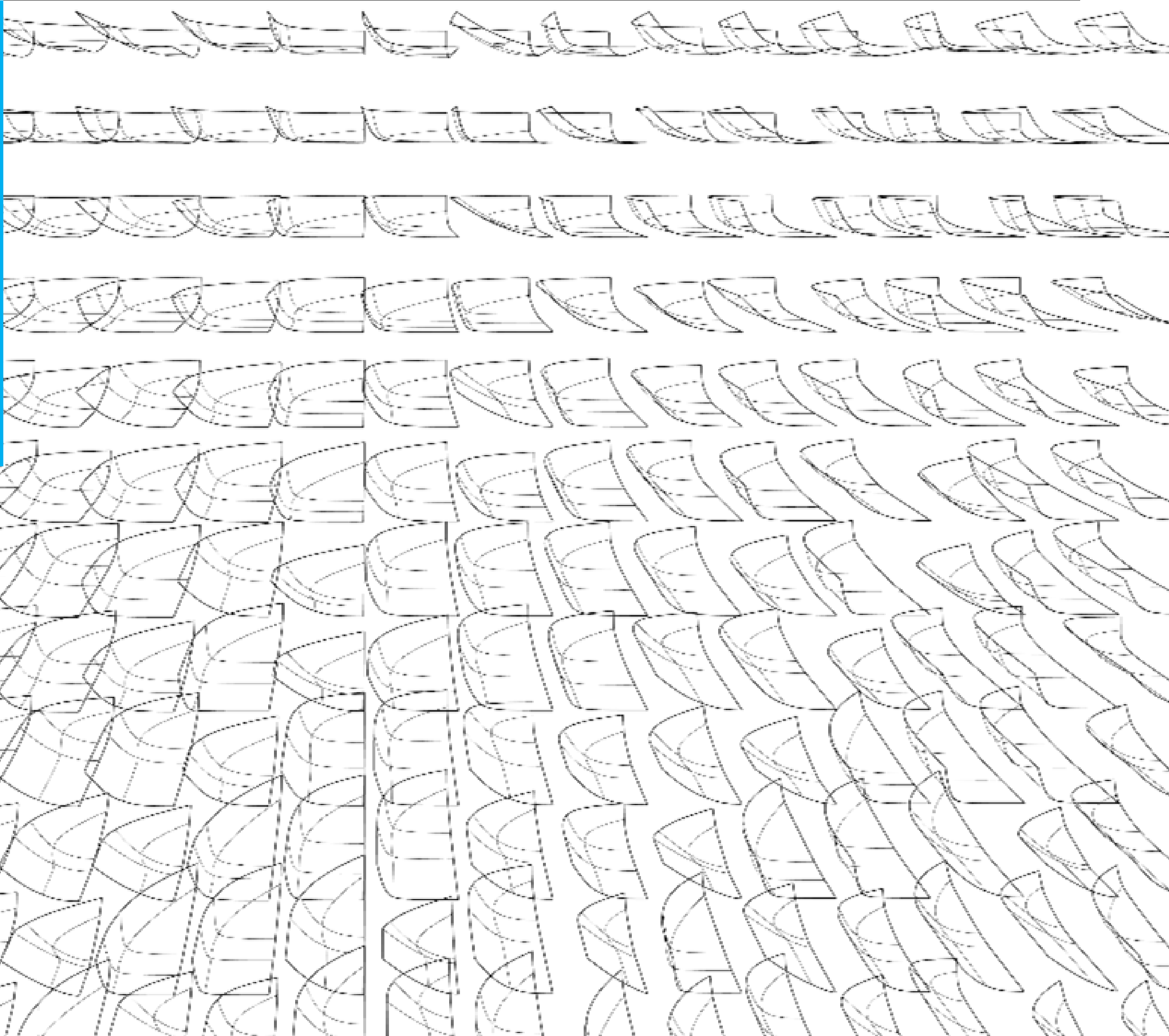
HULL GENERATION FOR FAST CONCEPT EXPLORATION

Development of a Brute-Force Approach to Quickly Obtain Hull Shapes and a Resistance Prediction for Offshore Patrol Vessels

J.B.A. Maartens

Delft Universty of Technology



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HULL GENERATION FOR FAST CONCEPT EXPLORATION

Development of a Design Tool to Quickly Obtain Hull Shapes with a Resistance Prediction in the Concept Design Phase

By

J.B.A. MAARTENS

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Company supervisor	Ir. R.A. Huijsman
TU Delft supervisor	Dr. ir. R.G. Hekkenberg
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Thesis exam committee

Prof. ir. J.J. Hopman	Full Professor Ship Design, Production & Operations	TU Delft
Dr. ir. R.G. Hekkenberg	Associate Professor Ship Design, Production & Operations	TU Delft
Dr. ir. G. Smit	Assistant Professor Medical Instruments & Bio-Inspired Technology	TU Delft
Dr. V. Reppa	Assistant Professor Transport Engineering & Logistics	TU Delft
Ir. R.A. Huijsman	Development Engineer	Damen Shipyards Group

Preface

This thesis is written as final part of the Master of Science degree in Marine Technology at the Delft University of Technology. The subject has been a proposal from Damen Shipyards Gorinchem, as they have recognized the need to improve one of their business processes. This provided me with an opportunity to finally, after 6 years of studying Marine Technology, apply my gained knowledge to a practical problem. Well, ‘practical’, it was still a very deep dive into some specific theory, but I enjoyed learning new things and the practical purpose of my subject. Conducting this research as an intern at the R&D department of Damen has, therefore, been a very interesting, informative and nice experience. I can only recommend others to do the same.

From the Delft side I was supervised by Robert Hekkenberg, for which I would like to thank you. I wanted you as supervisor based on my experience from the Bachelor End Project, and I am very glad that you were willing to help me. I appreciate your critical thinking and feedback, which helped me to stay on the right track and to critically review my own work. So, thank you very much for the time and energy spent on supervising me.

I would also like to thank Renger Huijsman for being my supervisor at Damen. It was very helpful to regularly brainstorm with you about the direction of the research and the subject in general. Additionally, I liked your openness and willingness to help me, even at moments when you were called all the time about SeaXplorers and Amels vessels again. It was very nice having you as a company supervisor, so thank you for that. Additionally, I would like to thank the Offshore & Transport team from Damen R&D in general. It was a pleasure to reside in your rooms during my internship. I greatly appreciate all help I got, and enjoyed the discussions, dry humour, football talks and kibbeling bets.

I also found discussions with fellow students of great value. It was very helpful and nice to brainstorm, to talk about similar but also other topics, and to discuss the graduation process in general. I enjoyed it and hope to continue such discussions in our professional careers. A special thanks for Jiri de Vos, as we did a lot of successful projects together and you helped me to review this report. I will always appreciate your help and enjoyed working with you.

Last, but absolutely not least, I want to put some people in the spotlight which have nothing to do with daily work and boats. I would like to pay a tribute to my parents, who have always unconditionally supported me during my studies. I greatly appreciate the trust and freedom that you gave me. An homage to my girlfriend Janiek as well, for just being there for me and for the love I get from you. You three form the foundation that allow me to do what I do. Thank you for all the inspiration.

Jonas Bob Adrian Maartens

Delft, March 1st 2020

Contents

Abstract

Damen Shipyards Gorinchem has found deficiencies in the process of developing concept designs of Offshore Patrol Vessels (OPVs). There is a need to increase the efficiency of this process, meaning that (1) the speed has to be increased, (2) the accuracy of designs has to be increased and (3) the risk of deviations of the project plan has to be reduced. Analysis of the current concept design phase shows that the designer should get more insight in the design challenge, and that a more systematic and uniform design approach is required amongst different involved departments. Additionally, the lead time of developing concept designs is mostly delayed by two major bottlenecks: development of the hull shape and obtaining a resistance prediction.

In this thesis a conceptual design tool is developed to resolve these deficiencies, by providing a platform for fast hull concept exploration. Key of this approach is to pre-compute time-intensive design aspects such that the most critical activities are done before starting the design process. It uses a set of parent hulls for which the resistance is obtained by RANS CFD simulations. Based on the parents, a semi-parametric modelling technique is used to create new hull geometry. A kriging surrogate model is used to provide a RANS CFD resistance prediction to that new hull geometry. A brute-force approach is then adopted to fill a database with feasible hull shapes, which can be used by the conceptual design tool for hull shape concept exploration.

To test this concept a proof-of-concept database of 245.005 hulls of double-ended ferries is generated in a few days on a laptop with good memory capabilities. The geometry results and resistance predictions in the database have been assessed with a sensitivity study, cross-validation and comparison with the parent hulls. It is shown that resulting geometry is smooth and well-faired. The resistance results are sufficiently accurate for use in the concept design phase, but applicability is limited for low prismatic coefficients.

For application to OPVs further research into application of this approach to hull geometries with varying local details (bulb shape, tunnels etc.) is necessary. The approach seems promising to improve the concept design phase, as it (1) reduces time pressure in the design process significantly, (2) provides insight in how the resistance is affected by main dimensions of the vessel, and (3) reduces the number of departments which is actively involved in the design process. Putting the design tool in practice should reveal if this is indeed the case.

List of Abbreviations

ANN	Artificial Neural Network
BU	Business Unit
CA(G)D	Computer Aided (Graphical) Design
CFD	Computational Fluid Dynamics
D&P	Design and Proposal (department of Damen)
D&S	Defence and Security (product group of Damen)
DEF	Double-Ended Ferry
DoE	Design of Experiments
ETO	Engineer-to-Order
FFD	Free Form Deformation
Fn	Froude number
GA	General Arrangement
GUI	Graphical User Interface
KPLS	Kriging combined with a Partial-Least Squares method
KPLSK	Kriging combined with a Partial-Least Squares method and using the output in a universal Kriging model
KRG	Universal Kriging
LCB	Longitudinal Centre of Buoyancy
MARIN	Marine Research Institute Netherlands
MOGA	Multi-Objective Genetic Algorithm
NURBS	Non-Uniform Rational B-Spline
OPV	Offshore Patrol Vessel
QoI	Quantity of Interest
R&D	Research and Development (department of Damen)
RANS	Reynolds-Averaged Navier-Stokes
RBF	Radial Basis Function
RFI	Request for Information
Rhino	Rhinoceros
RMSE	Root Mean Squared Error
SMT	Surrogate Modeling Toolbox
STD	Standard Deviation
SVN	Support Vector Network
SVR	Support Vector Regression
VTC	Variation-to-Contract

1

Introduction

1.1 Motivation & problem definition

Service vessels and the ship design process

It is argued that ships are amongst the most complex, man-made products on earth [1]. They can be divided into two classes of ships, namely (1) transport vessels and (2) service vessels. This first class of ships is used to transport cargo or passengers between two places, such as a container ship or ferry. The second class of ships uses its cargo to perform missions at sea. Examples are naval vessels, pipe-laying vessels or dredgers.

In the western part of Europe the maritime industry is especially focused on designing and producing large, complex and integrated service vessels. In combination with the need for innovative designs, this leads to a very complex design process [2]. This design process contains interdependencies (e.g. circular relationships between design parameters) and has no prototype phase [3]. Especially this last matter is different compared to similar industries, such as the aircraft or car industry, caused by the fact that series-production is not the standard for service vessels. They are designed to perfectly meet the requirements of a client and often only one product is actually built. Such vessels are known as *one-offs* or *engineer-to-order* (ETO) vessels.

The design and construction of a service vessel most often takes more than one year. The design process can be divided into several stages, for which a schematic representation is given in Figure 1-1 [4].

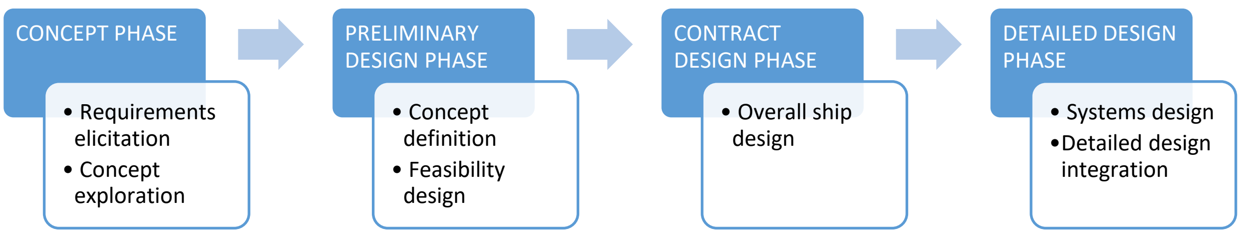

Figure 1-1: Schematic representation of the ship design process including, a description of the main tasks to be performed [4].

An alternative representation of the ship design process is the ship design spiral, which can be seen in Figure 1-2. It was first initiated by Evans [5] in 1959. While the design spiral converges to the centre new design phases are gone through.

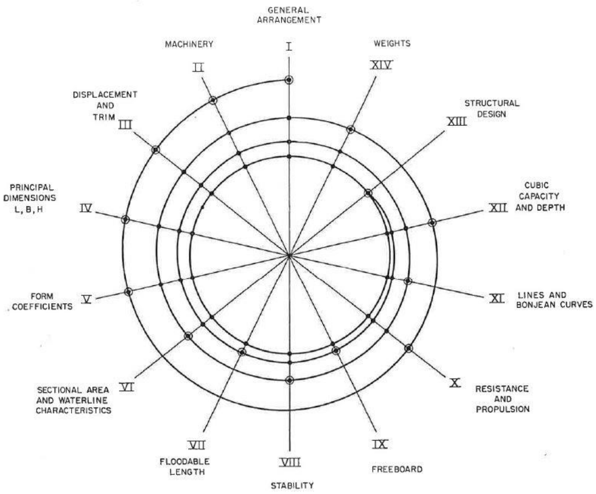

Figure 1-2: Ship design spiral [5].

The design spiral shows that ship design has an iterative and sequential nature. The starting point is a configuration of a ship design, often based on assumptions, rules of thumb, reference designs and experience of the designer. In each design phase at least one iteration is done, in which all design aspects are addressed sequentially. As the design process proceeds the level of detail increases and assumptions are replaced by exact calculations. The goal is to obtain a final balanced ship design after the contract design phase, which is made ready for production in the detailed design phase.

Due to the sequential nature there is a risk on delays, as all activities are interdependent and on the critical path. If one activity takes longer than planned, a whole iteration will be delayed as well. Additionally, another iteration has to be done if a mistake is made, also causing a delay.

The example of Damen

Damen Shipyards Group is a Dutch shipbuilding and engineering conglomerate company ('Damen' in short), founded in 1927. It produces a wide variety of vessels, amongst which ETO service vessels such as naval, offshore and research vessels. The Design & Proposal (D&P) department of the company is mainly concerned with translating customer requirements into the concept design of a vessel, in close cooperation with the Sales department. They are consequently responsible for requirements elicitation and concept exploration in accordance with Figure 1-1. The department is split up into different business units and product groups, of which one is the product group Defence & Security (D&S). They are concerned with developing ETO designs such as Offshore Patrol Vessels (OPVs). An example of an OPV is shown in Figure 1-3.


Figure 1-3: Example of an Offshore Patrol Vessel, the Damen OPV 1800 [6].

Within this product group it is recognized that the concept phase plays a key role in the design process. However, the current concept phase has its deficiencies: a need has grown to increase the efficiency of creating concept designs. In effect, this means that (1) the speed has to be increased, (2) the accuracy of designs has to be increased and (3) the risk of deviations of the project plan[1] has to be reduced. This need is fuelled by several reasons, which are listed below. Especially the development of the hull shape calls for improvement, since it is the most important piece of information in the concept phase.

1. **OPV market is becoming more important to Damen**

The amount of delivered D&S vessels and the contribution to the total turnover of Damen have grown significantly [7]–[10], making the product group more important to Damen. This is in line with an international trend of OPVs becoming more popular: it is the fastest growing segment of all naval vessels, resulting in an international order backlog of 284 OPVs, worth 40 billion dollars [11]. Global market reports predict a growth of the OPV market revenues, with an annual growth rate ranging from 3.84% [12] to 8.8% [13] until 2022 and 2023 respectively.

2. **Tender procedures cause high time pressure**

The customers of D&S products (typically governmental organisations) often use tender procedures for market consultation, gathering offers and selecting a manufacturer. Tender procedures can be characterized by pre-determined criteria, multiple participants, specific documents and file formats to be handed in, and fixed time periods to respond. As a consequence the time pressure to develop a tender offer can be very high, such that sometimes there is not enough time to accurately address high-risk design aspects. Speeding up (parts of) the concept design phase allows for more time to increase the accuracy and level of detail of the design. This would also reduce the risk on project deviations.

3. **Linear workflow is used**

For the concept design phase a design process of an iterative and sequential nature is used, very similar to the ship design spiral presented above. After analysis of this design phase, described in Chapter 2, it appears that obtaining the hull shape and a resistance prediction are major bottlenecks which delay the process in this linear workflow. Different departments are involved and dependent on each other's results. Concept designs contain inaccurate or outdated information, increasing the chance on project deviations. Mistakes and mismatches actually lead to delays and extra iterations.

4. **Commercial need to operate as planned**

There is always a commercial need to prevent delays (i.e. time loss) and to reduce cost. In the shipping industry Variation-To-Contracts (VTCs) are often used to define a deviation from the original contract, but then a fine would be introduced for the party which caused the deviation. Consequently, for the shipbuilder it is advantageous if projects are actually executed as planned in terms of costs, time and quality.

Problem definition

The following **problem definition** is formulated, summarizing the reasons that cause the need to improve the current design process.

> *A linear workflow is used in the concept design phase of Offshore Patrol Vessels, such that bottlenecks exist. Major bottlenecks are the development of a hull shape and obtaining a resistance prediction. These activities currently cause delays and are sometimes based on outdated information. Additionally, there is a lack of a predetermined working structure and design approach. There is, therefore, a need to increase the efficiency of creating concept designs of OPVs. This should be done to satisfy the commercial need of minimizing the development time of concept designs, such that the risk on project deviations is minimized.*

[1] Risks of deviations of the project plan can be expressed in costs, time and quality [77].

1.2 State-of-the-art

The question is how the problem as defined in the problem definition can be solved. Key in the problem is that two bottlenecks are present, due to a combination of a linear design approach and organizational issues. It is expected that combining separate solutions for these bottlenecks in a specific way could lead to the desired increase in efficiency of creating concepts.

A concept exploration tool could be a solution for resolving the bottleneck of developing a hull shape, as it is an effective measure for the designer to explore more possible solutions. By having a pre-generated design space in which specific design aspects are accurately addressed, hull shapes can be found more quickly and can be more accurate at the same time. Additionally, it can provide insight in how the performance of a hull shape can be influenced, such that designs potentially get more accurate. Therefore, concept exploration is described in 1.2.1. In order to come to this point, criticism on the design spiral is described as well in this section. Hereafter, solutions to resolve the bottleneck of resistance evaluation are described in 1.2.2. Last, the focus of this thesis is presented in 1.2.3.

1.2.1 Design spiral criticism and concept exploration approaches

The cause of the bottlenecks is related to the linear design approach, following from the characteristics of the ship design spiral. This representation of the design process is being criticized by researchers in the last decade. It is said to lock naval architects to first assumptions [14] and to be a too simplistic, linear representation of the complex ship design process which is actually non-linear [4]. Alternative design representations or methods mostly focus on improvements in the concept design phase, as it is acknowledged that this phase plays a key role in the ship design process. Most of the main design decisions are made in the concept design phase [1], [3]. Moreover, issues in the concept design phase mostly don't emerge as clear problems until later stages of the design, such as the detailed design phase [15]. In general, there is a need to gain knowledge about a design problem as early as possible, to increase the design freedom and to delay committed costs as long as possible [16].

One popular point of focus amongst academics is to provide designers more means to explore more possible solutions (i.e. solutions for given constraints), thus aiming at gaining more design problem knowledge and increasing design freedom. These studies focus on supporting the search for a balanced set of design options and corresponding design requirements [17]. It is referred to as concept exploration and has several benefits [17]:

- It provides an overview of the design and performance space, allowing for quick comparison and selection of promising concepts.
- It helps in prioritizing design aspects and finding the aspects which are of real importance.
- It provides insight in the interrelationships between design parameters and the performance space, providing the basis for making trade-off decisions.

For using concept exploration a design space is populated, such that the hull shape is readily available. Taking the above listed benefits into account, concept exploration could, therefore, be an effective measure to increase the efficiency of creating OPV concept designs.

In general, there are two approaches to populate a design space: those using optimization strategies and algorithms, and those using a brute-force approach. The most popular approach in literature is the optimization-based approach. Objective functions are employed to steer search algorithms, in order to find solutions that satisfy the objective functions the most ('optimal' solutions). Examples are the TU Delft Packing Approach by Van Oers [18] and UCL Building Block Approach [19], which employ these search algorithms to quickly generate a design space of system-layouts for 3D hull forms of naval ships. Other design aspects which are being generated are energy distribution systems [20], general arrangements [21] and hull shapes [22]. These, but also other examples, are distinctive from conventional approaches as they provide the designer with tools to rapidly explore the design space in the concept design phase. However, they require the designer to a-priori define the objectives to be used such that 'optimized' results are obtained. Duchateau [17] developed an interactive evolutionary search method for system-layouts without the need for a pre-defined objective. The designer can then generate a design space and adjust its search based on the insight gained during the search process.

Alternatively, in the brute-force approach no objectives or optimization strategies are defined. Systematic variation is used to fill a database with brute force, also referred to as full-factorial design. Effectively, no strategy is used to compute all possibilities, but a pre-defined grid is simply used for filling. This is a less popular approach caused by the high number of possibilities when the number of varied parameters becomes large, such that the needed computational time becomes impractically large. Nevertheless, it can be applied and might be beneficial for several reasons:

- For concept exploration it would not be needed to exactly define multiple objective functions (performance indicators) for filling the design space, which is a challenge on its own and often the reason to start concept exploration [17].
- Damen views the parameters used for defining hull shapes as discrete instead of continuous variables (e.g. beam is varied based on a fixed frame spacing). This allows for pre-defining all possible hull shapes.
- It allows for searching for solutions based on performance, i.e. reverse engineering.
- Computational power has been increasing exponentially in the last 70 years, potentially allowing future development of databases that actually contain all possibilities for a parameterized hull shape.

Other advantages of a brute-force approach are described in Chapter 4.

At the same time a lot of advantages from the optimization-based exploration approaches are still achieved, such that it has gotten some attention from academics. For example, a library-based approach was developed to fill the gap of design methods for selection of a hull form style [1]. A design space with hull shapes is filled and evaluated based on several design aspects [23]. However, the brute-force approach did not get as much attention as the optimization-based approach.

1.2.2 Resistance evaluation

The first estimation of the resistance is important in the design process. The result, together with an estimation of the propulsive efficiency, is leading for the propeller design, engine selection and other propulsive system aspects. It hereby also influences the total ship arrangement. There is, therefore, a need for an accurate and substantiated resistance prediction.

In the concept design phase the ship resistance is often evaluated by using statistical regression formulae, e.g. from Holtrop [24], [25] and Holtrop & Mennen [26]. Other options are systematic series or direct model tests, but these are often not applicable or only applied in later design stages for verification [27]. More recently Computational Fluid Dynamics (CFD) has become popular, which provides information about fluid properties by numerically solving fluid dynamics equations. This method has several benefits over the other methods:

- It potentially provides more accurate results than statistical regression and systematic series methods.
- It is more accessible (costs and time wise) than direct model tests, allowing for earlier use in the design process.
- It provides insight in the division of resistance components, and information about local issues such as pressure peaks.
- For systematic variation CFD also allows to investigate the influence of varied parameters on the resistance.

These advantages come at the cost of computation time and effort, as the working principle of CFD induces high computation times. This is especially true in the case of Reynolds-Averaged Navier-Stokes (RANS) CFD, needed to accurately assess the thick boundary layers in the aft part of hull shapes. Hence, CFD is often not directly applied in concept exploration studies, but rather for verification of a chosen design in the contract design phase.

A surrogate model can be used as a substitute for a CFD simulation in this case. The goal of such a model is then to predict the outcome based on regression analysis of a set of hulls for which CFD is already done, while using much less time and computational power. This can be especially valuable for when surrogate models are combined with concept exploration, as in that case the resistance has to be computed for a high number of alternatives. Multiple models are available and can be chosen based on the characteristics of the model to be imitated, such as plain polynomial models, radial basis functions, kriging and support vector regression [28].

In practice surrogate models have been applied successfully. For example, it has been used to predict the propulsion power and wake field quality of inland vessels [29], to optimize a bow shape for hydrodynamic resistance [30] and for approximation of Finite Element Method calculations [31]. Effectively, surrogate models are being applied for optimization-based concept exploration studies. They have not been applied in combination with brute-force approaches.

1.2.3 Focus of this thesis

Combining a brute-force approach with surrogate models might be contradictive: since the main objective of a surrogate model is to save on computation time, the brute-force approach will only increase computation time. Nevertheless, in the future this combination might be interesting for concept exploration studies when computational power has increased. The combination of brute-force and CFD for all hulls might still be too expensive, but the application of surrogate models instead of CFD in a brute-force approach can be promising if the surrogate models are accurate. Additionally, if all computations are done on beforehand, the time invested will not come at the same moment as the saved time. It can then be an effective measure to save time in the design process itself.

In this thesis the applicability and feasibility of a brute-force approach together with a surrogate-based resistance prediction method are tested. The combination seems a promising solution for the presented problems: as the most time-intensive and critical design activities are 'taken out' of the design approach and pre-computed, the time pressure is moved to before starting the design process. The hypothesis is that this makes a major contribution to resolving the bottlenecks and hereby increasing the efficiency of creating OPV concept designs.

In addition, by integrating the approach in a design tool, it is expected that this will increase the efficiency even more. It can be a user-friendly platform in which information can be managed, hereby automating tasks of the designer. Therefore, it is also a goal of this thesis to develop a conceptual design tool which facilitates the results of the pre-computation.

The approach will be developed and subsequently tested to solve the previously defined problem of developing ETO concept designs within Damen. Effectively, the Damen case will thus be used to test the developed approach, which should support the current design process of Damen. Next, the research set-up to develop the approach is described.

1.3 Research set-up

In relation to the problem definition that is defined, the research objective of this thesis can be formulated.

Research objective:

> *To develop a brute-force approach in combination with a surrogate-based resistance prediction method for concept exploration of hull shapes of Offshore Patrol Vessels. This approach should be integrated in a conceptual design tool which can be used to increase the efficiency of creating concept designs, by pre-computation of hull shapes and their resistance.*

For describing the rest of the research set-up, the research is demarcated and the research questions are defined.

1.3.1 Demarcation

As time is a limiting factor in this thesis project, the scope of the research is limited. The following list of characteristics of the thesis is set, which will function as boundary conditions.

- The thesis will be focused on concept design for one ship type: OPVs. This type of ship is identified as an ETO product within the product group D&S of Damen.
- The focus of the thesis is the development of an approach that speeds up the process of obtaining hull shapes but also provides more insight in the design problem, in order to increase the efficiency of creating offers in the concept design phase.
- The goal of this thesis is not to develop a totally new design approach, but rather to develop a solution that supports the current design approach to obtain a hull shape. The thesis focusses on post-processing of information that is present in the generated database of hull shapes, and providing a solution to do this in the most effective and efficient way. Integration of the solution in the current design approach is of importance.
- Damen has expressed the wish that solutions to be integrated in software should be transparent, traceable and of an integral character.

Another important boundary condition is that this thesis is conducted parallel to another project at the Research & Development (R&D) department of Damen. That study focuses on setting up a Design of Experiments (DoE) of hull shapes and using CFD to compute the resistance for those hulls. This results in a dataset of hull shapes with resistance results, such that the resistance can be used as a measure of performance of the hull shape. A surrogate model can then be used to predict the resistance for hull shapes which are not part of the dataset. **Setting up this dataset is <u>not</u> a part of this thesis: the output is provided by Damen and used as input for the design approach.** Set-up of the dataset is described in Section 3.2.

1.3.2 Research questions and methodology

In relation with the demarcation and the thesis' goal that is stated, the following **main research question** is defined.

> *How can the efficiency of creating concept designs of Offshore Patrol Vessels be increased while using a brute-force approach for generating concepts?*

In addition, sub-questions are formulated to ensure the research being in line with the demarcation and thesis' goal. The first sub-question focuses on analysing the current design approach in detail and distilling the needed improvements. By answering this question specific problems should be known, such that it can be justified whether the research focus of this thesis is correct.

1. *Which problems are present in the current design approach of developing OPV concept designs?*

After this analysis it becomes clear which needs are present within Damen. They are used to formulate functional requirements for the design tool, which are used as directive during the search for solutions that can satisfy the needs and requirements. These issues are addressed in the second sub-question.

2. *What are requirements for a design tool that supports and improves the current design approach?*

Sub-questions 1 and 2 are part of the analysis phase of the thesis. After answering these questions the next step is to explore possible solutions for the problems. The exploration of solutions to the two most important bottlenecks (obtaining a hull shape and making a resistance prediction) are addressed in the subsequent sub-questions. This is the start of the solution development phase of the thesis, in which the solution is being formulated.

3. *Which alternative hull generation method is the most promising to support the design approach in order to satisfy the need to acquire a hull shape much faster?*
4. *Which surrogate model is the most promising to predict the resistance of a new hull shape based on CFD results of parent hull shapes?*

Next, it is important to think about how these methods can be used to populate a design space. This design space is the database that will be employed in the concept design phase. This is the subject of the fifth sub-question.

5. *How can the chosen hull generation and resistance prediction methods be applied in practice to populate a design space of new hull shapes?*

After knowing these answers the last phase of the thesis starts, in which the developed solution is tested to find the performance. This is the validation and verification phase. In order to do so the solution is integrated in the Python programming language. In this environment testing is done, providing answers to the following sub-questions.

6. *How well does the approach perform in generating hull geometries and predicting the resistance of that new geometry?*
7. *How effective is the conceptual design tool as an instrument for D&P engineers to satisfy their needs?*

After having answered these last questions something can be said about the accuracy and trustworthiness of the developed solution. This will provide sufficient information to answer the main research question.

Above questions also indicate the methodology that is used to answer the main research question. Three phases have been mentioned: (1) the analysis phase, (2) solution development phase and (3) verification and validation phase. After going through these phases all research questions are answered in the fourth phase: the closing phase. Recommendations are provided there as well. The methodology with the used research methods can be seen in the thesis outline in Figure 1-4.

1.4 Thesis outline

The thesis outline can be seen in Figure 1-4.

Chapter 2 describes a thorough analysis of the current design approach, aiming at finding an answer to the first sub-question. The goal is to define the exact problems and needs that are present in the current design process, and justifying the research focus of this thesis. Thereafter, Chapter 3 focusses on formulating specific requirements to the design tool which can be used as a directive in the search for solutions. The second sub-question will hereafter be answered, such that the analysis phase is finished.

Chapter 4 describes the literature research that is conducted to find and select suitable methods for creating hull geometry and predicting the resistance. Additionally, the integration of these two methods into one design tool that supports the current design process is discussed. Hence, the fourth chapter aims at finding answers to the third and fourth sub-question. Chapter 5 focuses on describing how the chosen methods are applied to fill the design space, which will be used for concept exploration. It will provide an answer to the fifth sub-question. Effectively, this chapter describes how the theory from Chapter 4 is used for practical application in this thesis, consequently forming a blue-print to integrate the created model in software. These two chapters hereby present the solution development phase.

Hereafter, this solution is modelled in Python, in order to test the feasibility and performance. The results are presented in Chapter 6. This chapter also demonstrates the application of the results and presents the mock-up of a Graphical User Interface (GUI) of the conceptual design tool. Chapter 7 is about interpreting the results: are the results correctly modelled? Are realistic results obtained? Verification will tell if the design tool is correctly built. Validation is done by comparing the developed tool to the requirements which have been defined in Chapter 3. Effectively, Chapters 6 & 7 describe the results from the verification & validation phase.

Last, the thesis closes in Chapter 8 by presenting the conclusions and recommendations (the closing phase).

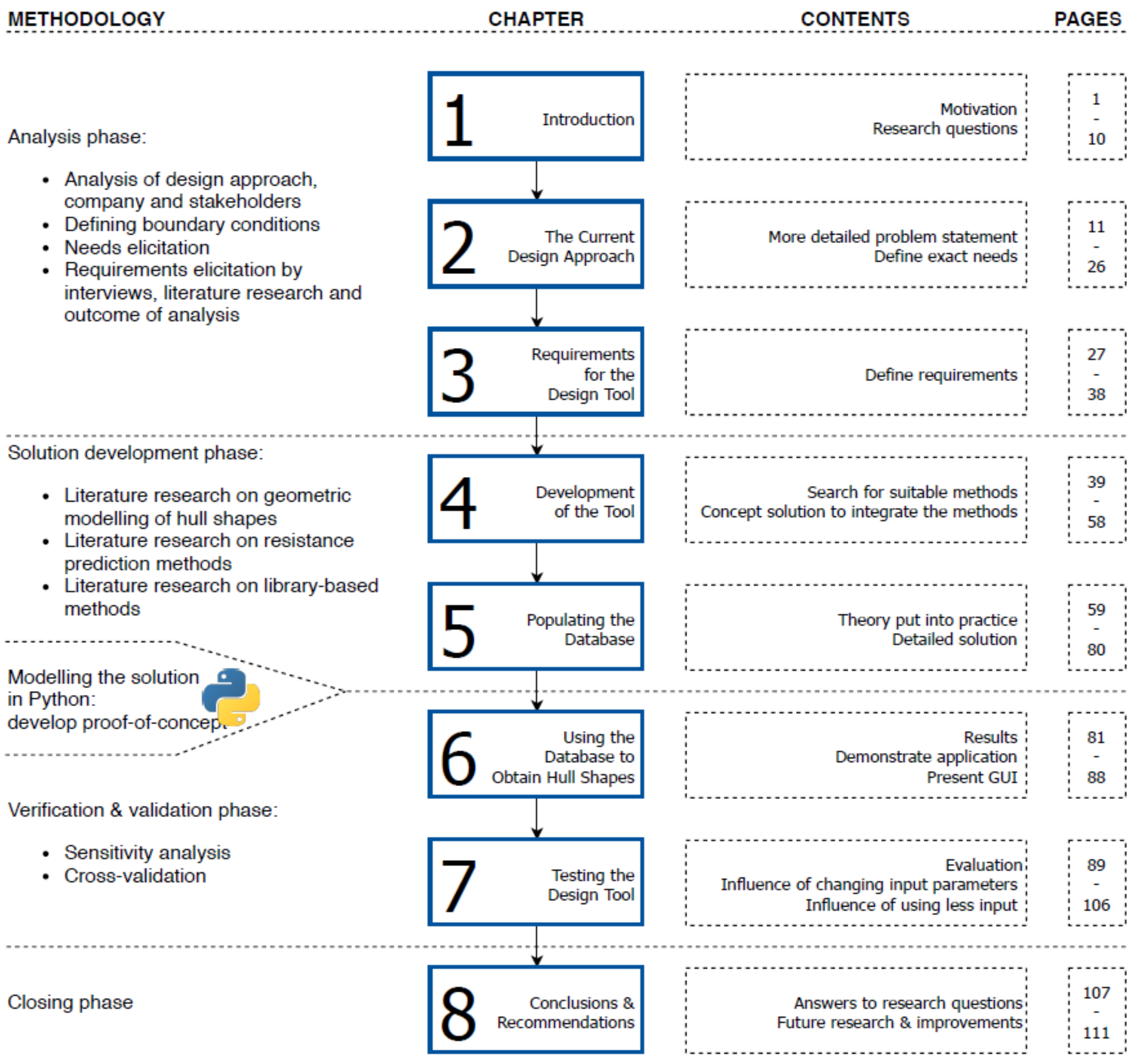

Figure 1-4: Thesis outline and used methodology.

2

The Current Design Approach

This chapter describes the analysis of the design approach that is currently used within the D&P department for OPVs in the conceptual design phase. Hence, it will form the answer to the first sub-question: 'Which problems are present in the current design approach of developing OPV concept designs?' The goal is to provide more context to the problem definition and to distil specific needs from the problems which are present. Effectively, this chapter is a justification for the general focus and research goal of this thesis. The reader who is not interested in this justification is referred to Chapter 3 for the requirements for the design tool, and to Chapter 4 for development of the core elements of the tool.

First, Paragraph 2.1 focuses on describing the environment in which the design process is executed. This provides useful information about the responsibilities and roles of the most important stakeholders, and the exchange of information between these stakeholders. Thereafter the characteristics and requirements of OPVs are analysed in Paragraph 2.2. This gives insight in what the focus of the concept design approach should be. Paragraph 2.3 hereafter describes the technical contents and specific steps of the concept design phase. The analysis results in characteristics of the current concept design approach and provides the exact problems which are present. Conclusions and specific needs for improvements are summarized in Paragraph 2.4.

The results of this chapter will be used in Chapter 3 to define specific requirements for the design tool which will be developed in this thesis. Both the needs from this chapter and the requirements from Chapter 3 will be used in Chapter 4 in a search for suitable solutions and to define an appropriate lay-out for the design tool.

