Master Thesis

Applying parametric optimisation in the concept exploration phase on naval support vessels

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Challenge the future

Master Thesis

Applying parametric optimisation in the concept exploration phase on naval support vessels

by

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Preface

The research described in this thesis has been carried out at the Defence Materiel Organisation (DMO) and focuses on the implementation of parametric optimisation in the concept exploration phase on naval support vessels. The project has been carried out to obtain the MSc. degree in Marine Technology in the specialisation of Ship Design. This thesis describes a new approach to generate, modify and optimise models in the concept exploration phase using parametric optimisation. This work would not have been possible without the help of a number of people, who I want to thank for their support.

I want to thank Austin Kana for our frequent meetings and for pre-reading my thesis. Also special thanks to Bart van Oers for his guidance throughout the process and always being prepared to answer my questions. Thanks to your feedback I was able to learn a lot during my master thesis. Many thanks go out to my other colleagues of the department DMO/AMS for good atmosphere at work and interesting discussions during the apple break.

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Andreas de Gaaij,

Delft, December 2019

Abstract

Five naval support vessels are being replaced. For this replacement two focus points are important. The first one concerns creating more unity within the fleet, achieved by using the hull geometry as a monolithic part. The second one concerns the aim to reduce harmful emissions by reducing the effects of the energy transition by minimising the resistance of the vessels.

The current design approach at DMO has deficiencies which limit the ability to vary hull forms and to analyse a large set of design options. Also propulsion power is predicted by regression lines only, which makes it difficult to evaluate novel hull forms. Motion predictions are only used in a later design phase. These deficiencies need to be resolved.

The technological opportunities which will be used to address these deficiencies are incorporating CAESES and RAPID in the concept exploration phase. CAESES is a CAD method with integrated optimisation algorithms which makes it useful to make hull form variations by using parametric optimisation. RAPID is a potential flow solver which can be used to predict the wave resistance on the geometry. The total resistance will be predicted by using Holtrop and Mennen for the viscous resistance components. The seakeeping capabilities are predicted by a simplified version of the linear strip theory. The main objective can be formulated as:

How can the unity and the energy transition be analysed in the concept exploration phase for the new generation naval support vessels with a hull geometry point of view using RAPID/Holtrop/seakeeping integrated with CAESES

Four validation studies have been performed. The test case studies are analysed on the differences in effective power and vertical displacement. The first conclusion is that the effective power will increase for a family design strategy in comparison to a single ship design strategy. The second conclusion is that the vertical displacement can be decreased when using a family design in comparison to the single design strategy. But only when the Logistic Support vessel is left out of the family of vessels, because of its restricted length. The design speed can be used as a design variable, but only when a more sophisticated power usage objective is used.

The new approach can be very useful in the concept exploration phase at DMO. The new approach uses a more advanced resistance objective in combination with hull variation. It can also predict the seakeeping capabilities in the concept exploration phase already. The integration of a potential flow solver and prediction on vertical displacement at the bow can be done within one optimisation and a study is possible within reasonable time (under six hours). This makes the new approach practical in the concept exploration phase.

Abbreviations and nomenclature

Abbreviations

2D two dimensional

BOA beam over all

B-spline basis spline

CAD Computer-aided design

CAE Computer-aided engineering

CAESES CAE System Empowering Simulation

CAPEX capital expenditures

Cb block coefficient

CoG Centre of gravity

CoR Centre of rotation

Cp Prismatic coefficient

CPC Centre Plane Curve

DMO Defence Materiel Organisation

DMP Defence Materiel Process

ECA Environmental Control Areas

ECN Ecole Centrale de Nantes

FdO Family design Open

FdR Family design Restricted

Fn Froude number

FOB Flat of Bottom

FOS Flat of Side

FP fore peak

F-splines fairness spline

GA Genetic Algorithm

GB Gigabyte

GM metacentric height

GMRES Generalised Minimal Residual Method

HOV Hydrographic Survey

ICE internal combustion engines

IMO International Maritime Organization

ITTC International Towing Tank Conference

JONSWAP Joint North Sea Wave Project

kN kilo Newton

kn knots

LCB longitudinal centre of buoyancy

LCC life-cycle cost

LHS Latin Hypercube Sampling

LCM Life Cycle Modelling

LOA length over all

LS Logistic Support

LWL length on waterline

MARIN Maritime Research Institute Netherlands

MT Marine Training

MDO marine diesel oil

MOGA Multi-Objective Genetic Algorithm

NLDA Netherlands Defence Academic

NSGA II Non-Dominated Sorting Genetic Algorithm II

NURBS nonuniform rational B-splines

OPEX operating expenditures

OPSCHOOL Operational School

Pe effective towing power

PEM polymer electrolyte membrane

PoI point of interest

RAM Random Access Memory

RANSE Reynolds-averaged Navier-Stokes equations

RAO Response Amplitude Operator

Rhino Rhinoceros

RNLN Royal Netherlands Navy

RTO Research and Technology Organization

SELCM Systems Engineering Life Cycle Model

SOFC Solid Oxide Fuel Cells

SS Submarine Support

VCG vertical centre of gravity

WL waterline

Nomenclature

NH_3 Ammonia

B_F friction

B_E eddy

B_W wave making

B_L hull lift

B_{BKN} bilge keel normal force

$B_{KH}kh$ bilge keel-hull interaction

CO_x Carbon oxides

$\omega_{enc,max}$ maximum encounter frequency

ω_0 wave frequency

K_{xx} roll gyradius

K_{yy} pitch gyradius

N_{total} number of panels for the whole ship

H_2 Hydrogen

h hours

$L_{panel,max}$ maximum panel length

$\lambda_{enc,min}$ minimum encountered wave length

m meter

NO_x Nitrogen oxides

P set of solutions

P' non-dominated set of solution

PM Particulate Matter

R_S Total resistance of the ship

R_w Wave resistance

R_F Frictional resistance as given in the ITTC-1957 friction formula

k_1 Form factor describing viscous resistance of the hull form in relation to R_F

R_{App} Resistance of appendages

R_B Additional pressure resistance of bulbous bow near water surface

R_{TR} Additional pressure resistance of immersed transom stern

R_A Correlation allowance

K_{zz} yaw gyradius

R_{aw} Ship added resistance in waves

s seconds

S search space

SO_x Sulphur oxides

t ton

T draft

Φ_v maximum vertical acceleration

Φ_r maximum relative vertical movement

V vessel speed

Definitions

The definitions are used for describing the design process currently used at Defence Materiel Organisation (DMO). Definitions are taken from an article of Robin Brouwer [1] or created by the author.

Capability: 'A type of system(s) or an individual that is required to accomplish a particular function' [1].

Function: 'A specific unit action that delineates how a particular aspect of a task is to be performed' [1].

Mission: 'An assignment with a purpose that clearly indicates the military actions to be taken, together with the underlying reasons [1]. A mission consists of operations to be carried out, simultaneously or in succession, by a military force in pursuit of a defined operational objective to fulfil the scenario aim. Generally, a mission will be made up by a group of operations. Missions are typically conducted by separate military forces spread in time and place and therefore can be assumed independent in probabilistic terms'.

Operability: 'The ability to keep a piece of equipment, a system or a whole industrial installation in a safe and reliable functioning condition, according to predefined operational requirements' [1].

Operation: 'A military action based on doctrines that supports a mission and consists of a set of tasks [1]. Missions and operations are closely related and often interrelated when defining the same set of tasks to be carried out. An operation is dictated by a specific supporting predefined goal. Operations may be regarded as a "toolbox", used to plan and organise the execution of a mission by dividing the job to be done into predefined and well trained parts'.

Task: 'A discrete event/action that enables an operation to be accomplished by individuals or organisations [1]. A task can be seen as an operation carried out by a single platform, in pursuit of an individual objective, mostly related to a single warfare area'.

Unity: 'Hull geometry as a monolithic part for multiple vessels'.

Contents

1

INTRODUCTION

This thesis concerns the implementation of parametric optimisation in the concept exploration phase on naval support vessels. A focus will be put on increased unity within the fleet and reduced harmful emissions. Section 1.1 specifies the context & focus points which will give the background of this project. With the information about the context available, the current approach and the technical opportunities are given in section 1.2. The research objectives will yield the questions to be answered in order to solve the problem, see section 1.3. The structure of the thesis is given in section 1.4.

1.1. CONTEXT & FOCUS POINTS

The Royal Netherlands Navy (RNLN) uses a large number of naval ships. Three key organisations work together and are involved during the procurement of warships [2]: Defence Staff, the RNLN and the DMO. The Defence Staff is responsible for the functional requirements and budget. The RNLN is the end-user and maintainer. The RNLN is also responsible for the overarching operational requirements and the concept of operations. DMO is responsible for the technical specifications and procurement.

DMO ensures that military personnel have modern, robust and safe materiel to work with [3]. The DMO is involved in the procurement, maintenance and sale of (used) materiel. Procurement is amongst others the making of a concept design of a vessel. By making a concept design, knowledge is gained about the estimated life-cycle cost (LCC).

A new project which is at hand is about the replacement of naval support vessels which are part of the small surface units. For this replacement two focus points are important. The first one concerns creating more unity within the fleet [4] and the second one concerns the aim to reduce harmful emissions. The naval support vessels account for around 10% of the total fossil fuel consumption of all the vessels of the RNLN [5]. This means the naval support vessels have a reasonable contribution to the impact of naval operations on the environment.

The first focus point concerns unity within the fleet. Unity within a fleet means to use the same equipment at every vessel. In the most extreme case of unity, all ships should be exactly the same. This raises the question how far unity can be applied within the renewed vessels, and what the consequences are of having more unity. The focus will be about the design strategy which should be used. Two types of design strategy have to be investigated. Normally, every support vessel is replaced one after another, with an individual focus. This is called the 'single ship design strategy'. Another strategy is to use a 'family design', all vessels will use parts that are exactly the same for every vessel. The part that could be the same for all support vessels is the hull geometry. Applying a family design hull geometry has its pros and cons. Research has to point out what the exact influence and effects are of applying one of these two design strategies.

The second focus point concerns the aim to reduce harmful emissions. Vessels need to comply with international rules and regulations, with exemption of ships of war. The Royal Netherlands Navy still wants to comply with the international rules and regulations where possible and has also set their own aims. The ambition of the RNLN is to reduce its fossil fuel dependency by at least 20% in 2030 and by at least 70% in 2050 [5]. These ambitions are more rigorous than the rules acting on emissions as published by the International Maritime Organization (IMO). IMO's Tier III limits will be active from 2021 onward. The emissions of Tier III are 75% lower than Tier II when in specified Environmental Control Areas (ECA). All ships who are operating in the waters of the North Sea and English Channel have to comply with these Sulphur oxides (SO_x) emissions limits [6]. Also if a naval ship is visiting North America and the Caribbean water, which is politically and strategically important, the vessels should be able to comply with Nitrogen oxides (NO_x) and Particulate Matter (PM) restrictions. Diesel engines produce NO_x emissions that are higher than the limits for the ECAs. This will limit the access to these ECAs of these ships. As the new generation support vessels are being operative after 2021, it is necessary to take these rules into account.

DESIGN STRATEGY, SINGLE SHIP DESIGN OR FAMILY DESIGN

Two different design strategies will be compared. The design strategy which is used nowadays is the design strategy with an individual focus. Every vessel is designed in isolation from the other vessels. This strategy will be called the "**Single ship design strategy**". The second strategy is currently investigated, namely the use of a platform approach. Three types of platform approaches can be used:

1. Modular approach
2. Integral approach
3. Scalable approach

The first one is the modular approach. Here products are derived by substituting and/or removing of modules [7]. The second is an integral approach. The platform is a single, monolithic part of the product. Individually designed portions can be added to the platform to get the final result. The third one is the scalable approach. Each platform has scaling variables that are used to 'stretch' or 'shrink' the platform in the desired dimensions. The focus point on increased unity concerns the geometry of the hull. The hull geometry can be used as a monolithic part for the support vessels, which is an integral approach. The strategy based on the integral approach will be called the "**Family ship design strategy**". This is one way to create the unity mentioned in the Sailplan 2030 [4]. Sailplan 2030 describes the ambitions of the RNLN for the year 2030. The modular approach can be used for system integration for example, but these types of systems will not be examined in this project. The scalable approach is not interesting to study because of the small amount of vessels it can be applied on.

To select one of the design strategies (single ship design, family ship design or a mixture of those), the advantages and disadvantages must be addressed. Only if enough information is available per stated argument, a well-considered decision can be made. Using the integral approach is not the objective, but can be a suitable alternative for the currently used strategy. Table 1.1 gives the advantages, disadvantages, opportunities and threats of the platform approach. Afterwards, every statement will be explained in bit more detail.

ADVANTAGES

One of the big advantages can be found during the engineering phase. Instead of having to perform detail engineering for every ship separately, this only has to be done once. More effort is needed for the engineering phase using the family design strategy, because of the increased complexity of different missions and functions it should fulfil [8].

Also the building phase can be done in a faster way. One only has to investigate how the building works once, instead for every ship separately. In the same way, the automotive industry works with series production instead of one of a kind build.

The sailors of the vessels have to be trained for only one type of vessel. Every vessel uses the same equip-

Advantages	**Disadvantages**
Engineering phase	Higher fuel consumption
Building phase	Less mission specific
Less training costs for personnel	
Opportunities	**Threats**
Lower amount of personnel (work pool)	Increase of work
Improved seakeeping	Introduction of new technologies
Further modularity available	Adaptable to reduced emissions
Lower material cost	Limited berth length
Less maintenance cost	
Less stock for spare parts	

Table 1.1: Pros and cons of 'one family' design strategy

ment. So instead of knowing a variation of systems, the focus can be put on only one. This will lower the training and familiarisation costs for personnel.

DISADVANTAGES

Higher fuel consumption can be a big disadvantage. The focus of 'one family' is not designed for one specific design point. Consequently the vessels will be bigger than strictly necessary. Bigger ships (larger dimensions and/or more displacement) have in general a higher fuel consumption. The operating expenditures (OPEX) of the support vessels will thus be higher.

As the requirements in 'one design' are taken to be sufficient for every ship separate, the focus per vessel is less mission specific. More equipment and/or space is available than otherwise provided. The increased size will consequently lead to higher capital expenditures (CAPEX).

OPPORTUNITIES

The amount of personnel (work pool) can be made smaller. All ships are operated in a similar way. This means personnel can be exchanged between the vessels. By doing this the total amount of sailors can be made smaller.

By using 'one family', the average size of the vessels tends to be higher. Longer vessels have improved seakeeping behaviour. This can be seen as an opportunity, because otherwise one has to design specifically for this improved seakeeping capability.

The hull geometries are the same. This makes the implementation of further modularity available, like system integration. To be analysed if modularity has higher advantages than disadvantages.

By knowing exactly in advance what materials are needed, the purchase of this can be done in an early stage. This will prevent delays and will lower the material costs [7].

The maintenance costs can be lower. More information is known about the systems, which makes maintenance easier which can reduce costs. The maintenance can also be monitored in a better way, which makes maintenance more efficient.

The stock for spare parts can be made smaller. The spare parts can be used for all vessels equipped with the same systems.

THREATS

The 'one family' ships are larger than otherwise designed. A consequence can be an increase of maintenance work. The area that needs to be painted is bigger for example.

The ships are produced one after another. During this time, new technologies will be introduced. These cannot be used in the design, otherwise the 'one family' strategy is not followed anymore.

Another threat is that some equipment or material is obsolete after some time. This is called the 'decay' time [9]. This introduces a threat as the possibility exists that the design has to change a bit in order to adjust for the changed equipment or material.

More berth length is necessary when using the ‘one family’ strategy, because of the increased average length of the vessels. This can be a threat as berth length is limited in a harbour.

REDUCE HARMFUL EMISSIONS

New regulations and environmental awareness make it necessary to reduce the emission of greenhouse gasses, such as Carbon oxides (CO_x), as well as harmful gasses such as NO_x, SO_x and PM [10]. Also the RNLN has declared the ambition to reduce its fossil fuel dependency, which means a transition to other energy sources [5]. The actions which have effect on the emissions of harmful emissions while in operation originate from:

1. Handling of the emissions itself
2. Power usage
3. Power generation

Presence of NO_x, SO_x and PM in the atmosphere is associated with human illnesses, degradation of the marine environment and acid rain. By using low-sulphur fuels, one can satisfy all current and proposed SO_x limits. RNLN uses F-76marine diesel oil (MDO) which is already a low-sulphur fuel type, as it contains a maximum of 0.5% sulphur [11][5]. Also PM-reducing techniques are mature and non-intrusive technologies. This means it is appropriate to focus on NO_x emissions as the primary problem. Methods to reduce or eliminate NO_x emissions from diesel engines are either through reducing the temperature of combustion (on-engine techniques) or by treating the exhaust gases in order to remove NO_x (after-treatment techniques) [12].

The power usage can be reduced in order to consume less fuel and consequently emitting less greenhouse and harmful gasses. Methods that are being investigated are amongst others the use of hybrid power plants, reducing the resistance of the vessel or applying life cycle analysis.

The power generation is about the way this energy is produced. The use of alternative fuels is necessary to become less fossil fuel dependant. Alternative fuels can also reduce the emission of greenhouse and harmful gasses. Four alternative power and energy concepts are explored by dr. ir. R. Geertsma [5]. These are polymer electrolyte membrane (PEM) fuel cells on liquid Hydrogen (H_2), PEM fuel cells on methanol, Solid Oxide Fuel Cells (SOFC) on methanol, internal combustion engines (ICE) on methanol and ICE on Ammonia (NH_3). More information about the different kinds of concepts is given in Appendix A.

These power and energy concepts are applied on the Hydrographic Survey vessel. The mass, volume, CAPEX and OPEX are presented in table 1.2. The values of MDO (F-76) are also given and can be used as a baseline.

Option	Mass [t]	Volume [m^3]	CAPEX power & propulsion [million euro]	OPEX power & propulsion [million euro/year]
MDO (F-76)	188	223	3.6	1.09
PEM liquid H_2	640	1300	9	2.6
PEM methanol	383	605	8	2.2
SOFC methanol	383	605	20	1.9
ICE methanol	332	434	3.9	2.5
ICE NH_3	415	613	5	1.6

Table 1.2: Power and energy of different concepts [5]

Table 1.2 gives an overview of the most promising power and energy concepts. MDO is used as a reference. What can be clearly seen in this table is the difference between the needed volumes. This has to do with the contained energy density by volume, which is the highest for MDO and lower for all other fuel types.

More volume is necessary for these alternative power and energy concepts compared to sailing on MDO. For the Hydrographic Survey vessel for example, $434m^3$ methanol is necessary instead of $223m^3$ MDO to attain the same range [5]. For a vessel, this lower contained volumetric energy density reveals itself in the following; More volume means less space onboard for other usage or one has to build a bigger vessel to facilitate this bigger bunker spaces. Also the weight will increase in comparison with the systems and fuel used nowadays, because of the lower contained energy density by mass for the alternative power and energy concepts. The mass will for example be 188 ton (t) when MDO is used and 333 t while using methanol [5]. Another option is reducing the range that could be reached. But this will limit the performance of the vessel, which is not desirable. Another conclusion was that a mature and cost-effective candidate is electrical propulsion in combination with internal combustion engines running on methanol. This power system will increase the capital cost with 10% (from 3.6 to 3.9 million euro) and will double the fuel cost (from 1.09 to 2.5 million euro per year) [5].

The increased capital cost and doubled fuel cost will be quite significant, as it is applicable to all support vessels of the new generation. Therefore, an increased effort should be made to reduce the effects of the energy transition on capital and operational costs. The goal of this focus point can be summarised as **reducing the effects of the energy transition**. One way to reduce the effects is by decreasing the power usage. By reducing the energy usage, the increase of weight, volume, CAPEX and OPEX can be restrained.

These studies clearly indicate that there is a relationship between the two focus points. The aim of the first focus point is to introduce more unity by using a family of hull designs. A disadvantage of using a family of hull designs is the higher fuel consumption. This in contrast with the second focus point. The aim of the second focus point is reducing the effects of the energy transition. This can be done by reducing the power usage of the vessels by looking at the hull geometry. A large variation of hull geometries needs to be analysed to understand the influence of certain design variables on the objectives, like reduced resistance. Also a large set of design options needs to be explored. Large design changes can still be applied in the early stage concept design. Software is needed to perform these variations and to explore a large design space. The software needs to modify the hull geometry and should predict the power usage, which can be done by a parametric optimisation tool. There is currently a gap in the current approach which limits the usage of these functions.

This thesis provides an important opportunity to advance the understanding of incorporating parametric optimisation in the concept exploration phase at DMO.

1.2. CURRENT DESIGN PROCESS AND TECHNICAL OPPORTUNITIES

The current design process and technical opportunities will give the reason behind this project. The current way to approach the focus points at DMO will be explained first. This will give the deficiencies of the current design process. The technological opportunities are provided afterwards.

CURRENT WAY TO APPROACH THE FOCUS POINTS

At DMO the Defence Materiel Process (DMP) is used. DMP is the process to go from specifying the requirements, to signing the contract to build and operation [2]. The DMP is an adjusted version of the Systems Engineering Life Cycle Model (SELCM). DMP can be divided into five steps, also see figure 1.1:

1. Statement of requirement and budget
2. Study-phase
3. Detailed study & development phase
4. Procurement preparation
5. Evaluation

To include more unity and to reduce the power usage from a hull geometry point of view for the support vessels, important design choices have to be made in the early design phase. The concept development takes place during the 'statement of requirements and budget' and in the 'study-phase'. The aim here is at concept exploration and concept definition respectively. The difference is in the number of alternatives considered and their level of detail [2]. In the concept exploration phase a wide range of options is explored to ensure that a balanced set of operationally relevant, technically feasible and affordable requirements is found. The purpose of this is to rapidly explore and evaluate different alternatives with respect to their basic technical and financial feasibility, and their operational effectiveness. This contributes to finding operationally relevant, technically feasible and affordable sets of requirements by highlighting important trade-offs as well as driving factors for performance, effectiveness and cost.

Inputs and performance assessments that are complete and suitable for the level of detail are required during concept exploration. Also sufficiently accurate estimates needs to be provided. These estimations should consider the effort of aspects not yet explicitly modelled at this stage. The output of the concept exploration phase is a variety of different ship concepts, at a certain limited level of detail. The most promising concept designs are selected and used in the next step: the concept definition phase [2].

In the concept definition the focus lies on de-risking by sufficiently detailing the description of the vessel. The exploration is less wide, but the level of detail will increase compared to the concept exploration phase. The purpose of the concept definition is to give more details about the description of the concept, in combination with a detailed assessment of the vessel's performance and cost. This to identify risks to the technical or financial feasibility and the operational effects. This contributes to the confirmation that the vessel will meet the requirements concerning cost, performance and effectiveness. At this stage issues can still be resolved without having a significant impact on the successful execution of the project [2][1].

The current DMP has deficiencies while addressing the focus points. The current design process has limited ability to create and vary hull forms. Also the propulsion power prediction is predicted using regression lines only, which makes it difficult to evaluate novel hull forms. The following is a brief description of the design method used nowadays at DMO to establish a hull design. In the concept exploration phase, the hull form is created by changing the shape and fullness of a pre-defined parent hull. These changes occur to create free space, to provide support for objects and to enclose objects[13]. The resistance is predicted for this adjusted geometry. But this works only one way. The hull form is namely not adjusted in order to get other values for the resistance prediction. Also, at this stage the predictions are based on regression lines only. More accurate predictions and optimisation studies are only performed during the concept definition [2]. The concept definition is a phase where the design freedom is already being limited. To have the most effect of optimisation, and to explore a wide set of design options, the objective acting on propulsion power should be incorporated earlier on in the design process. Also, more accurate predictions can lower the uncertainty during concept exploration.

The previous section has shown that deficiencies are present in the concept exploration phase. The current concept design process has limited ability to create and vary hull forms. Also the propulsion power is only predicted using regression lines. This makes it hard to evaluate novel hull forms. A new approach should be investigated to resolve these deficiencies, which is the goal of this research.

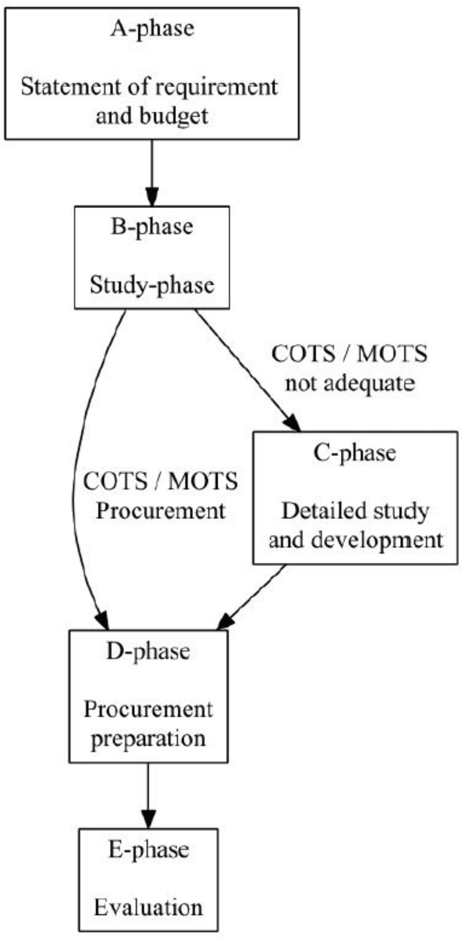

Figure 1.1: Defence Maritime Process [2]

TECHNOLOGICAL OPPORTUNITIES

The problems in the current DMP can possibly be solved by looking at technological opportunities. The technological opportunities that could be used exists of two tools. The Computer-aided engineering (CAE) method which could be investigated is the parametric optimisation tool CAE System Empowering Simulation (CAESES). This parametric optimisation tool can work in combination with the resistance prediction tool named RAPID.

CAESES is a tool developed by FRIENDSHIP-Systems. This software programme contains a CAE method, the possibility to connect with prediction models and has integrated optimisation algorithms. CAESES could be able to perform hull form variations by use of parametric optimisation. CAESES should therefore be capable to create and vary hull geometries to evaluate novel hull geometries. Also the propulsion power can be predicted using a more advanced prediction method.

RAPID is a potential flow solver developed by Maritime Research Institute Netherlands (MARIN). The potential flow solver can be used to predict the wave resistance of a vessel. Wave resistance is only part of the total resistance. The friction related resistance should be predicted by usage of other methods. The usage of the software RAPID should make the resistance predictions more sensitive and accurate. RAPID should also be helpful in the optimisation process. A requirement study has to point out if these tools meet the functionalities that are necessary. The requirements will be given in section 2.3. If not all requirements are met, one can extend the functionalities of the proposed technical opportunities to fulfil all needs.

To summarise, the DMP as used nowadays has deficiencies which can be solved by technological opportunities. Deficiencies in the current DMP makes it difficult to create and vary the hull forms. The propulsion power is only predicted by regression lines, which makes it hard to evaluate novel hulls. The technical opportunity to solve this is by incorporating parametric optimisation (CAESES) and a potential flow solver (RAPID) in the concept exploration phase.

1.3. RESEARCH OBJECTIVES

The research objectives consists of the main objective and the sub questions. By answering the sub questions, more knowledge is available to answer the main objective. The sub questions will be the backbone of this project. As said before, the main objective will be about the focus points for the new generation of naval support vessels. The focus points are increased unity within the fleet and reduced harmful emissions. The process used nowadays is lacking functionalities necessary for addressing these focus points. By using the technical opportunities a new approach can be designed which will be applied on the test case. This gives the main objective:

- **Main objective:** How can the unity and the energy transition be analysed in the concept exploration phase for the new generation naval support vessels with a hull geometry point of view using CAESES/RAPID integration?

To be able to solve the main objective six sub questions are formulated. Each one will give a small piece of the solution and/or will help by solving the next sub question. The first sub question concerns the functions and requirements of the naval support vessels which will be used for the design case. This will give more information about the input that is available and the output that is important. Section 2.1 will provide an answer to the first sub question question. The first sub question can be formulated as:

- **Sub question 1:** What are the requirements and operational profiles of the selected naval support vessels?

By analysing the functions and requirements of the naval support vessels, some conflicting demands may be present. These need to be analysed and will be presented in a design trade-off. The second sub question will be handled in section 2.2. The sub question can be formulated as:

- **Sub question 2:** What are the design trade-offs acting on the naval support vessels related to the hull geometry?

The third sub question concerns the design process used now, the missing functionalities and the requirements the new approach should have. This third sub question is answered in section 2.3. The sub question is formulated as:

- **Sub question 3:** How has the hull geometry been designed in the current design process, what functionalities are missing regarding analysis of the geometry of the hull and what are the requirements for the new approach to design the geometry of the hull?

The fourth sub question concerns the available methods which can be used within this new approach. First the necessary parts are being clarified. If this is done the possible methods per part can be analysed and selected. The selected methods combined will make the new approach. Also the setup is explained. The conclusion of the fourth sub question can be found in section 3.6. The fourth sub question can be formulated as:

- **Sub question 4:** What are the different components that are needed for the new approach and how will the setup be performed?

The model is ready to be used at this stage. A validation study is necessary to give proof of the reliability of the new approach. Only if the model is validated the output can be used with trust. This sub question will be answered in section 4.6. The fifth sub question will be:

- **Sub question 5:** How to validate the model?

The validated tool will be used on selected naval support vessels. This way more information can be obtained about the integration of the new approach within the concept exploration phase. The input for the model is given and the output will be analysed. This will give information about feasible designs which can be used in addressing the focus points. Trade-offs for the design strategy which should be followed and the consequences of certain choices are now ready to be investigated. The answer on the sixth sub question is given in section 5.4. The last sub question is formulated as:

- **Sub question 6:** Is the new approach capable to address the focus points which are present for the new generation of the naval support vessels with a hull geometry point of view?

If all sub questions have been answered, one is able to provide an answer to the main objective.

1.4. STRUCTURE OF THESIS

The sub questions will be answered in chronological order. The functions and requirements of the naval support vessels are analysed. This information will be used to set up the design-trade offs acting on these vessels. The design-trade offs are the input for the current process, the missing functionalities and the requirements of the new approach, see chapter 2. The separate parts of the new approach are modelled in more detail in chapter 3, the description of the new approach. The new approach is validated in chapter 4. If successful, the new approach can be used on the test case. See chapter 5 for the results of this application. At last, a conclusion and discussion is given in chapter 6.

2

Problem definition

The problem definition will elaborate the problem to solve. First the functions & requirements of the naval support vessels used in the design case will be explained, see section 2.1. The functions & requirements will give important design trade-offs, which will form the basis for the design evaluation. The design trade-offs which will be used in this project are explained in section 2.2. The subjects explained in the design trade-off are used in an analysis of the current design process. Here the current design process and the missing functionalities are given. This information will be used to set up the requirements of the new approach. Also the workflow of the new approach will be given, see section 2.3.

2.1. Functions & requirements of naval support vessels

The functions and requirements of the naval support vessels which will be used for the design case will be explained in this section. The operational profiles of the naval support vessels are also included. The conclusion of requirements and operational profile will provide an answer to the first sub question: 'What are the requirements and operational profiles of the selected naval support vessels?'

Selection of support vessels

Four types of support vessels from the small surface units are selected to be used in the design case. The vessels used are the Hydrographic Survey (HOV), Logistic Support (LS), Submarine Support (SS) and Marine Training (MT) vessels. Two vessels are needed for Hydrographic Survey, for all others only one vessel is desired. These five vessels have several operational design points in common which makes them ideal to include them in the design case.

The first point is the year when a renewed vessels should be in operation. All vessels should be renewed within six to fourteen years. This means almost every year a new vessel will be in operation [5].

All vessels have comparable dimensions. The range for length, beam and draft is almost the same for the Hydrographic Survey, Submarine and the Marine Training vessels. Only the Logistic Support deviates from this as its length and draft are limited. The minimum displacement is comparable for all vessels, as it is between 1000 and 2000 t [5].

The operational area of the vessels is comparable. They all work, most of their time, on the North Sea. Only the Logistic Support is operational in the Caribbean area. The Submarine Support vessel is active everywhere the submarines go.

There are also some differences between the vessels. The maximum speed and speed of transit are slightly different for all vessels. The maximum speed is between 12 and 15 knots (kn), and the speed of transit is between 10 and 14 kn. Also the tasks and mission payloads are different for the navy support vessels.

EXISTING NAVAL SUPPORT

The existing and future vessels will be analysed. The properties of the Hydrographic Survey, Logistic Support, Submarine Support and Marine Training vessels will be analysed and will be summarised in table 2.1 on page 13. The results of this study will be used in the analysis of the requirements for the future vessels. This will be done for the vessels if the single ship design or family ship design strategy is applied.

ZR. MS. SNELLIUS & ZR. MS. LUYMES

The Snellius and Luymes are the hydrographic survey vessels, see figure 2.1. Missions are related to bathymetric survey, localising of wrecks and obstructions, analysing of environmental changes such as tide and sediment and synoptic meteorological and oceanographic observations [14]. Furthermore it can be used as staff ship with a coordinating role in a national or international fleet. Because of its function of Research Vessel of Opportunity there has to be place for four containers. The crew consists of 21 persons with the capacity to carry 21 extra persons. This gives a total of 42 persons to accommodate. The vessels were built in 2003 and 2004. The expected period for replacement will be around 2033.

Its working area is mainly the North-Sea and Caribbean area. The vessel has a length of 81.4meter (m) and has a maximum speed of 12 kn during transit and 8 kn during survey [14]. The length on waterline (LWL) is 75.0m. For survey a Multibeam Echo Sounder, two Single-beam Echo Sounder Systems, a Motion Sensor and a Moving Vessel Sound velocity Profiler are installed. The beam over all (BOA) is 13.1m. The operational profile will consist of 240 working days on sea [15]. The other days are available for maintenance.

Figure 2.1: Zr. Ms. Luymes, A803 [16]

ZR. MS. PELIKAAN

The Pelikaan is used as support vessel for operations and training of the Marine Corps and the Coastguard of the Netherlands Antilles and Aruba, see figure 2.2. For disaster relief missions it is capable of making fresh water and has a fresh water capacity of 70t [17]. Help can furthermore be given in form of transport of goods and people. Sensors onboard are used for mapping the coast. The dimensions were restricted when built in 2006. This because of the limited space in the harbour of the island of Saba. The restrictions were a maximum LWL of 65m and a maximum draft (T) of 3.5m. The crew consists of 14 persons, with place for 12 semi-permanent persons and 45 temporary persons. This brings the total accommodation space to 74 persons. The replacement will take place around 2030.

Its working area is mainly the Caribbean area. The vessel has a length of 65.4m and has a maximum speed of 14.5 kn. The vessel should be able to operate at least 240 days of a year of which at least 210 days at sea [17][18].

Figure 2.2: Zr. Ms. Pelikaan, A804 [17]

ZR. MS. MERCUUR

The Mercuur is the support vessel of the submarines, see figure 2.3. It can supply the submarines with everything needed during a mission. Also the handling of test torpedoes is one of its functions [19]. The test torpedo is shot by the submarine, and the submarine support vessel takes this torpedo out of the water and prepares it for the next use. The ship is able to do this by having a torpedo hoist installation and a complete torpedo workstation onboard. The vessel can also give support in case of emergency situations with the submarines. There is equipment for evacuations, a dive team and a dive medical team onboard. The vessel is built in 1987. Replacement will take place around 2026.

Its working area is the same as the submarines, which is mainly the North-Sea and Caribbean area. The crew consists of 30 persons, 10 persons for the torpedo workstation and space to accommodate 8 extra persons. So there is place to accommodate 48 persons in total. The vessel has a length of the 64.8m and has a maximum speed of 14 kn [19].

Figure 2.3: Zr. Ms. Mercuur, A900 [19]

MOV VAN KINSBERGEN

The Van Kinsbergen is a training vessel for future naval officers, see figure 2.4. Practical nautical training of the Netherlands Defence Academic (NLDA) and the Operational School (OPSCHOOL) is being done on this vessel. To perform this function space is reserved for educational purposes and a very extensive secondary training bridge is present [20]. The vessel is built in 1999. Replacement will take place around 2025.

Its working area is mainly the North-Sea. The vessel has a length of 41.5m and has a maximum speed of 13 kn. The vessel should be able to operate at least 85% of the time a year [21]. The rest of the days is reserved for maintenance. The crew consists of 5 persons with the capability of accommodate 16 more students. So there is place to accommodate 21 persons in total [20].

Figure 2.4: MOV Van Kinsbergen, A902 [20]

Type	**Hydrographic Survey**	**Logistic Support**	**Submarine Support**	**Marine Training**
(Class) Name	Snellius, Luymes	Pelikaan	Mercuur	Van Kinsbergen
# in service	2	1	1	1
Δ_{max} [t]	1875	1150	1400	630
length over all (LOA) [m]	81.4 (75.0 LWL)	65.4	64.8	41.5
BOA [m]	13.1	13.2	12	9.2
T [m]	4.0	3.0	4.3	3.3
Speed max [kn]	12 (8 during survey)	14.5	14	13
Crew	21	14	30	5
Passengers (tot.)	42	71	48	21
Build year	2003 / 2004	2006	1987	1999
Engine power	1150kW	2*1492kW [22]	2*578kW	2*578kW

Table 2.1: Overview of specifications of current small surface units

NEW GENERATION NAVAL SUPPORT VESSELS

The functions of the Hydrographic Survey, Logistic Support, Submarine Support and Marine Training vessels are explained. Per ship type will be given what improvements are needed or which requirements are present for the new generation of support vessels. The conclusions of this review are presented in table 2.2. Also, the requirements of the family ship design strategy are given in this table. Two types for the family design are used. The 'restricted' and the 'open' design. The 'restricted' design will satisfy all given constraints from all selected naval support vessels used. To investigate what consequences this approach has, an alternative family design will be examined. This alternative design will be named the 'open' design. The word 'open' is used because the design variables are used in a more unrestricted way. The comparison between the 'restricted' and the 'open' design can introduce discussions about the given requirements. One can for example decide to leave one type of vessel out of the family design, or try to expand the feasible range of certain design variables.

Because of confidentiality, all given values are estimations but are comparable with the parameters used at DMO. The requirements have been consulted with Ir. Ruben Zandstra (April 2019) in order to make sure the used requirements will give a close approximation of the real vessels.

HYDROGRAPHIC SURVEY

The length of current vessel was chosen in order to have good seakeeping capabilities. The new generation must have at least the same seakeeping behaviour or better than the vessels used nowadays. The seakeeping capability is important to have enough possible operational days per year. Hydrographic survey can't be done with too much heave and/or pitch (W. van der Haar, personal communication, April 15, 2019). Bathymetric survey is performed by use of Multibeam and Single-beam Echo Sounders. The quality of the survey depends on the stability and the reliability of the measurement systems.

Furthermore the maximum draft is limited to the harbour of Den Helder at 8.0m [23]. The length over all will be between 50m and 100m. This will give a beam between 10m and 15m. A too slender hull shape will give problems to accommodate the propulsion system and will give stability issues [24]. The displacement must be higher than 1200 t to make sure all equipment can be placed onboard. The vessel is seakeeping driven. Meaning that high operability is the main driver behind the hull design. The transit speed has to be 11 kn, but during survey the speed is reduced to 8 kn.

LOGISTIC SUPPORT

The logistic support has to operate in the Caribbean Sea. The vessel is volume driven. The minimum amount of displacement has to be 1200 t. The minimal length is 50m and the maximum is 65m. This gives a beam between 10m and 15m. The maximum draft is 3.5m. These restrictions makes it still possible for the logistic support to reach all the important harbours. The most critical harbour is on the island of Saba. If the harbour of Saba is left out, the restriction on the maximum draft becomes 4.0m without a restriction on the length. The transit speed is 14 kn.

SUBMARINE SUPPORT

The submarine support vessel is volume and length driven. For the torpedo handling and torpedo workstation a large deck space is necessary, which gives a minimal length of $55m$ and a maximum length of $100m$. The vessel should have high operability in order to also function in bad weather conditions. This with a displacement of at least 1250 t in order to have space for all equipment. The beam will be between $10m$ and $15m$. The draft is limited at $8.0m$. The transit speed is 14.0 kn.

MARINE TRAINING

The current vessel has problems with its capacity and high risk on sea sickness [25]. So better seakeeping and more capacity is necessary in the future design. Better seakeeping capabilities will limit the risk of sea sickness. The length must be at least $50m$ and has a maximum of $100m$. The draft is limited at $8.0m$. The beam will be between $10m$ and $15m$. The displacement has to be larger than 1000 t. The speed of transit is 10kn and the maximum speed will be 12kn.

'RESTRICTED' FAMILY DESIGN

For the 'restricted' family design the given restrictions of the separate vessels are combined. The minimal or maximum requirements are taken to get a vessel which is capable to perform every mission. Counteracting restrictions will limit the design freedom. The 'restricted' family design will have a minimal length of $50m$ and a maximum length of $65m$. This with a maximum draft of $3.5m$. The beam will be between $10m$ and $15m$. The design focus is on the seakeeping capabilities in order to have high operability for the Hydrographic Survey vessels and lower sea sickness for the Marine Training vessel. While at the same time have low resistance in order to reduce the power usage. The minimal displacement is 1250 t. The speed of transit is 14kn with a maximum speed of 15 kn.

