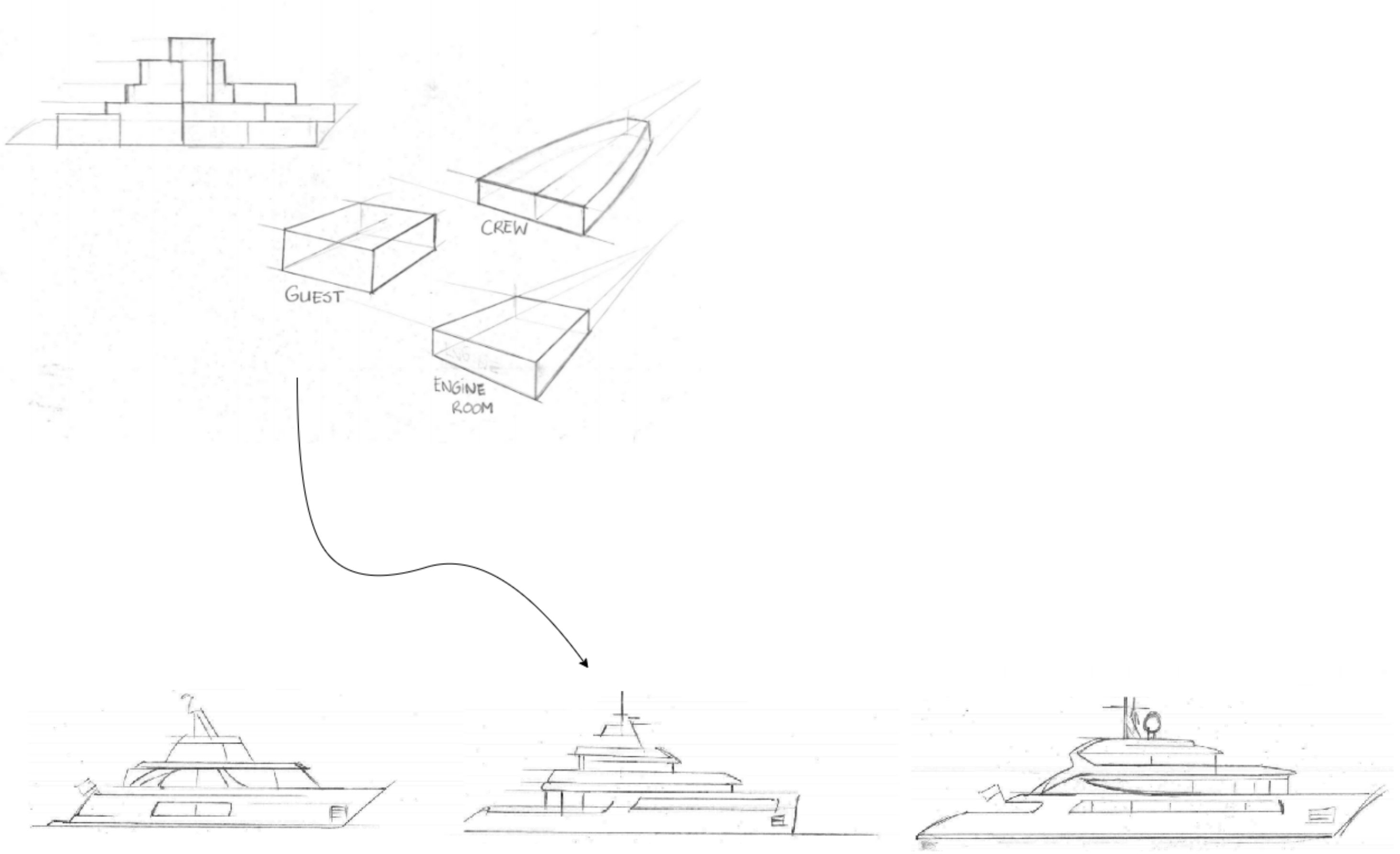
Design of a Feadship modular product platform

A modular design to reduce engineering costs and maintain customer value

A.H. Koppes
SDPO.19.037.m.



TU Delft

FEADSHIP
ROYAL DUTCH SHIPYARDS

Source cover image[5]

Thesis for the degree of Msc in Marine Technology in the specialisation of Design.

Design of a Feadship modular product platform

by

A.H. Koppes

Performed at

De Voogt Naval Architects

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Preface

This thesis is written to obtain the MSc degree in Marine Technology at the Delft University of Technology. The research is done at the De Voogt Naval Architects and supervised by the department of Ship Design Production and Operation of the faculty 3mE at the Delft University of Technology.

The aim of this thesis was to create a reusable yacht design to reduce engineering costs and maintain customer value. This was often very challenging since Feadship is well known for its fully custom yacht designs and "carte blanche" approach for each new design. Therefore, initial reactions on standardisation or reuse of parts of the designs were often critical, favouring more customation over less. Although the opportunities that reuse offers are clear to most, it might feel like forgoing Feadship's spirit. I believe this research offers some insights in the possible way to approach to a reusable design.

This thesis departed from the broad challenge of reducing costs in the range of smaller Feadships. Narrowing this scope towards a feasible MSc thesis topic was difficult. Although I felt hopeless at times,I always enjoyed going to the office in Haarlem. Its good atmosphere and nice people kept me going and contributed to the result I present here.

Therefore, I am grateful to everyone at De Voogt and especially the design department for making me feel welcome and appreciated. I would like to thank my supervisors, Ronno from de Voogt and Hans from TU Delft, for their contribution and feedback throughout the whole process. Furthermore, I would like to thank everyone within the Feadship Modular Design project and Marc in particular for providing input and feedback. Also, the regular coffee breaks with Lisette were helpful to keep going and stay motivated. Lastly, I would like to thank Silke, specifically for her feedback on my report, but also for just being there for me.

A.H. Koppes
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Summary

Feadships are luxury yachts produced at ship yards Van Lent and De Vries, with most yachts designed and engineered by De Voogt Naval Architecture. Feadships vary in length between 40 and 120 metres, but the yachts under 60 metres cost too much to attractively price them in the current market. To compete in the range under 60 metres, the cost price will have to be reduced. For Feadship, the market under 60 metres is interesting for two reasons: the large market and returning customers. The market for yachts under 60 metres is almost three times larger than the market above 60 metres. Of the yachts 80-90% are standard or semi-standard yachts. Therefore, this market has a high potential for Feadship, if they can develop a semi-custom yacht that is attractively priced. Furthermore, a large part of yacht owners that own a 60+ metres yacht previously owned a yacht below 60 metres. If Feadship can offer a yacht below 60 metres they are more likely to return at Feadship for a larger yacht. To reduce the cost price, the possibilities of design reuse are investigated. The following main question will be answered: How can design reuse be applied to a 50-60 metres Feadship, with the aim to reduce engineering costs, while maintaining Feadship's customer value?

Feadship is an engineer to order company (ETO). The customer order decoupling point (CODP) is at the start of the process. This indicates that the customer is involved from the very beginning. Design reuse enables the postponement of the CODP, if done correctly this will result in a reduction of costs. To identify the best parts for reuse, the diversity in existing yachts in this range is analysed. Furthermore, the customer value and engineering hours in a yacht are used together, to identify potential areas for reuse.

The existing yacht analysis identified five possible general arrangements and a set of rooms commonly found in this range of yachts. Furthermore, minimum and maximum values for: the amount of crew, guests, range, engine power and tenders are derived from existing yachts. These are used as requirements for the design reuse solution. The coupling of engineering activities and customer value showed five areas of interest for design reuse. These areas are: hull and powering, regulations for the naval architect, construction, mechanical systems and crew interior.

The possible design reuse option applied in this thesis uses modularity and will be referred to as: Feadship modular product platform. The Feadship modular product platform combines three integral platforms and eleven modules. Figure 1 shows the three integral platforms and table 1 lists the different modules. The integral platform forms the skeleton of the yacht, it provides the structural strength and includes the main technical components. For example, the engine room, propulsion pods, tanks, ac-units and the main ducting are part of the integral platform. The platform is divided in compartments of which some have a variable length. This enables the Feadship modular product platform to have a length between 50 and 60 metres. In the compartments, modules can be placed. Some have a fixed location and interior arrangement, whereas others can be customised within the available area. The modules consist of the interior finish and local technical solutions. For example, local HVAC ducting is designed within the module. The local ducting is connected via standardised connections to the platform.

The Feadship modular product platform can have a length between 50 and 60 metres and a beam of 10.15 metres. The modular yacht can accommodate a minimum of 6 and maximum of 12 guests and 10 to 16 crew. Furthermore, there are two possible engine configurations: 2x990 kW or 2x 1480 kW. Lastly a maximum of two 8 metre tenders can be stored. More customisation is possible on interior and exterior. The interior customisation level is different for each module. All crew modules have a standard interior arrangement, but the luxury modules such as lounges, guest rooms and owner's area can be customised within an available area. The exterior customisation is achieved by offering a variable deck length and not reusing the local exterior details. The variable deck length is achieved by increasing or reducing lounge areas. This will influence the longitudinal profile of the yacht. The local exterior details, such as the bulwark, transom and mast, will not be reused but customised for each yacht.

Even with this level of customisation, enough of the design can be reused to reduce engineering hours. In total a reduction of 25% of the hours in naval architecture, 36% of the construction hours, 64% of the mechanical engineering hours and 42% of the hours spent on interior is possible. The concept makes it possible to reduce the total engineering hours at De Voogt by 29%. This is possible because of the standardisation in crew and technical areas. Furthermore, a parametric construction and hull model to cope with the different sized compartments contribute to the savings. More savings are to be expected in the detailed engineering and in

the production. For the production an estimate is made using a learning rate of 95% for each doubling of the amount of yachts built. It is estimated that 6 yachts will be sold in the coming 10 years. If the yacht's selling price is 95% of a normal custom yacht and engineering costs for the first yacht increase by 50% because of engineering for modularity. Feadship will have to sell 5 yachts to earn back the initial investment in the platform.

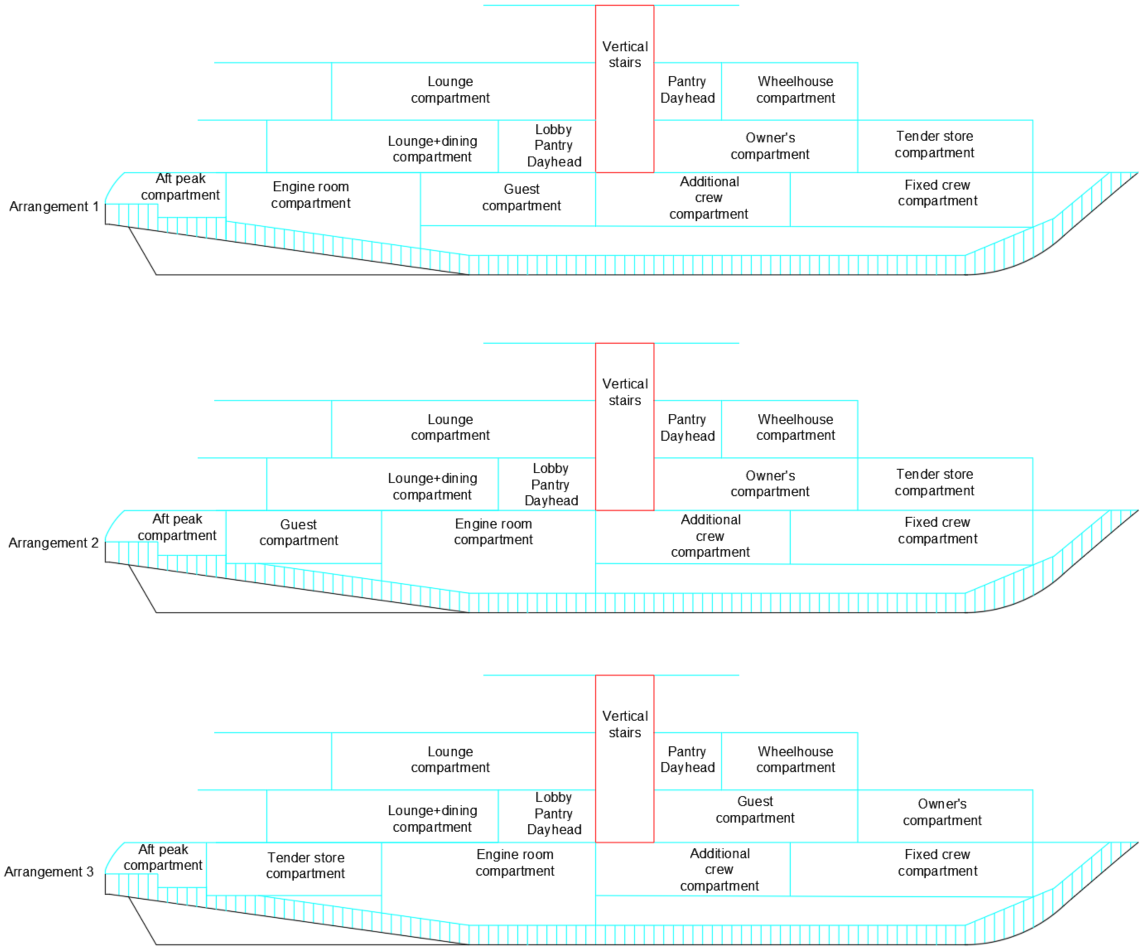


Figure 1: The three platform arrangements for the Feadship modular product platform.

Table 1: The location and possible customisation of the interior arrangement for each module

	Interior arrangement	Location
Five crew cabins and laundry	Standard arrangement	Fixed crew compartment
Crew cabin	Standard arrangement	Additional crew compartment
Galley	Standard arrangement	Lower deck or main deck
Mess	Standard arrangement	Additional crew compartment
Guests	To design within allowed space	Guest compartment
Lounge	To design within allowed space	Lounge compartments on main and bridge deck
Owner's suite	To design within allowed space	Owner's compartment
Staircase, pantry and dayhead	Staircase standard, pantry and dayhead adjoining staircase	Vertical stairs compartment
Wheelhouse, captain's cabin and office	Standard arrangements	Wheelhouse compartment
Engine room	Standard arrangements	Engine room compartment
Aft peak	Standard arrangements	Aft peak compartment

Contents

Preface iii

Summary v

Nomenclature ix

List of Figures xi

List of Tables xiii

1 Introduction 1

1.1 Problem setting . . . 1
1.2 Current Feadship design and production process . . . 2
1.3 Introduction of research question and key questions . . . 3
1.4 Report outline. . . . 3

2 Literature: design reuse and customer value 5

2.1 Cost reduction for customised products . . . 5
2.2 Definition of design reuse . . . 5
2.2.1 Product family development . . . 7
2.2.2 Product platform development . . . 7
2.2.3 Modularisation . . . 7
2.3 Four types of customer value . . . 8

3 Problem Diagnostics 11

3.1 Overview of existing design reuse concepts . . . 11
3.1.1 SL39: A platform with modular design options . . . 11
3.1.2 Feadship Lagoon Cruiser (FLC): A 34 metre platform . . . 16
3.1.3 F45: A 45 metre platform . . . 18
3.1.4 Navy design reuse concepts . . . 18
3.1.5 Other examples of design reuse . . . 19
3.1.6 Conclusion: Modularity during design and operation . . . 19
3.2 Deriving the product platform requirements . . . 21
3.2.1 Different lay-out variants depending on tender and engine room position. . . . 21
3.2.2 Rooms on board of yachts . . . 21
3.2.3 Product family boundaries for length, guests, crew, tenders, range and power . . . 24
3.3 Engineering hours per discipline for a 56 metre yacht . . . 24
3.4 Value for reuse potential in the engineering processes . . . 25
3.5 Construction and mechanical components as potential reuse areas . . . 27
3.6 Conclusion: multiple areas for reuse possible . . . 29

4 Designing the design reuse concept 31

4.1 Requirements for a 50-60 metre yacht. . . . 31
4.2 The modular design with three platforms and eleven modules . . . 32
4.3 Platform flexibility in length, beam and height stacking. . . . 35
4.3.1 Assessment method with regulations, construction, stability and influence on the process. . . . 35
4.3.2 Length . . . 37
4.3.3 Beam. . . . 38
4.3.4 Height stacking . . . 39
4.3.5 Conclusion: variable length, height stacking and fixed beam. . . . 40

4.4 Design of the platform and modules . . . 41
4.4.1 Multiple platforms to reduce complexity. . . . 41
4.4.2 Eleven modules to satisfy requirements and reduce engineering hours . . . 42
4.5 Exterior profile customisation. . . . 47
4.6 Solutions for construction and HVAC for the platform of changing length . . . 49
4.6.1 Basic construction principle and additional transverse stiffeners . . . 49
4.6.2 HVAC requirements . . . 51
4.6.3 Construction and mechanical engineering combined . . . 54

5 Concept evaluation **57**
5.1 Platform diversity . . . 57
5.2 Exterior customisation . . . 58
5.3 Interior customisation . . . 59
5.4 Reduction in engineering hours. . . . 62
5.5 The next step for the modular product platform and added benefits . . . 63
5.5.1 Lifetime . . . 64
5.5.2 Design and Sales . . . 64
5.5.3 Engineering . . . 64
5.5.4 Production. . . . 64
5.6 Costs and estimation of the possible profit . . . 65

6 Conclusion and recommendations **67**
6.1 Conclusion . . . 67
6.2 Recommendations . . . 69

Bibliography **71**

A Summary of the regulations for yachts in different sizes **73**

Nomenclature

β	Panel aspect ratio correction factor
Γ	Convex curvature correction factor
ω	Service type correction factor
Φ_A	Web area coefficient dependent on the loading model assumption
Φ_i	Inertia coefficient dependent on the loading model assumption
Φ_z	Section modulus coefficient dependent on the loading model assumption.
σ_s	specified minimum yield strength of material in N/mm2
σ_u	minimum ultimate tensile strength of the material $[N/mm^2]$
A_W	Web area
B	Moulded beam $[m]$
BM	Vertical distance from the centre of buoyancy to the metacentre $[m]$
Co_1	Correction factor 1 depending on plate location and function
Co_2	Correction factor 2 depending on plate location and function
Co_3	Correction factor 3 depending on plate location and function
D	Depth of the yacht $[m]$
E	modulus of elasticity $[N/mm^2$
f_δ	Limiting deflection coefficient for stiffener member
f_σ	Limiting bending stress coefficient for stiffening member
f_τ	Limiting shear stress coefficient for stiffener member
I	Inertia $[cm^4]$
k_s	$K_s = \frac{235}{\sigma_s}$ Higher tensile steel factor
k_{ms}	$\frac{635}{\sigma_s + sigma_u}$
KB	Vertical distance from the keel to the centre of buoyancy $[m$
KG	Vertical distance from the keel to the centre of gravity
KM	Vertical distance from keel to metacentre, also called hull stability $[m]$
l_e	Effective length $[m]$
L_r	Rule length $[m]$
L_{oa}	Length overall $[m]$
L_{wl}	Waterline length $[m]$
p	Design pressure $[kN/m^2]$

s Stiffener spacing $[m]$

t_p Plate thickness $[mm]$

Z Section modulus $[cm^3]$

T Draft $[m]$

List of Figures

1 The three platform arrangements for the Feadship modular product platform. vi

1.1 Different phases in the design and building of a Feadship 2

2.1 Visualisation of the two dimensional customer order decoupling point (CODP) 6
2.2 Visualisation of the different aspects found in literature and how these relate to each other . . . 6
2.3 Five types of product modularity visualised 8

3.1 Basic platform of the SL39 with the six open spaces for the modules 13
3.2 The four possible options for the SL39 lower deck guest cabins 14
3.3 The four options for the SL39 forward part of the main deck with the owner's area 14
3.4 The four options for the SL39 aft part of the main deck with the lounge and dining area 15
3.5 All options for the SL39 bridge deck 15
3.6 The general arrangement of a FLC 16
3.7 The guest room options for the FLC 17
3.8 General arrangements of the F45 platform 17
3.9 The US Navy TES concept with slot modularity 18
3.10 The Danish Standard Flex concept 19
3.11 2 different version derived from the FREMM platform 19
3.12 The modules and some variants of Ulstein's modular design approach 20
3.13 The ER yacht design concept of a yacht with module swapping capacity 20
3.14 Different deck lay-out possibilities identified from comparison shown for each deck 23
3.15 Each possible combination of decks 24
3.16 Percentage of time spent on the processes within each discipline 25
3.17 Reuse potential values assigned to the processes in the work breakdown structure 26
3.18 Example of an interior box drawing 27
3.19 Work breakdown schedule with the percentage of time and customer value for each process . . 28

4.1 The three different platforms for the modular design with all the compartments 32
4.2 Two different exterior longitudinal profiles from the modular product platform 33
4.3 A possible maximum length arrangement 34
4.4 A possible minimum length arrangement 34
4.5 The difference in design pressure for the 50 and 60 metre yacht 38
4.6 The difference in design pressure for the 10.57 metre and 8.81 metre beam 39
4.7 The three possible configurations with engine room and tender garage placement 41
4.8 Illustration of the limited tender garage height because of the depth and draft of the yacht . . . 42
4.9 The minimum crew and officer cabin areas for 560 to 3000GT 44
4.10 Arrangement of the first compartment with five cabins and a laundry[9] 44
4.11 Minimum and maximum possible arrangement for the second compartment 45
4.12 An example of a possible aft peak arrangement 46
4.13 Fixed arrangement of the wheelhouse, office and captains cabin 46
4.14 Staircase module example 47
4.15 On the left the straight bow and on the right the flared bow 48
4.16 In blue the outer hull lines of a straight bow and in black for a flared bow 48
4.17 Four different profiles to show the different exteriors 48
4.18 Maximum and minimum guest compartment length 50
4.19 The construction overview of the main deck for the minimum and maximum length 50
4.20 The construction overview of the bridge deck for the minimum and maximum length 50
4.21 The construction overview of the sun deck for the minimum and maximum length 51

4.22 Vertical alignment in the platform . . . 51
4.23 Two examples of the ducted HVAC system . . . 52
4.24 The division of interior areas over the different AC-units . . . 53
4.25 Schematic of the optimised ducting for AC-unit 4 . . . 55
4.26 A cross section of the fixed crew compartment with construction and mechanical aspects . . . 56

5.1 Four different longitudinal profiles possible of the modular product platform . . . 59
5.2 The three platform arrangements for the Feadship modular product platform . . . 60
5.3 Two lower deck arrangements to illustrate the difference due to different compartment lengths 60
5.4 Example of the main deck with the compartment lengths . . . 61
5.5 Example of the bridge deck with the compartment lengths . . . 61
5.6 The estimated reduction in engineering hours for each discipline . . . 62
5.7 The division of reduced engineering hours over each of the sub tiles of naval architecture . . . 62
5.8 The division of reduced engineering hours over each of the sub tiles of construction . . . 63
5.9 The division of reduced engineering hours over each of the sub tiles of mechanical . . . 63
5.10 The division of reduced engineering hours over each of the sub tiles of interior . . . 63
5.11 The expected reduction of production costs for each yacht that is built . . . 65
5.12 The cumulative profit for 4 different selling prices . . . 66
5.13 The cumulative profit for 4 different increase in engineering costs because of modularity . . . 66

6.1 The three platform arrangements for the Feadship modular product platform . . . 68

A.1 Table with explanation of the different rules that apply to different sized yachts . . . 73

List of Tables

1 The location and possible customisation of the interior arrangement for each module vi

1.1 Several competitors in the European yacht industry 2

3.1 Different design reuse concepts in maritime industry 12
3.2 Details of the Feadship yachts used in the comparison 22
3.3 Requirements and indications on main dimensionns for the product family 25
3.4 The requirements for the product platform derived from the regulations and database 29

4.1 The updated requirements for the product platform 31
4.2 The location and freedom in interior arrangement for the different modules 33
4.3 The compartment lengths of the integral platform 33
4.4 The modules for the maximum and minimum arrangement 35
4.5 Main dimensions of the existing Feadship 35
4.6 Scaled values for the maximum and minimum length overall 37
4.7 The estimated values to calculate the initial stability 38
4.8 Scaled values for the maximum and minimum beam 38
4.9 The estimated values to calculate the initial stability for a changing beam 39
4.10 Scaled values for the maximum and minimum depth 40
4.11 The estimated values to calculate the initial stability for a changing depth 40
4.12 Variation of main dimensions for the platform 40
4.13 All modules needed to full fill the requirements of both the customer and Feadship 43
4.14 The different module variants 43
4.15 Net and gross areas of the rooms in the first crew module 43
4.16 Net and gross areas of the rooms in the second crew module 44
4.17 Engine power and length for two MTU engines 45
4.18 The four different lengths of the engine room 45
4.19 Areas of the crew+ module derived from the four yachts 46
4.20 The maximum spans allowed for the different decks 49
4.21 Minimum and maximum calculated air capacities 53
4.22 Minimum and maximum capacity and dimensions of the four AC-units 54
4.23 Maximum air speeds for each type of air flow in a round or rectangular duct 54
4.24 The difference in maximum and minimum duct sizes for AC-unit 4 54
4.25 Optimised ducting to have enough capacity in the maximum and minimum arrangement 55

5.1 The platform requirements and realised values 58
5.2 The compartment lengths of the integral platform 59
5.3 The reduction in costs for production because of a learning rate of 95%. The third column shows the amount of production costs with respect to the total costs. 65

6.1 The location and possible customisation of the interior arrangement for each module 69

1

Introduction

This chapter describes what a Feadship is and why it is important for Feadship to build yachts under the 60 metres. After describing the problem background the main and key questions are introduced. The chapter ends with the outline of the report.

1.1. Problem setting

Feadships are luxury yachts produced at ship yards Van Lent and De Vries, with most yachts designed and engineered by De Voogt Naval Architecture. Feadships vary in length between 40 and 120 metres, but the yachts under 60 metres cost too much to attractively price them in the current market. Several competitors such as Amels, Heesen and others are able to build yachts at more attractive prices. In return for a lower price, customers are willing to accept lower levels of customisation and quality. To become competitive in the range below 60 metres, the costs of these Feadships will have to be reduced.

To compete in a market, Porter[27] identifies three strategies: cost leadership, differentiation and focus strategy. Cost leadership implies offering the lowest price without neglecting the other areas such as quality and service and serve the whole market. Companies with a differentiation strategy also serve the whole market but sell a unique product or service. With a focus strategy companies concentrate on a particular group, geographic markets or product line segments and therefore will not serve the whole market. Companies with a focus strategy still need to choose to be a cost leader or a differentiator within the sub market that they serve. Most competitors below 60 metres are looking for the cost leadership in the market by offering more standardised products such that design and building costs are reduced. Feadship has more of a differentiation strategy, the aim is to offer better quality and more customised yachts for the whole market. There are three big risks identified by Porter[27] for companies adapting a differentiation strategy. First, the price difference between cost leaders and differentiators becomes to large and customers are willing to sacrifice some of the extra added value for costs savings. Second, the customer's need for the differentiating factor reduces. Third, is a reduced perceived differentiation by imitation of competitors. Especially the first risk is clearly seen in the current market which forces Feadship to increase the added value on which they differentiate or reduce prices to close the cost differential to maintain their market position.

"Feadship is recognised as the world leader in the field of pure custom super yachts."[10] Over the past years the average length of super yachts is increasing [16], therefore, it might seem that Feadship can best focus on larger custom yachts as this is currently their best product. But in the global super yacht market there are almost three times more yachts below 60 metres compared to 60+. Also most of these yachts are production or semi production yachts. It is estimated that only 10-20% are custom yachts. This shows potential for Feadship if they are able to offer customised or partly customised yachts for more or less the prices of a standardised yacht. Another reason to stay in the segment below 60 metres market is that most owners of a 60+ yacht previously owned a yacht below 60 metres, if this yacht is a Feadship and they enjoyed it, they are more likely to buy a larger Feadship as well.

A few different European competitors are listed in table 1.1 together with the range they compete in and the country they produce their yachts.

Table 1.1: Several competitors in the European yacht industry

	Length Range [m]	Country
Oceanco	80-140	Netherlands
Heesen	30-80	Netherlands
Amels	55-83	Netherlands
Lurssen	60-220	Germany
Nobiskrug	60-143	Germany
Abeking Rasmussen	45-82	Germany
CBI navi	30-80	Italy
Perini	40-60	Italy
Benetti	40-90	Italy
Fincantieri	70-160	Italy

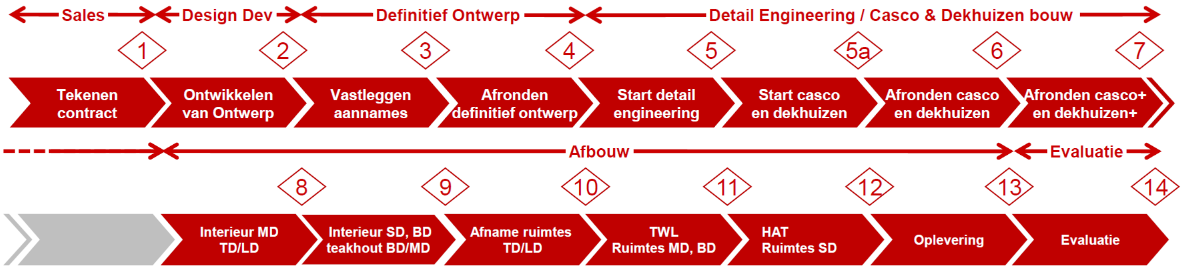


Figure 1.1: Different phases in the design and building of a Feadship[31]

1.2. Current Feadship design and production process

"There are yachts and there are Feadships"[10] Feadships are different for several reasons, at Feadship each project is started with a blank page and everything is possible. The client is involved in each step of the design and production process, which starts with a designer who translates the clients visions and dreams into a Feadship. This involvement itself will already create a unique and wonderful experience even before the ship is launched. With each project a new standard is created which ensures that every Feadship is better than the one before in terms of craftsmanship, design, engineering and construction. With yards located in the Netherlands, were craftsman are trained and skills are passed down generation on generation, an inherent Feadship quality is created.[10]

The design and production process is divided over different companies within Feadship. The first part of the process, in which the clients wishes are translated to a design and technical feasibility of the design is ensured, happens at De Voogt. The detail engineering and building happens at De Vries or Van Lent. A visualisation of the steps in the design and building process can be found in figure 1.1

Sales phase

The first part of the process is called the sales phase and consists of three sub phases and mainly takes place at De Voogt.

- Relation phase
- Design phase
- Contracting phase

The goal is to interest the client and to collect some wishes about style and size, which can be used in the design phase. In the design phase, ideas are developed and processed in to proposals, normally several iterations are made. One of the yards will be involved in this phase as well. This phase ends with basic agreements over specifications, costs, delivery and what the yacht should look like with block lay outs and renderings. In the next phase, the contracting phase, more ideas are developed and the level of detail is increased. Final costs are calculated and a milestone schedule is composed. The contracting phase ends with the signing of the contract.

Post contract phase
After signing the contract, the design development starts. This is a 8-12 week period in which the design is further developed to a point were mono disciplinary work can start. After this period the definitive design phase starts in which the mono disciplinary teams work parallel on the design. The delivery after this phase is a feasible design with a high enough level of detail to start the detailed engineering. The detail engineering is done at the yards and third parties. The mono disciplinary teams at the De Voogt are:

- Design
- Naval Architecture
- Construction
- Mechanical engineering
- Electricity
- Interior
- Exterior

After the final design, De Voogt hands over the design to the yard and they will continue with the detailed engineering and production. In this stage, De Voogt's involvement will be limited to regular checks of the similarity of the actual yacht and the designed yacht.