2.1 The concept design environment

This paragraph focuses on providing insight in the environment in which the design process is executed. The lessons-learned will be used to find a solution that suits the environment and solves issues which are present. First, the different phases of design and development and involved stakeholders are analysed in Section 2.1.1, in order to understand how the concept design phase relates to the total development process and the stakeholders. Section 2.1.2 thereafter analyses the Damen organisation and describes the most important internal stakeholders. Last, Section 2.1.3 focuses on analysing the exchange of information between internal stakeholders, in order to find why and which information is transferred, and why this sometimes goes wrong.

2.1.1 Design phases at Damen and involved stakeholders

The design process is not started until a sale is initiated by the Sales department. A possible sale can be initiated in two ways. A client can approach Damen based on market consultation and request an offer. Alternatively, Damen can take the initiative and approach the customer with an offer, for example when a public tender is set out.

Effectively, if both parties recognize a feasible project the design process can be started. All phases from project initiation to the delivery of a vessel can be seen in Figure 2-1.

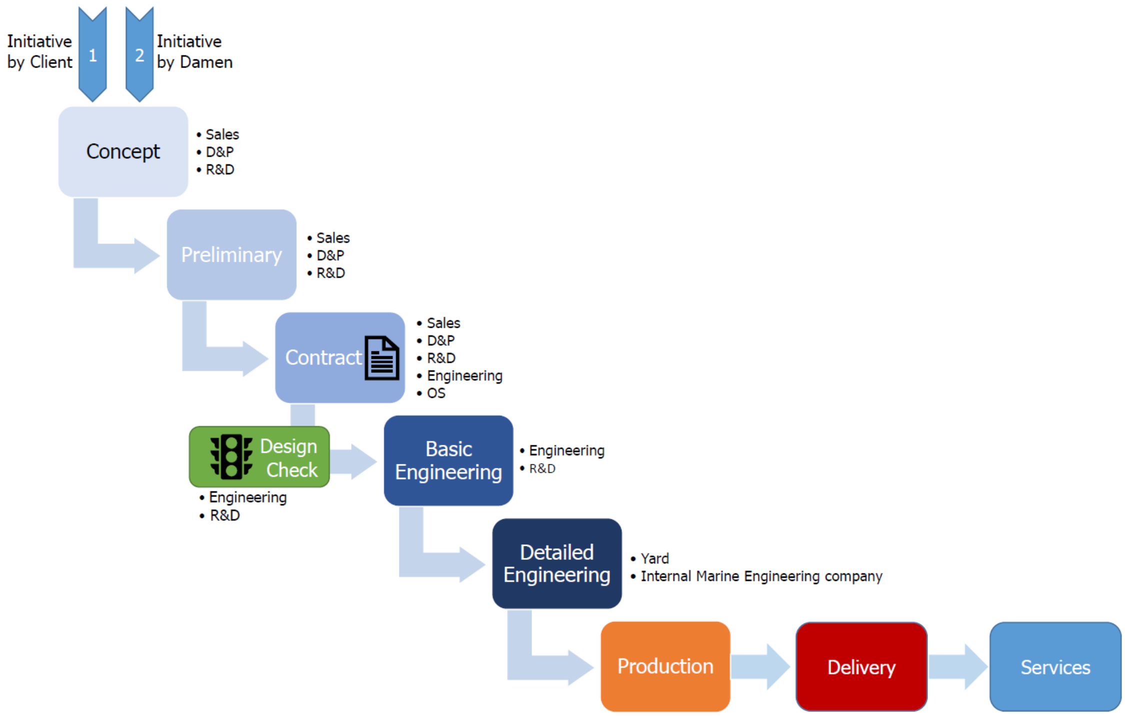

Figure 2-1: Phases in the ship design and production process within Damen including involved internal stakeholders.

A description of the activities per design phase can be found in Appendix A. It shows that the first three phases focus on exploring solutions and converging to one final ship definition which is detailed enough to be contracted. After signing the contract a design check is done within Damen. The design process is only continued if no design errors or high risks on (partial) project failure are found. Thereafter the basic and detailed engineering phases mainly focus on develop a complete and balanced design. Basic engineering includes completion of the design on a system level such that all functionalities are fulfilled. Detailed engineering focuses on developing a production strategy. After doing so the production of the vessel is started.

Most often, the Sales department works together with the D&P department to initiate a new project. The D&P department can help in assessing if a project is technically feasible and commercially viable to Damen, and will subsequently develop the first offer for the client. It is estimated that the D&P department invests time in 95% of the sales leads, after which 5% of those leads results in an effective contract after the contract design phase [32]. This indicates the importance of an efficient concept design phase.

Next, the most important internal stakeholders are identified and described.

2.1.2 Internal stakeholder analysis

Figure 2-1 also shows the internal stakeholders which are involved in each development phase. There are more internal and also external stakeholders in the development process than the ones which are presented in the figure, but some only have a minor effect on the design process. In Paragraph 2.2 the focus is put on the most important external stakeholder, the customer, by analysing the OPV as product and corresponding customer requirements.

In this section the most important internal stakeholders are identified and described. In order to find the internal stakeholders and their roles, first the Damen organisation is analysed to find the key internal stakeholders in the concept design phase. Thereafter the roles and responsibilities of these stakeholders are described. This information is needed to analyse the exchange of information between them, essential information to find out why there are problems in the current development of concept designs.

Analysis of the Damen organisation

A thorough analysis of the Damen organisation is performed, in order to map the hierarchical relations between departments and to understand their role in the design process. The full analysis is included in Appendix B. The goal of this analysis is to provide insight in the environment in which the design is performed, such that the solution that will be developed in this thesis actually suits the organisation.

The main outcome is that the company is split up into several business units (BUs). There are multiple departments in which there are separate teams to serve the BU. For example, the Sales and D&P department have a team dedicated to each BU. At the R&D department there are development teams dedicated to different product groups of the BUs. There are also research teams: they do not focus on BUs but on knowledge disciplines.

In this thesis the BU Offshore & Transport is of interest, as OPVs are in that group. There are supporting teams at the Sales, R&D, Engineering departments. At the D&P department a specialized group focuses on OPVs, namely the Defence & Security (D&S) group. These four parties are the key internal stakeholders in the concept design phase, and will be discussed in more detail next. This information also follows from the organisation analysis in Appendix B.

Key internal stakeholders and responsibilities

The **Sales department** is, logically, mainly concerned with managing the sales process. It obtains information about possible clients, initiates the sale, and support the process until the contract is signed. It is thus involved in the first three design phases.

Next in line is the **D&P department**: the first group with engineers in the line of product development. In general, their task is to translate customer requirements into a technical vessel definition. This is done by going through the first three design phases until the contract is signed. The D&P engineers will function as project manager during these phases, after which the project is handed over to a dedicated project manager. As mentioned, in most cases the contract phase is not reached, such that for these projects the D&P engineers spent most time on the concept design phase. Effectively, the department is responsible for capturing customer requirements, exploring solutions, formulating the project definition and further elaboration of the design until the contract design phase. This is thus the department which will actually do the concept exploration of hull shapes.

After singing the contract the design will be further elaborated by the **Engineering department**, while the project managers guide the total development process. They are, therefore, not directly involved in the concept design process, but will have to work with the resulting design. First, the design check is done by the department. However, the basic engineering phase is the main domain of the Engineering department, focussing on validating the design developed by the D&P department. This means that the technical feasibility is checked, the design on a system level is completed such that all functionalities are covered, and that final system suppliers are chosen. At this stage the use of assumptions should be minimized, e.g. model tests are performed to ensure that the hull can be used for reaching the contract speed. After doing so the detailed engineering will be done at a shipyard or dedicated marine engineering company, such that the Engineering department is less involved there.

The **R&D department** is split into two dedicated groups. The Research group is responsible for the creation of new knowledge and technologies, while the Development group functions as an intermediary between the Research group and the rest of the company. However, both groups play a key role as quality controller for the other departments of the company. This latter aspect is the most important role of R&D in the concept design phase, and is the main reason why they are consulted. In this thesis the Offshore & Transport development team is the most important team of R&D, as it provides expert information in the design process of OPVs on specific design aspects. They are able to do this because they are involved in projects throughout the product portfolio of Damen, such that they see a broad range of vessels. Besides those aspects, they are involved in almost all phases of the design, such that they are experienced with the most occurring design issues. Until the contract design space they are consulted by the D&P department, thereafter they are involved in doing the design check with the Engineering department, and can be consulted by this latter department during the Basic Engineering phase. Last, the R&D engineers will also go on Sea Acceptance Trials (SATs) to verify the produced vessels against the contract specifications, such that they see how effective the designs are in practice.

Next, the most important information exchanges in the concept design phase are described.

2.1.3 Exchange of information between internal stakeholders

As a consequence of having multiple internal stakeholders involved in the design process, a lot of information is exchanged between several departments. It is acknowledged that this is a problem within Damen: the wrong information is sometimes exchanged. Indicated flows of information between different departments within the first design iteration are shown in the organogram in Figure 2-2.

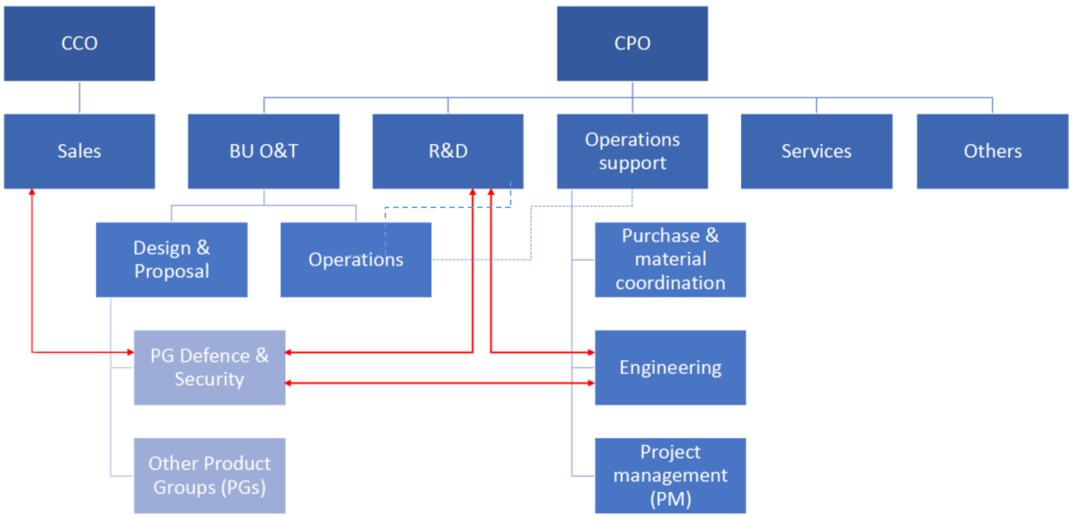

Figure 2-2: Organisational coherence between the D&S-group within CNBD with indicated flows of information in the concept design phase.

These exchanges of information between internal stakeholders are analysed, in order to find out which information is transferred, why it is transferred, and why sometimes wrong information is exchanged. Information is obtained by in-depth interviews with D&P and R&D engineers. In this section only the results of the analysis are presented, the full analysis is included in Appendix C. Following from this analysis, the conclusions below can be drawn.

- The D&P and R&D departments are mostly involved in developing the hull shape. This design aspect is also involved in most of the information requests to the R&D department.
- The design process contains elements of a linear and iterative nature, such as the design check. The project is 'thrown over the wall' with its responsibility from the D&P to the Engineering department.
- The Engineering department often finds design mistakes, which are caused in the first three design phases.
- Different departments use different approaches for version control, or even no version control. Sometimes a wrong version is sent to another department for work continuation.
- Sometimes assumptions for design aspects are preferred over a detailed calculation in order to save time. Most often this means that a design margin is applied, which could lead to oversized design characteristics or components. In essence no wrong information is used, but by using assumptions it is more uncertain that the right information is used. This leads to a higher risk on project deviations.

Especially the last three aspects contribute to the development of sub-optimal concept designs, which is a deficiency of the current design approach. The current lessons-learned will be used to indicate which information should be integrated in the design approach to be developed in this thesis, such that the approach starts adding value.

2.1.4 Conclusions

This paragraph aimed at describing the environment in which the concept design phase takes place within Damen. This is done by analysis of (1) the total development process from sale to ship delivery, (2) the internal stakeholders involved and (3) the exchange of information between these stakeholders. It turns out that the Sales, D&P and R&D departments are involved in the concept design phase, of which the last two play the most important roles. The D&P department is responsible for developing the first concept design, and often consults the R&D department for providing expert advice on design aspects which have a high technical risk. When analysing the exchange of information in the first three design phases it can be seen that there are some deficiencies which possibly lead to sub-optimal concept designs or cause a risk on project deviations.

This paragraph has provided information about the environment of the design process by focussing on the internal stakeholders. The results will be used to formulate specific needs in Paragraph 2.4, which are subsequently used to define requirements and development of the solution.

Next, the characteristics of OPVs and typical customer requirements are analysed, which will say something about the interests of the most important external stakeholder: the customer.

2.2 OPV characteristics & requirements

This paragraph focuses on describing the information that is known before the process of developing a concept design is started. Firstly, the characteristics of OPVs are analysed in Section 2.2.1. Products with different characteristics (e.g. an oil tanker and a frigate) require a different approach to product development as their mission requirements differ significantly. The goal is to find characteristics of a design process that correspond to the characteristics of OPVs. Thereafter, the customer requirements are analysed in Section 2.2.2, which are often presented in the form of Request for Information (RFI). By analysing these requirements something can be said about the interest of the customer, which is basically the most important external stakeholder for the concept design phase.

By analysing these two aspects, insight is gained in the starting information for concept design. This is useful information in this thesis, as a design tool is being developed that supports the concept design process.

2.2.1 Characteristics of the product

Offshore Patrol Vessels are special products. Not only as a vessel type, but also within Damen. The characteristics of the product are analysed, of which a full description is given in Appendix D. The most important characteristics are summarized below.

- OPVs can be used for a wide range of functions and missions, and can be deployed in several different environments. Most often they should be multi-mission capable.
- Most often the owner and/or customer is a governmental institution. That type of customer is often capable of formulating its own requirements. Therefore, the customer requirements are very specific. They vary for each customer, such that each customer demands a unique product. This is fortified by the fact that OPVs require long development times and have high total costs.
- As a result of the demand for a unique product with specific requirements and multi-mission capability, the OPV can be classified as an Engineering-to-Order (ETO) product. This is challenge for Damen, as the standardization concept is hard to apply to ETO products.
- The OPV as a ship type is in between commercial and naval, and can thus be seen as a niche product.
- The business strategy that is used for the classic Damen product, workboats, cannot be applied to ETO products such as OPVs. More focus should be given to product differentiation, customer relations and requirement elicitation for ETO products.

To realize product differentiation in general, a company should stimulate the development of creative and innovative ideas. The company should keep pursuing new solutions relentlessly, in order to keep ahead of competitors. Additionally, the company structure should be organized in such a way that these ideas can be converted in a profitable product as soon as possible. For the design process this means that it should be organized in such a way that innovative solutions are sought for. It should also be flexible enough to integrate new solutions.

To put focus on customer relations and requirements elicitation, the key activity in the first design stage should be to find out what the customer really wants and what his reasoning is. Only if that is truly understood, a project definition can be set up that represents the true intention of the customer. Only then a product can be developed that will fully satisfy the customer's needs, in order to establish a long-term relationship. That long-term relationship provides Damen with a satisfied customer that might return to Damen for a new order or services.

The design process for OPVs should match these characteristics. In Paragraph 2.3 it will be checked whether this is the case. Next, the other important piece of starting information, the customer requirements, will be analysed.

2.2.2 Customer requirements

For both possibilities in which a sale can be initiated, there comes a point in which all requirements are collected. This is often done by the customer itself in a Request for Information (RFI) document. The contents of an OPV-based RFI are interesting to analyse, in order to gain insight in what is important for the design of OPVs.

Goals of the RFI

The aim of the RFI in the process of designing and ordering this vessel is to gauge the interest and ability of ship building companies in designing and building the vessel. However, the customer may also aim at understanding the market capacity to his demand, and to understand the best practices which are used in the industry. In summary, the RFI forms a market test, to gain understanding of what the market can deliver against the key characteristics, costs and planning.

To gather this information the RFI contains input for the ship building company. Typically, an RFI contains multiple parts which describe the vessel to be designed. At least the following aspects are included.

1. Mission capabilities and operational profile
2. General vessel specifications and performance
3. Description of systems

The ship building company provides the customer with a configuration that suits the requirements stated in the RFI plus a first cost estimation. Additionally, proof by the ship building company is provided showing that it is capable (technically and financially) and has sufficient experience to deliver the vessel.

Typical RFI contents

The contents of a typical RFI for an OPV are included in Appendix D.4. For each aspect mentioned above several design aspects need to be clarified by the ship building company. Within Damen this is the task of the D&P department.

Concerning the operational profile, often a specific operating area is defined, for example the South China Sea. This area has specific operating conditions, such that a range can be given for ambient temperate, sea water temperature and expected sea states for example. This is analogous for the operational profile, as most of the missions are related to the operating area. For example, piracy is common around the Horn of Africa, and the occurrence of natural disasters like cyclones is also concentrated in certain areas of the world.

For the specifications of the vessel, often a range is given for main dimensions, displacement and deadweight. This is also common for the crew and complement size, for which sometimes a difference in gender is specified for naval vessels. This can consequently also be the case for an OPV if it will be designed to be part of a naval fleet. Also for performance parameters such as maximum speed, design speed, range and endurance often a minimum and maximum value are given.

In practice, the emphasis for an OPV is put on the mission capabilities and operational profile. Also specific systems which distinguish the design from other ships and which support the mission capabilities play an important role, causing a larger contribution of this design aspect to the total solution. Comparing this to other ship types (commercial and naval), this focus on mission capabilities and operational demands can also be seen for naval vessels. This is less the case for commercial vessels, as they are mostly built for one specific missions: transporting of goods or providing a service. Hence, in the context of ship types and translating customer requirements into a technical solution, the focus on mission requirements is an import aspect to take in mind.

The objective for D&P engineers is to develop a platform that is able to execute the missions stated in the RFI, supported by the systems that are required by the customer and other systems deemed necessary. The challenge is to do this whilst remaining within the boundaries of the given specifications and optimizing performance. This can be seen as **the design problem** for the D&P engineers.

2.2.3 Conclusions

This paragraph focused on analysing the starting information for a concept design phase. It can be seen that the characteristics of OPVs as a product require a different business strategy, which requires a different design approach than for the classical Damen products (tugs). To achieve Product Leadership for OPVs, more emphasis should be put on stimulating innovating designs. Also Customer Intimacy should be pursued, by giving sufficient attention of customer requirement elicitation and designing a product that truly satisfies these requirements. In the next paragraph it is checked whether this is the case.

The customer requirements are for OPVs often captured in an RFI, which is set up by the customer itself. It contains information concerning (1) mission capabilities and operational profile, (2) general vessel specifications and performance and (3) a description of systems. For OPVs the mission capabilities are often emphasized, which should be taken into account when defining a technical specification of the vessel: the definition should serve the mission capabilities.

The next paragraph describes how this input is converted into a concept design.

2.3 Concept design of OPVs

This paragraph focuses on describing the technical contents and specific steps of the concept design phase of the design process for OPVs. It is done by extruding detailed information about the process that is used to obtain a very first design, and capturing which assumptions and rules are used. The main goal is to find the exact problems which are present in this part of the design process. To do so, first the way in which the starting information is used is described in Section 2.3.1. Thereafter, the first design iteration is analysed in Section 2.3.2. Last, design aspect to which often extra attention are given are described in Section 2.3.3.

2.3.1 Distillation of starting information

Before starting the design process starting information needs to be defined by the engineers. This step focuses on gathering all available information and pooling it in one document. Input can come from customer requirements or information (the RFI), information from the Sales department, or information from a tendering authority or company. This input is subsequently used for translation into the technical definition of a ship by going through the design process.

Specifically for ETO projects within the D&S product group of Damen, the background of the customer is assessed by looking at the budget and knowledge of seamanship of the customer. This is done to prevent dealing with insolvent customers and to indicate the credibility of the information that is sent by the customer. Effectively, this can be seen as a risk assessment of the customer. The project is stopped if the risk on an infeasible project is too high for Damen.

Next, technical requirements are distilled from the starting information. Within the D&S group the following aspects are needed, which do not necessarily have to be obtained in this chronological order.

- Purpose of the vessel
- Main dimensions (ranges)
- Deck space and volume to accommodate rooms, spaces and systems
- Speed and range performance
- Crew and complement
- Rules and regulations
- Requirements for special systems
- Operational requirements

This list shows a lot of similarities with the information in an RFI. The emphasis on the mission capabilities are captured in the purpose of the vessel. Moreover, in the starting information it is already explicitly needed to express how much deck space and volume is needed to accommodate all rooms, spaces and systems, within a range of main dimensions. This is a first quantification of a technical solution in the design process. Information is be given by the customer or is based on reference vessels from Damen. The other design aspects are often already approximately known or can be estimated based on the information that is given by the customer.

All results are summarized in a 'project initiation document' by a D&P engineer. How this information is translated into a design is described in the next section.

2.3.2 The first design iteration

The first design iteration is started by translating the starting information into technical design aspects. This results in a hull shape with main dimensions, displacement and other technical parameters, and effectively should satisfy the customer requirements. In order to do so, the workflow in Figure 2-3 is gone through. A full overview of all the steps, including the sources of information for each separate step, is included in Table E-1 in Appendix E.

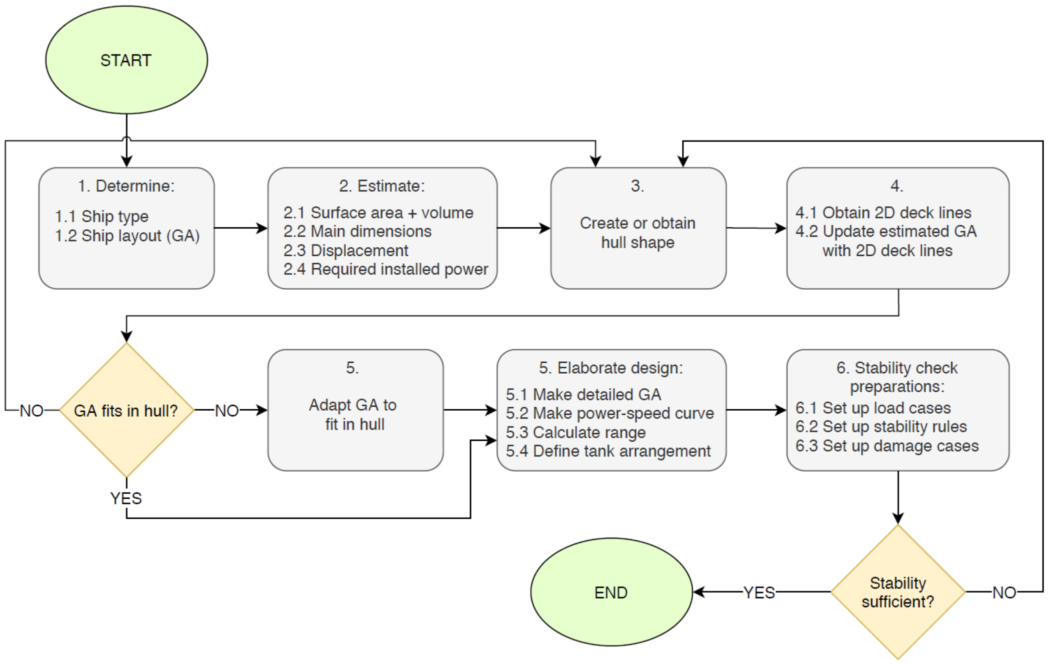

Figure 2-3: Concept design approach for OPVs within Damen.

It can be seen that in this approach the hull shapes plays a key role. Effectively, the design approach can be split up into two parts: one part that is focused on obtaining a hull shape, and another part that is focused on elaborating the design based on the hull shape. This makes the hull shape an important piece of information. Next, the first part is analysed, which focuses on defining the technical design aspects such that the hull shape can be created.

Translation into design aspects

The process of determining the technical aspects starts with determining a ship type for the design to be developed, which is done by a D&P engineer based on his experience and reference ships. A first approximation of the ship layout is determined, based on reference designs and the layout requirements of the customer. This results in a first General Arrangement (GA).

Subsequently, several steps are undertaken to define the hull shape, by estimating surface areas and volumes, main dimensions and the displacement. Also the required installed power is already estimated, as often the size of the engine and the propulsion configuration are determinative parameters for drawing the lines plan and GA. This is also done by using reference designs.

Effectively, the main resource of information are reference vessels. This has both advantages as disadvantages. An advantage is that using proven designs can enhance the speed of the design process, also the main drive to choose this option. Using proven designs can increase the chance of developing a successful design as well. However, a disadvantage is that new, non-existing and thus creative designs are side-lined, as all approximations are almost only based on reference vessels. This can nevertheless be accepted for the first design stage, as there is a high need for some trustworthy approximations, and innovative aspects could be implemented in later design stages.

Effectively, the result is an estimation of what the resulting hull should look like. The next step is to actually create or obtain that hull shape.

Obtaining the hull shape

There are two possibilities to obtain a hull shape: the designer can start drawing from scratch or a reference hull can be adopted.

Adopting a reference hull is also referred to as a parent hull. It aims at geometrically transforming the reference hull shape such that it obtains the desired characteristics. The reference hull should have similar geometrical properties or similar functional requirements. Within Damen it is recognized that OPVs generally have similar functional requirements and operational profiles, which promotes the use of a parent hull. Consequently, this option is used for almost all new OPV designs. This is not only the case for Damen, it is common practice in the shipping industry to use a parent hull as the basis for a new design [33]. There are two important reasons for Damen to choose this option:

- Experience shows that it is much faster than starting from scratch, which is seen as a length and tedious process.
- The performance of the new design can be approximated as the performance of the parent design.

This last point enhances one of the commercial key aspects of Damen, as they sell 'proven designs'. It also is a reason to pursue a parent hull as example for the new design; engineers want to reduce risks and, therefore, try to imitate a design that has proven itself to be successful and effective.

To find a reference hull a database of reference OPVs is already set up within the D&S product group. It is up to the D&P engineer to select the most suitable hull. A suitable hull could be a hull that has the same ratios of main dimensions (e.g. L/B-ratio or B/T-ratios) as the estimated dimensions of the new hull. Also a hull can be chosen that was used for the same mission capabilities, e.g. for high-speed patrolling in sea state 6, in combination with other customer requirements (i.e. a certain length, displacement or crew size).

Geometrical modification can be done with hull transformation methods, for which parametric toolboxes are included in almost all hull design computer software, such as MAXSURF. Those toolboxes can be used to select a transformation method which will change selected hull parameters (e.g. position of LCB) such that a hull shape with a desired form parameter (e.g. block coefficient C_B) is obtained.

A risk of this approach is that the new hull does not meet the customer requirements, but better suits the customer requirements of the reference hull. For naval vessels of the US it led to higher costs than planned, schedule delays and quality problems [34]. It is advised to only adopt a reference hull when the operational and other significant requirements are similar, and when the reference hull is relatively young [35].

Starting from scratch can, therefore, be an outcome for cases where there are no similar reference vessels. Additionally, the naval architect is not fixed to any relation to the reference vessel, such that a larger design space can be explored [34]. It is done by drawing a new hull shape manually. A specific procedure has to be followed, starting with defining desires points, then curves and eventually surfaces that will form the hull shape surface. It then comes down to the experience and skills of the D&P engineer draw a satisfying hull shape that meets the customer requirements.

A parametric approach can be used to reduce the amount of laborious work. Numerical parameters that define the hull can be used to execute mathematical algorithms which then construct a hull surface. However, these algorithms are still not flexible enough to construct complex hull surfaces [36], such that manual adjustments are needed in practice. Nevertheless this approach is sporadically chosen, but only if no suitable reference vessels are available.

After a first hull shape is obtained, several other design aspects such as resistance, power, speed, range and stability are addressed. These activities are described next.

Elaborating the design

After obtaining the hull shape the design is further developed. In general, the goal is to obtain all general vessel specifications and performance of the RFI (see 2.2.2).

First, a check is done to see if the GA fits in the hull shape. If this is the case the design process will continue. If not, there are two possibilities to make it fit: (1) the GA is a modified to fit in the hull or (2) the hull shape is adapted such that the GA fits. The first option is preferred over the second, as this would not cause rework of creating a hull and obtaining 2D deck lines. After this check the GA will fit in the hull shape, such that a first hull shape is obtained.

Next, an indispensable step in the process is to get a resistance prediction. Currently this is most often done by using software such as MAXSURF, in which regression methods like Holtrop & Mennen or Savitsky provide a resistance prediction. It is acknowledged that Holtrop & Mennen is used most often for OPVs at Damen. However, there is always a difference between that result and the actual trial resistance. A correlation factor is determined from the difference between trial and prediction resistance, which can be used to transform the Holtrop & Mennen prediction to a more accurate prediction. If CFD is used to evaluate the resistance, a correlation factor is also determined to transform the CFD resistance to trial resistance. The difference in this case is caused by simplifications in setting up the geometry model for CFD.

After obtaining the rest of the results a stability assessment is done. The design iteration is finished if the assessment shows that the hull complies to requirements of a classification society. If not, there are three options to improve the result: (1) the load cases are reviewed, (2) the lay-out is adapted (e.g. tank arrangements) or (3) the hull form is changed. Preferably, the first attempt to solve the problem is done by reviewing the load cases, thereafter the lay-out and lastly the hull form should be changed. This order is preferred as the first option costs the least time while the third option would require much more time, as change in other aspects of the design have to be made. For example, if the hull form is changed a new power-speed curve has to be computed as well.

When looking at the main resource of information in this second part of the concept design approach, it can be seen that reference vessels play a less significant role than in the first part. The second part is more focused on developing and verifying the design, and adapting the design if changes are needed. Summarizing, two checks are executed: to check if the GA fits in the hull form and if the resulting design is a stable hull according to criteria from a classification society. By doing these checks two small iterations are added to the complete first iteration. Effectively this should lead to a balanced concept design of an OPV.

Time aspects

Currently, the process takes a minimum of approximately 115 hours and a maximum of approximately 138 hours, which is roughly the same as 14 to 17 days for one engineer. As mentioned in the introduction, the time in which the total concept design approach is done is under pressure as most often tender procedures are used, which include strict deadlines. It is commercially advantageous if the design is as accurate as possible, such that the risk on project deviations is as low as possible. However, increasing the accuracy costs time as this is most often done by consulting the R&D department. Effectively, this causes a trade-off between the accuracy and the time in which a concept design is developed. Since time pressure is high, this often results in insufficient accuracy of the concept design.

Another important aspect considering time in the concept design approach is that most of the activities have to be preceded by another activity: a clear critical path can be recognized. It is shown that the obtainment of the hull shape is of significant importance, as the second part of the design process cannot be started without a hull shape. Additionally, a wrong hull shape can ultimately lead to a design that doesn't satisfy stability criteria. In the most disadvantageous case all steps following the obtainment of the hull shape have to be repeated, which prolongs the total lead time and costs of the project. If the risk of these issues is high, the D&P department will consult the R&D department for expert advice. The next paragraph focuses on design aspects for which this often happens.

2.3.3 Additional attention to specific design aspects

Extra attention to specific design aspects is given when the risk is high that a chosen aspect is inaccurate. It is acknowledged that for concept design of OPVs at Damen this is often the case for the hull shape and the resistance prediction.

The hull shape is also of great importance in the later design stages, as it is related to the performance of the vessel in terms of powering, seakeeping behaviour, and can cause issues such as bad stream inflow to the propeller. This is also the reason why the hull shape is the most important piece of information that is exchanged between the D&P and R&D departments, following from the analysis described in Section 2.1.3. It is then investigated how the shape of the hull can be changed such that it performs better (i.e. lower resistance, better seakeeping behaviour).

For the resistance Holtrop & Mennen is sometimes not sufficient, as it does not provide insight in the relationship between the shape of the hull and the resistance. Only by trial-and-error it can then be investigated how the hull shape should be modified such that it get beneficial resistance characteristics. The R&D department can be consulted, which can do CFD simulations and studies to obtain these insights. Optimization studies can be done in order to obtain an 'optimized' hull shape. In effect, the R&D department potentially provides a hull shape with a lower resistance, provides insight in how the hull shape can be adapted to obtain more favourable results and can do this with high accuracy.

However, multiple other groups consult the R&D department, such that there are waiting times for the D&S group. Requesting expert advice for the hull shape or resistance prediction consequently often causes a delay of the design process. This is often done to increase the accuracy of the design and thus to reduce the risk, such that obtaining the hull shape and obtaining the resistance prediction are bottlenecks in the concept design phase.

2.3.4 Conclusions

This paragraph focused on describing the technical contents and specific steps of the concept phase of the design process of OPVs. The goal has been to find the exact problems which are present.

It has been found that the design approach starts with distilling all starting information. Thereafter this information is translated into a technical design by going through several design steps. This whole process can effectively be split in two parts by the activity of obtaining the hull shape. The first part focuses on obtaining the hull shape. For estimating and determining design aspects (including the hull shape itself) most often reference vessels are used, as it is expected to be faster and to cause fewer risks. After obtaining the hull shape the second part focuses on developing and verifying the chosen configuration, and adapting the configuration if needed. Therefore the second part is of an iterative and sequential character, where specific steps have to be preceded by others.

Summarizing, the following problems are present in the current concept design approach.

- Often reference vessels are used, leading to the use of assumptions which decrease the accuracy of the concept design. The risk on project deviations hereby increases. It is also in contrast with the need to pursue Product Leadership as described in 2.2.1.
- Often assumptions are preferred over accurate and low-risk computations of design aspects, as this latter would take more time. This is done as the time pressure is high in tender procedures, which are conventional.
- The approach is sequential and iterative, such that it is delayed if one activity is delayed. This often happens to increase the accuracy of a design aspect, as the R&D department has to be consulted for expert advice. Obtaining the hull shape and obtaining a resistance prediction are therefore major bottlenecks.

These deficiencies will cause the concept design to be sub-optimal or to contain errors. Additionally, the sequential and iterative character of the process prolongs the total development design time.

2.4 Summary

This chapter has described a thorough analysis of the design approach that is used for OPV concept design at Damen. The first sub-question can consequently be answered, which is repeated below.

> *Which problems are present in the current design approach of developing OPV concept designs?*

This chapter started with describing the environment in which the concept design phase takes place. It turns out that the Sales, D&P and R&D departments are involved in the concept design phase, of which the last two play the most important roles. The D&P department is responsible for developing the first concept design, and often consults the R&D department for providing expert advice on design aspects which have a high technical risk. After analysis of the exchange of information in the first three design phases it can be seen that due to time constraints and different version control policies, sometimes wrong information is used in the design process.

OPV characteristics and requirements have been analysed subsequently, showing that the ship type can be seen as a niche product considering its multi-mission capability (in-between naval and commercial) and required business strategy. For Damen a different design approach should be pursued for OPVs than for other product groups, such as tugs. The value disciplines Product Leadership and Customer Intimacy should be pursued. This means that more emphasis should be put on stimulating innovating designs, and sufficient attention should be given to customer requirement elicitation and designing a product that truly satisfies these requirements

Last, the technical contents and specific steps of the concept design approach have been described and analysed. It is found that the approach can be split in two parts by the activity of obtaining the hull shape. The first part focuses on obtaining the hull shape. For estimating and determining design aspects (including the hull shape itself) most often reference vessels are used, as it is expected to be faster and to cause fewer risks. After obtaining the hull shape the second part focuses on developing and verifying the chosen configuration, and adapting the configuration if needed. Therefore the second part is of an iterative and sequential character, where specific steps have to be preceded by others. Several problems have been recognized in this approach, causing delays, design errors and a sub-optimal concept design.

Next, specific characteristics and problems are listed in 2.4.1, forming the answer to the first sub-question. Thereafter, specific needs are defined in 2.4.2, which will be used as a directive in the search for a solution.

2.4.1 Conclusion

The following characteristics and problems of the concept design approach are problems.

- Multiple departments are involved, causing bureaucracy and delays. Departments don't consult each other because it costs too much time, and rather include design margins. Additionally, not all departments use version control, such that sometimes a wrong, dated version is used for analysis. Hence, sub-optimal concept designs are made.

- The concept design approach is of a linear, iterative nature. It can be characterized as 'over-the-wall' engineering, such that each activity is not started until the preceding phase is finished. There is a need for more communication and earlier participation of departments that only become involved after the design check.

- Often reference vessels are used, leading to assumptions such that the accuracy of the concept design is reduced. The risk on project deviations is hereby increased. Additionally, it is in contract with the need to pursue Product Leadership.

- Due to the linear nature of the approach and the waiting time when needing expert advice, obtaining the hull form and a resistance prediction are major bottlenecks. This promotes the use of assumptions, again reducing the accuracy and increasing the risk on project deviations. If it is chosen to wait on expert advice, the lead time of developing a concept design increases.

- Traditionally, Damen was market oriented as it focused on Operational Excellence for workboats. For OPVs the company has to become customer oriented, so more focus should be given to Customer Intimacy. This requires more attention to capturing the true intention of the customer and being dedicated to providing a product that fully satisfies the customer's needs.

By providing these problems the first sub-question is answered. Needs to improve the design approach are present, which are described next.

2.4.2 Need for improvements

The aforementioned problems lead to the specific needs.