'OPEN' FAMILY DESIGN

The 'open' family design will use the input of the separate vessels, but will try to combine them in a more open design. This way not all requirements of the ship specific designs will be met, but this will make clear what the impact is of the given restrictions. This will give a length between $50m$ and $100m$, a beam between $10m$ and $15m$ and a maximum draft of $8m$. This with a displacement of minimal 1200 t and a maximum speed of 15kn. The speed of transit is 14kn. Also the seakeeping capabilities will be analysed in order for high operability for the Hydrographic Survey vessels and lower sea sickness for the Marine Training vessel.

Type	**Hydrographic Survey**	**Logistic Support**	**Submarine Support**	**Marine Training**	**Family design Restricted**	**Family design Open**
Δ_{min} [t]	≥ 1200	≥ 1200	≥ 1250	≥ 1000	≥ 1250	≥ 1200
LOA [m]	50 – 100	50 – 65	55 – 100	50 – 100	55 – 65	50 – 100
BOA [m]	10 – 15	10 – 15	10 – 15	10 – 15	10 – 15	10 – 15
T [m]	2.0 – 8.0	2.0 – 3.5	2.0 – 8.0	2.0 – 8.0	2.0 – 3.5	2.0 – 8.0
Transit speed [kn]	11 (8 at survey)	14	14	10	14	14
Operational year	2033	2030	2026	2025	2025-2033	2025-2033

Table 2.2: Overview of specifications of new build small surface units

OPERATIONAL PROFILE

The operational profile consists of the speed and the corresponding time this speed is maintained per year. Also the total operational days are given. This will give a total amount of time the ship will be in service, and the amount of time per speed during the days at sea. The data is based on information of the current vessels, and is assumed to give a good definition of the operational profile of the new generation naval support vessels.

- Hydrographic Survey vessel: 240 working days and the other days (125) are available for maintenance. The operational level needs to be higher than 85% [15].
- Logistic Support vessel: 168 working days and the other days (197) are available for maintenance. The operational level needs to be higher than 85% [18].

- Submarine Support vessel: 140 working days and the other days (225) are available for maintenance. The operational level needs to be higher than 85% [26].
- Marine Training vessel: 180 working days and the other days (185) are available for maintenance. The operational level needs to be higher than 85% [21].

The operational profile is used to calculate the hours (h) every vessel is sailing on a specific speeds. The sixth column, 'Total per speed', gives the values for the family design vessel. The assumption has been made that the operational profile of every vessel is independent of the design strategy chosen (single or family design). There will be two Hydrographic Survey vessels. This is taken into account in table 2.3 by using the total hours of the two vessels combined. Also the percentage of a certain speed on the total in calculated. The last column gives the cumulative order.

Speed (Kn)	**HOV(h)**	**LS(h)**	**SS(h)**	**MT(h)**	**Total per speed(h)**	**% of total**	**Cumulative**
1	0	0	0	0	0	0.0%	0.0%
2	0	0	0	0	0	0.0%	0.0%
3	1728	0	0	0	1728	7.4%	7.4%
4	0	0	0	1296	1296	5.6%	13.0%
5	0	0	336	0	336	1.5%	14.5%
6	0	0	0	0	0	0.0%	14.5%
7	0	403	0	0	403	1.7%	16.2%
8	6336	0	0	1944	8280	35.6%	51.8%
9	0	0	0	0	0	0.0%	51.8%
10	0	0	1344	864	2208	9.5%	61.3%
11	2880	0	0	0	2880	12.4%	73.7%
12	576	0	1512	216	2304	9.9%	83.6%
13	0	0	0	0	0	0.0%	83.6%
14	0	3427	168	0	3595	15.5%	99.1%
15	0	202	0	0	202	0.9%	100%
Total per ship(h)	11520	4032	3360	4320	23232	100%	100%

Table 2.3: Overview of operational profile of naval support vessels per year

CONCLUSION OF REQUIREMENTS AND OPERATIONAL PROFILE

The functions and requirements are given of the naval support vessels. The conclusion shall give an answer to the first sub question: 'What are the requirements and operational profile of the naval support vessels used for the design case?'.

The vessels are selected because of the urgency to be renewed within six to fourteen years, the comparable dimensions and the working area. The requirements for the new generation naval support vessels are combined in table 2.2. The operational profile is different for every vessel. The maximum speed is different, but also the time spent on the lower speeds. The hydrographic survey vessels have a transit speed of 11 kn, but a speed of 8 kn during survey for example. The operational profile of all vessels is given in table 2.3.

2.2. DESIGN TRADE-OFFS

Although the vessels have lots in common, some conflicting demands are to be reviewed. Conflicting demands means that some functions give contradictory results, like increased functionalities with reduced costs. The design trade-offs are explained first. Afterwards a conclusion is given which provides an answer to the second sub question:'What are the design trade-offs acting on the naval support vessels related to the hull geometry?'

TRADE-OFFS

The first trade-off concerns the power usage. The power usage can be influenced by the hull geometry by looking at the propeller power. The propeller power is predicted by use of the effective towing power (Pe), the hull efficiency, the open water efficiency and the relative rotative efficiency [27]. A more comprehensive study would include all the groups of efficiencies, but for now only the effective towing power will be used. The effective towing power should be low for every vessel of course, but some vessels have higher influence on the total power consumption than other vessels. When looking at the operational profile, the Logistic Support vessel is sailing at high speed for a long time. While the Marine Training vessel is sailing most of its time at reduced speeds. The Hydrographic Survey vessel has a lot of operational hours, but at moderate speeds. The same goes for the Submarine Support vessel which has most of its operational hours at moderate speed. This gives difficulties for the family design vessel. This vessel will not have one speed of transit. But will rather be used on a lot of different speeds.

The importance of the operational effectiveness in seaway are also different per vessel. The Hydrographic Survey vessels are specially designed for high operability. The equipment used during survey cannot be used with too much heave or pitch. Reduced vertical displacement is preferred. This low relative vertical displacement is also needed for the Submarine Support vessel. It can be operational for a longer amount of time if the displacements are not too severe onboard. Especially when operations are performed on the revised torpedoes, large displacements are unwanted to reduce accidents onboard. The seakeeping capabilities are also of high importance for the Marine Training vessel. The persons onboard can become seasick because of high vertical accelerations, which is a big problem of the Marine Training vessel used nowadays [25]. Experiments pointed out that vertical accelerations in particular are responsible for motion sickness, while rolling and pitching have slight influence [28]. Low accelerations are wanted for a more pleasant journey. The Logistic Support vessel is less affected by its seakeeping behaviour, as it is sailing behind the storm. But still, it should be able to operate when there is need for it. All in all, the seakeeping capabilities will be of high importance for the family design vessel. The family design vessel should have low relative vertical displacement as well as low vertical accelerations.

CONCLUSION OF DESIGN TRADE-OFFS

The conclusion of the design trade-offs shall give an answer to the second sub question: 'What are the design trade-offs acting on the naval support vessels related to the hull geometry?'

Although the vessels are selected because of similar requirements, some conflicting design trade-offs may be present. The first trade-off has to do with the power usage. For the Logistic Support vessel lower effective towing power is of high importance. While for the Marine Training vessel, because of its reduced speeds, effective towing power is less of an issue. The remaining vessels are more equally balanced. The seakeeping capabilities are of high importance for the Hydrographic Survey vessels, the Submarine Support vessel and the Marine Training vessel. For the Hydrographic Survey vessels the vertical displacement is the main motion to look at. For the Marine Training vessel the focus is at lower vertical accelerations. For the Submarine Support vessel, vertical accelerations and vertical displacement are equally important. Seakeeping capabilities are of less importance for the remaining vessels. These design trade-off should be included in the selecting procedure later on.

2.3. DESIGN PROCESS

By use of the functions and requirements of the vessels, important design trade-offs are mentioned. The project will be limited to only look at the hull design & geometry. The current approach to include hull design & geometry in the process is explained. Afterwards the missing functionalities are given which occur during the current approach. These will be the basis to describe the requirements of the new approach. Afterwards the global workflow of the new approach is given. In the end a conclusion is given which gives answer on the third sub question:'How has the hull geometry been designed in the current design process, what functionalities are missing regarding analysis of the geometry of the hull and what are the requirements for the new approach to design the geometry of the hull?'

CURRENT APPROACH

The bureau of Life Cycle Modelling (LCM) of the Maritime Systems Division is involved with the first two steps of the total DMP, see section 1.2. These steps are the 'Statement of requirement and budget' and the 'Study-phase'. These steps have different objectives which are supported during concept exploration and concept definition respectively [2].

The focus of the concept exploration phase is placed on rapidly exploring and evaluating a large set of alternative concept designs. The result is a wide range of low detailed feasible designs. This way major trade-offs are identified and explored. This in contrast with the concept definition step, where the focus is on the requirements analysis, synthesis and verification phases in order to decrease risks. The concept definition gives more details about the concept designs, which are needed for detailed assessment of the vessel's performance and cost [1].

The input of the concept exploration phase consists of rough data such as a description of spaces and main systems in the ship. These are based on the operations it should perform. The operations are translated into tasks and functions to the level of interest and the level of detail necessary for the modelling tool [1]. Resistance and powering estimations are based on regressions lines of a set of model tests. This will give quick predictions, but the uncertainty can be quite high.

Also, only rough data is available which is insufficiently detailed to be used by certain higher fidelity tools. The end results should be a cost-effectiveness trade-offs for a range of technically feasible alternatives. At DMO an approach is used based on the design building block methodology. In this methodology systems are represented by building blocks. These blocks are placed into a positioning space by a packing-algorithm [29]. This so called PACKING approach is used within the concept exploration phase. Also hull shape modifications are integrated in this approach.

Variations used are on performance levels for range and speed. The synthesis model is in search for ship concepts that are large enough to accommodate all systems and meet speed and range requirements. The feasibility of these requirements are modelled as constraints. The variations of models, and the inclusion of constraints, is managed by the Non-Dominated Sorting Genetic Algorithm II (NSGA II) optimisation algorithm. This algorithm will typically search for minimum capital and operational costs, while still meeting all limitations depicted from the necessary systems and operability requirements. Minimum capital and operational costs are correlated to length, displacement and fuel consumption. Also, an effectiveness assessment is performed. This will consider the choices in ship design, operational areas, and operability in waves, which affect the number of days the vessel can be used per year.

The concept definition phase continues where the concept exploration phase ends. Some overlap is present though. The focus has shifted towards more detailing and accuracy rather than exploration. To accomplish this, more complex prediction tools are used. First the vessel is described using numerical block definitions. QUAESTOR is the program used to handle these blocks. These blocks in QUAESTOR are combined with the geometrical representation in the Computer-aided design (CAD) program Rhinoceros. This can be used as input for other tools for resistance prediction, weight estimation and motion calculations. MARIN's SHIPMO seakeeping code is used to predict the motions onboard. SHIPMO is based on strip theory and cannot be used in an earlier phase, as a highly detailed geometrical model is needed to work and calculations take a lot of time. The predictions on motion are therefore not considered during the concept exploration phase. The same resistance prediction tools are used as in the concept exploration phase, but can be modified by combining the resistance prediction method with a more detailed propulsion model. A more detailed and accurate design model is available at this stage which will improve the accuracy.

MISSING FUNCTIONALITIES

Some important design trade-offs are presented in the functions and requirements of the selected naval support vessels. These have to do with the focus points introduced for this project. The design trade-offs have to do with power usage and seakeeping capabilities. This project will only look at the influence of hull geometry on these design trade-offs, as described in the section 2.2. The current design process has limited ability to create and vary hull forms. In the exploration phase, where the main dimensions are being defined, only the feasibility on the given constraints is being used. This will create a design which is feasible, but isn't necessary optimal. Also the propulsion power is predicted by regression lines only. This makes it difficult to evaluate novel hull forms. A study on reduced resistance is incorporated during the concept definition phase, but the main dimensions are already set. Large improvements are not to be expected because of this limited design freedom. A functionality is needed to not only incorporate feasible designs, but which is also capable to create and vary the hull geometry itself for given objectives.

The second trade-off is the seakeeping or operability of the vessel. Operability, or the amount of possible operational days per year on sea, can be influenced by the hull geometry. Main dimensions are again defined in the exploration phase. But motion calculations are only used in the concept definition phase. This is acceptable if the range of the design variables is limited, and the created designs are in essence meeting these operability requirements. But for the support vessels used in this design case, the operability is one key element which should be included in the exploration phase. The current approach is lacking functionalities to address the design trade-offs that belongs to this. A motion objective should be included early on, by inclusion of the seakeeping capabilities in the concept exploration phase already.

REQUIREMENTS OF THE NEW APPROACH

The missing functionalities can be transformed to a set of requirements, which the new approach should meet. The following aspects should always be present in the concept exploration phase:

- It should only use information typically available in the concept exploration phase. More detailed information will become available in a later stage in the design, based on information created by the concept exploration phase.
- It should be fast as only limited amount of time is available. The level of accuracy should be sufficient for comparison purposes, but as a certain level of uncertainty is present, there is no need to predict in too many digits. The running time should preferably be lower than six hours. This makes it possible to perform one study overnight, or during one work shift.
- The concept exploration phase will be highly successful if many variations are performed. Many variations, with lots of feasible designs, will mean that a wide range of the design space is accessed, which will increase the chance the optimum choices are depicted.

Requirements originating from the design trade-offs are:

- It should include a motion objective focusing on vertical displacement and vertical acceleration
- It should include a power usage objective
- The optimisation method should handle multiple objectives
- It should be a reusable approach, to be used for different kind of support vessels
- It should use a basic set of parameters as input for motion and resistance predictions
- It should reduce human interaction, so preferably an automated process

WORKFLOW OF THE NEW APPROACH

This list of requirements for the renewed process can be sorted in three main groups. The first group has to do with handling the input and the creation of (feasible) geometries. The second group is the post processing on the created designs. These are the objectives which should be met, and the way how to give a value for these objectives. In this design case, two objectives are being of interest. The two objectives used are: effective towing power and motion. The last group is the optimisation method. The optimisation method will analyse the results, and will give directions for the change in input which are used by the first group. This loop can be repeated until a predefined stop criteria is met. This criterion can for example be the number of iterations, total running time or if no further improvements on the objectives are attained [13].

The creation of feasible geometries, which can automatically be changed, is being accomplished by CAESES. This parametric tool will create a geometry which can be numerically changed by only a few design variables. The initial design, the selection of the design variables and the way these design variables changes the geometry are all to be solved by the naval architect [13].

The selecting of the effective towing power prediction method depends on how the method fits into the concept exploration phase. The selection will be based on the trade-off between accuracy and computational speed [30]. The computational speed is the time that is available per evaluation. But nonetheless also a minimal level of accuracy should be obtained. High accuracy will require a high fidelity method which also increases the calculation time. For the new approach, lower fidelity tools should be used. This because lower computational time is needed to analyse many variations. So different methods should and could be used for different phases in the design process.

The motion prediction method is also based on a trade-off between accuracy and computational speed. Higher fidelity tools will give higher accurate predictions, but require detailed input and more computational power. Lower fidelity tools are faster, but introduce more uncertainty. So the level of detail available in the concept exploration phase is leading in choosing a suitable method. If multiple methods are suitable, the trade-off between accuracy and computational time is relevant.

The third group is the optimisation method. The parametric CAD programme will create feasible geometries, and prediction methods are used to give values for the objective functions. The optimisation method should converge to an optimum in a short amount of time. This gives the possibility to perform more iterations in the same amount of time, increase the accuracy of the predictions or to expand the design space.

The new approach will have a global workflow which can be seen in figure 2.5. Here the three groups can be seen. On top the parametric modelling, in the middle the objective functions and the optimisation at the bottom. The new approach requires input to work, which consists of the range and description of the design variables. These design variables will make it possible for the parametric modelling to adjust the geometry of the reference design. The option consists to add constraints which should be treated by the approach. These constraints can be a minimal displacement and/or stability criteria.

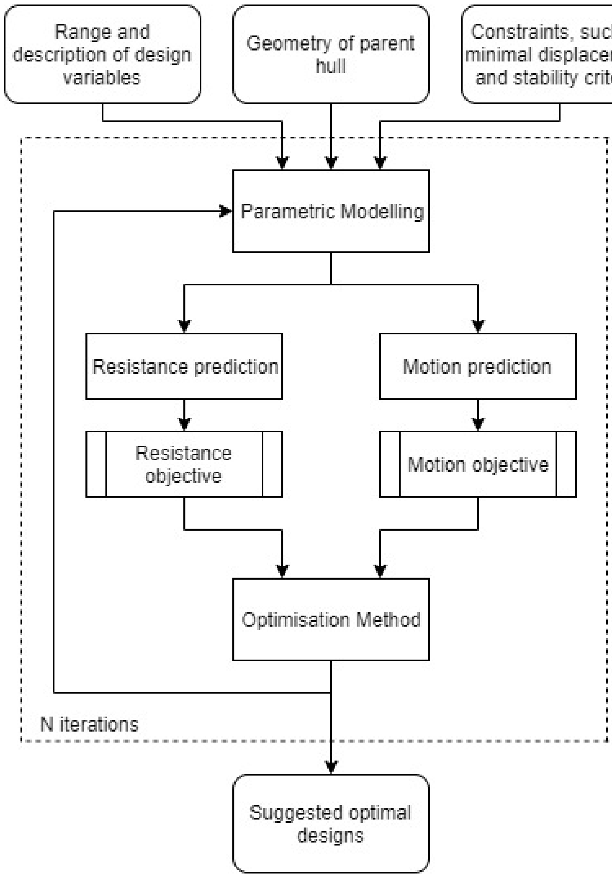

Figure 2.5: Global flow diagram

CONCLUSION ON REQUIREMENTS OF NEW APPROACH

The conclusion of the design process shall give an answer to the third sub question: 'How has the hull geometry been designed in the current design process, what functionalities are missing regarding analysis of the geometry of the hull and what are the requirements for the new approach to design the geometry of the hull?'

The hull geometry is designed by using several tools such as PACKING, QUAESTOR and Rhinoceros. All of these tools have their own specific function within the concept exploration or concept definition phase. However, some functionalities are missing regarding the analysis of the geometry of the hull. The current design process has limited ability to create and vary hull forms. The resistance is only predicted after a feasible hull model is generated, rather than used within an optimisation. This will create a hull form which is feasible, but not necessarily optimal.

Another function that is missing is the incorporation of motion predictions during the concept exploration phase. These are only calculated in the concept definition phase, where the design freedom is already limited. The missing functionalities are used to set up the requirements of the new approach. The requirements are divided in aspects which should always be present during the concept exploration phase, and aspects originating from the design trade-offs.

3

DESCRIPTION OF THE NEW APPROACH

The new approach consists of three groups. The first group is the parametric design tool, which is explained in section 3.1. The second group consists of the objectives. The effective towing power (Pe) modelling is given in section 3.2. The potential flow code, RAPID, is part of the modelling of Pe. The connection of this software and other related settings are given in section 3.3. In section 3.4 the motion modelling is explained. The third group, the optimisation method modelling, is explained in section 3.5. In the last section, 3.6, a conclusion is given to answer the fourth sub question:'What are the different components that are needed for the new approach and how will the setup be performed?'

3.1. PARAMETRIC MODELLING

The software named CAESES is used for the parametric modelling. First information is given concerning this program. It will continue with a description of the geometry modelling. The parent hull, used for the validation and the test case, is the result of this geometry modelling. The design variables are all parameters that can be adjusted during the optimisation. To make sure only feasible solutions are generated, some constraints are necessary, which are explained in the last part of this section.

CAESES

A major concern during the optimisation procedure is to generate feasible hull designs. Every unique set of design variables gives another geometry. But not every set gives a feasible solution. Therefore, constraints are used to make sure the geometry is a feasible one. The range of the design variables and the value of the constraints can change per vessel to match the desired requirements. The generation of feasible design within this design space should be accomplished in an automated way. This could be accomplished by using a parametric model. A parametric model is a collection of parameters, all in finite-dimensional parameter spaces [31]. The parametric tool named CAESES, developed by FRIENDSHIP-Systems, is used for this purpose.

The CAESES-FRIENDSHIP-Framework is a software programme which contains a CAD interface, a possibility to link with prediction models and has integrated optimisation algorithms. This makes it a multi-usable package with easy integration of one kind of calculation which can be used for the next one. This method consists of three steps [32]:

- Design of set of basic curves such as deck, waterline, sides, bottom, centre plane etc.
- Modelling of design sections derived from the basic curves.
- Generation of a set of surfaces that interpolate the design sections.

The hull form is represented by a set of basic curves within CAESES. The geometry is made by providing topological information (water-line, centre-line, deck-line) and a set of section curves [31]. All of these curves are either fairness spline (F-splines) or basis spline (B-spline). The surface of the hull is generated by interpolating the section curves. These section curves can be parametrically modelled. This parametric way of creating geometries is more suitable for automatic generation than other CAD programs, because of its integrated workflow. With only a limited amount of design variables with their upper and lower values, a large variety of hull geometries can be generated [33].

GEOMETRY MODELLING

To work with CAESES several settings needs to be adjusted in order to work in the desired way. First a parent model should be made, which can be modified using parameters. So the aim is to create a hull form, which can be changed with only a limited amount of parameters. But still gives a faired, and feasible hull design. This will be explained in geometry modelling. The geometry will be used as input for the prediction models. The parent hull is made using the Fast Monohull manual from CAESES [34], and is based on the current Hydrographic Survey vessels. A more detailed explanation of all used settings can be seen in Appendix B.

To begin with, a Centre Plane Curve (CPC) is made. The CPC will give the contour of the hull form at the centre plane. One can see the stem, middle part and the stern. The created CPC can be seen in figure 3.1.

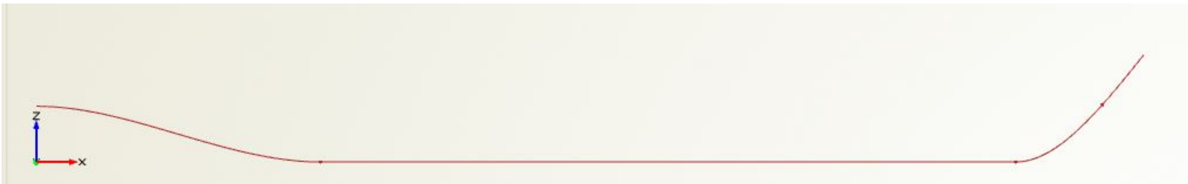

Figure 3.1: 'CPC' of geometry

The second curve consists of the Flat of Side (FOS). This will give the flat side at maximum beam. This curve is important for influencing the block coefficient (Cb) and longitudinal centre of buoyancy (LCB). The line of the FOS can be seen in figure 3.2.

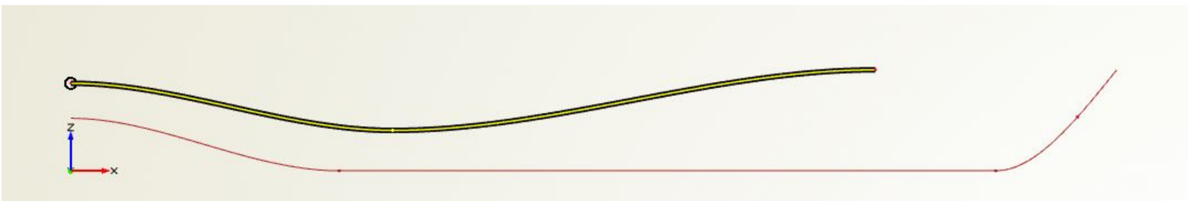

Figure 3.2: 'FOS' of geometry

The third curve is the deck curve. It will intersect with the FOS, and will influence the shape of the stem. This gives a deck curve as can be seen in figure 3.3.

Figure 3.3: Deck curve of geometry

The fourth curve is the Flat of Bottom (FOB). The FOB is the flat part of the bottom section. The FOB curve can be seen in figure 3.4.

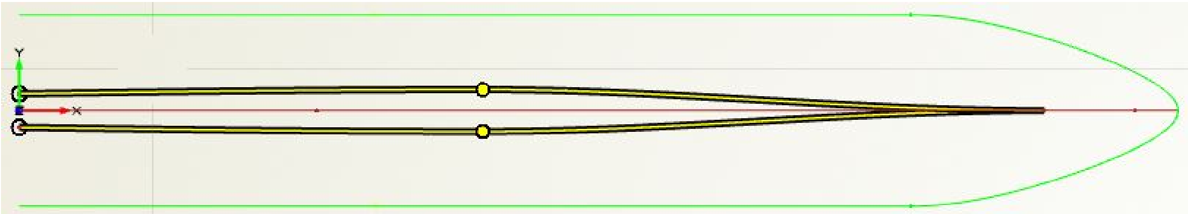

Figure 3.4: FOB curve of geometry

The fifth and last curve is the waterline (WL). It will intersect at the stem defined in CPC and the FOS, at a certain level of T. The WL can be seen in figure 3.5.

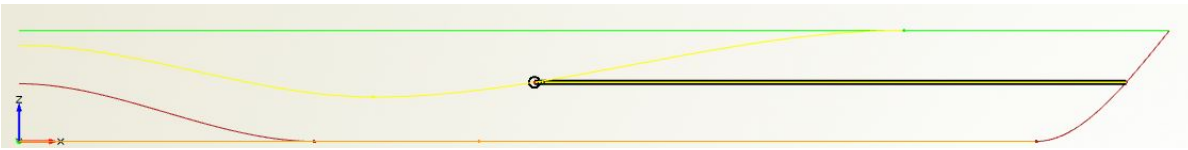

Figure 3.5: Water line of geometry

The created curves are used to create the surface of the hull. With use of curve engines, a meta surface is created. A meta surface is a way to design a surface using complex curve descriptions. The surfaces created are nonuniform rational B-splines (NURBS) surfaces. The settings of the curve engines and the usage of the meta surfaces are given in the CAESES manual [34]. A side view of the geometry obtained is given in figure 3.6. A lines plan is also available of this parent hull, see Appendix E.

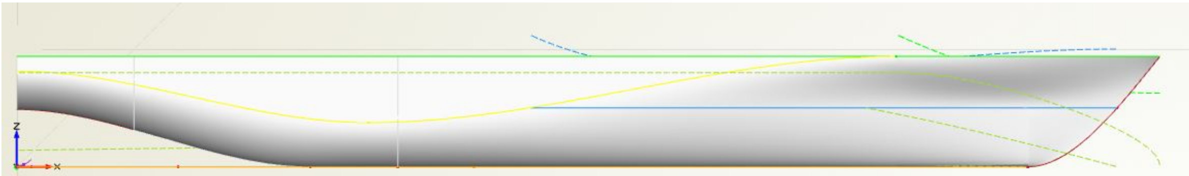

Figure 3.6: Side view of the geometry

The LWL can also be calculated. The LOA and LWL are different because of the the stem which is inclined. The LWL is calculated by introducing a point where the stem and waterline are intersecting. The length from the stern towards this point over the x-axis is the LWL.

DESIGN VARIABLES

The design variables have to be chosen in such a way that there is enough design freedom, but that a reasonable amount of the hull geometries are feasible solutions. The amount of design variables will influence the calculation time. But more variables will increase the amount of geometries that can be generated, and so increasing the potential success of the concept exploration phase. The design variables which are active are presented in table 3.1.

Design variable	**Unit**
Draft	[m]
LOA	[m]
Beam	[m]
Entrance Angle at WL	[degree]
Stem distance	[m]
X-frame indication	[-]
Z-frame indication	[-]

Table 3.1: Overview of design variables used to create the geometry

A short description will be given of the influence of the design variables:

Draft: Increasing the draft will increase the viscous resistance, because of an increased wetted area. The wave making resistance is hardly effected by the draft of the vessel. A higher draft will give better initial stability to the vessel. Increasing the draft is an easy way to increase the displacement of the vessel. This can be helpful if the minimal displacement constraint is violated.

LOA: The length over all will have effect on the wave making and viscous resistance. A longer ship will have a lower Froude number (Fn) for constant velocity. This will lower the wave making resistance. The viscous resistance however will rise. This because of an increased wetted area. The length will also have a big influence on the motions of the vessel. A longer vessel will have better seakeeping performances for pitch and heave than a shorter vessel. The roll motion is hardly affected by the length.

Beam: A smaller beam makes the vessel more slender. Slender ships will have lower wave making resistance and a lower viscous resistance. The stability will also be affected. The smaller beam will cause a lower metacentric height (GM) which is negative for the intact stability. The beam needs to be in a certain range. The following ranges are used from [35]. The beam/draft ranges will be from 2.5 to 5.5. Lower than 2.5 would face serious stability problems, while anything higher than 5.5 would be in he range of semi-displacement or planing hull forms. The beam also influences the motions of the vessel.

Entrance Angle at WL: The entrance angle will change the stem of the vessel. Larger entrance angles will give more volume towards the stem, while a lower entrance angle will do the opposite. Smaller entrance angles will lower the wave making resistance. However the slender hull form may have higher viscous resistance as result of the larger wetted area.

Stem distance: A short stem distance means a more vertical stem, while a long stem distance will give a stem with a smaller gradient. See Appendix B for the formulation of the stem distance. The stem distance will have influence on the volume distribution of the vessel. A short stem distance will create more volume at the stem region. A long stem distance will have the opposite effect.

X-frame indication: The volume distribution can be shifted more towards the stem or towards the stern of the vessel. This will change the LCB of the vessel. This can be adjusted by using the 'X-frame indication'. A low value for the 'X-frame indication' will move the LCB towards the stern, while a high value will move the LCB towards the stem.

Z-frame indication: The volume distribution can shifted up and downwards. The 'Z-frame indication' will influence the fullness of the hull. A high value of 'Z-frame indication' will create a slender hull form, while a low value will create a very full hull form.

The naval architect can make its own selection of design variables to use. The design space increases when more design variables are used. There are namely more variations possible. Introducing more design variables will however require more calculation time. The advice is to only select the design variables which have the largest influence on the chosen objectives. A sensitivity study can help by analysing which design variables have the most effect on the objectives. Also the range of the design variables can be changed after studying the results of the sensitivity study. This to place the focus of the study on a specific design area.

CONSTRAINTS

The dimensions of the ship are connected to the functions of the ship. The mission profile and layout give the requirements and constraints on the design. By analysing the functions, the boundary conditions can be found. The given specifications of the new generation support vessels, see section 2.1, gives the range of some design variables and the constraints of the design. These constraints are implemented in an a-priori approach. This means the constraint is applied before the design iterations has been made. An advantage of the a-priori approach is that the generated concepts have a high probability to meet all requirements. While a disadvantage is that by using a constraint beforehand, the proposed solutions will be biased. The concept exploration phase is used to evaluate trends and the consequences of certain design choices. By using constraints one is limiting the design space. The probability exist that a feasible design is not being handled, because of limitations set beforehand without knowing the result of it.

The minimum displacement constraint which acts on every vessel, is used in the following way. This constraint is in fact not a design variable that can be adjusted, but rather a result of the other input values. In CAESES the hydrodynamic features of the generated hull are calculated. One of the results is the displacement of the current hull for the input parameters acting for a specific evaluation. This displacement can be compared with the minimal displacement a specific vessel needs to have. The minimal displacement of the naval support vessels are given in section 2.1. If this constraint is violated, the hull is unfeasible and will not be used for further calculations. This will limit calculation time. The constraint will have the following function:

$$\text{Volume} > \text{Minimal Volume}$$

Another constraint is used for the stability. A feasible design needs to have enough stability to satisfy the restrictions found in the rules and regulations. The constraint acting on the stability is formed as follows. The parametric modelling tool will try different sets of design variables. The assumption is that stability is highly dependant on the draft and beam of the vessel. In the Systematic Series of MARIN, values are given to ensure good stability at a first guess [35]. Note, this will not guarantee that the design is meeting all rules and regulations acting on intact and/or damage stability. The constraint will have the following function:

$$2.5 < B/T < 5.5$$

3.2. RESISTANCE PREDICTION MODELLING

The effective towing power objective is one of the two objectives used at the new approach. The resistance at desired speeds, the propulsive efficiencies and transmission efficiencies determines the required brake power [27]. This influences the power usage. Minimisation of the resistance is therefore an important issue in ship design. The objective acting on the power usage will be limited to effective towing power only. This because not enough information is known to determine the propulsive and transmission efficiencies for every variant. The effective towing power (Pe) is calculated with the formula $P_E = R_s * V$. Total resistance of the ship (R_S) is the total resistance for a specific vessel speed V.

The resistance is a design objective that will be used for all vessels in this research report. The resistance will be predicted by use of the potential flow solver RAPID, from MARIN, which is based on a raised panel method [36]. The potential flow-solver can be used to predict the wave resistance [33].

The potential flow solver is based on inviscid flow theory. This means resistance based on viscosity, like friction, are not taken into account. The frictional resistance can be estimated by use of a flat-plate approximation, which is based at the local Reynolds number [33]. Flat-plate approximation are used within the theory of Holtrop and Mennen, with the International Towing Tank Conference (ITTC)-1957 formulation for the value of $k1$. The combination of RAPID and Holtrop and Mennen will be used to predict the total resistance. Another method, which is used by a research team from Ecole Centrale de Nantes (ECN), is a Reynolds-averaged Navier-Stokes equations (RANSE) solver. RANSE solvers can predict the hydrodynamic behaviour with high accuracy, but are more difficult to use and are more time consuming than potential flow solvers [37]. This makes a RANSE solver not useful for an optimisation study, but can be used in a later phase to increase the accuracy of the resistance predictions of the final design.

Holtrop and Mennen can also calculate the wave resistance, which makes the usage of RAPID unnecessary. But it has been decided not to do this. Holtrop and Mennen is based on regression lines from a large database of existing vessels. By only using a limited amount of input parameters, a prediction can be made on its performance. The predictions will only be accurate when models are in the boundary conditions of the method. Extrapolation on the regression lines will happen when the boundary conditions are violated. This makes Holtrop and Mennen only usable for common hull forms, while it has difficulty for novel hull forms.

RAPID on the other hand, will use the geometry of the model as input. So changes in the geometry, which are not affecting the design parameters, will give different results by RAPID while Holtrop and Mennen will treating both designs as being the same. So RAPID is much more sensitive for small changes where Holtrop and Mennen will only give a global prediction based on several input parameters. This makes RAPID way more suitable for optimisation studies. The usage of potential flow solvers within an optimisation study is also made possible by the more powerful computers nowadays. Furthermore, RAPID will be able to perform predictions on novel hull forms, and can also be applied on complex vessels like multi-hulls.

The new approach will be used during the concept exploration phase. Here fast results and easy implementation are necessary to analyse a large variation of models. The trends or regions where the possible optimised models can be found are helpful to explore and analyse the design space. The most promising resistance prediction method for this call is a potential flow-solver.

The resistance prediction modelling will be build up the following way. First the simplifications are given. Afterwards the resistance calculations are described. The last part will concern the resistance objective as used within the new approach.

SIMPLIFICATIONS

Some simplifications are present in the suggested process. These simplifications will affect the resistance prediction and/or motion prediction, but will make the usage easier and better to understand. The simplifications are:

- No appendages in geometry
- No propulsive efficiency
- No bulbous bow in geometry
- No bow and/or stern thruster tunnel in geometry
- No added resistance calculations due to rough water
- Limitations in the prediction of waves in the stern region.

The appendages will have effect on the resistance prediction and the motion prediction. The impact of the appendages on the motions will be analysed in the motion prediction modelling, see section 3.4. Appendages will increase the viscous related resistance because of the increased wetted area.

The resistance is acting on the effective towing power (Pe). The Pe multiplied with the propulsive efficiency gives the propeller power. The absence of the propulsive efficiency is limiting the approach to predict the power usage in a more advanced way.

The bulbous bow can be designed to reduce the wave making resistance. The bulbous bow has the most effect on the design speed and design draft. On other speeds or drafts, it can even increase the resistance. The bulbous bow can also be used to accommodate a sonar.

The bow and/or stern thruster tunnel will probably be present in the final design and will create extra resistance especially on higher speeds. In rough water, high waves and wind will increase the resistance of the vessel. Normally this is taken into account by using an added resistance factor.

In order to use RAPID in a comparison study, the results should be highly predictable. RAPID is based on inviscid flow theory, which excludes the effect of boundary layers, dead water zones behind a transom, or flow separation [36]. These effects makes the predictions of the zone behind the transom unpredictable. The consequence is that the stern region should remain in the same shape as much as possible. This limits the design freedom of the transom geometry.

CALCULATION RESISTANCE

The total calm water resistance can be described as [38]:

$$R_S = R_w + (1 + k_1) * R_F + R_{App} + R_B + R_{TR} + R_A$$

The R_S is the summation of all resistance acting on the vessel. The Wave resistance (R_w) becomes dominant at higher values of Fn. For lower values of Fn, the Frictional resistance as given in the ITTC-1957 friction formula (R_F) is responsible for the majority of the R_S. The R_F should be multiplied by k_1, the Form factor describing viscous resistance of the hull form in relation to R_F (k_1). The Resistance of appendages (R_{App}) is for the rudder, shafts, skeg and stabiliser fins for example, but also for the bow and stern thruster tunnels. In the design case, these appendages are not taken into account. The Additional pressure resistance of bulbous bow near water surface (R_B) is also not present in the current design case. The Additional pressure resistance of immersed transom stern (R_{TR}) is caused by separation of the flow at the immersed transom stern. The input values for the R_{TR} are calculated by CAESES. The last part is the Correlation allowance (R_A).

The wave making resistance, viscous resistance and other components are calculated in different ways. The wave making resistance, R_w, is calculated by use of the potential flow code RAPID. Next to potential flow theory, viscous flow theory plays an important role. The viscous resistance, $(1+k_1)*R_F$, is obtained by using the ITTC-1957 formula. The other components, and the cooperation between the different compositions, are predicted by the empirical formulation of Holtrop and Mennen [39]. This combination will give fast but reliable results to compare different design hulls [40], which is the objective of this process.

The input and output of the viscous resistance calculations can be seen in table 3.2. How the equations are used by the program CAESES can be seen in Appendix C. Here the code is given of the Feature Definition. The input is generated by CAESES for every variation.

Input	**Output**
Length [m]	k_1
Breadth [m]	R_F
Mean Draft [m]	R_{TR}
Forward Draft [m]	R_A
Transom Draft [m]	
Transom Area [m^2]	
Displacement [m^3]	
Wetted Surface [m^2]	
LCB [m]	
Speed [kn]	
Density [Kg/m^3]	
Viscocity [m^2/S]	
Prismatic coefficient (Cp) [-]	

Table 3.2: Input and output of resistance calculations

RESISTANCE OBJECTIVE

The objective is to minimise the total resistance of the vessel. The total resistance is the sum of the wave making resistance and the viscous resistance. This can be formulated as:

$$\begin{aligned} \min(R_S) &= R_{wave} + R_{viscous} \\ R_{wave} &= R_{w3} \text{ (predicted wave resistance from RAPID)} \\ R_{viscous} &= (1+k_1)*R_F + R_{TR} + R_A \end{aligned}$$

3.3. RAPID

For the wave making resistance, the potential flow code RAPID will be used. RAPID is a standalone program, which can be connected to the CAESES-FRIENDSHIP-Framework. First the method is described. Afterwards the connection will be explained. The mesh density is selected at last.

METHOD

The wave resistance will be calculated by use of the free-surface potential flow code RAPID [41]. This panel method computes the wave pattern and wave resistance by solving the steady nonlinear free-surface potential-flow problem iteratively. After convergence the complete inviscid kinematic and dynamic boundary conditions are satisfied and the dynamic sinkage and trim are incorporated [42]. Rankine source panels are located on the hull surface, and at a small distance above the wave surface. Panel distributions are automatically adjusted between iterations, as are dynamic trim and sinkage. In each iteration, the boundary conditions are imposed in collocation points on the hull and on the last free-surface iterate, and the resulting system of equations is solved by a preconditioned Generalised Minimal Residual Method (GMRES) solver.

Two values for the wave making resistance are calculated by RAPID, Rw1 and Rw3. Rw1 is calculated by integrating the pressures over the hull while Rw3 is calculated by computing the wave energy [42]. In theory, these two values should be the same. But in practise this isn't always the case. The wave energy is calculated by use of the cross section of the waves behind the transom. Rw1 is much more precise, but doesn't always give a value. While by Rw3 almost always a value is calculated. Rw3 is much more suitable for comparing different hull forms. Whilst Rw1 can be used for increased accuracy afterwards. As the objective is to compare different hull forms, and many feasible variants need to be provided, Rw3 is the wave making resistance value that will be used.