1.3. Introduction of research question and key questions

The objective of this thesis is to reduce the costs of a 50-60 metre yacht by creating a reusable design which improves the ratio between engineering costs and customer value of a 50-60 metre Feadship. This is done by analysing the current engineering process and distribution of hours between different engineering disciplines within De Voogt and link these processes to the customer value of a yacht. These two combined create the basis to decide on the parts of a Feadship design which can be reused. To determine the requirements of a 50-60 metre Feadship the current 50-60 metre Feadships are analysed resulting in a list of requirements. To decide on how to reuse parts of the design, existing design reuse applications within the maritime industry are assessed.

The outcomes of the questions and analysis above will result in the answer of the main question: How can design reuse be applied to a 50-60 metre Feadship, with as goal to reduce engineering costs, while maintaining Feadship's customer value? The reusable design is further evaluated by showing the possible final designs and determine the possible reduction of engineering hours.

1.4. Report outline

This report will start with a literature study on design reuse. Chapter 2 will identify ways of reducing costs on customised products from literature. A definition for design reuse is introduced and enablers for design reuse are identified. Chapter 2 ends with defining four types of customer value.

Chapter 3 collects the requirements for a reusable design from existing Feadships. It starts with describing existing design reuse concepts. Existing yachts are used to determine the variety in deck arrangements. To identify the engineering processes suitable for reuse, the distribution of engineering hours for a 56 metre yacht are visualised. This is done using the work breakdown structure of De Voogt. In the same work breakdown structure a customer value is assigned to each of the processes. The hours and customer value together reveal potential processes that a design reuse option should affect.

In chapter 4 the requirements and potential reusable processes are used to design the Feadship modular product platform. The integral platform and different modules will be discussed in detail. This chapter ends with an assessment of the changing requirements for construction and HVAC and how to deal with these changes.

Chapter 5 evaluates the Feadship modular product platform. First, the requirement are evaluated. Second, the exterior customisation options followed by the interior customisation options. Third, is an evaluation of the reduction in engineering hours. The chapter will then continue with discussing the next step in the platform development and highlighting some of the additional benefits that arise when a modular platform is used. The last part of this section shows the calculation of the expected profit and how this is depending on the selling price and engineering costs.

The reports ends with the conclusion and recommendations. In the conclusion the Feadship modular product platform is described once more. Also, the possible customisation options are discussed and the effect of the reuse on engineering hours. The recommendations describe additional actions that are needed to develop the Feadship modular product platform. Furthermore, some remarks on the possible benefits and implementation of a modular strategy are made.

2

Literature: design reuse and customer value

In this chapter the relevant literature will be discussed. The chapter will start with literature on solutions for reducing the costs for the production of customised goods. This identifies design reuse as a possible solution. Therefore, more literature on design reuse is used to form a definition for design reuse. Enablers for design reuse are introduced and modularisation as a possible solution is investigated in more detail. The chapter will end with literature on customer value. Four different types of customer value are introduced: functional, experiential, symbolic and financial.

2.1. Cost reduction for customised products

The design and production of customised goods against mass production prices is called mass customisation. Currently the design and engineering process at Feadship can be classified as Engineer to Order(ETO) with the Customer Order Decoupling Point(CODP) based at the start of the design project in most cases. ETO companies are defined as:"Engineering companies who by definition deliver products which are engineered to the specific requirements of the customer."[15] and CODP is defined as: "A customer order decoupling point separates decisions made under certainty from decisions made under uncertainty concerning customer demand."[30] The CODP can be represented in two dimensions as shown in figure 2.1. The two dimensions represent the engineering dimension and production dimension. Feadship is currently positioned in the top left corner of the figure, marked in red. This shows that the engineering is done to order and production is made to order. The time axis shows the lead time of engineering and production, the place of the CODP indicates at which percentages of the lead time the customer is involved. Therefore, the location of the CODP indirect shows how much of the design can be influenced by the customer. Parts of the design created before the CODP can possibly be reused to reduce costs. This is confirmed by Haug, Ladeby and Edwards in "From Engineer to order to mass customization" in which they state that an ETO moving towards mass customisation will need to standardise their engineering work by defining parts of the solution space which leads to a postponement of the CODP.[15]

2.2. Definition of design reuse

The postponement of the CODP and the definition of a finite solution space can also be categorised as design reuse. Design reuse can be defined as:"reusing designs whose reuse brings business benefits for a company."[26] A distinction has to be made between design for reuse and design by reuse, design for reuse is the process of creating a basic design with reusable elements. Design by reuse is the next step in which the design is reused to create variants and final customer products. With this distinction design for reuse can be seen as the enabler of design by reuse. Design reuse can reduce developing costs and time because of reduced effort and risks, resulting in overall cost reductions, a better time to market, shortened testing and quality improvements. [26] Also a lower level reuse can be enabled which will create the possibility to reuse or update documents such as specification, test plans, models etc. [12] Design reuse is often applied to increase the competitiveness of companies with respect to lead time and costs. [24]

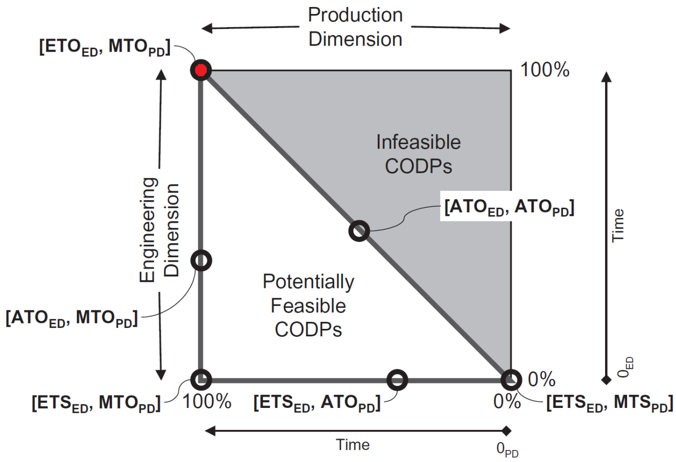


Figure 2.1: Visualisation of the two dimensional customer order decoupling point (CODP) with on the horizontal axis the production dimension and on the vertical axis the engineering dimension. The current process at Feadship is positioned in the left top corner, marked in red. The subscripts ED and PD stand for engineering dimension and production dimension respectively. ETO stands for Engineer to Order, MTO for Make to Order, ATO for Adapt to Order, ETS en MTS stand for engineer/make to stock.[30]

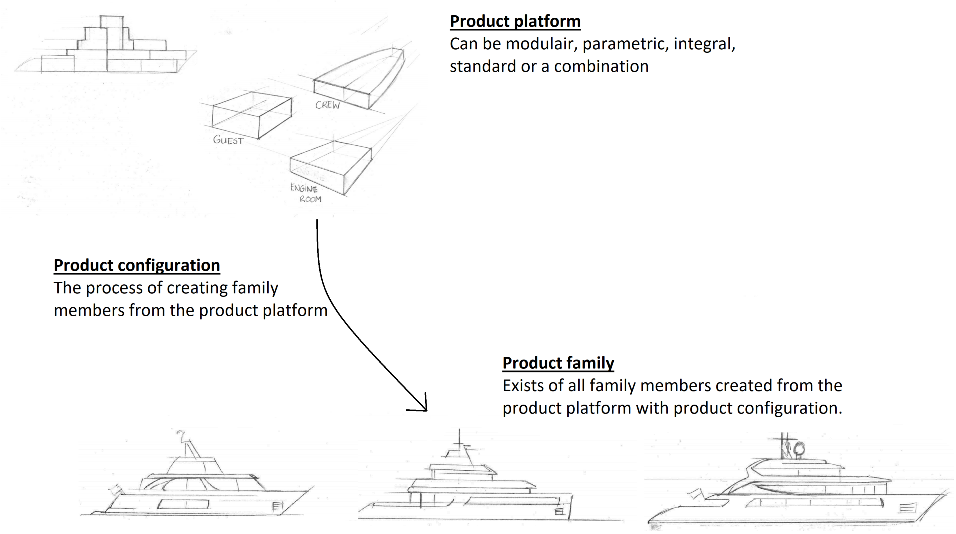


Figure 2.2: Visualisation of the different aspects found in literature and how these relate to each other.[5]

To enable design reuse, a few concepts are important such as product family, product platform, product configuration and modularisation, parametrisation, standardisation. [26] Figure 2.2 shows how these concepts relate. A product platform is the basis and can be modular, parametric or integral/standard or a combination of these parts. The product platform contains the "building blocks" for each final product, called a product family member. Product configuration is the process of creating different designs using the product platform, this creates new family members. The product family member is a finalised product created from the product platform and all the family members together make the product family.

A collection of the important aspects and literature regarding product family development and product platform development will be discussed first. Afterwards more information on modularisation, parametrisation and standardisation as ways of designing different parts of the product platform is discussed. Section 3.2 describes the product family development for a 40-60 metre yacht, while chapter 4 discusses the product platform development and product configuration. Chapter 5 evaluates if the product family members fulfil the requirements.

2.2.1. Product family development

A definition of a product family is given by Meyer en Lehnerd: "A product family refers to a set of similar products that are derived from a common platform and yet possess specific features/functionality to meet particular customer requirements."[20] A product family represents a group of customers with common needs, therefore it facilitates the mapping between customer needs and a company's capabilities. [17] The product platform as described in 2.2.2 captures the commonalities in customer needs and acts as the basis for each product family member. Therefore the product family development can be seen as a understanding the customer whereas the product platform development is the creation of a basis to create different designs with common customer needs and room to differentiate. The product family development is done in section 3.2 and will set the boundaries of what the product platform should be able to produce.

2.2.2. Product platform development

A product platform is defined as: "A structured, coherent collection of resources, including systems and template hierarchies, textual components, variant, rules and interface definitions, from which a range of customized product definitions can be derived."[8] Another definition more coupled to the mass customisation principle is presented by Jiao and Tseng: "A product platform provides a technical basis for catering to customization, managing varieties and leveraging existing capabilities."[17] A product platform is the basis for a single member of a product family. In developing a platform two basic approaches can be distinguished: top down and bottom up. "A top down approach a company strategically manages and develops a family of products based on a product platform and its derivatives."[33] A bottom up approach uses commonalities in existing designs to create a platform from which the individual products can be derived. [33] As discussed in section 2.2.1, a bottom up approach will be used.

Nieuwenhuis identified three main platform approaches which are similar to the three platform approaches introduced in section 2.2: a modular approach, an integral or standardised approach and a scalable or parametric approach. With a modular platform approach, product family members are created by replacing, adding or removing modules which can be complemented by individually designed parts of the product. An integral platform approach reuses a fixed part of the design, for example the hull and construction on which individually designed parts can be added. A scalable approach uses several scaling variables to adjust the platform in one or more dimensions such that an unique family member is created. A platform might consist of more than one approach. For example, an integral platform can be combined with several modules to create family members. The modular platform approach will be discussed in more detail below in section 2.2.3

2.2.3. Modularisation

Modularity has the same basic commonalities in each field of study, it is always the division of a larger system in smaller parts or components. The idea is that modules are more or less self-sufficient and the parts can be recombined to generate multiple end products. [8] A definition of modularisation given by Schilling is: "A continuum describing the degree to which a system's components can be separated and recombined."[32] A similar definition but more specific for maritime sector is used by Erikstad who defines design for modularity as: "Explicit actions towards sub-dividing the ship into well defined parts and components that can later be recombined according to given rules and procedures."[7] By using modularity a variety of end products can be produced using the same set of modules, which yields several benefits: the complexity of the product is manageable, parallel work is possible and future uncertainty can be accommodated better. [2]

Ulrich defines five types of product modularity based on how the final product is build, in figure 2.3 the five modes are visualised [35]:

- Component sharing, various products use the same module or component.
- Component swapping, by adding small components different variants can be created.
- Cut to fit, modules can be adjusted by parameterising.
- Bus, components can be attached via an interface to the same platform.
- Sectional, modules can be freely combined by introducing common interfaces.

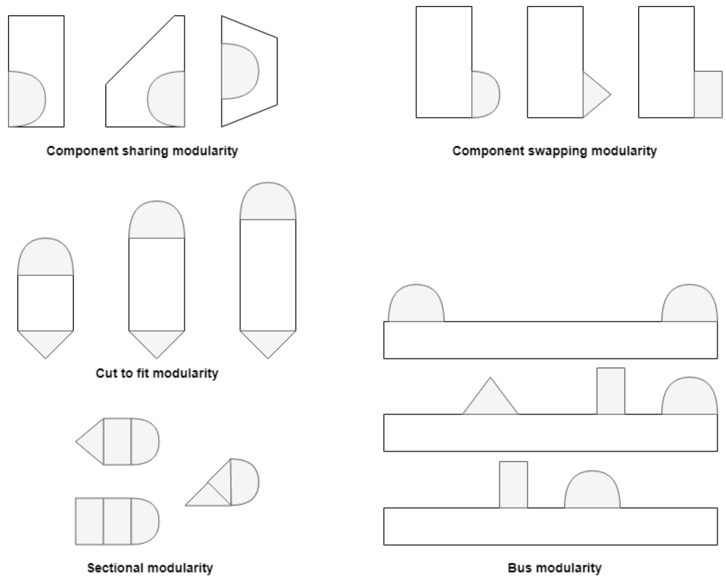


Figure 2.3: Five types of product modularity visualised, the figures is based on a figure from [35]

2.3. Four types of customer value

To define what customer value is at Feadship and how this can be related to the engineering processes, the general concept of customer value is firstly defined. Woodruff lists various definitions of customer value. [37] All the definitions have in common that customer value is something that is perceived rather than objectively determined. Furthermore, in customer value there will always be a trade-off between what a customer receives and what they give up to acquire the product. In this report the definition of Woodruff will be used: "A customer's preference for and evaluation of attributes, attribute performance and consequences that are perceived trough the consumption process."[37] This definition states that customer value is composed of two parts: perceived value during purchase and during use. It is clearly a perception of a single customer and therefore, it can be different for each customer.

Both Colgate and Doyle identify 4 major types of value in a product[1, 6]:

- Functional/instrumental
- Experiential/hedonic/social
- Symbolic/expressive/psychological
- Financial/cost/sacrifice

The functional value relates to the wishes of a customer and to which level the product is able to fulfil the desired functions and characteristics of the specific customer. The experiential value relates to the emotions and feelings of the customer, such as pleasure, fun, but also network benefits in a business to business setting for example. The symbolic value relates to the psychological meaning, how someone feels about buying or possessing the product and how these feelings relate to self worth or self concepts. The financial value relates to the costs for a customer to acquire the product, this can be in terms of money but also in time, cognitive and many other ways. These concepts will be used to define customer value for Feadship's customers later on.

Some research on customer value is focused on creating an expression for value. The expressions created by this research can be used to identify ways of increasing value. Browning derived an expression depending on performance affordability and timeliness. This expression is shown in equation 2.1 and the equations for affordability and timeliness in 2.2 and 2.3.[4]

$$Value \propto \frac{Performance}{Affordability * Timeliness} \tag{2.1}$$

$$Affordability \propto \frac{1}{Product\ development\ cost + Production\ cost + Operating\ cost + Margin} \tag{2.2}$$

$$Timeliness \propto \frac{1}{Product\ development\ time + Production\ time + Distribution\ time} \tag{2.3}$$

In the equation for value, the performance part still depends on the customer and can be assessed using the first three of the four types of value discussed above. Affordability and timeliness are depending on the product development and on the production process, and relate to the last major type of customer value, financial/cost value.

For Feadship the functional value comes from the different functionalities on a yacht, for example, extra tenders, lounges, amount of guests and crew etc. In the current way of full customisation this functional value is optimal since the features of the yacht are determined in conjunction with the customer. To create the highest functional value while reusing parts of the design, enough diversity should be offered on features that are most important to a customer.

The experiential value is mostly determined when the yacht is used, but also being part of the designing and building process can be a unique experience which adds value. The experiential value of a custom yacht compared to a yacht created with design reuse can be more or less similar. Symbolic value can be increased by choosing for green alternatives but also the Feadship brand adds symbolic value as a renowned super yacht builder. The financial value represents both time and costs, this is the value which is affected the most by reusing parts of the design. As reducing engineering costs and time will reduce the denominator of equation 2.1 and thereby increase the total value.

3

Problem Diagnostics

This chapter collects the requirements, variety in general arrangement, time divisions of engineering processes and customer value linked to those processes. This will form the base for the decisions in chapter 4. The chapter starts with an overview of existing design reuse concepts from both Feadship and other companies, to give an idea of existing solutions and possibilities for design reuse. Afterwards requirements are determined, this is done using a database of 40-60 metre yachts and a visual comparison of existing Feadships between 40-60 metre. Originally the aim of this project was to create a concept for the whole range between 40-60 metres. This has changed to 50-60 metres after this part of the research was already done. Therefore, this chapter will analyse yachts between 40 and 60 metres. By using existing yachts to derive the functional requirements, the requirements should represent the wishes of the customers. A visual comparison is used to understand how much diversity is needed in general arrangement and features of the platform. For this comparison only Feadships are used. To identify the most time consuming engineering processes, the work breakdown structure(wbs) of De Voogt is used. For each of the processes, the time in percentages is shown. The same processes are rated for experiential and symbolic customer value. The combination of these two values will give an indication of the possible time savings and the effect it will have on the customer value if the product of these processes were to be reused. The results of the database, the visual comparison and the assessment of engineering hours and customer value together act as the input to make decisions during the product platform development.

3.1. Overview of existing design reuse concepts

Several examples of design reuse in the maritime industry can be identified, where mostly modularisation is used to achieve the design reuse. In this section, three previous design reuse concepts of Feadship will be discussed, together with mostly navy vessels and a few other reuse examples as well. An overview of the designs can be found in table 3.1. First, the three Feadship designs will be discussed, followed by a brief description of each of the remaining concepts.

3.1.1. SL39: A platform with modular design options

The SL39 is a 39 metre platform designed in 2006 with the intention to be able to start the building and sell the yacht during the construction. The platform consists of an integral platform with place for six modules using a type of bus modularity. Each of the six different module locations has four possible modules, because of the bus modularity there is no need for large changes to the platform when choosing different options. The SL39 product family has three family members built in 2008 and 2009.

Figure 3.1 shows the basic platform with the empty spaces for each of the modules. The six open module spaces can be found at the following locations:

- Guest quarters on lower deck
- Owner quarters on main deck forward
- Lounge and dining area on main deck aft
- Lounge on the bridge deck

Table 3.1: Different design reuse concepts in maritime industry

	Type	**Maker**	**Sort of reuse**
US Navy TES	navy	US Navy	Modular in use by swapping modules
Standard Flex	navy	Danish navy	Modular in use by swapping modules
FREMM	navy	French Italian Navy	Reusable platform
MEKO frigate family	navy	Blohm+Voss	Modular in use by swapping modules
Littoral combat ship	navy	US Navy	Modular in use by swapping modules
SIGMA	navy	Damen Schelde	Modular in design
MOPCO	navy	abeking and rasmussen	Modular in use by swapping modules
Modular ship hull design IIT	container	Indian Institute of Technology	Modular in design
Modular design strategy Ulstein	Offshore supply vessel	Ulstein	Modular in design
SWATH	SWATH offshore	Abeking and Rasmussen with Lurssen werft	Modular in use by swapping modules
FLC	yacht	Feadship	Modular options in design
SL39	yacht	Feadship	Modular options in design
F45	yacht	Feadship	Standard with interior options
Super Expedition	yacht	ER yacht design	Modular in use by swapping modules

- Mid space on bridge deck starboard
- Mid space on bridge deck port side

The options for each of these spaces are shown in figures 3.2 through 3.5. The exterior styling of the SL39 can be customised to the wishes of the client.

In theory, the SL39 concept offers 1312 unique combinations of modules In practice, however, the modules show lots of similarities, reducing the actual variation offered. Also, the main parameters are already fixed regarding range, speed, number of crew and tenders, reducing the possibility to deliver exactly what the customer wishes.

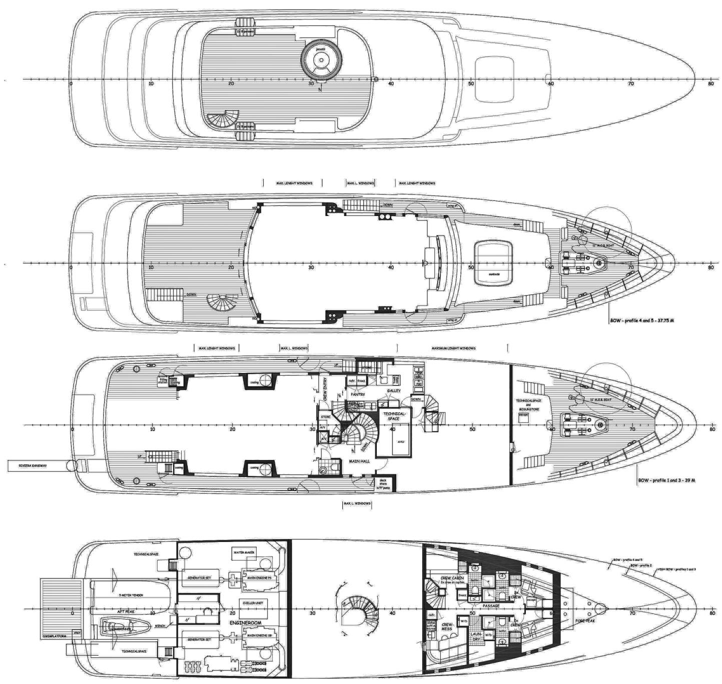


Figure 3.1: Basic platform of the SL39 with the six open spaces for the modules[9]

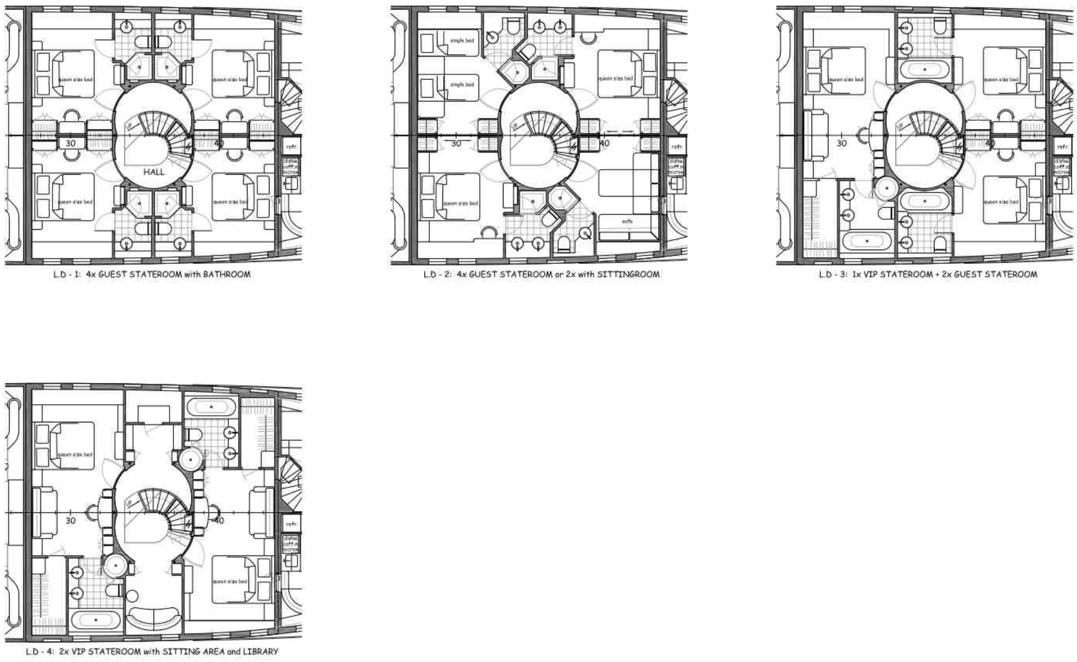


Figure 3.2: The four possible options for the SL39 lower deck guest cabins. The first option shows 4 identical rooms, the second option shows two normal staterooms and two staterooms that can be converted from a sitting room to a stateroom. The third option has one large VIP room and two normal staterooms. The last and fourth option features two VIP staterooms.[9]

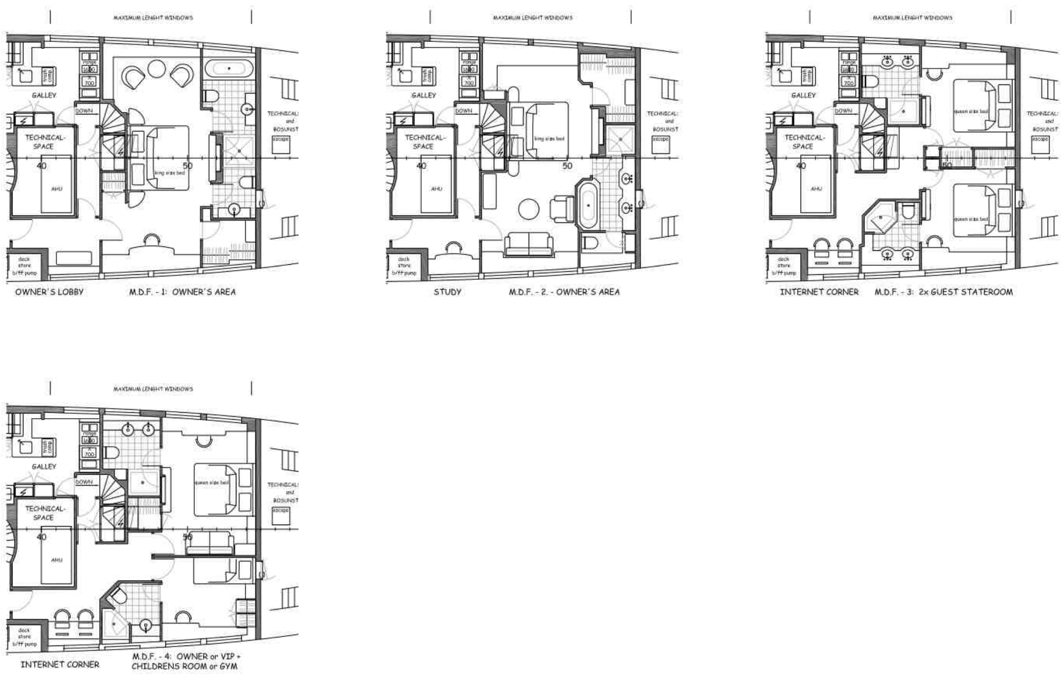


Figure 3.3: The four options for the SL39 forward part of the main deck with the owner's area. The first two options have a different bathroom and sitting area arrangement. The last two both have an extra room which can be used for extra guests.[9]

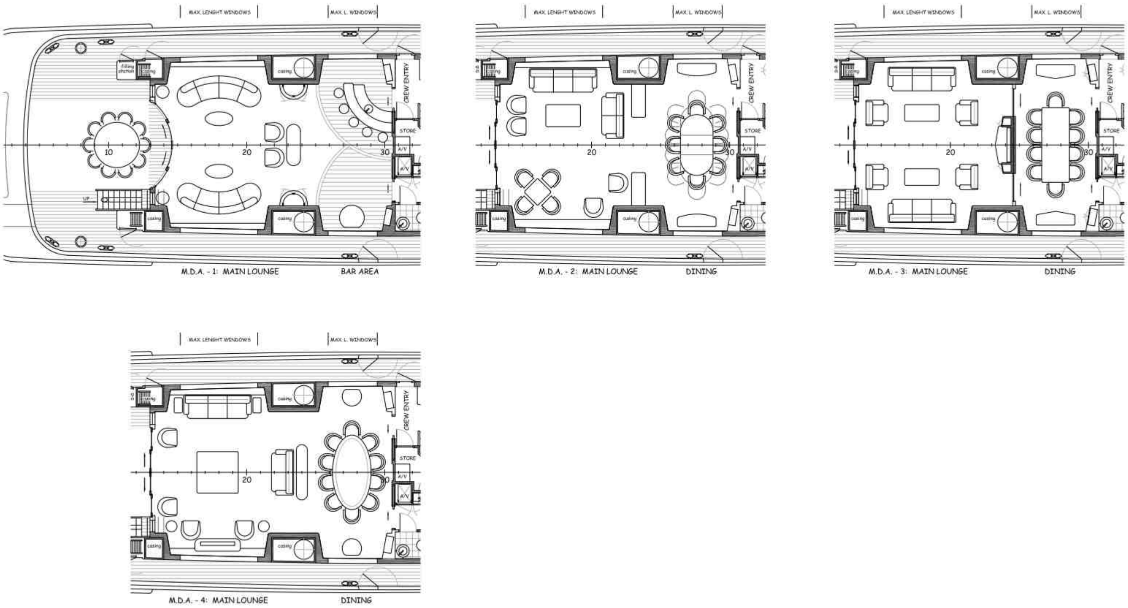


Figure 3.4: The four options for the SL39 aft part of the main deck with the lounge and dining area. These four options offer the same functionality but in different arrangements, the first has a bar, the second and fourth both feature a dining with different seating arrangements. The third has a separate dining room.[9]

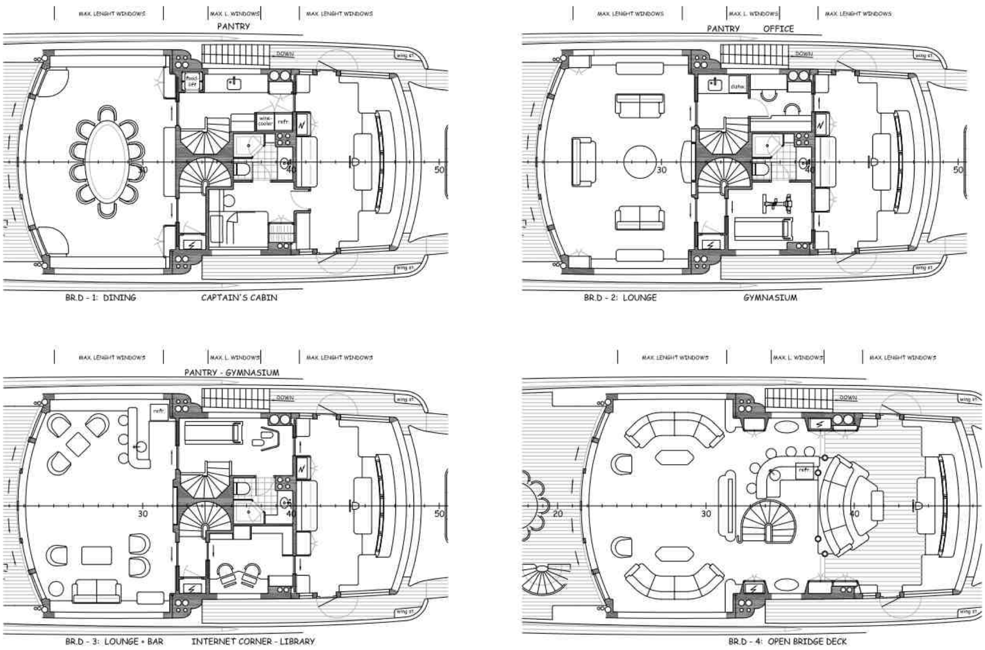


Figure 3.5: All options for the SL39 bridge deck, the three possible module spaces each have multiple options which are all shown in these four options. Different combinations of these spaces is still possible to some extent. The first offers a captain's cabin and pantry, the second and third offer an office, small pantry and gymnasium. The fourth option is an open deck bridge deck with a bar in the middle.[9]

3.1.2. Feadship Lagoon Cruiser (FLC): A 34 metre platform

The Feadship Lagoon Cruiser is designed in 2014 on request of a client. This means that the client was already involved during the design. The product platform has an integral platform which is reused for each new yacht and to which limited changes can be applied, an example of such changes is shown in figure 3.7. There are also various options to add desired extras such as diving equipment or a jacuzzi. The FLC product family consists of five yachts.