(1) The **speed** of the design process has to be increased.

(2) The designer has to get **more insight in the design challenge**, such that:
   a. The accuracy and level of detail of a ROM design can be increased.
   b. The influence of interdependent design parameters on each other and the overall performance of a design becomes more clear.
   c. A larger design space can be explored.

(3) A **more systematic and uniform design approach** is needed, such that:
   a. Fewer departments have to be actively involved during the process, but their expert advice and data can still be consulted.
   b. Different stakeholders use the same approach, for example version control.

As described in the introduction Damen has expressed interest to satisfy these needs by using a design approach based on systematic variation of hull shapes. The results of the systematic variation is a dataset of hull shapes with resistance results, which from now on is referred to as the CFD dataset. Consequently, an extra need is defined.

(4) To include the use of **a database with hull shapes** in the design process, which should be filled by **systematic variation of a base hull shape**.

These four needs will be used as a directive for the solution to be developed. These solutions will be integrated in a design tool, analogous to the goal of this thesis. The next chapter (3) focuses on defining specific needs to this design tool.

Effectively, it is now justified why the approach for developing concept designs of OPVs needs to be improved. It is also justified why this thesis will focus specifically on improving the development of the hull shape and obtaining a resistance prediction: they are the most important piece of information in the design process and consequently additional attention is often given to these aspects. Due to the linear workflow, design mistakes and the general habit to go to another department for expert advice for these aspects, the whole concept design phase is often delayed. As an effect, more simplifications and assumptions are used, thus lowering the accuracy of the design, which on its turn increases the risk of project deviations. Concluding, the development of the hull shape and obtaining the resistance are the heart of the problem.

3

Requirements for the Design Tool

This chapter describes the development of requirements for the design tool that will be developed in this thesis. The need for improvements which have been distilled in Chapter 2 are used as starting points, providing the 'whys' but also which improvements are needed. Defining requirements is important as it will help in defining boundary conditions and preventing unnecessary work. Additionally, it might enhance the quality of the design tool. The goals of this chapter is to define specific requirements. Additionally, an overall description of the tool is provided and the dataset of hulls with resistance results is further introduced.

First, an introduction to the design tool is presented in Paragraph 3.1. It starts with describing the motivation, scope and goals of the tool, after which the intended activities, input and output are defined. Effectively, this paragraph provides a description of how the tool should function. Hereafter, Paragraph 3.2 describes the CFD dataset in detail, presenting the motivation, nature and intended use of the dataset. The information that is provided in Paragraphs 3.1 and 3.2 together with information from Chapter 2 is converted to a list of specific requirements for the design tool, which is presented in Paragraph 3.3.

The specific requirements will be used for literature exploration and development of the solution in Chapter 4. Additionally, at the end of this thesis the requirements are used for validation of the design tool in Chapter 7.

3.1 Introduction of a Design Tool

This paragraph described an introduction to the design tool that will be developed in this thesis. To do so, amotivation for setting up a tool is presented first in 3.1.1. Subsequently, the scope and goals of the tool are elaborated in 3.1.2. An overall description provides information about how the tool should function, which is presented in 3.1.3.

3.1.1 Motivation

Adopting a brute-force approach implies that a database with a large number of hull shapes will be filled. Effectively, this database has to be provided to the D&P engineer in order to perform .concept exploration and to determine which hull is the most suitable. Together with every hull shape, information has to be provided which can be used by the designer to assess a hull shape. Which information this exactly should be is described in 3.1.3, but it is sure that a wide variety of information needs to be provided. There is a danger of losing the overview due to the large number of hulls and variety of information. It is therefore necessary to develop a design tool, in which the information can be properly managed and consulted. This has several other benefits:

- A design tool contributes to automation of design tasks and is user-friendly, hereby:
  - Increasing the speed
  - Reducing the risk on mistakes
  - Enhancing acceptation of the tool
- It allows for adding multiple other design aspects or features in the future.
- It is a platform for information management and exchange. This is useful for maintaining the current relationship between the R&D and D&P department. Information can be managed by the R&D department and consulted by the D&P department. Thus, a new developer-user relationship will then exist.

Effectively, it is expected that a design tool will contribute to increasing the efficiency of the concept design phase. A conceptual design tool will therefore be developed in this thesis.

3.1.2 Scope and goals of the tool

The scope of the design tool is defined by the context in which it will be used, and for what purpose it will be used.

The D&P department will use the tool in the concept phase of the design process to obtain a first version of the hull shape. In addition, a prediction of the resistance of this hull shape should be provided to the user as well, together with hydrostatics and other characteristics that are needed by the designer to assess the performance of the hull. Effectively, the design tool will facilitate the interaction between the D&P engineer and the pre-computed database of above-mentioned information. The specific hydrostatics and characteristics that are needed to do so are presented in Section 3.1.3.

The goal of the tool is, very generally, to satisfy the needs which have been defined in Paragraph 2.4. Effectively, the tool has the following main goals. In this chapter substance will be given to these goals, such that they become more specific.

1. To increase the speed of the design process by obtaining a hull shape with verified resistance predictions much faster
2. To get more insight in the design problem of designing a hull shape, in general by providing understanding in how input (requirements) relate to the performance of a hull shape (resistance, wake-field, motions etc.)
3. To be an integral and central platform for obtaining a hull shape such that fewer departments have to be actively involved in the design process

The second need raises some questions about what insight is, and how the design problem and performance can be defined. In general it can be said that the design problem is to obtain a hull shape of specific dimensions which satisfies the customer requirements the most. These customer requirements are to facilitate certain mission capabilities and systems for a specific operational profile. The challenge is to do this whilst remaining within boundaries of specifications (e.g. main dimensions) and optimizing performance. Performance can be defined by certain objective functions, such as that the hull shape's resistance is minimized, the wake-field is as uniform as possible and motions in waves are minimized. As mentioned in the demarcation this thesis only focuses on the resistance as a measure of performance of a hull shape.

But what is insight? For the specific case of concept ship design, insight can be defined as understanding of the relations between the design space and performance space [17]. In this thesis the design space can be seen as the input that is needed to obtain a hull shape. The performance space is the output, i.e. the hull shape and its performance. Insight is thus understanding of the relation between that input and output, i.e. how the output (the hull shape and the performance of this hull shape) is influenced by the input parameters (reflected by the needs of the designer). By using that insight the user can make adaptions to the hull shape to improve the performance, i.e. to reduce the resistance.

Next, an overall description of the tool is presented, such that it is clear how the tool should function.

3.1.3 Overall description

User needs & intended activities

For this thesis only one primary intended user is considered: the D&S group of the D&P department of Damen. Management and development of the tool is intended to be done by the R&D department of Damen. By having these roles the current division of responsibilities in the design process, as defined in 2.1.2, is maintained. As described in 2.4.2, it has also emerged that there is a need for a more integral design approach: fewer departments should be actively involved and different stakeholders should use the same approach. By adapting this division of responsibilities, the tool should cause that the D&P consults the design tool instead of consulting the R&D department.

The user needs are reflected by the general needs that are present at Damen (see 2.4.2). They are intended to be satisfied by letting the tool execute certain activities, which are repeated and described very generally below. These activities will be explained and clarified in Paragraph 3.3.

- Provide a hull shape that is matching the user input (either by actually constructing geometry or by looking up the right geometry from a database)
- Predict the resistance over a range of speeds for the hull shape that is provided
- Provide other relevant results (hydrostatics, hull characteristics etc.) to assess the performance of the hull and to provide additional insight in the effect of hull design choices on the performance of the hull
- Exporting and saving of a selected hull shape

To perform these activities certain input is needed, which is described next.

Available and required input

By following the current design approach a lot of information is already available. For the tool it is assumed that it will simply replace the current activity of obtaining a hull, such that the order of activities in the design process will not be changed when implementing the tool. The following information is therefore available.

- Ship type
- Estimated general layout
- Estimated surface areas and volumes
- Estimated main dimensions (L, B) and displacement
- Estimated required power

In the demarcation of the introduction (1.3.1) a dataset of hull shapes with resistance results was first mentioned. The resistance results have been obtained with CFD, such that from now on this dataset is referred to as the CFD dataset. This dataset will function as parent hulls, to create new hull shapes and get a resistance prediction. By implementation of the tool and the CFD dataset, the designer also needs to have an estimation of the parameters used for parametrization of the parent hulls. It must therefore also be available as input for the design tool. The CFD dataset will be further introduced in Paragraph 3.2.

The tool will then be used to convert input to output. Effectively, no optimisation is performed. The desired output is described next.

Desired output

The D&P department needs particular information in order to (1) assess the performance of a hull shape that is designed or chosen and to (2) continue with the rest of the design process. Hence, these two factors determine what the desired output is.

From a broader perspective the desired output can be defined as the production result of the tool. This is the information that is needed to continue with the design process, and contains the following aspects.

- A 3D hull shape that is:
  - Matching the input characteristics
  - Sufficiently faired and smooth (no major fairing problems)
- A resistance curve of the hull shape over a range of speeds
- Additional hydrostatics and hull characteristics

From a more narrow perspective, the designer of the hull needs to obtain certain information to directly assess the performance of the hull shape that he is designing, i.e. to check if the result is satisfactory. In general this information consists of the same information that is presented above, where the hull shape is visualized as an image, in CAD software or as a lines plan. The question then arises which additional hydrostatics and hull characteristics need to be generated as output.

Based on literature [37], [38], general knowledge and in consultation with the D&P department the following hydrostatics and hull characteristics should be generated as output. This should provide enough information for getting a first impression of the performance of a particular hull shape and for continuing the design process with the chosen hull shape.

- Block coefficient (C_B)
- Prismatic coefficient (C_P)
- Length overall (L_{OA})
- Displacement weight (Δ)
- Area of the wetted hull (S)
- Area of the waterline surface (A_{WL})
- Area of the midship section (A_M)
- Longitudinal position of the centre of buoyance (LCB)
- Longitudinal position of the centre of floatation (LCF)
- Vertical position of the centre of buoyancy (VCB)
- Transversal area moment of inertia ($I_{T\,(x)}$)
- Transversal metacentric radius (BM_T)
- Transversal distance from the keel to the metacentre (KM_T)
- Longitudinal area moment of inertia ($I_{L\,(y)}$)
- Longitudinal metacentric radius (BM_L)
- Longitudinal distance from the keel to the metacentre (KM_L)

Other desired results should contribute to providing insight to the designer. These results should be integrated to clarify the abovementioned results, to present the correlation and sensitivity between parameters and resistance and to give additional information about the performance of the hull shape. Additionally, the user should be informed with information about the accuracy of the result, both for the hull shape and the resistance results. The following results are therefore also desired as output.

- A table with numeric resistance results over a range of speeds

- A plot showing the local sensitivity of the resistance to changes in an input parameter over a range of speeds (in percentage), computed by finite difference approximation.
- An estimation of the accuracy of the results:
    - Assessment of the accuracy of the resistance prediction
    - Assessment of fairing and smoothness of the hull
- A preview image of the resulting hull shape (for a first impression)

Points of attention to using the tool

As far as the desired tool is described up till now, it comes with some limitations concerning the applicability. In the current design process obtaining the hull is most often done by manually modifying a parent hull (as described in 2.3.2). Whether the D&P engineer chooses to use a parent hull or to start from scratch, some considerations have to be made. Hence, the designer is forced to actively think about these considerations by using his knowledge and experience.

By replacing this process by a tool, it might happen that these considerations are made by the tool. It will therefore not be directly clear why the results are what they are, which can be dangerous. Mistakes might then be hard to recognize, such that wrong results are used. It should therefore be prevented that the tool will be a black-box.

Additionally, in the case that the tools works properly and is able to provide accurate results, those results are only useful if the correct input is used. Hence, the quality of the output of the tool is just as good as the quality of the input that is provided to the tool. Obtaining a hull shape faster is useless if the input parameters are not determined correctly or if they are wrong.

These points of attention might be hard to address when using the tool. Generally, it is essential for a user of the tool to realize that the results of the tool might not always be the answer to his problem. The quality of the result and the results themselves should therefore always be questioned and critically reviewed. Any measure of uncertainty (e.g. variance, confidence interval) of a prediction should therefore be given to the user. Additionally, the user should make sure that the input to the tool is correct. Then and only then the tool is potentially useful. Making sure that the input to the tool is correct can be done by invest some of the gained time (by using the tool) in the process of defining the input. For example, more effort can be put in validation of customer requirements or comparison with reference vessels. By automating these activities the high-speed character of the design process can still be ensured, but this would require some research and development. An example of a tool that could contribute to automation is Quality Function Deployment (QFD) [39].

The black-box problem can be mitigated by setting up the working model and tool such that all activities, calculations and results are visible and traceable to the user. Hence, the tool should be open and responsive.

Next, the dataset of hull shapes with resistance results is described.

3.2 Description of the CFD dataset

This section describes the nature of the CFD dataset, which will form an important set of input for the tool that will be developed. The most important information from this dataset are resistance predictions which have been computed with CFD for a range of hull shapes. First, the reason to initiate the CFD dataset and the relation with the abovementioned goals is described.

3.2.1 Motivation for setting up a CFD dataset

The dataset of CFD-analysed hull shapes has been initiated by both the D&P and R&D departments of Damen. It has been the first answer by the R&D department to the increasing need of the D&P

department to increase the efficiency of making offers in the concept design phase (i.e. market pull). Complementary, the R&D department wants to automate certain tasks as they are spending a significant amount of time on these tasks (i.e. technology push), while making sure that the correct data is used. This is in line with the responsibilities of both departments which have been described in Section 2.1.2.

Recognizing these needs, a project was started with the goal of creating a systematic series of OPV hulls. Instead of doing this in the traditional way in a model basin [27], Damen has the facilities to obtain the same results with CFD simulations. In this way much more hull shapes can be evaluated, providing results which can be immediately used in the design process while being less costly than model tests at the same time. By application of regression methods resistance trends can be found, such that the resistance of other hull shapes (not in the series) can be predicted as well. Effectively, the goal is to provide the D&P department with the geometry of the systematic series and a resistance prediction method.

3.2.2 Using the CFD dataset to achieve the goals

Hence, the question is how to use the CFD dataset of hull shapes to achieve the goals from 3.1.2. The hypothesis is that this CFD dataset is the basis of speeding up the concept design phase of OPVs, by providing a platform for obtaining a new hull shape with a resistance prediction. The CFD-analysed hulls can function as parent hulls.

By optimizing the process of transforming these parent hulls and providing a resistance prediction, e.g. by automation with a tool, the design process can be sped up. Hence, for both obtaining new hull shapes and predicting the resistance of a new hull shape, the CFD dataset is a very appropriate instrument. It can thus be used to satisfy the first goal. The input are parameters that define the hull shape (e.g. main dimensions, form coefficients, displacement etcetera). The output are the hull shape itself (3D geometry) and performance indicators (e.g. resistance).

Then there is the second goal: to create insight for the designer. As described above, this means that the designer should be provided with information about the relation between the input and output, such that he gets understanding in how the performance can be changed beneficially. This is possible since both input and output are now available. For example, local sensitivity of the resistance to changes in the input parameters can be computed, or scatter plots showing the correlation between the resistance and the input parameters can be drawn. As such, the second goal can be obtained as well by using the CFD dataset.

Last, there is a need to create an integral platform for obtaining a hull shape. By creating a tool that facilitates the automation of obtaining a hull shape, predicting the resistance and provides information that gives insight to the designer, one can do this is such a way that the division of responsibilities as given in Section 3.1.3 is realized. By doing so, a central, integral tool is created, which will cause that fewer departments are involved in the design process. Hence, if that is done the third goal is achieved as well. Next, it is described how the CFD is actually set up.

3.2.3 Set-up of the CFD dataset

To agree with the business interests of Damen, the systematic series should be a representation of the OPVs that Damen has produced or is intended to produce.

The CFD dataset is set up by following the steps in Figure 3-1. This approach is based on an method that has been developed by MARIN[2] [40]–[42]. It focuses on combining low- and high-fidelity CFD methods such that the results have the same accuracy of a high-fidelity CFD method, while reducing

[2] MArine Research Institute Netherlands, https://www.marin.nl/

the computational burden of this method. This is known as a 'surrogate model', which will be discussed in more detail in Paragraph 4.2.

Hence, the end result is a set of 3D hull shapes with a resistance curve. After obtaining the high-fidelity resistance results they are validated and a correction factor is determined. This could be done by for example comparison of the results and model tests. This correction factor can then be used to convert the CFD resistance to trial resistance, which is the actual predicted ship resistance. This correction is necessary because in CFD certain appendages (rudders, propellers etc.) and physical phenomena (e.g. added resistance due to hull fouling) are not incorporated.

1	BASE HULL • A base hull is constructed and parameterized with independent parameters
2	EXTREME HULLS • Extreme hulls are constructed, one for each parameter
3	DESIGN OF EXPERIMENTS • A design space is set up by using a Design of Experiments (DoE)
4	LOW-FIDELITY CFD • All the hulls in the DoE are CFD analysed with potential flow (low-fidelity CFD)
5	OPTIMIZATION • Only the surrogate hull forms on the Pareto front are selected for further processing • Select a DoE method and surrogate model that provide the most accurate resistance prediction
6	INSPECTION • Check the selected hulls: add hulls by visual inspection and inspection of the design space • Geometry is obtained for all hulls
7	HIGH-FIDELITY CFD • The selected hulls are CFD analysed with RANS (high-fidelity CFD)
8	RESULTS • Resistance curve is obtained for all selected hulls

Figure 3-1: Activities to set up the CFD dataset for the OPVs.

Application to OPVs

For the OPV series the base hull shape is parameterized by using seven parameters, which are shown in Table 3-1. These parameters have been selected for two reasons: (1) they have a significant influence on the resistance and (2) they are often used for defining an OPV hull shape.

Table 3-1: Parameters used for the hull parameterization of OPVs.

Parameter	*Abbreviation*	*Unit*
Length on the waterline	L_{wl}	[m]
Beam	B	[m]
Draught	T	[m]
Position of the fore shoulder	PFS	[% of L_{wl} w.r.t. APP]
Position of the aft shoulder	PAS	[% of L_{wl} w.r.t. APP]
Deadrise angle	β	[deg]
Immersion of the transom	$\Delta z_{transom}$	[m]

The extreme hulls that are used are thus constructed for each of these parameters. By using this approach the deformation of hull shapes can be defined in a non-dimensional way. This is done by representing the deformation as a range between -1 and 1. In this range 0 is the parameter value of the base hull. If the parameter value is 1 the extreme hull is obtained, which is larger than the base hull. If a parameter value of -1 is used, the deformation is directed towards the centre of the hull, i.e. the resulting hull is smaller than the base hull. This approach is based on another method from MARIN [22], which has also been used as deformation method in the later studies [40]–[42]. This method will be explained in more detail in Paragraph 4.1.

The CFD dataset of double-ended ferries

IMPORTANT

Setting up the CFD dataset is a complex and time-consuming process. There are multiple critical steps which require multiple stakeholders to perform certain activities or to provide information that is needed to set up the base and extreme hulls. Especially running the RANS CFD simulations is very time-consuming. Due to this time-consuming nature and circumstances out of the authors control, the CFD dataset for OPVs was not available during this thesis.

Fortunately, a dataset of double-ended ferries (DEFs) is available which is set up according to the steps in Figure 3-1. An example of a DEF built by Damen is presented in Figure 3-2. A distinctive feature of these vessels is that they are symmetrical with respect to the mid-ship section. Effectively a DEF has two similar bows and no conventional transom. This is advantageous for ferries as they don't have to turn around while berthing at terminals, and vehicles don't have to change direction when unloading.

This CFD dataset will, therefore, be used to develop and test an approach which can be used to increase the efficiency of creating OPV concept designs.

Figure 3-2: Design of the Dokter Wagemaker, a Damen-built double-ended road ferry [78].

The steps in Figure 3-1 have already been performed for this ship type, providing a dataset of 25 hulls. The set-up of this dataset is done in a similar way, though different parameters have been used. These parameters are shown in Table 3-2. The draught is not varied, but fixed at a constant value of 2.22 meter.

Table 3-2: Parameters used for the hull parameterization of DEFs.

Parameter	*Abbreviation*	*Unit*
Length overall	L_{oa}	[m]
Beam overall	B	[m]
Entrance angle on the waterline	β	[deg]
Block coefficient	C_B	[-]
Main-frame coefficient	C_M	[-]

Important to state here is that variation of an individual parameter should be done such that the other parameters remain constant. For example, while varying the block and main-frame coefficients the length or the beam should remain unchanged. For the OPV dataset it is the case that every parameter can be varied independently, without changing any of the other parameters. However, for the DEF dataset only the length, beam and main-frame coefficient can be changed individually. If the entrance angle or block-coefficient is varied, at least one of the other parameters will change as well. This can be seen as a mistake by Damen in defining the extreme hulls. Nevertheless, variation of all parameters can be interesting as it could result in hull shapes with reduced resistance. This issue will be described in more detail in Chapter 5 (Section 5.1.1).

Next, the dataset has been used within Damen to find a set of parameters that provides the most accurate results in regression analysis. Logically, these are parameters that describe the form of the hull shape. They are therefore non-dimensional, as this provides more information about the form than only the dimensions. An additional advantage is that potentially fewer parameters can be used to describe the hull form, e.g. the L/B-ratio can be used instead of the length and beam separately. In general they are also useful as they often correlate with resistance: especially the slenderness ratio maintains a strong relationship with the wave-making component of the resistance [37]. Effectively, the set of parameters in Table 3-3 provided the most accurate results.

Table 3-3: Non-dimensional parameters of the DEF dataset used for regression.

Parameter	*Abbreviation*
Length over beam ratio	L/B
Beam over draught ratio	B/T
Slenderness or length over volume ratio ($L\nabla^{-1/3}$)	SR
Block coefficient	C_B
Prismatic coefficient	C_P
Entrance angle on the waterline[3]	β

Characteristics and resistance results of those hulls can be found in Appendix F. Additionally, characteristics of the base and extreme hulls can be found there as well. Next, it is described how these results will be used in this thesis.

Use of the DEF CFD dataset in this thesis

Although the hull shapes of OPVs and DEFs are different, the CFD dataset can still be used to prove that the concept works to achieve the goals. It will thus be used to develop an approach and tool which can also be applied to OPVs, such that when the OPV dataset becomes available that tool can be used to reach the goals as described in 3.1.2. Effectively, though a different dataset is used the goal of this thesis remains the same.

To construct the geometry a method for constructing new hull geometry based on the hulls from the CFD dataset should be obtained. That hull can then be deformed into the desired shape of the user. To predict the resistance a regression method should be obtained. The regression method can then be used to predict the resistance of any hull shape within the boundaries of the dataset. In this thesis a tool will be developed which will pre-compute those activities, such that they are automated for the designer. This concept will be applied to the DEF dataset and in the future to the OPV dataset.

The rest of this chapter is dedicated to providing an overall description of this tool and defining specific requirements.

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[3] An angle has a unit (e.g. degrees) but is non-dimensional, as it can be expressed as a ratio between two distances which have the same unit.

3.3 Specific requirements

This paragraph focuses on defining specific requirements to the design tool, which can be seen as the 'whats'. They are formulated based on the information in Paragraphs 3.1 and 3.2, and will function as constraints for selecting and designing the solution in the forthcoming chapters. Additionally, they will be used for validation of the tool that will be developed.

The specific requirements consists of functional, non-functional and external interface requirements. For the sake of overview only the functional requirements are provided in this report, the non-functional and external interface requirements are included in Appendix G. Only descriptions of these last two groups are included in this paragraph. The functional requirements are presented in the next section, as they are important for the development of the design tool in this thesis.

3.3.1 Functional requirements

The functional requirements describe the desired behaviour between input and output. There are three main functionalities, coupled to the goals of the tool, to which specific requirements are set.

Providing a hull shape

The following requirements focus on the geometry of the hull. It is recalled that the dataset of DEFs is used as described in the previous paragraph. As the hull shapes from the CFD dataset have all been parameterized with the same 5 parameters, they are a common factor and therefore easy to use as input. The request of a user for a new hull shape, defined by the 5 parameters, should be granted. In other words: the hull shape that is returned to the user should indeed have the same values for all of the 5 parameters as the user input.

- A user should be able to define a hull shape by providing numerical values for the 5 parameters which are used for the initial CFD dataset (Table 3-2).
- A hull shape should be presented to the user, which should have the same properties as the user input, so as defined by using the 5 parameters of the initial CFD dataset.
- Only hull shapes of DEFs are to be provided.

Predicting the resistance

The following requirements focus on the resistance prediction. They follow from the definition of the CFD dataset, or the concerns that have been raised in Section 3.1.3.

- The hull shape that is presented to the user should be provided with a resistance prediction over a range of pre-defined speeds, namely $Fn = [0.15, 0.20, 0.25, 0.30]$.
- The resistance prediction of a hull shape should be based on the resistance results of the CFD dataset.
- A resistance prediction plot should be provided with a confidence interval around the predicted value, indicating the accuracy of the prediction.

Providing insight in the design problem

The requirements related to providing insight are in general focussed on providing information to a D&P engineer to assess the performance of a hull shape. In addition, it focusses on providing information about how input parameters affect the performance of the hull. The preview image of the hull should show as much as possible from the hull shape, leading to the need for a view of each plane and one perspective view. The user should also get an indication of which parameter has the highest correlation with the resistance, by providing a plot showing the relative sensitivity computed by finite difference approximation. That information can be used to change the input such that a hull shape with a better performance can be obtained. Last, an indication should be given to the user to show how the selected hull is related to the CFD dataset. This given an indication of how trustworthy and accurate the prediction is, and can be visualized with a scatter plot. The following requirements represent these needs.

- A list of hydrostatics and characteristics (presented in Section 3.1.3) of the selected hull shape definition should be provided.
- A preview image of the resulting 3D hull shape should be provided, showing the hull shape from four views:
  - Top view: xy-plane.
  - Side view: xz-plane.
  - Front view: yz-plane.
  - Perspective view: viewing the hull shape in 3 dimensions.
- A plot showing relative sensitivity of the resistance curve to changes in the input parameters over a range of predefined speeds should be provided.
- A figure with multiple scatter plots should be provided which shows the defined hull shape in the design space of the initial CFD dataset for all combinations of input parameters.

3.3.2 Non-functional requirements

The non-functional requirements specify the criteria which can be used to assess the functioning of the tool. Hence, these requirements say something about how the tool should function, how it should be designed and how it should perform. They consist of 4 different types:

- Performance requirements
- Robustness requirements
- Usability & responsibility requirements
- Transparency, traceability & modularity requirements

All non-functional requirements can be found in Appendix G.1. The most important requirements for this thesis are that the hull shape should be in an adequate condition for use in the concept design phase, and that the resistance prediction may have a maximum margin of 5% on the corresponding speed. Additionally, the tool should be as transparent as possible: it should be clear to the user how results are obtained, such that calculations, reasoning and relations are traceable. Effectively, this provides insight in the trustworthiness of the results and enhances the acceptance. This important to let the user critically review the results, as they should not be taken for granted.

3.3.3 External interface requirements

The external interface requirements specify how the tool will have to communicate with external interfaces. An external interface could be a Graphical User Interface (GUI) for the user to use the tool, or another software programme in which the results should be represented.

Implementing a GUI might be in contrary with the point about transparency in the previous section: if the GUI works well users might not have the need to figure out how the model behind the tool works, but they will just be interested in obtaining results. Nevertheless, it is assumed that a GUI contributes to speeding up the design process. This can thus be seen as a trade-off between transparency and speed. Speed is then preferred as that is part of the main goal of this thesis and the tool. To be as transparent as possible can still be pursued though, for example by making the model behind the GUI available for inspection. Hence, a requirement to develop a GUI is defined as it is expected that this is beneficial for the speed of the design process.

All external interface requirements can be found in Appendix G.2. They consist of user interface, user interaction and software interface requirements.

3.4 Conclusion

This chapter can be considered as a Statement of Requirements to the design tool that will be developed in this thesis. It is important to define requirements before actually starting to develop a tool, in order to define boundary conditions and prevent unnecessary work. This promotes clarity and enhances the quality of the final product. The second sub-question, therefore, focused on defining requirements for the design tool to be developed.

> *What are requirements for a design tool that supports and improves the current design approach?*

Hence, specific requirements have been defined in Paragraph 3.3, such that this paragraph forms the answer to the second sub-question. In order to define those requirements the scope and goals of the tool have been introduced in Paragraph 3.1. User needs, intended input, intended output and constraints to using the tool have been described here as well, effectively describing how the tool should work.

The CFD dataset has been introduced in Paragraph 3.2. Since this specific dataset is not available for OPVs, a similar dataset for double-ended ferries (DEFs) is used to develop and test the approach which can be used to increase the efficiency of creating OPV concept designs. By using this dataset, the first two goals presented in Section 3.1.2 can be achieved, while the third goal can be achieved by creating a tool that facilitates the automation of the three most important activities. These activities are (1) to obtain a hull shape, (2) to predict the resistance and (3) to give insight to the designer. They are also used to define the specific functional requirements. In the case of this thesis, providing insight is providing understanding in how changing the input leads to a change in the resistance.

The specific requirements are the most important result of this chapter. The 'whys' and 'whats' have now been described. They will be used in the next chapter to search for the 'hows': solutions that meet the requirements. After developing the tool, the specific requirements will again be used for validation of the tool in Chapter 7.

Next, Chapter 4 will focus on finding the right techniques for hull geometry deformation and the resistance prediction. The results will be used to present a high-level description of the model that will drive the design tool.

4

Development of the Tool

This chapter describes the development of core elements of the design tool that will be developed in this thesis. The needs and requirements from the previous chapter are used as guidelines. Effectively, the goal of this chapter is to define a solution that satisfies these needs and conforms to the requirements.

Two core elements are treated separately. First, Paragraph 4.1 focuses on finding a technique to obtain new hull shapes. The second core element is the resistance prediction of a new hull shape, which is elaborated upon in Paragraph 4.2. For both elements different alternatives are described and compared, in order to choose the most appropriate technique. In Paragraph 4.3 the two core elements are combined and integrated in the design procedure, in order to present a high-level description of the model behind the tool. A database of hull shapes is introduced, after which it is described how the tool and database will interact such that the needs are satisfied and the requirements are met. This provides a first high-level description of the total solution.

This overview, together with the working principles of the hull deformation and resistance prediction techniques, will be used in Chapter 5 to describe in detail how the database will be filled. Additionally, it provides input for Chapter 6, where the use of the database will be elaborated upon in more detail.

4.1 Obtaining new hull shapes

The goal of this paragraph is to select a method which can be used to obtain a new hull shape. That method will subsequently be integrated in the design tool. In order to understand how new hull shapes can be obtained, first different representation techniques and possible file formats are described in Section 4.1.1. Thereafter possibilities to obtain a hull shape are discussed in Section 4.1.2, which boil down to partial parametric methods (i.e. hull deformation techniques). Only these methods are considered, as the parent hulls from the CFD dataset will be used to create new hull geometry. The paragraph concludes with a qualitative comparison between the hull deformation techniques based on pre-defined requirements, used to select the most suitable hull deformation technique. This is presented in Section 4.1.3.

4.1.1 Representation and saving of a ship's hull

Non-Uniform Rational B-Spline (NURBS) are acknowledged to be the most-widely used definition for representation and manipulation of geometry in CAD systems [37]. Effectively, also for the representation of hull forms in the ship design process NURBS curves have become the standard, together with Bézier and B-spline curves [33], [43]. Examples of these three representation techniques can be found in Figure 4-1.

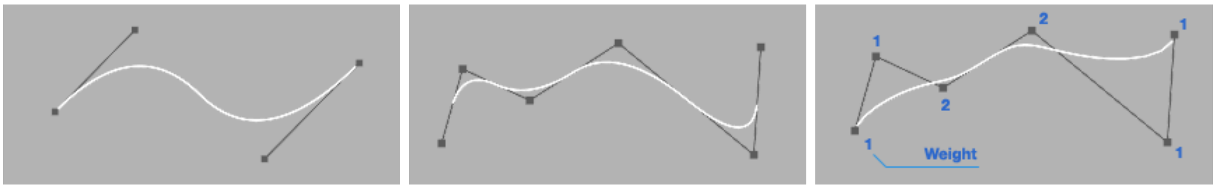

Figure 4-1: From left to right, a comparison between a Bézier spline, an open B-spline and NURBS with weighted control points [44].

The NURBS representation has proven to be of great value, as it can take the exact shape of any conic section or circular arc. Effectively, NURBS curves provide a representation that compromises both conics and free-form curves. In general they can be used to represent any curve, to any degree of accuracy [37]. This representation is also used for definition of the parent hulls of the CFD dataset, and as defined in the non-functional requirements for robustness the definition also has to be used for the new hull shapes.

Effectively, a NURBS curve is defined by a set of weighted control points, a knot vector and the order of the curve. A NURBS surface is the tensor product of two NURBS curves, i.e. patches that are fitted together such that geometric continuity (positional, tangential and curvature) is established. This means that the patches are connected such that the boundaries of the curves are invisible, which is mathematically represented by the geometric continuity. A surface can be decomposed in a U- and V-direction, while a curve only has a U-direction. A surface also has a W-direction, which is positioned orthogonal to the surface.

Deforming a NURBS curve and surface can be done by changing either the control points, knot vector or order. However, changing the knot vector, order or number of control points cannot be simply done, as they are interdependent and subjected to rules (e.g. see [45]). Deformation of the geometry is, therefore, mostly done by changing the location of the control points.

As defined in the non-functional requirements the NURBS surface has to be saved as a .IDF file, and .3dm, .IGES or .STEP file (see also Appendix G.1.3). The .IDF file is well-interpretable for humans, such that NURBS surface information (control points, knot vector and curve order) can easily be extracted. The other files allow for importing the geometry in CAD applications which are often used in the ship design process.

By knowing the technique behind the NURBS representation, it is now known how NURBS geometry can be changed. Methods to do so are described in the next section.

4.1.2 Possibilities to obtain a hull shape

In the previous section it has become clear how hulls can be represented and should be saved. The next relevant question is which possibilities there are to obtain a hull shape.

In general there are two possibilities, which were already mentioned in Paragraph 2.3.2. One can start drawing from scratch, or a parent hull can be adopted and modified. Different researchers confirm that there are two general hull design techniques. For example, Harries et al. [46] divides different Computer Aided Geometric Design (CAGD) into two groups, the so-called *conventional* and *parametric* techniques. Per group different approaches can be recognized, as can be seen in Figure

4-2. An important distinction can be seen in the parametric techniques, which is divided into partial and fully parametric design. If a partial parametric strategy is followed, a parent hull is needed which is subsequently modified such that it gets the desired characteristics. A parent hull is not needed for conventional and full parametric methods, in that case a new hull geometry is drawn from scratch.

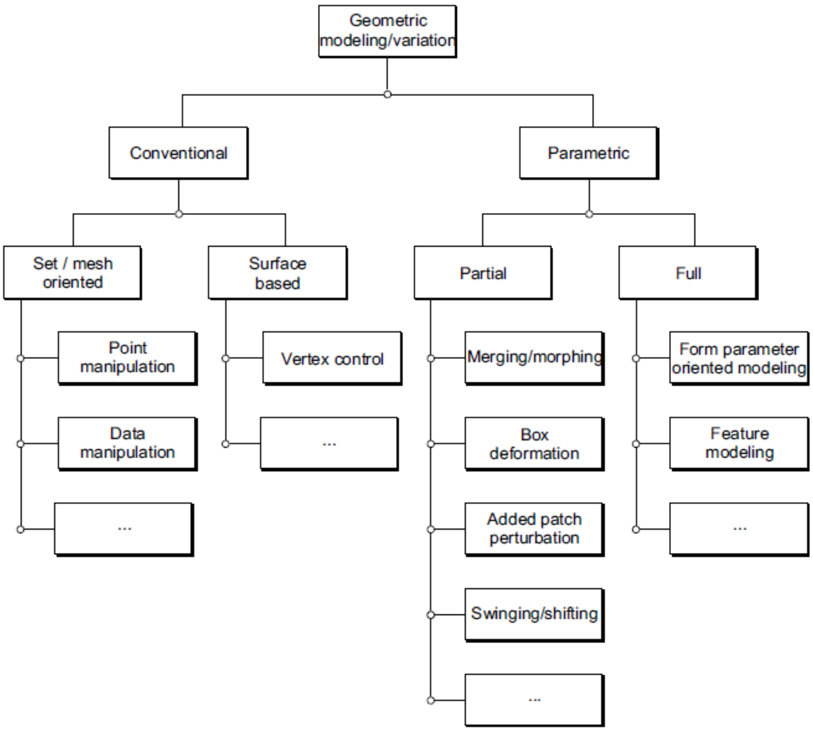

Figure 4-2: Possibilities for geometric modelling and variation [46].

In this thesis the CFD dataset provides a set of hull shapes with resistance results. A part of this set are parent hulls: the rest of the hulls inherits from them. When using regression analysis to do a resistance prediction for a new hull shape based on the CFD dataset, more accurate resistance predictions can be expected when this new hull shape is geometrically related to the hulls in the CFD dataset. The new hull shape should, thus, inherit from at least one of the parent hulls of the CFD dataset. Effectively, a partial parametric method should be used as deformation method.