Connection with CAESES

The output of the geometry modelling should be adjusted to be usable by RAPID. The input needed by RAPID, which should be provided by the geometry modelling, is a mesh file. This file can obtain one or more meshes that cover the hull. The mesh is only loaded correctly if the following guidelines are followed [43]:

- Panels are defined only on the port side of the ship
- Panels are grouped in strips that go from forward to aft
- In each strip, the panels are grouped from keel to deck
- Panels are structured, that is, quadrilateral
- The panelling of a segment is topologically rectangular (each strip has the same number of panels)

Furthermore, the number of panels should be such that the panels are small enough to smoothly cover the hull. For a typical ship the number of panels will be between a few hundred up to a few thousand. The panel mesh is created within CAESES by using the MeshEngine function. This will use the surfaces of the geometry to create a structured mesh. The options of the MeshEngine, like 'Swap Domain' and changing the domain itself, gives the ability to meet up with all guidelines. See figure 3.7 for a close up of a part of the created mesh.

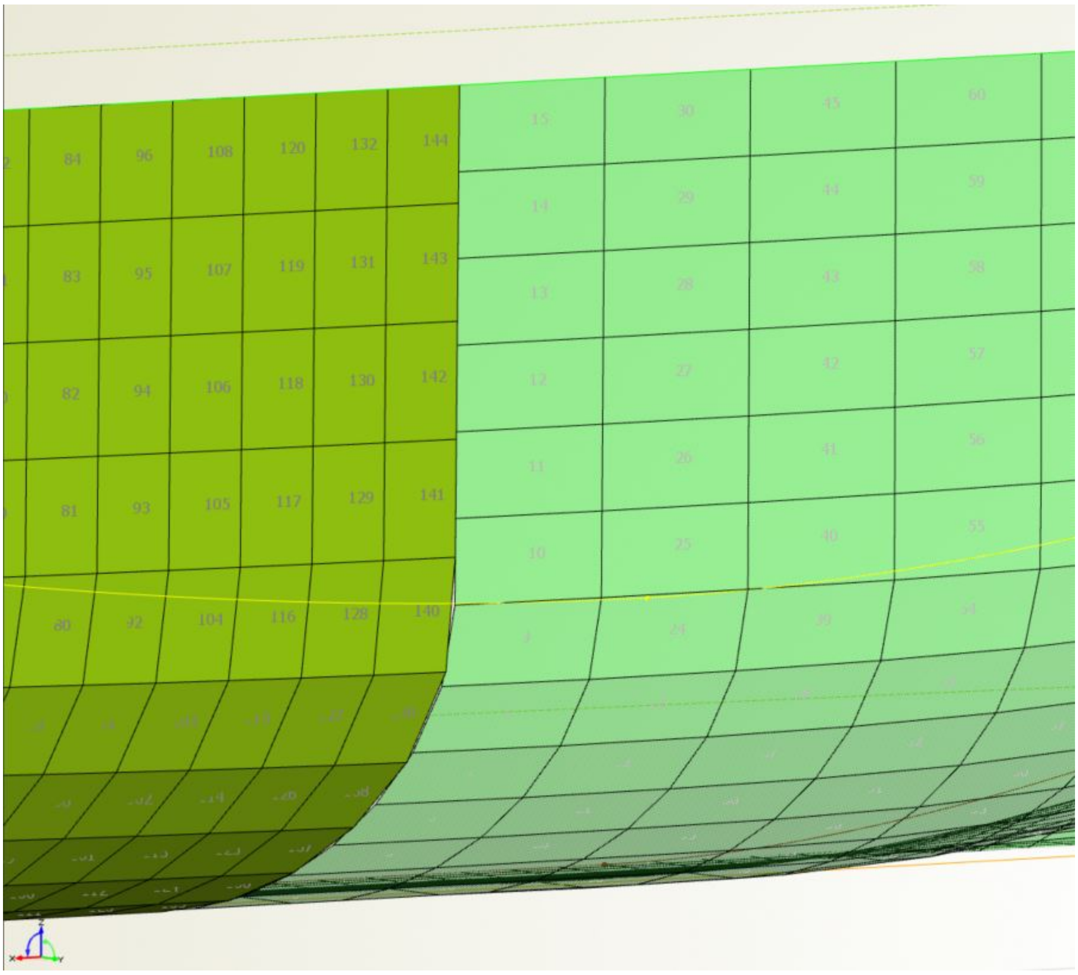

Figure 3.7: Created mesh of a part of the hull

The mesh density has to be chosen manually. The mesh size has influence on the accuracy of prediction, on the calculation time and on the Random Access Memory (RAM) needed for the calculation. To assure that the same mesh size is used for every iteration, a variable mesh density formulation is being used. This way, regardless of the dimensions of the geometry, the same mesh density is present. For every surface the beam, height and length are computed. This value is used to calculate the number of panels needed in x-and-y-direction. With the use of the function 'IntegerValue' the number of panels in the two directions is always an integer number. The number of panels that shall be used is chosen by performing a study on performance.

SELECTING MESH DENSITY

The mesh density needs to be selected. The mesh density has influence on the calculation time and the accuracy of the calculations [40]. A more dense grid will have more panels to compute which increases the calculation time. A too dense grid can result in impractical calculation times. The total calculation time for one study should preferably be lower than six hours. But even shorter calculation times, without loosing accuracy, are preferred. The accuracy however benefits from more panels. Especially on places with large geometrical changes like the stern and bow area. The grid will only be used by the resistance prediction tool RAPID in this stage of the research. But in further research the possibility is open to use the same mesh file for motion prediction using a higher fidelity tool. That is taken into account by already looking at the maximum panel length which is required to be used for motion predictions. After the maximum panel length is given, a study is made by using the results from RAPID. This will give more information about dependency of the accuracy and corresponding mesh density.

MAXIMUM PANEL LENGTH

The maximum panel length ($L_{panel,max}$) can be calculated with the method described in the user manual of PRECAL [44]. In this method the advice is to use at least five points within one 'encountered' wave length. With other words, the length of one panel should at least be five times smaller than the minimum encountered wave length ($\lambda_{enc,min}$). First calculate the maximum encounter frequency ($\omega_{enc,max}$):

$$\omega_{enc,max} = \max | \omega_0 - \frac{\omega_0^2}{g} * V * cos(\mu) |$$

With this frequency the minimum encountered wave length is calculated:

$$\lambda_{enc,min} = \frac{2 * \pi * g}{\omega_{enc,max}^2}$$

The maximum panel length is a fifth of this encountered wave length:

$$L_{panel,max} = \frac{1}{5} * \lambda_{enc,min}$$

The wave frequency (ω_0) is taken as $1.5 rad/s$. The vessel speed (V) will be 15 kn. The reason behind this is that a higher velocity will cause smaller panels, so the maximum speed is chosen. This input will give a $L_{panel,max}$ of $0.5m$, or four panels per square meter.

With this maximum panel length, an estimation can be made of the number of panels for the whole ship (N_{total}). This can be done with:

$$N_{total} = \frac{\frac{1}{2} * B + T}{L_{panel,max}}$$

This gives a total number of panels of at least 2175 for the parent hull.

MESH DENSITY STUDY

The number of panels of the raised free water surface can be adjusted by the user, but is kept on the custom value given by RAPID. A lower amount will increase the calculation speed, but especially for lower speeds this can create under fitted wave predictions. The wetted area is calculated by a feature of CAESES. The speed has been set to 12 kn. A somewhat lower speed will create more wave patterns alongside the hull. More waves will act on the same hull length. With bigger panels, less panels are present per wave. This will increase the chance of under fitting. This happened by a mesh smaller than one panel per m^2. The number after the mesh name indicates the amount of panels per meter. So Mesh 1 means that approximate one panel is present per meter (1 panel per m^2), while Mesh 4 means that there are approximate four panels per meter (16 panels per m^2). The wetted area of the parent hull is 989.3 m^2. Keep in mind that in CAESES only half of the vessel is simulated. Due to symmetry this simplification is possible. The calculation time is also registered. Small errors are present because of the non uniform testing environment. The background tasks of the computer can have a small influence on the calculation time per mesh size for example. The influence of the amount of panels on the calculation time can be seen in table 3.3

Mesh name	Number of panels	Time [min]	R_w [kN]
Mesh 1	489	0:56	11.59
Mesh 2	1956	1:06	11.17
Mesh 3	4401	1:27	11.07
Mesh 4	7824	1:56	11.04
Mesh 5	12225	2:47	11.02
Mesh 6	17604	4:11	11.00
Mesh 7	23961	11:33	10.99
Mesh 8	31296	16:42	10.99

Table 3.3: Panels and time per mesh density

The predicted resistance per mesh type is also analysed. This gives more information about the accuracy of the different mesh densities. The minimum mesh number to choose, according to the maximum panel length, is Mesh 2. As can be seen in figure 3.8, the resistance is still moving towards the limit. When keeping in mind the calculation time, the maximum panel length and the accuracy, there has been chosen to use Mesh 3 for further calculations. This mesh is a good compromise between the three criteria. The calculation time is increased with 21 seconds compared to mesh 2. But the accuracy has moved quite a lot towards the limit. Further increasing the density will have less effect. The computation time will increase rapidly, while the accuracy is only a fraction better than before. The panel length, of $0.33m$, is smaller than the maximum of $0.5m$. This grid can thus be used for further research with other motion solvers. Also the needed RAM while using Mesh 3 is still usable. While testing, the maximum RAM needed per variant was 1.5Gigabyte (GB). The computer used has 12GB of RAM installed. Some RAM is also reserved for CAESES itself and to run the operating system Windows (3GB in total). Which causes the maximum number of pending evaluations to be $9/1.5 = 6$. The processor installed is an Intel i7-3630, quad core, with eight logical processors. This is sufficient to run the six variations at the same time.

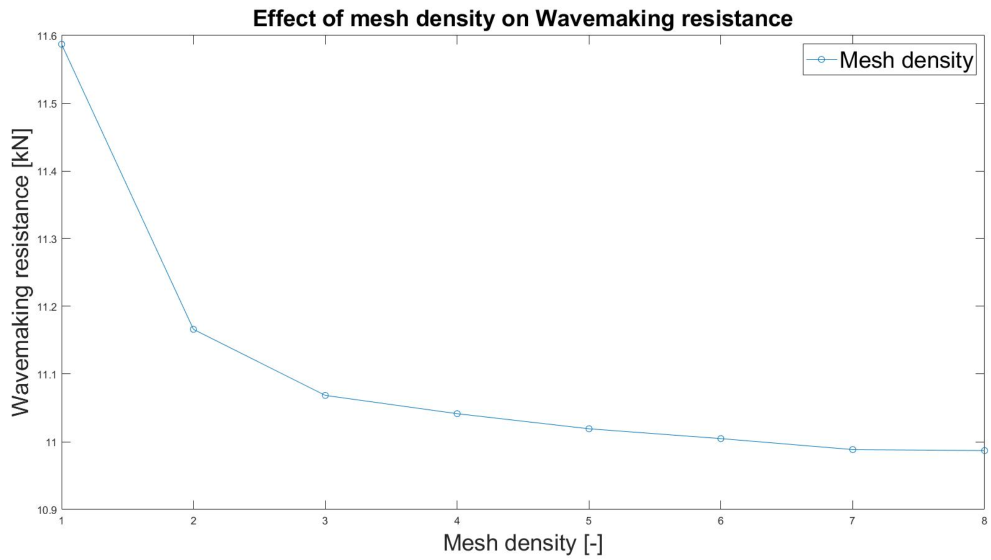

Figure 3.8: Effect of mesh density on wave resistance

See figure 3.9 for a graphical interpretation of the different mesh sizes.

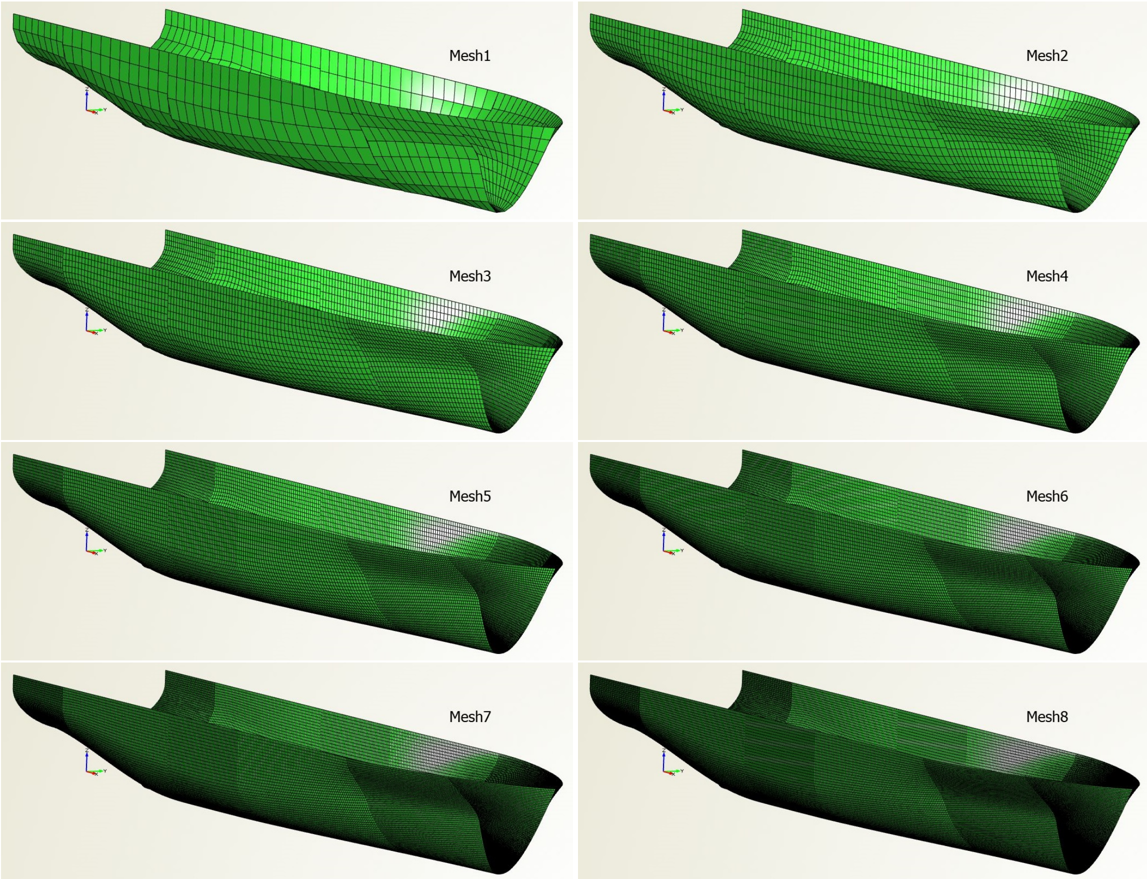

Figure 3.9: Mesh densities 1 till 8

3.4. MOTION PREDICTION MODELLING

Ship motions can be predicted by a lot of methods. Model test, RANSE solvers or strip theory are widely used methods. Most of the research teams, working on parametric optimisation, are using predictions based on strip theory. At DMO, the strip theory based prediction tool SHIPMO is used, but only during the concept definition phase. The downside of (linearised) strip theory is that highly detailed input is required and computations take a lot of time.

The motion prediction modelling method should fit in the concept exploration phase. This means it should use the input available in this phase, should be fast and predictions should be accurate enough to make comparison available. At this phase only information about the geometry of the outer hull is available. For calculations with strip theory, also information about the Centre of gravity (CoG), GM and moment of gyration is needed. These kind of information is still subjected to a lot of uncertainty. Moreover, these calculations takes a lot of computational time.

Another method is most likely more suitable for this duty. The lower fidelity tool that is used comes from the paper of Jørgen Juncher Jensen [45]. The closed-form expressions of linear strip theory is a simplified version of the linear strip theory [45]. The simplification is made by neglecting the coupling terms between heave and pitch. Also the sectional added mass is assumed to be constant and equal to the displaced water. The simplified method is compared with detailed motion analysis and predictions from various strip theories. The main findings of using this methods, as described in the conclusions of the paper of Jørgen Juncher Jensen [45], are:

- The input parameters are those who are known at the early-stage ship design, namely: length, beam, draft, block coefficient, water plane area coefficient, heading and speed. With these input parameters the frequency response functions for the motions and accelerations of monohull ships can be predicted.

- The simplified formulas have been validated using results from model tests and strip theory calculations on four ships of a wide variety of main dimensions and operating conditions.
- The formulas predict the motions and accelerations fairly accurately, with exception of: heave is to small for $\lambda/L > 1$, pitch is too large in the region of $\lambda/L > 1$ for Fn larger than 0.2 and the roll is too large in the region of the resonance frequency.
- The closed-form expressions are capable to use for long term predictions taking into account the operational profile of the vessel and the wave scatter diagram.

Although its limitations, the speed of the calculations is increased and only some main parameters are necessary compared to strip theory methods. The input parameters mentioned, are indeed already known in the concept exploration phase. The simplified formulas have been validated with model tests and strip theory results, see figure 3.10 [45].

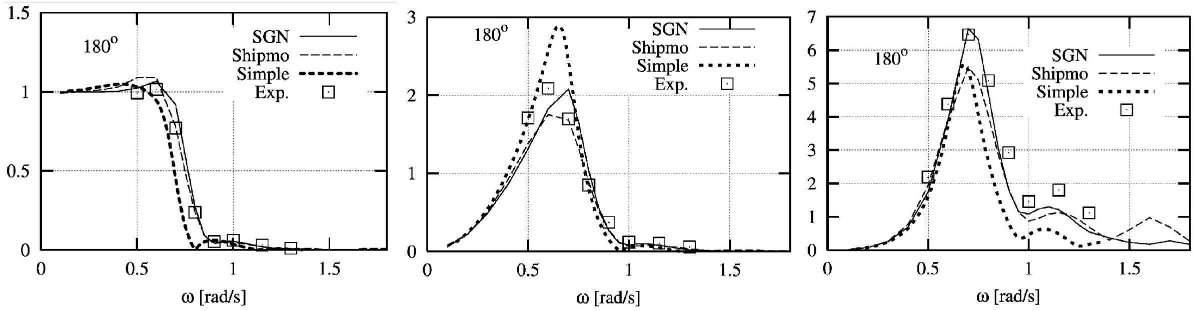

Figure 3.10: Heave motion (m/m), pitch motion (m/m) and vertical acceleration ($(m/s^2)/m$) at Fn=0.59. Squares represent results form model tests, dashed and full thin lines are linear strip theory results, and thick dashed lines denoted ‘simple’ are from the closed-form expressions [45].

The limitations on heave and pitch will have its influences on the predicted motions. A validation study has to make clear if the method is capable to predict the relative merit for vertical displacement and vertical acceleration between different designs. The capability to use it for long term predictions is a nice feature to have. At a later phase in the DMP one can switch to a higher fidelity tool, like strip theory (SHIPMO), RANSE or model tests, if the design is almost finished and highly accurate predictions on the seakeeping capabilities are necessary.

The motion prediction modelling is structured in the following way. First the simplifications are given. Then the motion calculations are described. The last part concerns the motion objective as used within the new approach.

SIMPLIFICATIONS

This method of the closed-form expressions based on linear strip theory brings some simplifications and accuracy limitations. These limitations comes from the conclusions of the paper of Jørgen Juncher Jensen [45]:

- Heave response is smaller than reality when $\lambda/L > 1$ (wave longer than the ship’s length)
- Pitch response is larger than reality around $\lambda/L = 1$ for Fn larger than 0.2
- The simplified formulas predict zero pitch in beam sea (90 degrees)
- Pitch and heave movements are considered to have a phase difference of 90 degrees

- The theory assumes very deep water waves

The Fn used in the calculations will have a maximum of 0.35 (by 15 kn and 50m length). The pitch response is thus expected to differ from reality, especially for small vessels at high speed. This is something to take into account while analysing the results. Especially the uncoupled heave and pitch motions will have its influences on the vertical displacement and vertical acceleration. Assumed is that, despite the smaller or larger response than reality, the method can predict the relative merit between different designs for vertical displacement and vertical acceleration. A validation study on the motion objectives has to prove if this assumption is indeed true.

The absence of appendage in the geometry will have influence on the motion predictions. The motions will be effected because of the damping certain appendages can introduce. Especially the roll motion will change a lot, as around 25% of the roll damping comes from the bilge keels, see figure 3.11. The components included are friction (B_F), eddy (B_E), wave making (B_W), hull lift (B_L), bilge keel normal force (B_{BKN}) and bilge keel-hull interaction ($B_{KH}kh$) [46]. Roll motion should therefore only be predicted when bilge keels are included. The results will otherwise not be representative for the reality.

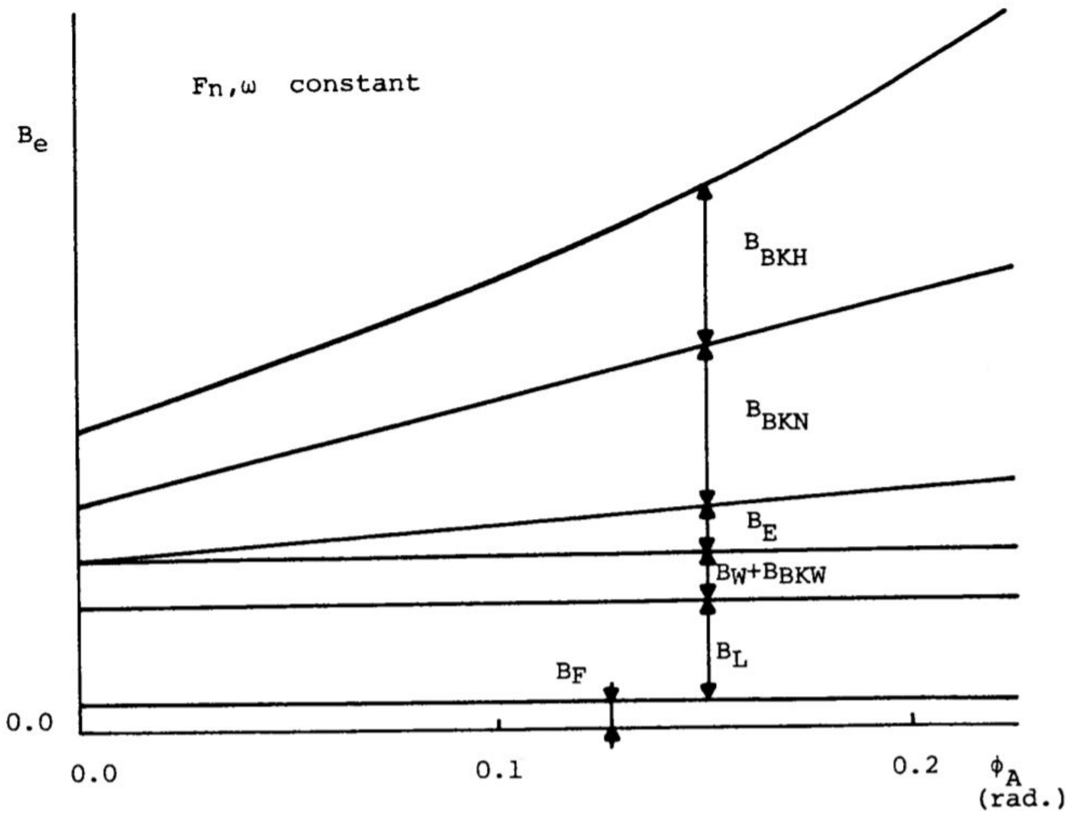

Figure 3.11: Relative magnitude of roll damping components dependent on roll amplitude [46]

CALCULATIONS MOTION

These functions have been programmed to work within the CAESES environment. With only limited input parameters, a prediction can be made for the motions of the vessel. The input and output parameters can be seen in table 3.4. The output parameters are used as objective function for the optimisation method. The feature used within CAESES, based on the given equations, can be consulted in Appendix D.

Input	Output
Length [m]	Vertical displacement [m]
Breadth [m]	Vertical Acceleration [m/s^2]
Draft [m]	Pitch Movement [m/m]
Cb [-]	Heave Movement [m/m]
Fn [-]	
Heading angle [degree]	
Position of Interest [m]	
Wave amplitude [m]	

Table 3.4: Input and output parameters of motion functions

MOTION OBJECTIVE

The motion objective will be used to distinguish hull designs on its seakeeping behaviour. In general the seakeeping performance in sea states is used for comparison [47]. The new process will use a slightly different approach. Instead of using a specific seakeeping criterion at a given speed and in specified sea conditions, the objective will be to acquire as good seakeeping qualities as possible [32]. "Ship responses at sea are minimum when the corresponding peak value of their Response Amplitude Operator (RAO) is minimum" and that, therefore, "seakeeping optimisation can be achieved on the basis of regular wave results only", according to Grigoropoulos [47].

A downside of only looking at the relative responses is that events related to the submerged part of the hull are not taken into account. These events have to do with slamming of the bow and propeller emergence. This shortcomings are assumed to be negligible because minimisation of the relative responses provides an indication that the probability of corresponding events (slamming and propeller emergence) will also be reduced [47].

For the motion objective, values of the maximum vertical acceleration (Φ_v) and maximum relative vertical movement (Φ_r) at a point 0.1LWL behind forward perpendicular, in head waves, have been chosen. This place will have relative high vertical displacement, and also high vertical accelerations, because it is far from the Centre of rotation (CoR). The bridge and (possible) sonars are placed close to this point. The vertical acceleration has effect on the seakeeping responses on humans (seasickness) [48], an important motion for the Marine Training vessel. Vertical displacement has effect on the seakeeping events (slamming, propeller emergence, deck wetness etc.). This motion is also important for hydrographic survey work, and for torpedo handling at the Submarine Support vessel. The motion objectives are:

$$
\begin{aligned}
min(MotionObjectiveDisplacement) &= max(\Phi_r)\\
min(MotionObjectiveAcceleration) &= max(\Phi_v)\\
max(\Phi_r) &= \text{maximum vertical displacement at position } x \text{ for } \omega\\
max(\Phi_v) &= \text{maximum vertical acceleration at position } x \text{ for } \omega\\
x &= \text{ (80\% forward as seen from midship)}\\
\text{Heading angle}\beta &= 180\,\text{deg}\\
\omega &= \text{lies between 0 and 2 rad/s}
\end{aligned}
$$

The vertical displacement and acceleration will be calculated on the ω_0 interval 0 till 2 rad/s. The maximum is calculated by using a for loop. The wave frequency is split up in 1000 points. For every point of ω the displacement and acceleration can be calculated. By taking the maximum value which is present in this interval, the objectives are ready to be used.

3.5. OPTIMISATION METHOD MODELLING

The optimisation will use the results of the geometry modelling and the prediction software to find the optimal ship hull given the objective function. Only hull designs which comply with the given constraints and which are feasible will be used. The freedom to generate geometries has to be big enough to ensure a large enough area of possible hull designs is taken into account, but small enough in order to produce feasible models. To reach this goal, the range of the design variables can be controlled. Seven design variables are used for the test case. The ranges of some design variables comes from the requirements, see table 2.2. The ranges of design variables which are not specified in this table have been selected in a different way. The Entrance Angle at WL, Stem distance and X-and-Z-frame indication variables are selected in such a way that the minimum and maximum values give a feasible hull when applied on the parent hull.

The optimisation algorithm serves as a tool to focus and acquire the optimised results without assessing every single possible design. The problem of optimisation algorithms can be that a local optimum has been found, while the global optimum is not found. Different algorithms deal with this problem in their own way. For example a hybrid version that first search globally, and uses this information to search on a more local level.

A study has to be performed to investigate what optimisation method is most suitable for the new approach. Also the settings of the optimisation method should be tested. Settings are for example the amount of evaluations and the number of generations that will be used. These will have impact on the ability of the optimisation method to converge to an optimum, but will also influence the calculation time. First the method is selected and the settings are depicted afterwards.

SELECTING METHOD

The method will be selected based on the computational time, and the corresponding Pareto front of the results. The Pareto front is the visualisation of the globally Pareto-optimal set, which is the non-dominated set of the entire feasible search space (S). Among a set of solutions (P), the non-dominated set of solution (P') are the values that are not dominated by any member of the set P. The Pareto-optimal set is the trade space which fundamentally exists unless more information is added to the problem statement. A solution X_1 is said to dominate a solution X_2 if both conditions 1 and 2 are true [49]:

1. The solution X_1 is strictly better than X_2 for at least one objective $f_j(x)$
2. The solution X_1 is no worse in all other objective $f_j(x)$ than X_2

With:

$$f_j(x) = (f_1(R_s), f_2(\text{VerticalDisplacement}), f_3(\text{VerticalAcceleration}))$$

Three methods are investigated. These methods are available in CAESES, which makes integration very easy, and are all based on Genetic Algorithm (GA). The methods used are: NSGA II, DAKOTA - Global Optimisation and DAKOTA - Global Optimisation on Response Surface. To make a fair comparison, the range of the design variables is the same for all methods. See table 3.5 for the used values of the design variables. This for a design speed of 14 kn and a minimum displacement of 1200 t. The maximum number of evaluations per method is 400, which is taken as a first guess. A study will be used afterwards to investigate the effect on the objectives (Rs, Vertical Displacement and Vertical Acceleration) for different numbers of evaluations. The aim is to have low calculation times (preferably under six hours), with a global optimum as a result.

Design Variable	**Units**	**Lower limit**	**Upper limit**
Draft	$[m]$	2	8
LOA	$[m]$	50	100
Beam	$[m]$	10	15
Entrance Angle at WL	[degree]	15	30
Stem distance	$[m]$	5	12
X Frame Indication	[-]	0.1	0.9
Z Frame Indication	[-]	0.1	0.9

Table 3.5: Design variables for optimisation

NSGA II

The NSGA II is a genetic algorithm. Genetic algorithm belongs to the class of evolutionary algorithms [24]. This because the techniques which are used are inspired by the Darwinian evolutionary theory. Aspects such as inheritance, mutation, natural selection and recombination can be recognised in genetic algorithms. [50].

The procedure of NSGA II consists of six steps:

1. A number of variant geometries is generated.
2. An equal number of off-springs is formed.
3. The total number of parents and offspring is sorted to levels according to non-domination.
4. The geometries of each level are ranked with respect to their crowded distance of each solution in the population.
5. A new generation is being produced with a population number equal to the initial one.
6. Steps 2 to 5 are repeated.

Crowding comparison procedure is used to make sure that diversity among the non-dominated solutions occurs. In crowding comparison two different solutions p and q are present where p dominates if the following is reached [33]:

$$\begin{cases} f_j(x_1) \leq f_j(x_2), \forall j \in \{1,...,n\} \\ f_k(x_1) \leq f_k(x_2), \forall k \in \{1,...,n\} \end{cases}$$

Where x_1 and x_2 are the design variables for geometries p and q respectively. The settings for the selection study are presented in table 3.6. Every generation will consist of a population of 12. This will give a total of $12 * 33 = 396$ evaluations. The maximum number of pending evaluations is set to six.

Max number of generations	33
Population Size	12
Mutation Probability	0.01
Crossover Probability	0.9

Table 3.6: Settings NSGA II

DAKOTA - SENSITIVITY STUDY

The DAKOTA methods, designed by a team of Sandia National Laboratories, are designed for advanced parametric analyses to enable design exploration [51].

The DAKOTA methods are available for the (local or global) multi-objectives optimisation. DAKOTA has also the ability to perform a sensitivity analysis. This kind of analysis gives insight in what the influence is of different design variables, but also creates a result pool which can be used by the optimisation algorithms. The sensitivity analysis is based on Latin Hypercube Sampling (LHS), which ensures an evenly distributed set within the design space. Two global optimisation methods are available within DAKOTA: Global optimisation or Global optimisation on response surface.

Both methods are genetic algorithms. One good ability of genetic algorithm is that it is using the total search space. This gives a high potential to find the global optimum. This is especially good when not so much is known about the domain. However, there are some troubles with converging to the actual optimum. When the search is terminated, one will never know how close the result is to the global optimum [24]. It can only be expected that the best result is in the vicinity of a local or global extreme. The final results is only an approximation of the global optimum.

The DAKOTA methods need a result pool to start with, for creating a response surface for example. This result pool is created in the Sensitivity study. The maximum number of evaluations of the sensitivity study is set to be 100, see table 3.7. DAKOTA gives the advice to have at least five evaluations per design variable. With seven active design variables, the minimum number of evaluations should be 35. But not all evaluations will be feasible solutions. Some will not meet the volume constraint, the stability constraint, while others are on the boundary of the capability of RAPID and will not converge to a solution. So by taking a bit larger set of data, there is a higher confidence that the minimum amount of useful evaluations is acquired.

Max number of evaluations	100
Max number of pending evaluations	6

Table 3.7: Settings DAKOTA - Sensitivity study

DAKOTA - Global Optimisation

The global optimisation is a Multi-Objective Genetic Algorithm (MOGA). GA needs a lot of evaluations, which makes the method only suitable if the computation is not too time consuming [52].

Max number of evaluations	400
Number of pool results	100
Number of generations	33

Table 3.8: Settings DAKOTA - Global optimisation

By having 33 generations, every generation will consist of $400/33 = 12$ evaluations. The maximum number of pending evaluations is set to six, to keep enough processor power available for other work, and by limiting the needed RAM. An overflow of RAM will cause errors, which stop the optimisation process entirely.

DAKOTA - Global Optimisation on Response Surface

The global optimisation on response surface is also a Multi-Objective Genetic Algorithm, but uses a response surface that is updated after every evaluation [52]. The initial response surface is created by using the Sensitivity study. The generated and updated response surface is used by the algorithm to reduce the number of evaluations. This is especially valuable if the evaluations are expensive.

Max number of iterations	400
Number of pool results	100
Number of solutions considered	33

Table 3.9: Settings DAKOTA - Global optimisation on response surface

By having 33 iterations, and every iteration will consist of 12 solutions, a total of $33 * 12 = 396$ evaluations will be considered. For this optimisation the maximum number of pending evaluations is set to six.

Output

The output will consist of a Pareto front. Every method will have approximately the same number of evaluations. The generated Pareto fronts can be compared with each other. The best method will have a Pareto front that gives the best results for all objectives. If this does not provide a definitive answer, then selection can be based on the computational time. See figure 3.12 for the comparison between the different optimisation methods.

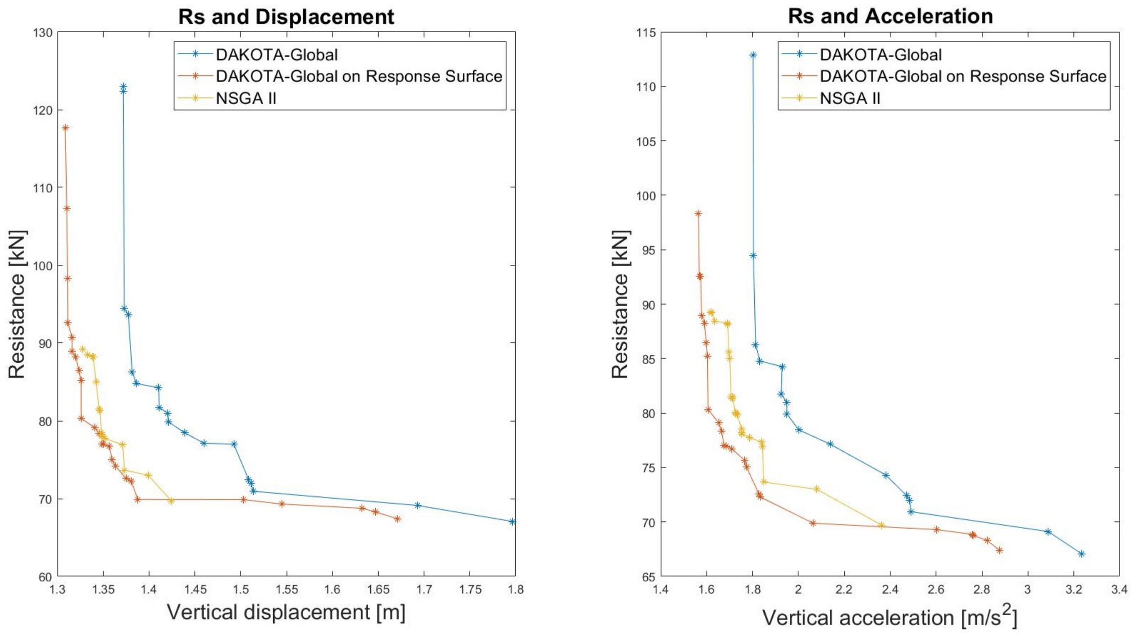

Figure 3.12: Pareto front for different optimisation methods

Although the number of evaluations is approximately the same for every optimisation method, the generated Pareto fronts of the methods are different. Based on the Pareto fronts, DAKOTA - Global on Response Surface gives the best results. The Pareto front of DAKOTA - Global on Response Surface is dominating the Pareto fronts of DAKOTA - Global and NSGA II. The models with the lowest values for the vertical displacement and the vertical acceleration have been found by DAKOTA - Global on Response Surface. The model with the lowest value for the resistance objective has been found by DAKOTA - Global. The total number of evaluations, the number of models on the Pareto front, the utopia point and the calculation time are provided in table 3.10. DAKOTA - Global on Response Surface has not only a dominating Pareto front, also the calculation time of this method is the lowest. Low calculation time is an advantage, especially in combination with the dominating Pareto front. This because a study can be performed faster, the number of evaluations can be increased or the accuracy of the prediction tools can be increased. A decreased calculation time has the advantage that the naval architect can quickly review the obtained results. More evaluations will increase the chance of creating even better design solutions. Increasing the accuracy will increase the computational time, but will decrease the uncertainty of the predictions.

Method	Total #	# on Pareto front	Utopia point (Rs, Mov, Acc)	Time in hours
DAKOTA Global	400	20	(67.1, 1.37, 1.80)	6:08
DAKOTA Global on Resp. Surf.	396	29	(67.4, 1.31, 1.57)	4:41
NSGA II	396	28	(69.7, 1.33, 1.62)	5:26

Table 3.10: Time in seconds and hours per study for every optimisation method

The aim is to have the best global optimum on the Pareto front, preferably in the lowest amount of time. The global optimum can be visualised in figure 3.12. Here the red line, DAKOTA-Global on Response Surface is favourite. This method is dominating the other alternative methods. Also low values for resistance has been found, and the lowest values for vertical displacement and acceleration have been found. The DAKOTA-Global on Response Surface is also the best method if one looks at the computational time, see table 3.10. Less time means faster results, more evaluations or increased accuracy.

The DAKOTA-Global on Response Surface will be selected as the optimisation method for the new approach. For the result pool a DAKOTA sensitivity study will be performed beforehand. The sensitivity study will consist of 100 variants. The settings of the DAKOTA-Global on Response Surface method can now be selected.

SELECTION SETTINGS

The number of variants of the result pool, the number of generations and the number of iterations is chosen arbitrary. A different set of values will be used to see what the effect is of changing the number of variations on the capabilities of the optimisation method. To analyse this, the process is run with a large maximum number of iterations. The Pareto front can be visualised for intermediate iteration numbers, to see the Pareto front evolve.

INPUT

The input is the same as used for the selection of the optimisation method. The DAKOTA-Global Optimisation on Response Surface method is used, as it provided the best results, in the least amount of time. The maximum number of iterations is set to 600 and a Pareto front is plotted for every 200 iterations. More iterations will be impractical for the case study, because of the preferred maximum computational time of six hours and the limited amount of memory available on the computer.

OUTPUT

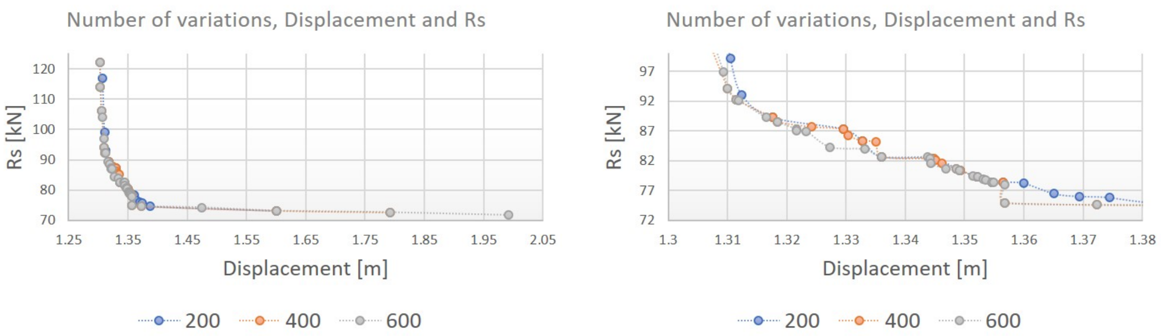

Figure 3.13: Effect of number of iterations on vertical displacement and R_S on left, and right a close up

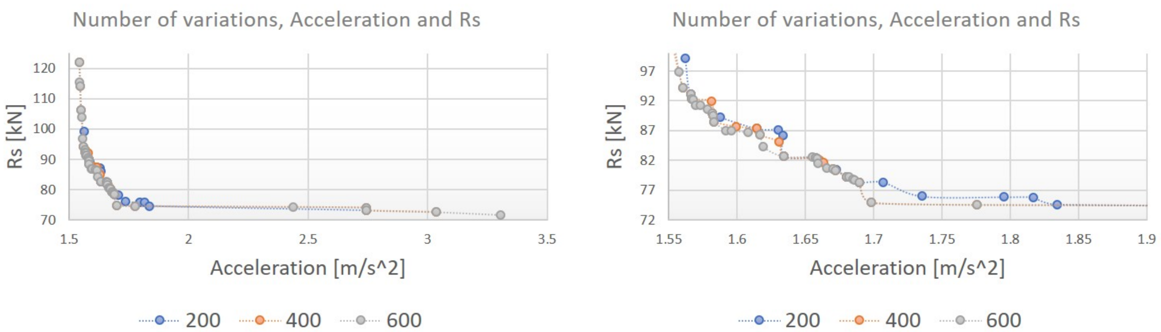

Figure 3.14: Effect of number of iterations on vertical acceleration and R_S on left, and right a close up

The Pareto front is indeed providing better values for the objectives for an increased number of iterations, as can be seen in figure 3.13. But the difference between the different Pareto fronts is rather small. So no large improvements are recognised. For practical reasons, the maximum number of iterations is kept at 400. The computational time is acceptable, and one can say with confidence that a good enough optimum design is provided.