Figure 3.6 shows the general arrangement of the FLC platform. The possible variation between yachts is limited to arrangements of interior rooms. There are however various basic options offered, these are all listed below. Besides these options much more customisation was possible on request of the customers.

- Main engine, two possible main engines can be provided, a 600 kW and a 1340 kW increasing the top speed from 15,5 to 19-20 knots.
- Hardtop extension, the hardtop on the sun deck can be made longer for more shade.
- Polished stainless steel cutwater
- Sky light in owner's area, a 1.4x2m skylight can be fitted in the deck forward of the wheel house.
- Hull colour, standard hull colour is white but also gray, black, blue and green are possible.
- Stabilisers, these can be installed if desired.
- Underwater lights, a total of eight underwater lights can be fitted in the aft ship.
- To easily fill the tender a diesel filling hose reel with gun can be mounted.
- Sewage treatment plan, to be able to take longer journeys a sewage treatment plant can be installed.
- Dive compressor, if desired a dive compressor can be fitted.
- Spa, on the sundeck a circular four persons spa can be placed.

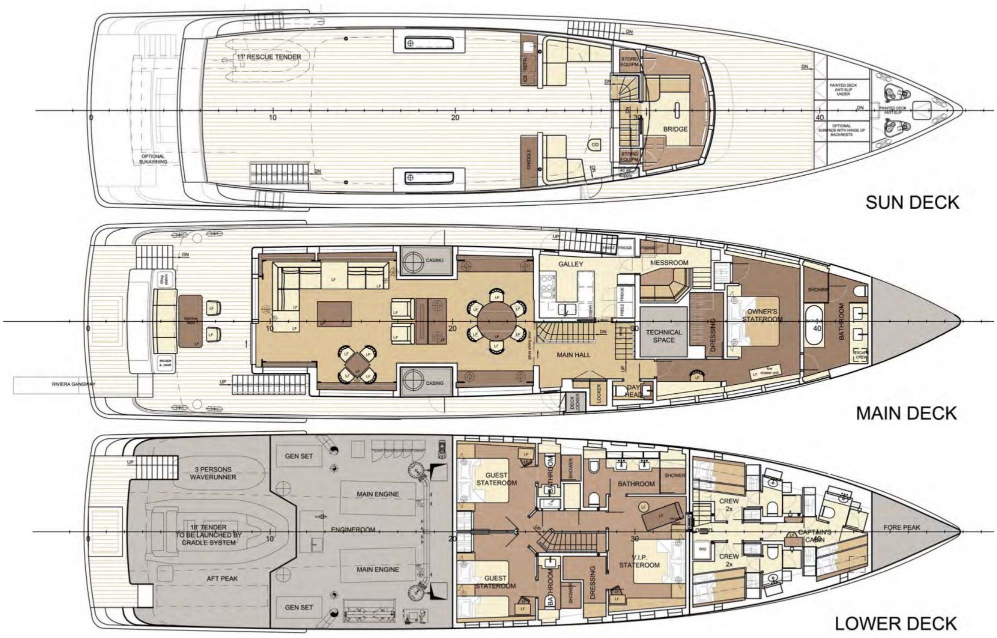


Figure 3.6: The general arrangement of a FLC[9]

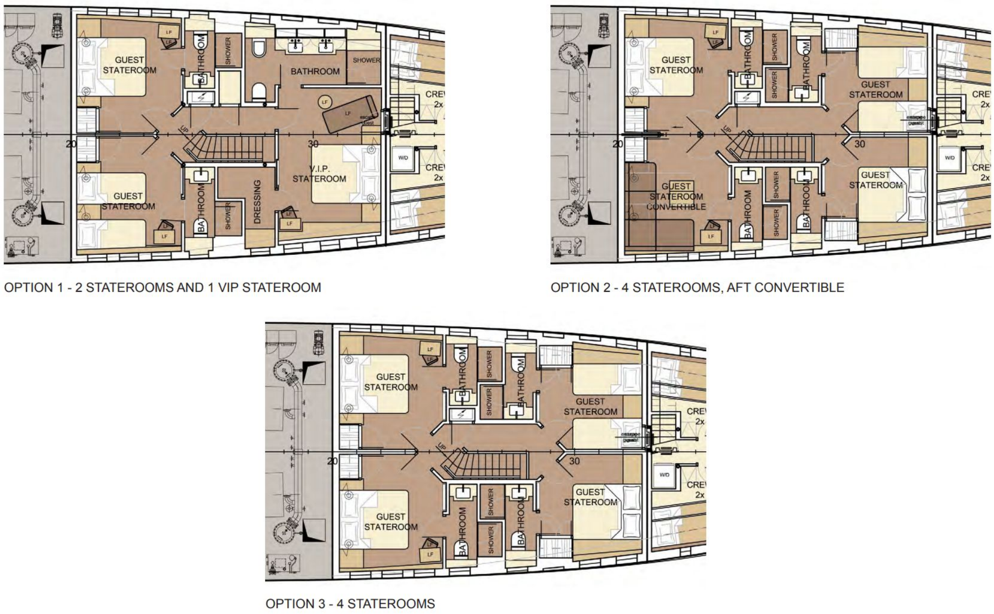


Figure 3.7: The guest room options for the FLC[9]

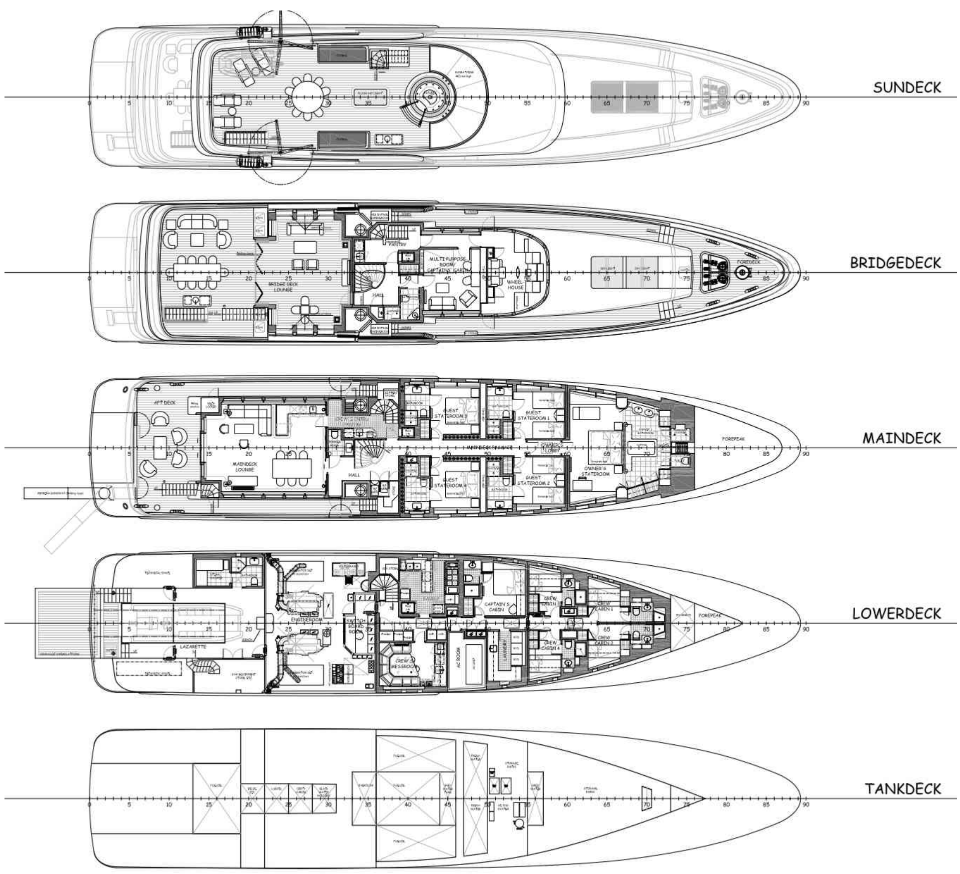


Figure 3.8: General arrangements of the F45 platform[9]

3.1.3. F45: A 45 metre platform

The F45 is a 45 metre Feadship just under the critical level of 500 gross tonnage (GT) and was designed to be sold during or at the end of the building process. Yachts over 500GT have to comply to different regulations and therefore it is beneficial to stay under this level. The F45 is an integral platform with standard lay-out and technical equipment but different styling options. There are also possibilities to make small changes to a room but there are no standard modules from which different room lay outs can be chosen. Essentially, there is one option which is the interior styling of which four different themes can be chosen: Miami, Monaco, Milano and Nautical. In figure 3.8, the basic general arrangements of the F45 can be found. The product family of the F45 platform consists of six different yachts which are built in two sets of three.

3.1.4. Navy design reuse concepts

Most of the design reuse concepts listed are navy vessels, the first one is the US Navy TES already described by Jollif in 1974. [36] It uses slot modularity on an integral platform (a variant of bus modularity, but with a specific interface for each component/module place) to swap modules and be able to fulfil different missions. The US Navy TES can be seen in figure 3.9 with the different modules. Different product family members are created by adding different modules, creating different functionalities.

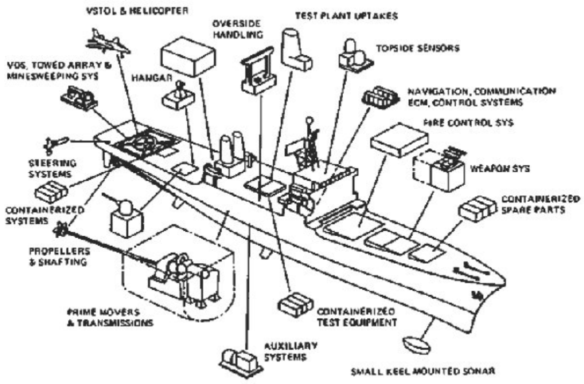


Figure 3.9: The US Navy TES concept with slot modularity to increase the mission capability[36]

The second is a slightly newer but similar design, the Standard Flex is a platform with exchangeable weapon and system modules. The modules use bus modularity to connect to the platform. By swapping the modules, the ship can take on different roles. The first generation was built in the 1990's and has two possible integral platforms for the modules to be used on. The second generation was designed in 2000 and consists of three differently sized platforms. Figure 3.10 shows the 1990 and 2000 standard flex vessels, together with several possible modules. The Royal Danish Navy has currently over 100 modules on stock and at least 30 ships have been built. [23]

The FREMM frigates is a design project between France and Italy, three versions of the FREMM exist: an Anti Submarine Warfare, an Anti Air Warfare and a General Purpose version. Both France and Italy use these versions as an integral platform to which modifications are made to derive their own specific frigate with specific equipment. In total the product family will consist of 18 ships, the first one was launched in 2012 and the last one will be launched in 2022. In figure 3.11 two versions of the FREMM frigate can be seen. [25]

The MEKO is another modular in use vessel which is able to switch payload modules such as weapons and sensors easily, reducing downtime and making it capable of executing different missions. The US navy's less successful version of the MEKO is the littoral combat ship. The littoral combat ship is also designed to be able to swap modules such that different missions can be carried out. However, swapping occurs rarely and most US literal combat ships have a fixed task.

The SIGMA (ship integrated geometrical modularity approach) class naval vessels offer high flexibility in design at reduced costs by using modules. There are three main platform types: a frigate, a corvette and a fast attack corvette. The modules use sectional modularity, making it possible to re-configure the lay-out or add modules to increase the length.

MOPCO is similar to the Standard Flex and MEKO concept and is designed by Abeking & Rasmussen. It also uses modules with standard interfaces to be able to rapidly change the capability of the ship between missions.

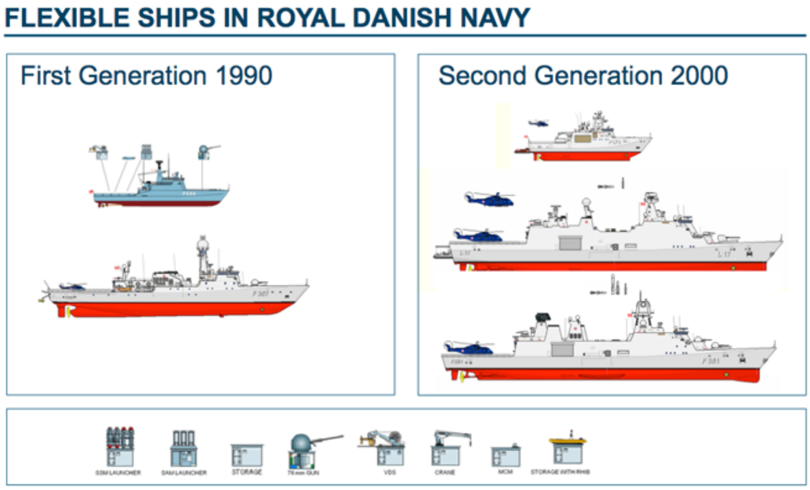


Figure 3.10: The Danish Standard Flex concept[23]

Figure 3.11: 2 different version derived from the FREMM platform[25]

3.1.5. Other examples of design reuse

Other examples of design reuse can be found in the offshore and transport vessels. A very good example of a modular platform is the Ulstein modular offshore supply vessel design. It exists of different hull and equipment modules which can be combined in ships of different lengths and with different functions using mostly sectional modularity. The modules and a few of the ships that can be made with the modules can be found in figure 3.12.

The SWATH@A&R concept has a SWATH platform and place for a mission module, which can be swapped using component swapping modularity. This makes it another example of modular in use ship.

The Indian Institute of Technology developed a modular container ship with 2 fore bodies, 2 accommodation modules and 6 mid bodies and 1 stern. This results in 12 different ships of which 6 are intended for container shipping and 6 others as a tanker or bulk carrier. This modular platform uses sectional modularity to be able to combine the different modules. [21]

The last example is a concept yacht designed by ER Yacht Design, the yacht can both be a family yacht as well as a serious expedition yacht by using component swapping modules in the form of containers of different sizes. This can add extra accommodation, laboratories or for example extra storage for tenders and toys. A picture of two different arrangements can be seen in figure 3.13

3.1.6. Conclusion: Modularity during design and operation

The above examples show different applications of modularity both during design and operation. Most navy vessel use modularity during operation to extend the capabilities of the vessel and reduce down time. Other examples which are of more interest for this project are: the Ulstein offshore supply vessel, the SIGMA naval vessel or the merchant ship design from the Indian Institute of Technology show modularity in design to reduce design time and costs. These concepts all create a series of family members with the same beam but a difference in length and functionalities.

Figure 3.12: The modules and some variants of Ulstein's modular design approach[7]

Figure 3.13: The ER yacht design concept of a yacht with module swapping capacity to change it from family yacht to an expedition yacht[3]

3.2. Deriving the product platform requirements

The functional value of a yacht is used to derive the requirements for the platform. The value is found using a bottom-up approach with existing yachts from Feadship. First, different general arrangements are visually compared to find common arrangements. Then, the different spaces on a yacht are analysed and finally, the product family boundaries are set, using the database and regulations.

3.2.1. Different lay-out variants depending on tender and engine room position

Different yachts between 40 and 60 metres length over all are used in the visual comparison. By comparing the yachts, the amount of variety needed in the general arrangements is determined. The details of the used yachts can be found in table 3.2. From the visual inspection of all the general arrangements, it appears that there are only a few large differences between the yachts. In this section, the common rooms of each deck will be discussed first, and afterwards the derived variations will result in a few choices which covers most of the lay outs. The possible deck variations are shown in figure 3.14.

Sun deck has an outside lounge and most of them have a jacuzzi, lay-out 1.1. In some yachts the tender is stored on the aft of the sun deck, lay-out 1.2.

Bridge deck always has the following elements: outside lounge, inside lounge, captains cabin and the bridge all shown in option 2.1. Sometimes, especially more towards the 60 metres there can be a pantry, ship office or some extra luxury space just behind the bridge. This is considered as different usage of the luxury space and therefore not seen as a variation. There can also be outside tenders on the bridge deck, these are positioned just aft of the bridge on both sides of the yacht, but this is not common to do anymore and therefore this will not be used as an option.

Main deck consists of an outside lounge, inside lounge, the owner rooms and possible guest rooms and a galley depending on the tender location. There is room for tenders on the main deck, these can be stored in front of the owners cabin inside a tender garage, lay-out 3.1. The front deck outside tender storage is a not very common anymore and therefore not used as an option, this also holds for the tender storage on the aft instead of an outside lounge. Another possible variation sets the guest rooms on the main deck when a large tender store is present on the aft of the lower deck. In this configuration the galley is placed at the lower deck, lay-out 3.3. Lay-out 3.2 shows the arrangement without tenders, which is used when the tender is stored on the sun deck.

Lower deck houses the engine room, crew cabins and it is possible to have guest rooms, a galley and a tender store. In the aft peak, there is always room for some small toys. The main variation at the lower deck is in the position of the engine room and guest rooms. The engine room can be positioned aft which places the guest rooms more in the middle of the yacht, lay-out 4.2. Or these two can be switched, placing the guest rooms aft and engine room in the middle, lay-out 4.1. There is also a variation which places a large tender store in the aft resulting in the guest rooms moving up a deck and the galley moving down, lay-out 4.3.

Tank deck at the larger yachts, the tank deck can be high enough to house some crew storage and technical spaces but the tank deck is at the moment not seen as an extra variation.

The variation in lay outs can be covered by tender placement, guest rooms, engine room and galley. This variation leads to a few common general arrangements for each decks, these are shown in figure 3.14. From these decks a few combinations can be made in which one of the decks houses the tenders, which therefore limits the combinations. Also, the large tender storage on the lower deck is only possible in combination with the guest rooms at the main deck. With these restrictions five possible combinations exist. Each of the unique combinations is shown in the tree diagram in figure 3.15.

3.2.2. Rooms on board of yachts

From the visual comparison different rooms can be identified, the rooms can be collected in three categories: crew, luxury and technical. In the three columns below the different rooms are listed. The first column consists of the crew rooms, the second of the luxury rooms and the lasts column lists the technical parts. The crew rooms as listed all have to be used in the concept, some might be combined in a module. The list of luxury rooms can be reduced to seven different rooms in which the inside lounge, library, office and dining can be combined. Although they have a different function for the owner, in technique and location these spaces can be seen as equal. Of the technical parts identified on the yachts, the outside tender store is seen as a bit old-fashioned. A swimming pool is not common on a yacht below 60 metres. The technical space can have multiple functions, for example an AC-room, but also in the aft peak technical space is used to house the

Table 3.2: Details of the Feadship yachts used in the comparison[9]

Loa [m]	Lwl [m]	Bmld [m]	Boa [m]	T [m]	Free board [m]	GT [ton]	Max Speed [kn]	Range Speed [kn]	Range [nm]	Engines Power [kw]	# Owner Guest	# Crew	Fuel cap[l]	Water Cap[l]
51,21	43,59	9,72	10,07	2,15	2	765	15,5	12	4200	1492	10	11	72400	16700
53,5	48,46	9,9	10,3	3,37	1,95	857	15	12	4500	2236	10	11	97250	28600
55,05	48,97	9,9	10,3	3,47	1,85	891	15,4	12	4500	2236	10	12	99800	29000
57,6	50,5	10,15	10,5	3,25	1,95	941	15,5	12	4500	2280	8	13	104000	12000
46,2	44,58	9	9	2,25	2,1	406	19	12	4500	2834	10	7	51000	16000
46,4	44,78	9	9	2,25	2,3	423	16	10	5500	1790	11	9	51000	16000
44,2	38,3	8,7	9,1	2,75	1,75	499	14,7	10	3850	1790	8	7	41000	12000
47,35	43	9,2	9,6	2,92	1,91	589	14,5	10	4000	2160	10	9	50000	12000
58	57,4	11,03	10,95	2,6	2,3	888	16	12	4000	2160	10	11	85000	20000
51	49,3	10,4	10,8	3,35	0,83	902	14,5	11	4500	1790	10	13	90000	20000
55,21	49,01		9,4	2,65		740	15	10	4500	1790	10	12	70000	15000
49,43	47	7,9	8,2	1,85	2,55	498	28	10	1600	5370	10	9	42900	13250
54,5	53,8	10	10,4	2,84	2,36	931	15	12	4500	2160	12	11	125000	25000
40	34,6	8,7	9	2,75	1,9	405	13	10	4500	1000	10	8	52750	17600
51,75	46,5	9,98	10,4	3,2	2,1	863	15,5	12	5500	1492	13	12	103300	26000
46,5	41,15	8,85	9,25	3	1,9	562	14,3	13	5200	1492	10	11	105000	24000
42,56	38,1	8,6	9,2	2,7	1,9	443	14	11	4300	1074	8	7	59500	19500
44,65	38,65	8,8	9,2	2,7	1,85	499	14,5	10	4500	1576	8	9	40000	10000
44,65	38,65	8,8	9,2	2,7	1,85	499	14,5	10	4500	1576	10	9	40000	10000
44,65	38,65	8,8	9,2	2,7	1,85	499	14,5	10	4500	1576	12	9	40000	10000
44,65	38,65	8,8	9,2	2,7	1,85	499	14,5	10	4500	1576	10	9	40000	10000
44,65	38,65	8,8	9,2	2,7	1,85	499	14,5	10	4500	1576	10	9	40000	10000
44,65	38,65	8,8	9,2	2,7	1,85	499	14,5	10	4500	1576	10	9	40000	10000
57,47	50,77	10	10,5	3,15	2,1	1001	16,8	12	5000	3000	12	12	100000	20000
56	49,7	10	10,4	3,15	1,9	920	15	11	4000	2160	10	14	75000	20000

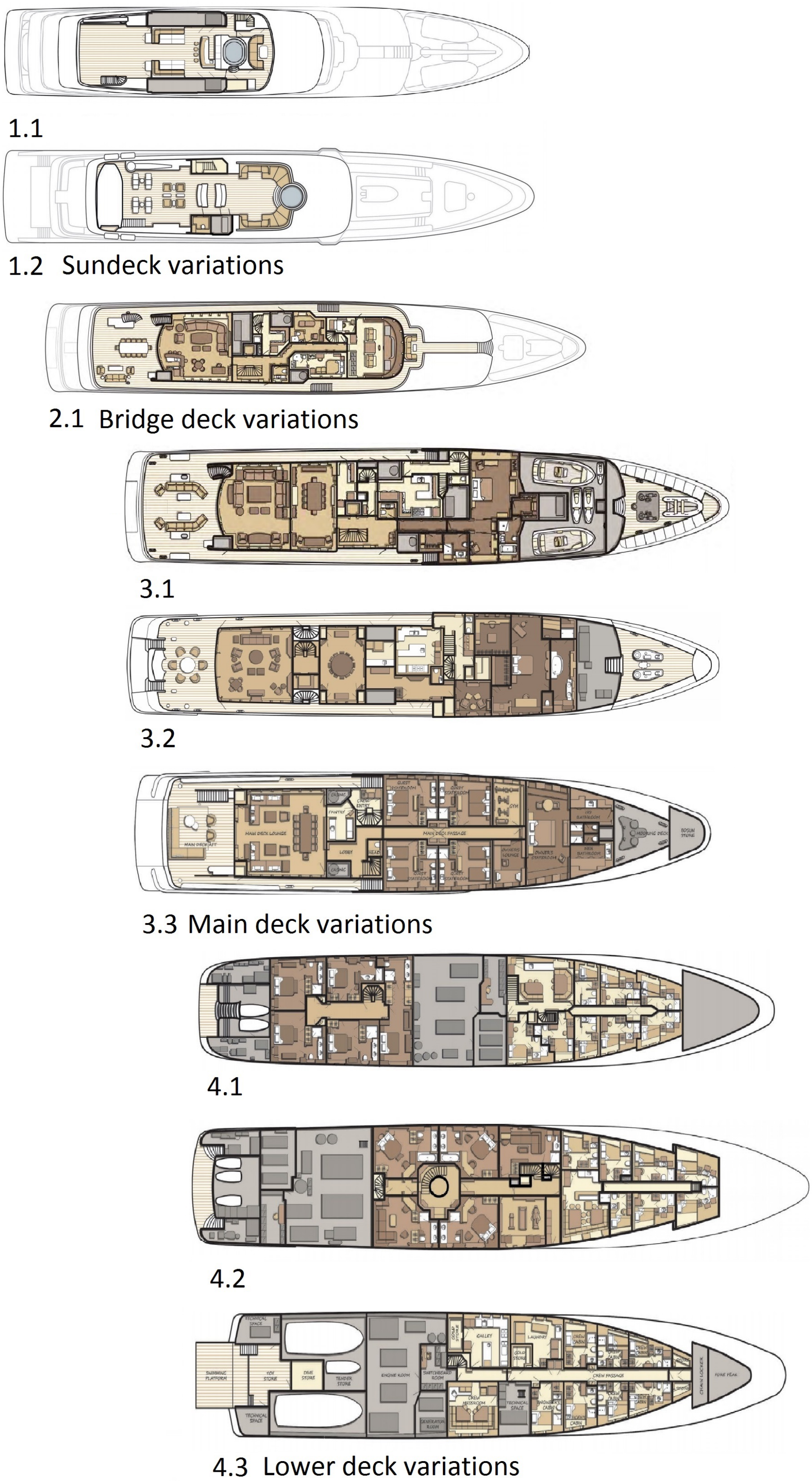


Figure 3.14: Different deck lay-out possibilities identified from comparison shown for each deck[9]

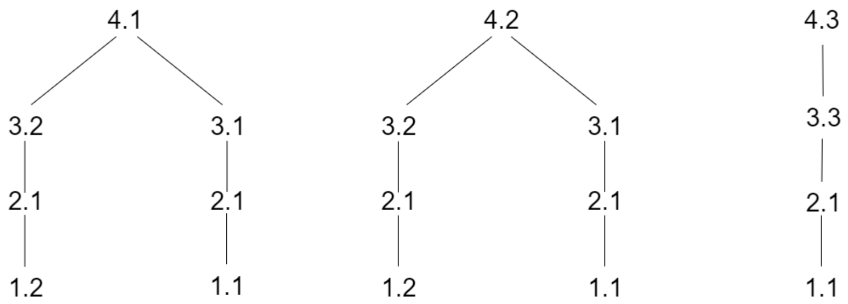


Figure 3.15: The tree diagram shows each of the possible combinations from the decks in figure 3.14[9]

passerelle. Because the outside tenders are old-fashioned and a swimming pool is not seen so often below 60 metres these will be dropped from the list of technical spaces needed on the modular concept.

- Crew cabins
- Mess
- Laundry
- Storage
- Pantry
- Galley
- Wheel house
- Captain's cabin
- Ship office
- Outside lounge
- Inside lounge
- Owner's rooms
- Guest rooms
- Head and powder rooms
- Gym
- Library
- Office
- Dining
- Beach club
- Jacuzzi
- Toy store
- Outside tender store
- Inside tender store
- Swimming pool
- Technical space
- Engine room

3.2.3. Product family boundaries for length, guests, crew, tenders, range and power

To reduce the amount of options to explore, boundaries are set for the total product family. Some of the minimum and maximum values are based on regulations, while others are derived from a database with yachts between 40-60 metres. The 40-60 metres length over all is chosen because recent market studies show a large amount of yachts being build in this range and therefore a lot of potential customers. Also an owner of a yacht larger than 60 metres most likely had a smaller yacht before. By offering competitive yachts in this segment Feadship might be able to create customer loyalty. The other boundaries, which can be seen on the left in table 3.3, represent functional requirements of the product family. The minimum amount of guests is 8 as this is the minimum in the database. The maximum is set to 12, if more than 12 passengers are on board the large commercial yacht code [13] is not valid anymore and the yacht will have to comply with the stricter passenger yacht code. The amount of crew should vary between 7, the minimum defined in the manning policy manual [29], and 16, based on the maximum in the database. At most two tenders will be allowed, and the tender length should not exceed 8 metres, based on existing Feadships. Also 1 or 2 jetskis or waverunners need to be stored in a so called toy storage. A minimum range of 3500 is used to be able to sail across the Atlantic ocean. Engine power is based on the yacht database, a minimum of 1000 kW and a maximum of 3500 kW is used.

On the right in table 3.3 are boundary indications, these are not seen as requirements since on themselves these do not represent functional value. These numbers do however give an indication about the expected size of the product platform and therefore are shown in this table. The numbers are the minimum and maximum values for the representative yachts in the database.

3.3. Engineering hours per discipline for a 56 metre yacht

The main goal of reusing parts of the design is to reduce costs by reducing engineering hours. To identify which parts of the design process take up most of the hours, the distribution of hours over the different disciplines is analysed using the work breakdown schedule as used within De Voogt. These are the engineering

Table 3.3: On the left are the minimum and maximum capacities for the product family which are requirements for the product platform. On the right are indications from the database with yachts to give an idea about the measurements.

Requirements		
	min	max
Length[m]	40	60
# of passengers	8	12
# of crew	7	16
# of tenders*	1	2
Size of tenders	0	8
Extra toys	1	2
Range[nm]	3500	5500
Engine power[kW]	1000	3540

Boundary indications		
	min	max
Beam[m]	8.5	11.5
Draft[m]	2.6	3.55
Depth[m]	4.5	5.32
Gross tonnage	405	1226

hours after signing the contract. Therefore, the design department, which is normally the second discipline in the work breakdown schedule, is left out of the analysis. The planning of a 56 metre yacht, which is seen as a representative yacht for the 40-60 metre range, is used to calculate the percentages of time spent on each process. The yacht has a maximum speed of 15 knots and can accommodate 10 guests and 14 crew. The hull is made of steel and the superstructure of aluminium. The results of the analysis are visualised in figure 3.16, this figure shows the work breakdown schedule together with the percentage of hours of each second level tile.