This raises the question on how the parent hulls can be used as parents to obtain a new hull shape. To answer this question some requirements for the hull deformation technique in this thesis are described. Subsequently, the different partial parametric methods will be described.

Requirements to a hull deformation technique

In order to select the most suitable hull deformation technique, some requirements are defined. They will be used to make a qualitative comparison of the available partial parametric methods. The starting points for these requirements are the following.

- 3D geometry is available of 25 DEF hull shapes.
- To create these hull shapes 6 parent hulls were used, such that there were 5 parameters defined for systematic variation.
- Six non-dimensional parameters have been selected for regression analysis, as these provided the most accurate results.

All 25 hulls consist of one NURBS surface, which is smooth and well-faired. The geometry of each hull has the following characteristics.

- The NURBS surface is defined by 30 control points and is non-rational, i.e. all control points have the same weight of value 1.

- There are 6 control points in the U-direction and 5 in the V-direction.
- The size of the knot vector is 8 in U-direction and 7 in V-direction.
- The degree of the surface is 3 in all directions.
- The geometry is saved in .3dm and .IDF file formats.

In accordance with the requirements in Chapter 3, the problem as described above, and literature [47], the requirements for the hull deformation technique in Table 4-1 have been defined. A division is made between requirements which are necessities (indispensable) and requirements which are desired but not necessary (extra). They are all clarified below the table.

Table 4-1: Requirements to the hull deformation technique.

Indispensable requirements	Should not cause major fairing problems or unwanted shape characteristics
	Geometry should remain a NURBS surface
	Suitable for global deformations (systematic variation) in the concept design phase
	Applicable to the CFD dataset, using all 6 parent hulls
	Accurate deformation results
	Independent parameters
Extra requirements	Seamless connection to the CFD dataset
	Create shapes outside the design space
	Clear and easy to understand
	Suitable for local deformations

It is required that new hull shapes are sufficiently smooth and well-faired, such that the deformation technique should not cause major problems with these aspects. Moreover, for practical considerations it is required that new hull geometry is a NURBS surface as well. As the tool focuses on the early design stages and obtaining a first geometry definition for the hull, only global deformations are needed. Nevertheless, it is an extra if a deformation technique is also suitable for local deformations. This could be applied in later design stages for optimization purposes, or might be used for OPVs in the concept phase to deform local details such as the bulbous bow.

The technique should be applied to the CFD dataset, such that at least one but preferably multiple parent hulls are used to enhance the accuracy of the resistance regression. Input for obtaining a new hull shape is a set of values for the 5 parameters that are used for variations. The resulting hull shape should have the same 5 values for those parameters, such that is should be accurate in providing geometry. The parameters which are varied should be independent from each other, such that each parameter influences the new hull geometry uniquely.

Additionally, it is desired if the deformation technique can be seamlessly connected to the CFD set. In other words, the six available parent hulls will all be used as parent hulls and the same considerations are made. The main consideration is that the parent hulls indicate the boundaries of the design space. It is also beneficial if is it possible to generate shapes which are outside the design space, as then more options can be explored by the designer. Last, it is beneficial for developers but also users of the tool how geometry is deformed, such that deformation technique should be clear and easy to understand.

Description of promising semi-parametric methods

In order to find and select the most suitable partial parametric method an extensive analysis of five methods is done. The full analysis is presented in Appendix H. For the sake of overview only the most important outcomes for each analysed method are presented in this report. The conclusions on the analysis are presented subsequently in Section 4.1.3. In that section a comparison between selected methods and the requirements in Table 4-1 is presented, which leads to the most preferred hull deformation method. Next, the outcomes of the swinging and shifting methods are described first.

Swinging and shifting are synonyms for the two most used hull deformations methods: Lackenby and affine transformations. They can both only be used for global deformations.

Lackenby transformations (also known as swinging or Lackenby shifts) are done by shifting frames in longitudinal direction, while keeping the shape and area unchanged [48]. This can be used to obtain a hull with a specific prismatic coefficient, LCB and position of the parallel mid-body. Effectively, this can be done by shifting rows of control points with the same longitudinal coordinate. Additional control points can be added to obtain more control over the surface.

Uniform stretching is an affine transformation known as shifting [46]. It is used to scale the main dimensions in the three orthogonal axes. Useful geometrical properties are preserved, for example the smoothness of the parent hull. Other well-known affine transformations are translations, shears or rotations. Versluis [49] translated locations of the ordinates in longitudinal direction, in order to obtain a hull with a specific sectional-area curve (SAC), block coefficient or LCB.

In **free form deformation (FFD)** some free control nodes are defined as design variables [50]. By coupling these nodes to groups of NURBS control points the position of these control points can be changed by moving the control nodes. This is only effective if the number of control nodes is lower than the number of NURBS control points. If that is realized the major advantage is that the method is computationally cheaper. However, geometry constraints cannot be taken into account. It is mostly applied for optimization studies.

Box deformation is similar to free form deformation as one cannot directly control the hull geometry, but an additional definition is used to control the hull geometry [46]. However, in this case a bounding box is used around the geometry to be deformed, which is coupled to the hull geometry.

Radial Basis Functions (RBF) interpolation uses a radial function: a function for which the value at a certain point only depends on the distance between that point and the origin of the function. Fixed and movable control nodes can be defined. The movable control nodes are the design variables. Fixed control nodes keep the NURBS surface unchanged near the control nodes, such that geometry constraints are satisfied. After changing the position of the control nodes, RBF interpolation between the fixed and movable control nodes is applied to calculate the displacement of the NURBS control points. By following this procedure less design variables would be needed than in the case with a NURBS representation, such that it also becomes computationally cheaper. It allows for direct calculation of hydrostatics and other characteristics [51], and is also mostly used for optimization studies. Additionally, this method can be used for both local and global deformations [50].

Morphing & merging is one method, originating from the animation industry where it was used to smoothly merge two images into one new image [52]. This is achieved by creating intermediate forms between multiple extreme parent forms, which are used to create a new shape by linear superposition [47]. Weights can be assigned to each of the parent forms. This is the deformation method which was used to create the variations of hulls in the CFD dataset.

At least two shapes are needed as parent shapes. A morphing parameter par can be defined, indicating the weight of the extreme shape (d^{extr}) to be used. This is mathematically represented in Eq. (4-1). As the new shape (d^{new}) is a linear combination of the two shapes, the weight of the base shape d^{base} is always $(1 - par)$. Moreover, for the morphing parameter it yields that $0 \leq par \leq 1$. If par equals zero than the new shape is equal to the base shape, while par amounting one would result in the new shape being equal to the extreme shape.

$$d^{new} = (1 - par) \cdot d^{base} + par \cdot d^{extr} \tag{4-1}$$

This principle can also be used for a case with multiple extreme shapes. Additionally, it can be applied to other geometry types such as meshes. Constraints can be incorporated by having common characteristics amongst the base and extreme shapes. Effectively, it can be used for both local and global deformations. It can also be used for extrapolation of shapes, by using a morphing parameter larger than 1 or smaller than -1. As there can be a direct link between the parent shapes and their parameters, this method also allows for direct calculation of hydrostatics and other characteristics.

Added patch perturbation can be seen as a generalization of a surface shift [53]. A patch is placed on top of the original geometry, and subsequently used for deformation. Again less control nodes can be used to relocate the control points of the original hull geometry. For the surface patch any representation can be used, such as a Bézier or NURBS surface. By superimposing the surface patch on the offsets of the original geometry one can obtain the deformed geometry.

This method can be used for both local and global hull deformations, and also for other geometry types such as meshes. Any type of shift function can be used for the patch surface, such that a wide variety of shapes can be produced. Only few design variables are needed, such that the computational effort is reduced compared to directly controlling NURBS control points. It is acknowledged that this method is also mostly used for optimization problems in the later design stages [47].

Next, a qualitative comparison based on these analysis is made in order to select one method.

4.1.3 Qualitative comparison of hull deformation techniques

In the beginning of the previous section indispensable and extra requirements have been stated. They will be used to choose a hull deformation technique.

Five partial parametric modelling techniques have been described. It can already be concluded that RBFs, FFD and Added Patch perturbation are not particularly suitable as deformation technique in this thesis. They are both more suitable for optimization studies in later design studies and local deformations, than for global deformations for systematic variation in the concept design phase. As the tool requires a global deformation tool, these techniques are excluded for use in this thesis.

For selection both swinging & shifting and morphing are assessed based on the requirements in Table 4-1. The result can be seen in Table 4-2, following from the analysis of these techniques as discussed in the previous section. A green check mark indicates that the requirement is satisfied, while a red cross indicates the opposite. If both signs are displayed, the requirement is only partly satisfied.

Table 4-2: Comparison matrix of selected hull deformation techniques.

	Swinging & shifting	*Morphing*
No fairing problems	✓	✓
Remain NURBS surface	✓	✓
Suitable for global deformations	✓	✓
Applicable to CFD dataset, using all 6 parents	✓ / ✗	✓
Accurate deformation results	✓	✓
Independent parameters	✓	✓
Seamless connection	✗	✓
Create creative & innovative shapes	✗	✓ / ✗
Understandable	✓	✓ / ✗
Suitable for local deformations	✗	✓

Hence, it follows that only morphing fully complies to the indispensable requirements. Using swinging & shifting transformations, no full use of the six available parent hulls will be taken. It can only be applied to one hull shape at a time, requiring multiple subsequent steps to obtain a new deformed hull shape.

For the extra requirements morphing is also preferred. It can seamlessly be connected to the CFD dataset, as it can be applied to the six parent hulls at a time. Another plus is that it can be used for local deformations. In contrast the technique is a bit more harder to understand than swinging & shifting. A point of attention of both swinging & shifting and morphing is that they are not able to provide 'out-of-the-box' innovative shapes. Extrapolation in morphing can however be used to circumvent this issue.

Concluding, morphing is the preferred deformation technique. It will be used to construct a new hull shape based on the user input and the six parent hulls from the CFD dataset. Integration of this technique in the model behind the tool will be discussed in Paragraph 4.3. A more detailed description of how morphing is applied in this thesis to generate new hull shapes is given in Chapter 5. Next, the selection of a surrogate model is discussed.

4.2 Predicting the resistance of a parent-based hull shape

The previous paragraph has taught us how a new hull geometry could be obtained. The next step is to find a suitable surrogate model which can be used to predict the resistance of the new hull geometry. This is the subject of the current paragraph.

An introduction to surrogate models is given in 4.2.1, providing information about how they will be used in this thesis. Requirements for a surrogate model are defined as well. Section 4.2.2 hereafter presents popular surrogate models, after which the most suitable ones are described. An analysis of practical applications of promising models is given as well. Last, a qualitative comparison is done based on the pre-defined requirements, for which the outcomes are described in 4.2.3.

4.2.1 Introduction to surrogate models

A surrogate model (also referred to as metamodel or response surface model) is a substitute for an expensive simulation, and aims at providing a 'cheaper' replacement for that simulation. Often cheaper means computationally cheaper, such that less time is spent on simulations. For more information about surrogate models in general, the reader is referred to literature such as [28], [54].

Traditionally, when handling data to make predictions, models can be divided into two groups: regression models and classification models. This latter type focuses on identifying to which group output belongs, while the first type focuses on providing a numerical prediction for the output. Since a numerical prediction for the resistance is desired in this thesis, a regression-based surrogate model should be used.

General principle of a surrogate model for regression

To explain the different regression methods, the general principle of regression, surrogate modelling and corresponding terminology is explained.

Regression is applied to define the relationship between input values (x) and output values (y), based on observations of that output to pre-defined input. A mathematical expression can be formulated, i.e. a regression formula (f), that defines this relationship. That expression can subsequently be used to obtain a prediction $(\hat{y}_i)$ for an input value (x_i) that was not included in the original dataset (x). The prediction $\hat{y}_i$ is the Quantity of Interest (QoI).

When using vector notation, the following formulation for the prediction when using a surrogate model can be defined.

$$\hat{\boldsymbol{y}}_i = f(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{x_i}) \tag{4-2}$$

Use of a surrogate model in this thesis

In order to search for a suitable surrogate model, one wants to know how this surrogate model will be used. Additionally, requirements for the surrogate model can be defined.

The starting point is that the CFD dataset contains different hull geometries, for which resistance results have been obtained with high-fidelity, expensive RANS CFD analysis[4]. A surrogate model will be used for regression results of these resistance results. The goal is to let the surrogate model provide a resistance prediction for new hull shapes, with the same accuracy as the CFD simulations but in much less time. These new hull shapes are obtained with morphing.

In order to do this, the surrogate model needs to be trained first. In the light of the description above, this means that the relationship f will be defined. Effectively, the other parameters can be defined as well.

- Input values $\boldsymbol{x}$: non-dimensional parameters of all hulls in the CFD dataset (6 dimensional)
- Input value y: resistance results of all hulls in the CFD dataset
- Input value $\boldsymbol{x_i}$: non-dimensional parameters of the new hull
- Output value $\hat{y}_i$: resistance of the new hull

Effectively, for training the model only x and y are used. They define the relationship f, which can be used to predict the resistance $\hat{y}_i$ for a set of non-dimensional parameters x_i.

Requirements to a surrogate model

The challenge of selecting a suitable surrogate model mainly concerns of finding a surrogate model that is suitable for this problem. Requirements to the surrogate model are presented in Table 4-3. Again, a division is made between requirements which are necessities (indispensable) and requirements which are desired but not necessary (extra). Explanations are presented below the table.

[4] More information about the fundamentals of CFD can be found in literature such as [27], [39].

Table 4-3: Requirements to the surrogate model.

Indispensable requirements	Suitable to capture non-linear behaviour of the wave-making resistance
	Applicable to a problem with 6-dimensional input, 1-dimensional output and 25 training points
	Sufficiently fast for 6-dimensional training data
Extra requirements	Provide an uncertainty estimate
	Proven predictive performance for regression (accuracy in case studies)

It is indispensable that the surrogate model can represent the relationship between hull geometry and ship resistance. Ship resistance can in this case be decomposed into its two main components: the pressure component R_p and the viscous component R_v. The viscous component contains the frictional resistance and viscous pressure resistance, while the pressure component is analogous to the residual or wave-making resistance. Especially the wave-making component has non-linear properties in relation with the speed, causing that the total ship resistance shows non-linear behaviour as well (especially at higher ship speeds). It can be assumed that this is also the case for the relationship between the ship resistance and the non-dimensional parameters which are used for regression.

It is also essential that the surrogate model is capable of handling multi-dimensional input. The set of non-dimensional parameters has a dimensionality of six. The output is 1-dimensional (only resistance). As there are 25 hulls in the CFD dataset, there are 25 training points. Some surrogate models are known to become increasingly slow for complex or high-dimensional problems. However, since the training data is 6-dimensional, the problem cannot be said to be high-dimensional. It is required that the surrogate model is sufficiently fast for this dimensionality.

To satisfy the requirements defined in Paragraph 3.3, it is desired that the surrogate model should be able to predict the accuracy of the predicted resistance, e.g. by providing the variance or a confidence interval. This is not a necessity as an uncertainty estimated can always be computed afterwards, for example by a cross-validation study. Nevertheless, it is beneficial if a surrogate model itself already provides an uncertainty estimate, as it enhances the speed of the total process and can be used for tuning. Last, the predictive performance of surrogate models in similar case studies will also be used to compare the different models. It is beneficial if a model provided the most accurate predictor in the studies.

4.2.2 Description of regression-based surrogate models

With the requirements defined, the search for a suitable surrogate model can start. Popular surrogate models are described first.

Popular surrogate models

Different people from different disciplines (e.g. aerospace, chemical industry, geo-statistics, naval architecture) have addressed the theory of surrogate models to provide an overview of the primary groups of surrogate models that are available [28], [31], [55]–[58]. Popular regression methods which seem popular amongst all disciplines are listed below.

- Linear & polynomial regression (least-squares)
- Radial Basis Functions (RBF)
- Kriging
- Artificial Neural Networks (ANN)

- Support Vector Networks (SVN)
- Decision Tree regression

Subsequently, the question arises which surrogate model would be appropriate to use to provide a resistance prediction for an 'unknown' geometry. Some of the listed regression methods do not seem appropriate for use in this thesis.

Linear regression models with least-squares fitting are only suitable for linear problems [59]–[61]. This makes these models not suitable as a regression method in this thesis. A **polynomial regression model** can be suitable, as these can cover a much broader range of data as the corresponding basis function can built a higher-dimensional space. A resistance curve is often approximated as a second-order polynomial fit, though this is a major simplification. Higher-order polynomials might thus be suitable to be used as a surrogate model in this thesis.

Artificial Neural Networks (ANNs) are particularly suited for optimisation purposes in engineering, but also for classification [59], [60]. They are capable of handling non-linear models, as the hidden layers can be of any form. For complex problems ANNs become computationally expensive and difficult to interpret. Additionally, tuning of the hyperparameters (e.g. neurons and hidden layers) has to be done which becomes a computational burden for complex problems. It is also sensitive to feature scaling [62]. Hence, it seems that ANNs are not particularly suitable as a surrogate-based regression method for this thesis.

Decision Tree regression provides a very well-interpretable regression method, but can be inaccurate for complex functions. Random Forest regression is a variant that provides more accurate results, but is less interpretable [60], [62]. Advantages of both methods are that different types of data can be used at the same time, e.g. numerical and categorical, and multi-output problems can be modelled [62]. However, Decision Tree regression can be unstable, such that a completely different tree is returned for a small change in the input data [62]. Neither of the two methods provides smooth surfaces and are prone to overfitting if the trees become large [60]. Overfitting in statistics is disadvantageous as the surrogate model is then probably not accurate in predicting a new value (which is not in the input x), despite the fact that it fits the input data better.

Hence, these methods do not seem promising for application in this thesis. Next, the other listed methods, higher-order polynomials (2nd or higher), RBFs, kriging and SVNs, will be analysed in more detail.

Analysis of promising surrogate models

The four promising surrogate models are analysed thoroughly, in order to find the most suitable method for application in this thesis. The full analysis can be found in Appendix I.1. This section only describes the outcomes of the research done on the methods.

A **polynomial regression model** is a generalization of a linear regression model. The interpolant is replaced by a polynomial with a degree higher than 1. As an effect the output will be non-linear with respect to the output. The general formula of a polynomial regression model can be seen in Eq. (4-3). In the case of this thesis the variable x would be multi-dimensional.

$$\hat{y} = \beta_0 + \sum_{j=1}^{n} \beta_j x^j \tag{4-3}$$

The variables β_j are coefficients that need to be estimated such that the models fits the input data. In the fitting procedure the order of the polynomial (j) and the interpolant (β_0) can be chosen. This can be done based on the nature of the problem that should be modelled. Subsequently, fitting is typically done by solving a least-squares equation for the difference between the prediction and the data points. The strengths of polynomial regression are its simplicity and computational efficiency [29], [55]. Moreover, the method is easy to understand and to analyse. However, the simplicity also decreases the applicability: they work well for low-dimensional problems but are not suitable for high-dimensional or highly non-linear problems. Overfitting might occur when high orders are chosen.

Radial Basis Functions (RBFs) provide a regression formula which consists of a linear combination between a weight λ and the function value of a radial function $\varphi(x)$. This is also the general form of any kernel-based method, which is shown in Eq. (4-4).

$$\hat{y} = \boldsymbol{\lambda}^{\mathbf{T}}\boldsymbol{\varphi} \tag{4-4}$$

$$\hat{y} = \sum_{i=1}^{n} \lambda_i \varphi(|x - c_i|) \tag{4-5}$$

Eq. (4-5) shows the general prediction formula for an RBF. The variable x is the input data to be modelled, while c_i is the centre of the i-th basis function. The difference is thus the radial distance between these two points, for which often the Euclidean distance is used. The weights λ_i should be fitted before regression, similarly to β_j for polynomial regression. This can be done by interpolation [28].

For this radial function $\varphi(x)$ different forms can be used, providing great flexibility. Additionally, Eq. (4-5) is linear in terms of the weights λ_i, but still the predictor $\hat{y}$ can express non-linear responses by the choice of the radial function. This makes RBFs a very flexible but simple method. The form of the method has proven to be powerful, as it is the general form of any kernel-based method [29]. Effectively, RBFs are often used as a kernel in kriging, ANNs and SVNs [60], [61].

Kriging is said to be a particular case of an RBF: it can be seen as another basis function which is a variant on a Gaussian RBF [28]. The kriging basis function has the form as presented in Eq. (4-6). By using this definition as a kernel in the general prediction formula in Eq. (4-4), the prediction formula for kriging in Eq. (4-7) is obtained.

$$\varphi = \exp\left(-\sum_{i=1}^{n} \theta_j \left|x_j^{(i)} - x_j\right|^{p_j}\right) \tag{4-6}$$

$$\hat{y} = \sum_{i=0}^{n} \beta_i f_i(x_j) + Z(x_j) \tag{4-7}$$

The first term $\sum_{i=0}^{n} \beta_i f_i(x)$ represents the trend, i.e. large-scale variations. Different trend functions can be chosen, dependent on the problem that needs to be modelled. The second term $Z(x)$ represents the error, i.e. the covariance of the prediction, and is modelled by a stochastic (Gaussian) process with zero constant mean. Its correlation structure is a function of the Euclidean distance $\left(x_j^{(i)} - x_j\right)$. The larger the distance is from a data point, the larger this term $Z(x_j)$ gets. Hence, a kriging prediction is more accurate if the sample points are dense in a region of the design space, while a less dense region provides a larger spread in the prediction. In effect, the predicted value $\hat{y}$ equals the mean of the Gaussian process that is modelled.

Compared to RBF the most important advantage is that an uncertainty estimate of the prediction can be obtained. Another major, general advantage is that one can choose appropriate trend and correlation functions, such that a wide variety of functions can be modelled. This makes kriging well capable of modelling highly non-linear models. It is a powerful predictor, while only a few parameters are needed to do so [55]. Another advantage is that it a regression constant can be added, such that an error between the prediction and observations is allowed [28]. The flexibility can also be a weakness, as obtaining all the hyperparameters can be a computational burden for high-dimensional problems or problems with a lot of observations. Kriging is recommended for problems with a dimensionality below 20 [55] or a couple of dozens [62].

Support Vector Networks (SVNs) are often used as classification model, but a regression model is also available which is known as Support Vector Regression (SVR) [28]. The main principle is that a tube with a width of ε represents an allowable error, which is used to separate the observations. The prediction is only dependent on the observations that are located outside or on the ε-tube. Those observations are called *support vectors* and are used for making the prediction. The observations in the ε-tube are excluded for predicting the output $\hat{y}$. This can be advantageous in cases where a process should be modelled for which it is known that there are errors or noise. For example, the finite mesh size in CFD causes a grid error, which can be approximated with a grid convergence study. Using SVR less observations are used for doing predictions, thus saving on computation time.

Just as for kriging is the case, SVR is a kernel-based method and thus a special case of an RBF model. The general prediction formula in Eq. (4-8) is used for SVR.

$$\hat{y} = \mu + \sum_{i=0}^{n} \lambda_i \varphi(x, x_i) \tag{4-8}$$

Again, φ represents a basis function, which is multiplied with a weight λ_i and added to a base term μ. For the basis function different forms can be chosen, such as a linear, polynomial, Gaussian or kriging form. Finding the base term μ can be done by exploiting the so-called Karush-Kuhn-Tucker conditions. More information for the procedure of estimating the hyperparameters can be found in [28]. Hence, SVR is very similar to RBF and kriging as a kernel function is used to estimate correlation between observations, after which the coefficients are determined with a fitting procedure.

An advantage of SVR is that incorrect observations (outliers) do not have a large effect on the predictions [29]. It can also be used for a problem where the dimension of the input is larger than the number of observations. Next to that, a regularization parameter can be used to determine the shape of the predictor, and thus whether it will be flat or more attracted to the observations [29], [57]. This provides a lot of flexibility and could prevent overfitting. However, similar to kriging, SVR might become slow if the number of observations is high [60].

From these descriptions alone not a clear preferred surrogate model can be chosen. Therefore, practical applications of these surrogate models in other studies is analysed, which is described next.

Application in other studies

The selected surrogate models have already been applied in practice. This section describes the outcomes of some case studies, in order to see which insights have been obtained for similar cases in which surrogate models were used. The complete analysis of these case studies can be found in Appendix I.2.

Four different specific cases of surrogate models have been analysed, which can be seen in Table 4-4. Additionally, several applications which are found in various engineering disciplines and general books on surrogate modelling have been analysed as well.

Table 4-4: Analysed applications of surrogate models to similar problems.

Subject	*Researchers*	*References*
Predicting power and wake field quality of an inland vessel	Rotteveel	[29]
Bulbous bow shape optimization for hydrodynamic resistance	Guerrero, Cominetti, Pralits & Villa Cominetti	[30] [63]
Multi-fidelity procedures for hull form optimization (from MARIN)	Scholcz, Gornicz & Veldhuis Veldhuis, Gornicz & Scholcz Scholcz & Veldhuis Raven & Scholcz	[64] [40] [41] [42]
Comparison of surrogate models for approximation of Finite Element Method calculations	Prebeg, Zanic & Vazic	[31]
Applications from various engineering disciplines and books on surrogate modelling	Various authors from: - Ship design - Chemical engineering - Aerodynamics - Water resource engineering - General books	 [65] [55] [56], [59] [57] [28]

In the study of Rotteveel on inland vessels [29] the goal was to find design guidelines for sterns of inland vessels. Seven different surrogate models were compared based on predictive performance for propulsion power and wake field quality (quantified by an objective function). It appeared that kriging and SVN have a better predictive performance for propulsion power and wake field quality compared to other surrogate models. Kriging was subsequently chosen and used for surrogate-based optimization of the shape of a parameterized stern. By using this surrogate model more power and wake field results could be obtained without actually running a large number of CFD simulations, which was normally needed to obtain those results.

Guerrero et al. [30] and Cominetti [63] conducted a study on optimizing the shape of a bulbous bow such that the hydrodynamic resistance is minimalized. Kriging was used as surrogate model, as it captures the hydrodynamic behaviour well. A comparison with a second-order polynomial surrogate was also made, which clearly showed the differences in how well non-linearities can be captured. Kriging was very well able to capture the non-linearities, while the second-order polynomial couldn't. It was shown that kriging indeed is an effective surrogate model in surrogate-based optimization, as a maximum resistance reduction of 7% compared to a baseline shape was achieved.

Scholcz, Gornicz, Veldhuis & Raven, all from MARIN, published several reports on surrogate models as well [40]–[42], [64]. First, the hull shape of a tanker was parameterized and a Design of Experiments was set up. This design space was analysed with CFD and a surrogate model was sought for that could predict the power and a wake field objective function based on the CFD results. It was shown that Universal Kriging performs best in predicting the wake field quality, and Universal Kriging and polynomial regression perform equally well in predicting the power [64]. Hence, also in this case the number of CFD simulations to obtain those results could be reduced. Subsequently, Universal Kriging and a Quadratic Polynomial were used and compared to a Multi-Objective Genetic Algorithm (MOGA) to find a hull shape with the best powering and wake field characteristics [41]. It was shown that both surrogate models provided results that were close to the MOGA Pareto front, but the surrogate models took one day of computing while the MOGA took two weeks. Infilling (providing the optimal results as training results to the surrogate model) was applied and proven to be a good instrument to improve the accuracy of the kriging predictor.

In another research it was shown that for predicting the outcome of normal stress calculations in thin-walled ship structure elements a second-order polynomial and RBF provide the best predictor

[31]. In this case Finite Element Method (FEM) calculations would normally be used, but these are computationally expensive. Kriging was also taken into comparison, but it did not provide accurate predictors.

From case studies from other engineering disciplines interesting insights can be found as well. For a *six humps camel back function* a kriging surrogate model provided the most accurate prediction [65]. Modelling of aerodynamic performance of gas turbine blades can be done with CFD as well. A comparison of surrogate models shows that kriging provides the best predictor of a pressure loss coefficient and deviation angle [59].

Next, the lessons-learned are used in the qualitative comparison, in order to select the most suitable surrogate model.

4.2.3 Qualitative comparison of regression-based surrogate models

Based on the literature that is available and the characteristics of each surrogate model, a qualitative comparison is made between the methods that have been described above. By doing so the most suitable model can be selected from the group of polynomial regression, RBFs, Kriging and SVNs.

To recall: the nature of our problem is that a resistance prediction should be obtained by a change in geometry. This change in geometry is quantified by 6 non-dimensional parameters. CFD analysis provides HF resistance results for 25 different hull geometries at four different speeds, decomposed into a pressure and viscous part. The non-dimensional parameters of those 25 hulls are available. Especially the wave-making component of the resistance shows non-linear behaviour to a change in speed or hull geometry. A surrogate model is desired that can use this data to predict the resistance of a hull shape that is not in the CFD dataset. Requirements to the surrogate model have been stated in Table 4-3.

Four promising surrogate models have been described and similar case studies have been presented in the previous section. From the outcomes of these analyses it can be concluded whether the pre-set requirements for the surrogate model are satisfied for each of the four surrogate models which have been described. In Table 4-5 a comparison matrix can be found, showing how each surrogate model performs for each of the requirements. Again, a green check mark indicates that the requirement is satisfied, while a red cross indicates the opposite.

Table 4-5: Comparison matrix of selected surrogate models.

	Polynomial regression	*RBFs*	*Kriging*	*SVNs*
Captures non-linear behaviour	✗	✓	✓	✓
Applicable to the problem	✓	✓	✓	✓
Sufficiently fast	✓	✓	✓	✓
Provide an uncertainty estimate	✗	✗	✓	✗
Proven predictive performance	✓	✓	✓	✓

Below it is explained which findings were used to establish these results.

From the description of the surrogate models it follows that polynomial regression is probably the most efficient model considering computational time, which would come at the cost of accuracy compared to the other models. The model is not good in capturing non-linear behaviour. RBFs, SVNs and kriging have the possibility of selecting a kernel function which makes them more flexible, thus improving the fit with the true function that should be modelled. For the sake of accuracy polynomial regression is not selected for application in this thesis.

It is said that RBFs, SVNs and kriging are very similar to each other, such that they are sometimes interchangeable. However, there are some differences. Kriging is more flexible as there are more tuning parameters. Additionally, kriging provides an uncertainty estimate of the prediction. Kriging and SVNs both have the possibility to let the prediction not intersect with the observations, which can prevent overfitting such that the prediction function is closer to the true function. Hence, considering these features kriging and SVNs are preferred over RBFs.

The outcome of the different case studies is used as a decisive tool. For polynomials some support was found [31], [64], but only one was for predicting propulsion power and the other was for predicting structural stresses. The same is valid for RBFs, for which only one research is similar to the problem in this thesis [29], [31]. SVNs provide an accurate predictor as well, but this is also only supported by one similar research [29]. Kriging is the most popular surrogate model, as multiple researches point out that it provides the most accurate predictor [29], [30], [40]–[42], [59], [63]–[65].

Concluding, most of the research shows that kriging provides the most accurate predictions. Some research is very similar to the problem that is encountered in this thesis: a prediction of ship resistance of a new geometry should be obtained by using a surrogate model which is trained by the outcomes of expensive CFD simulations. Especially the research of Rotteveel [29], Guerrero et al. [30] and MARIN [40]–[42], [64] show similarities and prove that kriging is a very suitable surrogate model for this problem. Additionally, it is well-suited for complex, non-linear functions, which also the nature of the wave-making component of the resistance. Kriging also has a major distinctive advantage that it provides an uncertainty estimate, and that it allows to not intersect the observations. For those reasons kriging is selected as a surrogate model in this thesis.

A more detailed description of how kriging is applied in practice in this thesis to provide a resistance prediction for new hull shapes is given in Chapter 5.

4.3 High-level description of the model

Suitable techniques have been chosen to perform the two most important functions of the tool: to obtain new hull shapes and to provide a resistance prediction for these shapes. Subsequently, these techniques have to be implemented in the current design process. This paragraph focuses on describing this integration, i.e. a high-level description of the model that performs the functions. The description can be used as a blueprint of the solution for the rest of this thesis, and for integrating these solutions in suitable software packages.

It is first described how the tool will be integrated in the design process in Section 4.3.1. Thereafter the idea of creating a database with hull shapes is introduced in Section 4.3.2. Last, a more detailed description of the working principle of the tool is given in Section 4.3.3.

4.3.1 Integration of the tool in the design process

In Chapter 2 the current concept design process has been described. By integrating the techniques some of these steps will be changed. The steps of the current design process can be found in Table E-1 in Appendix E. By integrating the tool in the design process, effectively step 7 and 12 of this table can be (partly) done with the tool. An overview of the design process in which the design tool is integrated can be seen in Figure 4-3.

Note that the design tool already provides a resistance prediction while it is not directly used. It is only used after it is sure that the detailed GA fits in the hull shape to obtain a power-speed curve (step 12). The main advantage of this order is that a hull shape can be selected (or not) on its resistance performance. To employ the feature of selecting a hull shape based on its performance even more, a database of hulls with resistance predictions can be set up. This is discussed next.

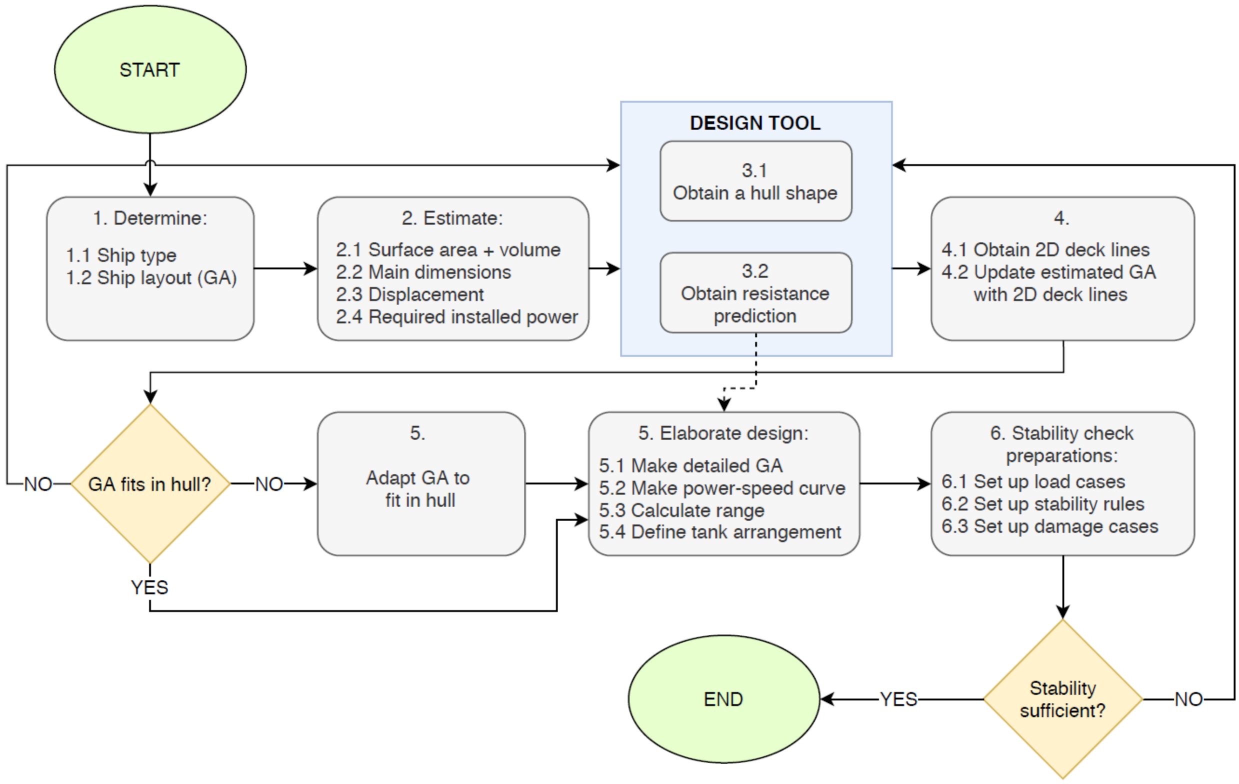

Figure 4-3: Placement of the design tool in the design process.

4.3.2 Introducing the generation of a database

The design tool as placed in Figure 4-3 can be set-up in roughly two ways such that the requirements from Chapter 3 are satisfied. The hull shape and resistance prediction can be constructed and computed on request (i.e. a posteriori), or this can be done a-priori by predefining all possible designs. Doing it on request is advantageous as unnecessary work is prevented (one does not need all possible hull shapes). Most often it is also not feasible to construct all possible hulls and provide them with resistance predictions, as the number of possible hulls can quickly become impracticably large.

For example, if a hull shape is parameterized with 6 parameters, each with 100 possible values, there are 100^6 possible hulls. Assuming a computation time of $1/10^{th}$ of a second for each hull, this would take 10^{11} seconds i.e. approximately 3711 years.

On the other hand, a database or brute-force approach is possible at Damen, because the problem of finding suitable hull dimensions is considered to be a discrete instead of a continuous problem for practical reasons. For example, the frame spacing often determines in which steps the beam of a hull shape is varied. Constraints can be applied (e.g. maximum L/B-ratio) to remove 'unbalanced' or infeasible designs. This also reduces the total number of possible designs and thus also computation time.