3.6. CONCLUSION OF NEW APPROACH

The conclusion of the new approach shall provide an answer to the fourth sub question: 'What are the different components that are needed for the new approach and how will the setup be performed?'

The new approach will consist of four different parts. The parametric modelling is performed by use of CAESES. A hull form is developed which can be adjusted by seven design variables. Two constraints will make sure that only feasible designs are generated.

The resistance prediction will consist of two components. The wave making resistance is predicted by the potential flow solver RAPID, while viscous effects are taken into account by use of Holtrop and Mennen. These two combined will give the resistance objective [kN]. A study has been performed to select the settings of RAPID.

The motion prediction is performed by a simplified version of the linear strip theory. By use of this method, one can predict several motions such as the vertical displacement and the vertical acceleration of the vessel at a point of interest and for different headings. The motions in head waves at 0.9*LWL will be analysed. The motion objective is split in two: the maximum vertical displacement [m] and the maximum vertical acceleration $[m/s^2]$.

The predicted values of the objective functions will be used by the optimisation method, which will in return change the design variables. Three types of optimisation methods were tested and DAKOTA - Global Optimisation on Response Surface gave the best results. The solution has converged with acceptable accuracy by using 400 iterations. The computational time was with 4:41 hours lower than the preferred maximum of six hours.

The approach has been visualised in figure 3.15. The reliability of the method can be proven by performing a validation study, which is provided in the next chapter. After the tool is validated, it can be applied on the test case.

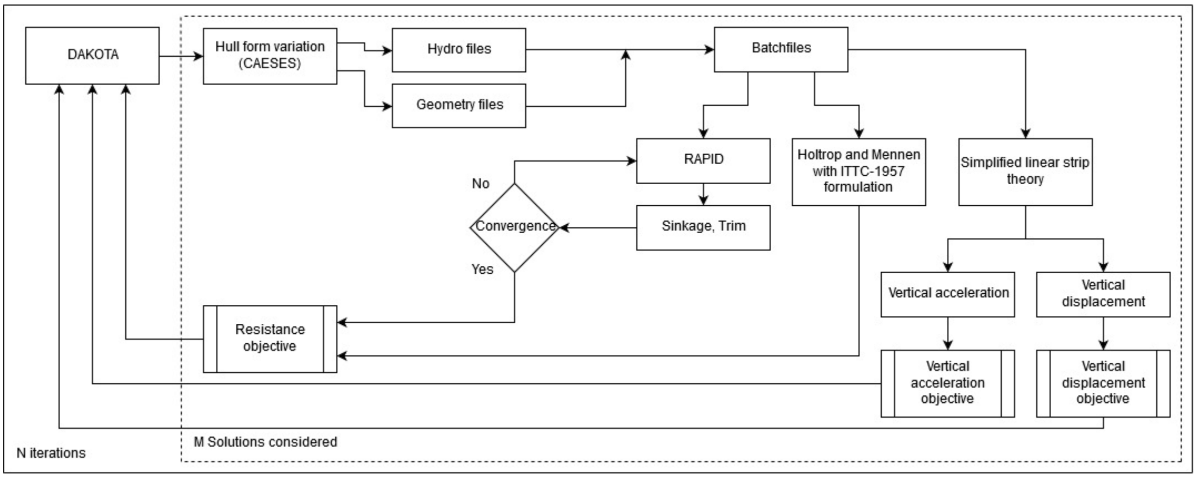

Figure 3.15: Flow diagram of the new approach

4

Validation study

The validation study consists of four items.

- Accuracy of resistance prediction
- Influence of resistance components on output
- Accuracy of motion prediction
- Validation of proposed optimised models

The accuracy of the resistance prediction should be validated to investigate if the predicted resistance is comparable to values from model tests and/or existing vessels. The influence of the resistance components on the output will make clear how different parts of the resistance influences the outcome. The accuracy of the motion prediction concerns the comparison in seakeeping performance between the proposed models. A simplified method is used to perform the predictions. The validation study has to give proof if this method is indeed capable to distinguish the seakeeping performances between the vessels. The generated hull geometries are also analysed to see if the trends are according to the expected trends. This will be done in the validation of proposed optimised models.

Feedback on the requirements will be formulated after the validations are completed. The last section will give the conclusion of the validation study, which shall also provide an answer to the fifth sub question: 'How to validate the model?'

4.1. Accuracy of resistance prediction

The resistance prediction is made up by $R_S = R_w + (1+k_1) * R_F + R_{TR} + R_A$ with RAPID taking care of the R_w and all other components by formulas described by Holtrop and Mennen. The benefits of using a combination of these two methods is given in section 3.2. The combination of a potential flow solver for the wave resistance and frictional resistance estimations by using a flat-plate approximation, based on the local Reynolds number is already widely used for optimisation purposes, as can be seen at the NATO Research and Technology Organization (RTO) Task Group [33]. However, validation has to give answers on the question how accurate these predictions are compared to towing test results or reality. This can be formulated as: What is the accuracy of the used resistance prediction objective. The hypothesis is:

- The accuracy of the resistance prediction is good for comparison between generated hull geometries, but predictions will differ from higher fidelity tools or reality.

RAPID is, while keeping in mind some restrictions, good for comparing different hull designs. This is essential for an optimisation study. Especially in combination with the frictional resistance components, submerged transom resistance and appendage resistance, the comparison should be adequate. Comparing the results with higher fidelity tools or reality, however, will show differences. Differences occur because of numerical errors, viscosity of the water, limitations of the prediction tools etc. In the concept exploration phase, many variations in hull forms and a large set of design options need to be explored. Many variations can be examined, which is beneficial for the concept exploration phase. Higher accuracy can always be obtained at a later stage, by using the more demanding higher fidelity tools.

SETTINGS

The validation of the resistance objective will be done by comparing the results with an existing vessel. The geometry of this existing vessel is rebuilt and used as input for the new approach. The result will be compared with the results available from towing tank experiments. The model used for comparison is the HOV vessel, from which a scale-model has been tested by MARIN. The geometry of the real vessel can't be used however, because of its confidential status. So the HOV has been redesigned in CAESES. The parameters from the CAESES model are compared with the values from the HOV. This can be seen in table 4.1. The value of $1+k$ is also confidential, and is only given as a percentage of each other. A lines plan comparison is also made and can be seen in Appendix F. Differences between the two vessels are mainly at the stem. The HOV has a sonar bulb in the front. This sonar bulb will increase the wave making resistance as well as the viscous related resistance. Also the fullness of some parts is slightly different. The prediction is that the viscous resistance of the CAESES model is slightly lower, because of the different stem, lower displacement and lower wetted surface. The wave making resistance should show only little differences.

Parameter	Value of HOV	Value of CAESES model	Difference compared to HOV in %
1+k	[-]	[-]	-1,69
Draft a.p.	4 [m]	4 [m]	0,00
Draft f.p.	4 [m]	4 [m]	0,00
Lpp	75 [m]	75,1 [m]	0,13
LWL	75 [m]	75,1 [m]	0,13
B	12.8 [m]	12,8 [m]	0,00
Displacement	1814 [m^3]	1795 [m^3]	-1,05
Displacement salt water	1859 [mt]	1840 [mt]	-1,03
Wetted surface without app.	1031 [m^2]	1013 [m^2]	-1,75
Wetted surface with app.	1061 [m^2]	1043 [m^2]	-1,70
Rho	1025 [Kg/m^3]	1025 [Kg/m^3]	0,00
Viscosity	$1,19*10^{-6}$ [m^2/S]	$1,19*10^{-6}$ [m^2/S]	0.00
LCB	-1.5 [m]	-1,53 [m]	2,00
Cb	0.472 [-]	0,467 [-]	-1,18

Table 4.1: Parameter values of CAESES model and comparison with HOV

ANALYSIS OF RECEIVED OUTPUT

The towing tank results of from MARIN and the results from the model are compared. The speed range is from 7.0 kn to 13.0 kn. Due to its confidential status the comparison only exist of percentages of the differences, see table 4.2. The Rw3 value from RAPID is used for calculating the wave resistance.

Vs [kn]	Vs[m/s]	R_S [%]	R additional [%]	R_w [%]
7,0	3,6	-12	-3.2	-27
7,5	3,9	-13	-3.2	-29
8,0	4,1	-13	-3.2	-29
8,5	4,4	-14	-3.2	-30
9,0	4,6	-14	-3.2	-30
9,5	4,9	-15	-3.2	-30
10,0	5,1	-15	-3.2	-32
10,5	5,4	-16	-3.2	-32
11,0	5,7	-17	-3.2	-34
11,5	5,9	-19	-3.2	-37
12,0	6,2	-20	-3.2	-38
12,5	6,4	-21	-3.2	-39
13,0	6,7	-23	-3.2	-42

Table 4.2: Comparison in % of model compared to towing tank results

The results in table 4.2 give different results than expected. The additional resistance components are indeed slightly lower and are consistent for all speeds (3.2% lower). This difference can be explained by the lower displacement and lower wetted surface of the model created in CAESES. The wave making resistance is 30% lower on average. This is a very large difference and is the result of the predictions of RAPID because of the differences in the geometry. The viscous related resistance, predicted by Holtrop and Mennen, is incorporated in R additional. The predictions from RAPID are only a rough estimation as is proven in this validation. The impact of the stern region is hard to predict and RAPID is not capable to predict the wave patterns in such a way that it is also a prediction of the total wave making resistance. Also the geometry of both models is not the same. The HOV has a sonar bulb on the stem which is not modelled in the CAESES model for example. This sonar bulb will increase the wave making resistance significantly. Also air resistance is not taken into account in the model, while it was included in the towing tank results. All these differences add up to the big difference between the two models. The R_S is however consistent for the lower speeds and rising for the higher speeds. The top view of the wave patterns of the validation model is given in figure 4.1.

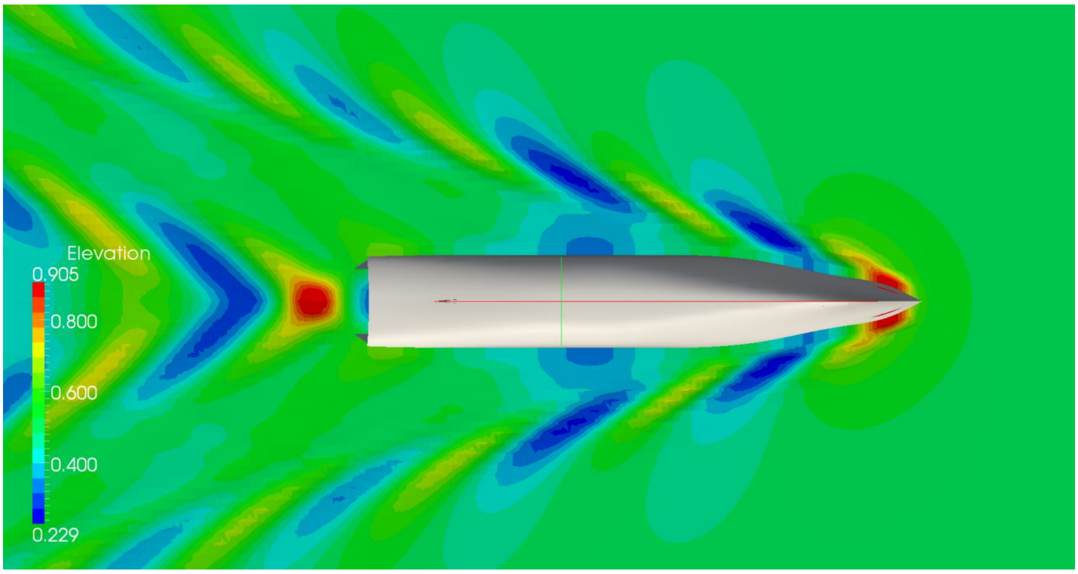

Figure 4.1: Top view of validation model at 13kn

CHANGING OF PANEL PRESSURE PREDICTION METHOD

RAPID can use two methods to predict the wave making resistance. These are Rw3, used for comparison purposes, and Rw1, which should have a higher accuracy. The same comparison has been made, but now Rw1 is used instead of Rw3. The results of this comparison can be found in table 4.3.

Vs [kn]	Vs[m/s]	R_S [%]	R additional [%]	R_w [%]
7,0	3,6	-2.0	-3.2	0.2
7,5	3,9	-5.4	-3.2	-9.0
8,0	4,1	-6.2	-3.2	-11
8,5	4,4	-7.7	-3.2	-15
9,0	4,6	-10	-3.2	-19
9,5	4,9	-11	-3.2	-21
10,0	5,1	-12	-3.2	-22
10,5	5,4	-13	-3.2	-24
11,0	5,7	-14	-3.2	-26
11,5	5,9	-15	-3.2	-29
12,0	6,2	-16	-3.2	-29
12,5	6,4	-16	-3.2	-28
13,0	6,7	-17	-3.2	-29

Table 4.3: Comparison in % of model compared to towing tank results

By using Rw1, the predicted R_S is closer towards the towing test results. For low velocities, the R additional is dominant over the R_w. For higher velocities, the R_w becomes more important. While the difference of R_S is smaller by using the values of Rw1, the values of the R_w are less consistent. The difference of R_w is changing from 0.2% towards -29.2%. This in comparison to a change of R_w from -27% towards -42% for using the Rw3 values. So using Rw1 is more accurate, but less consistent. Whilst Rw3 is quite consistent, but less accurate. This statement can also be visualised. The absolute and normalised difference between the towing test results and the prediction made by CAESES, using both Rw3 and Rw1, can be seen in figure 4.2.

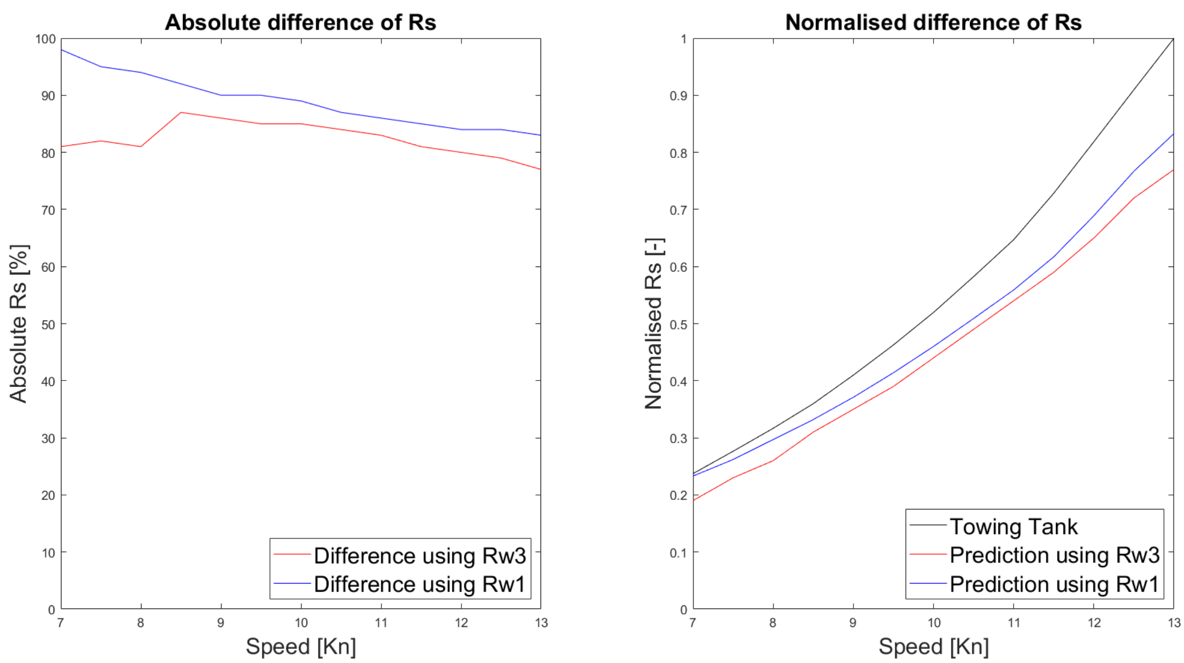

Figure 4.2: Absolute and normalised differences between towing test results and prediction made by CAESES

By using Rw1 instead of Rw3, the total ship resistance is closer to the towing tank results. However, there is still a too large difference to claim that the resistance prediction is highly accurate. So the hypothesis was partly true. The prediction tool can be used for comparison between generated hull geometries. Especially when using the values of Rw3. For more accurate values, one can use the values of Rw1 or a higher fidelity tool can be used. The results show a bigger difference than expected, probably because of the sonar bulb which was not incorporated in the CAESES model. Also limitations are acting on the usage of the tool. The stern area is hard to predict using RAPID because of side effects of inviscid flow theory (see section 3.2), so this area should be kept untouched in order to preserve the comparison capability of the tool. The values of Rw3 will be used for the new approach, as these results are more consistent, and should provide good results for comparison purposes. Furthermore, post processing of the results should be done with caution (like selecting the fuel tank size, propulsion system and predicting the LCC). This means more research is needed for the resistance validation, because of the large difference in predicted total resistance. Note, the validation is only based on one vessel, which was also equipped with a sonar dome. The absence of this sonar dome in the remade version has a large influence on the difference in Rw and Rf. A recommendation is to also use other vessels in the validation.

4.2. INFLUENCE OF RESISTANCE COMPONENTS ON OUTPUT

The resistance objective consists of two components. The wave making resistance which is predicted by RAPID, and all other components (like friction resistance) predicted by the empirical formulation of Holtrop and Mennen. The question arises what the effect of this separation is on the results of an optimisation study. This will be tested by a validation study. The question to answer is: What are the differences in output if only RAPID is used for the resistance objective function, or also other components are included. Two sets of resistance objective functions will be used for this validation. One only uses R_w, predicted by RAPID, for the objective function, and the other one uses R_w and all other components for the objective function. The hypothesis is:

- Only using R_w will create a long, slender hull, to minimise the wave making resistance. The other resistance components will penalise too large vessels mainly because of increased wetted surface. This will induce a trade-off for the optimisation to come up with balanced geometry, which has low wave making resistance and low additional resistance.

The R_S is low when the summation of R_w and additional resistance components is low. Because of the low speed of the vessels, the impact of R_w will be relatively low. So a smaller vessel, with low wetted surface, will probably give the lowest possible R_S. This will increase the R_w slightly, but the decreased frictional related resistances will compensate this. If one is only decreasing the R_w, a different trade-off will be used. A small vessel will have higher Fn, which will increase the impact of R_w, and a bigger vessel, with low Fn, will give a decreased impact of the R_w.

SETTINGS

Two types of settings are used, both acting on the resistance objective. One only uses the prediction of RAPID, R_w, while the other one uses all resistance components. For both optimisation studies, the same constraints of minimal displacement and stability criteria are active. The design speed is 14kn with a minimal displacement of 1200t, see table 4.4. The design variables and optimisation settings are the same for both runs, see table 4.5.

Variable	**Value**	**Units**
Speed	14	[kn]
Volume constraint	>1200	[m^3]
Heading angle	180	[degree]
Wave amplitude	1	[m]
Position of Interest	0.9*LWL	[m]

Table 4.4: Parameters used for validation of influence of resistance components on output

Design Variable	Units	Lower limit	Upper limit
Length	$[m]$	50	100
Draft	$[m]$	2	8
Beam	$[m]$	10	15
Entrance Angle at WL	[degree]	15	30
Stem distance	$[m]$	5	12
X Frame Indication	[-]	0.1	0.9
Z Frame Indication	[-]	0.1	0.9

Table 4.5: Design variables for validate the influence of the frictional resistance

The first resistance objective is set as: $R_S = R_w$. The second resistance objective is set as: $R_S = R_w + (1 + k_1) * R_F + R_{TR} + R_A$. The motion objectives are the same for both studies, namely the vertical displacement and vertical acceleration for head waves at 0.9*LWL. Comparison will take place by looking at the Pareto front. The resistance objective will be plotted both against the vertical displacement and the vertical acceleration. However, the values of only taking R_w will always be lower than the value if all resistance components are used. This can be solved by using all resistance components for visualising the Pareto front, but don't use them for the objective, see table 4.6.

	RAPID only for resistance Objective	All components for resistance objective
Objective	R_w	$R_w + (1 + k_1) * R_F + R_{TR} + R_A$
Pareto visualisation	$R_w + (1 + k_1) * R_F + R_{TR} + R_A$	$R_w + (1 + k_1) * R_F + R_{TR} + R_A$

Table 4.6: Settings of objective functions and Pareto visualisation

Analysis of received output

The analysis is done on the realised Pareto front of both optimisation studies. Also the utopia points are calculated. The graph representing the output can be seen in figure 4.3.

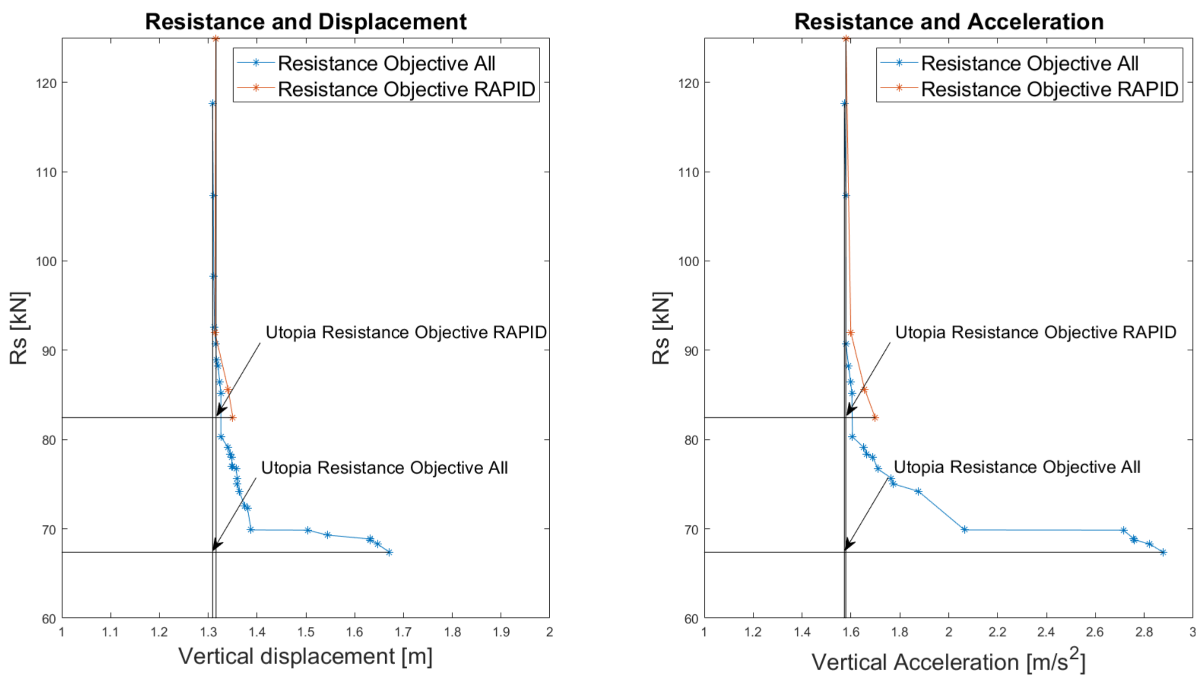

Figure 4.3: Pareto front of both optimisation studies

As expected, the realised values for the motion objective are almost the same for both types of objectives.

But the values for the resistance objective differ. The utopia point of the optimisation using only RAPID for the resistance objective is (82.5 [kN], 1.32 [m], 1.58 [m/s^2]). The utopia point of the optimisation using all components for the resistance objective is (67.4 [kN], 1.31 [m], 1.57 [m/s^2]). The one using only RAPID as objective shows higher R_S than the objective using all resistance components. This is in line with the hypothesis. This means that the new approach should use all components for the resistance objective. This because the viscous related resistance components have a large impact on the R_S. CAESES is better performing if all components are used.

4.3. ACCURACY OF MOTION PREDICTION

The motion prediction validation will give proof of the capability of the used method in predicting the motion of the vessel [47]. The hypothesis of the accuracy of the motion prediction is:

- The motion prediction is capable to compare the different models on vertical displacement and vertical acceleration.

The motion prediction looks at the maximum relative vertical displacement and the maximum vertical acceleration. The ranking from good to worse seakeeping capabilities should be analysed with help of a higher fidelity tool. The sequence, and thus the comparison between the different designs, is an important feature the renewed process should contain. Furthermore, the validation consists of study on the influence of different values of GM. As little is known about the value and the CoG of the vessel, rough estimations are used. The validation has to point out what the effect is of these estimations.

SETTINGS

To validate the usage of the simplified motion prediction method, a higher fidelity tool is used. But first an optimisation study is performed. This optimisation will create a Pareto front. Four designs on this Pareto front will be chosen. The selection will be based on the different values for the objective functions. With use of a higher fidelity tool, the two dimensional (2D) strip theory, the seakeeping performance of the selected designs will be compared. The validation is successful if the sequence found by the simplified method is the same as predicted by the higher fidelity tool. This means that the renewed process is capable to distinguish and compare the seakeeping performance in a fast and accurate manner.

An optimisation has been made with the design variables as given in table 3.5 and 4.8. The optimisation has been carried out with 33 iterations and every iteration will consist of 12 solutions.

Variable	**Value**	**Units**
Speed	11	[kn]
Volume constraint	>1200	[m^3]
Heading angle	180	[degree]
Wave amplitude	1	[m]
Position of Interest	0.9*LWL	[m]

Table 4.7: Parameters used for motion validation

A Pareto front has been generated after the optimisation is done. Also the utopia point is calculated. The utopia point has the coordinates of the minimum value of all three objective functions (R_S, displacement and acceleration). The best solution is the design which has the closest distance to this utopia point. The distance is calculated using Euclidean metric formulation. The values of the objective functions of every proposed design should be scaled first. The calculation of the distance is otherwise useless, because of the difference in units of every objective. Every objective is normalised by dividing the objective value by the maximum value of that objective. This maximum value comes from all other proposed models on the same Pareto front. The result is that all values will be between zero and one.

Design Variable	Units	Lower limit	Upper limit
Draft	$[m]$	2	8
LOA	$[m]$	50	100
Beam	$[m]$	10	15
Entrance Angle WL	[degree]	15	30
Stem distance	$[m]$	5	12
X Frame Indication	[-]	0.1	0.9
Z Frame Indication	[-]	0.1	0.9

Table 4.8: Design variables for motion validation

By calculating the smallest distance, the most balanced model is selected. But for some vessels, one objective can be more important than the other objectives. This can be solved by adding a weight factor to each objective. A higher weight factor will force the selection towards a proposed design with better capabilities for the objective on which the weight factor is applied. This method will be used to select the four proposed designs on the Pareto front for the motion validation. Design 1 is selected for lowest resistance, design 2 is selected for lowest vertical displacement, design 3 is selected for the lowest vertical acceleration and design 4 is selected for a balanced output, see table 4.9.

Name	Rs	Displacement	Acceleration
1: Lowest Rs	100	1	1
2: Lowest Displacement	1	100	1
3: Lowest Acceleration	1	1	100
4: Balanced	1	1	1

Table 4.9: Weighting factors for four proposed designs on the Pareto front

The Pareto front and the selected designs can be seen in figure 4.4.

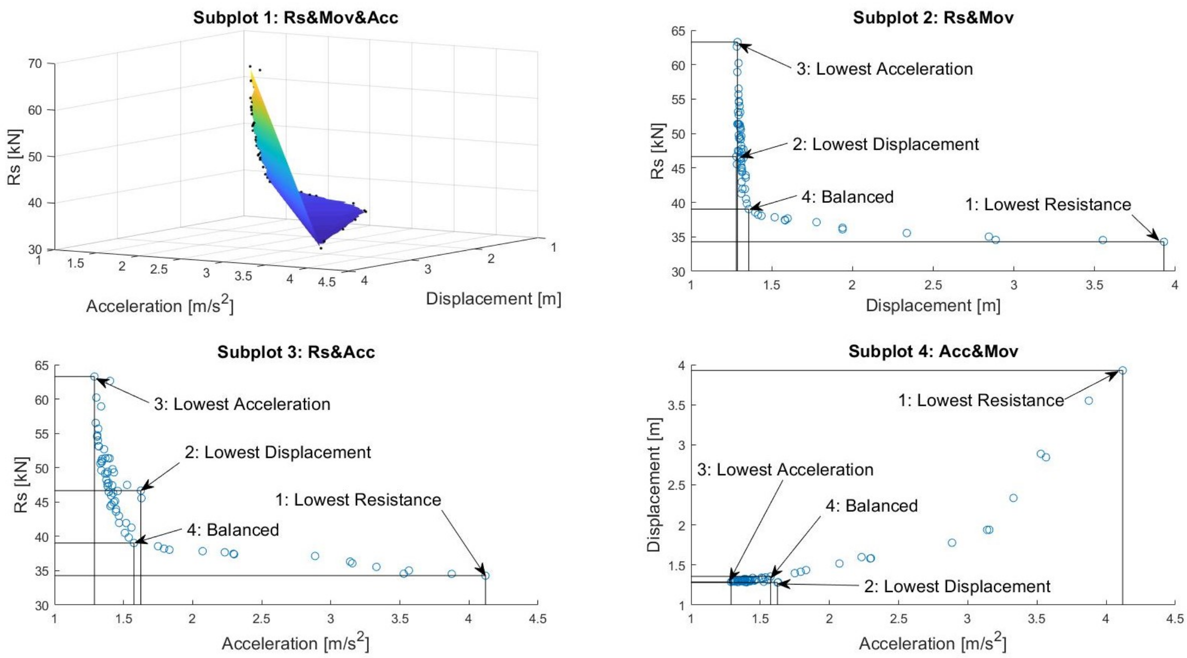

Figure 4.4: Pareto front with selected designs

The four selected designs will be used in the validation study for the motion and resistance prediction. The parameters from the designs are given in more detail in table 4.10. The volume (m^3) and Cb of these models are also given.

Design	1 (Resistance)	2 (Displacement)	3 (Acceleration)	4 (Balanced)
Draft [m]	4.70	2.02	2.33	3.38
LOA [m]	59.8	99.6	99.6	96.8
Beam [m]	10.1	12.4	12.7	11.4
Entrance Angle WL [degree]	22.3	28.8	29.3	15.3
Stem distance [m]	11.6	5.34	5.86	10.6
X Frame Indication [-]	0.657	0.539	0.151	0.615
Z Frame Indication [-]	0.814	0.438	0.139	0.633
Volume [m^3]	1210	1345	1867	1214
Cb [-]	0.454	0.625	0.653	0.517
Resistance objective [kN]	34.3	46.7	63.3	39.0
Max vertical displacement [m]	3.93	1.28	1.29	1.36
Max vertical acceleration [m/s^2]	4.12	1.62	1.29	1.58

Table 4.10: Parameters of design for motion validation

To prove the optimisation performances on motions the selected hull forms are tested with a higher fidelity tool. This comparison has been made by usage of the motion prediction program *MaxSurf Motion*, which is based on 2D strip theory. An academical license of *MaxSurf Motion* was provided by the TU Delft, which is the reason why this program has been used. This higher fidelity tool is used in the following way. A trimesh has been created in CAESES which can be imported in MaxSurf for every selected design. The location of interest is 0.1 LWL aft of the fore peak (FP), at $0m$ offset and $0m$ height. The absolute position will differ per design as the LWL is also changing. The motion will be analysed for the design speed of 11kn. The headings used are 180, 135, 90 and 45 degree. The spectrum is a Joint North Sea Wave Project (JONSWAP) type, and a characteristic height of $4m$ is used. Furthermore, a modal period of 9.993 seconds (s) is used with an average period of 8.367 s, a zero crossing period of 7.875 s and a peak enhancement factor of 3.3.

The other parameter settings in MaxSurf Motion are as follows. The imported trimesh is mapped into 41 parts, which will be the 2D sections used by MaxSurf Motion. The vessel type is set to Monohull. The total roll damping is set to 0.075. The water density used is $1.025 t/m^3$. The mass distribution has a big influence on the seakeeping performances. As little is known for the given designs, the used values are only rough estimations. The roll gyradius (K_{xx}) is 0.4*B, the pitch gyradius (K_{yy}) is 0.25*LOA and the yaw gyradius (K_{zz}) is 0.25*LOA, which are all the default values. The vertical centre of gravity (VCG) is needed to calculate the GM of the vessel. The assumption has been made that the GM is between 0.5m and 1.5m for every ship. Three values for GM will be used in the validation: 0.5m, 1.0m and 1.5m. By using three values for GM, the influence of the VCG on the motions can be analysed.

In a later phase in the ship design, like the concept definition, a more accurate VCG needs to be calculated. But during concept exploration, this information is not always known, takes too much time to compute for a large variation of hull forms or has a too big uncertainty. Only the bare hull will be used, because of similar reasons. This means no bilge keels will be included. No bilge keels will create a large roll motion, but by looking at only the bare hull, the influence on motions of only the bare hull form can be analysed. In a later design stage the roll motion can be reduced further by looking at roll stabilising systems like bilge keels, anti-rolling tanks or active fins [53]. The VCG will be computed by use of the following formulas:

$$
\begin{aligned}
KB &= \text{Calculated in MaxSurf}[m] \\
BM &= I_T/\text{Displacement}[m], \text{Calculated in MaxSurf} \\
KG &= VCG[m], \text{input for calculation} \\
GM &= KB + BM - KG[m]
\end{aligned}
$$

These formulas are applied on the selected models. The longitudinal length of the point of interest (PoI) (which is at 0.9*LWL), the KB, the BM and the GM are given in table 4.11.

	Name	1	2	3	4
	PoI longitudinal [m]	50.7	87.4	87.4	83.0
	KB [m]	2.89	1.18	1.36	1.32
	BM [m]	2.35	6.59	7.47	5.20
GM=1.5	GM [m]	1.5	1.5	1.5	1.5
	KG (VCG) [m]	3.74	6.27	7.33	5.03
GM=1.0	GM [m]	1.0	1.0	1.0	1.0
	KG (VCG) [m]	4.24	6.77	7.83	5.53
GM=0.5	GM [m]	0.5	0.5	0.5	0.5
	KG (VCG) [m]	4.74	7.27	8.33	6.03

Table 4.11: Mass distribution and longitudinal position of Point of Interest (PoI)

ANALYSIS OF RECEIVED OUTPUT

For the comparison and validation, one will analyse the spectra at the PoI. The heave, pitch and roll RAO's and the vertical displacement and acceleration will be compared. The headings 180, 135, 90 and 45 degree are used. First the vertical displacement and acceleration will be compared. The results are given for a GM of 1.0m, and for 180 and 135 degree heading, see figures 4.5 and 4.6.

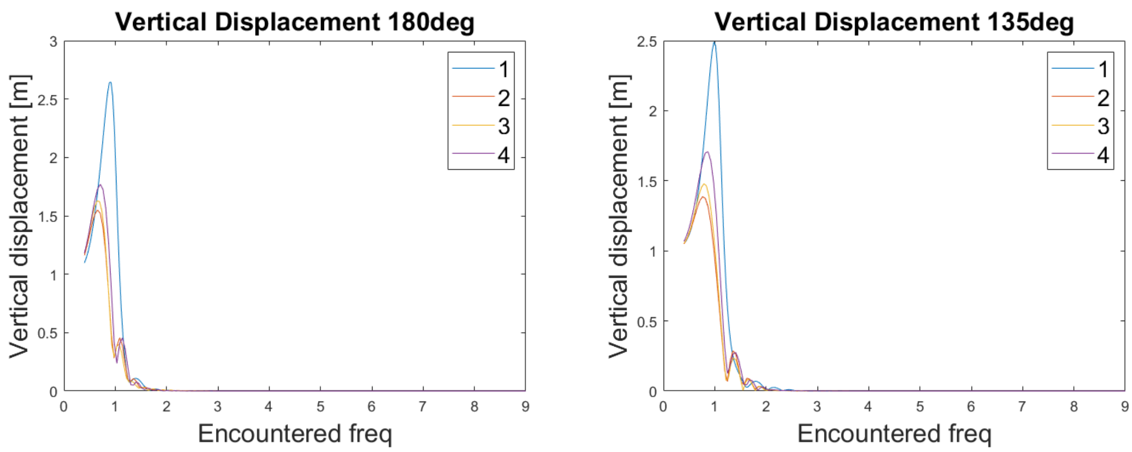

Figure 4.5: Vertical displacement (m) as function of wave frequency for different headings at 11 kn

The sequence for maximum vertical displacement, from high to low values, was predicted to be 1-4-3-2. The same sequence is found using MaxSurf Motion. For both headings, the found sequence is 1-4-3-2. The model with lowest resistance, but with highest displacement, has indeed the highest vertical displacement. The balanced model comes at the second place. The models 2 and 3 show only little differences, but this was also predicted by the simplified motion prediction method. Different values for GM didn't influence the results. The results for GM=0.5m can be seen in Appendix G. The complete results for GM=1.0m can be found in Appendix H. The results for GM=1.5m can be found in Appendix I. This means that the simplified strip theory is capable to compare different models on vertical displacement.

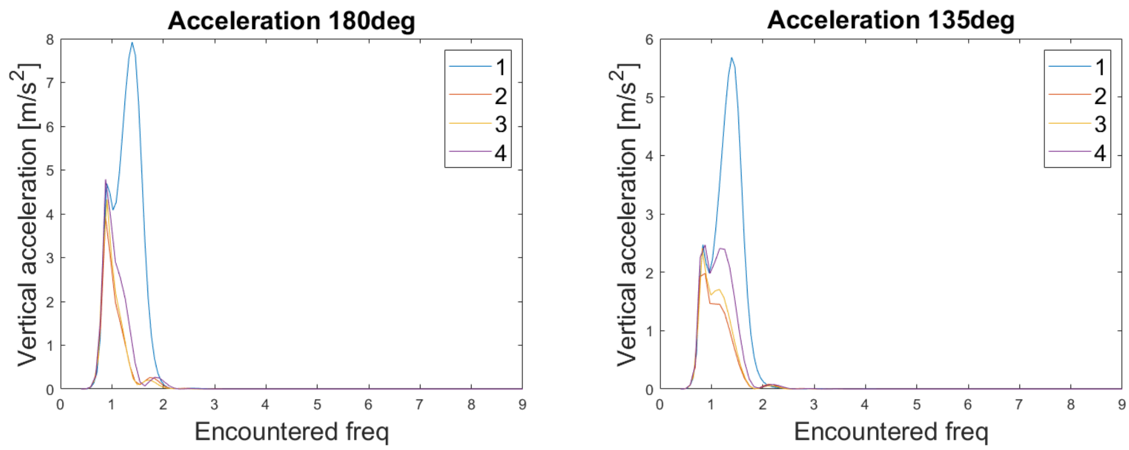

Figure 4.6: Vertical acceleration ($(m/s^2)/m$) at 0.1 L_{BP} aft of FP as function of wave frequency for different headings at 11kn

The sequence for vertical acceleration, from high to low values, was predicted to be 1-2-4-3. It becomes clear that model 1 has by far the highest acceleration. But the other models are close to each other, with the sequence 1-4-3-2 for both headings. The models 2 and 3 show only little difference. While the prediction was that models 2 and 4 should show little difference. This same difference can be seen for a GM of 0.5m and 1.5m. The found sequence doesn't correspond with the predictions made by the simplified method. This means the simplified strip theory is less capable to compare different models on vertical acceleration.

The difference between the accuracy of the prediction of displacement and acceleration has its origin in the fact that one differentiates the displacement two times to get the acceleration. The order O, becomes smaller with a larger uncertainty as a result. To acquire more accurate acceleration predictions, the order O of the displacement prediction should increase [54]. Also the position of the point of interest has a large influence on the predictions of the vertical displacement and acceleration .

The figures 4.7, 4.8 and 4.9 show the heave, pitch and roll respectively. This for a GM of 1.0m for the headings 180 and 135 degree.