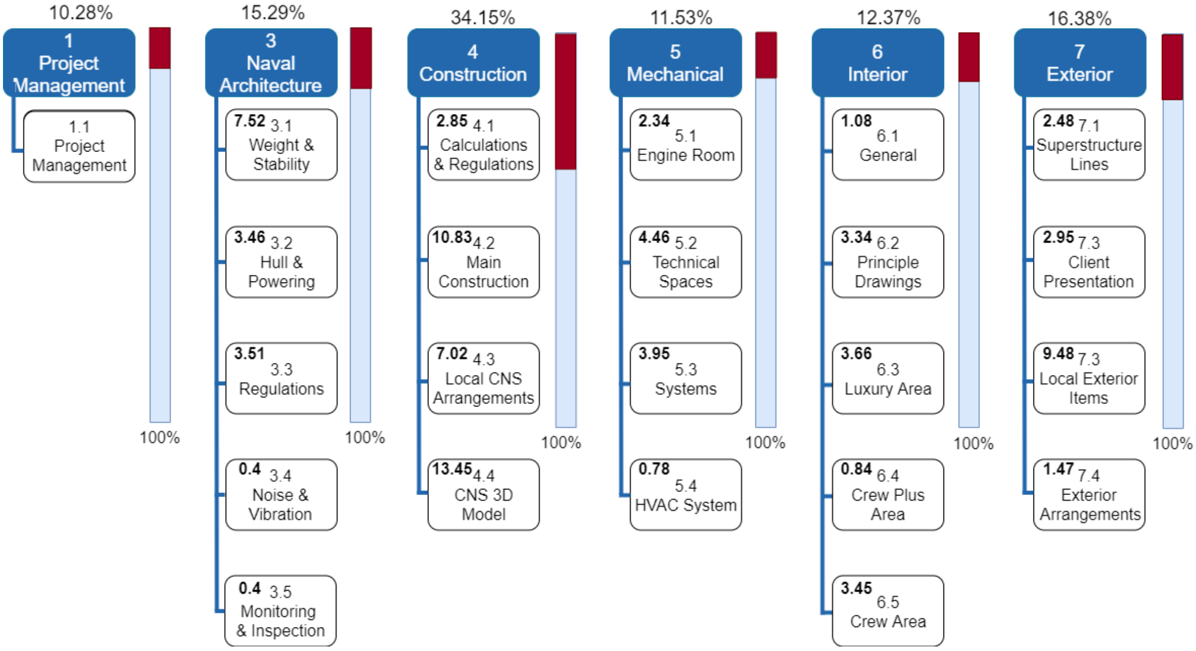


Figure 3.16: Percentage of time spent on the processes within each discipline, overhead are the cumulative percentages for the whole discipline and these are also visualised in the bar on the right of the discipline. Design is the second discipline normally in the work breakdown structure, but is left out of this analysis.

3.4. Value for reuse potential in the engineering processes

The reuse potential is determined by looking at the experiential and symbolic customer value created in the engineering processes. The value assigned to each of the processes in the work breakdown structure, is used to ensure that the possible reuse options that follow from the analysis of the work breakdown structure will not affect the customer value too much. Since the parts with a high customer value, are those requiring differentiation and therefore are not suitable for reuse. An overview of the values for reuse potential assigned to each tile of the work breakdown structure can be seen in figure 3.17. A number on a scale of 3 is given to each of the second level tiles of the work breakdown structure. A value of 3 is given to processes that have

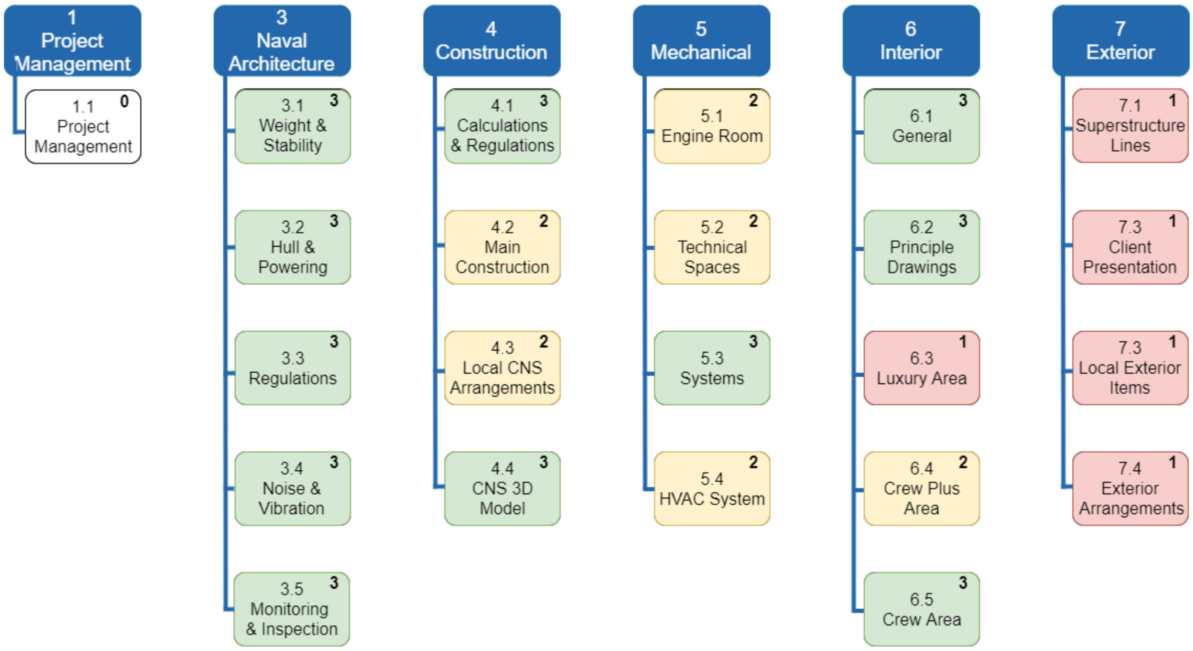


Figure 3.17: Reuse potential values assigned to the processes in the work breakdown schedule of De Voogt. Values have a range of 1 to 3, where red corresponds to value 1, which means low reuse potential, yellow to value 2, some reuse potential, and green to value 3, high reuse value. Design is the second discipline normally in the work breakdown structure, but is left out of this analysis.

little or no customer value and therefore high reuse potential. 2 is given when there is some reuse potential and 1 in cases where the processes have a low potential for reuse and therefore a high customer value. In figure 3.17, green corresponds to a value of 3, yellow to a value of 2 and red tiles have a value of 1.

Starting with the exterior: since exterior defines the appearance of a yacht, this discipline has high customer value and low reuse potential. More specific, experiential and symbolic customer value, since the looks of the exterior define a yacht's character. Therefore, in figure 3.17, tiles 7.1 to 7.4 are all rated 1. The process of tile 7.1 defines the details of the superstructure, tile 7.2 consists of a number of small details upon which the owner and the design team need to agree. Examples are railings, bar, seating and more. Tile 7.3 consists of more specific items such as exterior stairs, furniture and various miscellaneous items. Tile 7.4, the exterior arrangement consists of doors and windows in the hull and superstructure and various other arrangements.

Second the interior, number 6 in the work breakdown structure. Tile 6.1, general, is a check for feasibility and whether the arrangements comply with the rules, and is rated 3. Tile 6.2, the principle drawings, is also rated 3 because these are mainly overview drawings needed for the classification. Tile 6.3, the luxury area, is rated 1, this is where the owners and guests will reside when on board and therefore influences the customer value. The interior department creates box drawings for each of these rooms. These drawings show the available space for the architect and location of certain equipment which influences the arrangement in the room. An example can be seen in figure 3.18. These processes relate mostly to the experiential value, reuse will yield the same functional value but reduce the experiential value. Tile 6.4, Crew plus area consists of the captain's cabin, ship's office and wheelhouse lay-out. The wheelhouse is accessible for the owner or guests. Therefore, this area has some customer value and is rated a 2. Tile 6.5, the crew area, is rated 3 since these spaces will only be visited by the crew.

The mechanical part consists of 4 sub levels. Tile 5.1, engine room, and tile 5.2, technical spaces, are both rated a 2, these tasks set the arrangement within the technical rooms but the arrangement and especially the casings influence the space above the engine room. Furthermore, the in- and outlet of the AC-rooms are positioned in locations where owner or guests can reside and therefore can influence the experiential value. Tile 5.3, systems, is rated 3, tile 5.3 concerns system schematics and diagrams, the schematics are necessary for the classification and the diagrams are used for production. Tile 5.4 is rated 2 and consists of an early check to identify problem regions. Also a routing for the galley duct is proposed this large ducts should lead to the mast and therefore influences a large part of the yacht above the galley.

The construction work breakdown structure has 4 second level tiles. Tile 4.1, calculations and regulations, is rated 3, this part consists of strength calculations of the chosen construction. Tile 4.2, the main construc-

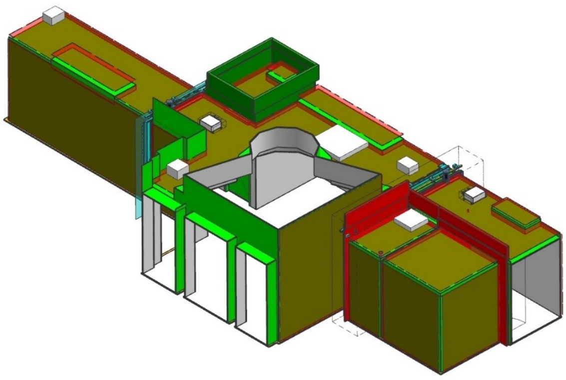


Figure 3.18: Example of an interior box drawing[9]

tion, is rated a 2 since the positioning of bulkheads, pillars etc. influence the arrangement and possibilities in the luxury rooms. The local construction arrangements of tile 4.3 are rated a 2. The construction of the local parts represent little customer value but since this construction is for a large part dependent of the location of these items it is still rated a 2. The last part of the construction is tile 4.4 the CNS 3D model in which all the construction details are 3D modelled is rated 3. Although the 3D model is useful in design and production of the yacht it has little value for the customer since it is mainly a 3D representation of the parts already created in the other construction process.

The last engineering part of the work breakdown structure, 3, Naval Architecture, has 5 second level tiles all rated 3. The naval architecture processes, are mainly evaluations of the designs produced at other disciplines. The outcomes of these processes are used to steer the other disciplines. The reuse of parts of the naval architectures engineering depends on the other disciplines. In processes in tile 3,2, decisions are made about engine power and tank capacities but these influence the functional value and not experiential or symbolic value. The functional value is already considered in the database and visual comparison.

3.5. Construction and mechanical components as potential reuse areas

When the customer value is multiplied with the percentage of time, 9 second level tiles of the work breakdown schedule have a value above 10. This is considered high enough to further investigate how engineering hours for these processes can be reduced. Because of the multiplication with experiential and symbolic customer value, these processes will only for a small part influence the customer value. Figure 3.19 shows the work breakdown schedule with the visualisation of the multiplied percentage of time and customer value.
The first one is tile 3.1, weight and stability, which is highly dependent on a lot of other design processes and disciplines. A reduction of engineering hours will be possible by reusing parts of the yacht. Since for the reused parts the weights will be known, the weight estimate will take less time. Every level of reuse will be beneficial but the higher the level the more engineering hours can be reduced.

Second is tile 3.2, hull and powering, these processes concern the resistance, linesplan, tanks, shaftline and appendage arrangements and also the sea trial before delivery. By using a standard propulsion and tank arrangement already a large part of the work can be reused.

Third is 3.3, regulations, which is again highly dependent on other parts of the design process. Full standardisation would make it possible to reuse most official documents and certificates. But a few standardised parts can be useful as well to reduce GT calculations. Or reuse parts of the watertight integrity or fire and safety plans. This will only be useful if it is clear which parts are reused and if these are reused without modifications.

In tile 4.2, the main construction, large spans and vertical aligning is most important. The possibility for vertical alignment is dependent on the general arrangement. To achieve a reduction in hours large parts of the design should be standardised. For example, a standard platform can reduce engineering hours if vertical alignment is guaranteed.

In tile 4.3, local construction arrangements, the construction around various equipment is designed in detail. The possible solution for the equipment foundations depend on the location and the main construction plan. Therefore, to reduce hours in the local construction the location within the main construction

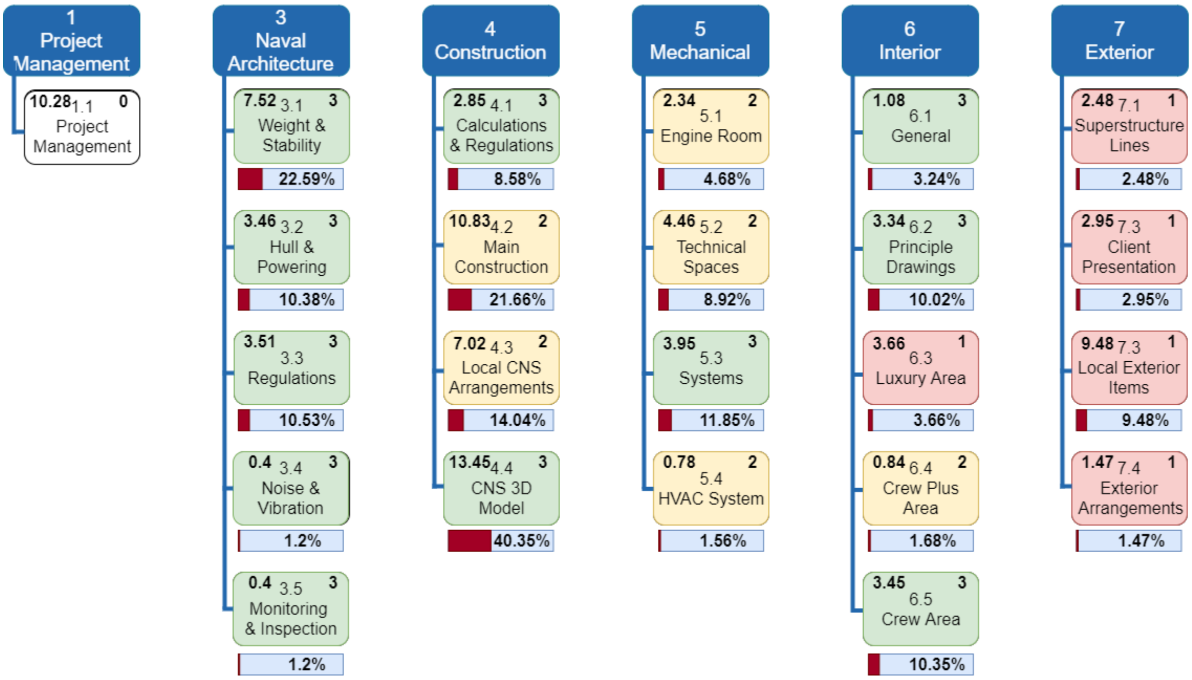


Figure 3.19: Work breakdown schedule with the percentage of time for each process and corresponding customer value, below each tile the multiplication of customer value and time is shown which is used as a measure for possible reuse. Design is the second discipline normally in the work breakdown structure, but is left out of this analysis.

should be kept the same. The equipment includes cranes, hull and bulwark doors, riviera gangway, mooring equipment, rudder, stabiliser, bow thruster and mast foundation.

Tile 4.4, the CNS 3D model, is the result of the decisions made in the other parts of the construction process. Therefore, benefits can be expected from standardisation in these parts. As long as it is done in a way that the complete part of the design can be reused and the interfaces are connected.

Tile 5.3 is the systems part of mechanical engineering discipline. The schematics and diagrams are a direct result of the chosen equipment and locations. The schematics only represent the connection between different equipment, these could be reused if the same equipment is used. The system diagrams show the equipment and connections in space and are used in production, these can only be reused if the parts of the yacht are completely reused

Tile 6.2, the principle drawings, are used to assess the available space for interior. In the interior space reservations are made for watertight or fire doors. Also, an overview of the HVAC system is created. The space reservation can be reused if doors and construction elements are kept the same. The HVAC overview is highly dependent on the arrangement within the luxury rooms and is therefore not reusable.

Last is tile 6.5, the crew area, the end product of this process is the technical lay-out of the cabins, galley, stairs, mess room, pantry, laundry and stores. The result depends on available space due to hull shape and construction principles. Reuse of these rooms is possible, if similar constructions are used.

In conclusion, to enable design reuse between yachts large parts of the construction and mechanical engineering equipment should be kept similar. Especially, vertical alignment of bulkheads and pillars are important. This becomes clear by analysing the time and customer value for each of the second level tiles in the work breakdown structure. 9 second level tiles show potential for reuse: 3.1, 3.2, 3.3, 4.2, 4.3, 4.4, 5.3, 6.2 and 6.5. By looking in to the processes and their interaction in more detail, specific parts of the yacht can be identified in which design reuse might be beneficial. For weight estimation and regulations the higher the degree of reuse the higher the benefits. For the main construction reuse can be enabled by keeping the same vertical alignment and pillar placement. The local construction arrangements consist of a few different parts listed below but for these to be reusable the possible locations should be restricted. For the mechanical components reuse is possible by using the same components and offer different capacities. For the last process, in tile 6.5, crew interior, full standardisation can be possible based on the amount of crew.

Examples of local construction arrangements:

- hull and deck openings
- anchor and mooring equipment
- crane foundations
- shaft line arrangement
- stabiliser foundations

3.6. Conclusion: multiple areas for reuse possible

In this chapter the functional customer value of a yacht is derived from the visual comparison and a database of existing yachts. The visual comparison shows a limited variation in general arrangements. Also, a list of rooms found on the existing Feadships is presented below. These rooms will be used in the modular concept, to create a functioning yacht and be able deliver the needed customer value. From the different decks five possible combinations are identified, the decks can be seen in figure 3.14 and the unique combinations in figure 3.15. The database of yachts is used to define the boundaries for the total product family. This will reduce the amount of solutions to be investigated in chapter 4. The boundaries derived from the database are presented in table 3.4.

To find the engineering processes, which the design reuse concept should affect, the distribution of hours is used together with a value for reuse potential. To determine this value experiential and symbolic customer value in the processes are used. Because of the combination of engineering processes and customer value, reusable processes with enough time savings and a small impact on customer value will be selected. This analyses identified 9 possible second level processes in the work breakdown structure, these processes should be affected by the design reuse concept to reduce the amount of engineering hours. The biggest part is in the construction processes in which vertical alignment and pillars are important aspects for the main construction. To enable reuse of the local construction, the possible locations should be reduced. The mechanical components, affect both the construction and the system schematics and diagrams. If a large part of the mechanical equipment can be standardised the reuse of the construction, schematics and diagrams for these components is possible. The conclusions of this chapter will be used in chapter 4 to make decisions during the design phase of the product platform.

- Crew cabins
- Mess
- Laundry
- Storage
- Pantry
- Galley
- Wheel house
- Captain's cabin
- Ship's office
- Outside lounge
- Inside lounge
- Owner's rooms
- Guest rooms
- Head and powder rooms
- Gym
- Beach club
- Jacuzzi
- Toy store
- Inside tender store
- Technical space
- Engine room

Table 3.4: The requirements for the product platform derived from the regulations and database

	min	max
Length[m]	40	60
# of passengers	8	12
# of crew	7	16
# of tenders	1	2
Size of tenders	0	8
Extra toys	1	2
Range[nm]	3500	5500
Engine power [kW]	1000	3540

4

Designing the design reuse concept

The modular design consists of three integral platforms and several modules to meet the requirements. During the platform design construction and mechanical engineering are both taken in to account to make decisions regarding flexibility and general arrangements. This chapter will start, with the requirements for yachts between 50-60 metres. Afterwards, the modular product platform is explained in more detail. The other sections of this chapter will elaborate on the choices made during the platform design, this starts with the integral platform design and continues with the different modules and how the construction and mechanical engineering is affected by choosing different modules to create a yacht. In this section three different parts of the modular platform will be referred to frequently, therefore, the definition for these will be given first.
Modular product platform, this is the total modular solution consisting of the integral platform and the modules.
(Integral) platform, the integral part of the modular solution of which three different versions are used. In the platform the construction, main ducting and some of the equipment is integrated. This will form the skeleton of the yacht.
Compartment, a compartment on the integral platform is the location where a module can be placed, some modules have a fixed design whereas others can have a custom design within a limited defined space. Also, some compartments will have only one module whereas others can house multiple modules. The integral platform is divided in eleven compartments.
Module, a module is the part that is fitted in the compartment. Within the module local piping and ducting is created to be connected on a fixed interface to the integral platform. Some modules have a custom design to increase customer value, other parts such as crew modules have a fixed design.

4.1. Requirements for a 50-60 metre yacht

Table 4.1 shows the requirements for a 50-60 metre yacht. Yachts under 50 metre, are left out of the scope in the remainder of this chapter. Yacht under the 50 metre, will have to be optimised for a maximum of 500 GT. This will require a different approach, with respect to the yachts above 50 metres.

Table 4.1: The updated requirements for the product platform

	min	max
Length[m]	50	60
# of passengers	8	12
# of crew	10	16
# of tenders	1	2
Size of tenders	0	8
Extra toys	1	2
Range[nm]	4000	5500
Engine power [kW]	2000	3000

4.2. The modular design with three platforms and eleven modules

The modular product platform consists of three integral platforms, the skeleton of the yacht, and eleven modules. The three platforms are shown in figure 4.1 and table 4.2 lists the different modules and module variants. The modules and platforms can be used in the product configuration process to create unique family members. The complete product family is able to offer the variety as discussed in section 4.1. The integral platform has eleven compartments in which the modules can be placed.

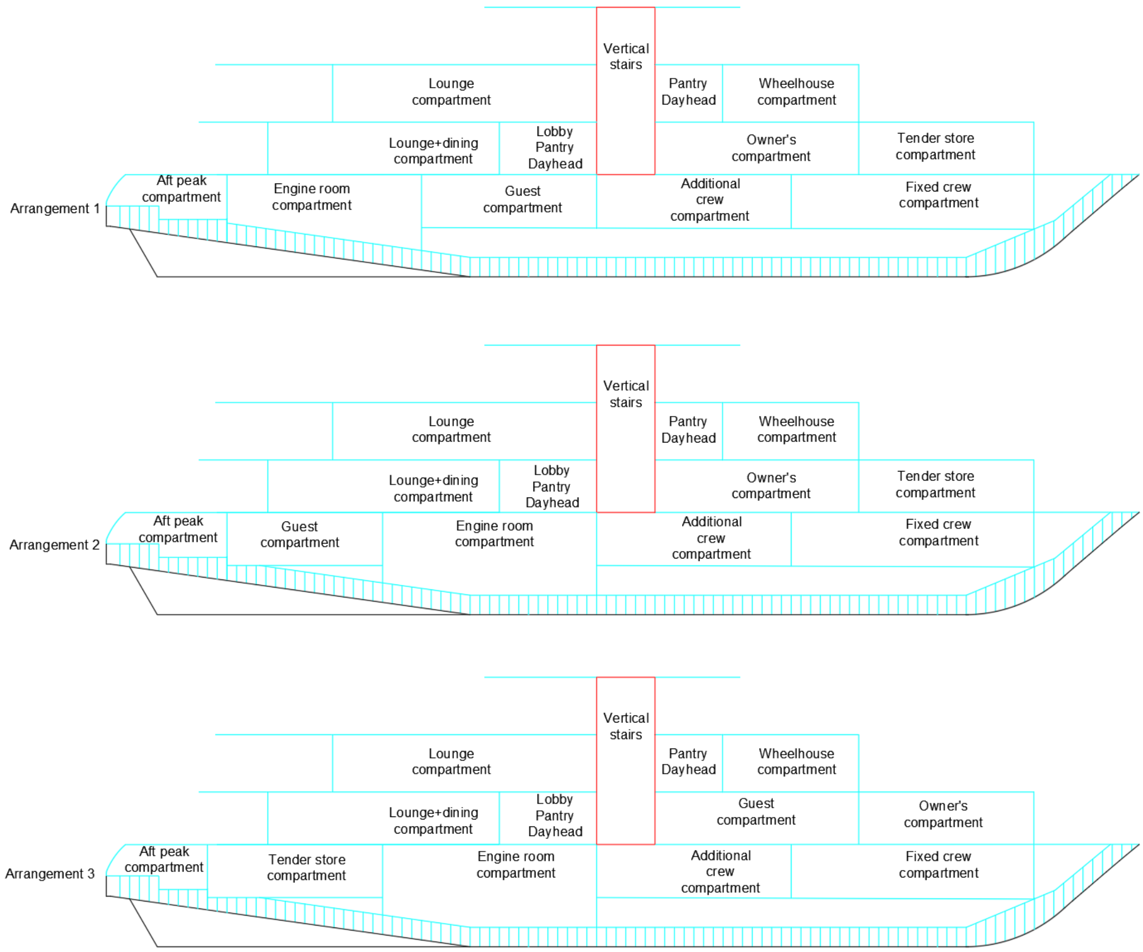


Figure 4.1: The three different platforms for the modular design with all the compartments

The additional crew compartment, guest compartment and aft peak compartment have a minimum and maximum length. The engine room compartment has four different lengths depending on the amount of power and location, the fixed crew compartment, tender garage and the vertical part of the stairs compartment have a fixed length. These lengths are summarised in table 4.3. For the other compartments on the upper decks the minimum and maximum length are a consequence of the lower deck modules. The different compartment lengths will result in a variable total length for the platform, also the height stacking is variable, this allows for more interior height if desirable. A relation exists between the sizes of the upper deck and lower deck compartments. These relations are slightly different for each platform, platform arrangement one in figure 4.1 will be used as an example. Arrangement one with the engine room aft is used because it will result in the largest yacht possible because of the large engine room. The list below explains how the area for the owner's suite and lounges are determined.

- **Owner's suite**, the area of the owner's suite is determined by the space between tender store and staircase. The tender store is located above the fixed crew compartment and the forward bulkheads are vertically aligned. The staircase is located aft of the additional crew compartment. Therefore, a larger additional crew compartment will result in a larger owner's suite.

Table 4.2: The location and freedom in interior arrangement for the different modules, the interior arrangement refers to the lay-out within a module. For example, the location of seating in the lounge. The location refers to the location within the platform.

	Interior arrangement	Location
Five crew cabins and laundry	Fixed arrangement	Fixed crew compartment
Crew cabin	Fixed arrangement	Additional crew compartment
Galley	Fixed arrangement	Lower deck or main deck
Mess	Fixed arrangement	Additional crew compartment
Guests	To design within allowed space	Guest compartment
Lounge	To design within allowed space	Aft of staircase on main and bridge deck
Owner's suite	To design within allowed space	On the main deck in front of the staircase
Staircase, pantry and dayhead	Staircase fixed, pantry and dayhead adjoining staircase	Aft of the additional crew compartment
Wheelhouse, captain's cabin and office	Fixed arrangements	Front of bridge deck
Engine room	Fixed arrangements	Engine room compartment
Aft peak	Fixed arrangements	Aft peak compartment

Table 4.3: The compartment lengths of the integral platform, for modules with a fixed length only a minimum value is displayed. Some compartments have a variable length when this is the case this is displayed in brackets behind the compartment's name. The compartments can increase in length with 0,50 metres, this is equal to the stiffener spacing.

	minimum length[m]	maximum length[m]
Fixed crew	12.5	
Additional crew(variable)	5.5	10.00
Engine room middle	8	11
Engine room aft	10	13.5
Guests(variable)	5.50	11
Tender store	9.00	
Aft peak(variable)	5.00	8.00
Stairs	3.00	

- **Lounges**, the size of the total lounge area depends on the size of the lower deck modules aft of the staircase and the profile of the yacht. The lounge has an inside and outside area, the ratio between inside and outside has a minimum and maximum. For the main deck the minimum is 1, in this case the inside area is equal to the outside area, the maximum is 2.33. For the bridge deck the minimum ratio is also 1 and maximum is 1.5

The exterior customisation can be done in three different ways: a flared or straight bow and the lengths of superstructure decks can be change. The profiles in figures 4.2 show some of the variation possible with the modular product platform. Interior customisation is possible due to the guest compartment, owner's suite and lounges which can be fully customised except for the beam. Also, due to the different platforms module locations can be chosen to the wishes of the client. A minimum and maximum interior arrangement can be seen in figures 4.3 and 4.4, platform arrangement one is used and table 4.4 shows a list of the used modules. More information about the module product platform customisation possibilities can be found in chapter 5.

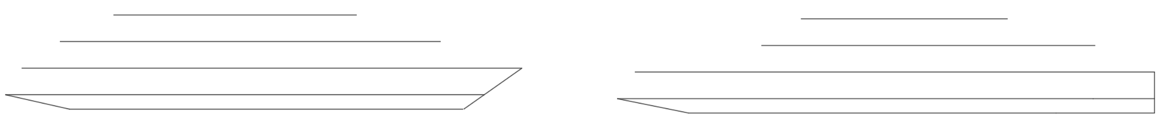


Figure 4.2: Two different exterior longitudinal profiles from the modular product platform

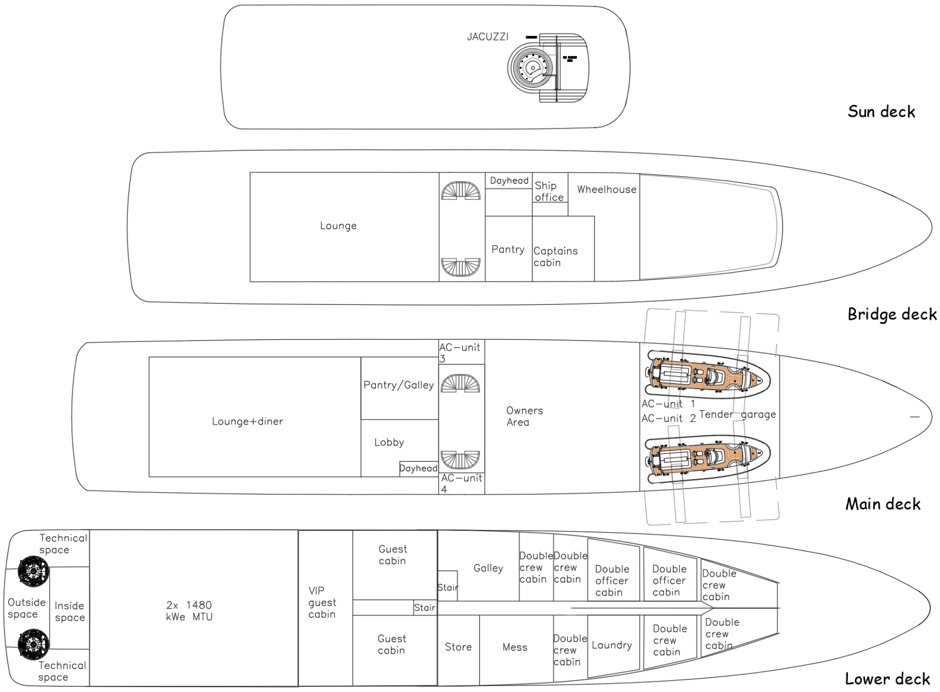


Figure 4.3: A possible maximum length arrangement, with three guest rooms, sixteen crew and a large owner's area and lounges.

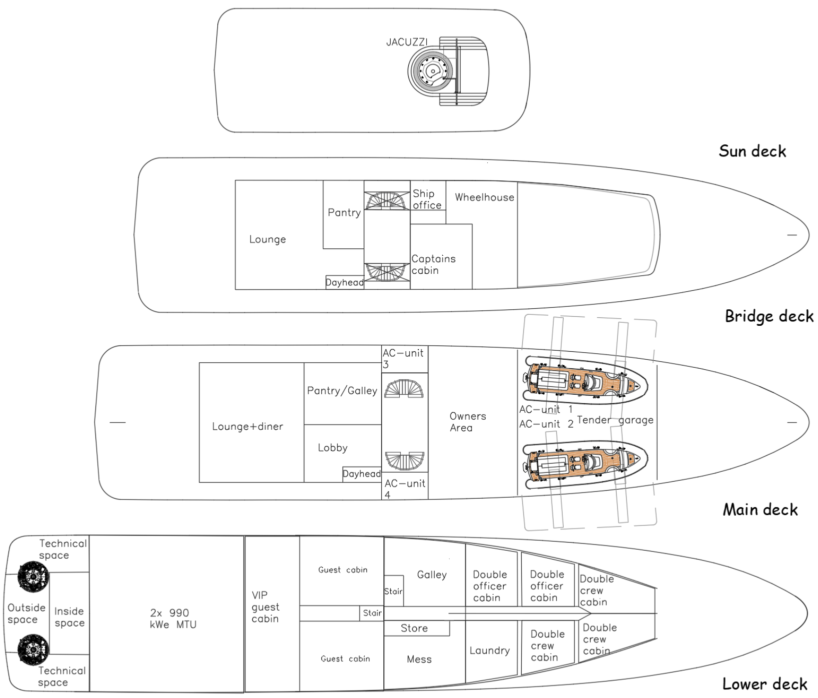


Figure 4.4: A possible minimum length arrangement with three guest rooms, the 2x 990 kW engines and the minimum arrangements for the additional crew compartment and for the owner's area. Also, the minimum inside/outside ratio lounge is used.