Additionally, there are several other reasons to generate a database (also referred to as a library [1]) instead of computation on request:

- One can also compute the performance space of all hulls. This can be used by the designer as extra information in its search for a suitable, balanced hull shape. It can also be used such that hulls are searched for based on their performance instead of definition (e.g. dimensions). This is known as a reverse engineering approach.
- Dependent on the computation time, a search algorithm is expected to be faster than an algorithm that constructs hull geometry and computes a resistance prediction.

- The designer is not fixed to one design, but can keep multiple options open in the first design stages. Additionally, if later in the design process it becomes clear that a selected hull is not feasible (e.g. GA doesn't fit or stability is not sufficient) similar alternatives are already available which can easily be selected.
- Compared to deterministic optimisation and stochastic optimisation, a simple brute-force approach could require least 'operations' to evaluate the same amount of alternatives [1]. Effectively, it would require less time for a designer to compare different alternatives with a database approach. It should be noted that the time for setting up the database is not taken into account.
- A brute-force approach could evaluate more solutions than an optimisation approach [1]. Again, the time for setting up the database is not taken into account.
- A database is well-suited for adding new information or adding modules that provide more information about the hulls in the database.
- A database allows upfront generation of practical design aspects like hull space previews, which would normally take more time if they have to be generated on request.

To the author's knowledge a brute-force approach has not been applied frequently in ship design, especially to accelerate the concept design phase. Several academic research focused on employing objective functions to steer search algorithms, in order to find those solutions that satisfy the objective functions the most. Examples are the TU Delft Packing Approach by Van Oers [18] and UCL Building Block Approach [19], which employ these search algorithms to quickly generate a design space of system-layouts for naval ships. Optimisation algorithms are used by Duchateau [17]. These, but also other examples, are distinctive from conventional approaches as they provide the designer with tools to rapidly explore the design space in the concept design phase. However, they require the designer to a-priori define the objectives to be used.

A brute-force approach is in contrast with these tools, as it doesn't require a-priori definition of objectives. It doesn't focus on a steered search algorithm, but on using a a-priori filled database to search for feasible designs within the design process. Hence, actual computing designs or calculating performance is already done, which is not the case for the examples given above.

Library-based approaches have been the subject of several researches, mostly focusing on providing an appropriate hull form style early in the ship design process [1], [66]. The intention there was to provide the designer with a tool to explore different alternative hull forms and styles. More recently this approach has been applied for a concept design study of a corvette [67], and was used to find hulls that fall within user-defined limits for weight and space of a reference library of 5832 mono-hulls. Next, the results were used to understand general trends and statistics within that search space. The sensitivity of the design to changes in input could also be found, just as uncertainty. Hence, for both applications the library of hull shapes was mainly focused on providing a platform for exploration of possible hull shapes. Nevertheless, it was acknowledged that such a library allows a designer to quickly search through the defined design space, thus possibly also increasing the speed of the design process. It can in theory also be used to search for appropriate hull shapes for only one hull form style.

Effectively, the hypothesis is that a database approach can contribute to satisfying the needs from Chapter 2 and requirements from Chapter 3. Especially the feature that the performance space can be computed on beforehand is beneficial, as this explicitly provides the designer information that gives insight about how the input influences the resistance of the hull shape (see also Section 3.1.2). Additional insight can be gained as a larger design space can be explored in a shorter time, and innovative designs can be pursued. By automating the filling of the database and doing it on beforehand, all stored hulls are readily available, thereby increasing the speed of the design process.

The brute-force approach is therefore preferred over other approaches, and is adopted in this thesis as model behind the tool. The design tool will effectively facilitate a search algorithm that looks for a hull within that database that meets the input requirements. Next, a high-level description of the tool that uses such a database is given.

4.3.3 Interaction between the tool and the database

The question now is how the tool should function such that it fits in the design process as described in Figure 4-3, and such that the brute-force approach is adopted. This question is for a large part already answered in Chapter 3 and this chapter. The tool will in fact be a graphical user interface (GUI) which will focus on obtaining data from a pre-computed database with hull shapes. A schematic overview of this procedure is given in Figure 4-4.

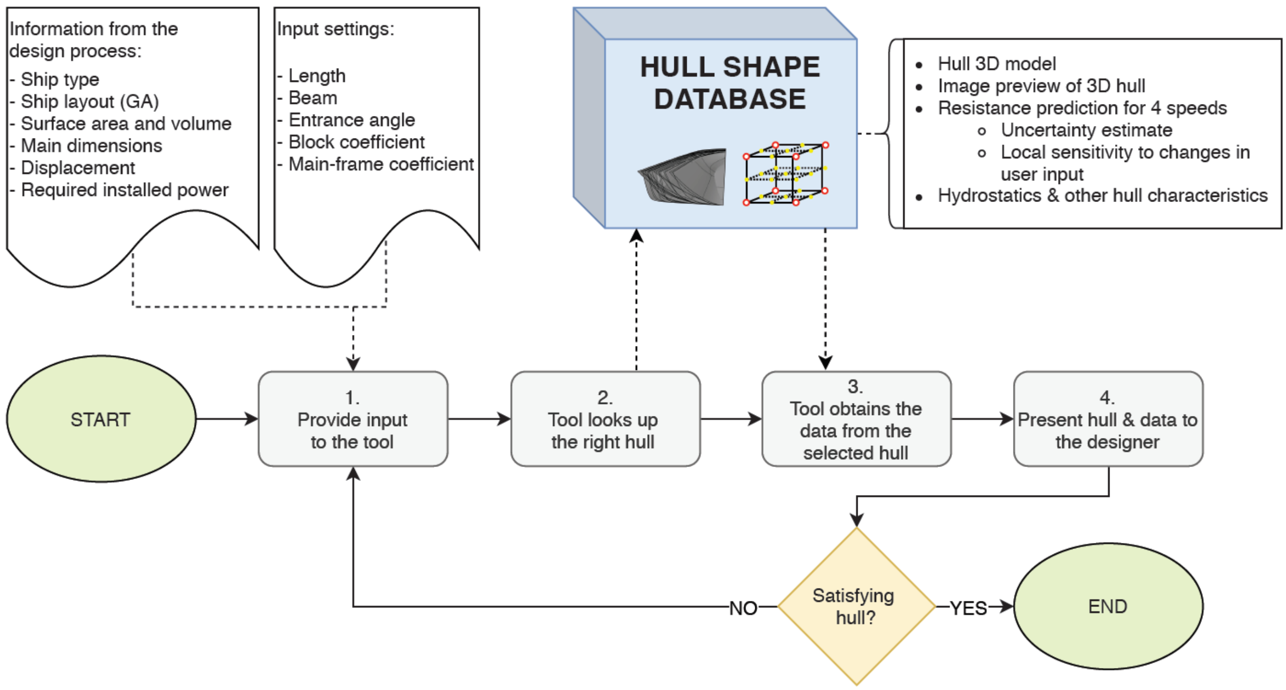

Figure 4-4: Overview of the tool working procedure.

The GUI will thus be the platform in which the designer can select the input settings, which have been defined as the length, beam, entrance angle, block coefficient and main-frame coefficient (Table 3-2). Based on this input the tool will select a hull shape from the database, and present the output to the user. Output consists of a 3D hull shape, a resistance prediction, hydrostatics and other hull characteristics. All specific hydrostatics and characteristics have been given in Section 3.1.3. Additional desired output are local sensitivity of the resistance to changes in the input parameters and estimations of the accuracy of the results.

Effectively, all abovementioned results will have to be precomputed for all possible hull shapes. Morphing is used to construct geometry for all defined hull shapes in the database, and subsequently kriging is used to do a resistance prediction for the hull shapes. A more detailed and specific description of how this will be done is presented in Chapter 5.

4.4 Conclusion

This chapter has described the development of the core elements of the tool. Hereby, it is the goal to answer the third and fourth sub-questions.

> *Which alternative hull generation method is the most promising to support the design approach in order to satisfy the need to acquire a hull shape much faster?*
>
> *Which surrogate model is the most promising to predict the resistance of a new hull shape based on CFD results of parent hull shapes?*

The first core element is the modification of parent hulls to obtain new hull shapes. After learning the different representation techniques and file formats, five promising groups of partial parametric modelling techniques have been described. Based on pre-defined requirements, it was shown that morphing is the preferred hull deformation technique for application in this thesis. It can be seamlessly connected to the CFD dataset, could also be used for local deformations and allows for extrapolation of hull shapes. Hence, morphing is used as hull deformation technique in this thesis, such that the third sub-question is answered.

The second core element is the prediction of the resistance of a new hull shape by using a surrogate model. Four promising surrogate models have been described, and relevant case studies of those models have been analysed. Again, a qualitative comparison was conducted based on pre-defined requirements in order to select the most appropriate surrogate model. Kriging is preferred for three reasons: (1) it is suitable for complex, non-linear functions, (2) it provides an uncertainty estimate and (3) case studies show that it is the most accurate predictor for similar problems (predicting the resistance or power of hull shapes). Hence, kriging is selected as a surrogate model in order to predict the resistance of newly created hull shapes in this thesis. The fourth sub-question is hereby also answered.

Last, focus is given to a high-level description of the tool. The place in the design process was first elaborated upon. A brute-force approach is adopted, such that a pre-defined number of hull shapes will be generated and evaluated, and made available to the designer. The main reasons for adopting this approach are that it allows for computation of the performance space and it is expected to be faster than a computation-on-request approach. Another advantage is that the designer will not be fixed to one design, but can keep multiple options open in the concept design phase. This increases design freedom and allows the designer to quickly select a similar hull shape if the current hull shape is not feasible.

The conceptual design tool will be used to obtain hull shape data from that database and present it to the user. The hypothesis is that this approach will contribute to satisfying the needs as defined in Chapter 2: to increase the speed of the design process, provide more insight and to have a more integral design approach. Hull shapes in the database will be constructed with morphing and a resistance prediction will be computed with kriging.

Summarizing, it is now known why certain choices for hull deformation and surrogate modelling techniques have been made. It is also known how the selected techniques (morphing and kriging) roughly work. That information will be used in Chapter 5 to describe how these techniques will be applied to this thesis and present the exact procedure to populate the design space in the database. The high-level description will be used as a blueprint to provide more detailed, low-level descriptions in that chapter.

5

Populating the Database

This chapter focuses on describing how the database will be populated. Chapter 4 provided techniques to obtain new hull shapes (morphing) and to get a resistance prediction for that new hull shape (kriging). The idea that the design tool will load hull shapes from a pre-generated database was introduced as well. The goal of this chapter is to define in detail how morphing and kriging are applied in practice such that the database will be populated.

A high-level approach of the filling process is described in Paragraph 5.1. The activities needed to do so are elaborated upon in the subsequent paragraphs. First, a low-level approach of generating new geometry by morphing is given in Paragraph 5.2. Paragraph 5.3 then provides descriptions of how the resulting geometry is analysed, in order to obtain the necessary hydrostatics and characteristics which are needed for the resistance regression. Predicting the resistance by kriging is described in Paragraph 5.4, in which Section 5.4.4 describes the selection of a kriging model that provides the most accurate predictor. Last, Paragraph 5.5 focuses on working out the last details before the database can be populated, which mainly concerns the definition of all hulls that will be in the database.

The lessons-learned and knowledge of the practical applications of morphing, the analysis of hull geometry and kriging will be used to set up corresponding Python scripts. The ultimate goal is to hereby create a Python environment in which the solution from this thesis can be tested. The resulting database will be discussed in Chapter 6. Testing of the results is done in Chapter 7.

5.1 Approach to populate the database

The goal of this paragraph is to describe the approach that is needed to fill the database. To do so, the desired contents of the database are first repeated below. Next, it is described in Section 5.1.1 which preparations are needed to provide this content for each hull shape. Last, a high-level overview of the procedure to fill the database is given in Section 5.1.2.

To be effective as a design tool as defined in Paragraph 4.3 and to be in line with the requirements from Paragraph 3.3, the database should contain the following for each hull shape.

- A 3D model of the hull shape,
- A resistance prediction for 4 speeds, including an uncertainty estimate and local sensitivity to changes in user input,

- Hydrostatics & other characteristics of the hull shape,
- Image previews of the hull shape.

These results will be generated by choosing one hull definition at a time, and computing each of them separately. The 3D model of the hull shape will be computed by executing the morphing procedure. Paragraph 5.2 provides a low-level description of this procedure. Thereafter, the hull shape can be evaluated to obtain its hydrostatics and other characteristics, which is described in Paragraph 5.3. The resistance prediction, including the computation of the uncertainty estimate and local sensitivity, will be computed by executing the kriging procedure and additional activities. This is elaborated on in Paragraph 5.4.

To generate all these results input is needed. Input is already available in the form of the CFD dataset, containing 25 parent hulls, characteristics of all these hulls and resistance results of all these hulls. In order to be able to use this input, some additional input is needed in the form of definitions of all hull shapes that will be included in the database. By adopting systematic variation, one only needs to define a step size for each parameter that is varied. These preparations are described in the next section.

5.1.1 Preparations to start the filling process

Defining the parent hulls, create DoE and run CFD

For this thesis the base and extreme hull shapes have already been provided by Damen, and the set-up was already presented in Paragraph 3.2. However, setting up these hulls would normally take a lot of time, probably most of the time for preparations. This is the main disadvantage of the adopted approach: preparations would take a considerable amount of time. Considering time, this thesis focuses on gaining time in the ship design process, making the preparations well worth. Key in this thesis is to pre-compute time-intensive design aspects such that the most critical activities are done before starting the design process.

Choosing a step size

For the CFD dataset the hull shape was parametrized with 5 parameters: length, beam, entrance angle at the waterline, block coefficient and main-frame coefficient. On beforehand a step size needs to be determined for every parameter, such that all hulls in the design space are defined. As mentioned in Section 4.3.2, Damen views the problem of selecting suitable parameters in the ship design as a discrete problem. For each parameter there is, thus, a discrete step size available.

A full-factorial approach will be used in this thesis to populate the database. As mentioned earlier, this has the downside of possibly having an impracticably large computation time. To cope with this issue the following approach is used to find an appropriate step size for each parameter.

- A first step size grid will be chosen that accurately represents the design problem of DEFs.
- It will then be checked if it feasible to use this grid in combination with the scripts that have been made and the computational power that is available.
- If it is feasible the design space will be generated.
- If this is not the case a more coarse grid will be chosen: this would also be sufficient to prove that the design tool is an effective measure to increase insight, be an integral platform and increase the speed of the design process.

Later, if the proof-of-concept is successful in reaching its goal, more powerful computation resources can be exploited to populate the database with the desired step size grid.

These activities are done after integration of the core elements in the computer software. It is described in Paragraph 5.5 which step size grid is desired, what its computational consequences are and which grid eventually is chosen.

From absolute values to the morphing parameter

The morphing procedure does not take the absolute value from a parameter as input, but takes the morphing parameter as input for each parameter. Repeating from Section 4.1.2: the morphing parameter can take any value between -1 and 1 such that 0 is the base hull and 1 is the extreme hull for that parameter. Hence, all hull parameters should be transformed to the morphing parameter space. This can be done by using Eq. (5-9).

$$par_i = \frac{p_{hull} - p_{base}}{p_{extreme} - p_{base}} \tag{5-9}$$

In this formula the morphing parameter is represented by par_i. The value of the parameter that needs to be transformed to the morphing parameter space is p_{hull}. The values of the parameter of the base hull and extreme hull corresponding to the parameter are represented by p_{base} and $p_{extreme}$ respectively, and are presented in Table F-1 in Appendix F.

For one hull shape there will be one morphing parameter for each parameter which is used for systematic variation (i.e. $i = \{L, B, \alpha, C_B, C_M\}$). If for example $par_L = 0.5$, the new hull shape will be a linear combination of half of the base hull and half of the extreme hull for the length. The length of the new hull shape will then be equal to the average of the base hull and the extreme hull for the length.

For the sake of overview one datasheet with all five morphing parameters for every hull will be set up, which will function as input for the filling process.

Note: As mentioned in Section 3.2.3, the parameters used for the parametrization of the hulls in the CFD dataset cannot all be varied independently. This can be seen as a mistake by Damen in defining the extreme hulls. This issue makes it very hard, if not impossible, to define the resulting hulls in the database on beforehand when multiple parameters are varied at the same time. Application of Eq. (5-9) is consequently not possible. For future applications it is therefore recommended to parametrize the base hull only with parameters which describe the dimensions of the hull directly in 1D or 2D.

Since the corresponding parameters used for hull parameterization of OPVs can be varied individually, Eq. (5-9) can be applied to the dataset of OPVs. Thus, defining all hull definitions of OPVs on beforehand is possible.

Nevertheless, varying all parameters in this thesis is still possible by only defining a grid for the morphing parameter. Multiple morphing parameters can also be varied at the same time, which is interesting for the sake of analysis. In potential this could result in hulls with a reduced resistance. Therefore, a grid of morphing parameters will be defined, instead of a grid of hull parameters. This is described in Section 5.5.2.

5.1.2 High-level description of the filling process

Effectively, if all input is known and the preparations are finished, the database can be filled. A logical approach to do so can be seen in Figure 5-1.

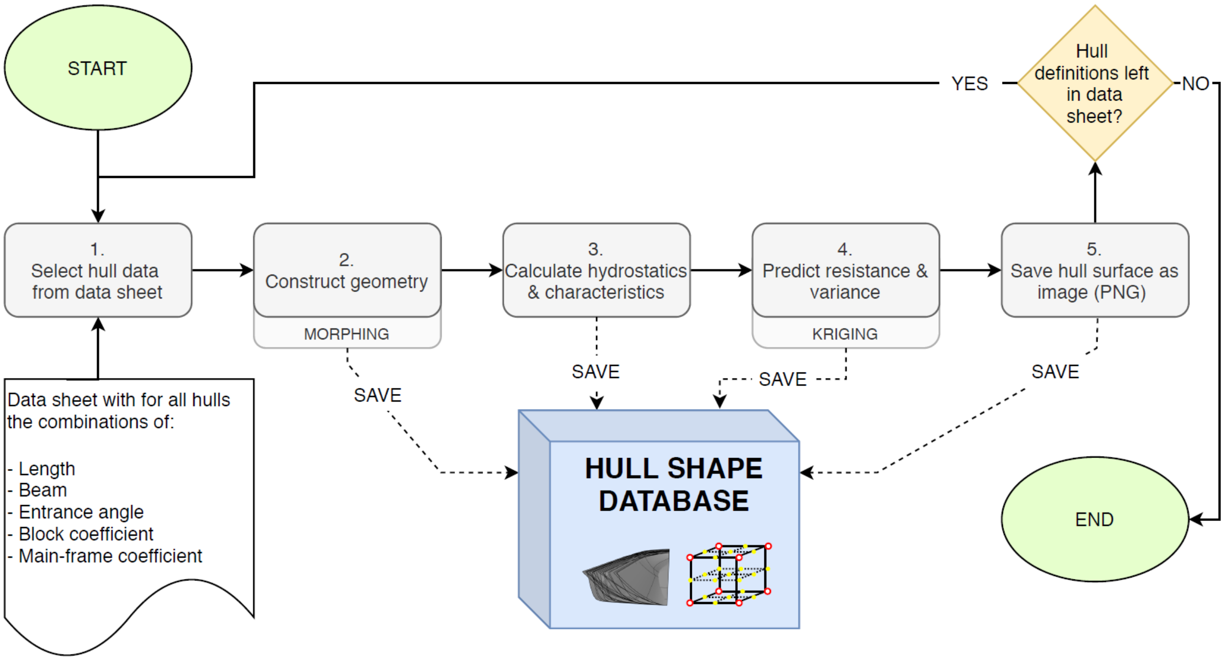

Figure 5-1: Approach to fill the database.

The process starts with constructing the hull geometry. Once this geometry is obtained it can be analysed such the hydrostatics and other characteristics can be obtained. By first doing this one also gets the right input for the prediction of the resistance. During obtaining the resistance prediction and its variance, the sensitivity to changes in the resistance results can be obtained as well. Last, an image is generated of the hull shape and saved in the database. All these activities will be described in the forthcoming paragraphs.

5.2 Constructing the hull shape: morphing

The first major step in the filling process is to create new geometry by morphing. This paragraph focuses how the theory of morphing is applied in this thesis to obtain new hull shapes. That information will later be used to set up Python scripts that perform morphing. Information about input and output is used to develop software architecture, which is described in Paragraph 5.5.

The whole morphing procedure can be divided in three global phases: pre-processing, the actual morphing and post-processing. A schematic representation can be seen in Figure 5-2. The next sections will consecutively describe these three phases in detail.

5.2.1 Pre-processing

Pre-processing focuses on preparations such that the actual morphing can be executed. The set of parent hulls of the CFD dataset consists of one base hull and five extreme hulls (one for each parameter). In Section 4.1.2 on page 41 the format of these parent hull has been described. Effectively, each hull shape is represented by only one quarter of the hull shape, for which 30 control points of one NURBS surface have been defined. The format of each parent hull is identical. Additionally, the 30 control points can be grouped in 6 rows of control points, as can be seen in Figure 5-3. This fact can be used for evaluating new hull shape to obtain hydrostatics and other characteristics, which is described in Paragraph 5.3.

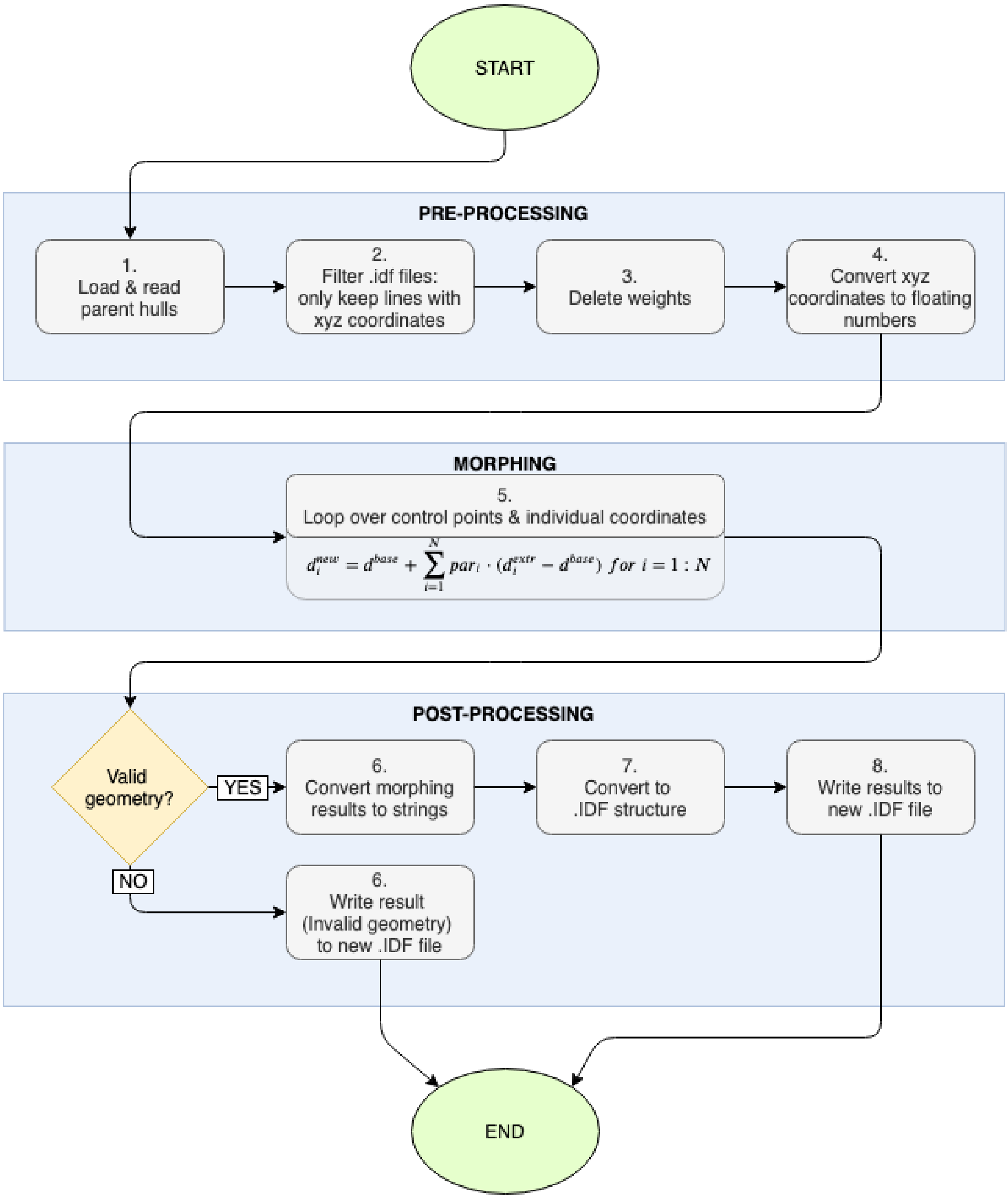

Figure 5-2: Low-level overview of the morphing procedure.

The only difference between the different hull shapes are the numerical values of the control points. Hence, these numerical values are the information that is needed to define a hull shape. Adapting them will lead to a new hull shape definition.

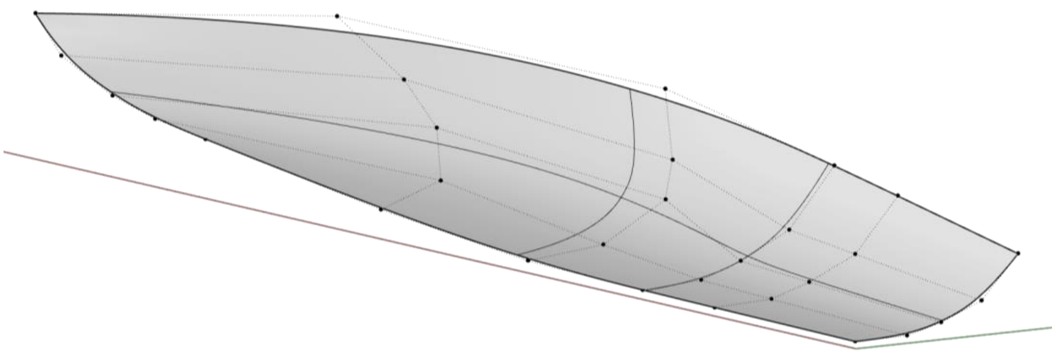

Figure 5-3: One quarter of the base hull with control points visible.

In order to obtain the numerical values of the control points the .IDF file in which the geometry of the parent hull is saved will be used. More information about this file format can be found in [68], [69]. The advantages of this format are that it is very well-interpretable for humans and that it is a neutral file-format. Consequently, the control points can easily be read and used, and the format can be opened in various computer applications (not only CAD applications).

Next, the information has to prepared for morphing. This focuses on creating a list of numerical values (floating numbers) of the coordinates of the control points, without any superfluous information. The necessary steps can be found in the pre-processing box in Figure 5-2 and will not elaborated any further.

Hence, the right information to be used are the numerical values of the control points, and these are found in the .IDF files in which the parent hulls are saved. By changing those values a new hull shape is obtained. How this is done with morphing is described next.

5.2.2 Constructing new hull geometry by changing the control points

This section describes how the control points of the parent will be used together with the morphing parameters to obtain a new list of control points. This new list represents the new hull geometry. Morphing is applied to execute this transformation.

The theory of morphing is now transformed to the specific case of this thesis. Morphing will create a linear combination of the six parent hull shapes. It is done by applying Eq. (4-1) to the coordinates of the control points, which for clarity is repeated below in Eq. (5-10).

$$d_i^{new} = d^{base} + \sum_{i=1}^{N} par_i \cdot (d_i^{extr} - d^{base}) \quad \text{for } i = 1{:}\,N \tag{5-10}$$

The variable d^{base} represents one specific x-, y- or z-coordinate of one of the 30 control points of the base hull. Similarly, d_i^{extr} represents one specific x-, y- or z-coordinate of one of the 30 control points of the extreme hull of parameter i (either length, beam, entrance angle, block coefficient or main-frame coefficient). Hence, d_i^{new} will represent one specific x-, y- or z-coordinate of one of the 30 control points. A schematic representation of how Eq. (5-10) would be applied in this thesis to obtain one coordinate of a new hull shape (d^{new}) can be seen in Figure 5-4.

Going through this procedure once results in one new coordinate. So, to obtain a new control point this procedure is done three times: for the x-, y- and z-coordinate. To obtain a new hull shape, i.e. 30 control points, the procedure is consequently done 90 times. This shows that it is advantageous that the hull shape can be represented by only a quarter of the hull shape in this case, as this saves on computation time. For OPVs and most other ship types half of the hull shape is needed for representation, such that it would (at least) double the computation time.

In practice, morphing can be executed in Python by elementwise operations on the matrices that define the coordinate points of the parent hulls (all 30×3) and the vector that defines the morphing parameters (size 5). The resulting geometry will also be defined by a matrix with shape 30×3.

To demonstrate the working principle and increase understanding, a practical example of morphing is included in Appendix J.1.

Next, the list of new control points will be post-processed.

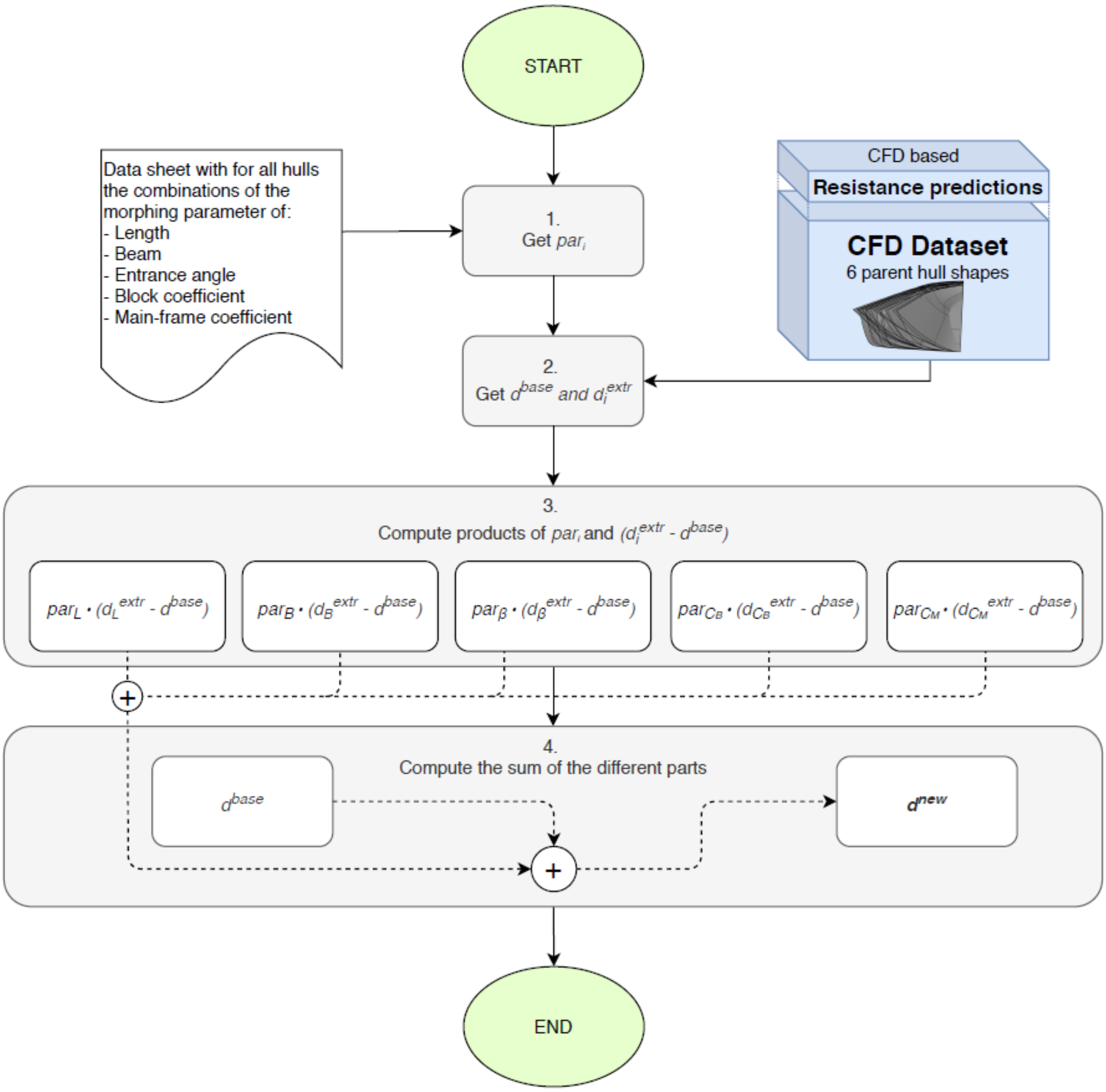

Figure 5-4: Procedure to obtain a new control point coordinate by morphing.

5.2.3 Post-processing

The first step of post-processing is to check if the geometry is valid. To do so the following five conditions have to be met.

- The L_{oa}/B_{oa}-ratio should not be less than 3.5 and should not exceed 7.2.
- The x-coordinates may not exceed the midship, i.e. be negative.
- The y-coordinates may not exceed the centreline, i.e. be negative.
- The order of the 6 rows of control points should remain the same.
- There should not be a protruding bow.
- There should not be a protruding side.

These conditions can be checked by analysing the coordinates of the control points. By definition of the NURBS surface, the surface itself is connected to the control points at the locations where the length and beam are maximum (see also Figure 5-3). That information can be used to calculate the length and beam of the total hull surface.

The protruding bow is verified by finding the x-coordinates of the bow, and checking if there are x-coordinates which are larger than x-coordinates of the bow. If that is the case then the geometry is invalid. In the same way it is checked if the side is protruding. The row order of the control points is checked by verifying if the minimum x-coordinate of each row is smaller than the minimum x-coordinate of the next row. The geometry is invalid if that is not true.

Due to the advantages of the .IDF file format, it is also very easy to write to an .IDF file. Therefore, the new hull geometry will also be saved in an .IDF file. This is only done if the geometry is valid. In order to do so, the list of control points is transformed into the appropriate format and saved. The necessary steps can be found in the post-processing box in Figure 5-2 and will not elaborated any further. If the geometry is invalid, nothing will be saved.

5.2.4 Summary

It is now known how the morphing procedure works, and which pre- and post-processing activities are required to do so. The total procedure as presented in the beginning of this paragraph describes all these activities, and can therefore be used as blueprint while integrating the procedure in Python. Results of the integration in Python will be presented in Chapter 6. Validation & verification of the tool which are related to morphing will be discussed in Chapter 7.

In the next paragraph it is discussed how a new hull shape is evaluated. This is an indispensable step to obtain the non-dimensional parameters for regression of the resistance, which will be described in Paragraph 5.4.

5.3 Evaluation of the hull shape

The goal of this paragraph is to provide a brief overview of how the 3D geometry obtained with morphing is analysed to obtain the desired characteristics. Obtaining these characteristics serves two purposes. The first is to compute the non-dimensional parameters which are the input for the resistance prediction. The second is to compute the hydrostatics and other characteristics which will provide insight to the designer.

An open-source Python toolbox has been used to generate surface points of the hull surface. This toolbox is described first in 5.3.1, followed by a high-level description of the procedure to calculate all hydrostatics and characteristics in 5.3.2.

5.3.1 Obtaining surface points of the hull shape

Based on the control points it is not possible to calculate geometrical properties of the hull shape. Surface points which actually describe the hull surface are needed to do so. For obtaining these points an open-source Python toolbox has been used. The NURBS-Python toolbox is a Python library capable of generating B-Spline and NURBS curves and surfaces, and provides multiple options for evaluating these instances, enables importing and exporting and includes a visualization interface. For this thesis this is advantageous as focus can be put on the design tool itself, rather than on developing an accurate NURBS generator in Python. The toolbox is developed within the academical environment of the Iowa State University (USA) and has been well-tested and peer-reviewed [70].

Effectively, the NURBS-Python toolbox is used for the following purposes.

- Generation of a NURBS surface of the hull shape, based on the control points obtained by morphing
- Generation of surface points of the hull shape
- Exporting of the hull shape as a NURBS surface in file formats that can be imported into software used within Damen (i.e. Rhinoceros)

These activities are also performed in that order. The toolbox includes a class which can evaluate that surface such that a list of points on that surface are obtained. Depending on the size and shape of the NURBS surface the size of that list ranges from 330 to 390 surface points. For hulls with high curvature more points are included to better represent that curvature.

This is illustrated for a hull that was used in a practical example of morphing (see Appendix J.1). A hull was desired with half of the extreme length and half of the extreme main-frame coefficient. The control points of that hull could be seen in Figure 5-5, and the resulting surface points can be seen in Figure 5-6. There are 21 rows of surface points, which can be considered as frames.

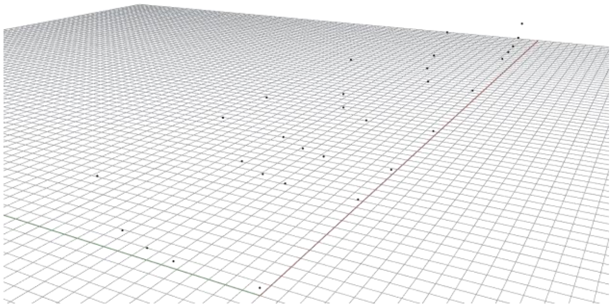

Figure 5-5: Example of control points for a new hull shape.

