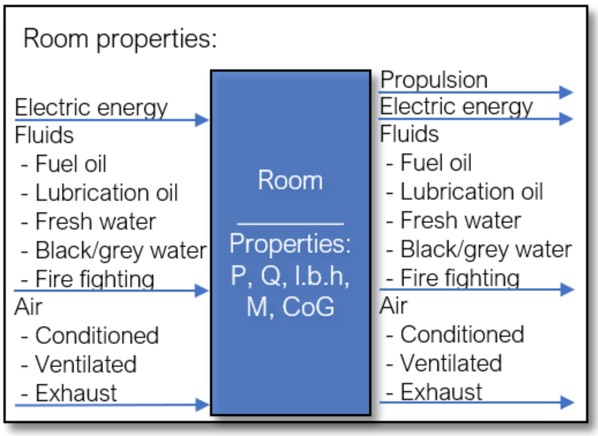


Figure 5.6: Room properties

The amount of incoming and outgoing air, fluids and electric energy determines the required routing to and from the room. To give a short example; Four main features of rooms are addressed by HVAC, these are air temperature, air humidity, CO_2-level and purity of the air (dust, bacteria and aromatic substances) [9]. For a crew cabin, the required HVAC system can be quantified by knowing how many people stay in the room, the desired air temperature, the ambient air temperature, the desired and ambient air humidity and the amount of CO_2 and water vapour exhaled per person. The most significant out of these characteristics decides on the actual required air flow through the AC unit and its required power. The duct dimensions can be derived straight from this, given a maximum air speed based on noise requirements. By making these kind of parametric relations for every room and knowing the principle solutions, space reservations for ducting, piping, AC units, engines, pumps and other equipment can be verified.

5.5.3 Height Mapping

The trick with scaling is to keep the height map with the right space reservations intact. Since the construction, piping and ducting are not scaled based on geometric proportions, scaling them will influence the integrated height map. The routing of piping and ducting are defined as principle solutions. However, since routing may have to cross the height map of a room to get to the next one, as illustrated in figure 5.7, merging the required pipe and duct capacities may rise over proportionate. This may happen for example when more crew cabins are added to a compartment in the dynamic platform when it is scaled to a higher length and all the cabins rely on the same AC unit. In case of such an incompliance the user of the dynamic platform is warned and a step back to stage three must be made to modify a part of the design so compliance can be met.

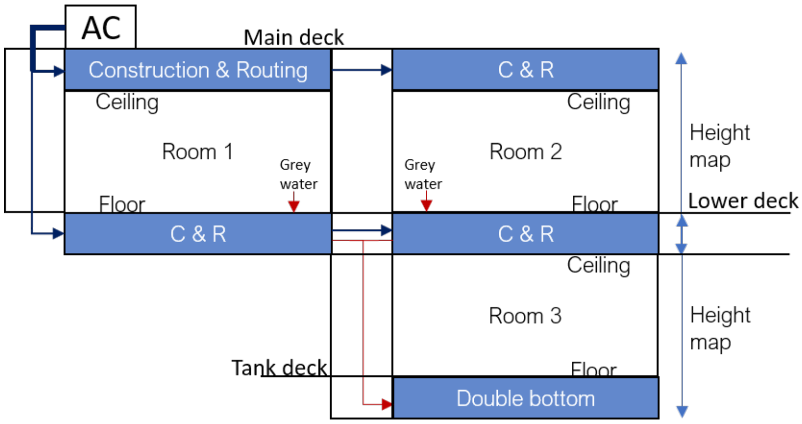


Figure 5.7: Height mapping

5.6 Conclusion

The S-T-O strategy suggests implementation of three design reuse principles. First of all a standard base with principle solutions for arrangement, construction and routing. Secondly, it suggests to apply modularity to account for anticipated modifications and to make sure that custom modifications are saved in a database as a new module. The third principle is to make the platform scalable based on the overall length of the vessel. This scalability is incorporated as it is expected to contribute to the customisation of yachts. The dynamic platform is scalable through parametric relations in a global model of the ship. The arrangement part in this is based on geometric scaling. The construction is based on a fixed frame spacing, a discrete number of geometrically scaled frames and stiffener dimensions that are scaled based on class rules. The length of ducting and piping is scaled geometrically, while their cross-sectional areas and thicknesses are scaled based on the required capacities that are dictated by the room properties.

The dynamic platform, as a part of the whole ship, imposes constraints to the way the superstructure is designed. On a global level these constraints are maximum dimensions, a maximum power consumption, a fixed total weight and a fixed centre of gravity. On a local, topological level, the superstructure has to match the items penetrating the main deck. Also some items, like AC units, need to be around or near a specific position.

The S-T-O strategy using the dynamic platform is expected to contribute to reduction of engineering lead time by cutting the iterations spent on reworking towards a design integrating the different design disciplines and tackling the space claim problem. The next chapter elaborates on the expected impact that the S-T-O strategy will have on the design routine at C-Job and the reduction of engineering lead time that it may bring.

6 Expected Impact on Yacht Design

With the aim to reduce engineering lead time for super-yachts, while maintaining the impression of a custom yacht towards the owner, the S-T-O strategy was proposed. In order to develop this method, three topics were analysed; the design process at C-Job, theoretic principles of design reuse and commonalities in existing super-yacht designs. This chapter elaborates on the expected impact of the S-T-O strategy on the design process at C-Job and therefore provides an answer to sub-question six; How would the dynamic platform impact the design routine at C-Job? It does so by formulating an educated expectation of the effectiveness and efficiency of the strategy in section 6.2. This section also elaborates on how the constraints to the superstructure design affect the reduction of engineering lead time and therefore contributes to answering sub-question five. After that, validation of the strategy is expressed, based on the expertise of engineers at C-Job and based on the evaluation of the literature studied in chapter 3. This chapter closes off with a discussion on the outcome of the S-T-O strategy, as a result of the validation.