Table 4.4: The modules for the maximum and minimum arrangement, a x is used when a standard module is used, a - is used when a standard model is not used. For modules with a variable length the length is listed.

	Maximum	Minimum
Five crew cabins and laundry	x	x
Amount of additional crew cabins	3	-
Lower deck galley	x	x
Mess ten persons	-	x
Mess fourteen persons	x	-
Guests	9.00 metres	9.00 metres
Main deck lounge	13.6 metres	6.75 metres
Bridge deck lounge	12.2 metres	5.66 metres
Owner's suite	5.76 metres	10.0 metres
Staircase module	x	x
Wheelhouse	x	x
Engine room	2x 1480 kWe	2x 990 kWe
Aft peak	5.90 metres	5.00 metres

4.3. Platform flexibility in length, beam and height stacking

To design the platform and modules, decisions should be made concerning the flexibility of the platform's main dimensions. The most important ones that also influence the modules are the length, beam and height stacking of the yacht. For each of these parameters an assessment on regulation, construction, stability and the influence on the overall process will be done to determine if a fixed or variable value is possible. In this section first the assessment method will be explained and afterwards each of the parameters will be assessed on the four criteria: regulation, construction, stability and influence on the process. At the end of this section the conclusion for a variable length, standard beam and variable height will be discussed.

4.3.1. Assessment method with regulations, construction, stability and influence on the process.

The assessment method for each of the criteria is explained before it is used to investigate the influence of variation of the length, beam and height stacking. The minimum and maximum values used in this assessment are scaled from an existing Feadship. The existing Feadship is a representative yacht for the range considered. The main dimensions of the existing Feadship can be found in table 4.5. First the applicable regulations will be discussed, second the construction, third the stability and last the influence on the process

Table 4.5: Main dimensions of the existing Feadship used as a basis to scale to maximum and minimum values for variation assessment

Length overall [m]	57.60
Length waterline [m]	51.11
Length rule [m]	49.58
Depth [m]	5.2
Beam [m]	10.15
Draft [m]	3.35
Displacement mass [ton]	910

For yachts, different regulations exist to ensure the safe operations, to protect its employees and to protect the environment. Which regulation applies, depends on the size of the yacht, the amount of guests and whether the yacht will be used commercially. Commercial use indicates that money is paid to stay on the yacht. If the owner wants to be able to charter the yacht, it should be able to sail commercially. If the yacht accommodates more than 12 passengers, it has to apply to the Red Ensign Group Yacht Code(REC YC) Part B. Otherwise REC YC Part A applies with milder regulations on for example safety. Other regulations that a yacht has to apply to are: [19]

- International Convention on Tonnage Measurement of Ships(ITC)

- International Convention for the Prevention of Pollution from Ships(MARPOL)
- Classification Society Rules and Regulations
- Convention on the International Regulations for Preventing Collisions at Sea(COLREGS)
- Maritime Labour Convention(MLC)

In appendix A a table is shown with examples of different requirements, depending on the size of the yacht. The 500 gross tonnage limit is important for various safety measures and sizes of crew cabins. Between 500 and 3000 gross tonnage the same regulations apply. This is also the range in which the platform will be. Furthermore, the platform will not accommodate more than 12 guests. Between 50 and 60 metres there are no large changes in regulations that apply. Another large influence on the requirements is the chosen classification society. Most yachts register with Lloyds. Therefore, in the design of this platform it is assumed that the yacht will register with Lloyds, Lloyd's "Rules and regulations for the classification of special service craft"[28] will apply.

Second the construction, for the main construction two different drivers exist: longitudinal strength and local scantlings. One of these will be limiting, in yachts of 50-60 metres this is usually the local scantlings. In a later design stage a check should confirm that the longitudinal strength is met as well. The local scantlings are described in the Special Service Craft rules for yachts. [28] The minimum requirements are determined using minimum values for: section modulus, inertia, web area and plate thickness. The formulas to determine the minimum values are shown below:

$$Z = \Phi_z \frac{p s l_e^2 k_s}{f_\sigma * 235} \quad cm^3 \tag{4.1}$$

$$I = \Phi_i f_\delta \frac{p s l_e^3}{E} * 100 \quad cm^4 \tag{4.2}$$

$$A_W = \Phi_A \frac{p s l_e k_s}{100 f_\tau \frac{235}{\sqrt{3}}} \quad cm^2 \tag{4.3}$$

For the minimum plate thickness two different formulas are used. The first one is a general formula and the second a plate function specific formula of which the coefficients change depending on the plate's function. The maximum of the two values should be used.

$$t_p = 22.4 s \gamma \beta \sqrt{\frac{p k_s}{f_\sigma 235}} * 10^{-3} \quad mm \tag{4.4}$$

$$t_p = \omega \sqrt{k_{ms}} (Co_1 \sqrt{L_r} + Co_2) \geq Co_3 \omega \quad [mm] \tag{4.5}$$

In the formulas 4.1 to 4.5 the only values depending on the main parameters are the design pressure and, for the specific plate thickness, the rule length. The design pressure at the base is for each parameter variation calculated using Lloyds SSC software. The design pressure will be used to define the difference in required construction. For the specific plate thickness the maximum difference in thickness will be calculated using the maximum values for Co_1 of 0.8. This value is used for the centre girder of the double bottom structure within $0.4L_r$ amidships.

The third assessment criterion is the stability. The initial stability will be calculated using approximation formulas, while for the damage stability the changes in watertight compartments as a consequence of the parameter change is estimated. The approximation formulas are derived from the Feadship database and are used within the company to assess initial stability in an early stage of the design. The following formulas are used:

$$BM = 0.11 \frac{B^2}{T} \quad [m] \tag{4.6}$$

$$KB = (\frac{L_{wl}}{4L_{oa}} + 0.4) T \quad [m] \tag{4.7}$$

$$KG = 0.95D \quad [m] \tag{4.8}$$

$$KM = KB + BM \quad [m] \tag{4.9}$$

In this stage of the design, the minimum value for KM is equal to the depth D of the yacht. The relation between KG and D is described in equation 4.9 and results in a minimum value of 1.053 for KM/KG

Last is the influence on the process. In this part of the assessment the influence on the design and engineering process will be discussed briefly. Just as the the influence on the customer value.

4.3.2. Length

The length can vary between 50-60 metres. In this part two cases, one with 50 metres length overall and the other with 60 metres length overall, will be used. The values for beam, draft and depth are kept the same. Because all values except the length are equal, the displacement will be scaled linearly. The scaling factor is determined using the length overall of the existing Feadship and the maximum and minimum length of 60 and 50 metres. The values for the maximum and minimum main dimension are presented in table 4.6. First, the influence of the length on the regulations will be discussed, second, the influence on construction, third, on the stability and last is the influence on the process.

Table 4.6: Scaled values for the maximum and minimum length overall. * indicates that rule length is not scaled but calculated using SSC software.

	max	min
Length overall [m]	60.00	50.00
Length waterline [m]	53.24	44.37
Length rule* [m]	51.11	43.03
Depth [m]	5.2	5.2
Beam [m]	10.15	10.15
Draft [m]	3.35	3.35
Displacement mass [ton]	948	790

The length can vary between 50 and 60 metre. When looking at the Large Yacht Code 3[13] regulations, this range will not imply any change in rules. The yachts will be between 500-3000GT. With a rule length under 61 metres, the Large Yacht Code requires a double bottom forward of the engine room.

As introduced in the beginning of this section, the local scantlings determine the construction principle. The local scantlings depend on the sectional modules, inertia and web area. These are all a function of design pressure and location. As can be seen in figure 4.5, the design pressure is almost equal for the largest part of the yacht. Only in the bow of the yacht an increase in design pressure occurs. Therefore, the construction scantlings can be kept equal, as long as the bow section is designed for the maximum length. For the plate thickness there are two possible limitation the general formula, this formula is depending on the design pressure. The second is the location specific formulas, which has a slight dependence on the rule length. The difference in the thickness, calculated using the rule length formula, is only 0.24 mm. The minimum value is 3.82 mm and maximum is 4.06 mm.

The used formulas for estimating the initial stability of the yacht, do not depend on the length of the yacht. As a result, the values for the maximum and minimum length are the same. The values can be found in table 4.7. The damage stability requires the yacht to keep the weather deck 75mm above the waterline. When extending the yacht, the compartment that is flooded will increase, but so will the other compartments which provide the remaining buoyancy. When the yacht is not scaled but just one compartment is extended the damage stability should be checked again. Another option is, to design the yacht in such a way, that it still has enough buoyancy when one maximum sized compartment is flooded and all the other compartments are minimum size.

In the design and engineering process, a variable length will offer a higher customer value since functionalities can be added or removed. If a fixed hull is used, the yachts with less functionalities will have excess space. This will result in a less optimal design. A variable length does imply that the hull will have to be scalable as well, but in the process this will not be too much of a problem. The current software used at De Voogt, already provide the opportunity to apply some changes in hull shape without modifying the whole model. Therefore, a variable length will be used.

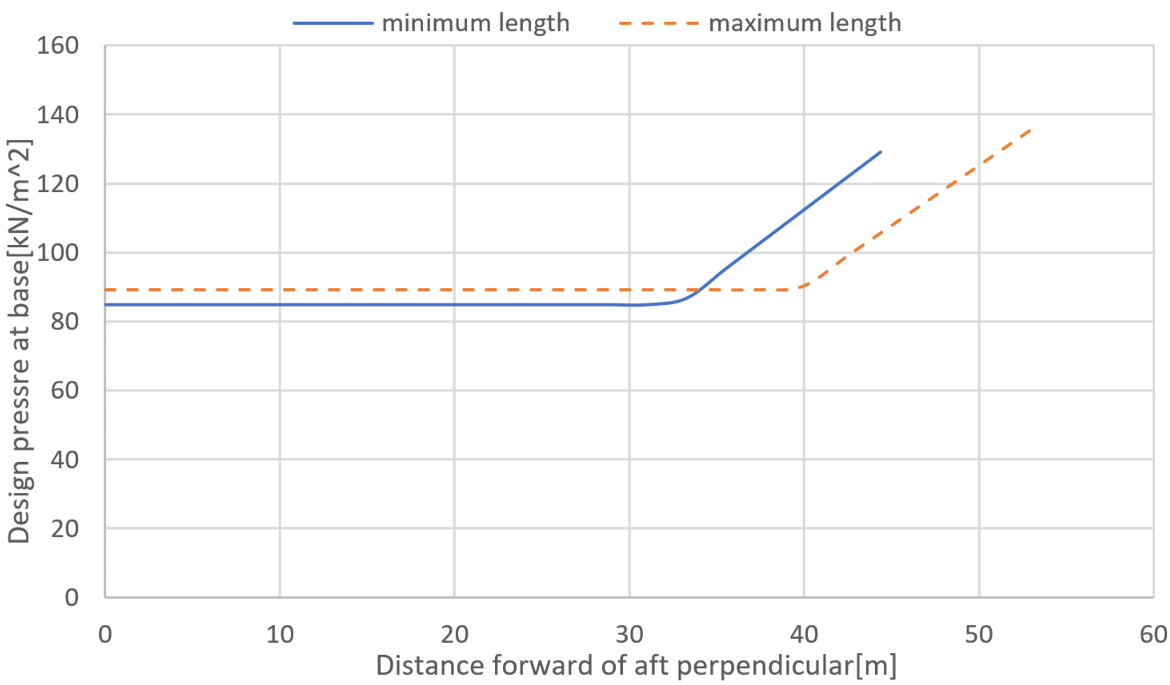


Figure 4.5: The difference in design pressure for the 50 and 60 metre yacht calculated using the SSC software

Table 4.7: The estimated values to calculate the initial stability

	min and max
KM [m]	5.47
KG [m]	4,94
KM/KG[-]	1.11

4.3.3. Beam

When the same scaling factors as with the length are used to determine the beam, the maximum will be 10.57 metres and the minimum 8.81 metres. All length, draft and depth parameters will be the same for the maximum and minimum beam. The only other parameter that changes, is the displacement, which will change linearly since the hull will be scaled in one direction. The main dimensions for the maximum and minimum beam can be found in table 4.8

Table 4.8: Scaled values for the maximum and minimum beam

	max	min
Length overall [m]	57.6	57.6
Length waterline [m]	51.11	51.11
Length rule [m]	49.58	49.58
Depth [m]	5.2	5.2
Beam [m]	10.57	8.81
Draft [m]	3.35	3.35
Displacement mass [ton]	948	790

There is no specific part of the regulation that dictates limitations on the beam. In most cases, the value for the beam will be the result of required stability. Which is defined in the Large Commercial Yacht Code regulation.

Changing the beam of the yacht does not influence the design pressure, this can be seen in figure 4.6. Therefore, the required modules, inertia, web area and thickness are not influenced. But if the same construction principle is used, and the beam is increased, the section modules and inertia will increase. Using

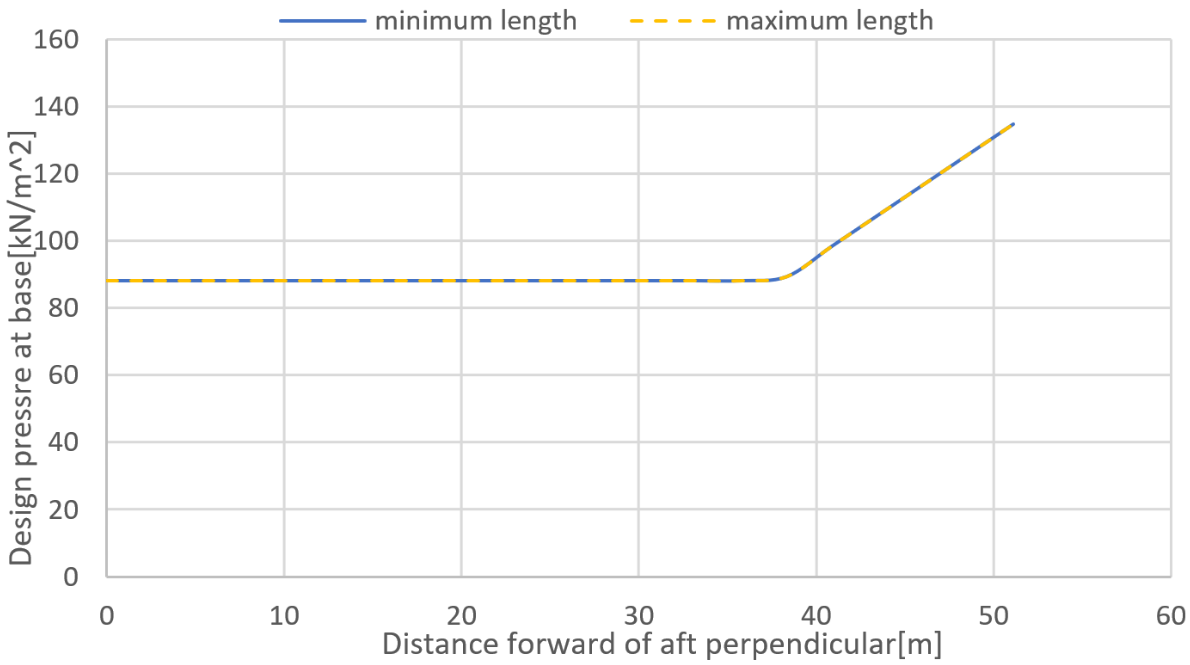


Figure 4.6: The difference in design pressure for the 10.57 metre and 8.81 metre beam calculated using the SSC software

the same construction will result in over design adding unnecessary weight.

The stability is strongly influenced by the beam. The maximum and minimum beam is used to calculate the different KM values. The KG values will be equal, since the estimation formulas only depend on the depth. The values for KM, KG and KM/KG can be found in table 4.9. For the minimum beam, the KG will already be above the KM. This will result in a negative initial stability. The combination of minimum beam and depth, is for that reason, not feasible. Feasibility can be guaranteed, if the depth is reduced or a higher minimum beam is used. For the damage stability, there will be no large changes due to the different beams. Increasing the beam will increase all compartments. The flooded compartment will have more volume, but this is also true for the remaining compartments. Increasing the beam can help for when the ship will start to heel in damages conditions.

Table 4.9: The estimated values to calculate the initial stability for a changing beam

	Case 1	Case 2
KM [m]	5,75	4,63
KG [m]	4,94	4,94
KM/KG[-]	1.16	0.94

In the process, a variable beam will reduce the over design and optimise the customer value. When the beam is to large, each of the luxury areas is wider than necessary. This will result in more high cost luxury square metres. Although it is better for customer value, a variable beam will also complicate interfaces as these will occur in the transverse direction. A flexible beam will require more flexibility in the used modules complicating the module design. Therefore, a standard beam will be used.

4.3.4. Height stacking

The height stacking influences the depth of the yacht. Therefore, the minimum and maximum depth will be calculated with the same scaling factors as for the length. The length, draft, beam and displacement will be the same for both cases. The main dimension are shown in table 4.10.

In the Maritime Labour Convention, a minimum headroom of 203 cm is required on crew decks. Furthermore, the ceiling of the crew's sleeping accommodation should be located above the deepest waterline restricting the draft. But these regulations do not impact the variable height stacking.

Table 4.10: Scaled values for the maximum and minimum depth

	max	min
Length overall [m]	57.6	57.6
Length waterline [m]	51.11	51.11
Length rule* [m]	49.58	49.58
Depth [m]	5.42	4.51
Beam [m]	10.15	10.15
Draft [m]	3.35	3.35
Displacement mass [ton]	948	790

The depth has no influence on the design pressure and minimum thickness required. But a difference in the height of the main deck, will influence the sectional properties. A lighter construction might be possible, when the construction is designed for the smallest height stacking.

Changing the depth changes the KG, resulting in two feasible cases for intact stability. The values can be found in table 4.11. The damage stability will increase if the main deck is stacked higher. Because the yacht's damaged waterline should be 75mm below the main deck. When the main deck is higher the yacht can take in more water before the waterline is at 75mm from the main deck. But the KG will also increase reducing the yachts initial stability.

Table 4.11: The estimated values to calculate the initial stability for a changing depth

	Case 1	Case 2
KM [m]	5,47	5.47
KG [m]	5.15	4.29
KM/KG[-]	1.06	1.28

A variable height stacking, will result in a higher level of exterior customisation. Since it does not influence the needed construction, but only implies constraints on the available construction height. Therefore, it might be useful to scale the height stacking with the length. A larger yacht will have more HVAC area requiring larger or more ducts. Also, a variable height stacking, offers the possibility for the interior height to be customised. Therefore, a variable height stacking will be used.

4.3.5. Conclusion: variable length, height stacking and fixed beam.

Using the assessment as discussed in this section, it is decided that the platform should have a variable length. The length will depend on functionality. A fixed beam is used to reduce complexity, on interfaces and module design. A variable height stacking is used for customisation of the interior height and be able to increase HVAC capacity in case of a larger interior area. To decide on the increase in heights, the difference in minimum and maximum HVAC capacity should be determined. The beam does influence the stability, for this reason the smaller yachts might have a slightly larger beam than usual with a standard beam.

To determine the beam value the stability is used as a limiting factor. The maximum values for draft and depth are taken scaled from the existing Feadship. This results in 3.49 metres draft and 5.42 metres depth. Using the stability estimate, as described in the beginning of this section, and the limitation that the hull stability should be larger or equal to the depth of the yacht. A minimum beam of 10.15 is calculated.

The main dimensions of the platform derived from this assessment are shown in table 4.12

Table 4.12: Variation of main dimensions for the platform

	minimum	maximum
Length overall [m]	50	60
Length waterline [m]	44.37	60
Draft [m]	2.91	3.49
Depth [m]	4.51	5.42
Beam [m]	10.15	10.15

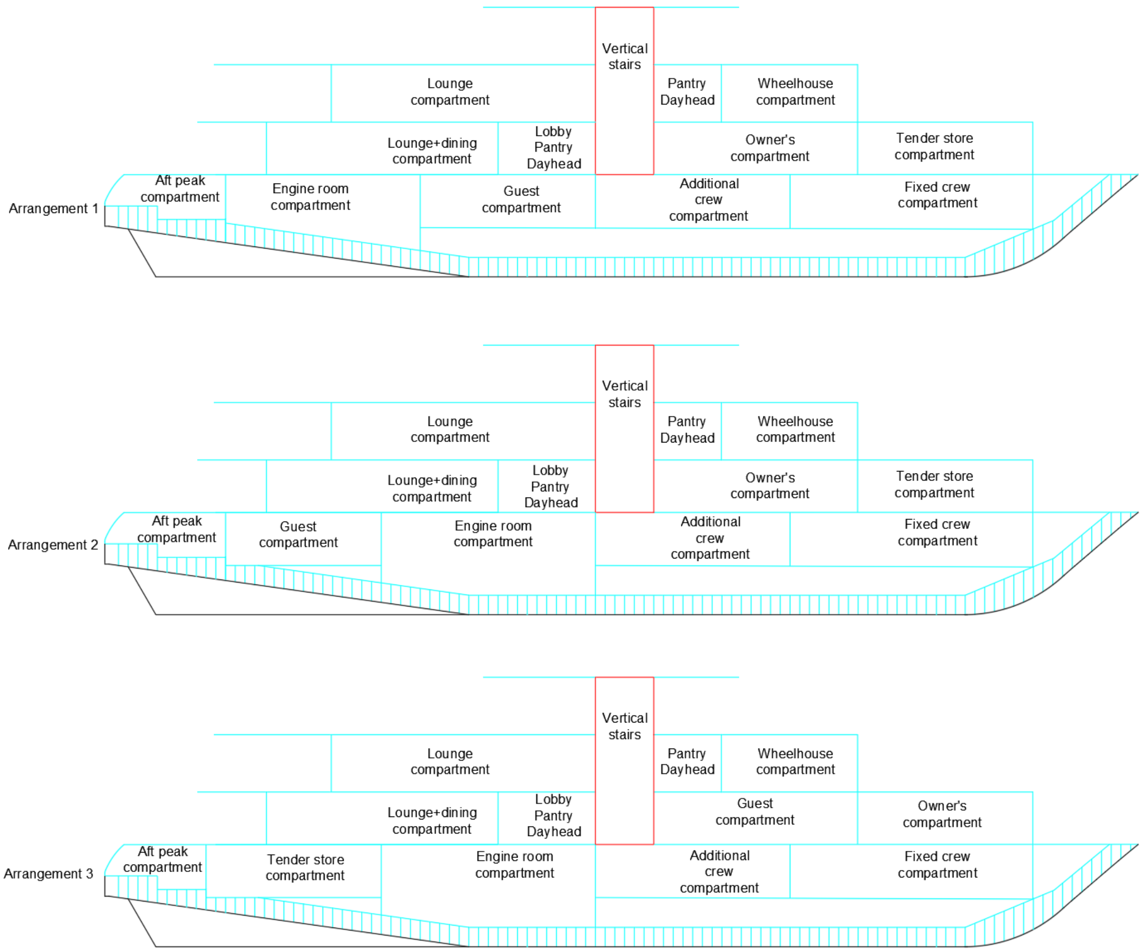


Figure 4.7: The three possible configurations with engine room and tender garage placement

4.4. Design of the platform and modules

In section 4.3, the flexibility is determined for the main parameters of the modular product platform. Together with the requirements from section 4.1, the platform and modules can be designed. This section will elaborate on the choices made, during the design of the platform and modules, and show what the platform and modules look like. The section starts with discussing the choice for multiple platforms in stead of one. Afterwards the modules are discussed in detail.

4.4.1. Multiple platforms to reduce complexity

For the integral platform part of the modular product three different options are used. These three options can be seen in figure 4.7. For the platform, it is important to strike a balance between multiple more complete platforms with fewer less complex modules, or a basic platform with more and complex modules. Specific functions such as construction, can be provided by the platform or by the module. The integral platform, as chosen for the modular product platform, consists of the double bottom with tanks and piping from the tanks to the engine room. Large equipment with a small impact on interior arrangement are integrated as well. Examples are: stabilisers and the bow thruster. Furthermore, the construction will be part of the integral platform, therefore, solutions are needed for a changing length. These will be discussed in section 4.6.1.

Because of the choice to include construction and the double bottom in the integral platform, modules with a large impact on the construction or double bottom are best to be integrated in the platform. The engine room and tender store are two modules with a large impact on the construction and double bottom. Therefore, these should be best integrated in the platform. If these are integrated in the platform, the location of these modules are restricted. The assessment on general arrangements in chapter 3, identified multiple locations for the engine room and tender store. Therefore, one platform will not be enough. To satisfy the

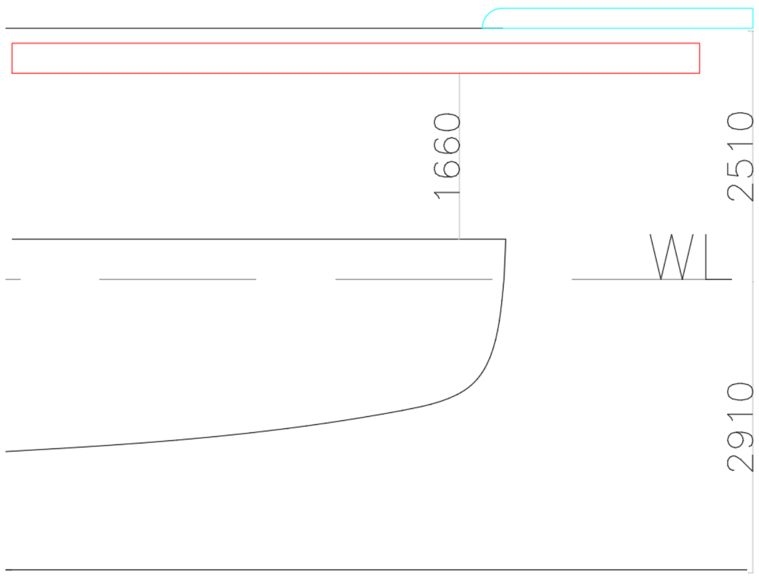


Figure 4.8: Illustration of the limited tender garage height because of the depth and draft of the yacht. In red the crane beam, in blue the tender garage hatch and the grey dashed line is the waterline. All dimensions are in millimetres.

different arrangements at least three platforms are needed. One will have the tender store on the lower deck and two platforms will have the tender store on the main deck. The difference for the two platforms with the tender on the main deck, is the location of the engine room. This can be in the middle or in the aft ship.

The tender garage will have a large influence on the depth of the yacht. This will result in a restriction on the main parameters, regarding draft and depth for the platform with the tender on the lower deck. This is illustrated in figure 4.8. To be able to launch the tender almost the maximum tender depth and minimum draft is needed. There is a little room to change depth and draft, the minimum hatch opening is about 1400 millimetres. For the two platforms with the tenders on the main deck, there is no restrictions on the range defined in the previous section.

4.4.2. Eleven modules to satisfy requirements and reduce engineering hours

Now that it is known what the platform consists of, the modules can be designed. To decide on what to combine in different modules, the function of the modularity for both the customer and Feadship is important. From a customer's point of view, the different modules should be able to give a certain flexibility in the general arrangement and/or be able to add functionalities. Such as, the amount of crew or guests. From the perspective of Feadship, the modularity should reduce the engineering hours. With these goals in mind and the information from chapter 3, the eleven modules in table 4.13 are identified. These modules fulfil the requirements for both the customer and Feadship. Table 4.14 shows the different variants for modules with more than one variant. The rest of this section will explain why these modules are used and discuss the arrangement and location of each module. The size is determined using regulation and average areas of four existing yachts.

Crew modules, to be able to create the required variety, in the crew area in the bow of the lower deck, four different modules are used. The first module consists of five crew cabins for two crew each and a laundry. The five crew cabins will facilitate accommodation for the minimum amount of ten crew on board. The minimum amount of officers is five, this is determined using the minimum manning policy of the Cayman Islands. [29] To comply with the commercial yacht code, two double officer cabins and three double crew cabins are needed. The fifth officer will be the captain. The captain will be accommodated in his own cabin on the bridge deck. This first module will have a fixed location in the bow of the yacht on the lower deck, since in the investigated Feadships in chapter 3 no variation is observed for these cabins. Because this module will always be placed in the bow extra care during the module design is needed, with respect to changing bow shapes. The bow shape can be very characteristic and is for that reason something a customer should be able to decide on. This is further discussed in section 4.5. The minimum size of a crew cabin is described in the Large Commercial Yacht Code 3. [13] An overview of the minimum sizes, for single and double rooms for crew

Table 4.13: All modules needed to full fill the requirements of both the customer and Feadship. The interior arrangement refers to the arrangement of furniture etc.