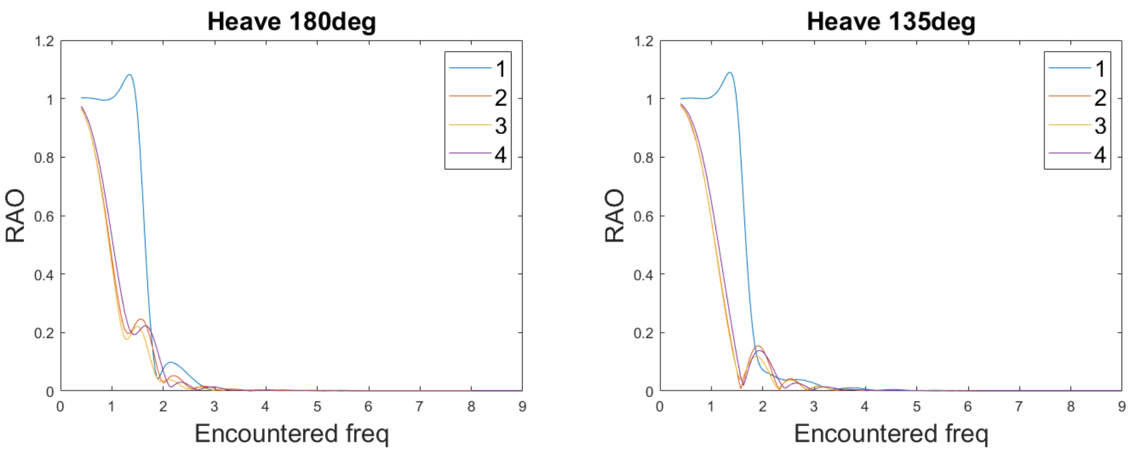

Figure 4.7: Heave motion (m/m) as function of wave frequency for different headings at 11kn

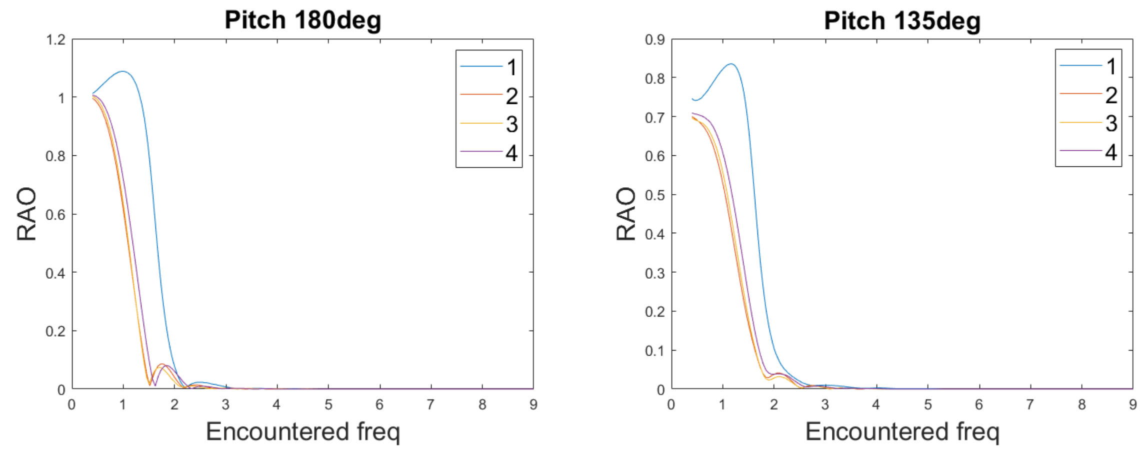

Figure 4.8: Pitch motion/k (m/m) as function of wave frequency for different headings at 11kn

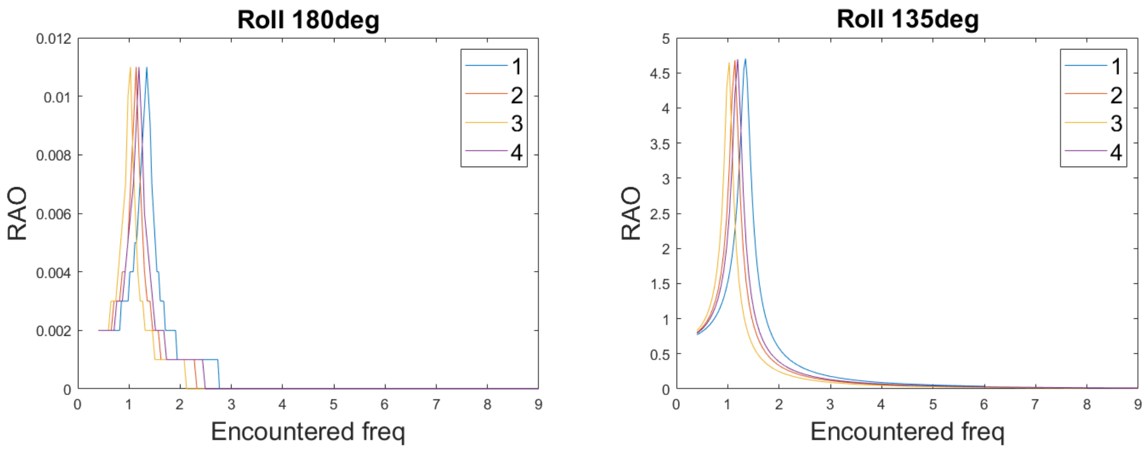

Figure 4.9: Roll motion/k (m/m) as function of wave frequency for different headings at 11kn

In these figures one can clearly see that model 1, optimised for lowest resistance, has the worst seakeeping capabilities. This model has RAO values above one, which means it is acting on the eigenfrequencies of the vessel. The geometry of model 1 is different than the other models. It has the highest draft (4.70 m), shortest length (59.8m) and lowest Cb (0.454), as can be seen in table 4.10. Especially the short length will have a significant influence on the vertical motions like heave, pitch and acceleration. The other models show similar behaviour, and show only little response.

The last comparison concerns the effect of the GM. The roll motion at 135 degree heading will be compared, see figure 4.10. The roll motion is indeed changing for different values of GM.

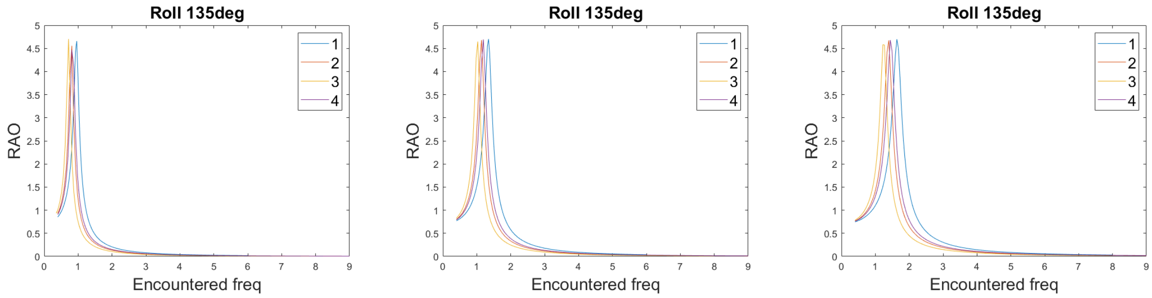

Figure 4.10: Roll motion as function of wave frequency for a heading of 135 degree at 11 kn for different values of GM

To conclude, the motion is partly validated. The new approach is capable to distinguish the differences in vertical displacement. The vertical acceleration predictions are only partly right. For comparison between models with large differences it is accurate enough. But when the models have comparable dimensions, the prediction becomes uncertain. The vertical displacement can thus still be used as an objective, while the vertical acceleration cannot be used anymore. To incorporate the vertical acceleration as an objective, one has to adjust the prediction method. This can be done by using a higher fidelity tool, by adjusting the simplified strip theory method or by expanding the validation study (other position of PoI and other headings). This advice will be incorporated in the recommendations. A positive correlation was found between vertical displacement and acceleration, as can be seen in figure 4.4. The rate of vertical acceleration is likely to follow the same trend as can be seen for vertical displacement. So low vertical displacement will probably also mean low vertical acceleration, which is not entirely true in reality. Vessels equipped with an X-bow have large vertical displacement, but low vertical accelerations for example. It is proven that the GM is hardly influencing the results, which is not a surprise when looking at head waves. The same sequence was however also found for other headings and values of GM using the higher fidelity tool, which means the seakeeping capabilities can already be predicted without knowing the exact details of the vessel.

4.4. VALIDATION OF PROPOSED OPTIMISED MODELS

Many models are proposed by each optimisation study. But validation has to give proof on the question if the proposed optimised models are indeed in line with the expected outcome. This will be studied with an analysis on the differences between the models on the Pareto front. The question to be answered is: What is the difference between the proposed models for optimised resistance and/or optimised seakeeping capabilities. The hypothesis is:

- For low vertical displacement, a long hull with a small beam is needed. For low resistance, low frictional resistance and low wave making resistance is desired. A balanced model will have a slender hull with a relative low Cb.

This will give the following values for the design variables. The length will be very high for the best seakeeping performances and will decrease for lower resistance. The beam will be low for good seakeeping capabilities and low for reduced resistance. The entrance angle at WL will be high for low vertical displacement. The entrance angle will be small to acquire low resistance. A slender bow will minimise the wave making resistance.

SETTINGS

The settings will be the same as for the validation of the influence of the resistance components, see section 4.2. The resistance objective using all components will be used. The output data of the suggested models will be analysed to confirm the hypothesis. See table 4.12 for the output data.

Name	Length [m]	Beam [m]	Draft [m]	Entrance angle [degree]	Total resistance [kN]	Vertical displacement [m]	Cb [-]
Design001	99.4	11.6	2.11	29.7	117.6	1.31	0.664
Design002	99.9	11.6	2.11	29.5	107.3	1.31	0.660
Design003	99.9	11.6	2.11	29.9	98.3	1.31	0.653
Design004	99.9	11.6	2.11	29.5	92.6	1.31	0.649
Design005	99.9	11.6	2.11	29.7	92.6	1.31	0.655
Design006	99.9	11.6	2.11	25.5	90.7	1.32	0.641
Design007	99.9	11.4	2.09	29.0	88.9	1.32	0.638
Design008	99.9	11.6	2.11	25.5	88.2	1.32	0.631
Design009	99.9	11.6	2.11	25.5	86.5	1.32	0.622
Design010	100.0	11.4	2.09	26.4	85.2	1.33	0.613
Design011	99.9	11.1	2.05	22.9	80.3	1.33	0.607
Design012	99.8	11.4	2.09	21.4	79.1	1.34	0.578
Design013	99.9	11.4	2.09	22.5	78.4	1.35	0.566
Design014	99.1	11.4	2.09	22.9	78.1	1.35	0.565
Design015	99.8	11.4	2.09	21.0	77.0	1.35	0.559
Design016	99.7	11.4	2.09	21.4	77.0	1.35	0.559
Design017	99.5	11.6	2.11	20.7	76.7	1.36	0.549
Design018	97.3	11.4	2.09	21.3	75.7	1.36	0.554
Design019	99.9	11.5	2.11	15.7	75.0	1.36	0.563
Design020	96.1	11.4	2.09	18.6	74.2	1.36	0.575
Design021	99.1	11.6	2.11	15.2	72.6	1.37	0.534
Design022	99.9	11.6	2.11	15.7	72.3	1.38	0.519
Design023	91.9	11.6	2.11	15.2	69.9	1.39	0.565
Design024	80.8	12.2	2.32	15.7	69.9	1.50	0.576
Design025	86.4	12.7	2.37	16.5	69.3	1.55	0.492
Design026	86.7	12.2	2.46	15.8	68.9	1.63	0.491
Design027	86.4	12.0	2.46	16.4	68.8	1.63	0.496
Design028	85.2	12.8	2.49	15.5	68.3	1.65	0.485
Design029	85.2	12.3	2.49	16.3	67.4	1.67	0.492

Table 4.12: Design variables and output parameters

ANALYSIS OF RECEIVED OUTPUT

See table 4.12 for the parameters of the models which are on the Pareto front. The values of the design variables, the obtained values for the objectives and additional data such as the Cb are given. A more extensive table can be found in Appendix J. The trends of the design variables on the objectives will be analysed. The trends are visualised by using all models which are generated during the study. Every dot is different variant, 400 in total.

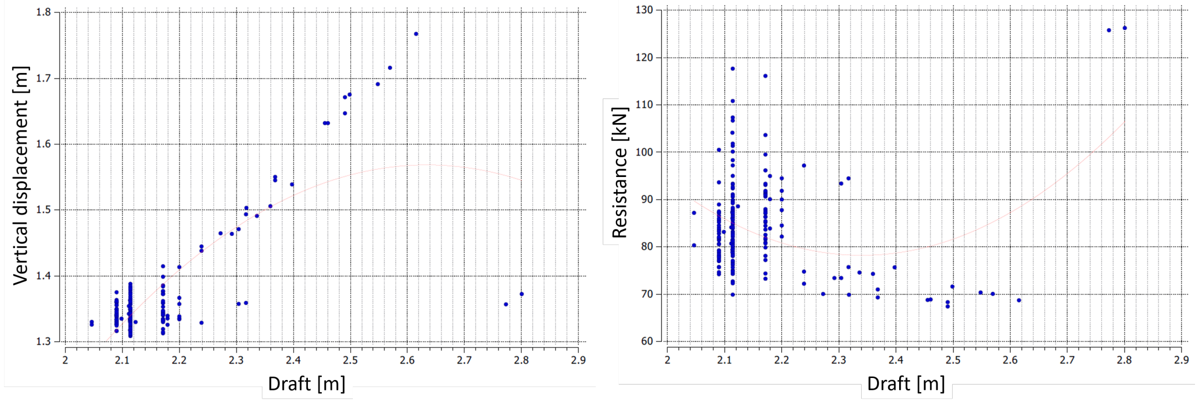

Figure 4.11: Vertical displacement and resistance versus draft

The design variable on draft acts like predicted, see figure 4.11. The draft is as low as possible while still meeting the stability constraint. For the lowest resistance, the draft is increased only by a small amount, but this can be the result of the increased beam.

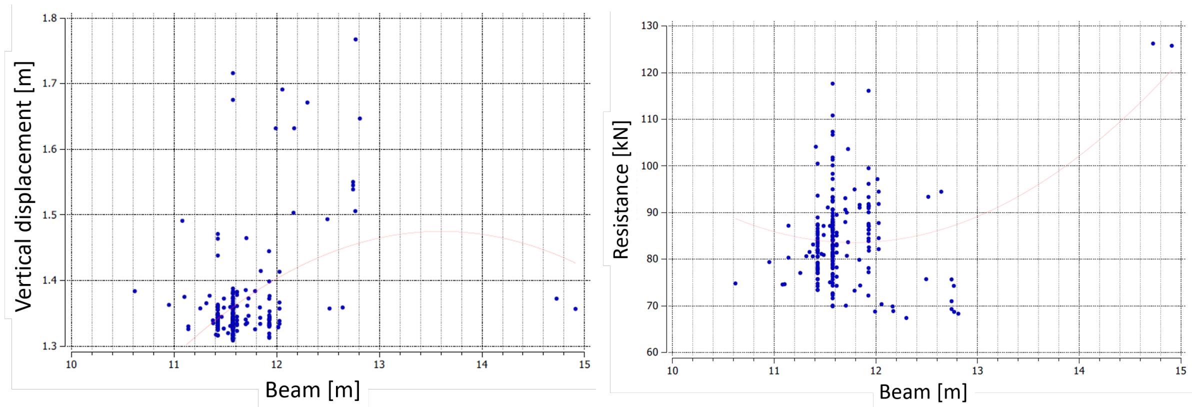

Figure 4.12: Vertical displacement and resistance versus beam

The beam parameter acts like predicted, see figure 4.12. The beam is in the lower range for the best seakeeping capabilities. For the lowest resistance, the beam is slightly higher. The increased beam can be a result of the lower volume while decreasing the total resistance. A certain minimum displacement should be achieved, otherwise a constraint is violated. To acquire this minimum displacement, the design will have an increased beam to increase the displacement.

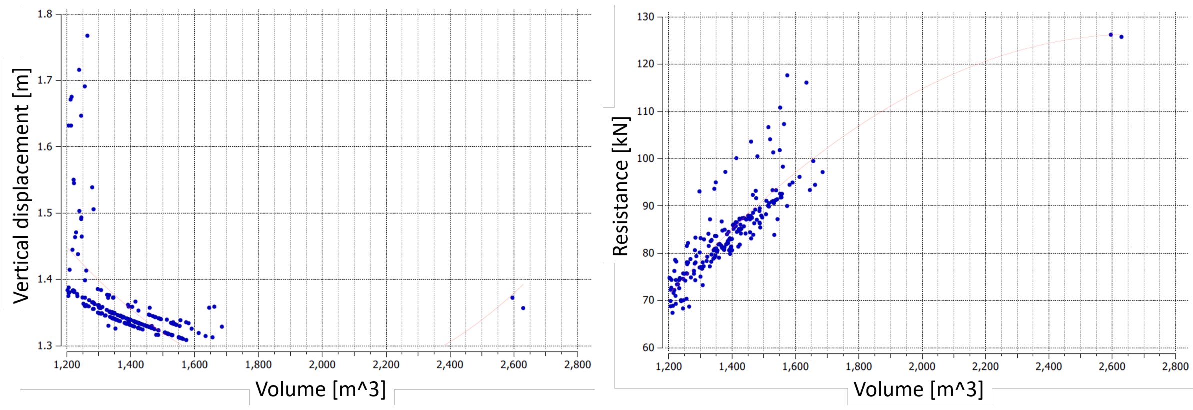

Figure 4.13: Vertical displacement and resistance versus volume

The volume is behaving like predicted, see figure 4.13. For better seakeeping capabilities, models with a high volume are proposed. Lower volumes are found for lower resistance.

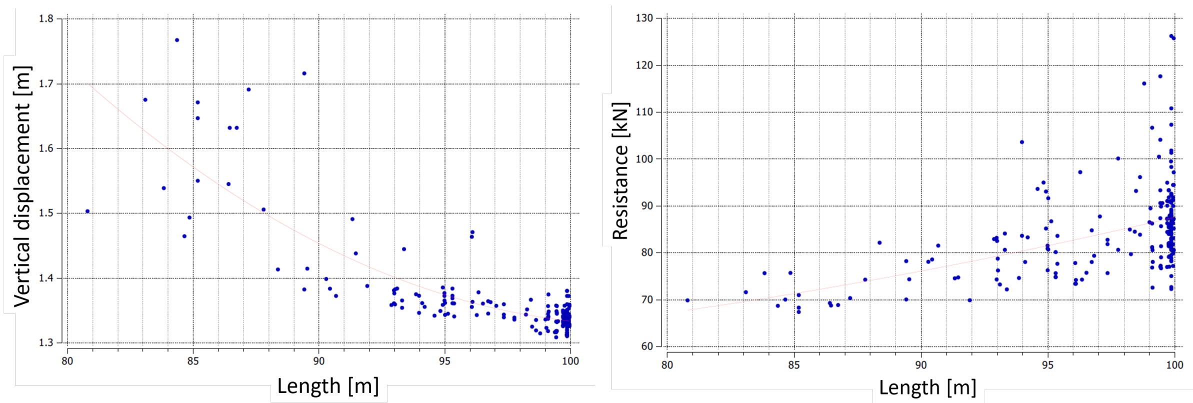

Figure 4.14: Vertical displacement and resistance versus length

The length parameter acts like predicted, see figure 4.14. The length is as high as possible for good seakeeping capabilities. The wetted area is decreased for smaller lengths. A lower wetted area will decrease the viscous related resistance, which is beneficial for the total resistance. Models with lower resistance are found for smaller lengths.

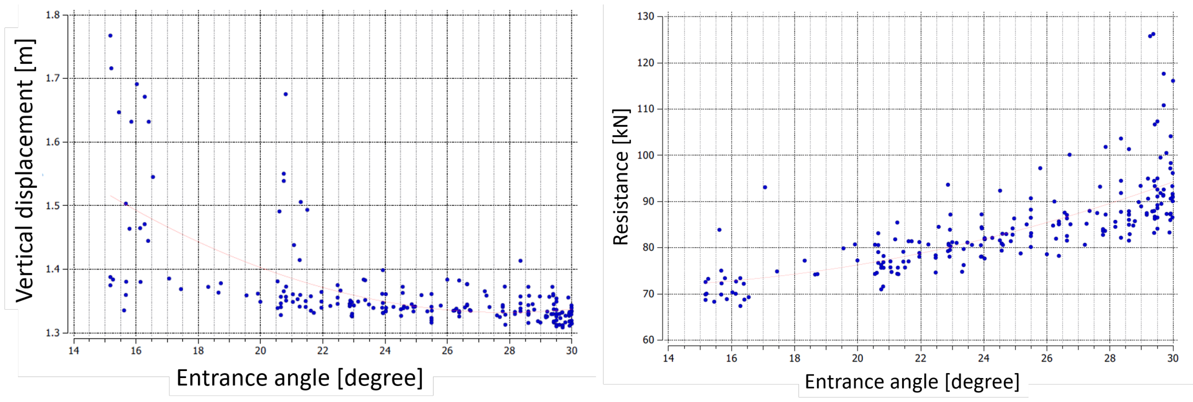

Figure 4.15: Vertical displacement and resistance versus entrance angle

The entrance angle at WL acts like predicted, see figure 4.15. The entrance angle is high for low vertical displacement. While for decreased resistance, the entrance angle becomes smaller.

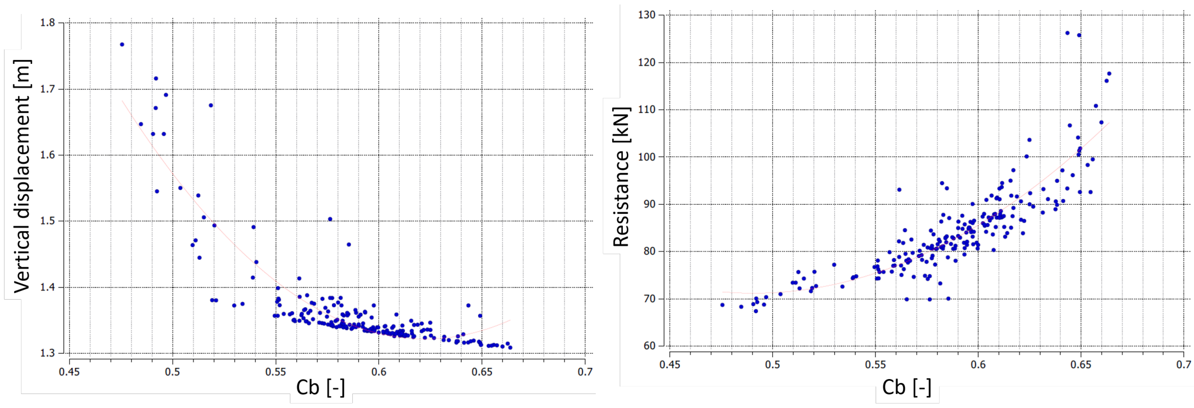

Figure 4.16: Vertical displacement and resistance versus Cb

The validation is continued with an analysis on the Cb, see figure 4.16. The obtained values are also acting as predicted. The highest Cb is found for the best seakeeping capabilities, while lower values of Cb are present for lower resistance.

All analysed parameters are acting like predicted. This means the relative merit is reliable.

4.5. FEEDBACK ON REQUIREMENTS

Validation studies have been performed on the resistance objective, the motion objectives and the optimisation algorithm. This section will give feedback on the given requirements of the new approach. The requirements were formulated in section 2.3 on page 18. The requirements are mentioned first, and feedback will be given afterwards. First the requirements that should always be present in the concept exploration phase:

- 'It should only use information typically available in the concept exploration phase'. All information is created and analysed within the same programme. So almost no additional information is required by the process to produce results. Necessary input is kept at a minimum, to make it easy to implement and to use it at a lot of different design cases. The input that should be provided is the geometry of the parent hull, the range and description of the design variables and design constraints.

- ‘It should be fast as only limited amount of time is available’. The focus on speed is present at all chosen tools. The geometry modelling in CAESES uses only limited amount of design parameters. Also the mesh generation is chosen to be detailed enough to create accurate results, without using too much computational power. The motion prediction method is based on a simplified version of the strip theory. This gave fast but reliable results for the vertical displacement prediction. Also the optimisation method is specially chosen to give the best results in a short amount of time.
- ‘The concept exploration phase will be highly successful if many variations are performed’. The amount of variations is chosen to be large enough to explore a large amount of the total design space. But limited to reduce the calculation time. Also the settings of the optimisation method are chosen in such a way that the solution convergence with acceptable accuracy.

Requirements originating from the design trade-offs are:

- ‘It should include a motion objective focusing on vertical displacement and vertical acceleration’. A simplified closed form method of the linear strip theory is chosen to predict the motion behaviour. This method is capable to compare the different models on maximum vertical displacement. The method was not accurate enough to compare the maximum vertical acceleration.
- ‘It should include a power usage objective’. By using the RAPID and viscous resistance as the resistance objective, accurate results can be obtained. By use of RAPID, small changes on the geometry have effect on the objective. With other words, the method is very sensitive to changes of the geometry. A disadvantage of the method is the high calculation time compared to empirical methods. But the optimisation method is specially designed to reduce the amount of iterations needed.
- ‘The optimisation method should handle multiple objectives’. Three optimisation methods, which are included in CAESES, were examined in the selection. All methods are Genetic Algorithm based and can handle multi objectives. The selected method, DAKOTA - Global Optimisation on Response Surface, gave the best results in the lowest amount of time.
- ‘It should be a reusable process, to be used for different kind of support vessels’. The initial geometry is the result of the input of the naval architect. The basic curves can be changed very easy, to adjust the hull form to the desired geometry. This makes it a reusable process which can be used for different kind of vessels. The parent hull used for the case study is based on the current Hydrographic Survey vessels, as the new generation naval support vessels will most likely look quite similar [5].
- ‘It should use a basic set of parameters as input for motion and resistance predictions’. The geometry can be adjusted by use of only seven design variables. The generated geometry will be used as input for the motion and resistance predictions. All necessary input for the selected prediction methods are available in the design phase it is used at.
- ‘It should reduce human interaction, so preferably an automated process’. All selected tools are working in an automated process. This still means, however, that the user should provide the program with all relevant data, such as the range of the design variables and the values of the constraints. Also the way the parent hull is designed and the influence of the design variables are subjects that have a large impact on the results.

4.6. CONCLUSION OF VALIDATION STUDY

The conclusion of the validation study shall provide an answer to the fifth sub question: 'How to validate the model'. Different parts of the renewed process are validated in order to prove its reliability.

The first validation focused on the resistance prediction. A comparison has been made between results from the renewed process and results obtained by a towing tank test. The differences between the results were larger than expected, mainly because of the sonar bulb which was not present in the used geometry. The same trend was found by using a more accurate prediction method of RAPID. The resistance validation should be expanded by including additional vessels. But, by looking at the literature, the combination of a potential flow solver and the viscous resistance components is widely used for comparison studies. So an optimisation study can be performed using these prediction tools.

In the second validation, the influence of the resistance components were analysed. By using RAPID in combination with Holtrop and Mennen gave better results than the results obtained by only using RAPID.

The third validation demonstrated the prediction capabilities of the motion objectives. The predicted sequence for vertical displacement was also found using a higher fidelity tool. The vertical acceleration prediction sequence was only true if large changes in dimensions are present. This means the prediction on vertical displacement can still be used as an objective, while the objective for vertical acceleration will not be used anymore. The recommendation is to also study the influence of other headings and other positions in height and longitudinal direction.

The fourth validation study was about the proposed optimised designs. The trends of the proposed optimised designs are the same as expected, like a long slender hull for better seakeeping capabilities, and a more compact vessel for lower resistance.

5

APPLICATION OF THE METHOD ON TEST CASE

The test case consists of three studies on the selected naval support vessels. The results of these studies can be used to answer the research question on addressing the focus points. Also the main question can be answered, if the suggested model is suitable within the concept exploration phase at DMO. The first study, see section 5.1, concerns the comparison between the design strategy which should be used. The second study, see section 5.2, gives information about the influences of the design speed. The third study, see section 5.3, concerns the differences between the current Hydrographic Survey vessel and optimised models. The last section, 5.4, will consist of a discussion and shall provide an answer to the sixth sub question: 'Is the new approach capable to address the focus points which are present for the new generation of the naval support vessels with a hull geometry point of view?'

5.1. COMPARISON BETWEEN DESIGN STRATEGIES

The model is designed to gather information for addressing the focus points. In this study the comparison between the single design strategy and the family design strategy are investigated. This will be done by comparing the total Pe [kWh] needed and the associated vertical displacement [m] for both strategies. The requirements (the range of design variables) and operational profile of every single vessel will be used as input, see table 5.1. A description of the terms 'open' and 'restricted' can be found in section 2.1. A parametric optimisation study is started which creates a Pareto front. A model on this Pareto front is selected and the Pe is calculated for the given operational profile (see table 2.3). Also the maximum vertical displacement associated for the given operational profile is calculated. When the calculations are performed for every vessel, a comparison can be made on the required Pe and associated vertical displacement. The hypothesis is formulated as:

- The single design strategy will require lower total propulsion power than the family design strategy. The 'open' design will also have lowerPe than the 'restricted' design. The motion capabilities of the 'open' family design strategy will be better than for the single design strategy. While the motion capabilities of the 'restricted' family design will be worse than for the single design strategy.

The prediction is that the total Pe will be lower for the single design strategy than for the family design strategy. The amount, and the key factors behind this difference, should be analysed. The 'restricted' design has strict limits on its design variables. This limits the design space and will give proposed models with higher resistance than obtained for the 'open' design. The motion of the 'restricted' design will be the worse. While an 'open' family design will have better seakeeping capabilities compared to the single design strategy.

SETTINGS

The input and output is given per vessel used in the test case. The input will consist of parameters used in the hydrodynamic optimisation tool. These are values like design speed, the minimal volume and other settings. Also the design variables and their ranges are given. This will be the input which is needed for the optimisation tool to generate results. These results will be given in the output. The output will consist of the Pareto front with possible feasible geometries. The Hydrographic Survey vessel and the Marine Training vessel will have their own Pareto front, while the Pareto fronts of all other vessels will be combined in one figure, because of their principal differences in required design speeds. These will be analysed and one vessel on the Pareto front will be used for further research. The parameters of the selected model are also given. See table 5.1. See Appendix K for a more detailed input per vessel.

Type	**Hydrographic Survey**	**Logistic Support**	**Submarine Support**	**Marine Training**	**Family design Restricted**	**Family design Open**
Δ_{min} $[t]$	≥ 1200	≥ 1200	≥ 1250	≥ 1000	≥ 1250	≥ 1200
LOA $[m]$	50 – 100	50 – 65	55 – 100	50 – 100	55 – 65	50 – 100
BOA $[m]$	10 – 15	10 – 15	10 – 15	10 – 15	10 – 15	10 – 15
T $[m]$	2.0 – 8.0	2.0 – 3.5	2.0 – 8.0	2.0 – 8.0	2.0 – 3.5	2.0 – 8.0
Design Speed [kn]	11	14	14	10	14	14

Table 5.1: Overview of specifications of the new generation naval support vessels

ANALYSIS OF RECEIVED OUTPUT

The settings for the parametric optimisation are ready to be used. The results from these optimisations will be analysed. To do this, post-processing is needed. First of all, a vessel needs to be selected for further research. The selected vessel is a proposed optimal design lying on the Pareto front. If the vessel is selected, the total Pe can be calculated. This is done with the formula $P_E = R_s * V$ [kW] [38]. The V in m/s is the speed found in the operational profile. The R_S comes from CAESES by calculations on the selected model for a set of different velocities. Also the time in hours for every speed is known, which will be used in the formula $kWh = P_E * h$. The sum of all Pe for all speeds for one type of vessel is the total effective towing power needed. This value is used for comparison purposes. The other objectives used in this study is the maximum vertical displacement.

The motion capabilities will be calculated in a similar way. The maximum vertical displacement is predicted for all speeds of the operational profile for the selected vessel. The maximum vertical displacement for a specific speed is multiplied with the amount of hours on that specific speed. The summation of all obtained values are divided by the total amount of hours, to get an average value which is describing the motion capabilities of the vessel.

HYDROGRAPHIC SURVEY (HOV)

The Pareto front can be seen in figure 5.1. The vessel is selected for having low vertical displacement, received by applying a weight factor of 1 for R_S and 2 for displacement, see table 5.7. These values have been chosen because low vertical displacement is two times as important as having low resistance for this type of vessel, see section 2.2 for the argumentation. The weight factors are chosen after analysing the influence of these values on the selection. The selected point is the closest to the Pareto utopia point. Lower values of motion will increase the resistance drastically. While for further reducing the resistance, the motion capabilities will be far of the optimum. The speed [kn] & [m/s], time [h], R_S [kN] and the values of the vertical displacement objective are provided by CAESES. The calculations of Pe [kWh] for a speed of 3 kn are given as an example:

$$P_E = R_s * V = 3.12 * (3 * 0.5144) = 4.82[kW] \text{ and}$$
$$kWh = P_E * h = 4.82 * 1728 = 8.33 * 10^3[kWh]$$

The average value of the vertical displacement objective, with input from table 5.2, is calculated by:

$$\text{Vertical Displacement Objective} = \frac{\sum(\text{DisplObj}_i * \text{Time}_i)}{\sum \text{Time}_i}$$
$$= \frac{1.22*1728+1.32*6336+1.41*2880+1.45*576}{11520} = 1.34$$
$$i = \text{Specific speed of the operational profile}$$

The predicted values for effective towing power and displacement can be seen in table 5.2. These values are sensitive to the operational profile used. The time and speed have a big influence on the output. The operational profile should therefore be made with close approximation to the profile used in reality. The values of the design variables of the selected model can be seen in Appendix K.

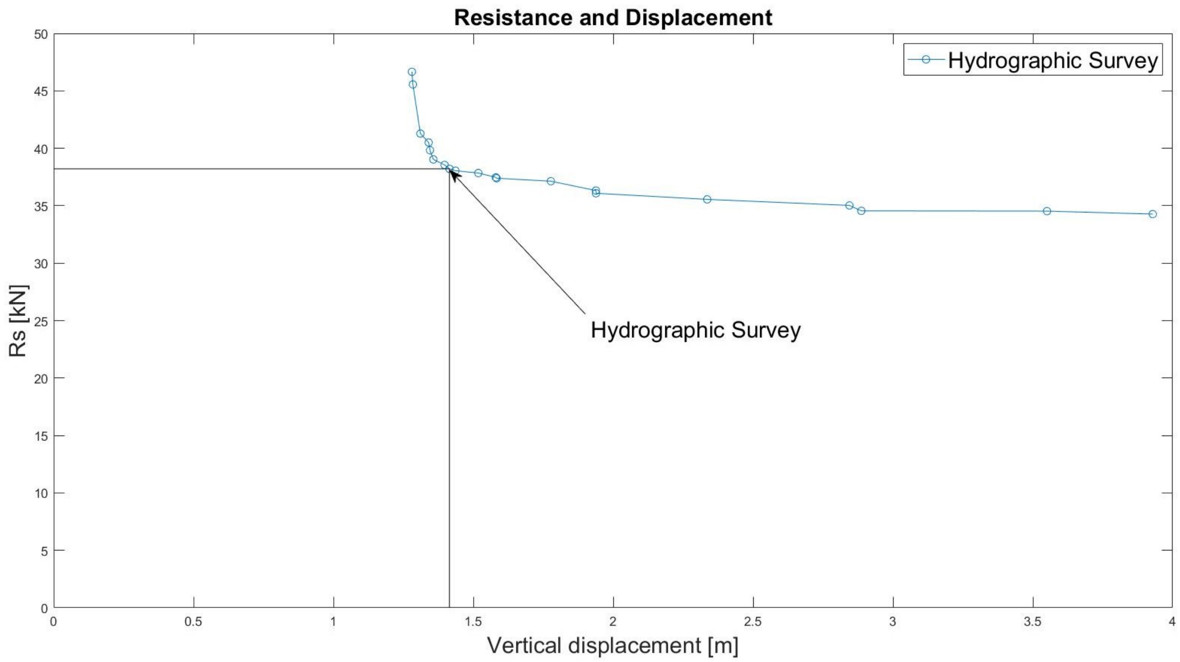

Figure 5.1: Pareto front of optimisation study, Rs and Displacement for HOV

Speed [kn]	Velocity [m/s]	Time [h]	R_S [kN]	Pe [kW]	Pe [kWh]	Displ Obj [m]
3	1.54	1728	3.12	4.82	$8.33*10^3$	1.22
8	4.16	6336	19.8	81.4	$516*10^3$	1.32
11	5.66	2880	38.2	216	$623*10^3$	1.41
12	6.17	576	47.8	295	$170*10^3$	1.45
Total	-	11520	-	-	$1,320*10^3$	1.34

Table 5.2: Operational profile and effective power for HOV

Logistic Support (LS)

The Pareto front can be seen in figure 5.3. The vessel is selected for having low resistance, received by applying a weight factor of 2 for R_S and 1 for displacement, see table 5.7. These values are selected because having low resistance is two times as important as having low vertical displacement for this type of vessel. This resulted in a geometry with lower resistance, but with higher motion as a result. The predicted values for effective towing power and displacement can be seen in table 5.3. The values of the design variables of the selected model can be seen in Appendix K.

Speed [kn]	Velocity [m/s]	Time [h]	R_S [kN]	Pe [kW]	Pe [kWh]	Displ Obj [m]
7	3.60	403	15.3	55.3	$22.2 * 10^3$	1.52
14	7.20	3427	67.4	485	$1,660 * 10^3$	1.91
15	7.72	202	80.9	624	$126 * 10^3$	1.95
Total	-	4032	-	-	$1,810 * 10^3$	1.88

Table 5.3: Operational profile and effective power for LS

SUBMARINE SUPPORT (SS)

The Pareto front can be seen in figure 5.3. The vessel is selected for having low vertical displacement, received by applying a weight factor of 1 for R_S and 1.5 for displacement, see table 5.7. These values have been selected because having low vertical displacement is one and a half times as important as having low resistance for this type of vessel. The predicted values for effective towing power and displacement can be seen in table 5.4. The values of the design variables of the selected model can be seen in Appendix K.

Speed [kn]	Velocity [m/s]	Time [h]	R_S [kN]	Pe [kW]	Pe [kWh]	Displ Obj [m]
5	2.57	336	8.88	22.8	$7.68 * 10^3$	1.22
10	5.14	1344	32.7	176	$236 * 10^3$	1.29
12	6.17	1512	46.2	316	$478 * 10^3$	1.32
14	7.20	168	61.9	540	$90.7 * 10^3$	1.36
Total	-	3360	-	-	$812 * 10^3$	1.30

Table 5.4: Operational profile and effective power for SS

MARINE TRAINING (MT)

The Pareto front can be seen in figure 5.2. The vessel is selected for having low vertical displacement, received by applying a weight factor of 1 for R_S and 2 for displacement, see table 5.7. These values are selected because having low vertical displacement is two times as important as having low resistance. The predicted values for effective towing power and displacement can be seen in table 5.5. The low vertical displacement will increase the resistance of the vessel. But the speed of transit is rather low for this vessel, which means the impact of this vessel on the total Pe will be small. The values of the design variables of the selected model can be seen in Appendix K.

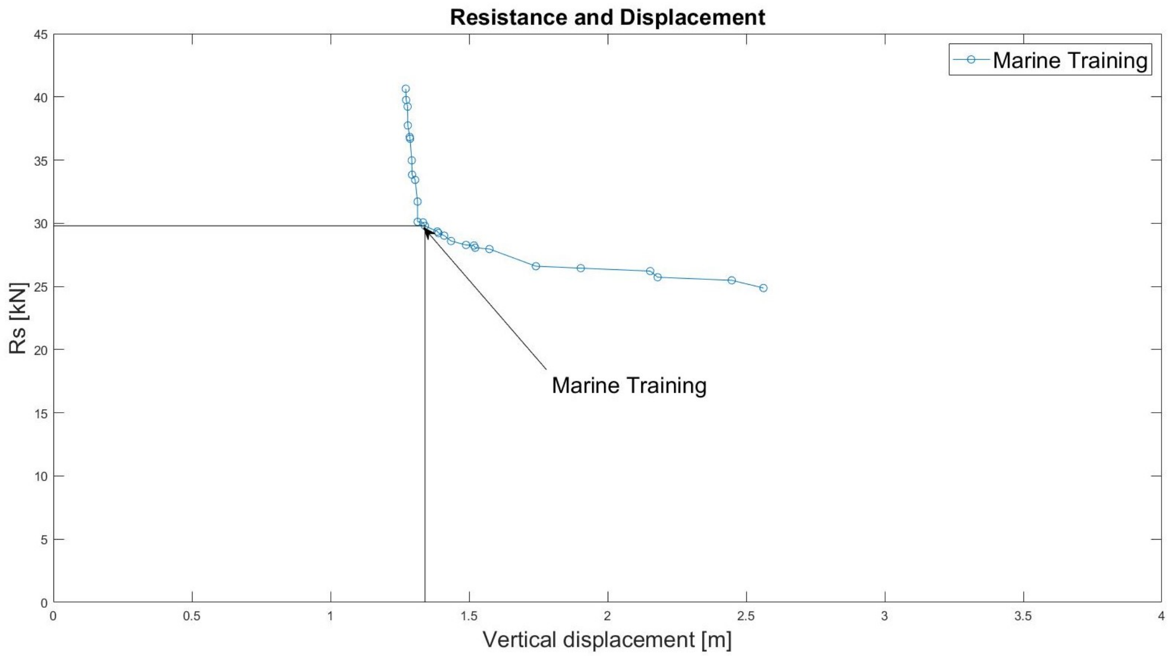

Figure 5.2: Pareto front of optimisation study, Rs and Displacement for MT

Speed [kn]	Velocity [m/s]	Time [h]	R_S [kN]	Pe [kW]	Pe [kWh]	Displ Obj [m]
4	2.06	1296	5.02	10.3	$13.4 * 10^3$	1.23
8	4.16	1944	18.7	76.8	$149 * 10^3$	1.30
10	5.14	864	29.8	153	$132 * 10^3$	1.34
12	6.17	216	44.5	274	$59.3 * 10^3$	1.39
Total	-	4320	-	-	$354 * 10^3$	1.29

Table 5.5: Operational profile and effective power for MT

FAMILY DESIGN RESTRICTED (FDR)

The Pareto front can be seen in figure 5.3. The weight factors of the Family design vessel are selected by taking the average of all weight factors applied on the vessels of the single design strategy. Remember that the HOV will contain two vessels. This gives a weight factor of 1 for R_S and 1.42 for vertical displacement.