6.1 Start of Design

To effectively apply the S-T-O strategy, the shipyard, designer or other client should be aware of the potential of using the dynamic platform in the first negotiations with their client; the future super-yacht owner. This is because the strategy will be most effective when the initial requirements of the yacht align the required functional input for the dynamic platform. This way, the yacht owner can consider the dynamic platform offer at his own pace. For effective application, also suppliers and sub-contractors need to be aware of the S-T-O strategy. As Nieuwenhuis [12] stated, this can be done via frame contracts. Clear predefined orders that have been communicated to a supplier of certain equipment on beforehand for example can contribute to ensuring on time delivery of parts for the shipyard.

6.2 Outlook on engineering efforts

The reduction of engineering lead time is the main expression of effectiveness of the S-T-O strategy. Effectiveness, however, could also be reduction of effort. In this thesis reduction of engineering lead time is aimed for by means of reducing effort. In other words, the aim of the strategy is to shorten the critical path by reducing the efforts that make this path. Although the effectiveness is leading in this thesis, also the expected efficiency is important for feasibility of the strategy. Striving for both an effective and an efficient solution means reducing both lead times and effort as well as limiting the amount of effort required for establishing the tool being the dynamic platform. The impact of stage two in the strategy is that some effort must be returned to the design process to keep track of the custom modifications that are done and to keep updating the module database to enhance effectiveness of the strategy in the future.

6.2.1 Effectiveness: engineering lead time reduction

Figure 6.1 shows how the impact of applying the S-T-O strategy is contemplated in two steps from the original engineering lead time. It is simplified to a distinction between design and production and between the hull and the superstructure. The hull in this case means everything below the main deck and the superstructure means everything from the main deck upwards.

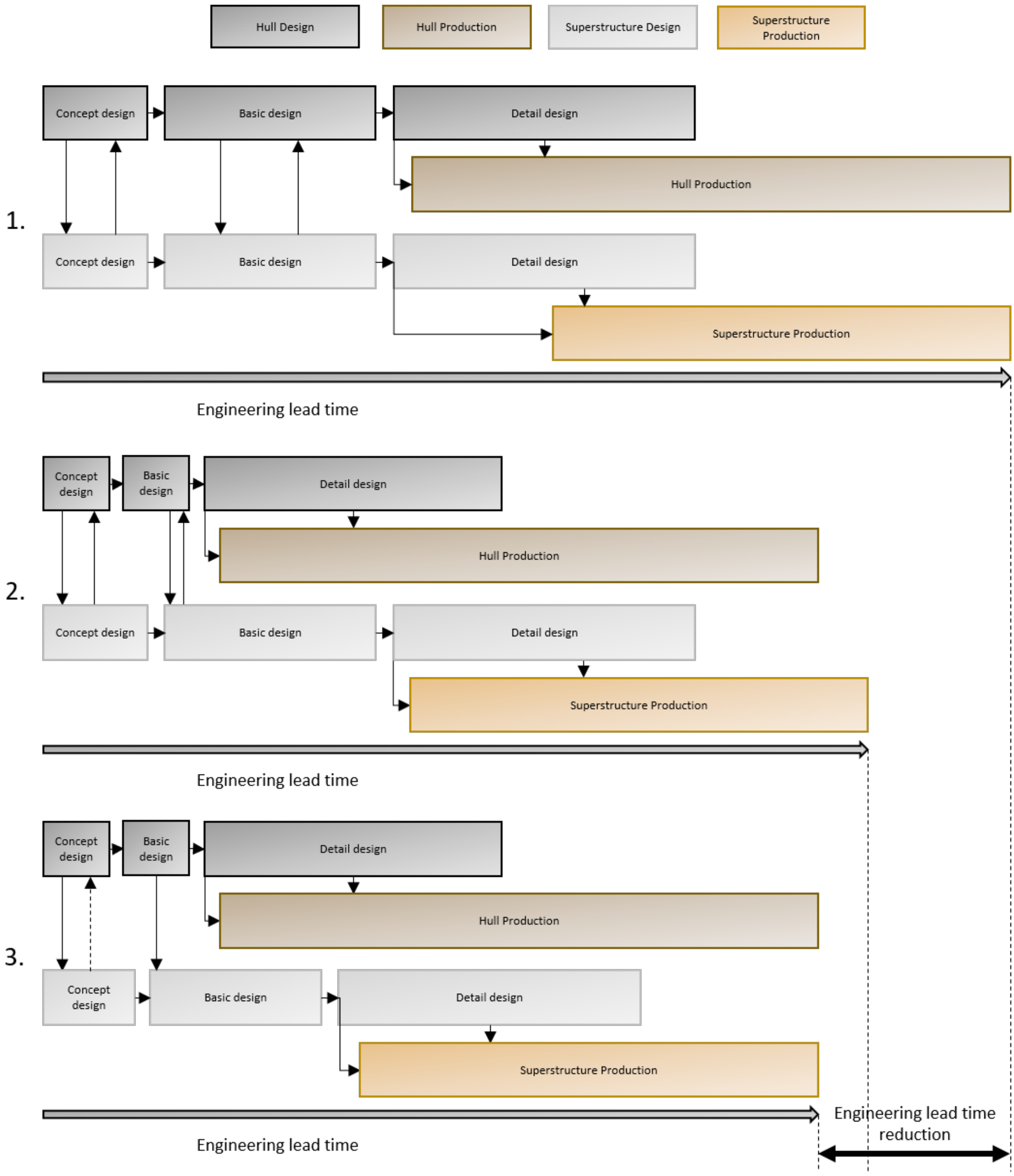


Figure 6.1: Engineering lead time reduction

The second timeline shows the impact of the strategy applied to the hull while the superstructure process is left untouched. There is already a profit of approximately a maximum of three months just by pulling end of production of the lower part of the vessel upfront. This is because in the current engineering lead time, the production of the superstructure is delayed by approximately these three months to make sure the production of the hull and superstructure is finished at the same moment. The duration of the concept and basic design stages together is roughly nine months. If the lead time of the concept and basic stages of current design of the lower part of the yacht are reduced by 30% due to application of the S-T-O strategy, then this three-month total engineering lead time reduction is already feasible.