	Interior arrangement	Variants
Five crew cabins and laundry	Fixed arrangement	1
Crew cabin	Fixed arrangement	2
Galley	Fixed arrangement	2
Mess	Fixed arrangement	2
Guests	To design within allowed space	1
Lounge	To design within allowed space	1
Owner's suite	To design within allowed space	1
Staircase, pantry and dayhead	Free to design adjoining the staircase	1
Wheelhouse, captain's cabin and office	Fixed arrangements	1
Engine room	Fixed arrangements	2
Aft peak	Flexible length, fixed arrangement	2

Table 4.14: The different module variants

	different options	
1x crew cabin	starboard	port side
Crew mess	10 persons	14 persons
Galley	lower deck	main deck
Engine Room	2x 1000 kW	2x 1500 kW
Aft peak	2x 1000 kW	2x 1500 kW

and officers, is shown in figure 4.9. From 560 to 3000GT a double crew cabin with en suite bathroom should be at least 7.00m^2. A double officer room with a bathroom can be 9.00m^2, if an off day room is provided. The wheelhouse may be used as an off day room. To make a space reservation for the first module, the gross areas are needed for the cabins and laundry. The net areas of the cabins are known from the Large yacht code. To calculate the gross area, the average ratio between gross and net area of all crew cabins of the four yachts is used. This ratio is 1.29, the corresponding gross areas can be seen in table 4.15. The laundry size is calculated using the average of the four yachts and has a gross area of 11.9m^2. The total gross area, for the first module with three crew cabins, two officer cabins and a laundry, is 62.3m^2 an example of how it can be arranged is shown in figure 4.10

The next three modules in table 4.13, can be placed in compartment two. Because not all modules have to be used, this compartment gets a variable length between 5.25 and 9.65 metres. The first module is the single crew cabin, with a port side and starboard side variant. Just as the crew cabins in the first compartment, this cabin will have a net area of 7.00m^2 and a gross area of 9.05m^2. This module can increase the number of crew by two members at a time, allowing for the required variety of ten to sixteen crew members. The crew mess module has two variants for ten and fourteen crew. The size of the mess is dependent on the amount of crew, the Maritime Labour Convention(MLC) states that 1.50m^2 should be available for each crew member to be expected in the mess at the same time. This way these two variants will be enough when it is not expected to have sixteen crew in the mess at the same time. The ten crew mess will have a net area of 15.0m^2. The gross area is calculated using a ratio of 1.21 between gross and net area. This is derived using the areas of the mess of the four yachts. The gross area is 18.1m^2. For the fourteen person mess the net area is 21.0m^2 and the gross area is 25.3m^2. The last crew module is the galley, the galley can have two locations as observed in chapter 3. Therefore, two variants are needed, one for the lower deck and one for the main deck. The galley will always be located on the port side of the yacht, to allow for preparations for the galley duct to rise to the sun deck. The size of the galley is determined using the average of the four yachts and will have a net area of 16.0m^2 and a gross area of 19.8m^2. The areas of the modules can also be seen in table 4.16 and a possible minimum and maximum arrangement is shown in figure 4.11

Table 4.15: Net and gross areas of the rooms in the first crew module

	Net area [m^2]	Gross area [m^2]
Double crew cabin	7.00	9.05
Double officer cabin	9.00	11.6
Laundry	9.78	11.9

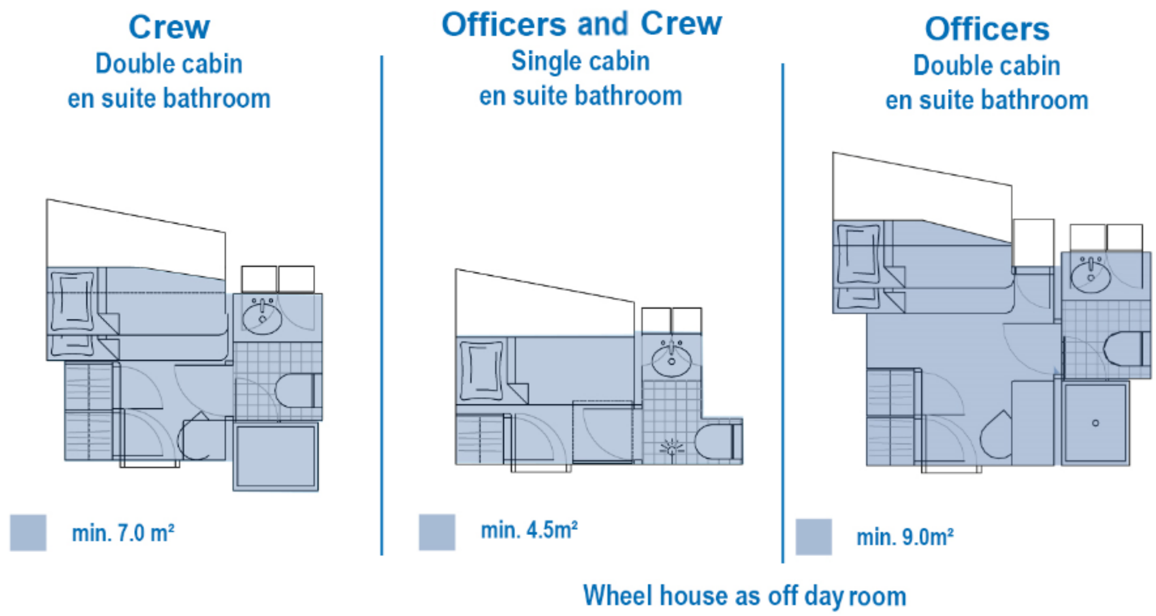


Figure 4.9: The minimum crew and officer cabin areas for 560 to 3000GT

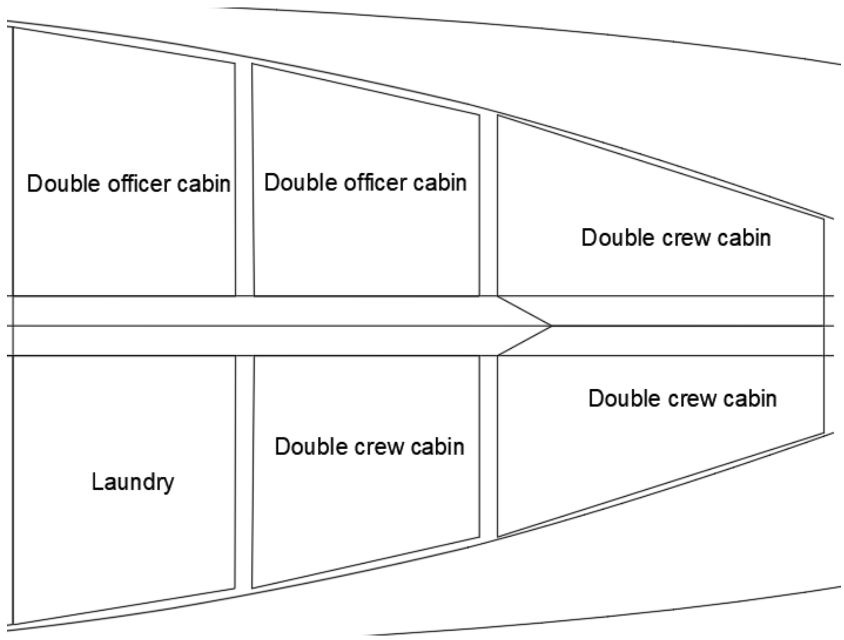
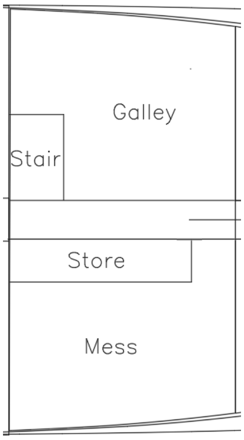


Figure 4.10: Arrangement of the first compartment with five cabins and a laundry[9]

Table 4.16: Net and gross areas of the rooms in the second crew module

	Net area $[m^2]$	Gross area $[m^2]$
Mess 10 crew	15.0	18.1
Mess 14 crew	21.0	25.3
Galley	16.0	19.8
Crew cabin	7.00	9.05
Stairs	3.00	3.90



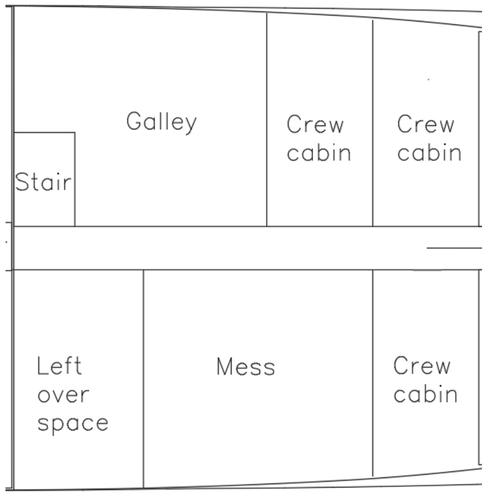


Figure 4.11: Minimum and maximum possible arrangement for the second compartment

Engine room and aft peak, the engine room can have two different locations. These location need different modules, because of the difference in available height between middle and aft. Also, two different engine powers will be available to be able to provide some flexibility in top and range speeds. This will result in a total of four variants for the engine room. As discussed in section 4.4.1 three platforms are used with the engine room at a fixed location. Two of the platforms have the engine room in the middle and the third has the engine room aft. A MTU engine is used as an example, in table 4.17 the two different engines can be found. An engine room volume is derived using the relationship between engine room volume and power of existing Feadships. Also, an average height for the engine room aft and engine room in the middle is derived. The engine room aft has an average height of 2.72 metres and the engine room in the middle has an average height of 3.37 metres. Table 4.18 shows the engine room lengths for the different powers and the aft or middle arrangement. The fresh and exhaust air of the engines will travel through casings that go up to the higher decks and mast. These casings will have to be routed through the lounges. This is the same way as it is usual done in Feadships of this size.

Table 4.17: Engine power and length for two MTU engines.[22]

	2x 1000kW	2x 1500kW
Engine Type	8V4000M33S	12V4000M33S
Power[kWe]	990	1480
Length[m]	3800	4500
Engine room volume [m^3]	278	371

Table 4.18: The four different lengths of the engine room

	Aft length[m]	Middle length [m]
2x 990kW	10	8
2x 1480kW	13.4	10.8

For the aft peak this will result in two variants, since the used pods will need to match the difference in engine power an aft peak module matching the 2x990 kW and the 2x 1480 kW will be needed. The actual propulsion power will be a bit less than the installed generator power. The aft peak, also, houses some of the technical spaces and a little inside space, this can be used for storage of toys or a small gym. The size of the aft peak is variable between five and eight metres, to be able to house the different pods and increase or reduce both the technical and luxury space as needed. Figure 4.12 shows an aft peak example of 5.50 metres with the pods, technical spaces and luxury space.

Guest cabins, the guest cabins can be designed within a fixed area. On the lower deck a minimum length of 5.50 metres is reserved for the guests. The average two person guest room has a gross area of 25.2m^2, with

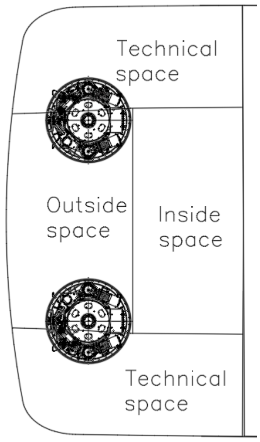


Figure 4.12: An example of a possible aft peak arrangement

a beam of 10.15 metres and additional space of $7.50m^2$ for stairs and a passageway the minimum of 5.50 metres is enough for two guest cabins. The maximum length is 10.7 metres, with a beam of 10.15 metres this will result in a gross area of $108.6m^2$. This is enough for four guest rooms and a passage way and stairs. Next to the four guest rooms on the lower deck, a part of the owners area can be used for a guest room to increase the amount of guests to ten.

Tender, the tender store can have two different locations. As discussed in section 4.4.1 the tender store has a fixed location on the different platforms, because of the large impact on structural requirements of the tender doors. Both tender stores have a length of 9.00 metres to be able to house a tender of 8.00 metres maximum. On the lower deck tender store, two tenders can be stored or one of the tender stores can be used as a beach club. For the main deck tender store, the whole area will be used for tenders and toys.

Crew+ areas, the crew+ areas are located at the bridge deck and consist of the captain's cabin, wheelhouse and a small ship office. For these spaces only one module will exist, since the location will always be the same and the size will not influence the functionality or customer value. The fixed arrangement is displayed in figure 4.13 and the areas are calculated using the average of the four yachts and shown in table 4.19

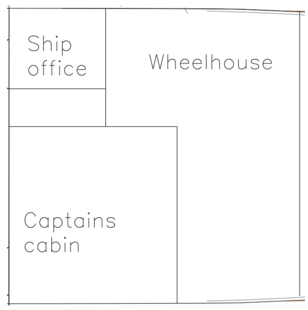


Figure 4.13: Fixed arrangement of the wheelhouse, office and captains cabin.

Table 4.19: Areas of the crew+ module derived from the four yachts

	Gross area $[m^2]$	Net area $[m^2]$
Captain's cabin	16.9	14.3
Wheelhouse	23.9	20.5
Ship office	4.40	3.20

Staircase, pantry, lobby and dayhead, this is a bit of a special module because the stairs module goes vertical over the different decks. By using such a module the vertical connection of pipes and ducts can be integrated in this module. The central staircase has a crew stairs and luxury stairs and on the main deck the galley or a pantry can be located next to the staircase on port side. On starboard, a dayhead and lobby are connected to the staircase. On the bridge deck, the staircase can have a pantry and dayhead on one of the two sides depending on the lower deck arrangement. Behind the stairs on the main deck, two AC-rooms will be located and enough space to route pipes vertically to the upper decks. The size of the staircase is kept similar to 3310, this is another design number in the same length and with both crew and luxury stairs in the middle of the yacht. An example of the staircase module on the main and bridge deck can be seen in figure 4.14

Figure 4.14: On the left the main deck staircase with pantry, lobby and dayhead and on the right the bridge deck staircase.

Luxury modules, the luxury modules are not so much modules but more space reservations. The luxury space can be engineered within the available area. A minimum and maximum area is determined, to allow for HVAC and structural provisions on the platform. The owner's area behind the tender store on the main deck has a minimum area of $46.0m^2$ and a maximum area of $81.0m^2$. The size of this area is related to the size of the additional crew compartment. The luxury areas ducting needs to be engineered within the available module space and a connection to the global piping and ducting of the platform will need to be standardised.

4.5. Exterior profile customisation

Customisation of the exterior profile can be done by changing the bow shape and the length of the superstructure decks. In the exterior profile of the bow two possible choices exist: a flared or a straight bow. The platform will need to be designed such that both options are possible. This will increase exterior customisation possibilities. The bow shape will affect the first two compartments with the crew areas. To determine the effect of a different bow shape two existing Feadships will be used, one with a straight bow and one with a flared bow The difference in exterior is shown in figure 4.15. The outer hull lines are plotted together and shown in figure 4.16. The difference is not so much in the shape but more in the location. Especially, for the lower deck. Because of the similar shape regardless of the straight or flared bow the same modules can be used. The lower deck will be longer on a straight bow yacht compared to a flared bow yacht with the same length over all.

More exterior customisation can be added by changing the length of superstructure decks. The lower deck length is determined by the used modules, but the superstructure decks can be varied because the size of the lounge is a customer choice. Different looking profiles can be created by varying the deck length, this is illustrated in figure 4.17.

Figure 4.15: On the left the straight bow and on the right the flared bow[11, 14]

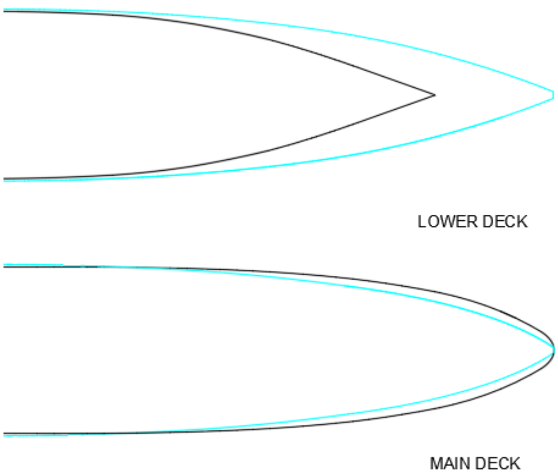


Figure 4.16: In blue the outer hull lines of a straight bow and in black for a flared bow

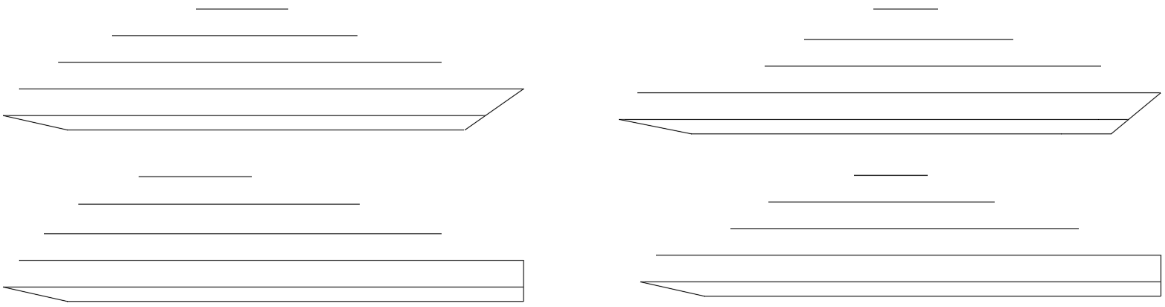


Figure 4.17: Four different profiles to show the different exteriors possible by changing bow shape and deck lengths

4.6. Solutions for construction and HVAC for the platform of changing length

The previous sections discussed the design and why the platform and modules are chosen as it is. Because the platform and modules are known, a technical assessment can be made to check the basic construction and HVAC design. The most important part, is to define how these aspects are able to handle the platform's changing length and interior area. The goal is to separate the local ducting of the modules and the global ducting integrated in the platform. This section starts with the construction aspect, a maximum primary stiffener height of $200mm$ will be used. This will result in a limiting span for the primary stiffeners. A way to cope with the changing spans, because of changing platform length, will be suggested. Furthermore, the vertical alignment that is used to reduce the construction complexity is discussed. Second, the mechanical aspect will be handled and more specific the HVAC requirements and ducting. The difference between the maximum and minimum HVAC capacity and ducting is calculated and a possible solution to cope with these different requirements is chosen. This section will finish with a cross section example of the technical ceiling space and how both, the construction and HVAC ducting, is integrated in a way that minimum changes are needed for platforms of different lengths and with different modules.

4.6.1. Basic construction principle and additional transverse stiffeners

To evaluate the effect on the construction, a basic construction drawing is created for the main deck, bridge deck and sun deck. The influence of the changing lengths will be discussed for each drawing. A full construction drawing or calculation will not be needed at this stage. Because the goal is to identify how to handle the increase in length, and not fully define and build the construction based on these drawings. The construction drawings are created for platform arrangement one of the three platform arrangements. Because the large aft engine room on platform one will result in the largest yacht.

In the main construction plan the biggest problems occur at large spans. For large spans, above six metres, large primary stiffeners are needed or additional transverse primary stiffening is needed to reduce the effective span of the longitudinal stiffener. To determine the maximum span for each deck and location, the construction principle of the existing Feadship is used. The maximum spans are shown in table 4.20, when different stiffeners are used other spans can be achieved but the spans and stiffeners as shown in table 4.20 will be used as a reference to assess the influence of the changing length.

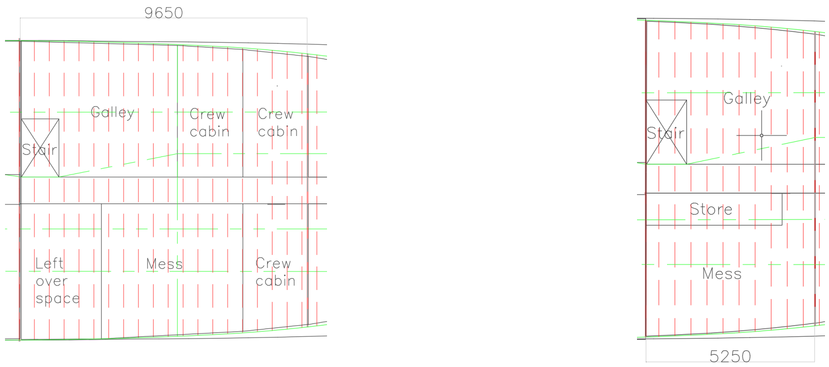
Table 4.20: The maximum spans allowed for the different decks based on the construction principle of an existing Feadship

	Maximum span [m]	Primary stiffener profile
Main deck	5.5	Rolled bulb 200x10 steel
Bridge deck lounge	5.0	T 200x100x10x15 aluminium
Bridge deck owner's cabin	6.5	T 200x100x10x15 aluminium
Sun deck	5.5	T 200x100x10x15 aluminium

A difference in spans will occur at multiple places in the modular design. For the lower deck for example the additional crew, the guest and aft peak compartment can have a length between 5.25-9.65, 5.5-10.7 and 5-8 metres respectively. When such a span in the aft of the existing Feadship have to be stiffened with only longitudinal primaries this will result in a primary stiffener with a height of 450mm Even if this height is available such spans still have a high risk for unwanted vibrations.

A simplified main construction drawing is made for the main deck, this drawing shows the difference in spans and how these can be reduced for the minimum and maximum compartment lengths. For the additional crew compartment, an extra primary transverse stiffener is added to reduce the span from 9.65 to 5.25 metres. This is done in the same way for the engine room, the aft peak and guest room compartment. The difference in construction for the additional crew compartment is shown in figure 4.18 and the total main deck can be seen in figure 4.19

The spans for the bridge deck construction are influenced by the length of the owner's compartment and the lounge. The owners area is depending on the length of the additional crew compartment. With the minimum length for the additional crew compartment the owner's cabin will not need additional primary stiffeners. When the length of the additional crew compartment increases a transverse stiffener will be added. Additional primary transverse stiffeners are also added in the lounge when the span exceeds 5 metres. The total bridge deck construction can be seen in figure 4.20. The forward part, with the tender store, will still be steel and will require some special engineering and is not drawn in this figure. The construction of the tender store can be reused in both platforms with the tender on the main deck.



(a) Maximum compartment length with additional transverse stiffening

(b) Minimum compartment length

Figure 4.18: Maximum and minimum guest compartment length, the green lines are the primary stiffeners and in red the secondary stiffeners.

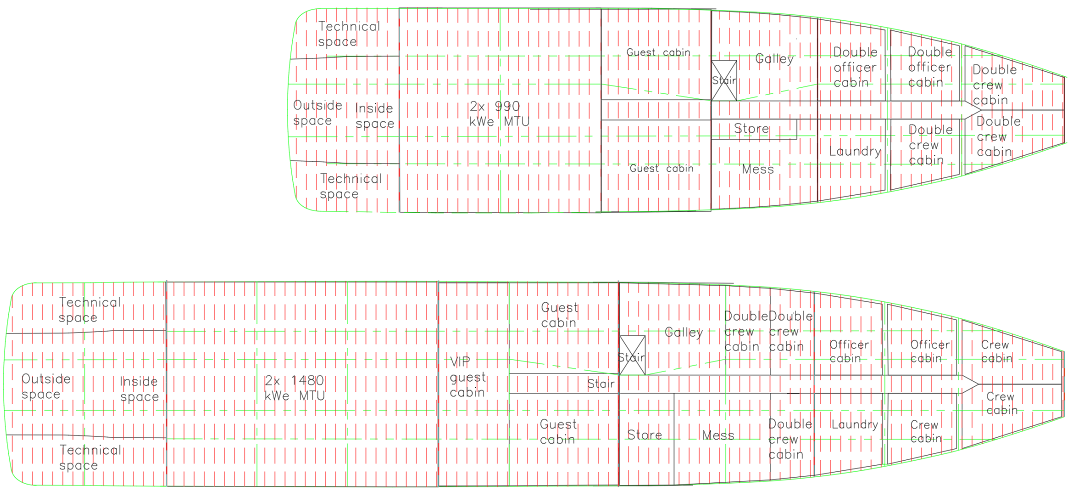


Figure 4.19: The construction overview of the main deck for the minimum and maximum length, in green the primary stiffeners and in red the secondary.

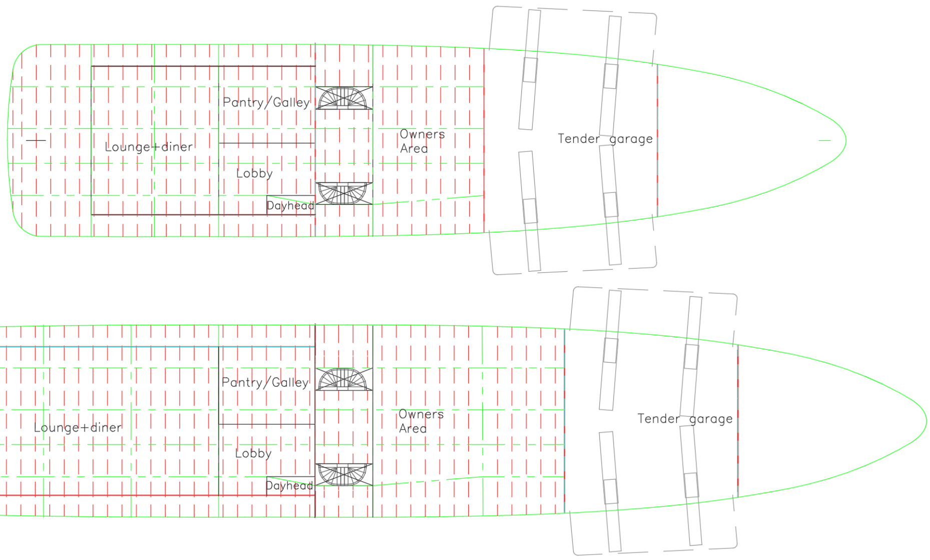


Figure 4.20: The construction overview of the bridge deck for the minimum and maximum length, in green the primary stiffeners and in red the secondary.

The bridge deck has a similar interior arrangement as the main deck, this will result in a similar construction principle for the sun deck as for the bridge deck. The lounge length has a minimum and maximum value. If the spans exceed five metre an additional transverse primary stiffener is needed. The difference in construction for the minimum and maximum length is shown in figure 4.21

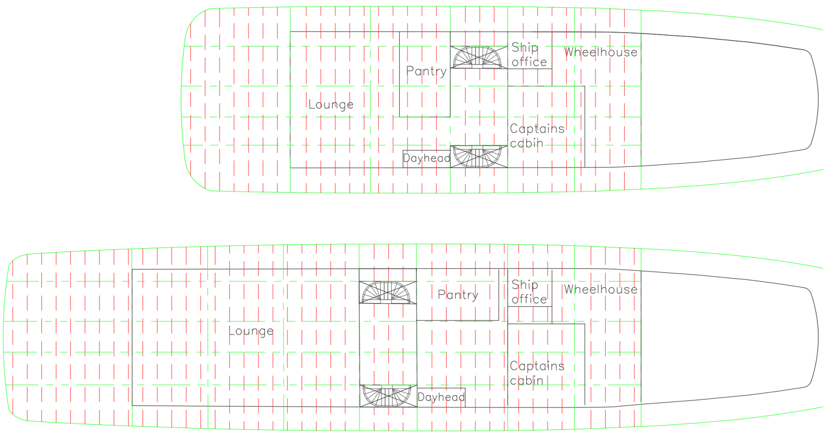


Figure 4.21: The construction overview of the sun deck for the minimum and maximum length, in green the primary stiffeners and in red the secondary.

In the construction vertical alignment will reduce the complexity. Therefore, a few compartments are designed such that vertical alignment is guaranteed. This is done in the bow of the ship with the wheelhouse, tender garage and wall between two crew cabins. Furthermore, the back of the vertical stairs module will continue over all decks to form a vertical alignment. This is both illustrated in figure 4.22 together with the alignment at the bow. Also the bulkheads will have a fixed relative location in the platform. In total 5 bulkheads are used, these are also shown in figure 4.22. The first bulkhead is at the front of the fixed crew compartment, the second after 4 crew cabins. The third is behind the additional crew compartment and the last two in front and behind the engine room.

4.6.2. HVAC requirements

Of the many pipes and ducts the largest ones are the HVAC ducts. These will be limiting in the height stacking. The goal is to create multiple layers to avoid crossings between local module piping and global piping integrated in the platform. To do this the HVAC capacity of each room is calculated using the volume, a minimum amount of air changes per hour and the amount of recirculated air. The rooms in one compartments are added together and multiple compartments can be serviced by one AC-unit. In total three AC-units are used of which the size and location are fixed. For each air flow of an AC-unit, the capacity and maximum air speed are used to calculate a minimum duct area. The duct area will be different for the minimum and maximum sized platform, therefore, a choice will need to be made for parametric ducting or accept a bit of over design and use one size of duct. This section will start with a short explanation of the HVAC system as it will

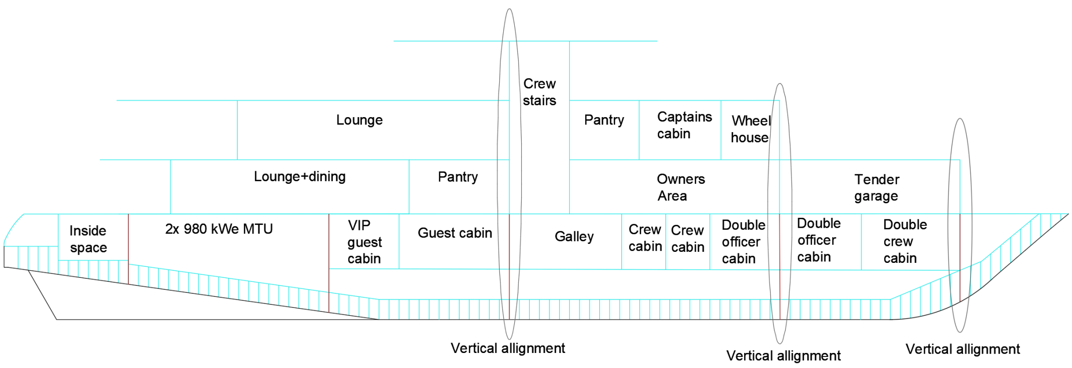


Figure 4.22: The three grey ellipses show the vertical alignment in the centre line cross section. The red lines on the lower deck show the five bulkhead positions.

be used on the modular product platform. Second, is the determination of HVAC capacity for the different compartments and the amount of AC-units needed. Afterwards, the size of the ducting for the maximum and minimum arrangements is calculated and a choice is made for the type of ducting and AC-units. This section will end with four schematics of the AC-units and their ducting.

For the air conditioning a ducted system is used, figure 4.23 shows the schematics of two possible configuration. Both have four different air ducts: a fresh, supply, recirculation and exhaust duct. Fresh air from outside and recirculated air from the room are mixed and treated in the AC-unit. From the AC-unit the supply air duct transports the air to the rooms. From the rooms a part of the air is removed by the exhaust duct and transported back outside. The difference in the two configuration is in the supply air duct. The configuration on top has a separate supply air flow for each room and the temperature of each flow is regulated in the AC-unit. The bottom configuration uses one supply duct and a heater in each room to control the temperature for each room. In both configurations the exhaust and recirculation duct of each room can be collected in one duct to feed to an exhaust or AC-unit. Both configuration can be used in the modular design depending on the type of room and location within the yacht.

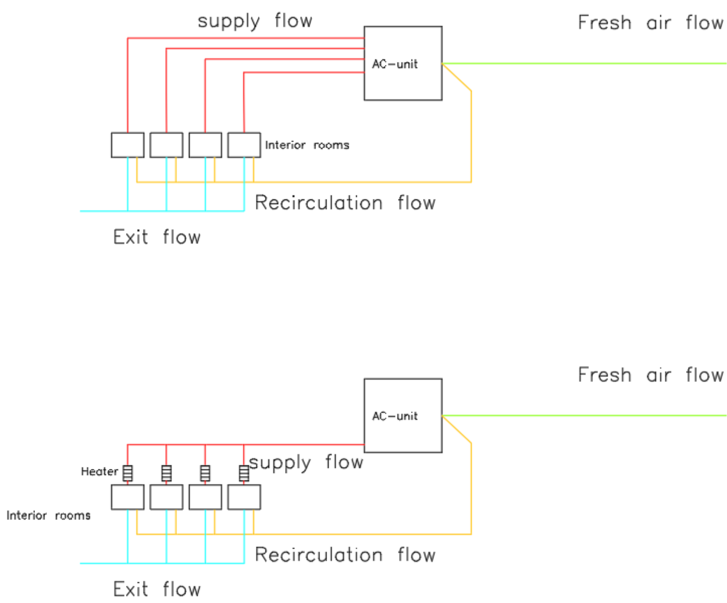


Figure 4.23: Two examples of the ducted HVAC system, on top the system with a separate air supply duct for each room and on the bottom a combined supply air flow duct and separate heaters for each room.

To determine the HVAC capacity, the net volumes of the different rooms is used. For each type of room, the amount of air changes per hour and recirculation percentage is defined. The calculated air capacities are displayed in table 4.21. A choice needs to be made on the amount and size of the AC-units. On existing Feadships between 50-60 metres one up to five AC-rooms are used. To make a decision two things are important. First, the penetration of watertight bulkheads. Second, the division between crew spaces and luxury spaces. Penetrating watertight bulkheads is expensive because the ducts need to be equipped with valves to make it watertight. The separation of luxury areas and crew areas is desirable, to be able to shut down part of the ac system when the owner is not on board. Also, the air exhaust and intake of crew and luxury areas can be located in different spaces. For the luxury areas more attention is paid to prevent mixing of exhaust and intake air.