The predicted values for effective towing power and displacement can be seen in table 5.6. The values of the design variables of the selected design can be seen in Appendix K.

Speed [kn]	Velocity [m/s]	Time [h]	Rs [kN]	Pe [kW]	Pe [kWh]	Displ Obj [m]
3	1.54	1728	3.32	5.14	$8.88 * 10^3$	1.26
4	2.06	1296	5.68	11.7	$15.2 * 10^3$	1.29
5	2.57	336	8.60	22.1	$7.43 * 10^3$	1.33
7	3.60	403	16.2	58.2	$23.5 * 10^3$	1.41
8	4.12	8280	20.9	86.2	$717 * 10^3$	1.46
10	5.14	2208	32.6	168	$370 * 10^3$	1.56
11	5.66	2880	39.3	222	$640 * 10^3$	1.62
12	6.17	2304	48.2	297	$685 * 10^3$	1.67
14	7.20	3595	73.3	528	$1,900 * 10^3$	1.76
15	7.72	202	85.8	662	$134 * 10^3$	1.80
Total	-	23232	-	-	$4,490 * 10^3$	1.53

Table 5.6: Operational profile and effective power for FdR

FAMILY DESIGN OPEN (FDO)

The Pareto front can be seen in figure 5.3. The weight factors are selected by taking the average of all weight factors applied on the vessels of the single design strategy. The weight factors are 1 for R_S and 1.42 for vertical displacement, see table 5.7.

	HOV	LS	SS	MT	FdR	FdO
Rs	1.00	2.00	1.00	1.00	1.00	1.00
Displacement	2.00	1.00	1.50	2.00	1.42	1.42

Table 5.7: Used weight factors per vessel

The predicted values for effective towing power and displacement can be seen in table 5.8. The values of the design variables of the selected design can be seen in Appendix K.

Speed [kn]	Velocity [m/s]	Time [h]	R_S [kN]	Pe [kW]	Pe [kWh]	Displ Obj [m]
3	1.54	1728	3.32	5.12	$8.85 * 10^3$	1.21
4	2.06	1296	5.68	11.7	$15.1 * 10^3$	1.22
5	2.57	336	8.61	22.1	$7.44 * 10^3$	1.23
7	3.60	403	16.1	58.1	$23.4 * 10^3$	1.26
8	4.12	8280	21.0	86.2	$714 * 10^3$	1.28
10	5.14	2208	32.9	169	$373 * 10^3$	1.31
11	5.66	2880	40.1	227	$653 * 10^3$	1.33
12	6.17	2304	48.7	301	$693 * 10^3$	1.35
14	7.20	3595	70.8	510	$1,830 * 10^3$	1.39
15	7.72	202	82.4	636	$128 * 10^3$	1.41
Total	-	23232	-	-	$4,450 * 10^3$	1.30

Table 5.8: Operational profile and effective power for FdO

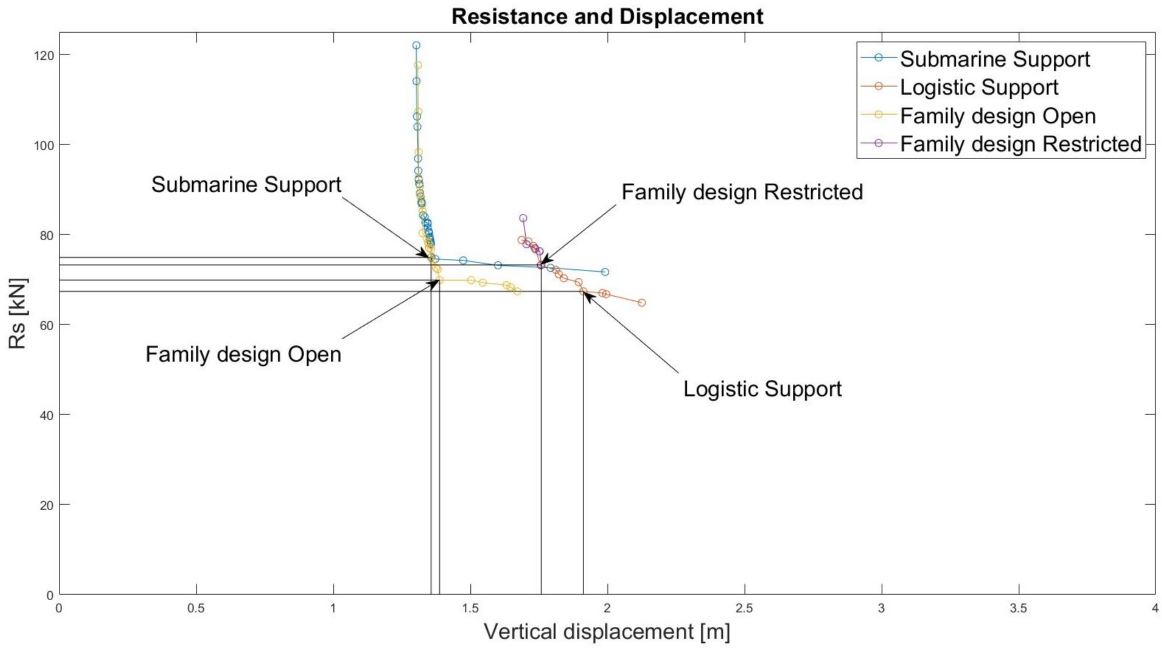

Figure 5.3: Pareto front of optimisation study, Rs and Displacement for LS, SS, FdR and FdO

The information of the Pareto fronts is summarised in table 5.9. The number of variations, number of variations on the Pareto front, values of the utopia point and values of the chosen design are provided for every vessel.

Vessel	Total #	# on Pareto front	Utopia point (R_S, Displ)	Chosen design (R_S, Displ)
HOV	447	20	(34.3, 1.28)	(38.2, 1.41)
LS	456	13	(64.9, 1.69)	(67.4, 1.91)
SS	411	39	(71.7, 1.30)	(74.9, 1.36)
MT	385	27	(24.4, 1.27)	(29.8, 1.34)
FdR	454	6	(73.3, 1.69)	(73.3, 1.76)
FdO	400	26	(67.4, 1.31)	(69.9, 1.39)

Table 5.9: Data of Pareto front and selected designs

COMPARISON

All values of the selected navy support vessels are calculated. These will be compared with each other. This will give information needed to address the focus points. The comparison will be between the single ship design strategy and the family design strategies. The single ship design will give the value for the motion objective and the Pe of the HOV, LS, SS and MT combined. The Pe of the single ship design is calculated by summation of all separate values of Pe. The value for the motion of the single ship design is obtained by calculating the average of the HOV, LS, SS and MT. Keep in mind that there will be two vessels for hydrographic survey, so the value of the HOV counts double. The results are summarised in table 5.10.

A comparison is made to analyse what the influence is of using more unity within the fleet. The comparison is about the effective towing power and the seakeeping capabilities. There is a trade-off between these two objectives, as they are mostly counteracting. The comparison has been made by using the results from the single ship design as a baseline, as can be seen in table 5.11.

Type	HOV	LS	SS	MT	Single ship design	FdR	FdO
LOA [m]	93.4	61.9	99.9	90.1	-	63.1	91.9
Beam [m]	10.9	15.0	11.0	10.5	-	14.6	11.6
Draft [m]	2.39	2.82	2.09	2.11	-	2.67	2.11
Volume [m^3]	1211	1211	1256	1028	-	1253	1206
Cb [-]	0.519	0.496	0.547	0.543	-	0.540	0.565
Pe [kWh]	$1,320 * 10^3$	$1,810 * 10^3$	$812 * 10^3$	$354 * 10^3$	$4,300 * 10^3$	$4,490 * 10^3$	$4,450 * 10^3$
Vertical displacement [m]	1.34	1.88	1.30	1.29	1.43	1.53	1.30

Table 5.10: Overview of specifications and objectives

Design strategy	**Single ship design**	**Family design restricted**	**Family design open**
Pe [kWh]	0.0%	+4%	+4%
Displacement [m]	0.0%	+7%	-9%

Table 5.11: Comparison between design strategies for seakeeping capability and propulsion power

The results, as shown in table 5.11, are mostly in line with the expectations. The total Pe is indeed higher if a family design strategy is used. However, the Pe of the restricted family design is slightly lower than for the open family design. The opportunity of having better seakeeping capabilities is also present if the 'open' family design is chosen. If all requirements of all separate vessels needs to be met, see the restricted family design, the seakeeping capabilities will on average be worse. However, if a more open approach is chosen, see the open family design, the seakeeping capabilities are improved for all vessels. So for seakeeping capabilities, the 'open' family design is favourite. The single ship design strategy is best for acquiring the lowest Pe.

Interestingly, there were also differences in the results of the Pe between the different family design strategies. By introducing family design, the total Pe is slightly increased by 4% for the restricted design and 4% for the open design, compared to the total Pe acquired by using the single ship design strategy. But this means there is almost no difference in Pe between the restricted and open variant. This can be explained by looking at the Fn values between these two alternatives. For the restricted design, a higher value of Fn is attained. This means more wave resistance, but lower frictional related resistance. For the open design, the value of Fn will be lower. So low wave resistance, but the increased wetted area will have increased frictional related resistance as a result. The viscous related resistance and the wave making resistance are perfectly balanced with almost same values for Pe as a result. So by using the family design strategy, the total effective towing power will always be higher. But the percentage is relative low compared to the single ship design.

The maximum vertical displacement is the lowest by using the open family design, with a reduction of 9% compared to the single ship design. The restricted family design will have an increased vertical displacement of 7%. The design variable with the biggest influence on the motion objective is the LOA. The restriction on the length will have a large impact on the maximum vertical displacement. This limited value for LOA comes from the requirements of the Logistic Support vessel. The draft limitation of this vessel is less of an issue, because all proposed concept designs have a draft lower than 3.5 meter. This means, that even if the 'open' design strategy is chosen, all relevant harbours can be reached. With exception of the harbour of Saba, but this can be solved by extending the berth. If this change in requirements is not acceptable, it is better to leave the Logistic Support vessel out of the family design. The design space will be too limited for the other vessels because of the strict requirements of one specific vessel. The consequence is that for the new generation naval support vessels, four vessels will share the same hull geometry, and one vessel will have its own hull design. The difference in length between the open and restricted family design, 63m and 92m respectively, will have its impact on its LCC. The OPEX will be comparable for both strategies. Only the CAPEX will be higher for the open family design because of its increased length.

The suggested models are of comparable volume. They are all close to the minimum displacement. The models are feasible if the displacement is larger than a given minimum, while still meeting all other constraints. The renewed approach is, without having a preference for minimal displacement, giving suggestions in the lower displacement regions. This effect is highly appreciated as this makes integration in the DMP easier. In the DMP, capital and operational cost are also involved. Capital costs have a positive correlation with displacement and length. Consequently, low capital cost are needed for vessels with low displacement on average. High capital cost is involved for longer vessels. A recommendation is to also include predictions on capital and operational cost within the new approach.

In summary, it has been shown from this study that applying a family design strategy is a good option from a seakeeping capability point of view. The maximum vertical displacement will decrease, but only if the 'open' strategy is chosen. On the other hand, the total effective towing power will rise slightly. With this information available, a better argued choice can be made between the design strategy to choose. But more information about the other pros and cons is necessary, as well as the interaction between all these topics. The length is higher for the vessels of the 'open' strategy. This will cause higher capital cost in comparison with the smaller vessels of the 'restricted' strategy.

5.2. INFLUENCE OF DESIGN SPEED

In the validation it is substantiated that the proposed geometries have design parameters as expected. The design speed of the family design vessel is selected to be 14kn. But not all vessels will have this transit speed. More information is needed to select the design speed of the family design. This is analysed by changing the design speed and comparing the results of the objective functions. The open family design is used for this study. The hypothesis is as follows:

- The optimal design speed is not necessarily the transit speed. Lower values of Pe can be obtained if a somewhat lower design speed is used. This change in design speed will not influence the motion objective a lot.

The transit speed is adjusted to analyse its influence. Three different design speeds are used, namely 14, 13 and 12kn. A parametric optimisation study is started for every design speed. The Pareto front is created and a model is selected. All obtained Pareto fronts are plotted in one figure. The seakeeping capabilities and the effective towing power can be calculated for every selected model.

SETTINGS

The comparison on the design speed is performed for three different speeds: 14, 13 and 12 kn. The Pareto front for all design speeds is generated, and a model on this front is selected, see figure 5.4. For all designs the total effective towing power and the motion capabilities are calculated and compared. The input values of the 'open' family design are the same as in section 5.1, only the design speed is different.

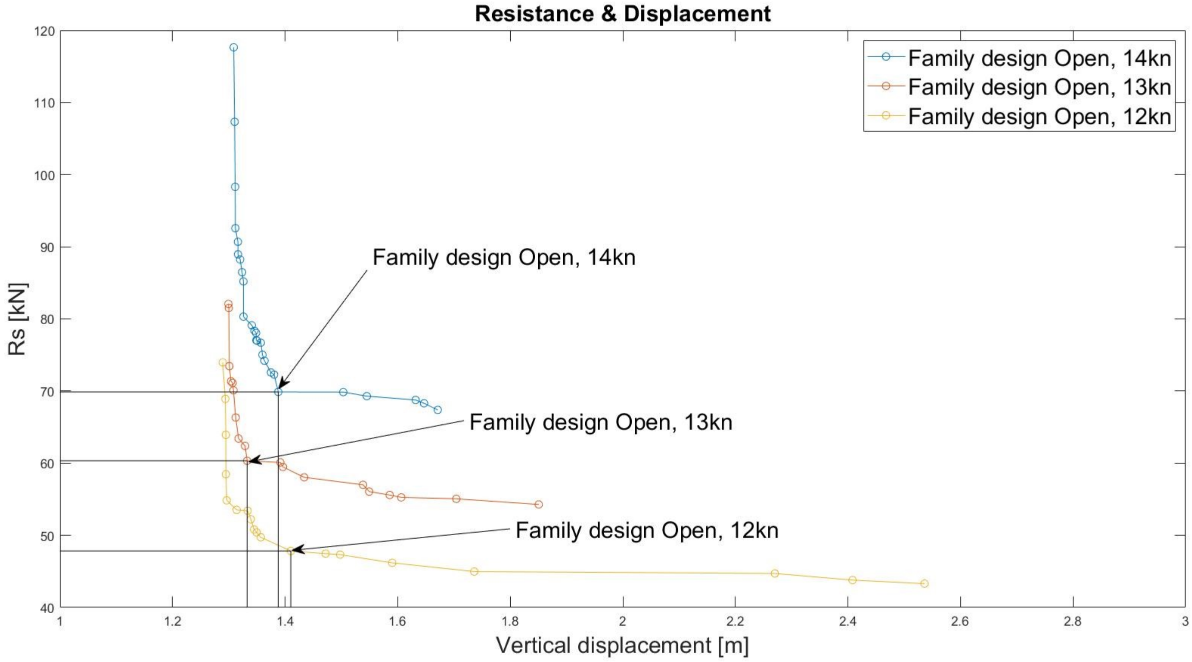

Figure 5.4: Pareto front of optimisation study on design speed for 14, 13 and 12 kn

The data of the created Pareto fronts and the selected design can be seen in table 5.12.

Vessel	Total #	# on Pareto front	Utopia point (R_S, Displ)	Chosen design (R_S, Displ)
FdO 14kn	400	26	(67.4, 1.31)	(69.9, 1.39)
FdO 13kn	361	19	(54.3, 1.30)	(60.3, 1.33)
FdO 12kn	353	19	(43.3, 1.29)	(47.8, 1.41)

Table 5.12: Data of Pareto front and selected designs

ANALYSIS OF RECEIVED OUTPUT

The calculations for the open family design vessel with a design speed of 14kn are already performed in section 5.1. The values obtained for a vessel with a design speed of 13 kn can be seen in table 5.13.

Speed [kn]	Velocity [m/s]	Time [h]	R_S [kN]	Pe [kW]	Pe [kWh]	Displ Obj [m]
3	1.54	1728	3.37	5.20	$8.99 * 10^3$	1.20
4	2.06	1296	5.77	11.9	$15.4 * 10^3$	1.21
5	2.57	336	8.76	22.5	$7.57 * 10^3$	1.22
7	3.60	403	16.5	59.4	$23.9 * 10^3$	1.25
8	4.12	8280	21.4	88.3	$731 * 10^3$	1.26
10	5.14	2208	33.7	173	$383 * 10^3$	1.29
11	5.66	2880	41.2	233	$672 * 10^3$	1.30
12	6.17	2304	50.4	311	$717 * 10^3$	1.32
14	7.20	3595	73.7	531	$1,910 * 10^3$	1.35
15	7.72	202	87.0	671	$136 * 10^3$	1.37
Total	-	23232	-	-	$4,600 * 10^3$	1.28

Table 5.13: Operational profile and effective power of FdO for 13kn design speed

The values obtained for a vessel with a design speed of 12 kn can be seen in table 5.14.

Speed [kn]	Velocity [m/s]	Time [h]	R_S [kN]	Pe [kW]	Pe [kWh]	Displ Obj [m]
3	1.54	1728	3.17	4.89	$8.45 * 10^3$	1.21
4	2.06	1296	5.42	11.2	$14.5 * 10^3$	1.23
5	2.57	336	8.22	21.1	$7.10 * 10^3$	1.25
7	3.60	403	15.4	55.4	$22.3 * 10^3$	1.28
8	4.12	8280	20.0	82.1	$680 * 10^3$	1.31
10	5.14	2208	31.4	161	$357 * 10^3$	1.35
11	5.66	2880	38.4	217	$625 * 10^3$	1.38
12	6.17	2304	47.8	295	$680 * 10^3$	1.41
14	7.20	3595	71.8	517	$1,860 * 10^3$	1.48
15	7.72	202	83.5	644	$130 * 10^3$	1.52
Total	-	23232	-	-	$4,390 * 10^3$	1.35

Table 5.14: Operational profile and effective power of FdO for 12kn design speed

Table 5.15 gives a summary of all important results.

Type	FdO 12kn	FdO 13kn	FdO 14kn
LOA $[m]$	97.6	99.9	91.9
Beam $[m]$	11.2	11.0	11.6
Draft $[m]$	2.32	2.04	2.11
Volume $[m^3$	1218	1216	1206
Cb [-]	0.505	0.559	0.565
Pe [kWh]	$4,390 * 10^3$	$4,600 * 10^3$	$4,450 * 10^3$
Displacement [m]	1.35	1.28	1.30

Table 5.15: Overview of specifications and objectives

The values of Pe and the displacement objective are compared with each other, see table 5.16. The model with a design speed of 14 kn is used as the baseline.

Design strategy	**FdO 12kn**	**FdO 13kn**	**FdO 14kn**
Pe [kWh]	-1%	3%	0%
Displacement [m]	4%	-2%	0%

Table 5.16: Comparison between design strategies for seakeeping capability and propulsion power

The results of table 5.16 are rather surprising. If the Pe is higher, the motion capability is lower, and the other way around. But what stands out in this table is the variability of these values. For a design speed of 12kn, the Pe is lower compared with the model of 14kn. But the vertical displacement has increased with 4%. The opposite is true for the model with a design speed of 13kn. The Pe has increased for this model but the displacement has decreased. This means that changing the design speed can influence the total Pe, but is also influencing the seakeeping capabilities. The only trend that could be used is that if one objective is rising, the other one is declining. But the same goal can be obtained by changing the weight factors. The the naval architect has the possibility to change the weight factors, to obtain lower Pe or to limit the maximum vertical displacement.

A clear benefit of lower Pe or displacement by changing the design speed could not be identified in this study. There are several possible explanations for this result. One possible explanation may be explained by the fact that the number of proposed models is not sufficient. Also the quality of the proposed designs is not the same for all optimisation studies. Or the accuracy of the calculations is too low. An alternative method to select the best design speed is by performing a calculation with the design speed as a design variable. Another improvement has to do with the propulsion objective. The objective should change from predicted resistance [kN] towards predicted delivered propulsion power [kWh]. These alternative methods are mentioned in the recommendations.

5.3. COMPARISON CURRENT AND OPTIMISED HYDROGRAPHIC SURVEY VESSEL

Comparisons have been made between the optimised models of the ‘single’ design strategy and the ‘family’ strategy. But what is the effect of the new approach if applied on an already existing vessel?

The current Hydrographic Survey vessels are representative for the family of support vessels. The geometry of the current Hydrographic Survey vessel is taken, see section 4.1, and used for an optimisation. The displacement is taken constant, see table 5.17. This is achieved by adjusting the draft to acquire the desired displacement. The predicted resistance and vertical displacement are namely better to compare if the displacement isn’t changing. The hypothesis is as follows:

- The Pareto front of the optimised Hydrographic Survey vessel will dominate the current design.

The design variables will influence the resistance and the vertical displacement. The generated Pareto front will probably dominate the current design. This means some models will have lower vertical displacement, lower values for Pe or both lower vertical displacement and Pe in comparison with the current model.

The values of the design variables can be 10% higher or lower than the original vessel, see table 5.18. This range is chosen arbitrary. Note, no exact values will be given for the entrance angle, stem distance, X and Z-Frame Indication because of confidentiality.

Variable	Value	Units
Speed	14	kn
Draft	2-8	m
Desired volume	1795	m^3
Heading angle	180	degree
Wave amplitude	1	m
Position of Interest	0.9*LWL	m

Table 5.17: Parameters used for optimisation of current HOV

Design Variable	Units	Lower limit	Upper limit
LOA	[m]	74.7	91.3
Beam	[m]	11.5	14.1
Entrance Angle WL	[degree]	-10%	+10%
Stem distance	[m]	-10%	+10%
X Frame Indication	[-]	-10%	+10%
Z Frame Indication	[-]	-10%	+10%

Table 5.18: Design variables for optimisation of current HOV

The output of the optimisation has been visualised with a Pareto front, see figure 5.5.

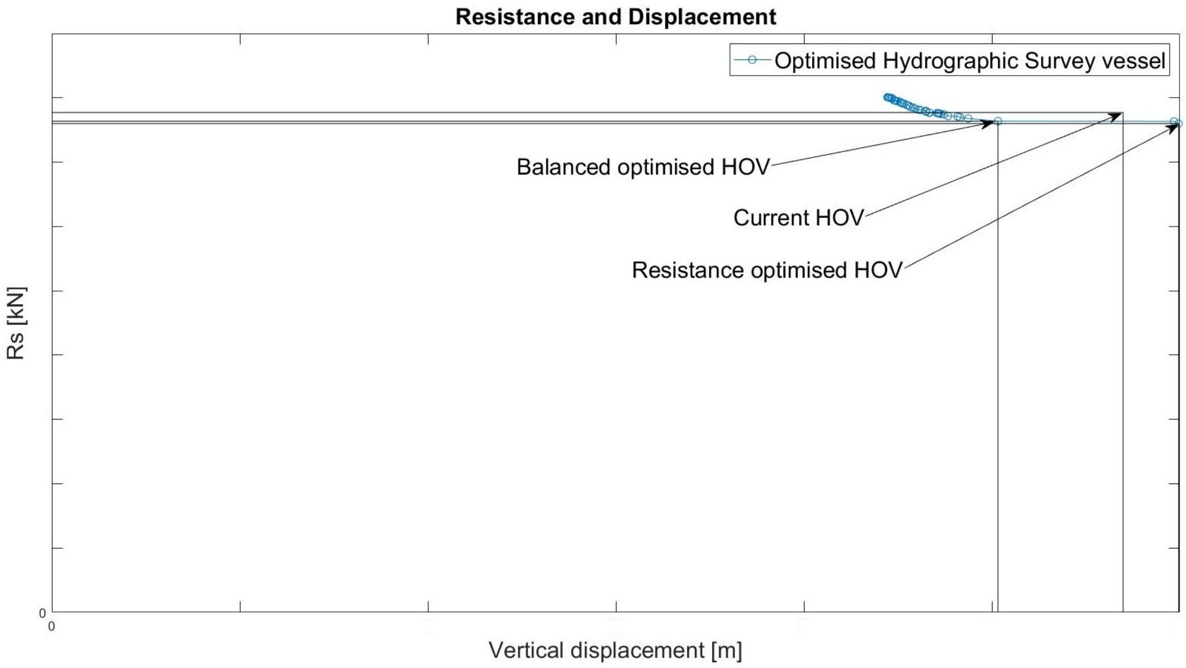

Figure 5.5: Pareto front of optimisation study on current HOV at 14 kn

Three vessels are marked in figure 5.5: the current HOV, the balanced optimised HOV and the resistance optimised HOV. The model of the current vessel is the same as used in the validation of the accuracy of the resistance prediction (see section 4.1). The operational profile of the family vessel is used to calculate the Pe and value of the vertical displacement objective. The balanced HOV is selected because it is dominating the current design in both resistance and vertical displacement. The resistance optimised HOV is the model with the lowest resistance. This model has been added to also select a model which will have a comparable value for the vertical displacement objective. Due to confidentially, the exact results will not be given, only the percentage of the difference of the final answers.

Name	Pe [kWh]	Vertical displacement [m]
Difference of balanced HOV (compared to current HOV)	+1%	-15%
Difference of resistance optimised HOV (compared to current HOV)	-6%	+3%

Table 5.19: Comparison of effective power requirement and vertical displacement of original HOV, balanced optimised HOV and resistance optimised HOV, applied on the operational profile of the family design vessel

The stated hypothesis is true, because the Pareto front is dominating the current model, see figure 5.5. The results of the comparison can be seen in table 5.19. The balanced optimised HOV will have an increased Pe of 1%, but will reduce the vertical displacement with 15%. This is a surprising result, as it was predicted to have reduced Pe and vertical displacement. This difference in Pe comes from the resistance prediction. The resistance of the current Hydrographic Survey vessel is higher than the balanced optimised model, but only for the higher vessel speeds. For the lower speeds the opposite effect was visible. This is the reason behind the higher value of Pe, despite the lower predicted R_S at design speed. The resistance optimised model gives the following results. The Pe will be reduced by 6%, but the vertical displacement will increase with 3%. Unfortunately no optimised model has been found which is dominating for both Pe and vertical displacement. But the conclusion can be drawn that by applying optimisation, one can reduce the Pe or vertical displacement of an already existing vessel. This conclusion emphasises the need for a more sophisticated power usage objective, and the influence of the operational profile. The recommendation is to make sure a detailed, and accurate operational profile is available.

5.4. DISCUSSION

The discussion will consist of three parts. First the consequences regarding focus points will be given. The consequences regarding the concept exploration phase at DMO will be treated in the second part. The third part will give the conclusion and shall provide an answer to the sixth sub question.

CONSEQUENCES REGARDING FOCUS POINTS

Two focus points were selected for the new generation of naval support vessels. The first focus point concerns increased unity within the small surface fleet. The second focus point concerns the ambition to become less fossil fuel dependent, in order to reduce harmful emissions.

The unity was reviewed by incorporating the single and family design strategy. This resulted in the usage of a parametric optimisation method, using objectives for minimising resistance and minimising vertical displacement. The results of this study gave more insight in the effect of the different design strategies. The focus point of reduced harmful emissions was only analysed with a hull geometry point of view. The power usage was analysed by predicting the effective towing power (Pe).

The effective towing power will increase slightly by using both the 'open' or the 'restricted' family design strategy compared to the single design strategy. However, by changing the weight factors, one can influence the selection of a model on the generated Pareto front. The selected vessel will have specific values of Pe and vertical displacement. The expertise of the naval architect is necessary to select the values of these weight factors, but the trends of the design variables on the objectives are also giving much information. A more sophisticated power usage objective is required to select the best design speed. The new approach can result in increased seakeeping capabilities or decreased power usage compared to an already existing hull geometry.

Some advice can be given which concerns the new generation naval support vessels. The Logistic Support vessel has a limited maximum length. This will induce higher vertical displacement for the family design. Ignoring this restricted length will improve the motion capabilities, see the 'open' family design. An advice is to exclude the Logistic Support vessel from the family design, or extend the berth of the harbour of Saba to make it accessible for longer vessels.

CONSEQUENCES REGARDING CONCEPT EXPLORATION PHASE AT DMO

The new approach is designed to be incorporated within the concept exploration phase at DMO.

The new approach can use existing hull models, from Rhinoceros (Rhino) for example, or can use models which are completely modelled within CAESES. When built with CAESES, the design variables can be selected very precise, because you are changing the design curves, and consequently the surface itself. By importing the hull geometry, only scaling can be applied.

The implementation of scripting makes it a very powerful tool, and makes it possible to be customised to be used within the DMP. It can be linked with the data that is available in the concept exploration phase. And the method can visualise the impact of certain design variables on the trade-offs that should be made.

The new approach uses methods that are selected to be good at comparison and to be fast. A study with 400 iterations takes approximately 4:41 hours. The chosen optimisation algorithm, DAKOTA global optimisation on response surface, is very efficient with its computational power. This resulted in a solution which has converged with acceptable accuracy in only limited amount of time.

Returning to the accuracy of the new approach, it is proven to be very handy for comparison purposes, but highly accurate results will not be available. This because of simplifications made, and by the selected methods. Accurate results are needed to predict the power usage, which will give input for the engine configuration and fuel supply. These are variable blocks within the DMP used nowadays. These blocks will still have a lot of uncertainty, which was one of the main reasons to look at these technical opportunities at the first place. But by having the comparison early on, one can use higher fidelity tools earlier on, as more information is provided by the renewed process.

Also the seakeeping capabilities can be addressed earlier on. In a stage where still a lot of progress can be made. The maximum vertical displacement can be predicted quite accurate with only limited input available. The maximum vertical acceleration can only be used for models with large variation in dimensions, and was therefore not used as an objective.

CONCLUSION OF CAPABILITY OF NEW APPROACH ON FOCUS POINTS

The conclusion of the capabilities of the new approach on the focus points shall provide an answer to the sixth sub question: ‘Is the new approach capable to address the focus points which are present for the new generation of naval support vessels with a hull geometry point of view?’.

The new approach is capable to compare different hull geometries on its predicted effective towing power and vertical displacement. The approach is used to perform three case studies for the new generation naval support vessels. This gave the following results. The Pe will be slightly higher while using the family design strategy in comparison with the single design strategy. The open family design was capable to increase the seakeeping capabilities compared to the restricted family design and the single design strategy. The design speed has to be chosen by use of a more sophisticated power usage objective. The new approach can increase the seakeeping capabilities or decrease the effective towing power in comparison with a current design.

6

Discussion and Conclusion

A new project is at hand which concerns the replacement selected vessels of the small surface fleet of the RNLN. Two focus points are selected for the new generation of naval support vessels. The selected naval support vessels are the Hydrographic Survey, Logistic Support, Submarine Support and Marine Training vessels. The first focus point concerns increased unity within the small surface fleet. The second focus point concerns the ambition to become less fossil fuel dependent, in order to reduce harmful emissions.

The power usage should be minimised in order to reduce the effects of the energy transition. This project is limited to only analyse the effects with a hull geometry point of view. The hull geometry can namely be used as a monolithic part for the support vessels. The power usage is analysed by predicting the effective towing power (Pe), which is calculated by use of the formula $P_E = R_s * V$.

The vessels are selected because of the urgency to be renewed within six to fourteen years, the comparable dimensions and displacement, the working area and design speed. The operational profile and requirements are different for every vessel.

Although the vessels are selected because of similar requirements, some conflicting design trade-offs are present. The first trade-off has to do with the power usage. For the Logistic Support vessel, lower effective towing power is of high importance. While for the Marine Training vessel, because of its reduced speeds, effective towing power is less of an issue. The remaining vessels are more equally balanced. The second trade-off has to do with the seakeeping capabilities. The seakeeping capabilities are of high importance for the Hydrographic Survey vessels, the Submarine Support vessel and the Marine Training vessel. For the Hydrographic Survey vessels the vertical displacement is the main motion to look at. For the Marine Training vessel the focus is at lower vertical accelerations. For the Submarine Support vessel, vertical acceleration and vertical displacement are equally important. Seakeeping capabilities are of less importance for the remaining vessels. These design trade-off should be included in the modelling of the hull geometry.

The hull geometry is designed by using several tools. All of these tools have their own specific function within the concept exploration or concept definition phase. However, some functionalities are missing regarding the analysis of the geometry of the hull. The resistance is only calculated after a feasible hull model is generated, rather than used within an optimisation. This will create a hull form which is feasible, but not necessarily optimal. Another function that is missing is the incorporation of motion predictions during the concept exploration phase. These are only predicted in the concept definition phase, where the design freedom is already more limited. The missing functionalities are used to set up the requirements of the new approach.

The new approach will consist of four different parts. The parametric modelling is performed by use of CAESES. A hull form is developed which can be adjusted by seven design variables. Two constraints are used; One constraint to obtain a minimum displacement, and another constraint for initial stability.

The resistance prediction consists of two components. The wave making resistance is predicted by the potential flow solver RAPID, while viscous effects are taken into account by use of Holtrop and Mennen. These two combined will give the resistance objective [kN]. A study has been performed to select the settings of RAPID.

The motion prediction is performed by a simplified version of the linear strip theory. By use of this method, one can predict the vertical displacement and vertical acceleration of the vessel at a point of interest and for different headings. The motion objectives are the vertical displacement [m] and the vertical acceleration [m/s^2] in head waves at 0.9*LWL.

The predicted values of the objective functions are used by the optimisation method, which will in return change the design variables. Three types of optimisation methods were tested and DAKOTA - Global Optimisation on Response Surface gave the best results. The solution will converge with acceptable accuracy by using 400 iterations. The computational time is with 4:41 hours lower than the preferred maximum of six hours.

Four validation studies have been performed. The predicted resistance was compared with results obtained by towing tank test. The differences between the results were larger than expected, mainly because of the sonar bulb which was not present in the used geometry. But, by looking at the literature, the combination of a potential flow solver and the viscous resistance components is widely used for comparison studies. So an optimisation study can be performed using these prediction tools.

In the second validation, the influence of the resistance components were analysed. By using RAPID in combination with Holtrop and Mennen gave better results than the results obtained by only using RAPID.

The third validation demonstrated the motion prediction capabilities. The predicted sequence for displacement was also found using a higher fidelity tool. The acceleration prediction sequence was only true if large changes in dimensions are present. This means the prediction on displacement can still be used as an objective, while the objective for acceleration cannot be used anymore.

The fourth validation study was about the proposed optimised models. The trends of the proposed optimised models are the same as expected, like a long slender hull for better seakeeping capabilities, and a more compact vessel for lower resistance.

The new approach is capable to compare different hull geometries on its predicted effective towing power and vertical displacement. The approach is used to perform three case studies for the new generation naval support vessels. This gave the following results. The Pe will be slightly higher while using the family design strategy in comparison with the single design strategy. The Logistic Support vessel has a limited maximum length. The seakeeping capabilities of the family design will increase compared to the single design strategy if the Logistic Support vessel is left out of the family design. The design speed has to be chosen by use of a more sophisticated power usage objective. The new approach can increase the seakeeping capabilities or the effective towing power in comparison with a current design.

Recommendations

6.1. Parametric modelling

It is the responsibility of the naval architect to provide the right input for new approach. The used parent hull is based on the current Hydrographic Survey vessels. This design can change for the new generation naval support vessels. The design variables, the range of the variables and the design constraints needs to be specified with more detail.

Part of the input is also the operational profile. The predictions will be more accurate if these operational profiles are more representative for the operational profile in reality.

The new approach can handle multi objectives. Other design objectives (besides to resistance and motion) can be incorporated in the approach. The approach will be more sophisticated by including objectives like life cycle cost.

The stability is very important for vessels, for navy vessels maybe even more. There are rules and regulations acting on the intact and damaged stability of naval vessels. These aren't included at the moment in the model. The stability is only modelled by having a constraint on the beam/draft ratio. A more sophisticated way of ensuring good stability is necessary, based on existing vessels, and/or inclusion of the rules and regulations which concerns intact and damage stability. This will also prevent the optimisation software to come up with unrealistic designs.

All optimised models have a minimal displacement because of the displacement constraint. The displacement should be constant to better understand the differences between the optimised models. The recommendation is to make the displacement constant, by adjusting the draft of the vessel. This makes comparison easier as it is not biased by a variety of different displacements.

6.2. Resistance objective

Instead of using one speed to optimise, the approach should use the operational profile to reduce the total power usage. This can be done by making the speed a design variable. Also the objective should be changed to cope with this change.

$$\min F(x)$$
$$F(x) = \frac{T_y}{T_0} * \frac{R_T}{R_{T_0}}\bigg|^{y}$$

Where:

$F_1(x)$ = weighted sum of the normalised total resistance in calm water at speeds y

T = time in hours at speed y

T_0 = total operational time in hours

R = resistance at speed y

R_{T_0} = total resistance

y = speed in kn

The power usage was based on the effective towing power (Pe). The recommendation is to use an objective based on the propeller power or the brake power instead [27]. This includes the use of the propulsive efficiency and the transmission efficiency. Low effective towing power doesn't guarantee low brake power, because of the influence of the propulsive efficiency and the transmission efficiency.

The resistance objective is using the calm water prediction. Calm water is only present on a part of the missions. It makes more sense to use the resistance in waves, so an addition shall be to calculate the Ship added resistance in waves (R_{aw}), based on simple geometry variables, in various seastates and headings.

6.3. Motion objective

The motions are predicted for head waves only. An adjusted objective can use the weighted sum of the vertical displacement and acceleration for different headings.

$$\min(F_2(x), F_3(x))$$
$$F_2(x) = \sum_i 0.5 * \frac{RMS(\Phi_r)}{RMS(\Phi_{r_0})}\Big|_i^y$$
$$F_3(x) = \sum_i 0.5 * \frac{RMS(\Phi_v)}{RMS(\Phi_{v_0})}\Big|_i^y$$

Where:

$F_2(x)$ = weighted sum of the normalised total vertical displacement at speeds y

$F_3(x)$ = weighted sum of the normalised total vertical acceleration at speeds y

RMS = Root Mean Square

Φ_r = vertical displacement

Φ_v = vertical acceleration

i = 135 and 180 degree headings(β)

y = speed in kn

To incorporate the vertical acceleration as an objective, one has to adjust the prediction method. This can be done by using a higher fidelity tool, by adjusting the simplified strip theory method or by expanding the validation study (other position of PoI and other headings). The motion objective as used now is only looking at head waves, for a point at 0.9*LWL. Different headings should be used, to incorporate motions like yaw and roll. Also the position can be changed. The position of the after deck and the bridge can also be taken into account. The position can also be changed in the validation study.

6.4. Validation study

The resistance objective is only validated by comparing the predictions with the towing tank results of the Hydrographic Survey vessel. This model was recreated in CAESES. The absence of the sonar bulb had a large effect on the wave making and viscous resistance. The tool has to be compared with other prediction tools or existing vessels to make the validation more complete. This can be done by using a geometry which already has all information available. Also the final results of the optimisation tool can be analysed in more detail, with a high fidelity (RANSE) solver for example, or measurements in a towing tank. By comparing the results of a parent hull and the optimised hull form, the predicted optimisation of the tool can be tested.

The motion objectives are validated by using a higher fidelity tool. The higher fidelity tool should also be applied for positions with adjusted height and longitudinal length, which will make the validation more representative.

6.5. OPTIMISATION

The new approach should include predictions on capital and operational costs. This will give more information about the LCC between the single design strategy and the family design strategy.