The S-T-O strategy, however, is expected to cut even more effort and lead time in the design phase of the lower part of the vessel. When looking at figure 2.4, using a standardised set of arrangement, construction and routing solutions would make many of the steps in the design routines of all three disciplines redundant. This makes sense, as omitting the iterations performed to solve grid mismatches and space claim clashes can only be done if the steps prior to them have already been finished. Figure 6.2 shows an alternative timeline with the paths of the three main disciplines, using the three stages of the dynamic platform.

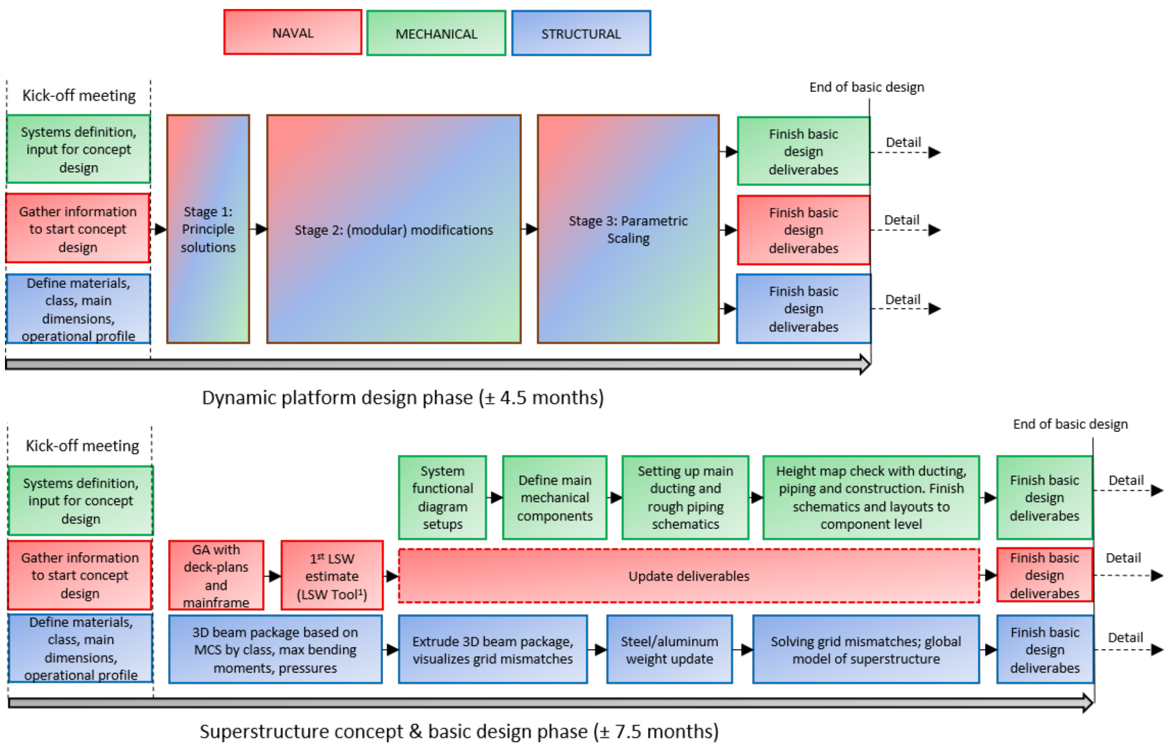


Figure 6.2: Schematic timeline of the disciplines in dynamic platform and superstructure design

Using the strategy, the first design iteration already provides a very accurate solution. The question therefore remains; what is the expected duration of the concept and basic design process of yachts below the main deck with application of the S-T-O strategy? At least there will still be a kick-off meeting and the basic design deliverables of each discipline will still have to be finalised. On top of that, local modifications must be engineered and the parameters for the space claim model must be set correctly. The assumption is therefore made that the concept and basic design lead time of nine months of the yacht below the main deck can be reduced by 50%. Looking at the third timeline in figure 6.1, this means that on top of the earlier mentioned three months, another one-and-a-half month can be saved if it was only for the 'hull' part of the vessel.

So, to go a step further, the total engineering lead time can be reduced even more if the lead time of the superstructure concept and basic designs are also reduced. This can be achieved by imposing the constraints from the interface of the dynamic platform as discussed in section 5.3.1 onto the superstructure. The constraints to the superstructure as they were proposed may shorten the design lead time of the superstructure enough already to gain the extra one-and-a-half month as the designer is forced to match the structural grid from the dynamic platform and because some of the major space claim items are already defined. Another way to reduce the design lead time for the superstructure may be to design the structural skeleton that matches the grid from the dynamic platform on beforehand. This skeleton can then maybe also include accurate space reservations for the main piping and ducting and staircases. The effects of the constraints to the superstructure are recommended to subject to further research.

The main take-away here is that at least three months total engineering lead time reduction can be achieved by applying the S-T-O strategy. More lead time reduction can be achieved if also parts of the superstructure are taken into the dynamic platform scope. Note that three months of engineering lead time reduction does not seem much, but the scope of this thesis was the design phase, as practised by C-Job. The reduction of lead time of the design phase it self is rather significant. As said, with a three month reduction and a nominal lead time of nine months, a 33% lead time reduction at C-Job is achieved. This estimation leads to questioning the expected efficiency of applying the strategy.

6.2.2 Efficiency of the S-T-O strategy

For the dynamic platform to take form a programmer should make an algorithm, or an optimisation model, that turns main concept drivers as input into the definition of the characteristics required for class approval in principle. The algorithm then optimises values in the pre-defined parametric ranges. Validation of the dynamic platform approach would then be achieved if the algorithm returns a feasible class approved design for each feasible set of input parameters. Time spent: An estimate is that the effort to fully build the dynamic platform with its space claim model and including the approval by class will not exceed the effort spent

Can the dynamic platform be realised with an equivalent amount of effort that is spent during three months of yacht design? The expected amount of required effort to establish the dynamic platform is estimated by dividing it in two parts. Firstly, there is the 'design part', and secondly there is the 'programming part'. Let's assume that designing the dynamic platform takes the same amount of effort as the actual concept and basic design of the lower part of a yacht that would fit in the dynamic platform spectrum. Then this is equals about four-and-a-half months of engineering effort by roughly fifteen people working full time, which would add up to around 9000 hours. If the programming part of the dynamic platform takes a similar amount of effort, then C-Job must sell six dynamic platform yachts at a one-and-a-half month-effort discount compared to the original offer to earn back the investment.