For the modular concept four AC-units are used, the division is shown in figure 4.24. The first AC-unit is used for the fixed crew and wheelhouse compartment and will be located in the tender garage. Both are crew areas and there is no need to penetrate bulkheads. The second AC-unit is used for the owners only and is also located in the tender garage. This one is not combined with the first AC-unit to be able to shut it down. Also, in the tender garage it is more easy to fit an additional AC-unit to only serve the owner. The third AC-unit is used for the guest cabins, additional crew area and stairs. This AC-unit will be located behind the stairs on the main deck. Both sides of the bulkhead can be connected via the main deck avoiding the valves. In this

Table 4.21: Minimum and maximum calculated air capacities, all values in m^3, for different areas in the yacht

	Min				Max			
	Supply	Exhaust	Recirculation	Fresh	Supply	Exhaust	Recirculation	Fresh
Fixed crew	1329	1188	168	1188	1329	1188	168	1188
Additional crew	1319	1223	222	1445	1914	1741	277	1963
Guest cabins	1822	784	1039	784	2129	978	1151	978
Owner's suite	1517	548	969	548	2675	891	1785	891
Stairs	648	877	0	877	890	1119	0	1119
Main deck lounge	2062	100	1962	100	3651	100	3551	100
Bridge deck lounge	1342	100	1242	100	3031	100	2931	100
Wheelhouse	1676	429	1278	429	1676	429	1278	429
Totals	11715	5249	6880	5471	17295	6546	11141	6768

AC-unit, the guests are combined with the crew, this is less optimal but an additional AC-unit in this location will take up a lot of the interior space. The fourth AC-unit is used for the two lounges and is located on the other side behind the stairs on the main deck. In table 4.22 the minimum and maximum needed capacity is shown in the second and fifth column. The dimensions in the other columns are derived from existing AC-units with enough capacity to match the needed capacity.

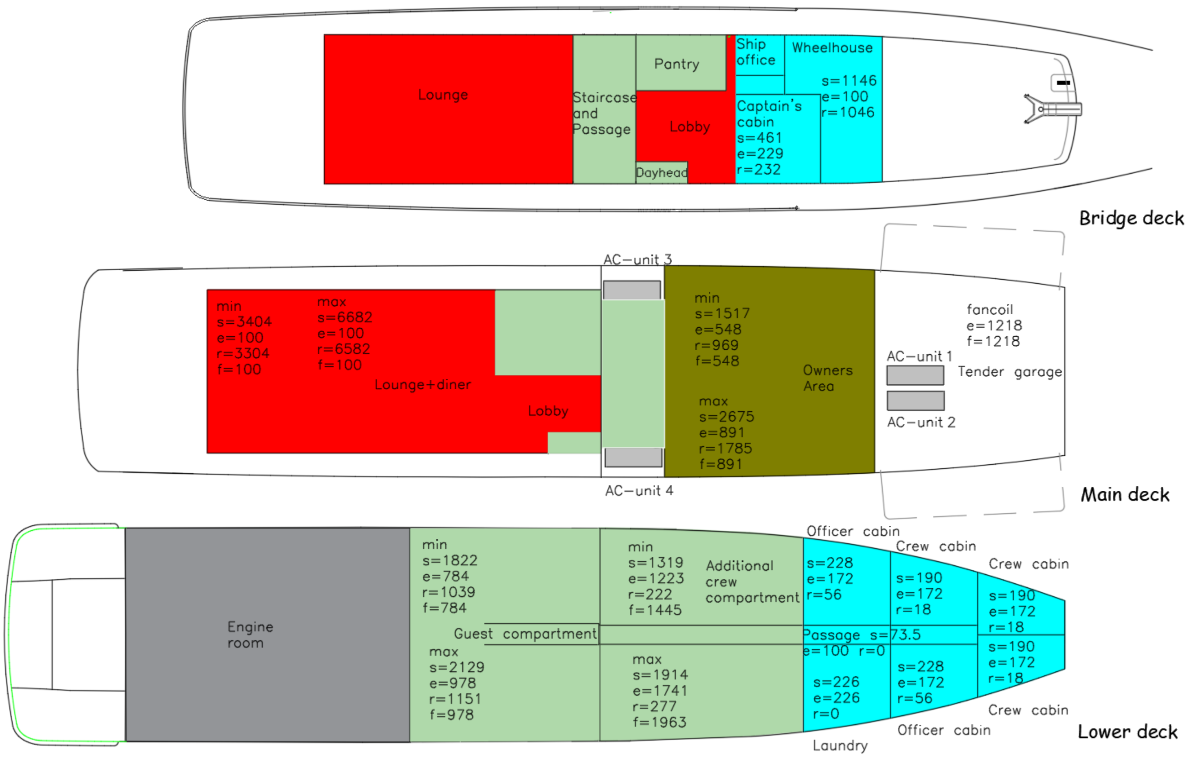


Figure 4.24: The division of interior areas over the different AC-units

With the capacities from table 4.21 and a maximum air speed per duct, the maximum and minimum size of the ducts can be calculated. The air speeds are shown in table 4.23. Besides the maximum air speed, there are also regulations for fire safety when penetrating fire zones. There are three categories depending on the area of the duct. If the area is less than $0.02m^2$ no additional measures are needed, if the area is between $0.02m^2$ and $0.075m^2$ the penetration length should be at least $900mm$. When the area is above $0.075m^2$ also a fire damper is needed. Therefore, if possible, the area of the duct should be below these values. For each compartment the ducting on the interface is chosen in such a way to reduce additional measures when penetrating a fire zone. Fire zones are needed around AC-rooms, stairs and tender store for example. There is no need for a main fire zone, since the accommodation will need exceed 48 metre. If possible round

Table 4.22: Minimum and maximum capacity and dimensions of the four AC-units

	Capacity [m^3]	Length [mm]	Width [mm]	Height [mm]	Capacity [m^3]	Length [mm]	Width [mm]	Height [mm]
AC1	3005	2800	780	780	3005	2800	780	780
AC2	1517	2600	780	780	2675	2900	780	780
AC3	3789	2800	880	1280	4933	2800	880	1280
AC4	3404	2800	880	880	6682	2800	980	1280

pipes are used, these can be purchased per metre and customised at the yard whereas the ducts need to be manufactured separately. The largest difference in duct sizes occur in the lounges, these are shown in table 4.24.

Table 4.23: Maximum air speeds for each type of air flow in a round or rectangular duct, ACS is supply air, ACF is fresh air, ACR is recirculation air and ACE is exhaust air.

Type	Ducts round Vmax	Ducts rectangular Vmax
ACS	15	5
ACF	5	4
ACR	4	4
ACE	4,5	4

Table 4.24: The difference in maximum and minimum duct sizes for AC-unit 4, PR is a pre insulated round duct and R is non insulated round duct

SYS	AC4 Max	AC4 Min
ACF-AC-unit 4	PR150	PR135
ACE-Main deck	R100	R100
ACR-Main deck lounge 1	500x300	450x350
ACR-Main deck lounge 2	500x300	
ACS-Main deck lounge 1	PR150	PR160
ACS-Main deck lounge 2	PR150	PR160
ACS-Main deck lounge 3	PR150	
ACS-Main deck lounge 4	PR150	
ACE-Bridge deck	R100	R100
ACR-Bridge deck lounge 1	400x300	400x300
ACR-Bridge deck lounge 2	400x300	
ACS-Bridge deck lounge 1	PR155	PR130
ACS-Bridge deck lounge 2	PR155	PR130
ACS-Bridge deck lounge 3	PR155	

The AC-rooms will be designed for the maximum AC-capacity. This is done because the size of the AC-units do not increase that much with increasing capacity, as shown in table 4.22. By designing for the largest dimensions, the integral platform will always be able to deliver the capacity needed. If the cost price of AC-units increase a lot with capacity, it is always possible to fit a smaller AC-unit to reduce costs. The ducting connections to the modules will also be designed for the largest capacity. This will result in space reservations for the maximum ducting on the integral platform. But when the capacity is less the choice can be made to only use two of the four air supply pipes in case of the main deck lounge for example. The optimised ducting of all AC-units can be found in table 4.25, these are not always the commonly used duct sizes. Therefore, if standard piping is to be used the duct might increase in size a bit. Figure 4.25 shows the schematics of the optimised ducting for AC-unit four.

4.6.3. Construction and mechanical engineering combined

For the construction and HVAC-system a way of handling the increase in length or interior area is discussed. The solution for the construction is to add additional transverse stiffeners. This way the spans are reduced

Table 4.25: Optimised ducting to have enough capacity in the maximum and minimum arrangement. For the owner's HVAC-unit and the lounges more pipes can be used if the capacity increases.

ACF-AC-unit 1	350x250
ACE-Fixed crew 1	R250
ACE-Fixed crew 2	R250
ACR-Fixed crew	PR125
ACS-Fixed crew starboard	PR125
ACS-Fixed crew portside	PR125
ACE-Wheelhouse compartment 1	R140
ACE-Wheelhouse compartment 2	R140
ACR-Wheelhouse compartment 1	PR250
ACR-Wheelhouse compartment 2	PR250
ACS-Captains cabin	PR100
ACS-Wheelhouse and office 1	PR125
ACS-Wheelhouse and office 2	PR125

	Max	Min
ACF-AC-unit 2	250x250	250x250
ACE-Owner 1	R160	R160
ACE-Owner 2	R160	R160
ACE-Owner 3	R160	-
ACR-Owner 1	PR270	PR270
ACR-Owner 2	PR270	PR270
ACS-Owner 1	PR150	PR150
ACS-Owner 2	PR150	PR150
ACS-Owner 3	PR150	-

ACF-AC-unit 3	850x350
ACE-Guests	R280
ACR-Guests 1	PR215
ACR-Guests 2	PR215
ACS-Guests 1	PR160
ACS-Guests 2	PR160
ACE-stairs module	R300
ACR-stairs module	-
ACS-stairs module	R150
ACE-additional crew compartment 1	R265
ACE-additional crew compartment 2	R265
ACR-Additional crew compartment	PR160
ACS-Additional crew compartment 1	PR155
ACS-Additional crew compartment 2	PR155

	Max	Min
ACF-AC-unit 4	PR150	PR150
ACE-Main deck	R100	R100
ACR-Main deck lounge 1	450x350	450x350
ACR-Main deck lounge 2	450x350	
ACS-Main deck lounge 1	PR160	PR160
ACS-Main deck lounge 2	PR160	PR160
ACS-Main deck lounge 3	PR160	
ACS-Main deck lounge 4	PR160	
ACE-Bridge deck	PR100	PR100
ACR-Bridge deck lounge 1	400x300	400x300
ACR-Bridge deck lounge 2	400x300	
ACS-Bridge deck lounge 1	PR155	PR155
ACS-Bridge deck lounge 2	PR155	PR155
ACS-Bridge deck lounge 3	PR155	

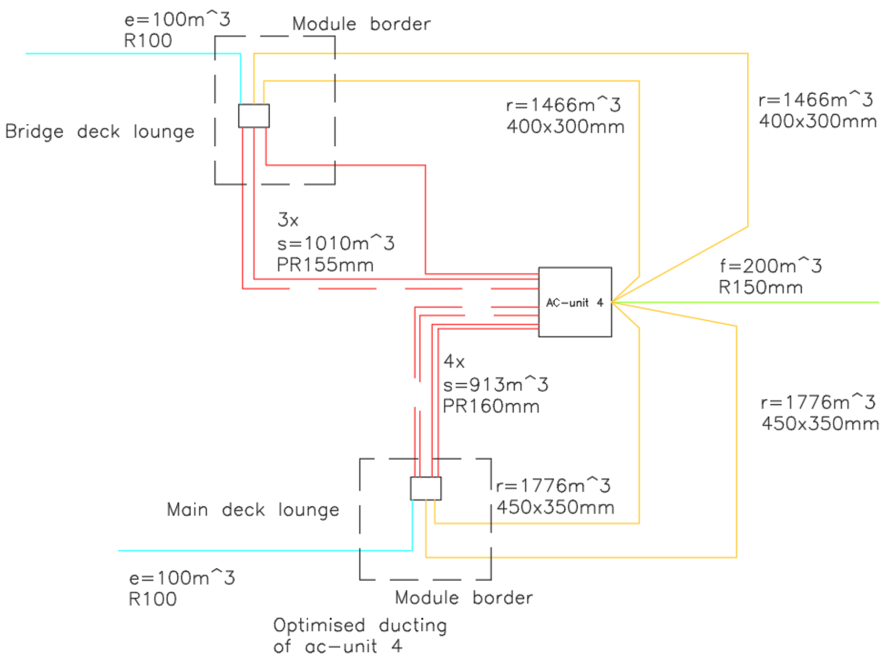


Figure 4.25: Schematic of the optimised ducting for AC-unit 4. Dashed ducting lines indicate ducts that are not needed when designing for minimum capacity. The solid rectangle represents the module room and the dashed rectangles show the module border on which the ducting needs to be connected, within the modules the ducting can be arranged as needed depending on the design.

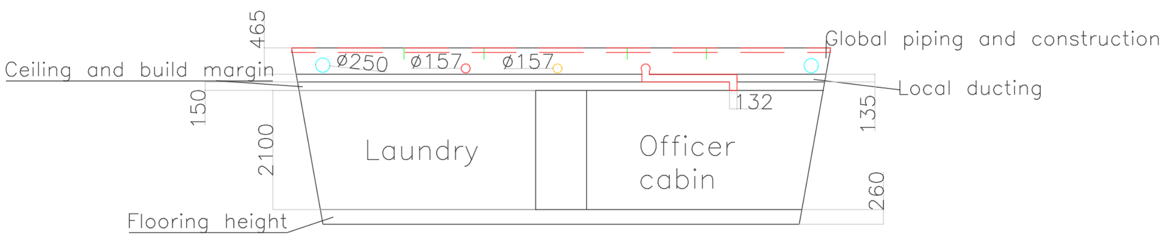


Figure 4.26: A cross section of the fixed crew compartment with height indications, the dashed red line shows the transverse stiffener, the green line show the primary longitudinal stiffeners. The blue duct is for exhaust air, the red one is for supply air and the orange duct is for recirculation air.

and the construction height can be kept low, this allows for the global ducting to pass underneath the construction. For the HVAC four units are used with the maximum capacity needed. Locations for these units are chosen in a way to minimise duct crossings with watertight bulkheads. Dimensions for the global ducting are also derived based on the capacity. In determining the duct size it is important to keep the duct area below $0.02m^2$ or if not possible below $0.75m^2$ to prevent extra measures for fire safety. This is not possible in all cases, therefore, some extra measures will be needed especially with some exhaust and recirculation ducts. With the information from the construction and HVAC part cross section can be made to show the available space for construction, global ducting and local ducting. One of these cross section is shown in Figure 4.26. This is the cross section of the fixed crew compartment, to illustrate the construction and ducting heights. By separating the local and global piping the module can easily by attached to the global piping of the integral platform.

5

Concept evaluation

In this section the Feadship modular product platform will be evaluated and the next steps to develop the platform will be discussed. First, an evaluation on the the product platform requirements from section 4.1 will be done. Second, the possible exterior customisation is visualised using different profiles and arrangements. Third, the possible interior customisation is evaluated on three aspects: compartment location, compartment size and module design. Fourth, will be a discussion about the expected reduction of engineering hours. This is determined using the detailed planning of a 56 metre yacht. The section will then continue with discussing the next step in the platform development and highlighting some of the additional benefits that arise when a modular platform is used. The last part of this section shows the calculation of the expected profit and how this is depending on the selling price and engineering costs.

5.1. Platform diversity

At the start of the design, requirements were set regarding the rooms on the yacht, size and amount of tenders, amount of passengers, amount of crew, engine power and range. This section will start with repeating these requirements and afterwards discuss how the current modular product platform is able to meet these requirements.

In table 5.1 the requirements are listed together with the realised values. The list below the table shows the different rooms as identified in chapter 3. The amount of guests required was a minimum of eight and a maximum of twelve, this is including the owners. In the design a minimum length for the guest compartment of 5.50 metres is used. This area offers space for two guest cabins with two beds each, together with two beds in the owner's area this makes six guests. In the owner's area additional guest cabins can be realised increasing the amount of passengers. Off course less than six is possible but not expected when it is assumed that existing yachts represent the wishes of the current clients. The maximum amount can be realised by using the maximum length of the guest compartment, 10.7 metres. This is enough for four guest cabins with two beds each, the remaining two guests and owners can be located in the owner's area.

The minimum amount of crew without captain is accommodated in the fixed crew module, this module has three double crew cabins and two double officer cabins resulting in ten beds. With this module the minimum requirement is met. By adding double crew cabin modules in the additional crew compartment this capacity can be increased to sixteen.

One or two tenders with a maximum length of eight metres is required, this requirement is also realised by providing a fixed tender compartment on the integral platform. This tender compartment is located in the front of the main deck or the aft of the lower deck depending on which platform is used. There is always room for two tenders but this is not mandatory one tender and some more toys can be stored for example.

There is not a fixed location for the additional toys that were set as a requirement. The tender store can be used to store at least one toy and as said it depends on the choice of tender if it is possible to store more toys. For smaller and lighter toys the aft peak can also be used, but since no provisions are made for cranes the toys should be able to lift by hand. Because no real location is set for these toys, it might be impossible in combination with the maximum amount of tenders. Therefore, this requirement is not fully met. A more specific design should show if it is possible.

At this moment the range requirement is not validated, to validate the range requirement more information about the resistance, tank capacity and speed is needed. But it is to be expected that this range requirement poses no problem for a yacht of this size, if a normal fuel tank capacity is used. Existing Feadships have a tank capacity around 100.000 litres. These can all sail between 4500 and 5500 nautical miles.

With a minimum engine power of 1880 and a maximum of 2960 kWe the requirement is considered met.

The list of rooms can all be found except for three, most are part of the different modules discussed in chapter 4. The toy store, gym and beach club are not directly represented in the different modules, but the gym can be located in the aft peak space or when the tender is stored on the lower deck one of the tender stores can be used for the gym. This would also be the place for a beach club. For the platforms with the tender on the main deck it will not be possible to create a real beach club. Some seating may be arranged in the aft peak room.

Table 5.1: The requirements as set in 4.1 on the left and the realised values for the modular product platform on the right. The * behind the description in the first column indicates that the requirements is not explicitly validated in this thesis. But from existing yachts it is expected to be feasible.

	Required		Realised	
	min	max	min	max
Length[m]	50	60	50	60
# of passengers	8	12	6	12
# of crew	10	16	10	16
# of tenders	1	2	1	2
Size of tenders	8	8	8	8
Extra toys*	1	2	1	2
Range[nm]*	4000	5500	4000	5500
Engine power [kWe]	2000	3000	1880	2960

- Crew cabins
- Mess
- Laundry
- Storage
- Pantry
- Galley
- Wheel house
- Captain's cabin
- Ship office
- Outside lounge
- Inside lounge
- Owner's rooms
- Guest rooms
- Head and powder rooms
- Gym
- Beach club
- Jacuzzi
- Toy store
- Inside tender store
- Technical space
- Engine room

5.2. Exterior customisation

In chapter 3 the exterior profile is identified as a part of the yacht with a lot of customer value. It is hard to define a level of exterior customisation, hence, it is hard to define if enough customisation is achieved. Therefore, the possible exterior customisation will be shown with examples instead of discussing if the requirements are met. Broadly speaking the longitudinal profile is defined by length and height of the decks. Different profiles can be created by varying these as is shown in figure 5.1. Some parts of the exterior profile can't be directly influenced, from the staircase module forward the yacht is full beam this has an influence on the exterior profile. Furthermore, the stairs will influence the location of the funnels on the sundeck, this will also influence the profile a bit. The location of the staircase is influenced by the length of the additional crew compartment, this way the location can be influenced but not directly. More detailed exterior customisation can be assessed in a later stage. For example, the influence on local construction for different sized or shaped windows.

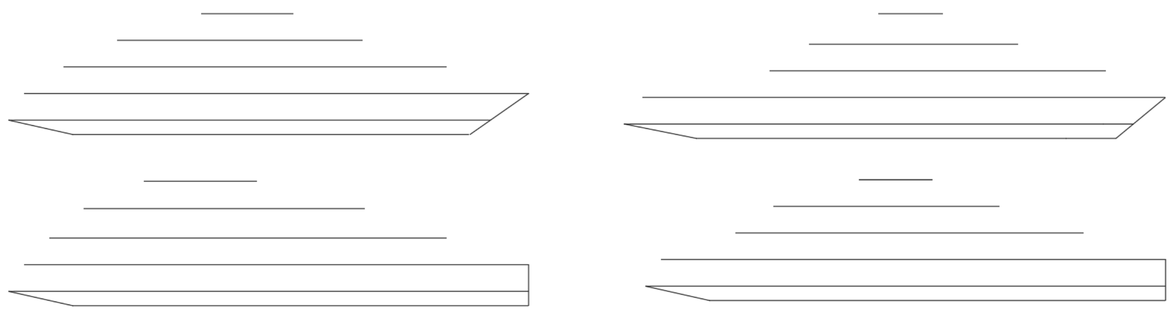


Figure 5.1: Four different longitudinal profiles possible of the modular product platform

5.3. Interior customisation

This section will discuss the possible customisation of the interior areas, the interior area customisation can be done in three ways: compartment location, compartment size and module design. The customisation will be discussed using examples, these examples are created from the modular product platform.

In chapter 3 the variety in general arrangement is reduced to five different combinations. These combination were made from four lower decks, three main decks, one bridge deck and two sun decks. One of the possible sun deck variations has the tender on the aft part of the deck. This is a bit old fashioned, therefore, it will not be needed to offer this option. The three remaining options can be created using the three integral platforms. The platforms have different compartment locations for the tender, guest cabins and engine room. Figure 5.2 shows the three platforms.

The second part of the general arrangement customisation can be done using variable compartment sizes. A minimum and maximum length for each of the lower deck compartments is defined. The upper deck compartments lengths are a result of the lower deck compartment lengths. Table 5.2 shows the possible minimum and maximum lengths of the different compartments. Figure 5.3 shows two possible lower deck arrangements with different compartment lengths. Matching main deck and bridge deck examples can be seen in figure 5.4 and 5.5. The red and blue stripes show the maximum and minimum size of the lounge.

Table 5.2: The compartment lengths of the integral platform, for modules with a fixed length only a minimum value is displayed. Some compartments have a variable length when this is the case this is displayed in brackets behind the compartment's name. The compartments can be increased by 0.50 metres at a time, this is equal to the stiffener spacing.

	minimum length[m]	maximum length[m]
Fixed crew	12.50	
Additional crew(variable)	5.50	10.0
Engine room middle	8	11
Engine room aft	10	13.5
Guests(variable)	5.50	11
Tender store	9.00	
Aft peak(variable)	5.00	8.00
Stairs	3.00	

The module design is the last part in the customisation of the interior. Design of the luxury modules enables the customer to choose the interior style and arrangement. This customisation adds a lot of customer value. The owner's area, guest cabins and lounges are seen as luxury modules.

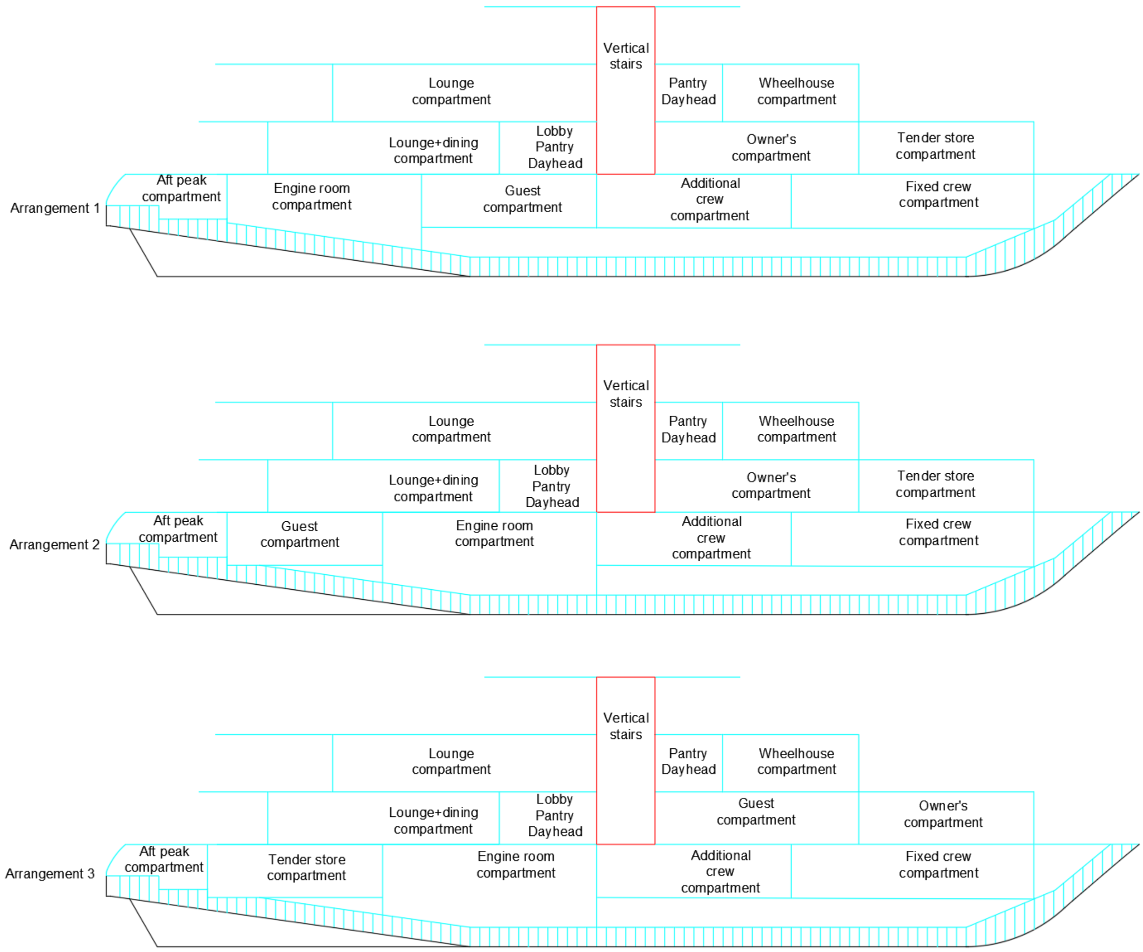


Figure 5.2: Three different platforms to offer the variety as discovered in the analysis of the general arrangements

Figure 5.3: Two lower deck arrangements to illustrate the difference due to different compartment lengths

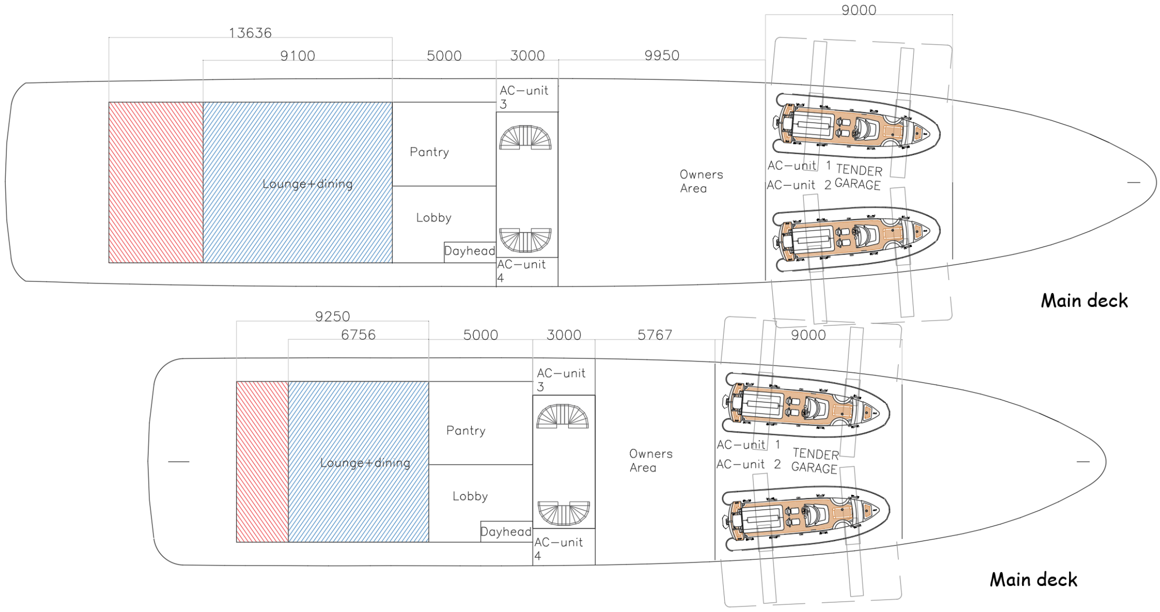


Figure 5.4: Example of the main deck with the compartment lengths, the striped areas show the minimum and maximum size of the lounges, in red the maximum and in blue the minimum size

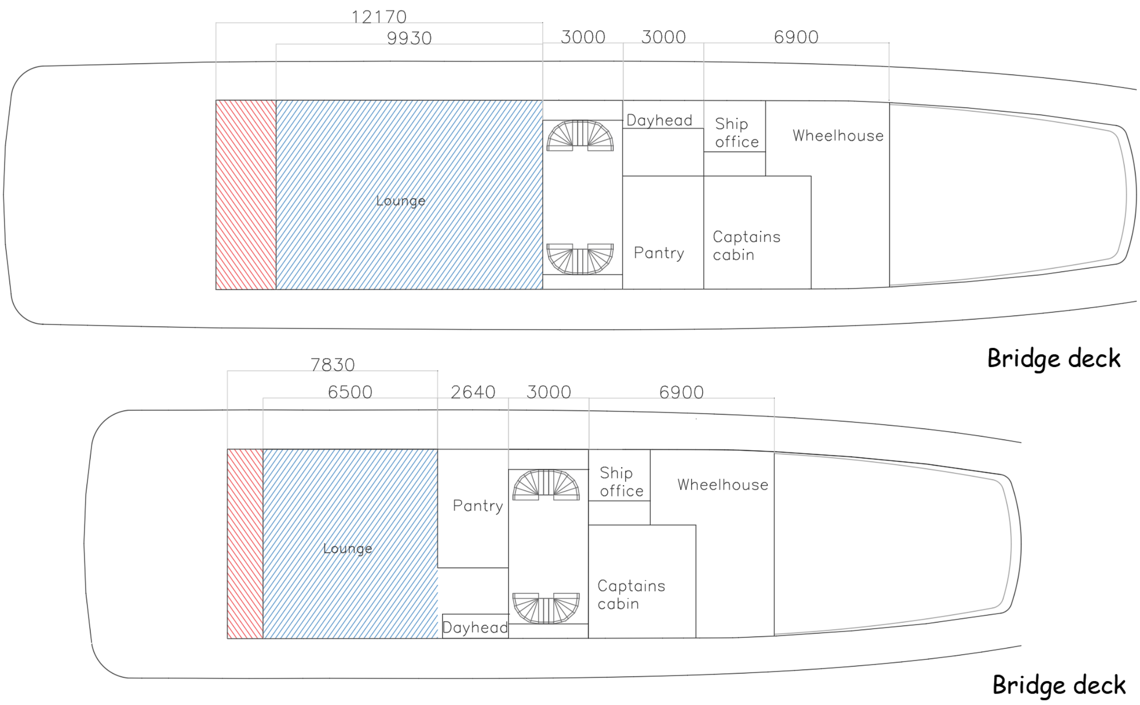


Figure 5.5: Example of the bridge deck with the compartment lengths, the striped areas show the minimum and maximum size of the lounges, in red the maximum and in blue the minimum size

5.4. Reduction in engineering hours

The goal of a modular design is to reduce engineering hours without losing a lot of customer value. To evaluate the reduction of engineering hours the detailed planning of a 56 metre Feadship is used. In this planning the workload for each task is documented. The tasks that are affected by the reuse are identified. An estimation of the possible percentage of workload reduction is made for each task that is affected. The total reduction is calculated as a percentage of the total engineering hours of that department. Furthermore, the total reduction on the engineering hours is calculated. Figure 5.6 shows both the reduction for each discipline and the total reduction. Chapter 3 identified nine tiles of the work breakdown structure with a weighted percentage above ten. This was seen as processes that show potential for reuse. Beside these areas the possible workload reduction for the other areas is assessed as well. This section will discuss each discipline starting with the naval architecture.