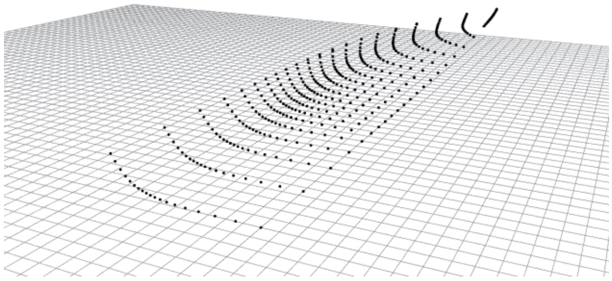

Figure 5-6: Example of evaluated surface points for a new hull shape.

These points are points on the actual hull surface and can thus be used for calculation of hull hydrostatics and other characteristics. It is described next which procedure is followed to perform these calculations.

5.3.2 High-level description of calculations

For generating the necessary geometrical properties an adaption to the surface points of the total hull is needed. Most of the hydrostatics and characteristics are based on the underwater part of the hull, while the current surface points define the total hull shape (i.e. also the part above the waterline). Therefore, adapted surface points are computed which only define the underwater body of the hull shape. The surface points of the whole hull are only used to calculate the length and beam overall (L_{OA} and B_{OA}).

The procedure in Figure 5-7 is then followed to calculate all hydrostatics and characteristics. A detailed explanation of how the underwater body surface points are obtained and calculation of all parameters can be found in Appendix J.2. They can be seen as low-level descriptions of all calculations.

Note: as described in Appendix J.2.9, an empirical formula has been used to estimate the wetted surface area of the hulls. It is recommended this approximation is replaced by an exact calculation. This can be done by calculating the arc length of each frame and integrating all arc lengths over the length of the hull.

After going through this procedure enough information is gathered to predict the resistance. This last activity is described next.

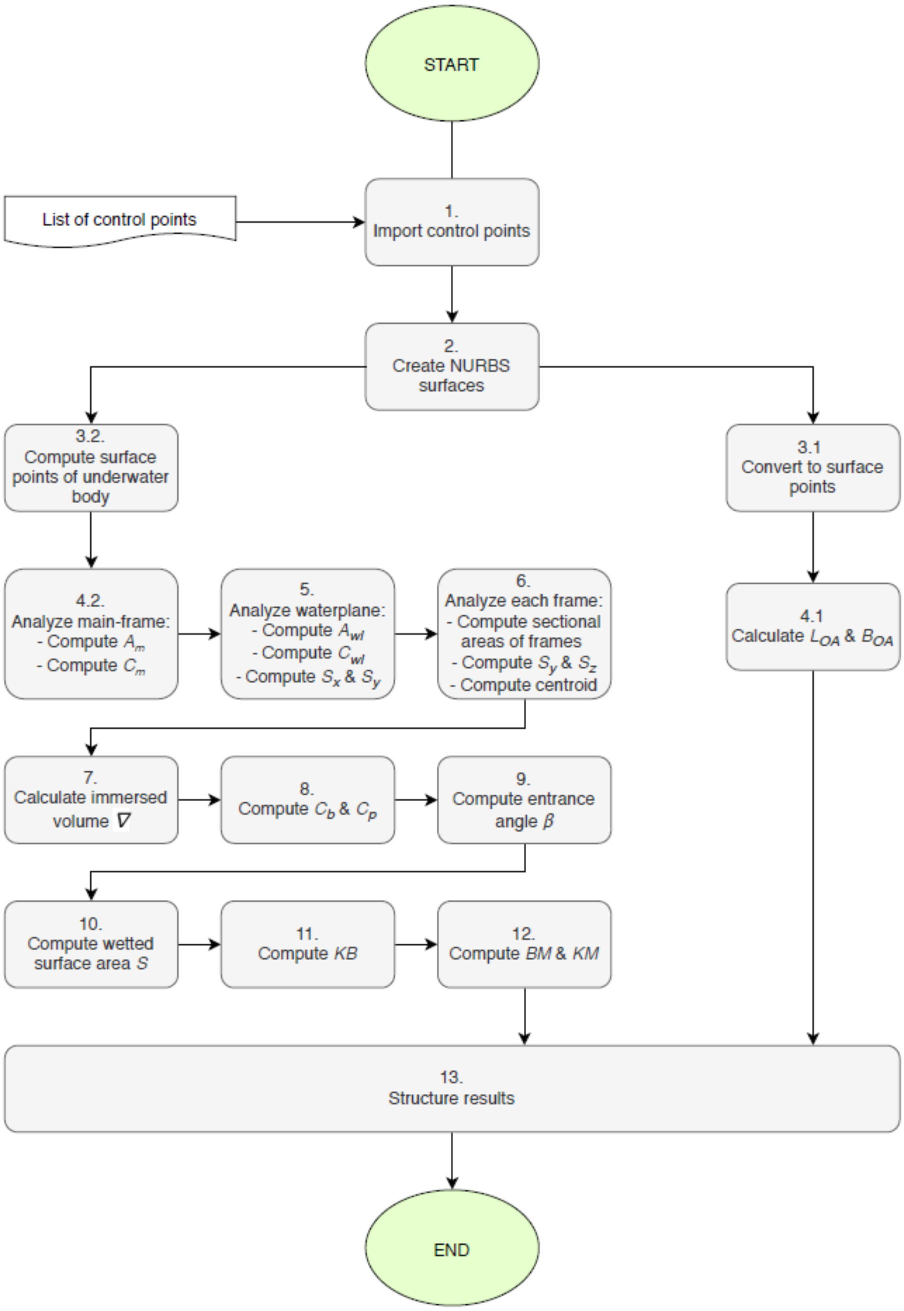

Figure 5-7: Procedure to calculate hydrostatics and other characteristics.

5.4 Estimating the resistance: kriging

In Paragraph 4.2 it has been described that the kriging surrogate model is chosen to predict the resistance of hull shapes, as (1) it is suitable for complex, non-linear functions, (2) it provides an uncertainty estimate and (3) case studies show that it is the most accurate predictor for similar problems. This paragraph describes how the theory of kriging is applied in this thesis to provide a resistance prediction of new hull shapes. That information will be used to set-up scripts in Python in which the solution can be tested.

In order to obtain a resistance prediction the procedure in Figure 5-8 is gone through. This should be done for four speeds separately: each of the speeds for which CFD was done. Again, the procedure can be divided into three steps: pre-processing, kriging and post-processing. The following sections (5.4.1, 5.4.2 and 5.4.3) will address them consecutively. Section 5.4.4 will focus on selection of a specific kriging model that is most suitable for this thesis.

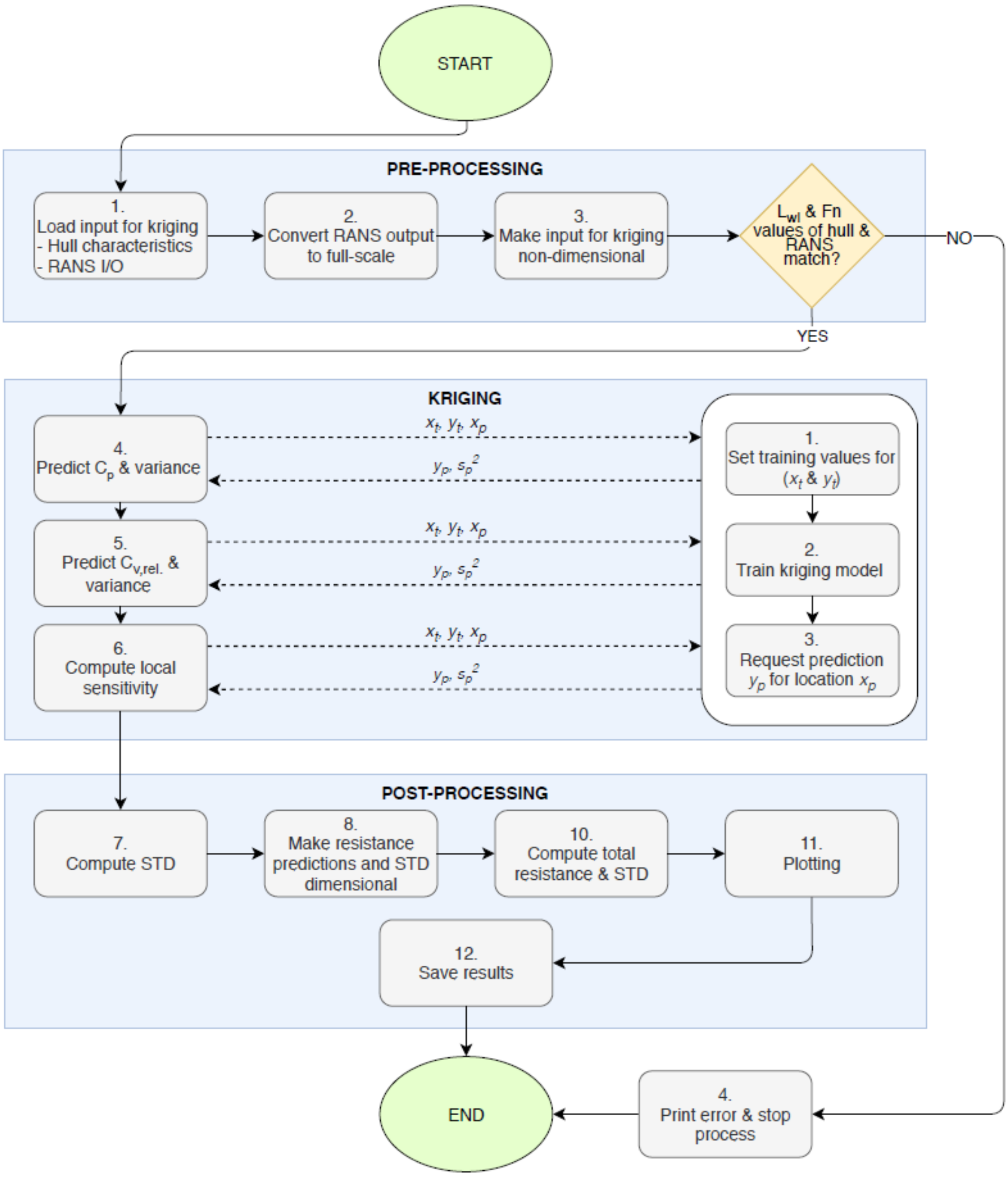

Figure 5-8: Low-level overview of the kriging procedure.

5.4.1 Pre-processing

Available input

The first step of pre-processing is to load the necessary input from the CFD dataset, and from the newly obtained hull geometry. As defined in Section 4.2.1, there are three sets of input.

From the CFD dataset the training data (indicated by a subscript t) is obtained. It consists of the resistance results (the observations y_t) and the non-dimensional parameters (the locations of these observations x_t). The non-dimensional parameters x_t are defined by the characteristics of the hulls in the CFD dataset, which can be found in Table F-3 in Appendix F.2. They are repeated below. Effectively, the shape of x_t is 25×6 since there are 25 hull shapes in the CFD dataset.

- L/B-ratio
- B/T-ratio
- Slenderness ratio
- Block coefficient
- Prismatic coefficient
- Entrance angle

From the newly created hull shape a set of characteristics is obtained by analysis, as described in the previous paragraph. These characteristics are used to computed the non-dimensional parameters for the new hull shape, such that the location for which a new prediction is desired (x_p) is obtained as well. The shape of x_p is 1×6.

The resistance results from the CFD dataset have been obtained for the viscous and pressure components separately. For obtaining a prediction of the total ship resistance these two components will be addressed separately as well, as it is expected that this increases the accuracy of the regression. Additionally, it can provide insight in how the total resistance can be influenced, as different hull parameters will have a different influence on these resistance components. For example, the wetted surface is highly correlated to the viscous resistance, but not to the pressure resistance. The slenderness ratio maintains a strong relationship with the pressure resistance [37]. Effectively, there are thus two sets of data for observations: the viscous (indicated with a second subscript v) and pressure resistance (indicated with a second subscript p). They are available for each hull for the four speeds for which CFD was done. Effectively, the shape of each of the sets is 25×4. All resistance results of the CFD dataset can be found in Appendix F.3. For doing the actual regression the resistance results are made non-dimensional as well by using resistance coefficients, which is described next.

Making the resistance input dimensionless

The total, pressure and viscous resistance are indicated by R_T, R_p and R_v respectively. Both resistance components are made non-dimensional with Eq. (5-11), in which ρ represents water density in $\frac{kg}{m^3}$, S the wetted surface in m^2 and v the ship speed in $\frac{m}{s}$. However, for regression of the viscous resistance coefficient, it is divided by the ITTC-1957 friction line ($C_{F,ITTC}$ in Eq. (5-12)), providing the relative viscous resistance coefficient in Eq. (5-13) [71].

$$C_x = \frac{R_x}{\frac{1}{2}\rho S v^2} \tag{5-11}$$

$$C_{F,ITTC} = \frac{0.075}{(\log_{10}(\mathrm{Re}) - 2)^2} \tag{5-12}$$

$$C_{v.rel.} = \frac{C_v}{C_{F,ITTC}} \tag{5-13}$$

Effectively, $y_{t,v}$ equals $C_{v.rel.}$ and $y_{t,p}$ equals C_p.

Other steps of pre-processing are converting the CFD output to full scale (it was done for half of the hull shape) and verifying if the geometry of the 3D model matches the geometry which is used in CFD.

Next, the actual resistance prediction can be obtained.

5.4.2 Obtaining a resistance prediction

Again, an open-source Python toolbox is adopted, which will now provide a kriging model. This is advantageous as focus can then be put on developing the design tool itself, rather than on developing an accurate and fast kriging model. This is described next, after which the procedures to get a prediction and the local sensitivity are discussed.

Introduction of the Surrogate Modeling Toolbox

There are multiple toolboxes available which are peer-reviewed and well tested, such as *scikit-learn* ([62], [72]), *GPy* [73] and *Surrogate Modeling Toolbox* (SMT) [61]. More toolboxes are available which focus on machine learning in general.

For this thesis the SMT is chosen. The models in the toolbox have been applied to several engineering problems and proven to be effective in providing accurate predictions [61]. The different models and use of the tool are well documented, such that it is easy to use. What also distinguishes SMT from other toolboxes is that it can handle derivatives, both as input for gradient-enhanced surrogate models as to generate output derivatives.

Specifically for kriging SMT provides four different models, and for each model there are three possible regression function types and two possible correlation function types. One of the models is a gradient-enhanced kriging model. As there are no derivatives available a priori, an adjoint solver would be needed to compute them. For this thesis this will not be touched upon, such that three models remain.

These remaining models are (1) 'normal' kriging, (2) kriging combined with a partial least-squares method (KPLS) and (3) a model that uses KPLS to first estimate the hyperparameters and subsequently use that outcome in the 'normal' kriging model with a lower dimensionality (KPLSK).

The 'normal' kriging is Universal Kriging. In Appendix J.3 it is explained in detail which formulas are used to calculate the prediction and variance with Universal Kriging. The two possible correlation function types are given as well.

KPLS was set up to deal with the issues of kriging for high-dimensionality. To estimate the parameters of the model the covariance matrix has to be inverted multiple times, which is computationally expensive. Partial least-squares (PLS) methods are used to find the hyperparameters which are less correlated with the response. That information is put in the covariance matrix a priori, such that the dimensionality and number of hyperparameters is reduced. Effectively, the size of the covariance matrix and the computational burden are reduced, such that it is also faster. The new prediction is obtained by constructing a new kernel (i.e. correlation function) which combines the original chosen correlation function with weights for each variable x. Subsequently the hyperparameters are estimated and the kriging prediction and variance can be obtained. More information about KPLS can be found in [74].

However, KPLS can be inaccurate for same cases, especially for modelling multimodal functions [75]. To improve this accuracy KPLSK was developed, which basically adds an extra step to KPLS. The same procedure is followed as for KPLS, until the hyperparameters are estimated. Then the extra step is to locally optimize the likelihood function of the 'normal' kriging model, i.e. for all variables x instead of only the variables which have high correlation with the output. This should result in a more accurate prediction, but will slightly increase computational time. After doing the local optimization the prediction and variance are obtained in an analogous way as for kriging and KPLS. The main advantage is that is can be applied to high-dimensional problems while providing accurate predictions. More information about KPLSK can be found in [75].

All three models can be applied to the problem that is present in this thesis, as the dimensionality is considered to be relatively low. For generating the database it might be beneficial to select the model with the lowest computational time, but this should not cause inaccurate results. To select the model with an acceptable combination of computational time and accuracy a cross-validation study in performed, which is described in Section 5.4.4.

The actual kriging

By adopting the SMT it is sufficient to go through the following steps to obtain one prediction.

1. DEFINING: A resistance coefficient ($y_{t,p}$ or $y_{t,v}$) and non-dimensional parameters of the CFD dataset (x_t) are provided to the kriging model.

2. TRAINING: The kriging model is requested to train.
3. REQUESTING: A prediction for the resistance coefficient for the new hull is requested from the model by providing the non-dimensional parameters of the new hull (x_p) as argument. As output the kriging model returns the prediction for a resistance coefficient ($y_{p,p}$ or $y_{p,v}$) and the variance of that prediction (s_v^2 or s_p^2).

This procedure can be applied to each of the three models that are available in the SMT. As mentioned, this will be done separately for each of the four speeds at which CFD was done. Hence, a total of 8 kriging predictions will be done (two resistance components, four speeds).

The danger of this approach is the black-box effect: it cannot be seen how the SMT computes the prediction and variance. In order to cope with this issue extensive verification of the resistance results is done, which is described in Chapter 7.

Computing the local sensitivity

Computing the relative sensitivity of the total resistance to changes in the input x_p is done with finite difference approximation. Therefore, two new sets of locations at which a prediction is desired ($x_{p,sens1}$ and $x_{p,sens2}$) are defined in matrix form. Every column of $x_{p,sens1}$ contains the six dimensionless parameters x_p, but on the diagonal every parameter is reduced with 0.1%. Effectively, $x_{p,sens1}$ has the following form.

$$x_{p,sens1} = \begin{matrix} 0.999 \cdot \frac{L}{B} & \frac{L}{B} & \frac{L}{B} & \frac{L}{B} & \frac{L}{B} & \frac{L}{B} \\ \frac{B}{T} & 0.999 \cdot \frac{B}{T} & \frac{B}{T} & \frac{B}{T} & \frac{B}{T} & \frac{B}{T} \\ SL & SL & 0.999 \cdot SL & SL & SL & SL \\ C_b & C_b & C_b & 0.999 \cdot C_b & C_b & C_b \\ C_p & C_p & C_p & C_p & 0.999 \cdot C_p & C_p \\ \beta & \beta & \beta & \beta & \beta & 0.999 \cdot \beta \end{matrix} \quad (5\text{-}14)$$

$x_{p,sens2}$ has the same form but than every parameter on the diagonal is increased with 0.1%. Subsequently, a kriging prediction is obtained for each of the columns, again for the pressure and relative viscous resistance components separately. The viscous results are converted with the ITTC friction line again, such that the total resistance coefficient can be obtained for both cases (C_{sens1} and C_{sens2}). The relative difference is then computed with Eq. (5-15), which can subsequently be used to calculate the relative sensitivity with Eq. (5-16).

$$Relative\ difference = \frac{C_{sens2} - C_{sens1}}{0.5 \cdot C_{sens1} + 0.5 \cdot C_{sens2}} \quad (5\text{-}15)$$

$$Relative\ sensitivity = \frac{0.5 \cdot (relative\ difference)}{0.001} \quad (5\text{-}16)$$

Effectively, the relative sensitivity is computed for the four speeds at which CFD is performed. It provides insight in how a change in one of the non-dimensional parameters affects the total resistance of the hull shape. However, since it requires 96 kriging predictions (12 locations, 2 resistance components, 4 speeds), this will also be the most expensive computation for which kriging is used. The actual resistance prediction only requires 8 kriging predictions (2 resistance components, 4 speeds).

5.4.3 Post-processing

Doing kriging as described above will provide predictions $y_{p,v}$ and $y_{p,p}$ for the viscous and pressure part respectively, together with their variances (s_v^2 and s_p^2). The standard deviation (STD) is then computed by taking the root of the variance of the predictions, for both resistance components separately. Subsequently, by using Eqs. (5-11) and (5-13) the resistance coefficients and STD can be converted to full-scale resistance results. By adding the two resistance components the total ship resistance is obtained. The STD of the total resistance is computed with Eq. (5-17).

$$STD_{total} = \sqrt{STD_p + STD_v + STD_{RANS}} \tag{5-17}$$

The STD from RANS CFD is mostly determined by the numerical error, which is dominated by the discretization error. Within Damen it is estimated that the STD due to this error amounts 6% of the total predicted resistance.

Next, plots showing the resistance curve can be generated. A bound indicating the uncertainty can be added, showing the 10% and 90% percentiles. These can be calculated as the distribution of the predictions are assumed to be Gaussian distributed. The expected values can then be computed with Eq. (5-18), in which μ is the predicted total resistance. The z-value corresponding to the 10% and 90% percentiles of a Gaussian distribution is 1.28.

$$R_{percentiles} = \mu \pm z \cdot STD_{total} \tag{5-18}$$

A plot of the relative sensitivity versus the Froude number can also be made for each non-dimensional parameter. After doing so all results are saved.

5.4.4 Selecting the most favourable toolbox options

The SMT provides different options for the surrogate model. A comparison is made between these options, with the goal to have a model that is as accurate as possible, while the computational time should be as low as possible. The available options are the kriging model, regression function type and correlation function type. Possible combinations are tested to obtain the accuracy, standard deviation of predictions and the total run time. Leave-one-out cross-validation is performed to do so, which is explained next. The influence of the hyperparameter θ on the lead time and accuracy is investigated thereafter.

Leave-one-out cross-validation

The principle of leave-one-out cross-validation is that one element of the training data is separated and that the rest of the training data is used to predict the outcome for the element that is taken away. The error can subsequently be calculated as the real outcome is known, and can serve as a measure for the predictive performance. This principle is applied to the hulls and resistance values from the CFD dataset, by following the steps below.

1. Each hull shape is taken out once and used to calculate the error of a kriging model. This is done for each of the twelve models.
2. The Root Mean Squared Error (RMSE) is then computed over the 25 hulls for which there are resistance results, such that for each model there is an RMSE for each resistance component and for each speed separately.
3. The mean RMSE is computed by taking the average over the four speeds.
4. The maximum possible error of the total resistance caused by the STD is calculated (i.e. the uncertainty bound as described above).
5. The time of each of the 25 runs is measured in order to get the average computation time.

The RMSE is calculated with Eq. (5-19).

$$RMSE = \sqrt{\frac{1}{25}\sum_{i=1}^{25}\left(y_{p,i} - y_{t,i}\right)^2} \qquad (5\text{-}19)$$

As an example, the predicted and true resistance curves for hull number 5 from Table F-3 (Appendix F.3) are shown in Figure 5-9. For the prediction a KRG model with a constant regression function and exponential correlation function is used. It can be seen that there are differences between the predictions and CFD results, i.e. errors which can be used for calculating the RMSE.

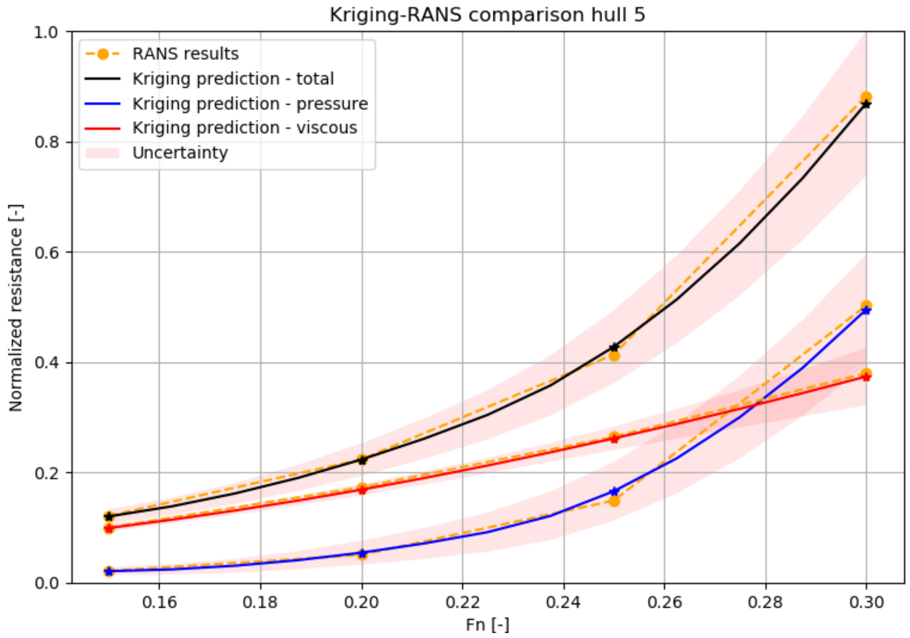

Figure 5-9: Normalized resistance components of the CFD results and kriging prediction for hull 5.

> **Note:** for creating a smooth resistance curve through the predictions, 3 points are added between every two predictions (the stars in Figure 5-9). The plotted curve is an interpolating B-spline curve with a degree of 2. This is true for all resistance curves in this report.

Since there are three models, two regression function types and two correlation function types, there are twelve possible combinations. The steps above are thus followed for every of these twelve kriging models. After doing so the results in the following tables are obtained. The RMSE for the viscous and pressure resistance can be seen in Table 5-1 and Table 5-2 respectively. The relative error at a Froude number of 0.3 and mean run time of each model are presented in Table 5-3.

For all tables a red-white-green colour gradient has been applied to indicate the maximum (red), mean (white) and minimum (green) values of each separate column.

Table 5-1: RMSE for the viscous resistance.

			RMSE [kN]				
Kriging model	Regression function	Correlation function	Fn = 0.15	Fn = 0.20	Fn = 0.25	Fn = 0.30	MEAN
KRG	Linear	Exponential	1.08	2.21	3.77	9.48	4.13
		Gaussian	0.83	2.45	3.83	9.84	4.24
	Constant	Exponential	0.41	0.89	2.30	5.63	2.31
		Gaussian	0.79	1.21	1.52	4.27	1.95
KPLS	Linear	Exponential	1.08	2.20	3.77	9.47	4.13
		Gaussian	1.04	2.77	4.06	10.21	4.52
	Constant	Exponential	0.33	1.11	2.19	5.03	2.16
		Gaussian	1.00	1.46	2.63	6.76	2.96
KPLSK	Linear	Exponential	0.94	2.21	3.85	9.47	4.11
		Gaussian	0.78	2.12	3.16	8.08	3.53
	Constant	Exponential	0.36	0.89	2.20	5.33	2.19
		Gaussian	0.81	1.51	1.83	4.37	2.13

Table 5-2: RMSE for the pressure resistance.

			RMSE [kN]				
Kriging model	Regression function	Correlation function	Fn = 0.15	Fn = 0.20	Fn = 0.25	Fn = 0.30	MEAN
KRG	Linear	Exponential	1.65	5.05	14.30	25.75	11.69
		Gaussian	2.07	5.40	18.34	31.93	14.44
	Constant	Exponential	2.42	6.87	15.31	29.73	13.58
		Gaussian	2.69	6.61	21.58	24.87	13.94
KPLS	Linear	Exponential	1.73	4.09	11.77	23.28	10.22
		Gaussian	1.68	3.80	12.06	22.46	10.00
	Constant	Exponential	1.98	6.83	16.85	30.26	13.98
		Gaussian	2.15	6.88	21.11	22.72	13.22
KPLSK	Linear	Exponential	1.72	5.61	14.00	25.15	11.62
		Gaussian	1.71	5.55	15.25	31.15	13.41
	Constant	Exponential	2.24	6.81	15.36	31.69	14.02
		Gaussian	2.29	10.12	22.85	28.43	15.92

Considering the errors it can be seen that the RMSE of all models is lower for the viscous resistance component compared to the pressure resistance component. This implies that the pressure part is more difficult to predict, probably caused by the fact that it has a more non-linear relationship with the non-dimensional parameters than the viscous part for increasing speeds. These differences can clearly be seen in the figures in Appendix F.3.2, showing the separate resistance components plotted versus the non-dimensional parameters.

It can also be seen that for both resistance components the RMSE increases if the speed increases. This effect can also be seen in the figures in Appendix F.3.1. Non-linearities in the relationship between the resistance and speed will naturally increase for higher speeds.

For the pressure component the KPLS model generally provides the most accurate results. This is surprising, as this model uses fewer hyperparameters to be faster at the expense of accuracy. Considering the regression and correlation functions, it can be seen that a linear regression function with an exponential correlation function provides the most accurate results for 2 out of 3 models. In the third case (KPLS) the difference is marginal between the two correlation functions.

For the viscous component no model is clearly the best, but it can be seen that a constant regression function yields the lowest RMSE for all three models. For this specific regression function it can also be seen that an exponential correlation function performs better at low speeds, while the Gaussian correlation function performs better at high speeds.

Overall, the best results for the mean RMSE are obtained for the pressure component when using the KPLS – Linear combination, for which both correlation functions yield good results. For the viscous component the KRG – Constant – Gaussian provides the lowest mean RMSE.

Table 5-3: Mean STD error at maximum speed and mean run time.

Kriging model	Regression function	Correlation function	Mean STD error at Fn=0.30 [%]	Mean run time [ms]
KRG	Linear	Exponential	12.6	183.9
		Gaussian	10.9	186.3
	Constant	Exponential	16.5	165.1
		Gaussian	10.0	161.9
KPLS	Linear	Exponential	15.9	39.9
		Gaussian	14.1	44.5
	Constant	Exponential	21.2	36.8
		Gaussian	13.0	39.8
KPLSK	Linear	Exponential	13.1	270.0
		Gaussian	10.4	288.5
	Constant	Exponential	16.6	252.4
		Gaussian	10.1	261.1

Considering the computation time of the models, it can be seen that all KPLS models provide the fastest prediction by far. KPLS models are approximately 4 times faster than KRG models and more than 6 times faster than KPLSK models. This is expected due to the way each model handles the hyperparameters. It can also be seen that a constant regression function is slightly faster than a linear regression function, but this effect is negligible with respect to the choice of the kriging model. Moreover, the Gaussian correlation function almost always causes a longer run time than the exponential correlation function.

In the results for the error caused by the standard deviation (STD) for the total resistance at the highest speed, it can be seen that Gaussian correlation function provide the lowest error for all kriging models, and thus creates a 'more certain' prediction. Moreover, the KPLS model seems to provide results with a high STD, probably caused by the fact that fewer hyperparameters are used.

Since time is an important factor to take into account when generating a database the KPLS model is chosen as kriging model for both resistance components. As follows from the tables above, this is also a good choice considering the accuracy of this model. For the pressure resistance component the KPLS – Linear – Gaussian combination provides the most accurate results. For the viscous component that combination is less accurate, but the KPLS – Constant – Exponential combination shows good results. Therefore, these two models are chosen as kriging models for the two resistance components. This leads to a mean RMSE of the total resistance of 10.2 kilonewton, which can also be seen in Table 5-4. Cross-validation results of other selected hulls are included in Appendix M, and are discussed in more detail in Chapter 7. Next, the influence of the hyperparameter θ on the error and run time is investigated.

Table 5-4: RMSE of viscous, pressure and total resistance for the chosen SMT settings.

Settings combination	*Resistance component*	*Fn = 0.15*	*Fn = 0.20*	*Fn = 0.25*	*Fn = 0.30*	*MEAN*
KPLS – Constant - Exponential	Viscous	0.33	1.11	2.19	5.03	2.16
KPLS – Linear - Gaussian	Pressure	1.68	3.80	12.06	22.46	10.00
	Total	1.64	3.90	12.49	22.71	10.19

Influence of the hyperparameter

The hyperparameter θ has a default value of 0.01, but another value could have a beneficial influence on the accuracy or lead time. It is varied from 10^{-30} to 10^{10} to find the most optimal values of θ for both models separately (θ_v & θ_p). The mean RMSEs of the total resistance and the separate resistance components have been computed and the mean computational time has been measured, again by doing leave-one-out cross-validation.

As the error of the pressure resistance is dominant for the error of the total resistance, it was chosen to fix the θ_p at certain values in the order of 10^{-8}. However, this led to unexpected and unexplainable behaviour: sometimes the RMSE of the pressure part became larger than the RMSE the total resistance. Additionally, the resistance curves were analysed, showing that the the STD is lower but predictions were often outside the 80% confidence interval. For using the resistance results it is desired that the actual results are within the confidence interval as often as possible. The accuracy also varied over the speed range, such that at some speeds a specific choice of θ_p led to more unrealistic resistance curves compared to using the default values for θ_v and θ_p.

Effectively, these results motivate that a kriging model should be selected and tuned for each speed, as the kriging prediction is done for each speed separately. It is difficult to train one model that is capable of both capturing the non-linear effects at high speeds, but at the same time not losing on accuracy at low speeds. Having one kriging model for each speed and resistance components separately, i.e. 8 different models in the set-up used in this thesis, would help in preventing these effects. For future implications it is therefore recommended to select and tune separate kriging models for every prediction separately.

Considering the mean computation time, no clear trends were found as well. It is therefore chosen to maintain the default values for both θ_v and θ_p at 0.01

5.4.5 Summary

This paragraph has described the practical application of kriging in this thesis. It is now known how kriging is used to predict the resistance of new hull geometry, but also how the standard deviation and local sensitivity of that prediction are obtained. A leave-one-out cross-validation study has been done choose options in the SMT: a combination of a kriging model, correlation function and regression function is selected that yields a low error compared to the CFD results and low computation times.

Tuning of the hyperparameter θ resulted in unrealistic and undesirable resistance curves, such that default values for hyperparameters were used. It also provided the insight that the method to predict the resistance could be improved in theory by selecting and tuning a kriging model for each speed and resistance component separately.

The low-level description of the kriging procedure will be used to set up the Python script which will provide the resistance prediction. Settings of the kriging model in that script have been found in Section 5.4.4. More extensive verification of the resistance results will be done in Chapter 7.

Next, the final preparations which are needed to start populating the database are discussed.

5.5 Final preparations to start filling

In order to start filling some final preparations have to be done. Based on the desired design space, which is discussed in Section 5.5.1, an estimation of the total filling time can made. The computer setup, estimated time and final design space are described in Section 5.5.2. The software architecture and database structure are discussed in Section 5.5.3.

5.5.1 The desired design space

The design tool should ideally have a database that contains all possible hulls, i.e. all possible combinations between parameters. As the problem of finding suitable hull dimensions is a discrete problem at Damen Shipyards, all possible values for each parameter can be defined. For the boundaries of the design space it is assumed that they are defined by the extreme hulls from the CFD dataset define these boundaries.

The desired design space is defined by the extreme values and desired step size for each parameter, and can be seen in Table 5-5. The choice for each parameter is discussed below the table.

Table 5-5: Boundaries, step size and number of possible values of all parameters.

Parameter	*Minimum*	*Base*	*Maximum*	*Desired step size*	*Unit*	*Possibilities*
Length	L_{oa} = 63.81 L_{wl} = 60.45	L_{oa} = 97.94 L_{wl} = 93.43	L_{oa} = 132.07 L_{wl} = 126.41	0.6	[m]	114*
Beam	B =12.40 B_{wl} = 9.14	B = 19.77 B_{wl} = 16.44	B = 21.06 B_{wl} = 17.52	0.3	[m]	29*
C_B	0.5010	0.5697	0.6384	0.01	[-]	14
C_M	0.5429	0.7465	0.9501	0.01	[-]	41
β	16.0	36.43	85.27	1	[deg]	70

* based on L_{oa} and B

The **length** is often varied by using the default distance between frames, the longitudinal frame spacing. Within Damen a frame spacing of 600 millimetres is used, such that the length should also be varied with 0.6 meters. A lower number is acceptable as well, but 0.6 should be able to be divided by that number and result in an integer (e.g. 0.3, 0.2 etc.).

For the **beam** the frame spacing is used as well, but in the transversal direction. Within Damen this distance is equal to 300 millimetres. Hence, the desired beam step size is 0.3 meters. The extreme hull for the beam is a special case in the CFD dataset, as it is acknowledged that the base hull is too large. Consequently, desired small hulls can't be generated. Extrapolation with morphing has been applied to get smaller hulls: the minimum morphing parameter for the beam was -5.94. Effectively, the CFD dataset contains hull which are relatively small compared to the base hull and extreme hull for the beam. The minimum boundary value for the beam are those of the hull with the smallest beam at the waterline, as that value is used for regression of the resistance values.

Both the **block- and main-frame coefficient** are not actively varied during the ship design process, but rather used as a performance indicator to assess a hull shape. However, the parent hulls and the morphing process allow for systematic variation, which will be done for the sake of analysis. It is assumed that a 1% step size for both parameters is acceptable in the concept design phase. The same is true for the **entrance angle**: it is assumed that a 1 degree step size is acceptable in the concept design phase. For the minimum value of the entrance angle the minimum value present in the CFD dataset is taken.

By multiplying all the possibilities the total number of hull shapes is obtained, which is equal to 133 million hull shapes.

5.5.2 Computational consequences

Creating 133 million hull shapes might take too much time to realize in the timeframe in which this thesis is conducted. Therefore, an estimation of the computation time is made.

Computer setup

For generating the database a Lenovo P52 workstation has been used. This laptop has the following characteristics.