6.3 Validation of the S-T-O strategy

The S-T-O strategy can be classified as an engineering design method. The method is partly based on standardisation and partly on simulation of design. Relevant validation methods are therefore found in the modelling process of Sargent [16] and the validation square of Seepersad et al. [17]. Both models, however, assume actual implementation of the method to be validated. This makes sense as a design method based on simulation, without implementation, remains a potential solution or strategy and not an actual application. Therefore from both Sargent's and Seepersad's validation models parts are used to validate the S-T-O strategy as best as possible, which comes down to achieving face validation and theoretical structural validity.

6.3.1 Theoretical structural validity

Seepersad defines a method to validate new engineering design methods by applying the 'validation square'. The validation square as shown in figure 6.3 is built on qualitative and quantitative evaluation of the suggested method. The effectiveness of the new method is validated by the left (structural) side of the square, which is the qualitative process. The efficiency is validated by the right (performance) side, which is the quantitative process. For now, theoretical structural validation is performed by evaluating the literature that forms the base for the new method.

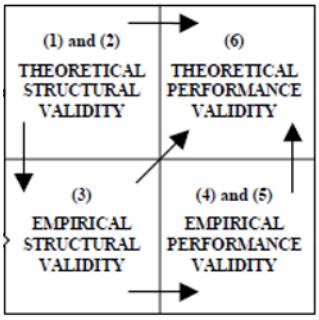


Figure 6.3: Seepersad's validation square

Theoretical structural validation means critically evaluating the literature used as a base for the S-T-O strategy. As Seepersad says; Constructs benchmarking for new constructs must be regarded as widely accepted. Chapter 3 gave a review of the literature from which the constructs that form the basis for the S-T-O strategy are taken. As Nieuwenhuis states, standardisation in mechanical systems and routing has good potential to reduce engineering lead time. Different yacht builders have shown that standardisation plays a part in their business model, leading to the thought that it contributes to a higher profit or engineering efficiency. Also the principles of modular design and parametric design are proven in shipbuilding applications and should be accepted as such.

6.3.2 Face validation

Two aligning concepts introduced in Sargent's paper are face validity and conceptual model validation. Conceptual model validation means examining the underlying theories and assumptions for correctness. The model representation of the problem entity should be accepted as reasonable for the intended purpose of the model. Face validity is done by having experts on the problem examine the conceptual model and see if it is correct and reasonable to serve its purpose.

Face validation is acquired by having experts at C-Job have a critical read through this thesis and by discussing the S-T-O strategy with classification society DNV GL and with yacht designer Espen Øino, who was introduced to the S-T-O strategy at the Monaco yacht show of

2019 using the poster shown in appendix C. Various engineers at C-Job have expressed their belief in the effectiveness of the strategy and the usefulness of its purpose. Another graduate student is already assigned to continue with the idea proposed in this thesis. Experts from DNV GL have expressed their interest and several meetings between members of C-Job and DNV GL have taken place to discuss the future of the S-T-O strategy and how the companies could help each other.

A major downside of the current formulation of the strategy is expressed as it being labour intensive. Despite the fact that R&D is always needs investments, the projected development duration of roughly 9000 hours is high. The short term efficiency of developing the dynamic platform seems quite low. Therefore the risk of developing the dynamic platform tool is considered a significant disadvantage. A more detailed road map of further research to the S-T-O strategy is expected to enhance confidence in the investment efficiency.

6.4 Conclusion

The S-T-O strategy is expected to accommodate engineering lead time reduction in the design phase of the non-owner spaces in super-yachts ranging between fifty to eighty meter of length. If the superstructure is assumed unaffected by the strategy, then a lead time reduction of three months can be achieved. This is possible because the production of the superstructure usually takes three months shorter than the production of the hull. Also, this reduction assumes awareness and preparedness of suppliers and sub-contractors such that they do not get on the critical path of the engineering lead time. With this three month reduction, the design and production of the superstructure become the critical path as more reduction is expected to be achievable in the design of the non-owner spaces. If the lead time of the design phase of the superstructure can also be reduced, then the S-T-O strategy is expected to accommodate four-and-a-half months engineering lead time reduction. In return, a rough estimation is made that an investment of 9000 hours is required to establish the dynamic platform. Therefore C-Job has to sell six dynamic platform yachts at a one-and-a-half month-effort discount compared to the original offer to earn back the investment. The S-T-O strategy is based on constructs from literature that was found trustworthy and engineers within C-Job and DNV GL expressed their belief in the strategies' potential. However, the investment of 9000 hours seems quite high.

Conclusion

Engineering lead time reduction in super-yachts is believed to be effectively accommodated by the Scale-To-Order strategy. This strategy was formulated based on the answering of six sub-questions to support the main research question. The answers to the sub-questions and the main research question are summarised respectively in this conclusion.

The design deliverables required for production are dependent on the duration of the iterative concept and basic design process. The aspects of the design phase that seem the most effective to seek time reduction in are mainly found in the iterations due to space claim, in particular of the technical systems and construction, and grid mismatches between the naval arrangement and the construction. High accuracy of space reservations in an early design stage is expected to contribute to engineering lead time reduction.

To avoid strong limitation of the level of customisation of the owner spaces, which for now are left engineered-to-order, types of design reuse most effective to apply for the design of the non-owner spaces in super-yachts are full design standardisation, modular design and parametric design. Together with the commonalities found in existing super-yacht designs, these design reuse principles are suggested accordingly in the S-T-O strategy.

Major commonalities are found in the functional arrangement of technical spaces and crew spaces. Major variations found in the arrangement are related to what is referred to in this thesis as owner spaces, such as the guest cabins. Investigation using a sample set of yachts has shown that within the range of fifty to eighty meters of overall length two distinct layouts can be used to represent all yachts globally. The applicability of these layouts can be enhanced by introducing partial modularity. The distinction between two layouts is based on a transition between ship lengths of sixty to sixty-five meters. Above this transition yachts tend to have an extra deck and an extra watertight compartment compared to yachts under the transition.