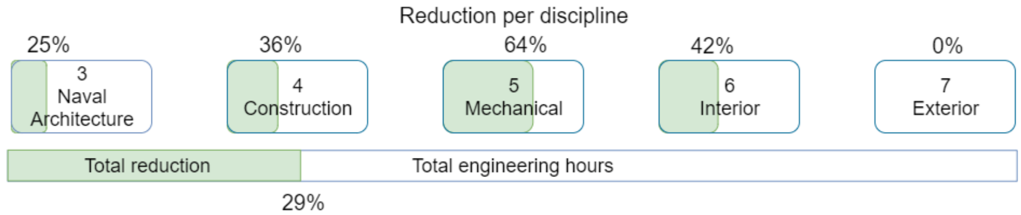


Figure 5.6: On top the reduction of engineering hours per discipline, the different sizes of the tiles correspond to the percentage of total engineering hours. On the bottom the total reduction is visualised.

The estimated reduction in engineering hours for the naval architecture discipline is 25%. Figure 5.7 shows the distribution of hours over the sub tiles of naval architecture. The naval architecture largely depends on input from other departments. For example, in weight, stability and gross tonnage calculations. Small variations will impact the result. A large part of the calculations are also used for classification. As a result a lot of the calculations will have to be repeated for each yacht, limiting the possible reduction of engineering hours. Tile 3.2 hull and powering provide the largest possible savings. The two engine options and standard tank arrangement reduce the work for tanks, shaft line and appendages. The stability and weight calculations offer potential reduction of 6%, especially in the first iterations. Furthermore, some savings can be expected for tile 3.3 regulations and more specific the fire and safety plans. In total the 25% reduction within the naval architecture will result in a 4% reduction on the total engineering hours.

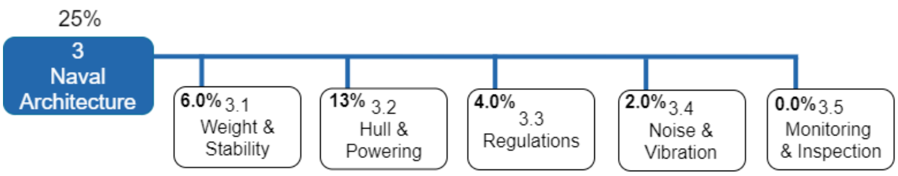


Figure 5.7: The division of reduced engineering hours over each of the sub tiles of naval architecture

Reusing parts of the design's construction give an estimated reduction in engineering hours of 36%. For the construction, tiles 4.2, 4.3 and 4.4 were identified as possible areas for a reduction of engineering hours. Figure 5.8 shows the distribution over the four tiles. A reduction of 14% is possible on tile 4.2, 7% on tile 4.3 and 15% on tile 4.4. For each task a percentage of reuse is estimated with a maximum of 90%. Since even drawings that are completely standard will have to be issued again for a new project. The drawings and calculations for the classification will have to be reproduced for each project, as a result not much reduction is expected. For the main construction, however, reduction in engineering hours are possible if a "smart" 3D model can be created. To be "smart" the 3D model should be able to update the construction for different sizes of compartments, as defined during the design. A part of the local construction items can be potentially reused. For example, the stabilisers, bow thruster, propulsion, rudders and tender garage can be reused on the same platform.

In the mechanical department the largest savings are to be expected. In total 64% of the engineering hours can be reduced. Figure 5.9 shows the division over the different tiles. The largest amount of hours can be reduced in the technical spaces. The standard arrangement of the aft peak and AC-rooms make reuse possible. The engine room model can be reused for a large part. Furthermore, from tile 5.3 systems, schematics and di-

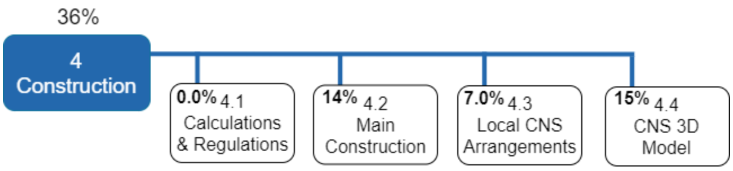


Figure 5.8: The division of reduced engineering hours over each of the sub tiles of construction

agrams can both be reused to some extend. The schematics show the piping on the general arrangement and can be reused for the standard parts of the yacht. The luxury rooms will have to be redrawn. The diagrams show more potential for reuse since these only show the schematic connections. The last tile, 5.4 HVAC, can be largely reused because of the standard AC. This part of the scope also consists of checking high risk areas, this will not be necessary since all risks will be known after the first design.

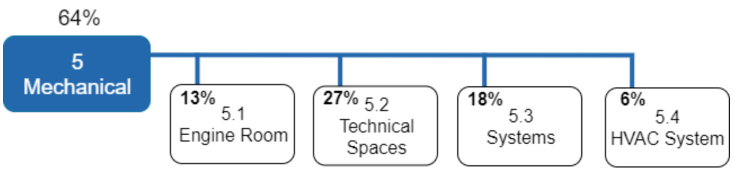


Figure 5.9: The division of reduced engineering hours over each of the sub tiles of mechanical

Interior is the last discipline considered in this evaluation. A total reduction of 42% is estimated. The largest part of this 42% is in the crew interior, figure 5.10 shows the reduction in engineering hours in the interior department. All the luxury areas will have to be redesigned for each yacht limiting the possible reduction in engineering hours.

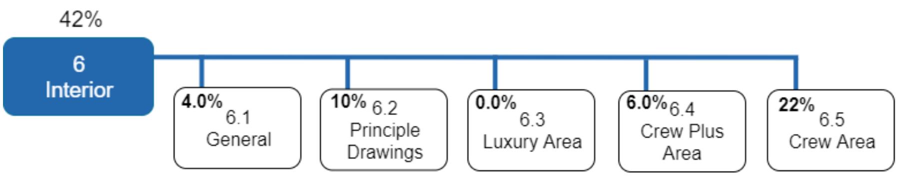


Figure 5.10: The division of reduced engineering hours over each of the sub tiles of interior

5.5. The next step for the modular product platform and added benefits

In the current state, the design can be used to inform customers on the possibilities of building a yacht with a modular approach. Information is available on the restrictions and the relations between different aspects of the design. A quantitative estimate for the cost reduction, within the engineering scope of De Voogt, is available. This section will first discuss the next step for the Feadship modular product platform. Second, the expected lifetime of the product platform will be determined. Lastly, additional benefits, besides the reduction in engineering costs, are presented for sales, engineering and production.

The combination of a concept design and expected benefits provide the ability to further develop the concept. The next step in this project will be to develop parametric models for the basic construction and hull shape. These can be used to verify the strength and stability and make a tank arrangement. In total two different hull shapes and three different constructions will need to be made. To do this a choice needs to be made on some of the main equipment. The choice for specific main equipment can also prevent a discussion with a customer during sales. When a potential customer is available the concept design can become a design number, which is further engineered.

The remainder of this section will discuss the expected life time of the platform and potential benefits in the different steps of designing, selling, engineering and using a Feadship. First, expected lifetime will be discussed. Second, the benefits in design and sales, engineering and production. Lastly, the influence on resale value will be discussed.

5.5.1. Lifetime

For the implementation at De Voogt it is important to know the time a platform can be used in sales. This mainly depends on three things: changing technology, changing regulations, changing customer value. If new technologies become available the equipment on the platform can become outdated. Customers will expect state of the art technologies on their yacht. But updating equipment is still possible on the platform. Another influence on the lifetime of the platform are the applicable regulations. For example, when regulations change regarding emissions or positioning of certain equipment the platform will need to be updated as well. Since the yacht will have to apply with the regulations at the time of building. The last big influence is the customer value. When customer value changes over time the design becomes outdated. For example, on older yachts it wasn't un common to have tenders open on the decks. In newer yachts this is not so common any more. The last few decades beach clubs become more popular as well. Aside from these the yachts more or less stayed the same. Therefore this will most likely not pose a tread for the platform's lifetime.

Although some changes happen over time to the technology, regulations and customer value, the platform with a few updates in between can have a lifetime of 10 years. Based on the last 20 years, it is expected to sell about 7 or 8 yachts between 50 and 60 metres in the coming decade. Of these 8 yachts, 2 yachts might be fully custom, this leaves about 6 yachts for the modular product platform.

5.5.2. Design and Sales

In the current process a long design period can precede the signing of a contract. Furthermore, contracts are signed with many uncertainties. With a modular product platform, various spaces are pre-defined and relationships between the different areas of a yacht are known. By varying the parameters that define these relationships, the consequences of choices are clear. Different choices in design can be coupled to associated costs. This makes it easier to explain why the yacht is priced as it is and what is offered for that price. This will reduce the cost uncertainties leading to a better cost estimation. Furthermore, the standardisation of large equipment on the platform, provides the position to negotiate with suppliers for better prices.

5.5.3. Engineering

Each of the engineering departments can benefit differently of a modular product platform. A lot of the engineering processes depend on each other. A part of the engineering time is spend in discussion between different disciplines. Because in the modular platform the changes are pre-defined, a solution already exist and these discussion will take up less time.

Automatisation possibilities arise because the expected variations are known. This is especially true for construction. Where the design follows the rules and evaluation of the design can be automised. This can be combined with the basic mechanical engineering in a 3D model. By doing so a large part of the solution is already provided, this will reduce the amount of discussion during design. Since the naval architecture largely depends on the other disciplines this will also directly benefit. The reduced solution space will also limit discussions and reduce uncertainties in the design.

For the exterior and interior engineering the implementation of the product platform will yield less direct benefits. Although, for exterior an increased knowledge of the influence of exterior options on the construction and mechanical engineering is needed. When this knowledge is created it can also be used in other projects. This will also reduce the uncertainties.

Finally all disciplines have to provide documents for the classification society. With the limited variation in the total solution, it might be possible to have the classification society approve the concept as a whole. As a result the documentation will not have to be created for each ship individually reducing the amount of work for a single yacht.

5.5.4. Production

For production, benefits can be made through the learning curve that exist for repeating activities. The learning curve uses a learning rate that expresses the reduction in costs if the production volume is doubled. Generally the learning rate in the shipbuilding sector lies between 80 and 85%.[34]. This will result in costs savings of 15 to 20% for each doubling in volume. In the Feadship modular product platform only a part will be reused. This can reduce the learning rate, but by providing feedback from the production to the engineering the learning rate can be improved again. In this case the learning rate for the whole product platform is assumed to be 95%. Although 6 different unique platforms are identified these still have many similarities. Making it likely that the production rate will improve, even if a different integral platform is used. With the learning rate of 95% after 10 yachts the estimated reduction in production costs is 15% for the last one. Figure 5.11 shows the reduction over the amount of yachts build.

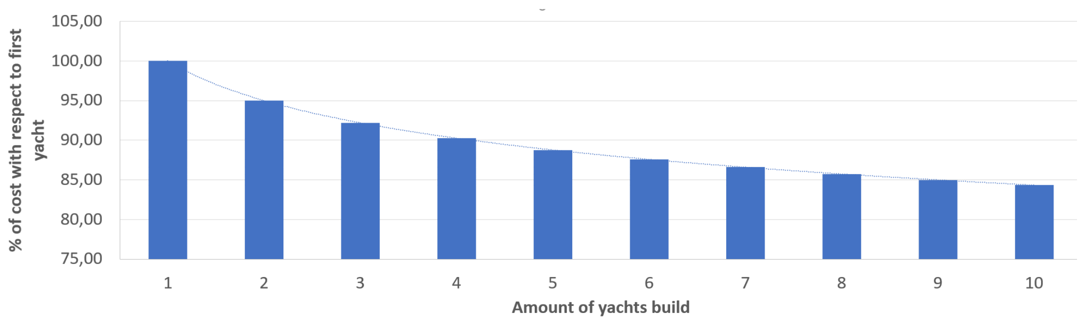


Figure 5.11: The expected reduction of production costs for each yacht that is built, according to the learning curve with an estimated learning rate of 95%

5.6. Costs and estimation of the possible profit

With both the reduction in costs for engineering and production available, an estimate can be made of the total profit depending on the amount of sales, selling price and engineering costs. This will provide some insights in the impact of selling price and engineering costs on the possible profit. The costs price of a yacht can be separated in to engineering, materials and production.

- 10% engineering
- 30% materials
- 60% production

To calculate the total reduction in production costs the 60% is multiplied with the reduction in production costs, as discussed in section 5.5.4. Table 5.3 shows the reduction of the production costs and the effect on the production costs with respect to the total costs.

Table 5.3: The reduction in costs for production because of a learning rate of 95%. The third column shows the amount of production costs with respect to the total costs.

nr of yachts	% of production costs	% of total costs
1	100,00	60,00
2	95,00	57,00
3	92,19	55,32
4	90,25	54,15
5	88,77	53,26
6	87,58	52,55
7	86,59	51,95
8	85,74	51,44
9	84,99	51,00
10	84,33	50,60

Furthermore, an increase in engineering costs for the first yacht is expected because of engineering for modularity. After the first yacht a decrease in engineer costs of 29% with respect to a custom yacht is expected. This is as determined in section 5.4. To compete with other yards, Feadship will have to sell the modular yacht at a lower price compared to the custom yachts. The influence of the selling price on the cumulative profit is visualised in figure 5.12. The influence on the profit is calculated for 4 different selling price values. The costs for engineering for modularity will result in a loss for the first yacht even if it is sold at the same price as a custom yacht. In this calculation the cost of engineering for modularity is estimated at 50% of the normal engineering hours. This will increase the total costs for engineering from 10 to 15% for the first yacht. When the yachts are sold at the normal price, already on the second yacht a profit can be made. If the yachts are sold at 95% of the normal price at least 5 yachts will have to be sold to be profitable.

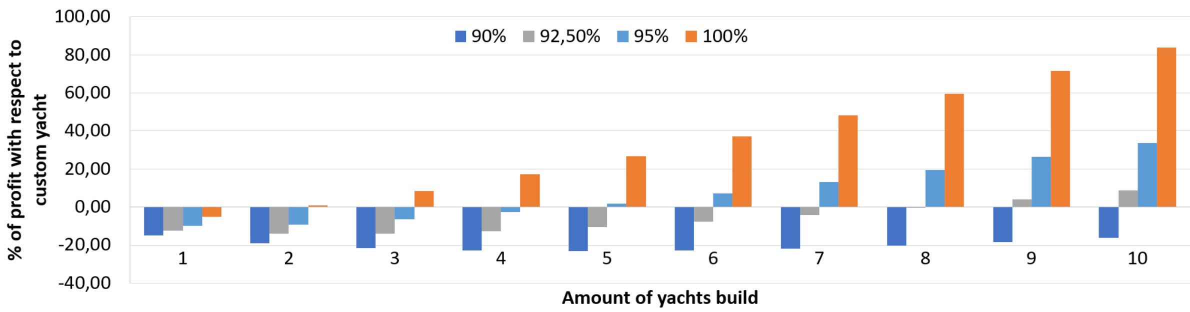


Figure 5.12: The cumulative profit for 4 different selling prices. In this calculation the expected increase in costs for engineering for modularity are set on 50%.

To investigate the impact of the costs for engineering, the engineering costs are increased from 12.5 up to 20% of the total costs. By doing so an estimated increase of costs because of the design for modularity of 25% up to a 100% increase is simulated. In this calculation the selling price is equal to a custom yacht. The influence on the cumulative profit can be seen in figure 5.13. Since the engineering costs are only 10% of the total costs, the impact on the total profit is limited. Since the impact of the increase in engineering hours is limited, the uncertainty about the exact value is less important.

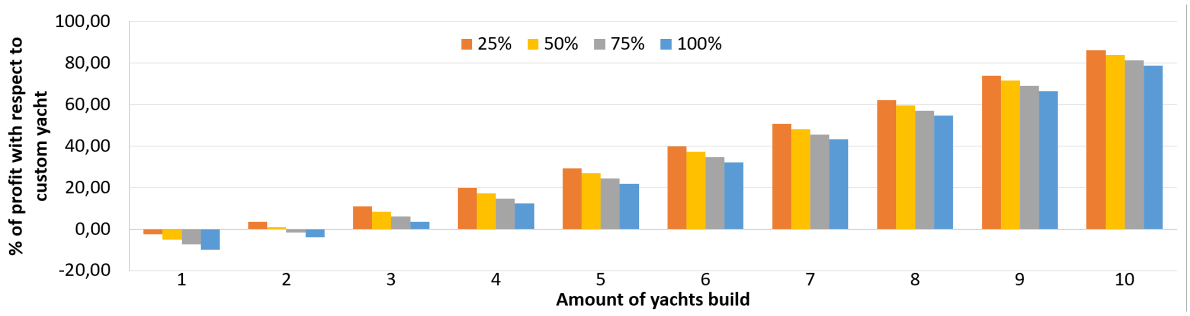


Figure 5.13: The cumulative profit for 4 different increase in engineering costs because of modularity. In this calculation the selling price is equal to a custom yacht.

6

Conclusion and recommendations

In the conclusion the Feadship modular product platform, the potential reduction in engineering hours and possible customisation will be discussed. Afterwards, a few general recommendations will be made and four topics will be discussed in more detail: the project's scope, the choice for three platforms, some remarks on the implementation of such a modular product platform and the costs of designing for modularity.

6.1. Conclusion

The main question to answer is: How can design reuse be applied to a 50-60 metre Feadship, with the aim to reduce engineering costs, while maintaining Feadship's customer value? A possibility is to use modularity in the design to strike a balance between reducing the engineering costs and offering enough customer value. In the Feadship modular product platform, three integral platforms are used, together with eleven modules. Figure 6.1 shows the three platforms and table 6.1 lists the different modules. The modular product platform can have a length between 50 and 60 metres and a beam of 10.15 metres. The modular yacht can accommodate a minimum of 6 and maximum of 12 guests and 10 to 16 crew. Furthermore, there are two possible engine configurations: 2x 990 kW or 2x 1480 kW. Lastly, a maximum of two 8 metre tenders can be stored.

The platform and modules are the result of a study on: a number of existing Feadships, the engineering hours at De Voogt and customer value in a yacht design. The platform forms the skeleton of the yacht, it provides structural strength and includes main technical components. For example, the engine room, propulsion pods, tanks, ac-units and the main ducting are part of the integral platform. The platform is divided in compartments of which some have a variable length increasing the possible customisation. The eleven different modules can be used to further increase the customer value. Different customisation possibilities exist for different modules. From a standard location and interior to only a set of rules for the module to adhere to. The modules have local piping and ducting to enable different arrangements. The local piping and ducting have a standardised connection to the platform.

The combination of platform and modules enables the reuse of parts of the design. This reuse will result in a reduction of engineering hours. In total a reduction of 25% of the hours in Naval architecture, 36% of the construction hours, 64% of the mechanical engineering hours and 42% of the hours spent on interior is possible. The concept makes it possible to reduce the total engineering hours at De Voogt by 29%. This is possible because of the standardisation in crew and technical areas. Furthermore, a parametric construction and hull model to cope with the different sized compartments contribute to the savings. More savings are to be expected in the detailed engineering and in the production. For the production an estimate is made using a learning rate of 95% for each doubling of the amount of yachts built. It is estimated that 6 yachts will be sold in the coming 10 years. If the yacht's selling price is 95% of a normal custom yacht and engineering costs for the first yacht increase by 50%, Feadship will have to sell 5 yachts to earn back the initial investment in the platform.

Even with reusing parts of the design, a high level of customisation is still possible. This customisation can be done on interior, exterior and functionalities as amount of crew, guests and engine power. The interior customisation level is different for each module. All crew modules have a standard interior arrangement, but the luxury modules such as lounges, guest rooms and owner's area can be customised within an available area. The exterior customisation is achieved by offering a variable deck length and not reusing the local exterior details. The variable deck length is achieved by increasing or reducing lounge areas. This will influence the longitudinal profile of the yacht. The local exterior details, such as the bulwark, transom and mast, will not be reused but customised for each yacht. The amount of guests and crew can be altered by changing the compartment lengths.

By using the Feadship modular product platform, a yacht can be designed between 50 and 60 metres. The yacht has all options that are normally seen on a Feadship in this range. A high level of customisation is possible to increase the value for the customer. Luxury rooms can be designed within an available area. Furthermore, exterior customisation options influence both local details and the longitudinal profile. Despite the high level of customisation, a reduction of 29% on the total engineering hours can be expected.

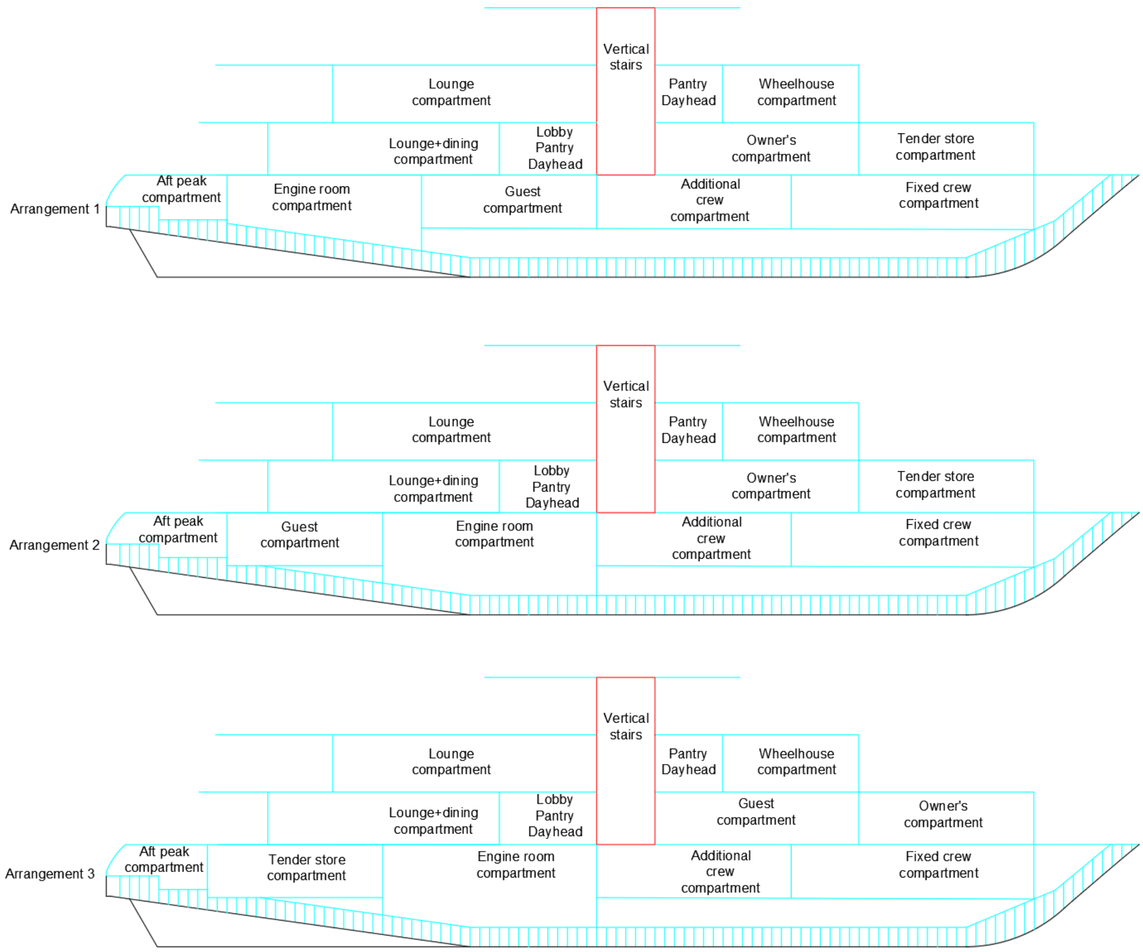


Figure 6.1: The three platform arrangements for the Feadship modular product platform

Table 6.1: The location and possible customisation of the interior arrangement for each module

	Interior arrangement	Location
Five crew cabins and laundry	Standard arrangement	Fixed crew compartment
Crew cabin	Standard arrangement	Additional crew compartment
Galley	Standard arrangement	Lower deck or main deck
Mess	Standard arrangement	Additional crew compartment
Guests	To design within allowed space	Guest compartment
Lounge	To design within allowed space	Lounge compartments on main and bridge deck
Owner's suite	To design within allowed space	Owner's compartment
Staircase, pantry and dayhead	Staircase standard, pantry and dayhead adjoining staircase	Vertical stairs compartment
Wheelhouse, captain's cabin and office	Standard arrangements	Wheelhouse compartment
Engine room	Standard arrangements	Engine room compartment
Aft peak	Standard arrangements	Aft peak compartment

6.2. Recommendations

In general, the current concept will need to be analysed in more detail. Areas such as stability and construction are discussed briefly. Also, choices are made concerning arrangements, these are made mainly by using existing Feadships. For a further design, a more experienced designer can create arrangements that better represent the current customer's wishes. Nevertheless, the way of analysing customer value and relating this to engineering processes will be useful to base decisions on. Furthermore, the design approach of focusing on the technical aspects that will change with different custom designs, can be used in the same way for slightly different arrangements or yacht sizes. The recommendations will discuss four different topics in more detail: the project scope, the choice for three platforms, implementation and the estimate of the possible profit.

The goal of the modular product platform is to reduce the cost price of the yacht without losing customer value. This thesis only uses the scope of De Voogt. The scope of the Voogt consists of relatively more construction work than mechanical engineering. This can also explain why the percentage of engineering hours for mechanical engineering is the lowest of all disciplines. The scope is used to identify possible areas for the reduction of engineering hours. When the total scope is used more and/or other areas of interest might be discovered. To determine the total cost reduction, the total scope of engineering and building a yacht needs to be used. The current analysis only determined the reduction of the engineering work at De Voogt and made a rough estimate of the reduction in production costs. A full scope analysis will be needed to assess if the cost reduction is enough to attractively price the modular yachts in the market.

In the modular product platform design phase, a choice is made for three different platforms. This choice is made to reduce module complexity. It is expected that engineering three different platforms might be cheaper than engineering highly complex modules for multiple locations. For example, the engine room has two locations. The engine room has a large impact on the construction of the double bottom and tanks. Designing such a flexible module might be more expensive than designing two platforms where it is integrated. This expectation should be investigated in more detail to verify if multiple platforms is less expensive compared to highly complex modules.

This thesis only investigates the design of a modular product platform and how this affects the engineering costs. Another important part is how to market the concept. In previous modular concepts, customers asked for modifications that were not accounted for during the design of such a concept. This would result in a large amount of overwork increasing the costs. Therefore, when selling a concept, it is important to know its limitation. At sales, they should not sell the concept with more modifications than it is designed for. This will ask for a different kind of sales tactic compared to full custom yachts.

An estimate is made of the expected profit based on rough figures. To limit the financial risk of the project, a better estimate of the costs of engineering for modularity and possible cost reduction in production is desirable. With a more accurate estimate for these costs a good selling price can be determined and the project can continue to a design number.

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A

Summary of the regulations for yachts in different sizes

	max 12 passengers, REG YC Part A					13-36 passengers, REG YC Part B	
	<500 GT	500-3000 GT		> 3000 GT	>5000 GT	any GT	
			> 85 m Lr			up to 120 persons	>120 persons
Stability	short range yachts: Intact stability only		Intact and damaged stability SOLAS 90 (damage extent B/5)			if lifeboats: intact (IS2008 incl wind criterium) and probabilistic damage (SOLAS)	intact (IS2008 incl wind criterium) and probabilistic damage (SOLAS) and "enhanced survivability" (2 compartment damage)
	Intact and damaged stability (pinhole damage)					No lifeboats: intact (IS2008 incl wind criterium) and probabilistic damage (SOLAS) and "enhanced survivability" (2 compartment damage)	
Construction	hinged WT doors, double bottom as per LR guidance	WT doors sliding except spaces not normally occupied by personnel, longitudinal strength gradually more important, double bottom as per LR guidance	WT doors sliding except spaces not normally occupied by personnel, longitudinal strength required, double bottom as per "SOLAS unusual bottom arrangements"			WT doors sliding plus floatability assessment (determining if doors may be open at sea), double bottom as per "SOLAS unusual bottom arrangements"	
Fire	only galley and engine room insulated, fabric treatment	All spaces insulated, main vertical zone (max 48m), fixed fire fighting and adressable detection & alarm system				All spaces insulated, main vertical zone (max 48m), fixed fire fighting and adressable detection & alarm system PLUS restricted interior materials	
LSA	4 life buoys, throw overboard life rafts, non-SOLAS rescue boat (Short Range Yacht no rescue boat)	8 life buoys, throw overboard life rafts, SOLAS approved rescue boat	8 life buoys, davit launched life rafts and 2 SOLAS approved rescue boats			Lifeboats plus davit launched life rafts plus 2 recue boats (life boats may double as rescue boats)	
						davit launched life rafts plus 2 recue boats (see impact on stability)	davit launched life rafts plus 2 recue boats
Navigation	paper charts, magnetic compass, gyro compass, GPS, depth/speed, radar, AIS, LRIT, BNWAS	Paper charts or non approved ECDIS, magnetic compass, gyro compass, pelorus, GPS, depth/speed, radar, AIS, LRIT, BNWAS, bridge wing visibility		2x ECDIS, magnetic compass, gyro compass, GPS, depth/speed, 2x radar with tracking aids, AIS, LRIT, BNWAS, bridge wing visibility			
Communication	general alarm, 12x flares, VHF DSC, MF/HF with DSC, Inmarsat, Navtex, emergency battery, EPIRB, SART					as Pt A plus public adress system	
MLC	double cabins incl en suite 6.2 m2, wheelhouse = dayroom equivalent	double crew cabins 7.0 m2 incl en suite, double officer cabins 9.0 m2 incl en suite, single officer cabins gradual (2 @ 500GT, 5 @ 2999GT), wheelhouse (or lounge) = dayroom equivalent		double crew cabins 11.0 m2, all officers single 5.5 m2	crew as well as officers all single 5.5 m2	double crew cabins 7.5 m2, triple 11.5 m2, quadruple 14.5 m2. Officers single 5.5 m2. Master, chief & first officer have adjoining day room	as previous, additional STCW qualifications, max 10% Occasional Workers
Machinery / Electrical	emergency battery 3 hrs	self contained emergency generator (SOLAS intent: air cooled and above bulkhead deck) 18 hr endurance				self contained emergency generator (SOLAS intent: air cooled and above bulkhead deck) 36 hr endurance	self contained emergency generator 36 hr endurance plus SOLAS Safe Return to Port

Figure A.1: Table with explanation of the different rules that apply to different sized yachts [18]