OS:	Windows 10
Processor:	Intel Core i7-8850H @ 4.30 GHz
Memory:	32GB RAM @ 2400 MHz

Testing showed that with this computer it takes approximately 1.5 seconds per hull definition to go through the filling process, as defined in Figure 5-1.

Estimation of computation time

It is estimated that by applying the constraints as defined on page 65 approximately 25% of all possible hull definitions will be invalid. Effectively, 100 million hulls would be included in the database, taking approximately 4.7 years to fill. This is thus not feasible for this thesis, such that a more coarse grid will be defined.

Providing input to the morphing model

In accordance with the goal in 5.1.1, as more coarse grid is defined to develop the proof-of-concept of the database. This is done by definition of a grid of morphing parameters, as for the DEF dataset the hull definitions cannot be determined on beforehand. For each morphing parameter a linearly spaced vector with morphing parameters is defined. The extreme values of these vectors are chosen such that they result in a design space that contains hulls with the parameters as defined in Table 5-5. For example, for the entrance angle the minimum and maximum values of the morphing parameter are set at -0.45 and 0.9. This results in a database in which the minimum and maximum values of the entrance angle are approximately 16 and 85 degrees.

The parameters below have been defined.

$$par_L = [-0.9 \quad -0.8 \quad \dots \quad 0.8 \quad 0.9]$$
$$par_B = [-5.5 \quad -5.25 \quad \dots \quad 0.25 \quad 0.5]$$
$$par_{C_m} = [-0.45 \quad -0.3374 \quad \dots \quad 0.7875 \quad 0.9]$$
$$par_{C_b} = [-0.9 \quad -0.45 \quad 0 \quad 0.45 \quad 0.9]$$
$$par_\beta = [-0.45 \quad -0.3374 \quad \dots \quad 0.7875 \quad 0.9]$$

The vectors contain 19, 25, 13, 5 and 13 values respectively. This leads to 401.375 possible hull definitions. Again, approximately 75% remains by applying the constraints, such that 300.000 hulls remain. It is expected that this amount of hull shapes is sufficient to test the effectiveness of the design tool. If it is shown that the set-up is satisfying, a database with all possible hulls could subsequently be generated by improving the set-up and exploiting more powerful computational resources.

This grid results in an approximated total computation time of 125 hours, which is assumed to be acceptable. For practical purposes the filling process is split up into 5 parts, each taking approximately 25 hours. For every part one of the elements of the morphing parameter of the block coefficient is used, as the corresponding vector can be divided into 5 parts.

5.5.3 Software architecture & database structure

Actual integration of all the previously mentioned procedures is done in Python. The reader is referred to Appendix J.4 to find the full description of the software architecture and database structure used for populating the database. This section very briefly describes these aspects.

An overview of all scripts and description of this software architecture is included in Appendix J.4.1. Key is that one main script is written that calls function in eight scripts, such that the steps in Figure 5-1 are followed in succession for each individual hull. The main script ensures that all pre-defined hulls will be evaluated.

Next, the main script will save valid hulls in the database. A specific structure is chosen to do so, which is described in Appendix J.4.2. Descriptions of saved files are included as well. Effectively, four groups of files are being created: (1) a hull description file, (2) hull geometry files, (3) resistance related plots and (4) hull geometry previews. A directory is created for each individual hull in which these files are saved. Additionally, the numerical results of all hulls in the database are bundled in one Comma-Separated Values file. This allows for analysis of the design space after filling the database, and could also be used by a search algorithm as back-end of a GUI.

5.6 Conclusion

This chapter has in detail described the model that is used to populate the database. The goal is to answer the fifth sub-question:

> *How can the chosen hull generation and resistance prediction methods be applied in practice to populate a design space of new hull shapes?*

A high-level description was first defined in Section 5.1, after repeating the desired contents and defining the preparations that have to be made before filling the database. Effectively, this paragraph already provides the answer to the fifth sub-question. Five steps are gone through to populate a design space: (1) hull definitions are pre-defined, (2) hull geometry is constructed with morphing, (3) hydrostatics & characteristics of the new hull shape are computed, (4) the resistance of the new hull shape is predicted with kriging and (5) all results are saved in a database. In the consecutive paragraphs the working principles of the different core elements of the model (steps 2, 3 and 4) have been elaborated. Step 1 and 5 are described in the last paragraph (5.5).

The procedure for morphing has been extensively described in Paragraph 5.2. Pre- and post-processing steps have been addressed as well. An overview of the procedure can be used as blue-print for integrating the solution in Python. Paragraph 5.3 focused on describing methods to evaluate the hull shape, in order to the necessary hydrostatics and hull characteristics. This clarified how all results and image previews have been obtained, such that is can be integrated in Python as well.

The prediction of the resistance with kriging was discussed in Paragraph 5.4. The open-source Surrogate Modeling Toolbox for Python is used to provide a Kriging model. It provides different models, and for each model multiple regression functions and correlation functions. A leave-one-out cross-validation study has been conducted to find the accuracy and run time of these models, such that the combination of settings could be selected that results in the lowest run time and Root Mean Squared Error (RMSE). For the pressure component the Kriging model with Partial Least Squares method (KPLS) with a linear regression function and Gaussian correlation function is chosen, while for the viscous component a KPLS model with a constant regression function and exponential correlation function is chosen. Combining both models results in a mean RMSE of the total resistance of 10.2 kilonewton. Analysis on the tuning parameter showed that the method to predict the resistance could be improved in theory, by selecting and tuning a kriging model for each speed and resistance component separately.

Last, final preparations to populate the database have been discussed in Paragraph 5.5. The most important outcomes of this paragraph are the grid for the design space, an overview of the software architecture and the structure of the directory in which the database will be saved. These will serve as blueprints for setting up the scripts in Python.

Hence, the model to fill the database can now be set up. After filling the database the results will be analysed. This is described next, in Chapter 6.

6

Using the Database to Obtain Hull Shapes

The model from Chapter 5 has been integrated in Python, with the main goal to have a proof-of-concept database which can be used for testing of the performance of the model. The results of testing are described in Chapter 7. The aim of this chapter is to briefly present the results of the database and describe how they can be used. The results are lessons-learned, which will be used to formulate conclusions and recommendations in Chapter 8.

In this chapter the design space in the database is described in Section 6.1. Here, the computational results, distribution of parameters and distribution of resistance results are discussed. Subsequently, methods to navigate through the database are presented in Section 6.2. Search algorithms can be employed to do so. Last, the development of a Graphical User Interface (GUI) is described in Section 6.3. This GUI will effectively be the conceptual design tool, and will facilitate these search algorithms. The designer can provide user input in this GUI and request the output in the form of the hull shape, the resistance prediction and the other required output.

6.1 Analysis of the resulting design space

This paragraph provides a brief description of the resulting database in the database. First, computational results are presented in 6.1.1. Hereafter, the distribution of input parameters and other hull characteristics are discussed in 6.1.2. Last, the distribution of resistance results is described in 6.1.3.

6.1.1 Computational results

As defined in Section 5.5.2, it was estimated that the database would contain 300.000 hulls, taking 125 hours to generate. Eventually this estimation has been a bit conservative. Of the 401.375 hull definitions 245.005 were valid, i.e. 61.04%. The total computation time amounted 106.5 hours: an average of 1.56 seconds per hull shape. The results for each of the five runs in which the database was generated can be found in Table 6-1.

Table 6-1: Computational results.

	par_{Cb} = 0.9	par_{Cb} = 0.45	par_{Cb} = 0	par_{Cb} = 0.45	par_{Cb} = 0.9	**Total**
Number of valid hulls	47274	52884	54759	50313	39775	**245005**
Percentage valid hulls [%]	58.9	65.9	68.2	62.7	49.5	**61.04**
Total nr. of hull definitions	80275	80275	80275	80275	80275	**401375**
Run time [hours]	20.7	22.0	24.5	21.5	17.7	**106.5**
Average run time per hull [s]	1.575	1.498	1.613	1.541	1.602	**1.564**

Considering consumed space, on average each directory of an individual hull consumes approximately 640 KB on disk. Effectively, the total database consumes 146 GB on disk. The .CSV file containing the output of all hulls consumes 246 MB on disk.

It is also interesting to check the division of consumed space per file type in the hull directory. The following division is found.

Table 6-2: Division of consumed space per filetype of each individual hull.

File type	*Size on disk [KB]*	*Nr. of files*	*Avg. size per file [KB]*
STL (geometry)	160	1	160
IDF (geometry)	4	1	4
JSON (all results as text)	8	1	8
PNG (hull preview images)	212	5	42.4
JPEG (resistance images)	256	5	51.2

The JSON file, in which all numerical results are saved, allows for generating the PNG and JPEG images later, e.g. only when a hull is requested in the GUI. It can now be concluded that this indeed could save a lot of space, but it will also speed up the filling process significantly. Another useful improvement would be the replacement of the STL file by a .3dm file, which saves approximately 104 KB. Effectively, each folder would then have a size of only 68 KB, such that the total database would consume only 15.9 GB on disk.

6.1.2 Distribution of the input parameters & characteristics

The spread of the input parameters and other relevant hull characteristics is presented in histograms, which can be found in Appendix K, Section K.1. Other relevant values are summarized in Table 6-3.

When these values are compared to the results from the CFD dataset (see Appendix F.2), it can be seen that most of the values in the database have a wider range than in the CFD dataset. For the purpose of analysing the database that is a good thing. It can be expected that for hulls which are outside of the boundaries from the CFD dataset the resistance prediction is less accurate.

An extreme outlier is the maximum value of the entrance angle. The maximum value of that parameter in the CFD dataset is 51.2 degrees, opposed to 88.6 degrees in the database. The minimum value for the entrance angle in the database is relatively low as well, approximately 13 degrees compared to 16 degrees in the CFD dataset.

Table 6-3: Distribution of input parameters and other characteristics

Parameter	*Minimum*	*Maximum*	*Average*	*Median*
L_{wl} [m]	59.60	128.48	91.79	90.82
B_{wl} [m]	8.51	19.66	14.85	14.92
β [deg]	12.94	88.64	36.66	33.14
C_b [-]	0.3715	0.7900	0.5765	0.5760
C_m [-]	0.5558	0.9717	0.7947	0.8057
C_p [-]	0.4241	0.9524	0.7340	0.7433
S [m^2]	475.7	2605.2	1272.8	1235.0
Volume [m^3]	450.2	4141.3	1776.5	1709.6
L_{oa} [m]	66.54	128.69	95.27	94.17
B_{oa} [m]	12.59	20.44	17.18	17.48
L/B [-]	3.51	10.50	6.27	6.26
B/T [-]	3.83	8.86	6.69	6.72
L_{oa}/B_{oa} [-]	3.54	7.20	5.58	5.65
B_{oa}/T [-]	5.67	9.21	7.74	7.87
SL-ratio [-]	5.34	10.32	7.65	7.66

Additionally, the difference in parameters is analysed as well. To do so, all columns of one parameter are sorted and the difference is computed. For all parameters the minimum value of that difference was zero, i.e. there is another hull which has the same value for that parameter. The maximum difference showed that high differences occur for the wetted surface, the volume and the length overall. For the first two parameters this is not strange, as they have relatively large values. However, for the length overall it is strange, as the average difference was equal to zero. Upon inspection it showed that this large difference only occurs when the value of the morphing parameter changed. To prevent this issue a finer grid for the morphing parameter of the length can be chosen.

The difference was also used to find the two hulls which are the most alike. This was done by sorting the database based on the waterline length and then finding the row at which the norm of the differences is the lowest. Effectively, this resulted in a few shapes which have the same values for the morphing parameters except for the morphing parameter of the beam, which varied by 0.25. This is as expected, as for this parameter the most fine grid was used.

It can be concluded that for the purpose of analysing the results are satisfying. However, for a database which will be actually used in the design process very extreme outliers are not desired.

6.1.3 Distribution of the resistance results

Different plots of the relationship between parameters and the resistance results at the maximum speed have been included in Appendix H, Section H.2.

Upon first inspection it does not seem that any unnatural phenomena occur. These plots clearly indicate the boundaries of the design space in the database as well. Effectively, these plots could also be provided to the designer, such that he can select any combination of parameters for which a low resistance is expected. More thorough analysis of the resistance output is done in Chapter 7.

Another application could be to find a Pareto front in a plot, which could be used to find a Pareto-dominant hull. This hull is the best scoring hull for (at least) two objective functions. An example is given in Figure 6-1. The objective functions here are to minimalize the resistance and to maximize the ratio of KM to the draft. This last measure is beneficial since that would result in a high GM. Effectively, the pareto frontier would in theory go from the lower loft corner, along the outside points in the graph, towards the upper right corner. This example is presented to just demonstrate the possibility of creating it with the results from the database. However, there are other more logical object functions (e.g. wake object function) possible. Additionally, based on user input only hulls can be shown which comply to the user input, such that fewer hulls are shown in the Pareto plot compared to Figure 6-1. This then provides insight in the trade-off between the objective functions for fewer hulls, such that a quick selection can be made.

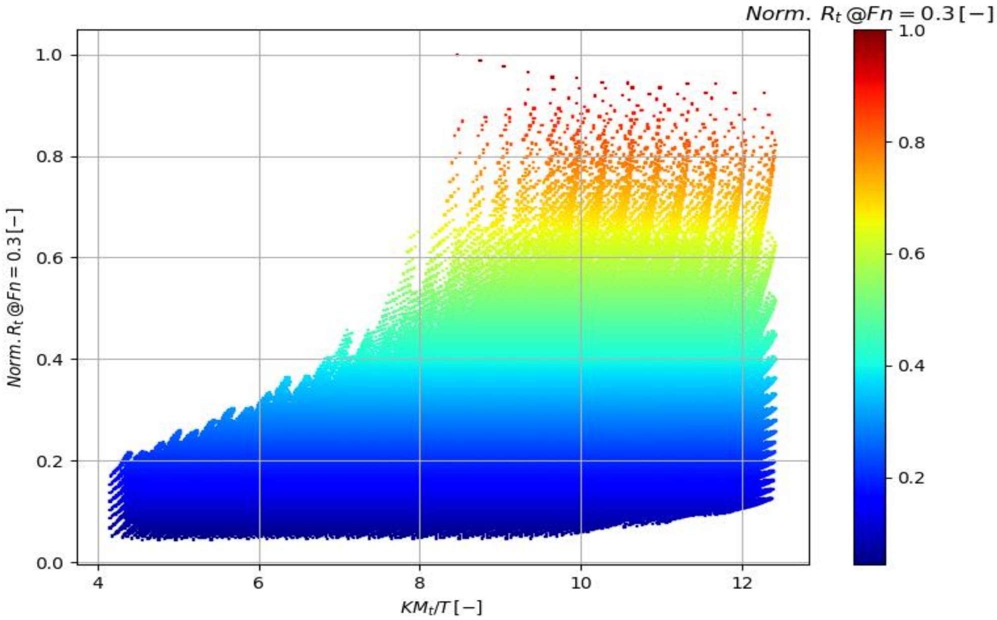

Figure 6-1: Maximum total resistance plotted versus the keel-metacentre distance divided by the draft.

Effectively, for now it is concluded that the resistance results seem logical. More thorough verification is done in Chapter 7.

6.2 Navigating through the database

In order to efficiently navigate through the database, suitable algorithms have to be selected that can select one or more hulls from the database based on the user input. In this paragraph descriptions of two possible algorithm are given, which can be used. The most simple one is a lookup algorithm, which is described in Section 6.2.1. A more advanced algorithm is a search algorithm, which can choose a specific hulls from a set of hulls which comply to the user input. It is described in Section 6.2.2. Both algorithms have not been applied in practice to the database yet, but these descriptions provide insight in how the GUI can be used in practice.

6.2.1 Lookup algorithm

For the first case it is considered that the user knows the exact values of the 5 input parameters, i.e. the parameters which have been used for variation. This is also the case when the user opens the GUI and needs to request a hull: he needs to define a hull shape with 5 exact values. The GUI will be further discussed in the next paragraph.

To do so a matrix is set up of the varied parameters of all hulls in the database. A conditional statement from Python is used to find the index of the row which contains the identical parameters. This can be considered as a search for ‘fixed’ parameters. Since all hull definitions in the database are unique, only one row will meet the condition. The index is subsequently used to load the rest of the output data. After loading it can be presented to the user.

6.2.2 Search algorithm

Now it is assumed that there are multiple hulls that comply to the user input, which will surely happen if the user will use the ability to fix certain parameters and leave others open for 'variation'. There will then be 'open' and 'fixed' parameters. These last parameters are not varied, but left open for the search algorithm. It will thus select all hulls of which the parameters are equal to the 'fixed' parameters, and for which the 'open' parameters may take any value. It is then up to the search algorithm to select the most suitable hull shape.

For example, the user might want to find a hull with a certain length and beam ('fixed'), but has no preferences considering the block coefficient, prismatic coefficient and entrance angle ('open'). There will be multiple hulls that have that specific combination of length and beam, which will all have different values for the 'open' parameters. The question then is: which of those hulls should be returned to the user?

A plausible wish of the user is that a hull shape is desired with the lowest possible resistance at the intended service speed of the vessel. Therefore, the service speed should be an input value too, as can be seen in the mock-up of the GUI in the next paragraph. This would require interpolation to obtain the resistance values of all possible hull shapes at the service speed. An even more simple case can be chosen: the hull with the lowest resistance at the highest speed is returned to the user. This shows that it is possible to integrate a custom search algorithm which returns the right hull to user, and can easily be verified.

Useful other features of the search algorithm are more advanced conditional statements, for example defining other types of parameters then only 'open' and 'fixed'. The 'between' condition could be introduced to let the user define an upper and lower boundary for parameters, such that the search algorithm only selects hulls for which specific parameters are in between those boundaries. This can be very useful when tender documents specify a range for certain parameters.

6.3 Developing a Graphical User Interface

This paragraph focuses on the development of the Graphical User Interface (GUI). A GUI is necessary as the size of the database is impractically large, and contributes to speeding up the design process. It can be an effective tool to provide information and insight to the designer, which can contribute to developing better designs.

Due to time constraints in the thesis project only a mock-up of the GUI has been created: the actual GUI has not been developed. However, the mock-up shows the different functionalities and features of the GUI, such that it is an effective instrument to design and improve the GUI. After agreeing on the mock-up, the GUI only has to be developed and tested.

First, Section 6.3.1 describes the starting points and methodology which have been used to develop the mock-up. The mock-up itself is presented subsequently in Section 6.3.2.

6.3.1 Starting points and methodology

Since the database contains 245.005 hulls and a lot of information is available for each of those hulls, an engineer is prone to lose oversight when he is not familiar with the set-up or information that is in the database. This is already one reason to set-up a GUI. As mentioned in Chapter 3, it can also contribute to speeding up the design process, as it facilitates smooth transfers of data from the database to the user.

After introducing the generation of a database in Paragraph 4.3, it became clear that the design tool will in fact be a GUI. It will focus on retrieving the correct output from the database, based on user input as has been described in more detail in Section 4.3.3. External interface requirements have been presented in Appendix G.2. Required functionalities and other requirements have been presented in Chapter 3 and Appendix G.2. They form the starting points for developing the GUI.

Considering the methodology, a first concept mock-up was first developed based on the requirements and functionalities. The first mock-up has been presented to the D&P engineers from Damen and critically reviewed. Based on the feedback improved versions have been made and again presented to the engineers. This iterative loop eventually converged to a final design, which is presented next. However, when using the actual GUI there will probably be some possible improvements, such that the final GUI will become an improvement of the final mock-up.

6.3.2 Mock-up: a desired concept

The final mock-up of the GUI contains two tabs, of which the second one is the most important. The first tab is the 'General' tab and can be found in Appendix H. It is not presented here, as the focus was put on developing an environment in which an engineer can provide input and ask for output. This is done by development of the mock-up of the 'Input – Output' tab, which can be seen in Figure 6-2. Effectively, the GUI will facilitate a search algorithm as described in the previous paragraph.

Figure 6-2: GUI 'Input – Output' tab.

The sliders can be used to define the parameters of the hull shape that should be searched for. When requesting a hull shape with the 'Provide Hull' button, the resistance, local sensitivity and geometry results are shown in the GUI. Additionally, the sliders of the output parameters will shift to the value of the presented hull shape.

It can be seen that there is a column in which certain parameters can be fixed, such that a search algorithm can be employed to search for multiple hulls and select the most suitable hull. A data entry for the service speed can be seen, which can be used by the search algorithm, e.g. for selecting the hull with the lowest resistance at the service speed. If the option of the fixed parameters is included, the output parameters can in theory also be varied by shifting the corresponding sliders. Effectively, as the sliders can only take values of parameters which are actually in the database, there will always be a possible result in the database. However, a sufficient number of parameter should then be 'open'. It is therefore recommended to do further research into the development of a search algorithm that can efficiently search through the database, such that an inverse design approach is obtained.

Above the local sensitivity plot a drop-down menu can be inserted, providing the possibility to show other useful plots. One figure which should be included is the position of the current hull in the design space of the CFD dataset, showing if the hull shape that is chosen is in a dense or sparse area in the design space. An example for the hull shown in the GUI mock-up can be seen in Figure 6-3. This provides an indication of the trustworthiness of the resistance prediction, as that prediction would be more unsure at sparse locations in the design space.

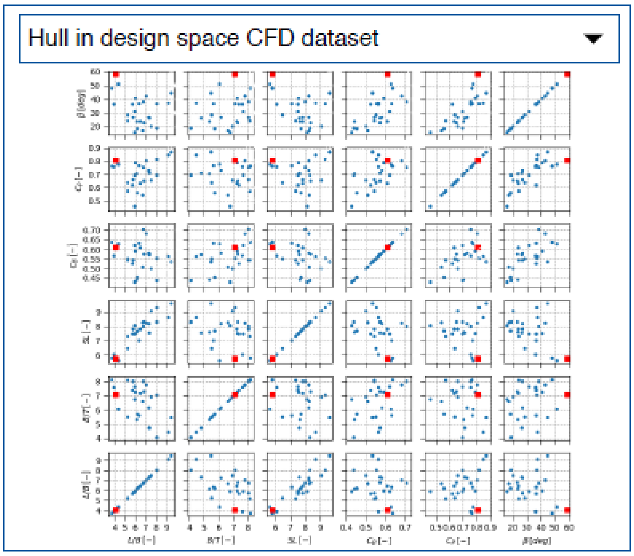

Figure 6-3: Scatter plots showing the position of the hull in the design space of the CFD dataset.

The tab setup allows for adding other relevant modules in ship design. For this thesis the focus is put on a module that provides a resistance prediction. In order to provide insight, the input and output have therefore been presented in one tab, such that it immediately becomes clear how a change in the input affects the resistance and geometry.

Additional tabs can be added for different design aspects, such as stability assessment, seakeeping behaviour or general arrangement. Hence, it also becomes more difficult to show the input and output at the same time, as the amount of output becomes too large and the user might be overloaded with information. A feature that could mitigate this problem is a comparison module, to which the user can export multiple hull shapes. By selecting a benchmark hull shape the designer can explore the database and find hulls which have more beneficial characteristics for certain design aspects than the benchmark hull. The goal of this exploration is then to find a hull shape with the best compromise of the different design aspects.

Effectively, the GUI can be seen as the conceptual design tool that is developed in this thesis, which can be used for concept exploration.

6.4 Summary

This chapter focused on briefly describing the database which has been generated, explaining how one can navigate through the database, and presenting the mock-up of a Graphical User Interface (GUI).

The database which is populated as a proof-of-concept was discussed in Paragraph 6.1. A large database of 245.005 hulls is generated, of which the parameters have a bit broader range than the CFD dataset. This is a good thing for

Additionally, this chapter provided examples of how the database can be used. Paragraph 6.2 described possible algorithms that can be used to efficiently navigate through the database. A very simple algorithm would be a lookup function, or a search algorithm that simply selects the hull with the lowest resistance at a specific speed. More advanced algorithms can be integrated as well, but it is recommended to first develop a simple algorithm.

A mock-up of a GUI has been developed and presented in Paragraph 6.3. It is the platform in which the designer can provide input, and in which the tool will present the output in the form of the resistance, local sensitivity and geometry results. This result can be used when actually developing a GUI. Nevertheless, when further developing the design tool the mock-up only can already be used to discuss useful features and functionalities.

In the next chapter (7) the geometry and resistance results in the database are tested thoroughly, in order to say something about the trustworthiness of the results.

7

Testing the Design Tool

This chapter describes verification and validation of the results generated in this thesis. The goal of this chapter is therefore to say something about the trustworthiness of the results. Verification will aim at checking if the correct geometry is generated, and if the resistance predictions provide accurate results. Validation aims at checking if the tool meets up to the pre-defined requirements.

First, in Paragraph 7.1 miscellaneous hull shapes are presented for which high curvature is expected, in order to find out if the hulls are sufficiently faired and smooth. Paragraph 7.2 described the sensitivity of the results for changing individual parameters, both for the geometry and the resistance. Thereafter Paragraph 7.3 presents resistance comparisons between two hulls from the CFD dataset and one hull from the database, indicating if the resistance results in the database are realistic. Leave-one-out cross-validation has also been applied to compute numerical errors for hulls from the CFD dataset, which is described in Paragraph 7.4. Last, the design tool is validated against the requirements which have been defined in Paragraph 3.3. Those results can be found in Paragraph 7.5.

All findings in this chapter are used to assess the performance of the model behind the tool. Hence, it can be seen as a check of the research results. This is an indispensable, last step to formulate an answer to the main research question, which is done in Chapter 8.

7.1 Examining geometry of miscellaneous hull shapes

Some extreme hull shapes in the database are loaded, showing combinations of very low or high dimensions and form parameters. This is done to see if the resulting geometries are sufficiently smooth and well-faired. Extreme hull shapes are expected to have high curvature in local details of the NURBS surface, causing fairing issues. Additionally, this shows what happens if the morphing parameters are varied simultaneously. If there are no fairing issues for these hulls, it can be expected that all hulls are well-faired and smooth. Lines plans are used to assess the smoothing and fairness of each hull shapes, and are included in Appendix N.

7.1.1 Slender hull

First a narrow, slender hull is looked up. This means that the hull has a low main-frame coefficient, low entrance angle, low prismatic coefficient, high L/B-ratio and low B/T-ratio. This also means a relatively high slenderness ratio.

Table 7-1: Characteristics of the selected slender hull.

L_{wl} [m]	B_{wl} [m]	T [m]	β [deg]	C_B [-]	C_M [-]	C_P [-]	S [m^2]	∇ [m^3]	L/B	B/T	SL
78.77	8.51	2.22	16.11	0.3949	0.5558	0.7105	623.7	587.4	9.26	3.83	9.41

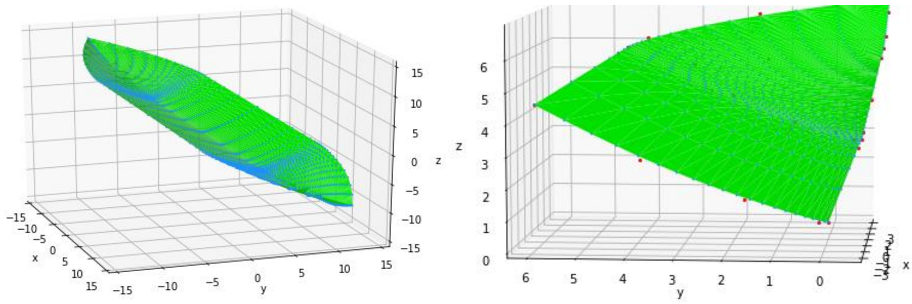

Figure 7-1: Geometry of the selected slender hull.

The V-shaped hull shape is indeed very slender. It can be seen that there is a dense region of the control points where the midship sections morphs into the bow region. There seem to be some odd-shaped waterlines around the dense region of control points. The lines plan of the hull shape is generated to verify if there is any unwanted high local curvature. It can be found in Appendix N.1.

It can be seen that the waterlines, buttocks and section generally look sufficiently smoothed and well-faired. There are some small flaws for which some minor adaptions are needed, such as an inverse entry to the centreline of the waterline at a draft of 1.5 meter. Additionally, the waterline at a draft of 0.5 meter protrudes outwards before going towards the centreline. These issues can be adjusted in the design process by repositioning control points near the locations where the issues occur. The buttock of the centreline seems to have double curvature, but after a closer look the area before the curvature is flat. In the sections double curvature is present for some sections, but this is not necessarily advantageous as it protruding happens above the waterline.

Despite these small issues the hull shape is can be considered to be sufficiently smoothed and well-faired, especially for use in the concept design phase.

7.1.2 Full hull

For the second hull the opposite form is looked for: a full, beamy hull which has high form coefficients, high entrance angle, low L/B-ratio, high B/T-ratio and a relatively low slenderness ratio. The characteristics of the selected hull can be seen in Table 7-2 and the resulting geometry is shown in Figure 7-2.

Table 7-2: Characteristics of the selected full hull.

L_{wl} [m]	B_{wl} [m]	T [m]	β [deg]	C_B [-]	C_M [-]	C_P [-]	S [m^2]	∇ [m^3]	L/B	B/T	SL
90.53	19.09	2.22	63.07	0.7624	0.9410	0.8101	1841.7	2924.8	4.74	8.60	6.33

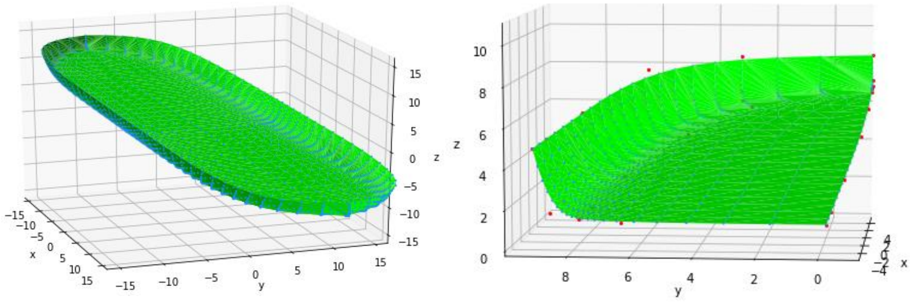

Figure 7-2: Geometry of the selected full hull.

It can be seen that the geometry is indeed quite full, U-sections can be recognized. The NURBS surface is smooth, also following upon more detailed inspection in Rhino. The lines plan (Appendix N.2) also shows satisfying results, as the waterlines, buttocks and sections are well-faired. Only the buttock of the centreline shows a very small knuckle near the end of the hull, but it is expected that this would not provide major problems. A very full hull therefore also seems suitable for immediate use in the concept design phase.

7.1.3 Hull with control points near the mid-ship

Last, a hull is looked for which problems might arise with the order of the control points. To prevent this problem a constraint has been used (see also Section 5.2.3). These hulls have a high main-frame coefficient, low block coefficient and a low length, such that rows of control points cluster around the main-frame. Characteristics and geometry can be found in Table 7-3 and Figure 7-2 respectively.

Table 7-3: Characteristics of the selected hull with control points concentrated near the mid-ship.

L_{wl} [m]	B_{wl} [m]	T [m]	β [deg]	C_B [-]	C_M [-]	C_P [-]	S [m^2]	∇ [m^3]	L/B	B/T	SL
63.12	13.61	2.22	20.24	0.4299	0.9473	0.4539	674.5	820.2	4.64	6.13	6.74

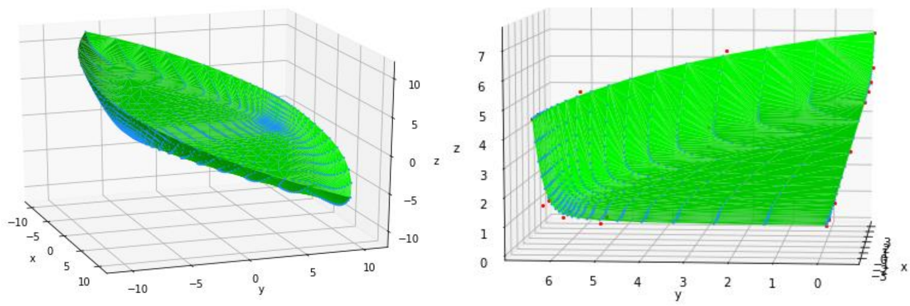

Figure 7-3: Geometry of the selected hull with control points concentrated near the mid-ship.

The control points are indeed close to each other around the mid-ship of the hull, as can be seen in figure above. However, this does not lead to fairing issues: the hull surface is well-faired and smooth. Inspection of the lines plan (Appendix N.3) also shows that there are not fairing or smoothing issues: all waterlines, buttocks and sections are well-faired. No weird or double curvatures can be seen.

7.1.4 Conclusions

Three hull shapes from the database for which high curvature can be expected have been analysed. It is shown that the hull surfaces are sufficiently smooth and well-faired, such that the hull shapes in the database can be used in the concept design phase. Only for a very slender hull some small issues were found in the waterlines, buttocks and sections. Nevertheless, these issues are assumed to be acceptable in the concept design phase. The rest of the hulls are well-faired and smooth enough, such that can be used in the concept design phase without any adaptions.

7.2 Sensitivity to changes in individual parameters

This paragraph describes the results of investigating how a change in an individual parameter affects the results, both for the geometry and the resistance. The goal is to check if the results in the database (i.e. the kriging predictions) are physically correct. The results which are used are obtained from the database by selecting hull shapes at specific values of the morphing parameters. First, Section 7.2.1 elaborates on results of the geometry. Section 7.2.2 focuses on verifying the resistance results.

7.2.1 Geometry

For the geometry hulls have been looked up at specific values of the morphing parameter. Every time only one morphing parameter is 'varied', thus keeping the rest of the parameters unchanged. First the variations in the length are checked.

Varying the length

For the length 5 hulls are looked up in the database. The morphing parameter of one of these hulls is zero for all variables, such that this hull is effectively the same as the base hull. The characteristics of all hulls can be found in Table 7-4, while the hull geometries can be seen in Figure 7-4.

It can be seen that while varying the length, almost all parameters remain unchanged. Only the entrance angle decreases for increasing length. This is a consequence of the way in which the prolonged hulls are 'scaled': the control points shift forwards such that the ratio of the midship section and the forward part changes. Logically, the wetted surface and displacement become larger for longer hulls as well.

The same happens for the **beam**: the entrance angle, wetted surface and displacement increase for increasing beams. The only difference is that in that case the length overall remains unchanged but the beam overall is increasing. Therefore the beam is not analysed any further.

Table 7-4: Characteristics of varied and base hull shape for varying the length.

PAR_L	L_{wl} [m]	B_{wl} [m]	L_{oa} [m]	B_{oa} [m]	C_b [-]	C_p [-]	C_m [-]	β [deg]	S [m^2]	∇ [m^3]
-0.8	67.04	16.43	70.06	19.77	0.5685	0.7616	0.7464	45.34	975.7	1389.9
-0.4	80.23	16.43	83.84	19.77	0.5685	0.7616	0.7464	40.22	1167.7	1663.3
0	93.42	16.43	97.62	19.77	0.5685	0.7616	0.7464	36.00	1359.6	1936.5
0.4	106.61	16.43	111.40	19.77	0.5685	0.7616	0.7464	32.48	1551.6	2209.9
0.9	119.80	16.43	125.18	19.77	0.5685	0.7616	0.7464	29.53	1743.5	2483.3

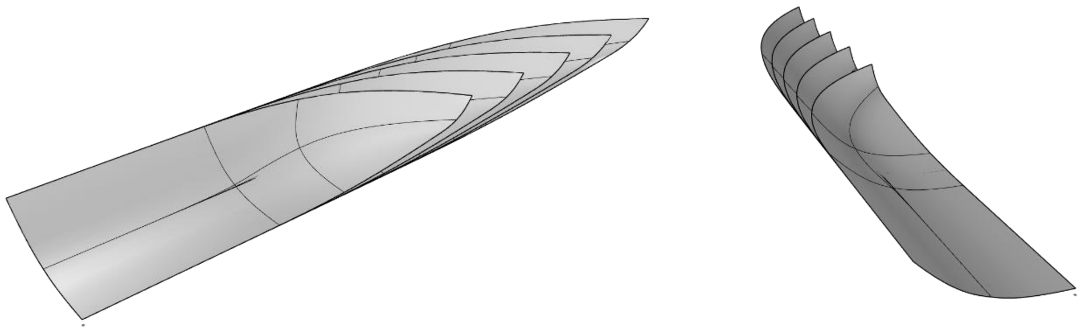

Figure 7-4: Geometries of hull shapes for varying length from two perspective views.

Varying the entrance angle

The same approach as for the length is followed. Five hulls with different entrance angles are looked up, of which the characteristics can be found in Table 7-5.

Table 7-5: Characteristics of varied and base hull shape for varying the entrance angle.

PAR_β	L_{wl} [m]	B_{wl} [m]	L_{oa} [m]	B_{oa} [m]	C_b [-]	C_p [-]	C_m [-]	β [deg]	S [m²]	∇ [m³]
-0.45	91.49	16.33	97.64	19.77	0.5126	0.6917	0.7411	27.32	1233.3	1700.1
-0.225	92.46	16.38	97.63	19.77	0.5404	0.7266	0.7438	31.14	1295.7	1816.7
0	93.42	16.43	97.62	19.77	0.5685	0.7616	0.7464	36.00	1359.6	1936.5
0.45	95.30	16.52	97.60	19.77	0.6225	0.8281	0.7517	50.51	1487.2	2176.0
0.9	97.11	16.62	97.57	19.77	0.6757	0.8926	0.7569	74.50	1617.3	2420.9

In contrary to the beam and length, more parameters are changing at the same time now. For increasing entrance angle it can be seen that the waterline length and all form coefficients are increasing. Especially the change of the length overall and the main-frame coefficient are not intended. These effects can also be seen in the hull geometries in Figure 7-5. Figure 7-6 shows a detailed view of the bow, showing the small difference in the length overall.