Typical construction layouts of the studied vessels show great commonality. Commonalities are found where the number and position of watertight bulkheads is consistent, the ducts and pipes are routed under and not through the girders, and the secondary stiffeners are longitudinally oriented. Also great commonality is found in the longitudinal frame spacing, which allows for the distinction of two frame spacings that match the two arrangement layouts. The HVAC principles are mainly common on arrangement level, where the air-conditioning systems are split over different areas in the vessel. The same applies for the grey/black water systems, that also show commonality in their systems layout. For HVAC, the systems layout varies strongly between central heating or using fan-coils.

With the known commonalities in yachts and the available design reuse methods, the S-T-O strategy suggests a tool called the dynamic platform. In this tool all three design reuse principles, full standardisation, modular design and parametric design are used. The scalable part of the dynamic platform can be based on parametric relations in a global model of the ship. The main parameter of the dynamic platform is the overall ship length, which can be varied in discrete steps that match the frame spacing. The arrangement part in this is based on geometric scaling. The construction is based on a fixed frame spacing, a discrete number of geometrically scaled frames and stiffener dimensions that are scaled based on class rules. The length of ducting and piping is scaled geometrically, while their cross-sectional areas are scaled based on the required capacities that are dictated by the room properties.

The dynamic platform, as a part of the whole ship, imposes constraints to the way the superstructure is designed. On a global level these constraints are maximum dimensions, a maximum power consumption, a fixed total weight and a fixed centre of gravity. On a local, topological level, the superstructure has to match the items penetrating the main deck. Also some items, like AC units, need to be around or near a specific position.

If the superstructure is assumed unaffected by the strategy, then a lead time reduction of three months can be achieved. This is possible because the production of the superstructure usually takes three months shorter than the production of the hull. If the lead time of the design phase of the superstructure can also be reduced, then the S-T-O strategy is expected to accommodate four-and-a-half months engineering lead time reduction.

With the knowledge gained in this thesis, an educated answer can be formulated to the main research question; How can reuse of design of the non-owner spaces on super-yachts, support reduction of engineering lead time at C-Job? Engineering lead time reduction in the design phase of super-yachts can be supported by doing three things to the non-owner spaces below the main deck. Firstly, standard base topology with standard construction, HVAC, piping and cable principles. Secondly, modular variations to the parts known to have more than one common function assignment. Other functional variations will have to be engineered-to-order, but to make the dynamic platform effective, these new solutions should match the grid of the adjacent spaces, so that the rest of the platform stays intact. Thirdly, sizing of the (standard) systems, including the construction, ducting and piping is done using a parametric model with the overall ship length as main input. This parametric sizing also serves as a check for space claim, stability, watertight and fire integrity, structural strength and compliance of power plant between the fuel supply and the exhaust.

Recommendations

Proposing the Scale-To-Order strategy in this thesis is like looking at the top of an ice-peak from a seagulls perspective. Developing the Scale-To-Order strategy further according to the projected expectation of nine-thousand hours suggests that a lot of work needs to be done before it pays off. Further research may be done on the following topics to take the Scale-To-Order strategy to the next level.

Three months engineering lead time reduction

Given the volume of expected required hours to establish full functioning of the dynamic platform, in a next iteration of S-T-O research the efficiency may be optimised for an effectiveness of exactly three months engineering lead time reduction. By reducing the level of detail to the arrangement, construction and routing solutions aimed for in this thesis less effort is cut in the designing of the lower part of the vessel, but perhaps this reduces more than proportionally the required amount of effort for establishing the dynamic platform. Standard solutions to specific constructions having a high impact on owner spaces like funnels, shell-doors, helicopter-decks and cranes may already contribute significantly to the effectiveness of the dynamic platform. With reducing the level of detail and the required effort for establishing the dynamic platform, the risk C-Job would take with this investment is reduced. Firstly, because the overall investment is lower, and secondly because the level of customisation to the yachts may be less constrained while still achieving three months of engineering lead time reduction.

Allowable ranges

The scalable part of the current strategy seems the trickiest part and also the most innovative. Making a full list of parameters and parametric formulations of everything in the global model and a first effort to define the allowable ranges of the parameters in the dynamic platform should make it more tangible. Perhaps yachts beyond the range of 50 to 80 meters can be served by the same tool. A first effort is being made by another graduate student at C-Job as we speak by modelling a parametric mainframe.

What is custom?

The counterpart of research to standardisation and commonalities in the lower part of the ship is the answering of the question what parts of the ship are the least common and what clients typically value the most. To know this may allow for standardisation to be taken to an even higher level whilst customisation of the aspects of the ship that are the greatest customisation drivers is still in effect.

Detail engineering

The level of detail aimed for with the current strategy is that of basic design deliverables. Since detail engineering is still the most time consuming part of the design process, further research to the feasibility of extending the S-T-O strategy to the detail design stage may be valuable.

Modularity

With the innovative nature of technology and shipbuilding, enhanced modularity in the S-T-O strategy may contribute to broadening its application field within the yacht sector, serving also less common yacht types. Research may for example be promoted for modular power plant configurations, allowing for alternative fuels to make their way into the dynamic platform.

Pre-outfitting

The examined construction plans from the selected reference vessel range showed that ducting through girders is rarely done. The dynamic platform opens up the opportunity to design for pre-outfitting more efficiently. An example for a pre-outfitting solution is shown in figure 6.4. An advantage of these kind of solutions may be a lower space claim in the height map by construction and routing. Another advantage may be the lower steel weight that such a construction would imply by creating greater extreme fibre distances, but cutting out material in the webs where no shear resistance is required. Pre-outfitting is a proven production method in other ship types like cruise vessels, so a double engineering lead time reduction can be achieved by implementing pre-outfitting in both the dynamic platform strategy and production at the shipyard.