The objectives are based on predictions from multiple tools. All these predictions should work together to give an accurate result for the objectives. First principle based modelling should be applied to find out if all parts of the objectives are covered by the prediction methods.

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A

Alternative Fuels

For lowering the emitted amount of hazardous emissions, three types of actions can be used. They can effect the handling of the emissions itself, apply on the power usage or on the power generation. Only the power generation by using alternative fuels will be explained here. For the methods concerning the handling of the emissions itself, or methods which are can be applied on the power usage, one can read the paper of D.J. Blatcher and I. Eames [12].

Five power and energy concepts are explored. These come from the paper of dr. ir. Rinze Geertsma and ir. M. Krijgsman [5]. The concepts are PEM liquid H_2, PEM methanol, SOFC methanol, ICE methanol and ICE NH_3. Also the current power and energy concept, which uses MDO F-76, is included and can be used as a baseline.

MDO F-76

IMO has set regulations on the amount of sulphur that fuel can contain. The maximum sulphur content will be 0.5 per cent m/m from the 1st of January 2020. This regulation means ships can use fuel oil which maximum sulphur content is lower than the stated amount, using alternative fuels or the use of an equivalent method to reduce sulphur oxide emissions (scrubber) [55]. MDO F-76 is the fossil fuel nowadays by the RNLN. F-76 is already a low sulphur fuel.

PEM liquid H_2

To use hydrogen as a fuel, onboard storage is required. This can be done in gaseous or liquid form or bound in metal hydrides [56]. Hydrogen will can be used as fuel for the polymer electrolyte membrane (PEM) fuel cell.

Methanol (CH_3OH)

According to a study published by the European Maritime Safety Agency, Methanol has been identified as good potential fuel alternative. This fuel can reduce both sulphur oxide emissions and carbon footprint in the shipping industry [57]. This because Methanol is sulphur-free, is clean-burning and can be produced from renewable feedstock. Experience with Methanol has been made by using it in a full scale ferry installation in 2015 on the Stena Germanica [58]. Methanol is widely available globally, but there is no infrastructure available to use it as a marine fuel. Methanol can be used as fuel for PEM fuel cells, Solid Oxide Fuel Cells (SOFC) or for internal combustion engines (ICE). The fuel itself has about half of the energy density of conventional fossil fuels. This will increase the fuel storage space which would be required on board a vessel compared to conventional fuels. The fuels can also be corrosive to some materials. Materials should be selected which are compatible with this [57]. Methanol is not rated as toxic to aquatic organisms. The fuel dissolve in water, is biodegradable and does not bio accumulate. This is important because of the potential risk if spilled to the aquatic environment which can happen by accidents such as collisions, groundings and foundering [57].

AMMONIA

Ammonia is a simple compound consisting of three hydrogen atoms bonded to a single nitrogen atom and has the chemical formula NH_3. It has a boiling point of -33.34 ° C at atmospheric pressure and is normally stored as a liquefied gas. Because of its chemical structure, it contains more hydrogen per unit volume than liquefied hydrogen. The hydrogen is tightly bound to the nitrogen, which makes it a very stable and difficult to ignite chemical [59].

Ammonia is acceptably safe in usage [59]. There is zero carbon, and no resultant greenhouse gases on combustion. The NO_x that is created can easily be neutralised with ammonia itself as active chemical reactant. If released in an accident, the ammonia is very difficult to ignite and because it is lighter that air and will dissipate upwards.

Option	Mass [t]	Volume [m^3]	CAPEX power & propulsion [million euro]	OPEX power & propulsion [million euro/year]
MDO (F-76)	188	223	3.6	1.09
PEM liquid H_2	640	1300	9	2.6
PEM methanol	383	605	8	2.2
SOFC methanol	383	605	20	1.9
ICE methanol	332	434	3.9	2.5
ICE NH_3	415	613	5	1.6

Table A.1: Power and energy of different concepts [5]

B

GENERATION OF PARENT HULL

A parent hull is generated. The geometry of this parent hull can be adjusted by changing the design variables. The parent hull will have comparable values as the Hydrographic Survey vessels, as this vessel is representing the family design vessel the most [5].

First several parameters are made: *Length*, *Height*, *Draft*, *Transom Draft* and *Stem distance*. The '*Transom Draft*' will have a value of 0.3m for the parent hull. The '*Height*' will have a value of '*Draft*+3.5'. This ensures enough free-board is available for all values for the draft. Next a Multi-Segmented Smooth Curve with two intermediate points is created, named the CPC. Here the start has an Y value of '*Draft*-*Transom Draft*' at a length of zero. The end has a Z value of '*Height*' at a length of '*Length*'. The first intermediate point is at height zero at length 20 and the second one is at height zero at a length of '*Length* - *Stem distance*'.

The second curve which is created is the FOS. Here the *FOS length* is inserted as '*Length*/1.3'. A beam parameter is made and called *Beam*. Two more parameters are made, namely *Z-frame indication* and *X-frame indication*. The '*Z-frame indication*' is defined as '*Z-frame indication***Height*'. The value of '*Z-frame indication*' has to be between zero and one. The '*X-frame indication*' is defined as '*X-frame indication***FOS length*'. The value of '*X-frame indication*' has to be between zero and one. Again a multi-segmented smooth curve is created with only one intermediate point. The start has an Z value of '*Height*-1' at a length of zero. The end is at a height of '*Height*' at a length of '*FOS length*'. The intermediate point has a height of '*Z-frame indication*' and a length of '*X-frame indication*' The Y position of all points is set to '*Beam*/2'.

The upper end will be defined by creating a deck curve. The deck curve will be made by using a multi-segmented smooth curve with one intermediate point. The height of all points is at '*Height*'. The start has a Y value of '*Beam*/2', and a X value of zero. This creates a wide after deck, which is necessary for the equipment of the vessel. The end point has a Y value of zero, and a X value of '*Length*'. The intermediate point has a Y value of '*Beam*/2', and a X value of '*FOS length*'. The fullness of part 2 has been given a value of 0.7. This makes the ending of the deck a bit sharper.

The vessel will have a flat bottom. This will be created by use of a FOB Curve. First a new parameter has been made named *bilgeWidth*, with a value of 1.4m. Next a multi-segmented smooth curve is created with one intermediate point. All values have a Z value of zero. The start is at a length of zero and has a Y value of '*bilgeWidth**0.8'. The end has a X value of '*Length* - *Stem distance*', and a Y value of zero. The intermediate point has a X value of '*Length*/2.5', with a Y value of '*bilgeWidth*'.

The last curve necessary to create the geometry is the WL. Before the creation a new parameter has been made, namely *Entrance angle WL*. The '*Entrance angle WL*' has a value of 15 for the parent hull. Now a F-Spline Curve is created. The start is at the intersection point of the FOS at a height of *Draft*, with a tangent of zero. The end is at the intersection point of the CPC at a height of *Draft*, with a tangent of '- *Entrance angle WL*'.

An overview of all used parameters, and their value or influence on one another can be seen in table B.1. The created curves are used to create the surface of the hull. With use of curve engines a meta surface is created. The settings of the curve engines and the usage of the meta surfaces are given in the CAESES manual [34].

Parameter	**Value**	**Unit**
LOA	*Length*	$[m]$
Height	*Draft*+3.5	$[m]$
Draft	*Draft*	$[m]$
Transom Draft	0.3	$[m]$
Stem distance	*Stem distance*	$[m]$
FOS length	*Length*/1.3	$[m]$
Beam	*Beam*	$[m]$
X-frame indication	*X-frame indication***FOS length*	$[m]$
Z-frame indication	*Z-frame indication***Height*	$[m]$
Bilge Width	1.4	$[m]$
Entrance Angle WL	*Entrance Angle WL (relative to center line)*	[degree]

Table B.1: Overview of parameters used to create the geometry

The used values for the parent hull and the appurtenant displacement can be seen in table B.2.

CAESES		
Parameter	Value	Unit
LWL	75	$[m]$
Beam	12.8	$[m]$
Draft	4	$[m]$
Entrance Angle WL	15	[degree]
Stem Distance	9	$[m]$
Transom Draft	0.3	$[m]$
X Frame Indication	0.583	[-]
Z Frame Indication	0.467	[-]
Displacement	1956	m^3

Table B.2: Parameters used for the parent hull form

C

RESISTANCE PREDICTION CALCULATIONS

```
double R((Speed*WaterlineLength)/Viscocity)
double Cf(0.075/((log(R)-2)^2))
double Rf(0.5*Density*WettedSurface*Speed^2*Cf)

double c12()
if(Draft/WaterlineLength<0.02)
    c12=0.479948
elseif(Draft/WaterlineLength>0.05)
    c12=(Draft/WaterlineLength)^0.2228446
else
    c12=(48.2*(Draft/WaterlineLength-0.02)^2.078)+0.479948
endif

double c13(1+0.003*0)
double Am(Draft*Breadth*0.9)
double Cp(Displacement/(Am*WaterlineLength))
double Lr(WaterlineLength*(1-Cp+0.06*Cp*LCB/(4*Cp-1)))
double k1(c13*(0.93+c12*(Breadth/Lr)^0.92497*(0.95-Cp)^-0.521448*(1-Cp+0.0225*LCB)^0.6906))

double k2(1.5)
double Cbto(0.01)
double Rapp(0.5*Density*Sapp*Speed^2*k2*Cf+Density*Speed^2*pi()*dbt^2*Cbto)

double Rb(0)

double At()
if(TransomDraft>0)
    At=TransomDraft*Breadth*0.8
else
    At=0
endif

double FnT(Speed/sqrt(2*9.81*At/(Breadth+Breadth*CWL)))
double c6()
if(FnT<5)
    c6=(0.2*(1-0.2*FnT))
else
    c6=0
```

```
endif

double Rtr(0.5*Density*Speed^2*At*C6)

double c4()
if (Draft/WaterlineLength<0.04)
    c4=Draft/WaterlineLength
else
    c4=0.04
endif

double CA(0.006*(WaterlineLength+100)^-0.16-0.00205+0.003*sqrt(WaterlineLength/7.5)
    *CB^4*c2*(0.04-c4))
double Ra(0.5*Density*Speed^2*WettedSurface*CA)

Parameter ViscousResistance(k1*Rf+Rapp+Rb+Rtr)
```

D

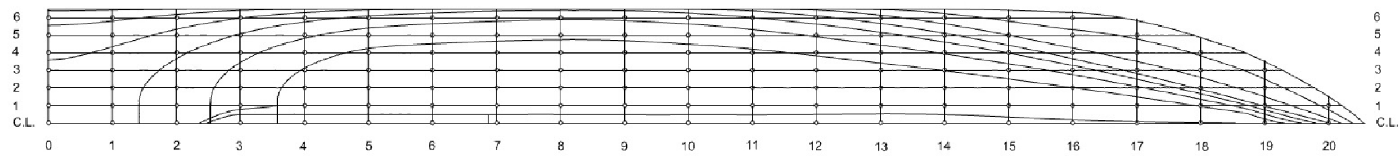
MOTIONS PREDICTION PROGRAM

```
//Constant parameters
double g2(9.81)
double betha(Heading*pi()/180)
double Breadth(W_Breadth*Block)
double position(Length*Pposition/200)

//Making of entity groups
entitygroup group_wave_freq()
entitygroup group_wave_number()
entitygroup group_eff_wave_number()
entitygroup group_smith_factor()
entitygroup group_alpha()
entitygroup group_sectional_hydro_damping()
entitygroup group_a()
entitygroup group_b()
entitygroup group_f2()
entitygroup group_F()
entitygroup group_G()
entitygroup group_eta()
entitygroup group_FRF_Heave()
entitygroup group_FRF_Pitch()

entitygroup group_Vertical_Movement()
entitygroup group_Vertical_Acceleration()
entitygroup group_Pitch_Movement()
entitygroup group_Heave_Movement()

//Evaluation of functions
unsigned i(0)
while(i<1000)
parameter wave_freq(0.05+1.95*(i/1000))
parameter wave_number(pow(wave_freq,2)/g2)
parameter eff_wave_number(abs(wave_number*cos(betha,true)))
parameter smith_factor(exp(-wave_number*Draft))
parameter alpha(1-Froude_N*sqrt(wave_number*Length)*cos(betha,true))
parameter sectional_hydro_damping(2*sin(0.5*wave_number*Breadth*pow(alpha,2),true)
    *exp(-wave_number*Draft*pow(alpha,2)))
parameter a(pow(1-wave_number*Draft,2))
```

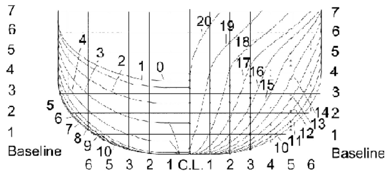
```
parameter b(pow((pow(sectional_hydro_damping,2)/(wave_number*Breadth*pow(alpha,3))),2))
parameter f2(sqrt(a+b))
parameter F(smith_factor*f2*(2/(eff_wave_number*Length))*sin(eff_wave_number*Length/2,true))
parameter G(smith_factor*f2*(24/(pow(eff_wave_number*Length,2)*Length))
    *(sin(eff_wave_number*Length/2,true)-(eff_wave_number*Length/2)* cos(eff_wave_number*Length/2,true)))
parameter eta(1/(sqrt(pow((1-2*wave_number*Draft*pow(alpha,2)),2)
    +pow(pow(sectional_hydro_damping,2)/(wave_number*Breadth*pow(alpha,2)),2))))
parameter FRF_Heave(Wave_Amplitude*eta*F)
parameter FRF_Pitch(Wave_Amplitude*eta*G)

parameter Vertical_Displacement(sqrt(pow(FRF_Heave,2) + pow(FRF_Pitch,2)*pow(position,2)))
parameter Vertical_Acceleration(pow(alpha,2)*wave_number*g2*Vertical_Movement)
parameter Pitch_Movement(sqrt(pow(FRF_Pitch,2)*pow(position,2)))
parameter Heave_Movement(abs(FRF_Heave))

//Assign values to group within the loop
group_wave_freq.add(wave_freq)
group_wave_number.add(wave_number)
group_eff_wave_number.add(eff_wave_number)
group_smith_factor.add(smith_factor)
group_alpha.add(alpha)
group_sectional_hydro_damping.add(sectional_hydro_damping)
group_a.add(a)
group_b.add(b)
group_f2.add(f2)
group_F.add(F)
group_G.add(G)
group_eta.add(eta)
group_FRF_Heave.add(FRF_Heave)
group_FRF_Pitch.add(FRF_Pitch)

group_Vertical_Displacement.add(Vertical_Displacement)
group_Vertical_Acceleration.add(Vertical_Acceleration)
group_Pitch_Movement.add(Pitch_Movement)
group_Heave_Movement.add(Heave_Movement)

i += 1
endwhile

parameter Max_Vertical_Displacement(max(group_Vertical_Movement))
Max_Vertical_Movement.CastTo(Double)
parameter Max_Vertical_Acceleration(max(group_Vertical_Acceleration))
Max_Vertical_Acceleration.CastTo(Double)
parameter Max_Pitch_Movement(max(group_Pitch_Movement))
Max_Pitch_Movement.CastTo(Double)
parameter Max_Heave_Movement(max(group_Heave_Movement))
Max_Heave_Movement.CastTo(Double)
```

E

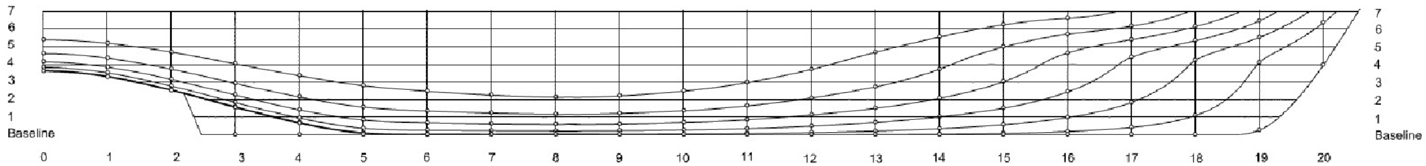
LINES PLAN PARENT HULL



C.L.
1
2
3
4
5
6
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20



Baseline
1
2
3
4
5
6
7
6 5 3 2 1 C.L. 1 2 3 4 5 6



Baseline
1
2
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4
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6
7
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

F

Lines plan comparison HOV and CAESES remake

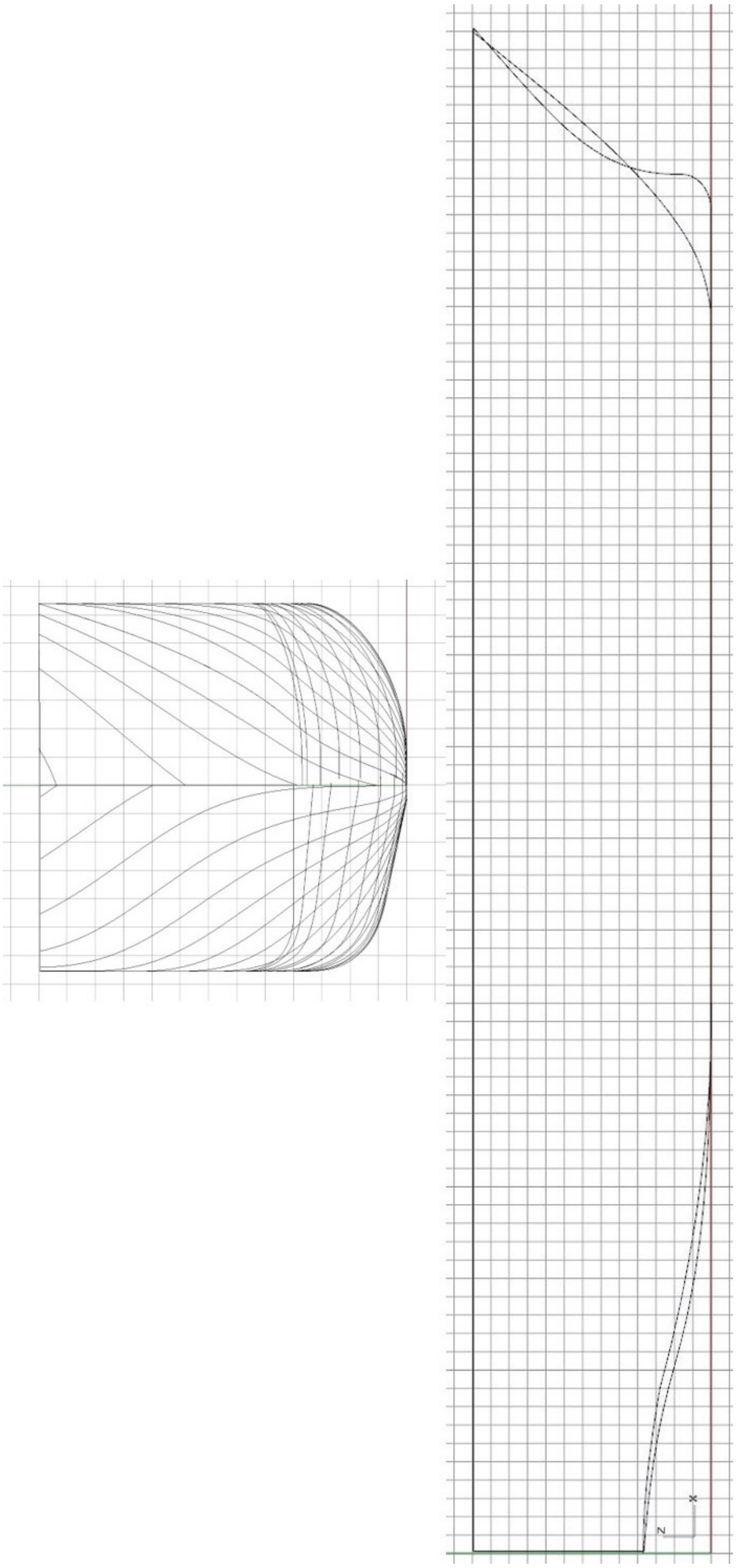

Figure F.1: Linesplan with left the HOV and right the model created in CAESES

G

Motion Validation GM=0.5m

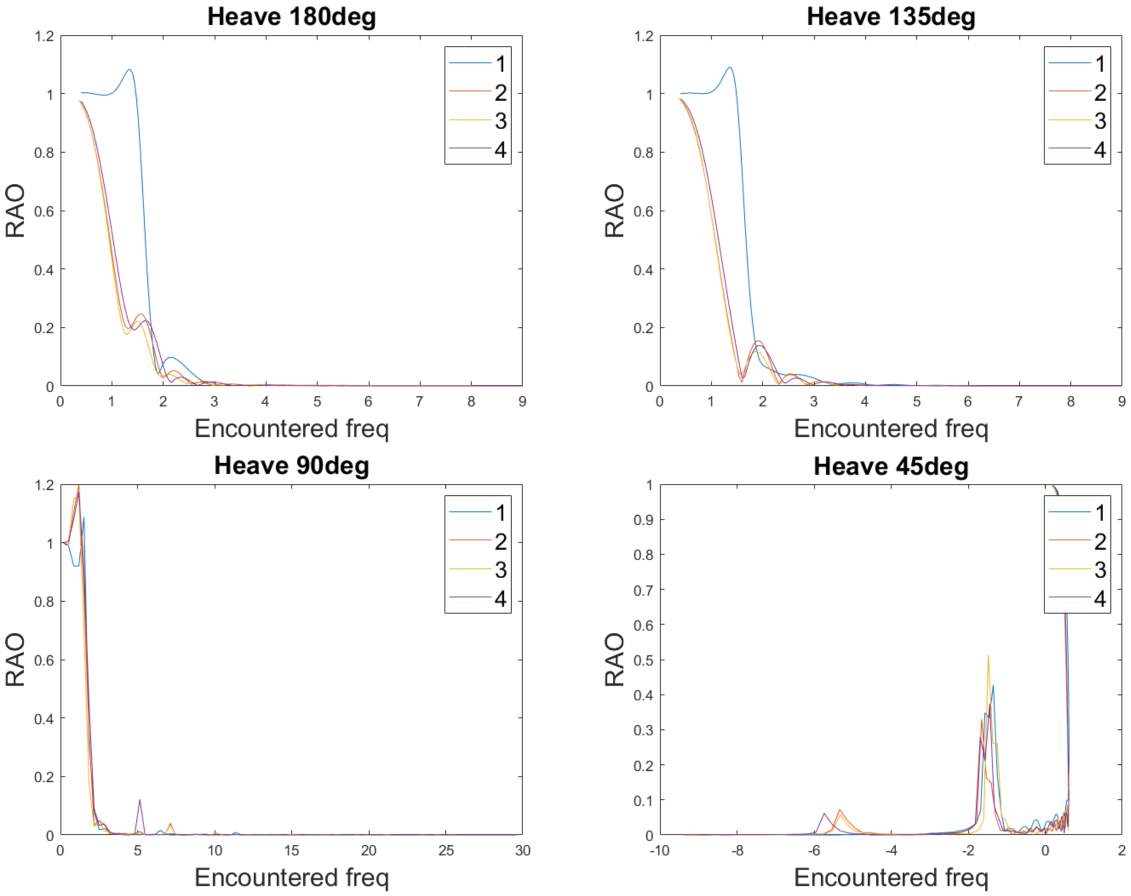

Figure G.1: Heave motion (m/m) as function of wave frequency for different headings at 11kn

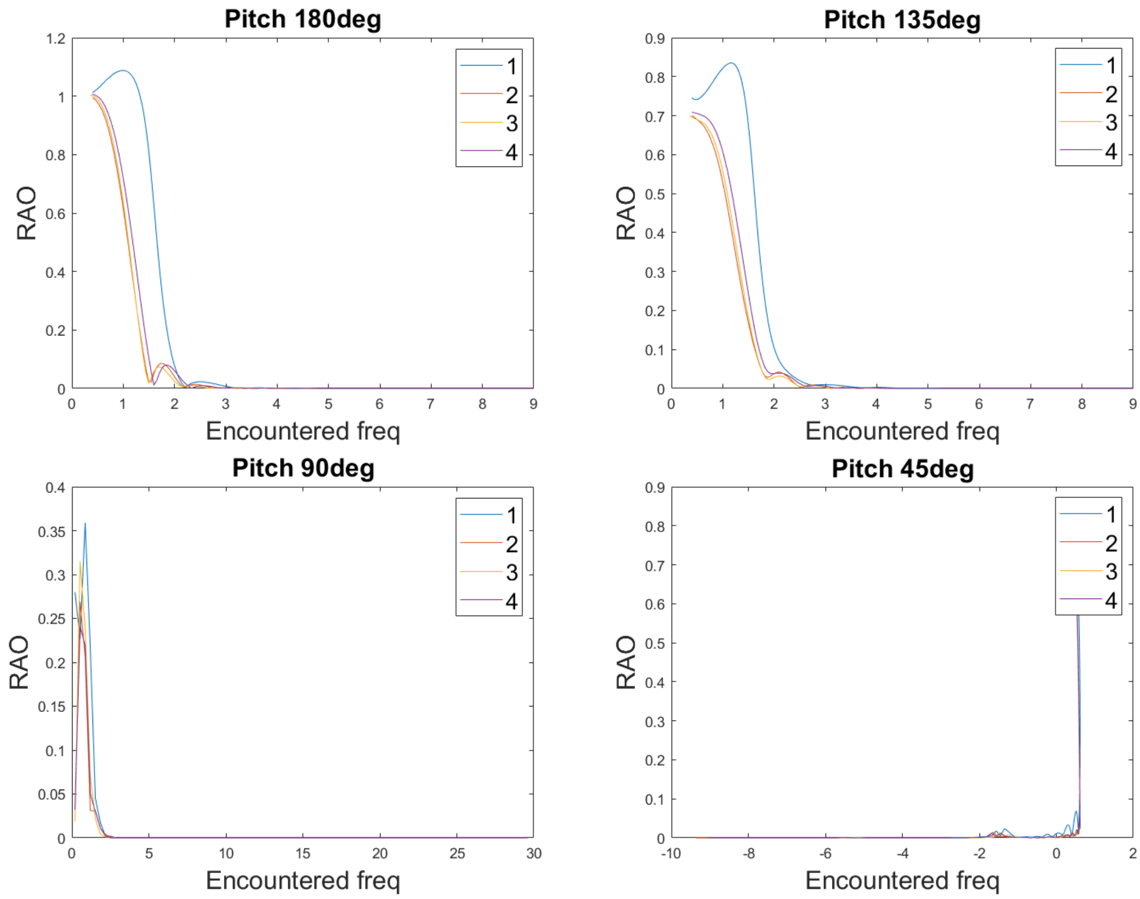

Figure G.2: Pitch motion/k (m/m) as function of wave frequency for different headings at 11kn

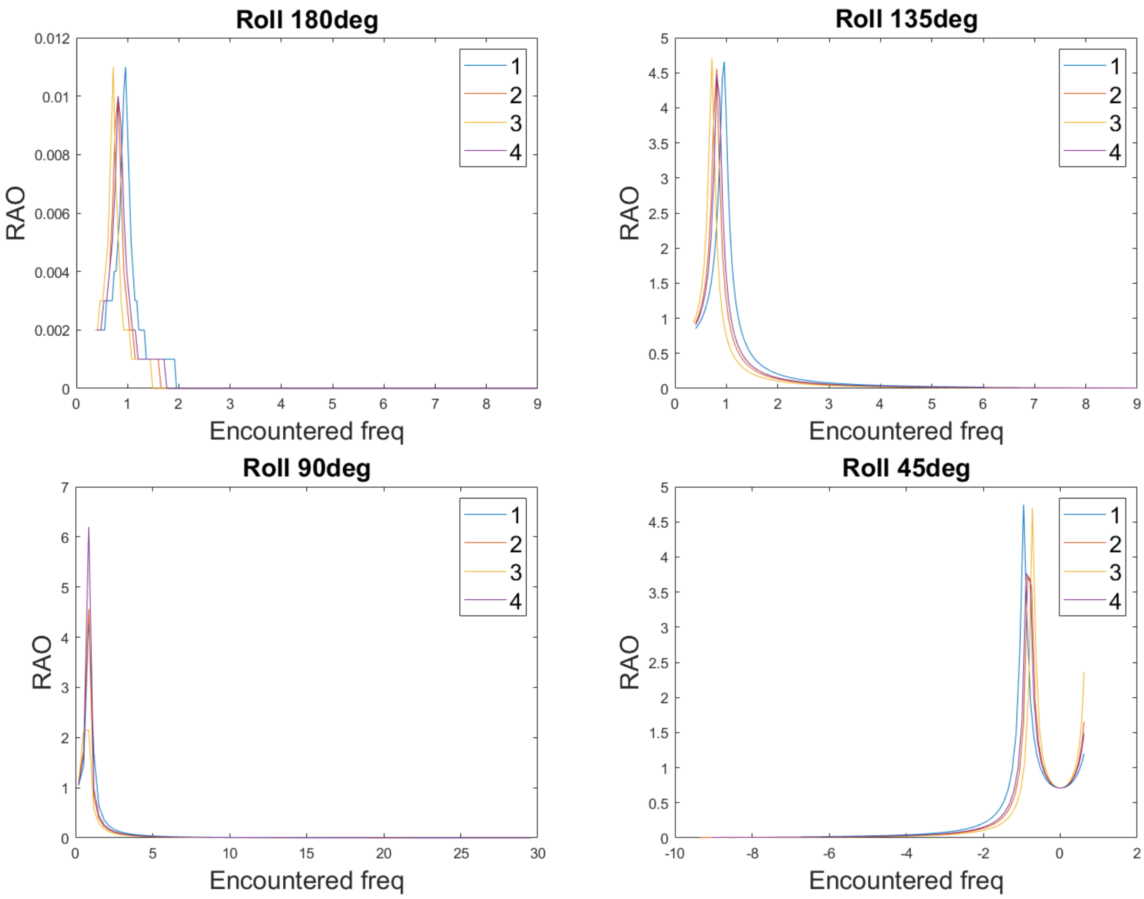

Figure G.3: Roll motion/k (m/m) as function of wave frequency for different headings at 11kn

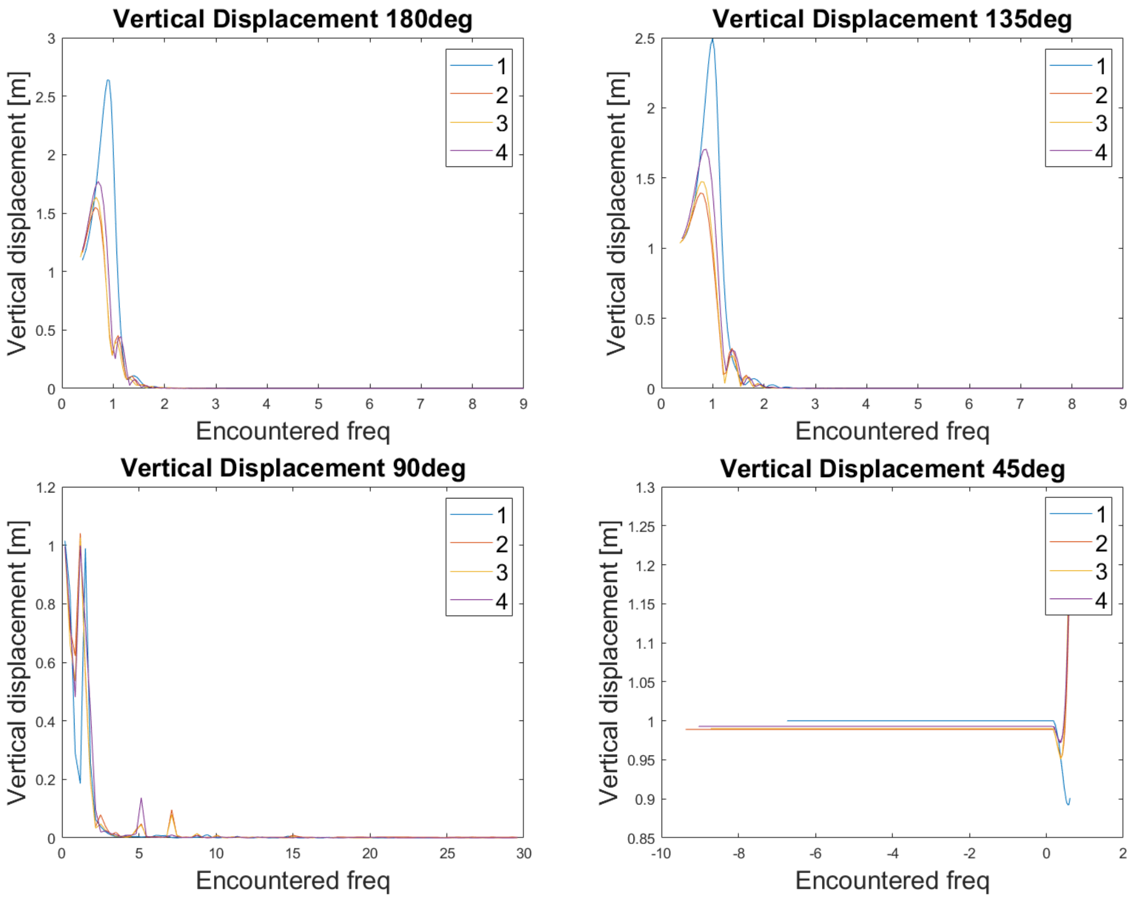

Figure G.4: Vertical displacement (m/m) as function of wave frequency for different headings at 11kn

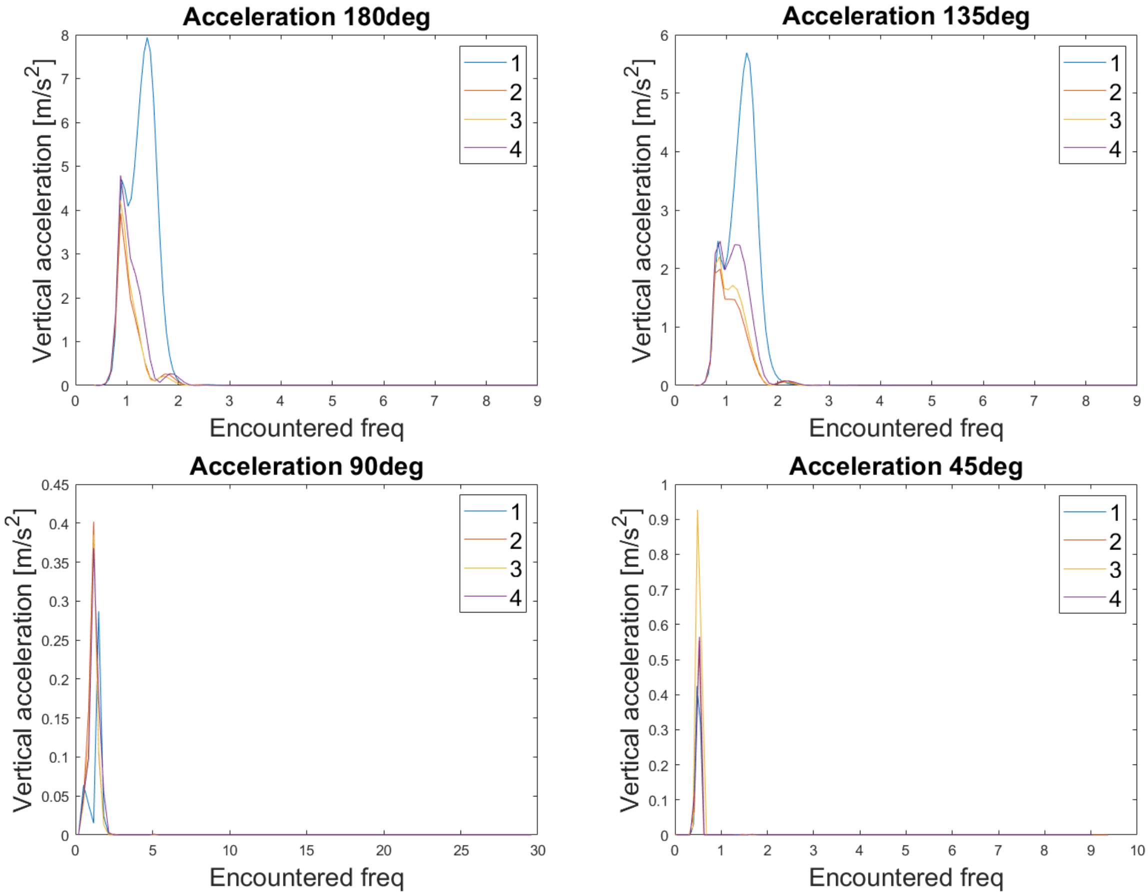

Figure G.5: Vertical acceleration ($(m/s^2)/m$) at 0.1 L_{BP} aft of FP as function of wave frequency for different headings at 11kn

H

Motion Validation GM=1.0m

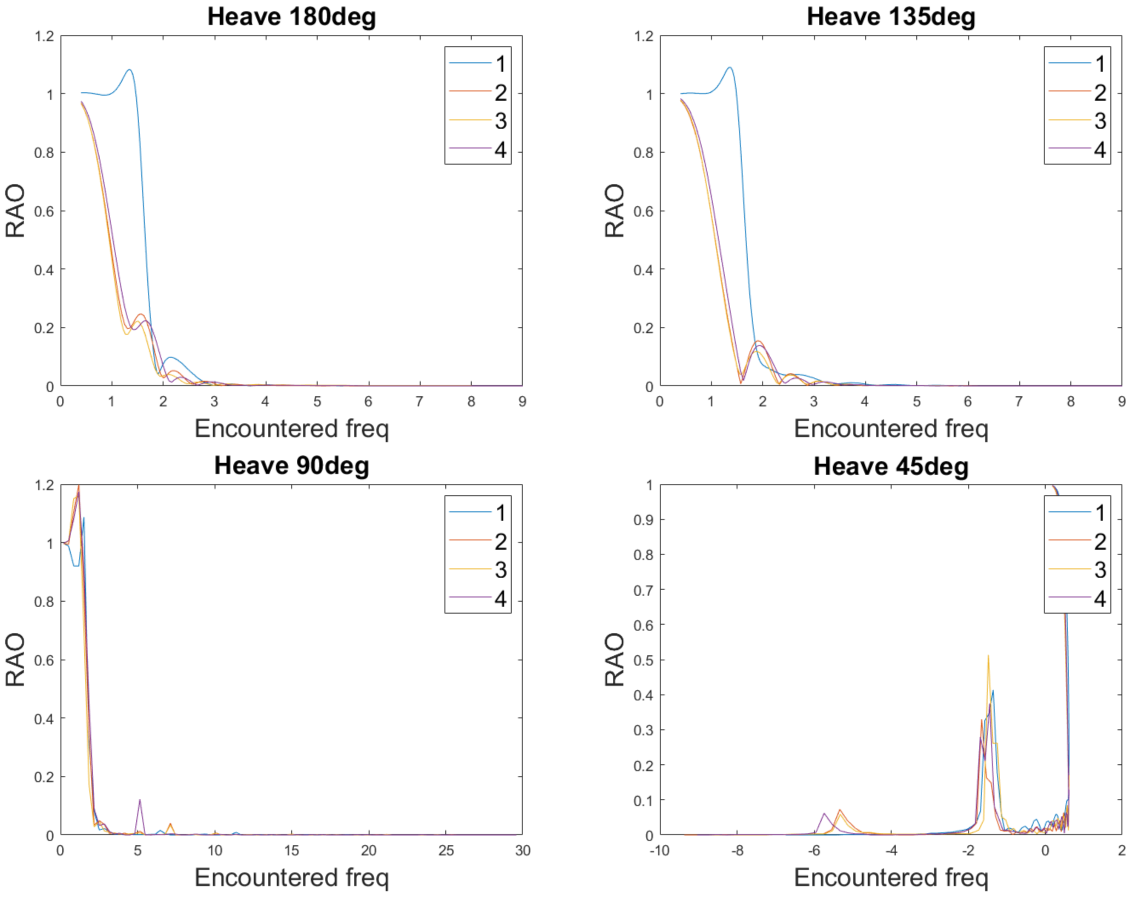

Figure H.1: Heave motion (m/m) as function of wave frequency for different headings at 11kn

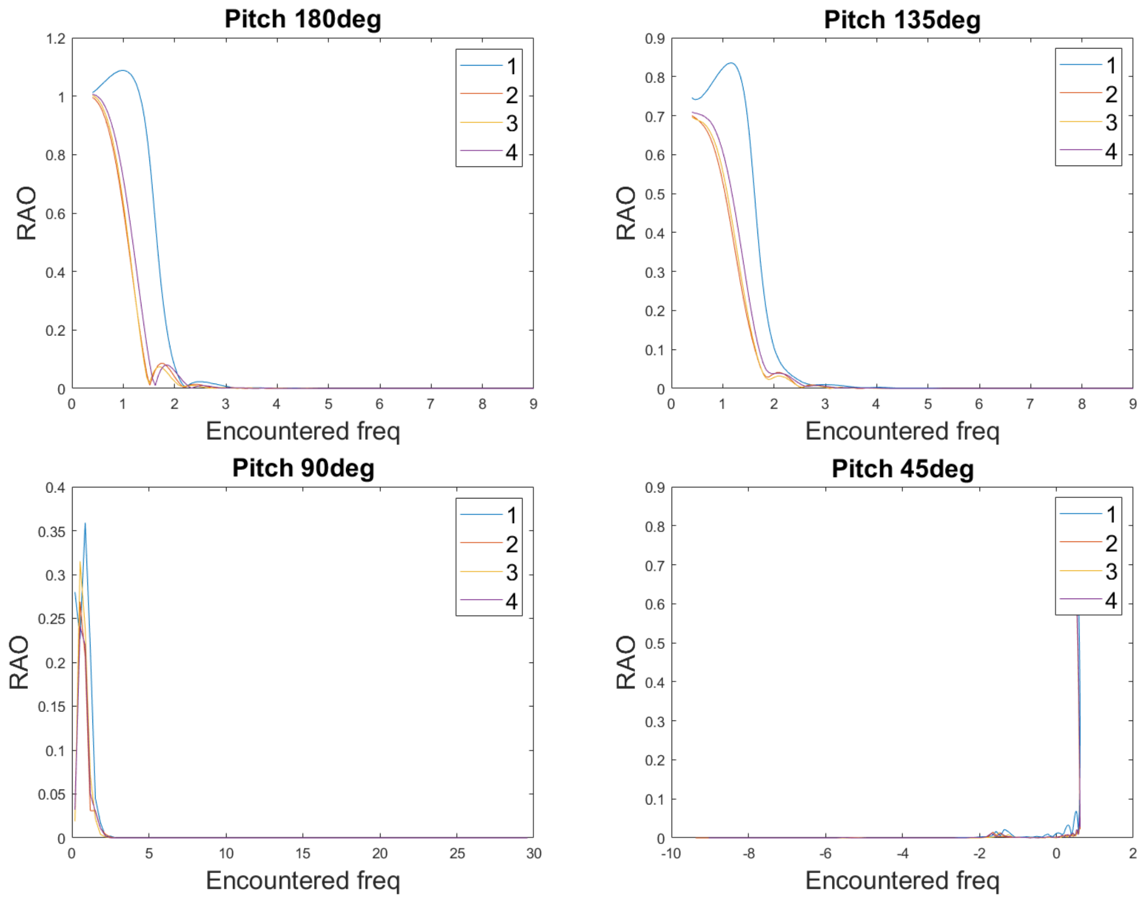

Figure H.2: Pitch motion/k (m/m) as function of wave frequency for different headings at 11kn

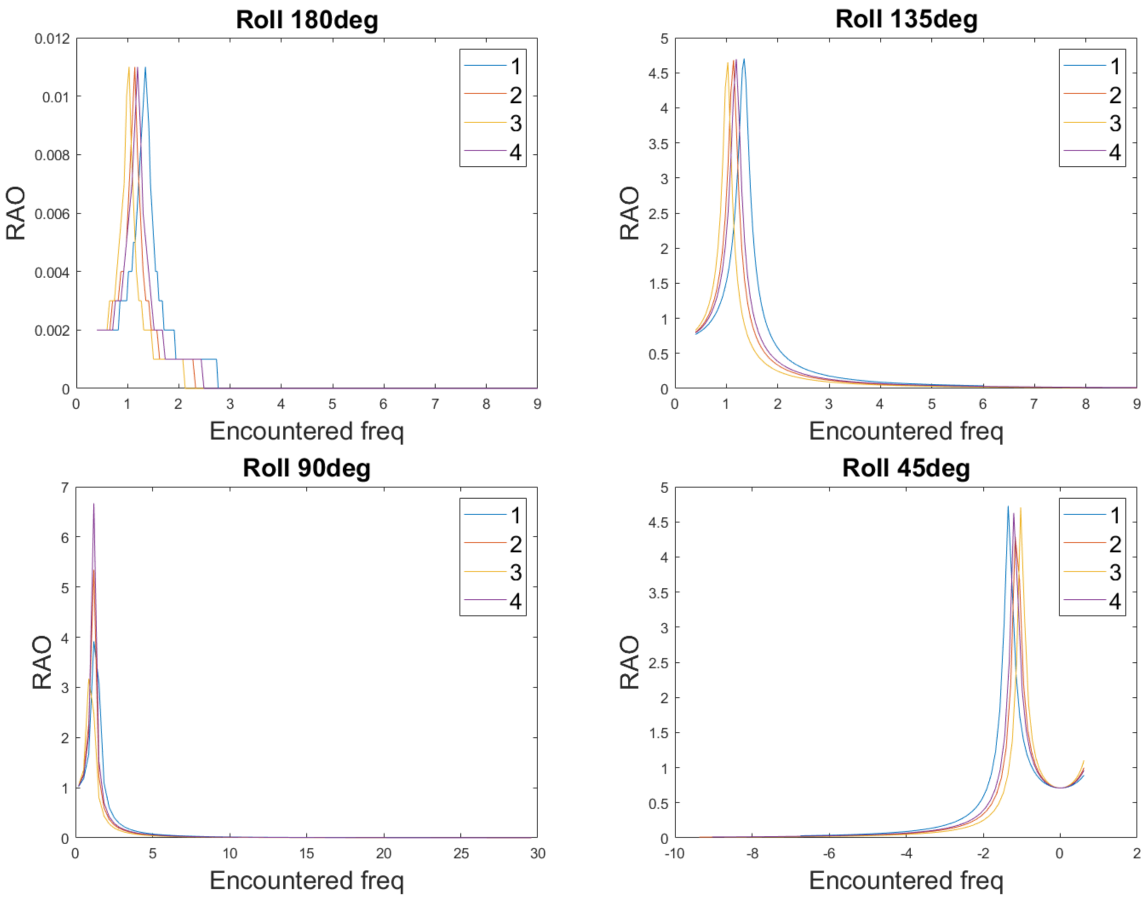

Figure H.3: Roll motion/k (m/m) as function of wave frequency for different headings at 11kn

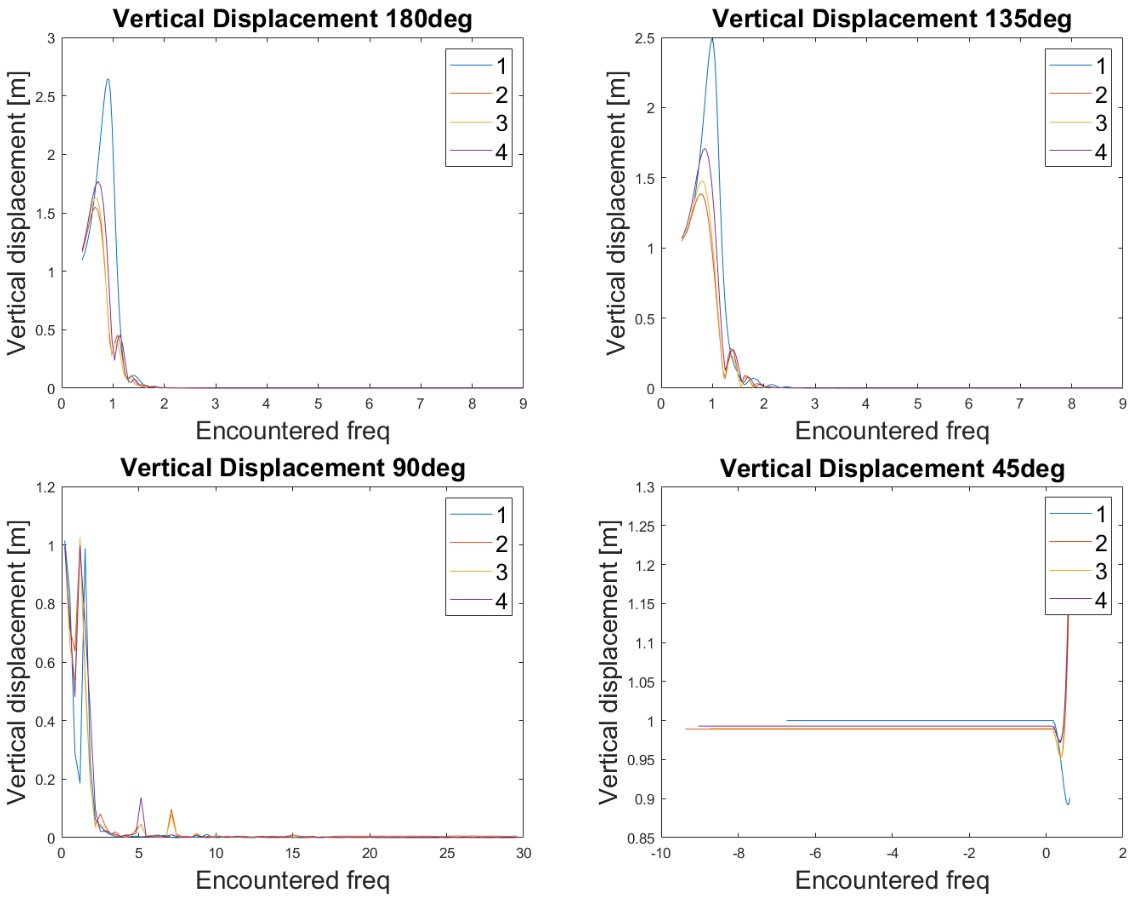

Figure H.4: Vertical displacement (m/m) as function of wave frequency for different headings at 11kn

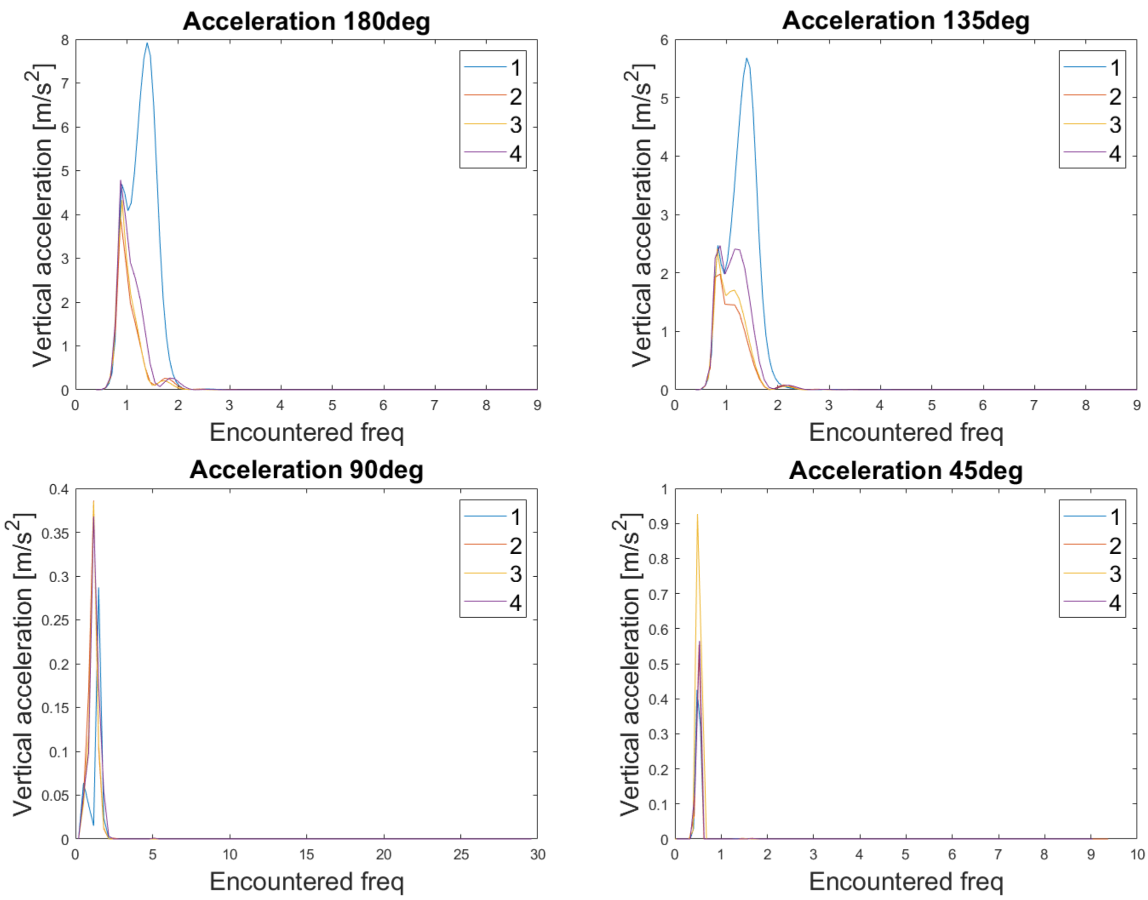

Figure H.5: Vertical acceleration ($(m/s^2)/m$) at 0.1 L_{BP} aft of FP as function of wave frequency for different headings at 11kn

I

MOTION VALIDATION GM=1.5M

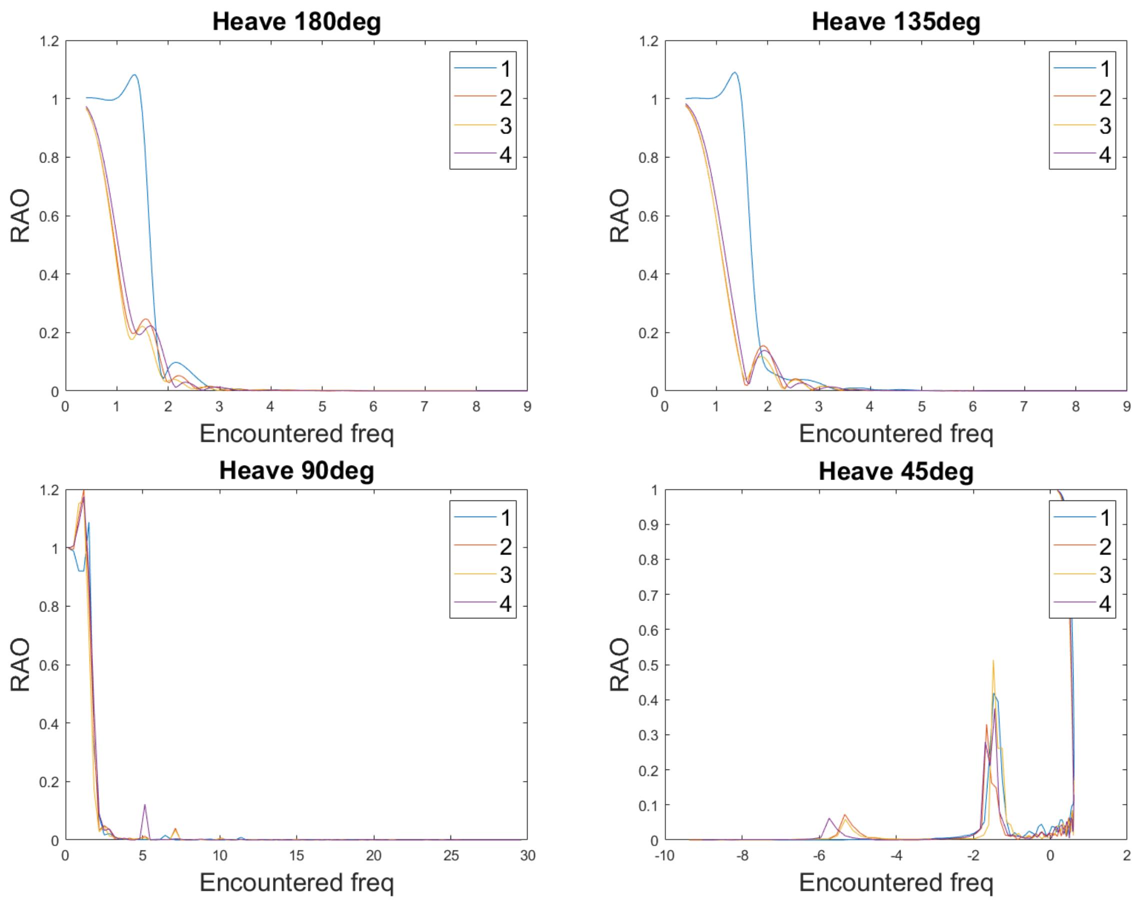

Figure I.1: Heave motion (m/m) as function of wave frequency for different headings at 11kn

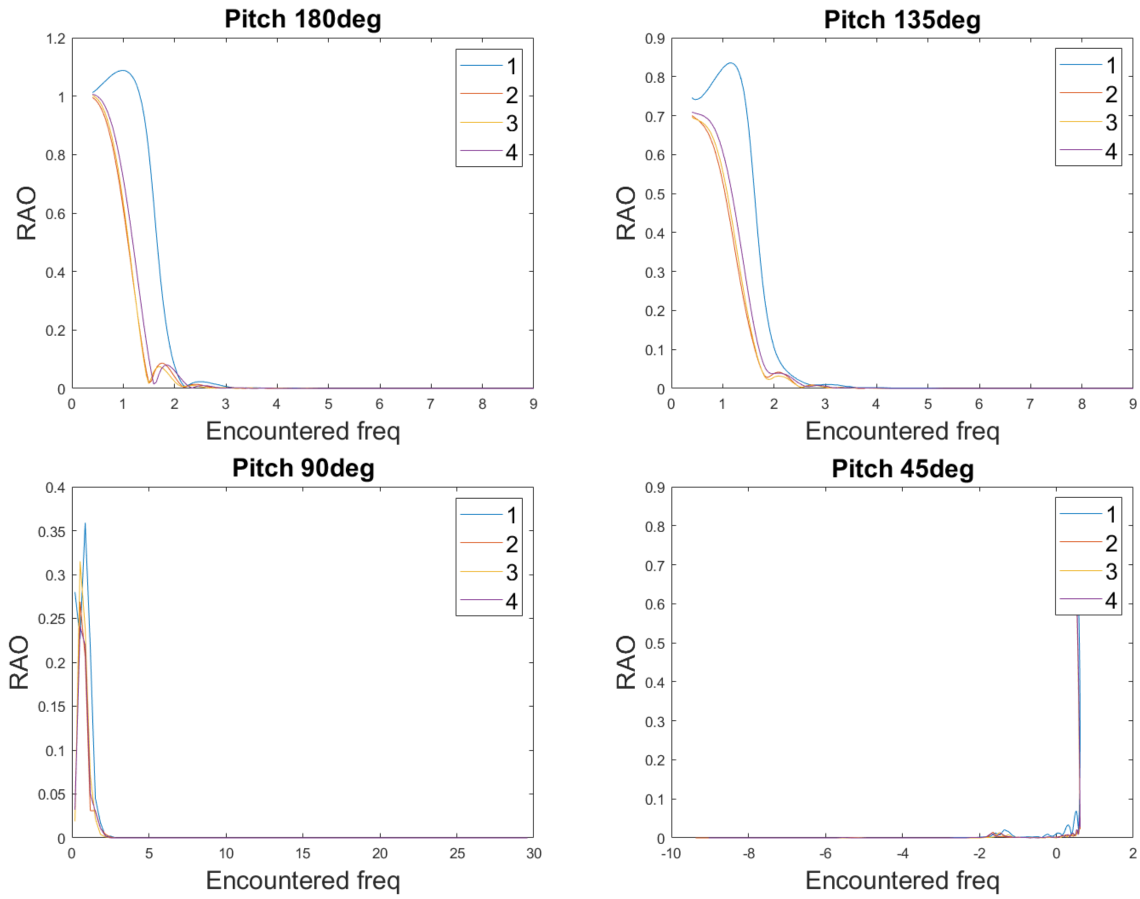

Figure I.2: Pitch motion/k (m/m) as function of wave frequency for different headings at 11kn

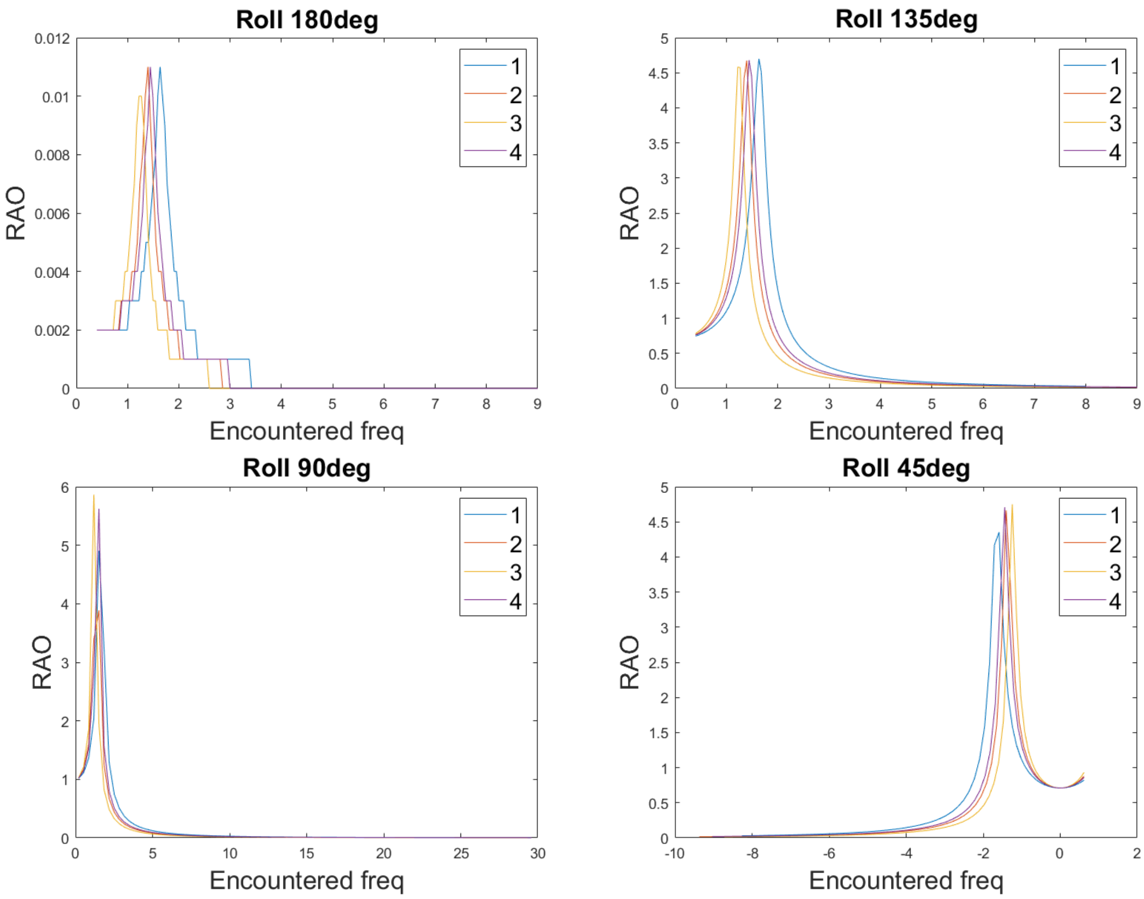

Figure I.3: Roll motion/k (m/m) as function of wave frequency for different headings at 11kn

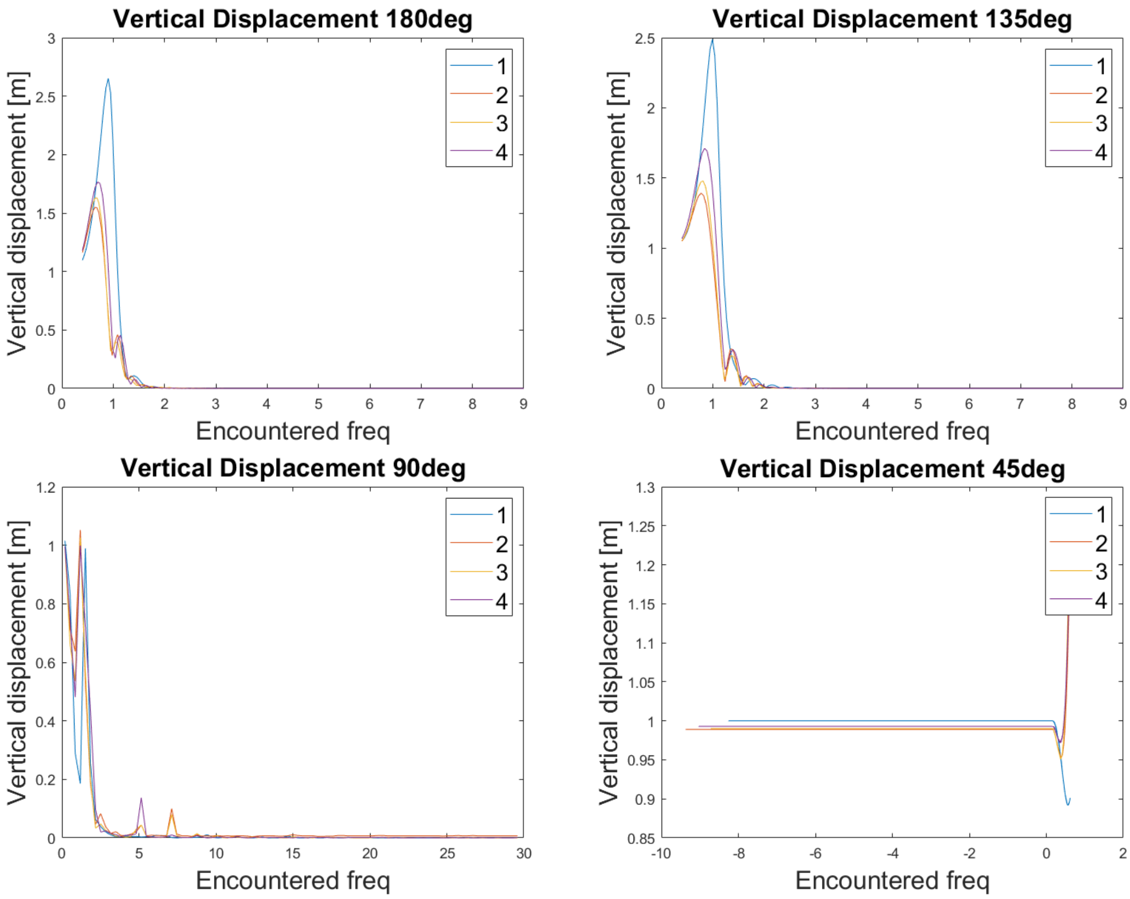

Figure I.4: Vertical displacement (m/m) as function of wave frequency for different headings at 11kn

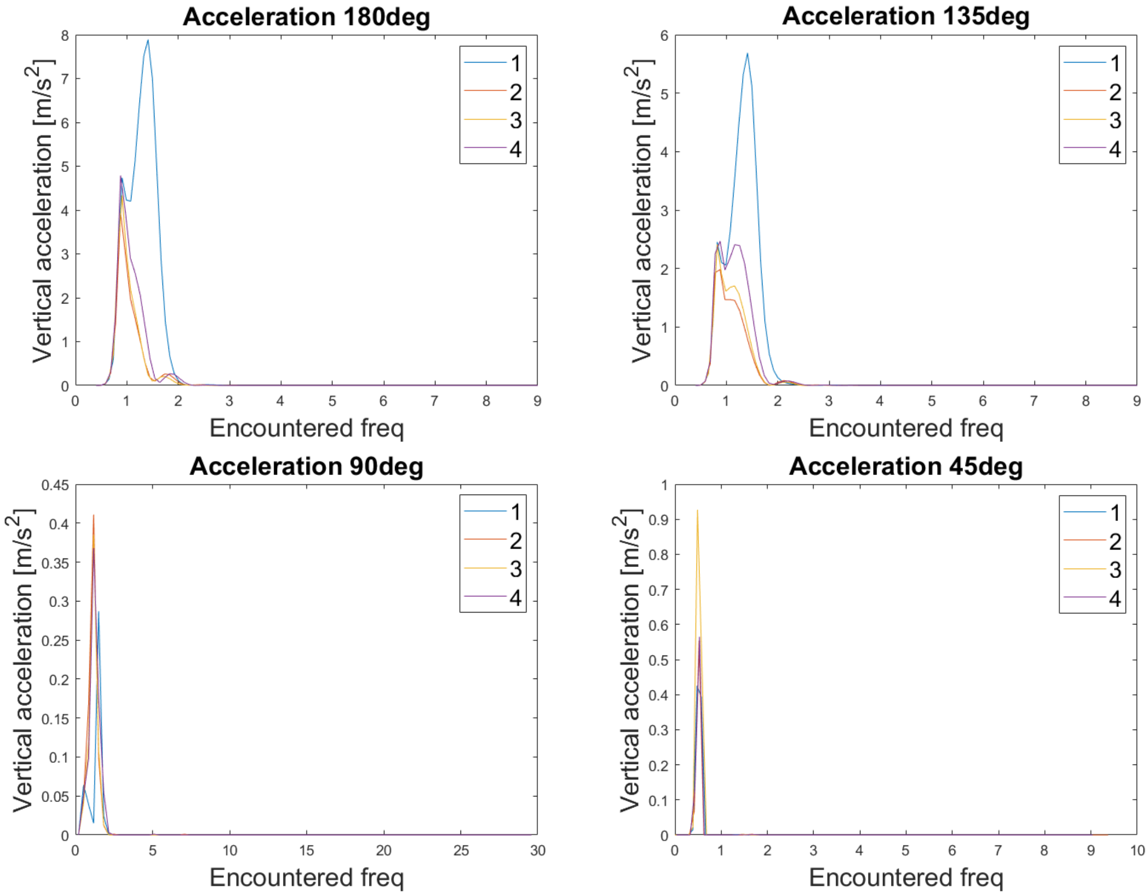

Figure I.5: Vertical acceleration ($(m/s^2)/m$) at 0.1 L_{BP} aft of FP as function of wave frequency for different headings at 11kn

J

OUTPUT OF VALIDATION OF SUGGESTED MODELS

Name	Length [m]	Beam [m]	Draft [m]	Entrance angle [degree]	Stem distance [m]	X Frame indication [-]	Z Frame indication [-]
Design001	99.4	11.6	2.11	29.7	5.60	0.122	0.183
Design002	99.9	11.6	2.11	29.5	6.75	0.203	0.192
Design003	99.9	11.6	2.11	29.9	5.02	0.299	0.250
Design004	99.9	11.6	2.11	29.5	5.00	0.399	0.192
Design005	99.9	11.6	2.11	29.7	5.91	0.452	0.129
Design006	99.9	11.6	2.11	25.5	5.20	0.689	0.112
Design007	99.9	11.4	2.09	29.0	5.02	0.440	0.271
Design008	99.9	11.6	2.11	25.5	5.20	0.586	0.169
Design009	99.9	11.6	2.11	25.5	5.02	0.517	0.236
Design010	100.0	11.4	2.09	26.4	5.02	0.508	0.372
Design011	99.9	11.1	2.05	22.9	5.04	0.408	0.340
Design012	99.8	11.4	2.09	21.4	5.02	0.593	0.406
Design013	99.9	11.4	2.09	22.5	5.02	0.724	0.791
Design014	99.1	11.4	2.09	22.9	5.02	0.691	0.877
Design015	99.8	11.4	2.09	21.0	5.02	0.663	0.731
Design016	99.7	11.4	2.09	21.4	5.45	0.653	0.814
Design017	99.5	11.6	2.11	20.7	5.37	0.549	0.867
Design018	97.3	11.4	2.09	21.3	5.02	0.790	0.814
Design019	99.9	11.5	2.11	15.7	11.65	0.553	0.320
Design020	96.1	11.4	2.09	18.6	11.11	0.483	0.288
Design021	99.1	11.6	2.11	15.2	10.61	0.600	0.346
Design022	99.9	11.6	2.11	15.7	11.10	0.520	0.727
Design023	91.9	11.6	2.11	15.2	10.61	0.612	0.278
Design024	80.8	12.2	2.32	15.7	10.56	0.703	0.211
Design025	86.4	12.7	2.37	16.5	9.78	0.740	0.741
Design026	86.7	12.2	2.46	15.8	9.91	0.244	0.810
Design027	86.4	12.0	2.46	16.4	9.21	0.326	0.804
Design028	85.2	12.8	2.49	15.5	11.26	0.468	0.741
Design029	85.2	12.3	2.49	16.3	11.42	0.468	0.741

Table J.1: Design variables of suggested optimal models

Name	Total resistance [kN]	Max vert displ $[m]$	Cb [-]	Volume $[m^3]$	Rw3 [kN]	Viscous resistance [kN]
Design001	117.6	1.31	0.664	1574	38.9	78.8
Design002	107.3	1.31	0.660	1564	29.9	77.4
Design003	98.3	1.31	0.653	1560	21.9	76.4
Design004	92.6	1.31	0.649	1551	17.2	75.4
Design005	92.6	1.31	0.655	1557	16.9	75.7
Design006	90.7	1.32	0.641	1530	17.3	73.4
Design007	88.9	1.32	0.638	1486	16.3	72.7
Design008	88.2	1.32	0.631	1507	15.9	72.4
Design009	86.5	1.32	0.622	1486	15.0	71.5
Design010	85.2	1.33	0.613	1429	15.4	69.8
Design011	80.3	1.33	0.607	1352	12.8	67.5
Design012	79.1	1.34	0.578	1345	13.1	66.0
Design013	78.4	1.35	0.566	1319	13.8	64.6
Design014	78.1	1.35	0.565	1307	14.0	64.1
Design015	77.0	1.35	0.559	1303	13.1	63.9
Design016	77.0	1.35	0.559	1297	13.4	63.6
Design017	76.7	1.36	0.549	1305	13.2	63.5
Design018	75.7	1.36	0.554	1258	13.5	62.2
Design019	75.0	1.36	0.563	1300	11.7	63.3
Design020	74.2	1.36	0.575	1252	12.0	62.2
Design021	72.6	1.37	0.534	1233	11.5	61.1
Design022	72.3	1.38	0.519	1206	12.7	59.6
Design023	69.9	1.39	0.565	1206	9.9	60.0
Design024	69.9	1.50	0.576	1239	10.4	59.4
Design025	69.3	1.55	0.492	1222	11.4	57.9
Design026	68.9	1.63	0.491	1213	12.5	56.3
Design027	68.8	1.63	0.496	1206	12.7	56.1
Design028	68.3	1.65	0.485	1245	10.8	57.5
Design029	67.4	1.67	0.492	1212	11.3	56.1

Table J.2: Output data of suggested optimal models

K

DATA OF TEST CASE STUDY

INPUT PARAMETERS

HYDROGRAPHIC SURVEY

Variable	Value	Units
Speed	11	[kn]
Volume constraint	>1200	[m^3]
Heading angle	180	[degree]
Wave amplitude	1	[m]
Position of Interest	0.9*LWL	[m]

Table K.1: Parameters used for optimisation

Design Variable	Units	Lower limit	Upper limit
Draft	[m]	2	8
LOA	[m]	50	100
Beam	[m]	10	15
Entrance Angle WL	[degree]	15	30
Stem distance	[m]	5	12
X Frame Indication	[-]	0.1	0.9
Z Frame Indication	[-]	0.1	0.9

Table K.2: Design variables for optimisation

LOGISTIC SUPPORT

Variable	Value	Units
Speed	14	[kn]
Volume constraint	>1200	[m^3]
Heading angle	180	[degree]
Wave amplitude	1	[m]
Position of Interest	0.9*LWL	[m]

Table K.3: Parameters used for optimisation

Design Variable	Units	Lower limit	Upper limit
Draft	[m]	2	3.5
LOA	[m]	50	65
Beam	[m]	10	15
Entrance Angle WL	[degree]	15	30
Stem distance	[m]	5	12
X Frame Indication	[-]	0.1	0.9
Z Frame Indication	[-]	0.1	0.9

Table K.4: Design variables for optimisation

SUBMARINE SUPPORT

Variable	Value	Units
Speed	14	[kn]
Volume constraint	>1250	[m^3]
Heading angle	180	[degree]
Wave amplitude	1	[m]
Position of Interest	0.9*LWL	[m]

Table K.5: Parameters used for optimisation

Design Variable	Units	Lower limit	Upper limit
Draft	[m]	2	8
LOA	[m]	55	100
Beam	[m]	10	15
Entrance Angle WL	[degree]	15	30
Stem distance	[m]	5	12
X Frame Indication	[-]	0.1	0.9
Z Frame Indication	[-]	0.1	0.9

Table K.6: Design variables for optimisation

Marine Training

Variable	**Value**	**Units**
Speed	10	[kn]
Volume constraint	>1000	[m^3]
Heading angle	180	[degree]
Wave amplitude	1	[m]
Position of Interest	0.9*LWL	[m]

Table K.7: Parameters used for optimisation

Design Variable	**Units**	**Lower limit**	**Upper limit**
Draft	[m]	2	8
LOA	[m]	50	100
Beam	[m]	10	15
Entrance Angle WL	[degree]	15	30
Stem distance	[m]	5	12
X Frame Indication	[-]	0.1	0.9
Z Frame Indication	[-]	0.1	0.9

Table K.8: Design variables for optimisation

Family design Restricted

Variable	**Value**	**Units**
Speed	14	[kn]
Volume constraint	>1250	[m^3]
Heading angle	180	[degree]
Wave amplitude	1	[m]
Position of Interest	0.9*LWL	[m]

Table K.9: Parameters used for optimisation

Design Variable	Units	Lower limit	Upper limit
Draft	$[m]$	2	3.5
LOA	$[m]$	50	65
Beam	$[m]$	10	15
Entrance Angle WL	[degree]	15	30
Stem distance	$[m]$	5	12
X Frame Indication	[-]	0.1	0.9
Z Frame Indication	[-]	0.1	0.9

Table K.10: Design variables for optimisation

FAMILY DESIGN OPEN

Variable	Value	Units
Speed	14	[kn]
Volume constraint	>1200	$[m^3]$
Heading angle	180	[degree]
Wave amplitude	1	[m]
Position of Interest	0.9*LWL	[m]

Table K.11: Parameters used for optimisation

Design Variable	Units	Lower limit	Upper limit
Draft	$[m]$	2	8
LOA	$[m]$	50	100
Beam	$[m]$	10	15
Entrance Angle WL	[degree]	15	30
Stem distance	$[m]$	5	12
X Frame Indication	[-]	0.1	0.9
Z Frame Indication	[-]	0.1	0.9

Table K.12: Design variables for optimisation

Output parameters

Values of design variables HOV

CAESES		
Parameter	Value	Unit
LOA	93.4	[m]
Beam	10.9	[m]
Draft	2.39	[m]
Entrance Angle WL	16.6	[degree]
Stem Distance	9.25	[m]
X Frame Indication	0.740	[-]
Z Frame Indication	0.738	[-]
Displacement	1211	[m^3]
Resistance objective	38.2	[kilo Newton (kN)]
Vertical displacement objective	1.41	[m]

Table K.13: Parameters of selected hull

Values of design variables Logistic Support

CAESES		
Parameter	Value	Unit
LOA	61.9	[m]
Beam	15.0	[m]
Draft	2.82	[m]
Entrance Angle WL	16.8	[degree]
Stem Distance	10.6	[m]
X Frame Indication	0.570	[-]
Z Frame Indication	0.344	[-]
Displacement	1211	[m^3]
Resistance objective	67.4	[kN]
Vertical displacement objective	1.91	[m]

Table K.14: Parameters of selected hull

Values of design variables Submarine Support

CAESES		
Parameter	Value	Unit
LOA	99.9	[m]
Beam	11.0	[m]
Draft	2.09	[m]
Entrance Angle WL	20.2	[degree]
Stem Distance	5.03	[m]
X Frame Indication	0.599	[-]
Z Frame Indication	0.779	[-]
Displacement	1256	[m^3]
Resistance objective	74.9	[kN]
Vertical displacement objective	1.36	[m]

Table K.15: Parameters of selected hull

VALUES OF DESIGN VARIABLES MARINE TRAINING

CAESES		
Parameter	Value	Unit
LOA	90.1	[m]
Beam	10.5	[m]
Draft	2.11	[m]
Entrance Angle WL	22.5	[degree]
Stem Distance	9.75	[m]
X Frame Indication	0.676	[-]
Z Frame Indication	0.824	[-]
Displacement	1028	[m^3]
Resistance objective	29.8	[kN]
Vertical displacement objective	1.34	[m]

Table K.16: Parameters of selected hull

VALUES OF DESIGN VARIABLES FAMILY DESIGN RESTRICTED

CAESES		
Parameter	Value	Unit
LOA	63.1	[m]
Beam	14.6	[m]
Draft	2.67	[m]
Entrance Angle WL	19.2	[degree]
Stem Distance	9.09	[m]
X Frame Indication	0.597	[-]
Z Frame Indication	0.188	[-]
Displacement	1253	[m^3]
Resistance objective	73.3	[kN]
Vertical displacement objective	1.76	[m]

Table K.17: Parameters of selected hull

VALUES OF DESIGN VARIABLES FAMILY DESIGN OPEN

CAESES		
Parameter	Value	Unit
LOA	91.9	[m]
Beam	11.6	[m]
Draft	2.11	[m]
Entrance Angle WL	15.2	[degree]
Stem Distance	10.6	[m]
X Frame Indication	0.612	[-]
Z Frame Indication	0.278	[-]
Displacement	1206	[m^3]
Resistance objective	69.9	[kN]
Vertical displacement objective	1.39	[m]

Table K.18: Parameters of selected hull