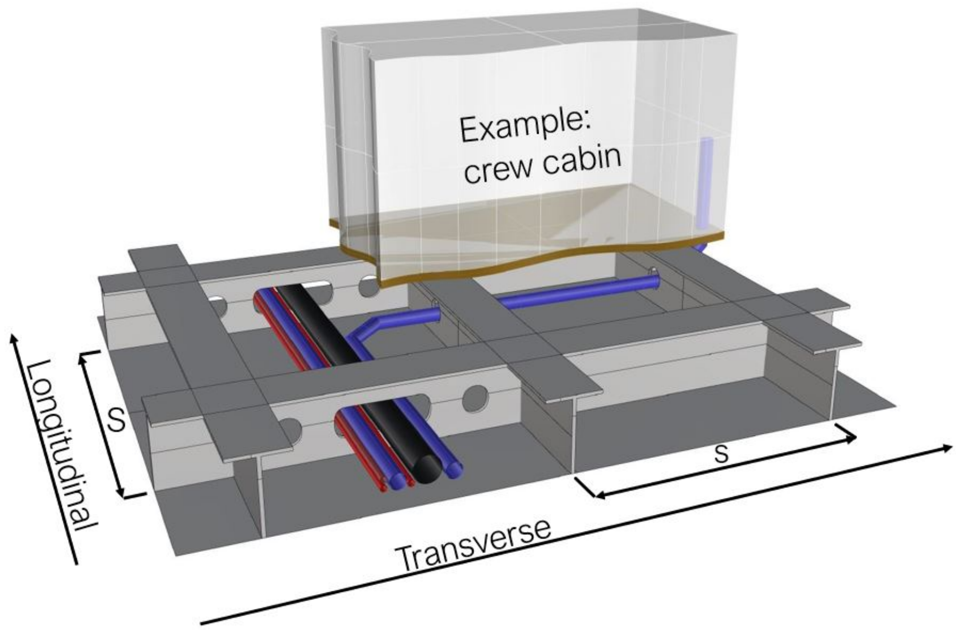
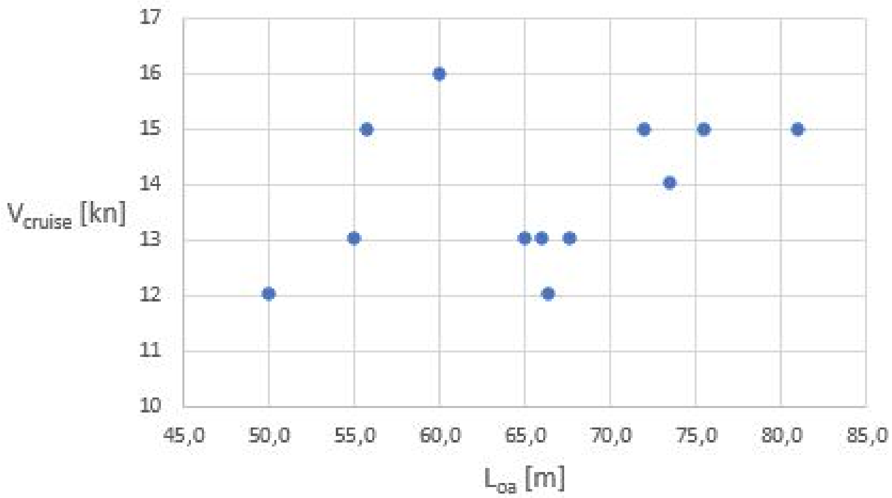
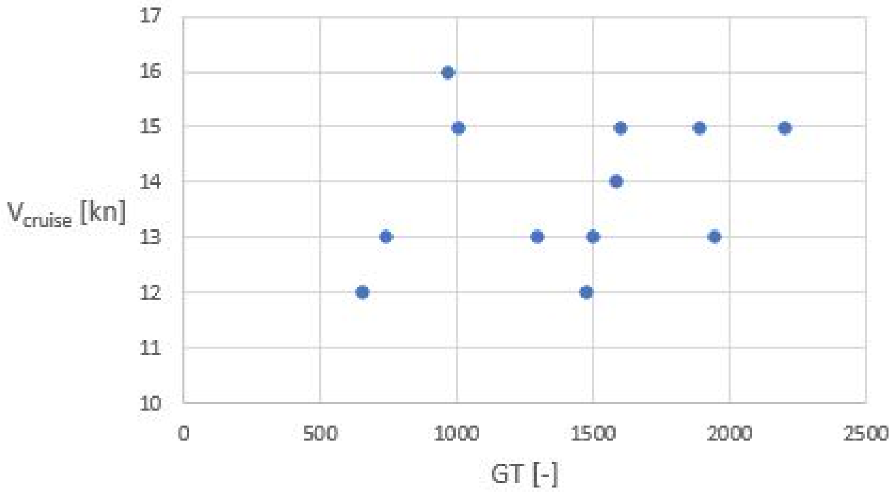


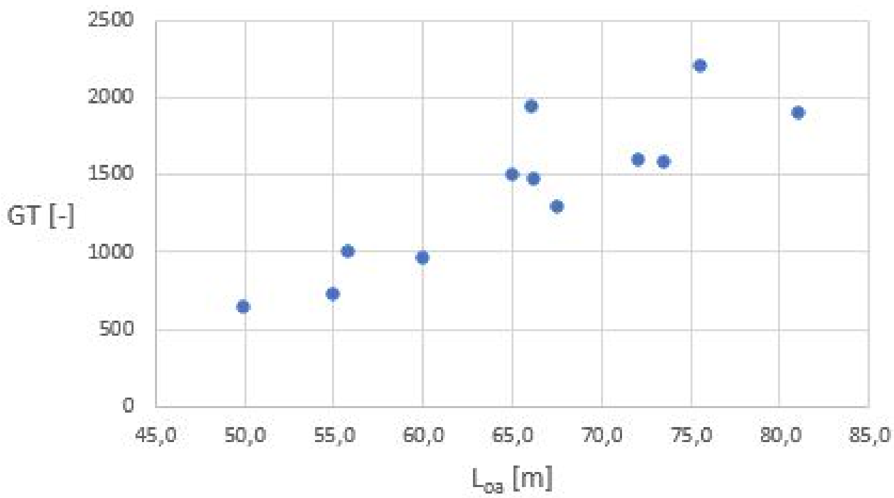
Figure 6.4: Deck structure with piping space claim

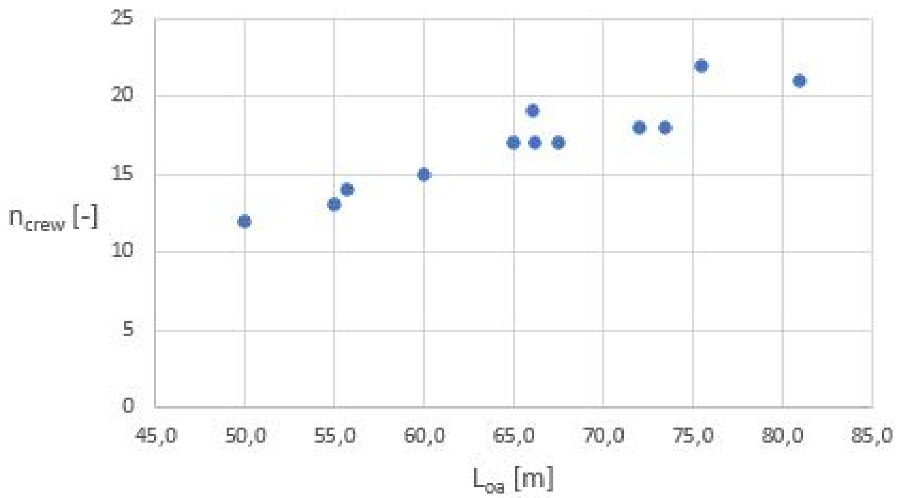
Appendices

A: Trends in reference vessels





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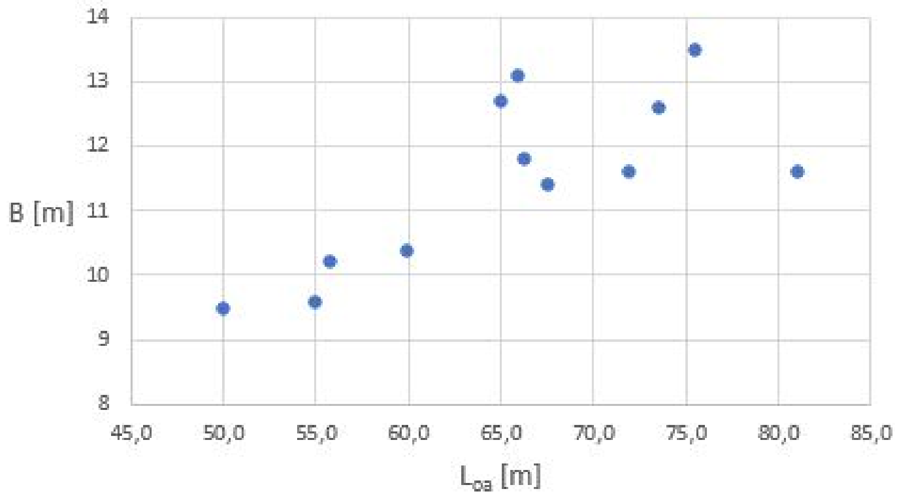
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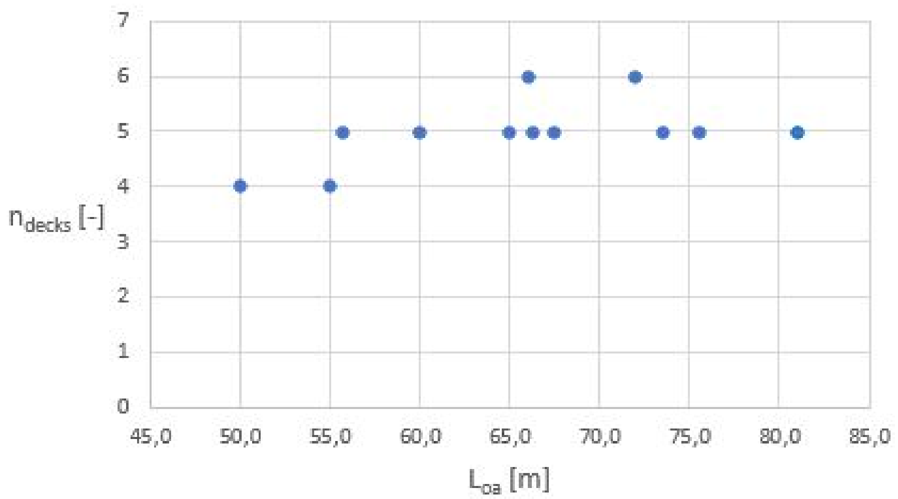
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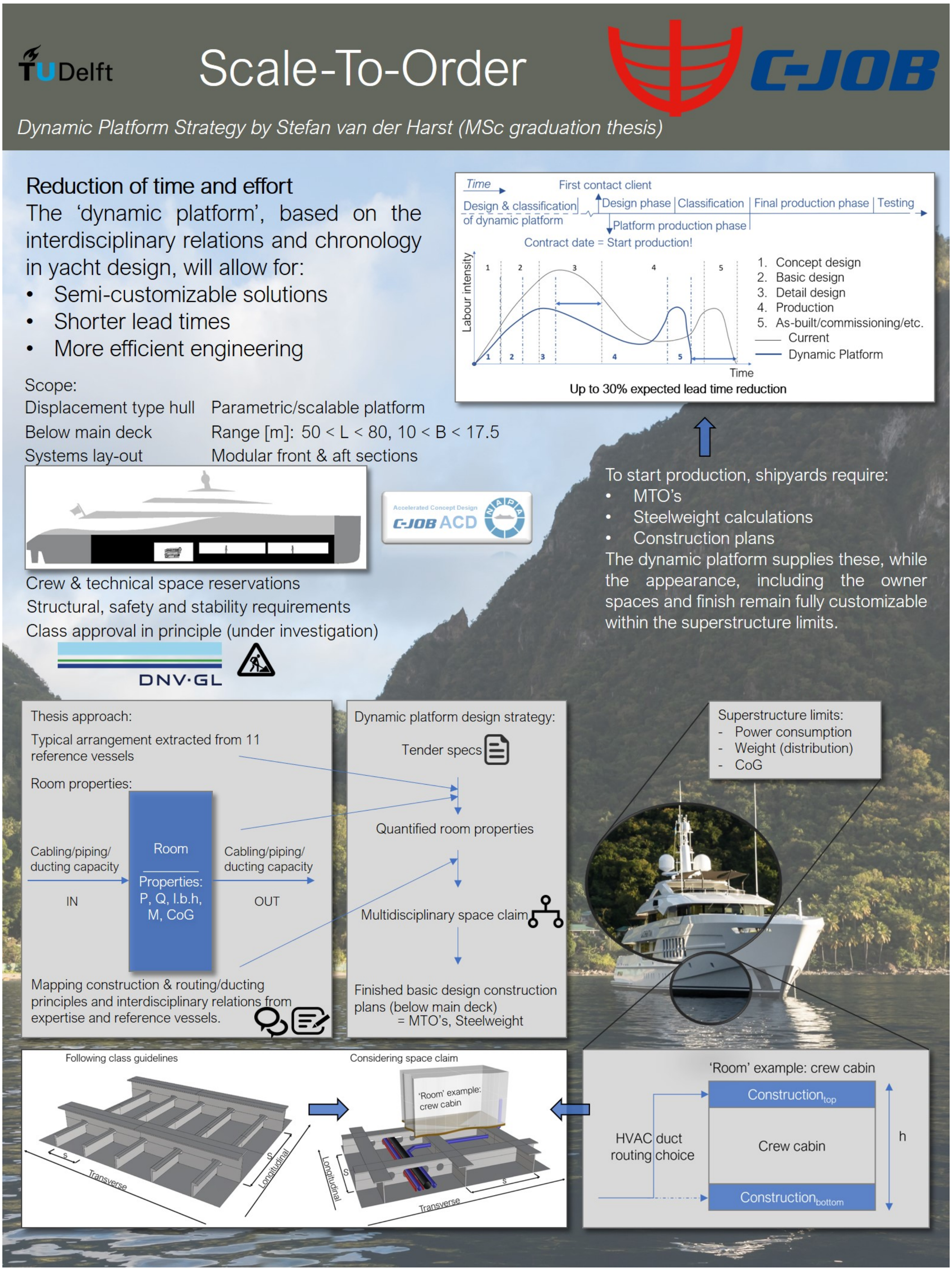
B: Functional areas per deck, allocated to compartments

Set of 12 super-yachts ranged 50 - 81 m																
Ship name	Beatrix	Vida	Taiba	Andreas L	Imagine	Invictus	Vanish	Icon	Solo	Siren	Anastasia	Air				
Builder	Cantieri navali di termoli	Heesen	Columbus	Benetti	Amels	Delta marine	Feadship	Icon	Tankoa	Nobiskrug	Oceanco	Feadship				
GT [t]	651	740	1013	971	1503	1943	1480	1295	1600	1585	2200	1893	Most common			
B [m]	9,5	9,6	10,2	10,4	12,7	13,1	11,8	11,4	11,6	12,6	13,5	11,6				
Loa [m]	50,0	55,0	55,7	60,0	65,0	66,0	66,3	67,5	72,0	73,5	75,5	81,0	50-60%		65-75%	
Tank deck	Undef				Undef	Undef										
Laundry	-	-	-	4		-	4	5	4	5	4	-	-	75%	4/5	80%
Stores	?	5	-	4			4	4	4,5	5,6	4,5	4	4/5	50%	4/5	100%
Tanks												?				
Stabilizers		3	4	2,5			4	4	?	2,5	?	5	double/single	100%	double/single	100%
Engineroom		-	2	2			3	3	3	3	3	2,3	2	66%	3	100%
Technical space		-	3	-			2	2	5	4	2	6	-	66%	1 comp	100%
Bow thruster		6	5	-			5	7/8	6	7	6	7	5/6	66%	5	100%
Stern thruster		-	-	-			2	1	-	-	?	1?	-	100%	1	60%
Crew mess	-	-	-	5	-	-	-	5	-	-	4	-	-	75%	-	75%
Crew Lounge	-	-	-	-			-	6	-	5	-	-	-	100%	-	66%
Crew cabins	-	-	-	-			-	6	-	-	-	-	-	100%	-	83%
Lower deck																
Beach club/spa/gym	-	1	-	-	1	1	1	1,2	1	1	1	1	1	w/	1	100%
Tender garage	1	-	1	1	2	2	2	-	2	2	2	2	or 1	100%	2	88%
Engine room	2	2	2	2	3	3	3	3	3	3	3	3	2	100%	3	100%
Guest cabins	3	3	3	3,4	4	4	-	4,5	-	4	-	4	3	100%	4	63%
Crew mess	5	4	4	-	5	5	4	-	4	5	-	5	4,5	75%	5	75%
Crew cabins	4,5	4,5	4,5	5,6	5,6	5,6	4,5	6,7	5,6	5	4,5,6	6,7	4,5	100%	5,6	100%
Main staircase	3	3	3	3	4	4	-	4,5	-	4	4	4	3	100%	4	75%
Galley	-	-	-	-	-	5	4	-	4	-	-	-	-	100%	-	63%
Crew Lounge	-	-	-	-	-	-	-	-	4	-	-	5	-	100%	-	75%
Laundry	?	4	4	-	-	5	-	-	-	-	-	5	4	50%	-	75%
Number of Crew	12	13	14	15	17	19	17	17	18	18	22	21				
Owner + guests	12	12	12	12	14	12	14	12	12	12	12	14				
Cruising speed (kn)	12	13	15	16	13	13	12	13	15	14	15	15				
Top speed (kn)		16			17		17,5									

C: Dynamic Platform Strategy poster version Monaco Yacht Show 2019



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