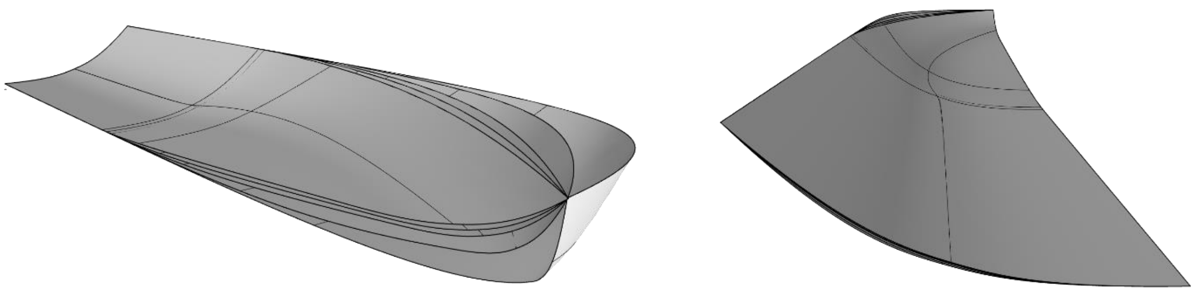

Figure 7-5: Geometries of hull shapes for varying entrance angle. The right picture shows that the main-frame coefficient is also influenced by varying the entrance angle.

Similar offsets are also present when varying the **main-frame** and **block coefficient**, causing a change in other parameters while individually changing one of these parameters.

The effects illustrated in Figure 7-5 are caused by the fact that the parameters used for parameterizing the base hull of the CFD dataset cannot be varied individually, as was described earlier in Section 5.1.1. The effect illustrated in Figure 7-6 is caused by another issue: there are very small deviations (in the order of millimetres) between specific points of the parent hulls. This was not discovered earlier, as it only becomes visible when a large morphing parameter is chosen for some of the parameters.

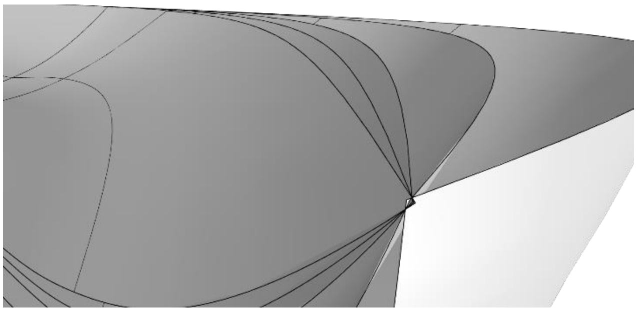

Figure 7-6: Detailed view of the bow of hull shapes for varying entrance angle, showing that the length overall is also influenced by varying the entrance angle.

Nevertheless, when this occurs the resulting geometries are smooth and well-faired, such that they can be used in the design process. However, for aesthetic reasons it is unwanted, such that it is recommended to make sure that all extreme hull shapes have exactly the same characteristics as the base hull, except for the parameter of which the hull is the extreme. This will also contribute to being able to pre-define the main dimensions of the hull shapes in the database before starting the filling process.

The same results are obtained for varying the **main-frame** and **block coefficient**: there are offsets but the hulls are all smooth and well-faired. For these reasons the analysis of those geometries is not further described. Next, the resistance results are checked.

7.2.2 Resistance

For checking the resistance all hulls are looked up which correspond to the change of an individual parameter, while keeping the displacement fixed. Keeping the displacement of the hull constant makes sure that the change in resistance is not caused by a change in displacement. The results are used to see how a change of an individual, non-dimensional parameter (used for resistance regression) would influence the resistance.

Varying L/B-ratio

For finding the sensitivity of the resistance to the L/B-ratio two parameters can be varied: the length and the beam. The resistance results obtained by varying the length can be seen in Figure 7-7. Four hulls have been selected which have a displacement of approximately 1590 m^3, while the maximum difference in displacement is only 0.17 m^3.

It can be seen that for a higher L/B-ratio leads to a lower resistance. This is as expected, as a more slender hull causes a relatively lower pressure resistance. This decrease should be lower than the increase of the wetted surface. Results for the separate resistance components can be seen in Figure 7-8 and Figure 7-9. Hence, increasing the L/B-ratio indeed causes higher viscous resistance but lower pressure resistance.

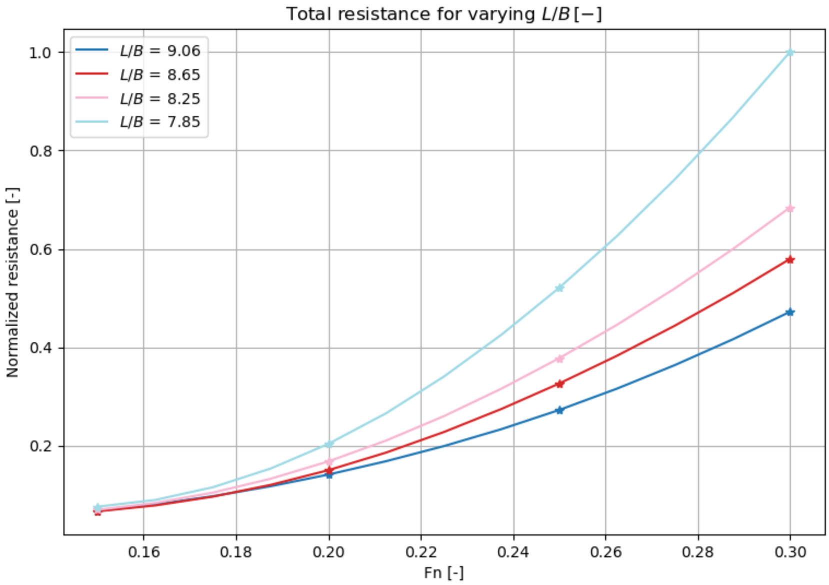

Figure 7-7: Total resistance results for hulls with various L/B-ratios created by varying the length.

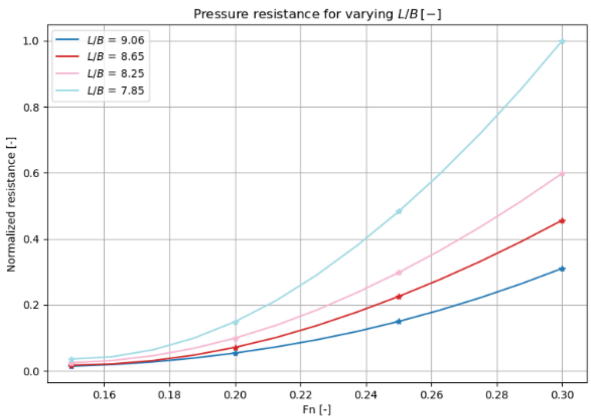

Figure 7-8: Pressure resistance for various L/B-ratios.

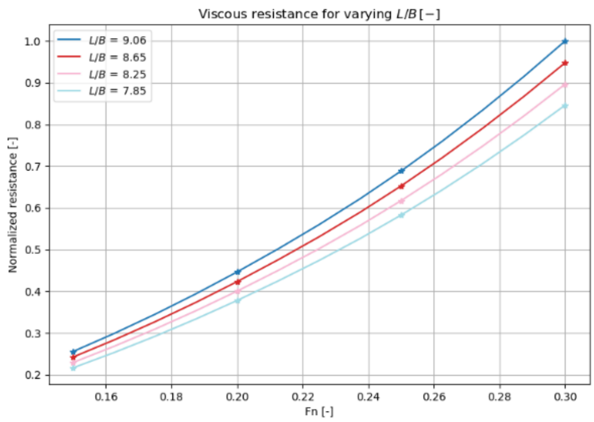

Figure 7-9: Viscous resistance for various L/B-ratios.

In the next section a higher B/T-ratio is analogous to a lower L/B-ratio. There, it can be seen that a lower L/B-ratio leads to a higher resistance. This is also physically correct, as the length in that case is fixed and a higher beam indeed would lead to a higher resistance.

Varying B/T-ratio

For varying the B/T-ratio only the beam can be varied. The corresponding resistance results are presented in Figure 7-10. Three hulls are selected with a displacement of approximately 1590 m^3, with a maximum difference of 0.44 m^3.

It can be seen that for increasing B/T-ratios the resistance decreases, especially at higher speeds. This is a consequence of the fact that the displacement is kept constant. By doing so, the block and prismatic coefficient will decrease for higher B/T-ratios such that a more streamlined hull is obtained. Effectively, the pressure resistance will increase, having most effect at higher speeds. Due to the lower coefficients the waterline length will decrease as well. Despite the higher beam, the total wetted surface will consequently decrease. Thus, the viscous resistance also decreases for higher B/T-ratios. Both effects can be seen in Figure 7-11 and Figure 7-12.

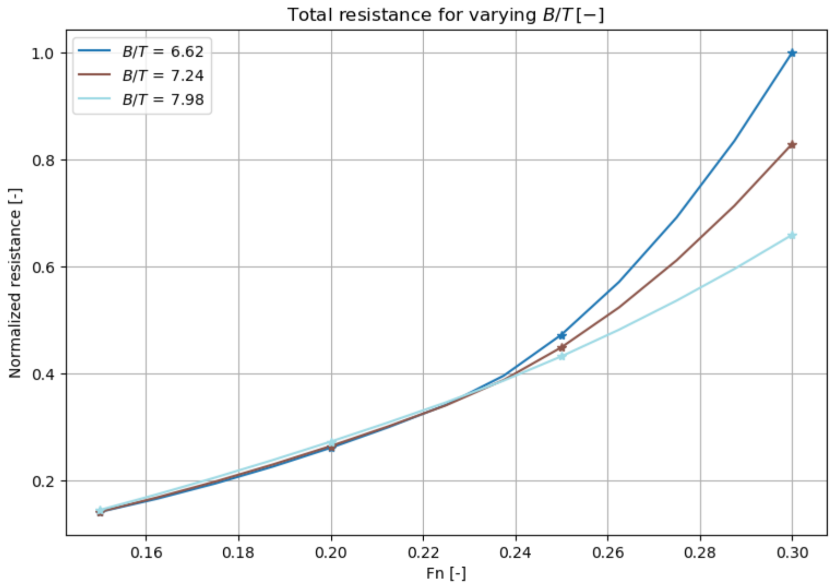

Figure 7-10: Resistance results for hulls with various B/T-ratios.

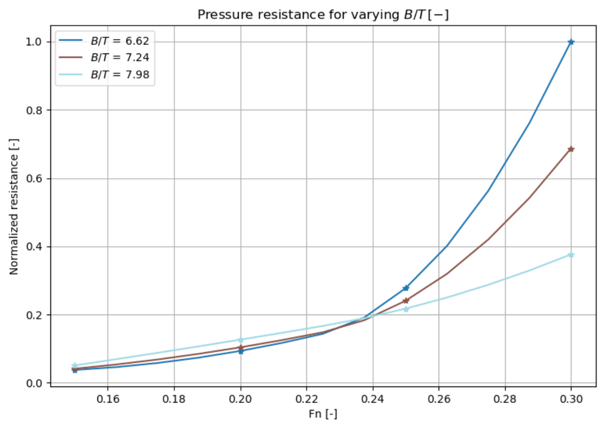

Figure 7-11: Pressure resistance for various B/T-ratios.

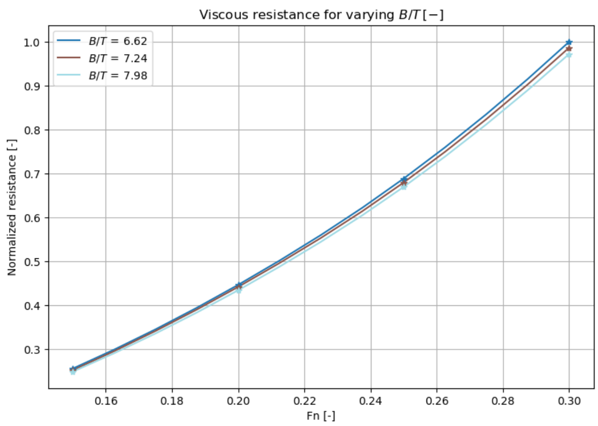

Figure 7-12: Viscous resistance for various B/T-ratios.

Varying slenderness ratio

The slenderness ratio can only be examined by changing the length of the hulls, if the displacement should be fixed. This thus results in exactly the same graph as in Figure 7-7, but the increasing L/B-ratios would have to be replaced by increasing SL-ratios. The plot for the slenderness ratio is therefore not presented. Effectively, increasing SL-ratios would lead to a lower ship resistance, which is also as expected in this case.

Varying entrance angle

The resistance results for the variation of the entrance angle can be seen in Figure 7-13. Again, the displacement is fixed and amounts 1590 m^3. The maximum difference is 0.88 m^3. As expected, changing the entrance angle at the waterline mostly effects the pressure resistance: it increases for higher entrance angles. The viscous resistance also increases, since the net wetted surface increases. Plots for the separate resistance components are not shown: the pressure resistance has the same trends as the total resistance, and the viscous resistance are almost straight lines with the expected behaviour. Hence, the effect of varying the entrance angle is also physically correct.

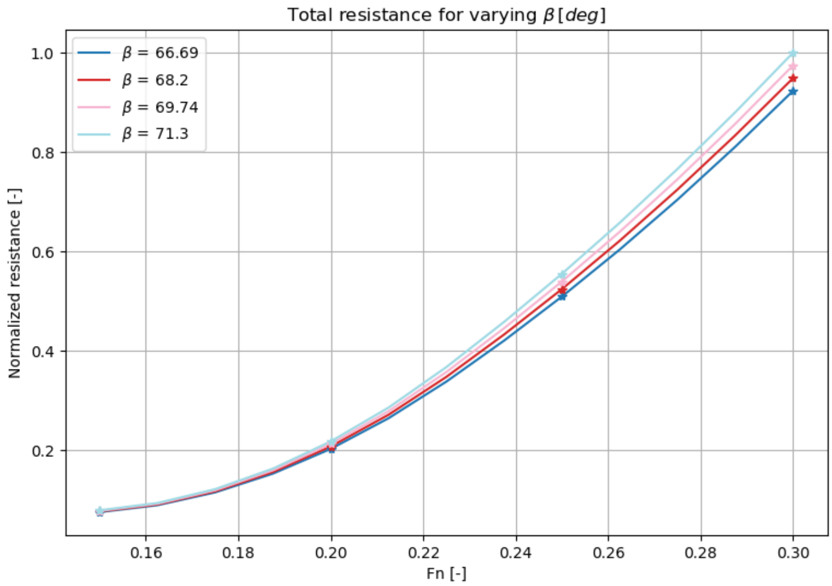

Figure 7-13: Resistance results for hulls with various entrance angles.

Varying prismatic coefficient

The effect of the prismatic coefficient is investigated by only varying the main-frame coefficient. Finding a variety of hulls for which only the form coefficient is varied is hard, so the block coefficient is also allowed to vary. The geometry of the hulls is shown in . Consequently, the displacement also varied a bit, but can still be considered to be fixed. The hulls with the prismatic coefficients of 0.7377 and 0.7616 have a displacement of 1994.3 and 1936.54 respectively. The other hulls have displacements ranging from 1907.0 to 1942.0 m^3. The resistance results can be seen in Figure 7-15.

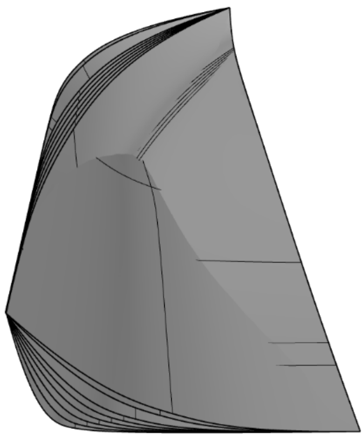

Figure 7-14: Geometry of the hulls with varying main-frame coefficients.

A higher main-frame coefficient is analogous to a lower prismatic coefficient, as the displacement is approximately fixed. Effectively, decreasing the prismatic coefficient leads to a more narrow hull, such that is expected that the pressure resistance decreases. The viscous resistance remains approximately unchanged. Both resistance components are shown in Figure 7-16 and Figure 7-17.

Hence, it can be concluded that the effect of the prismatic coefficient on the resistance is also correctly modelled. Another interesting effect that can be recognized is that increasing the prismatic coefficient increases the non-linearity of the pressure resistance. Effectively, the non-linearity of the total resistance also increases for higher prismatic coefficients.

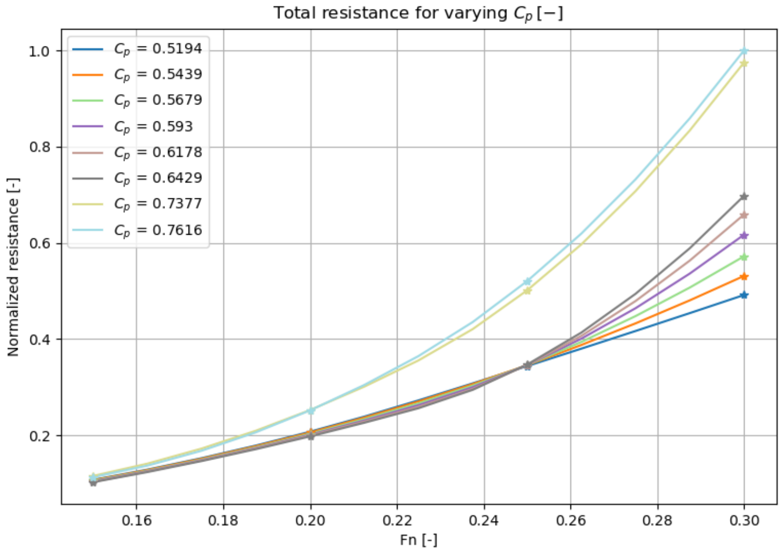

Figure 7-15: Resistance results for hulls with various prismatic coefficients.

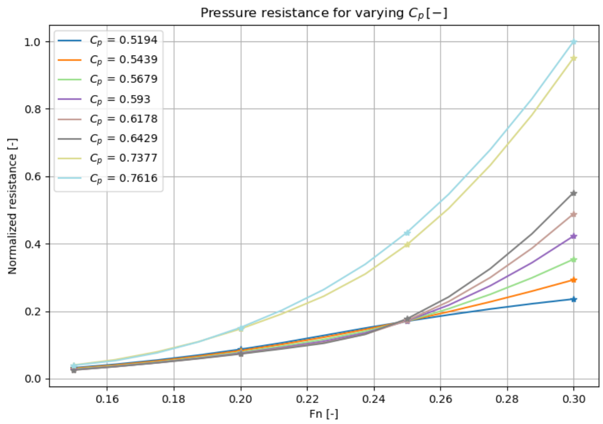

Figure 7-16: Pressure resistance for various B/T-ratios.

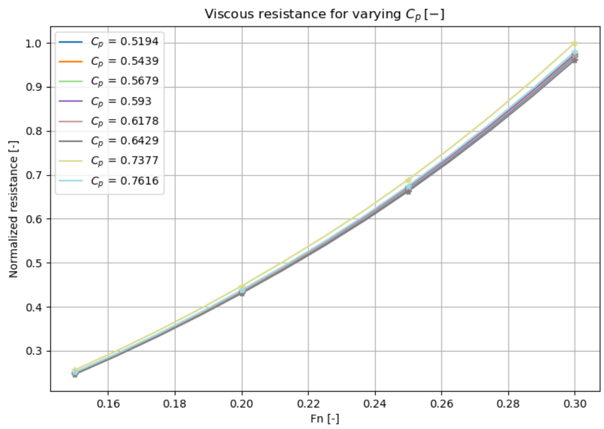

Figure 7-17: Viscous resistance for various B/T-ratios.

Varying block coefficient

In order to vary the block coefficient while fixing the displacement, only the length and beam can be varied (the draft is fixed for all hulls). This is already done for finding the effect of varying the L/B-ratio and B/T-ratio. Effectively, for increasing both the L/B-ratio and B/T-ratio a more streamlined hull is obtained when the displacement is kept constant, such that the block coefficient reduces. From those findings it can thus be concluded that reducing the block coefficient leads to a lower resistance. From the variation of the prismatic coefficient the same conclusion can be drawn, as increasing the prismatic coefficient is analogous to increasing the block coefficient for an approximately constant displacement.

7.2.3 Conclusions

The sensitivity study shows that for changing the individual parameters satisfying results are obtained. All geometries are well-faired and smooth, confirming the finding from Paragraph 7.1. However, offsets of certain parameters between the base and extreme hulls cause unwanted distortions in the created geometry. Nevertheless, the resulting hull shapes are useful in the design process.

The resistance results seem satisfying for changing individual parameters while keeping the rest of the parameters unchanged. No strange or unrealistic trends have been found: each variation of a non-dimensional parameter led to a resistance change which could be explained by physics. The next paragraph describes the effects of changing parameters on the resistance in more detail.

7.3 Resistance outcomes for 'in-between' hulls

Next, some checks are done which can tell if the resistance predictions are done accurately if multiple parameters are changed simultaneously. This is done by looking up a hull from the database and comparing it to 2 hulls from the CFD dataset. The approach is to first find two hulls from the CFD dataset of which the characteristics are similar, but still not similar enough such that a hull shape can be defined which is in between those two hulls. This last hull shape is looked up in the database, by using intermediate values of the characteristics of the hulls from the CFD dataset.

Subsequently, all resistance results are plotted and compared. In theory the resulting resistance from the 'database hull' should be somewhere in between, as the three hull shapes have similar shapes. The resistance results could then be scaled theoretically. This is only true if all characteristics of the database hull are in between the values of the hulls from the CFD dataset. Four different cases are analysed, which are described next.

7.3.1 Case 1

For the first case the hulls in Table 7-6 have been used. Hull 1 and 2 are hulls 6 and 7 from the CFD dataset respectively, as defined in Appendix F.2. This results in the resistance curves in Figure 7-18.

Table 7-6: Characteristics of hulls for case 1.

	L_{wl} [m]	B_{wl} [m]	β [deg]	C_B [-]	C_M [-]	C_P [-]	S [m^2]	∇ [m^3]
Hull 1	73.3	9.1	18.9	0.440	0.631	0.696	676	688
Database hull	74.80	10.12	22.82	0.4999	0.7079	0.7062	733.6	840.4
Hull 2	77.7	10.6	26.4	0.573	0.806	0.711	855	1080

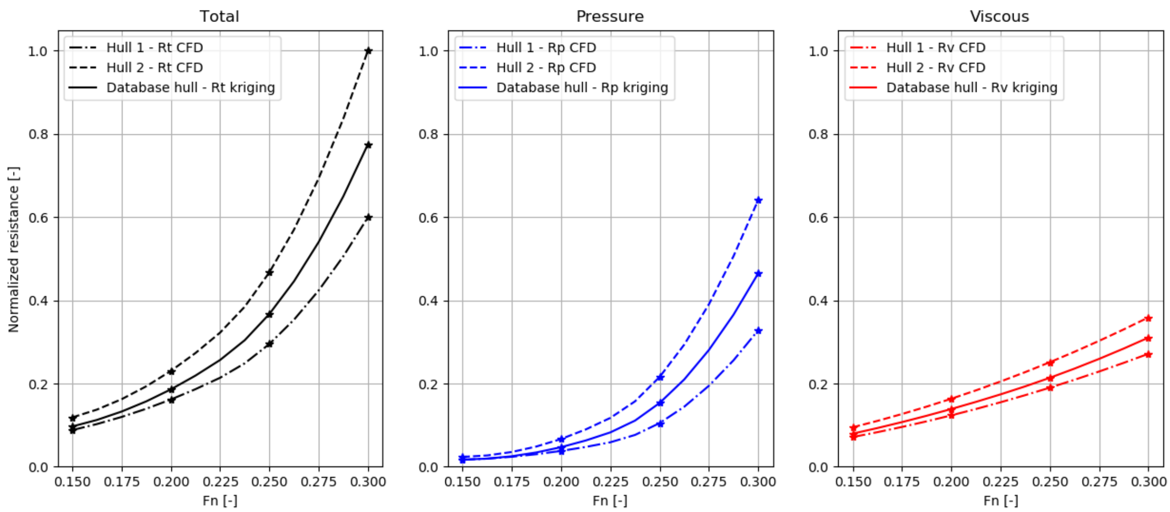

Figure 7-18: Resistance results for case 1.

It can be seen that the resistance prediction from the database is situated in between the results from the CFD dataset. For hull 1 the viscous component is dominating until higher speeds (approximately Fn = 0.28), while for hull 2 the pressure component becomes dominant at approximately Fn = 0.26. It can be concluded that in this case the kriging model provides an accurate prediction for both resistance components, and the resulting total resistance is correctly modelled as well.

7.3.2 Case 2

For the second case hulls with different shapes have been selected: lower prismatic and block coefficients and a higher main-frame coefficient. These hull shapes have more displacement located around the mid-ship and less in the forward and aft parts, consequently resulting in a different resistance composition. The characteristics are shown in Table 7-7.

Table 7-7: Characteristics of hulls for case 2.

	L_{wl} [m]	B_{wl} [m]	β [deg]	C_B [-]	C_M [-]	C_P [-]	S [m²]	∇ [m³]
Hull 1	89.0	15.0	16.0	0.429	0.937	0.457	1140	1330
Database hull	93.00	16.94	18.40	0.4616	0.9414	0.4903	1196.5	1613.9
Hull 2	93.9	18.0	24.1	0.543	0.945	0.574	1520	2090

Resistance results are presented in Figure 7-19. It can be seen that the viscous resistance component is correctly estimated, as it is in between the two hulls from the CFD dataset. It is closer to the results from hull 1, which can be expected as the wetted surface is also more similar to that of hull 1. The pressure component is not modelled correctly, as the predictions at Fn = 0.25 and 0.30 are too low. This is not expected as the characteristics of the database hull in Table 7-7 are all in between the values of the CFD hulls. Effectively, the total resistance is not modelled correctly.

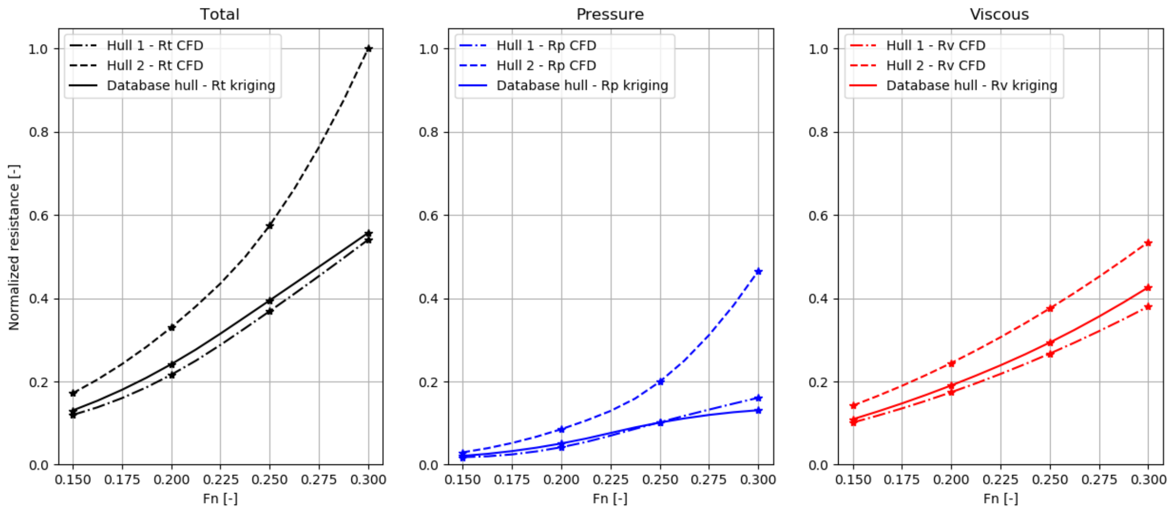

Figure 7-19: Resistance results for case 2.

However, it should be noted that the pressure resistance curve from hull 2 has a strange shape, as it has a linear trend instead of a second- or third-degree polynomial trend. These last trends are typical for the pressure resistance. It can be expected that the kriging model for the pressure resistance is disturbed by these values, such that is produces incorrect predictions at nearby locations. However, in order to verify this assumption the intermediate values of all steps in the kriging procedure should be assessed, which is not done in this thesis.

Another issue is that there are not many hulls in the CFD dataset with relatively low values for the prismatic coefficient. Hull 1 from this case is in fact the hull with the lowest C_p, and the second-lowest value is 0.542. For now it is therefore concluded that the coverage of the prismatic coefficient is insufficient to provide a resistance prediction for hulls with a prismatic coefficient of approximately 0.5.

7.3.3 Case 3

Next, hulls with a slightly higher prismatic coefficient are selected, as it is interesting to see if this provides better results than the second case. The characteristics can be found in Table 7-8. It should also be noticed that in this case the beam and the main-frame coefficient of the second hull are smaller, such that the shapes of the hulls are quite different. Resistance results are shown in Figure 7-20.

Table 7-8: Characteristics of hulls for case 3.

	L_{wl} [m]	B_{wl} [m]	β [deg]	C_B [-]	C_M [-]	C_P [-]	S [m²]	∇ [m³]
Hull 1	98.4	14.7	17.2	0.509	0.940	0.542	1320	1690
Database hull	99.35	14.02	19.84	0.5412	0.8670	0.6242	1252.9	1673.3
Hull 2	99.7	13.7	26.9	0.583	0.798	0.730	1330	1790

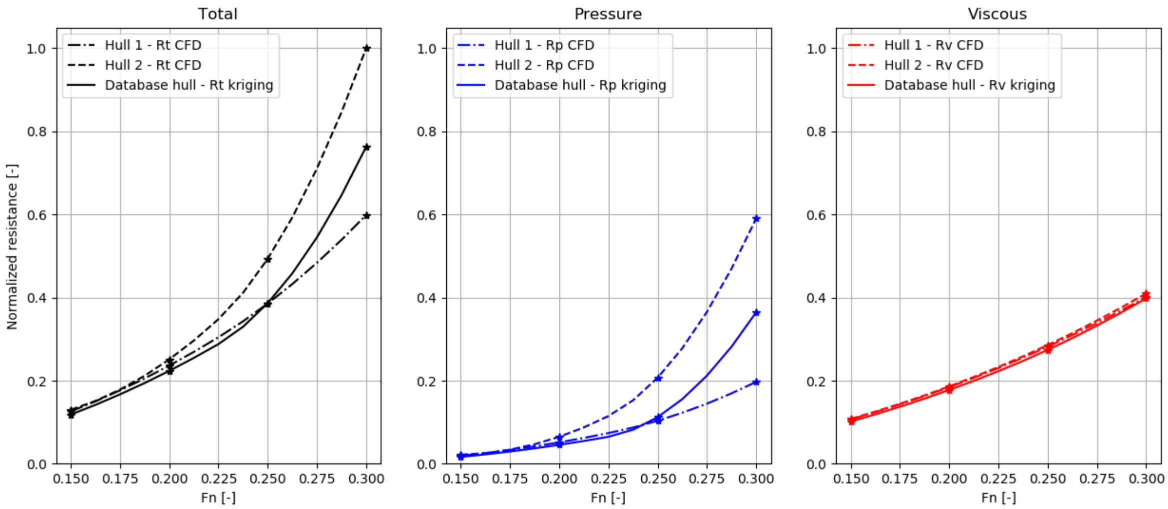

Figure 7-20: Resistance results for case 3.

In the viscous resistance plot it can be seen that these results are very similar, which is not strange due to the wetted surfaces of the CFD hulls which are almost equal. Since the wetted surface of the database hull is smaller, it is also not strange that its viscous resistance is a bit lower than the viscous resistance of hulls 1 and 2.

The pressure resistance is probably better predicted than in case 2, but still not fully satisfying. At low speeds it seems underestimated, as it is lower or equal to the results of hull 1. This similarity is probably caused by the common low values for the entrance angle, causing low pressure resistance. At higher speeds the values seem to be predicted more accurately, as it is in between the two CFD hull shapes. The general trend of the pressure resistance curve is more natural compared to case 2, probably caused by the higher value of the prismatic coefficient.

It should be noted here that the odd shapes of the pressure and total resistance curve are partly caused by the fact that these curves are approximated by a 2^{nd}-degree B-spline curve. By using this simplification, the curve wrongly represents the prediction between the Froude numbers of 0.20 and 0.25. Thus, it is in this case better to only look at the actual predictions (the stars in the figure) than to look at the curve. Nevertheless, the resistance can still be expected to be underestimated at the lower speeds.

7.3.4 Case 4

For the last case some larger, fuller hulls have been selected, which can be seen in Table 7-9. The resistance results are shown in Figure 7-21.

Table 7-9: Characteristics of hulls for case 4.

	L_{wl} [m]	B_{wl} [m]	β [deg]	C_B [-]	C_M [-]	C_P [-]	S [m^2]	∇ [m^3]
Hull 1	115.4	15.4	20.0	0.501	0.762	0.658	1630	2060
Database hull	117.63	16.09	24.98	0.6128	0.8906	0.6880	1779.8	2574.1
Hull 2	119.7	17.8	38.1	0.705	0.935	0.754	2150	3380

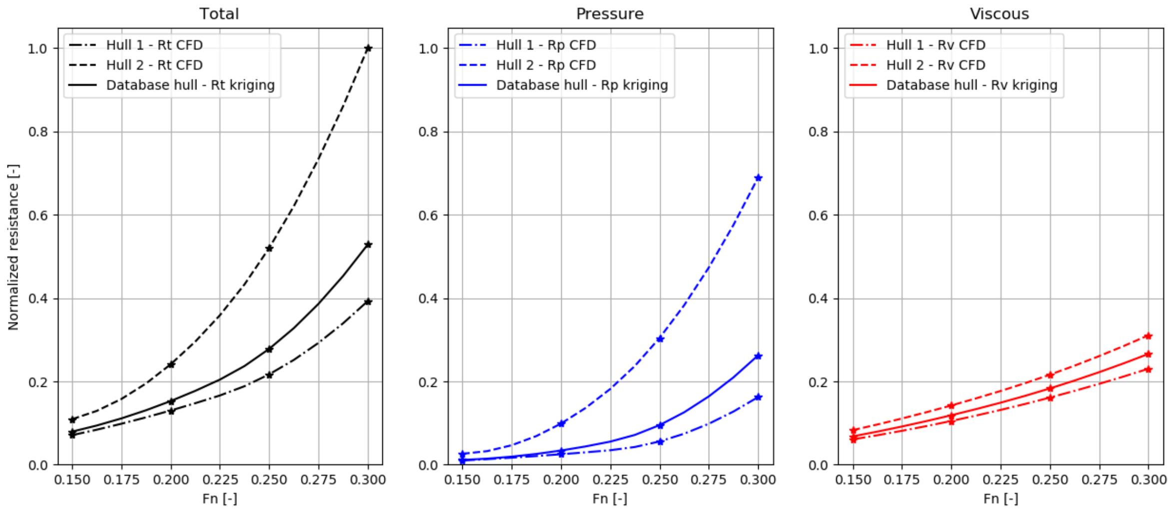

Figure 7-21: Resistance results for case 4.

It can be seen that for both resistance components the result is in between the results from the CFD hulls. Both components tend to go towards hull 1, which is as expected as the characteristics of hull 1 and the database hull are more alike. Similarly for case 1, it can be assumed that the resistance components of the database hull are correctly predicted.

7.3.5 Conclusions

It has been shown that the resistance prediction done with kriging for the viscous resistance is often accurate. In relation with hulls from the CFD dataset it seems that realistic results are obtained. This is not always true for the pressure resistance component. Especially for hulls with a low prismatic coefficient (below approximately 0.6) the pressure component shows unrealistic behaviour such that trend of the resistance curve is wrong. It seems that an the results become more accurate for higher prismatic coefficients (above 0.65), such that the pressure resistance is correctly modelled.

It can be expected that these inaccuracies disappear when hulls with low prismatic coefficients are added to the CFD dataset. Specifically for OPVs, an improvement could be to also use the longitudinal position of the centre of buoyancy (LCB) as an additional regression parameter, as this parameter is also correlated to the pressure component of ship resistance [76].

7.4 Leave-one-out cross-validation

For tuning and selecting the kriging model leave-one-out cross-validation was applied in Section 5.4.4. It can also be used to assess the prediction performance of the model, such that it is a replacement for doing actual CFD as verification. This paragraph focuses on describing the results of the leave-one-out cross-validation study, in order to provide a quantification of the accuracy. The required steps to perform leave-one-out cross-validation can be found Section 5.4.4. Only the results from the are presented here.

Some selected resistance curves can be found in Appendix M. The results for all cases are summarized below.

- For relatively low prismatic coefficients (<0.6) the uncertainty bound is relatively wide. This is caused by the scarcity of hulls with low prismatic coefficients in the CFD dataset.
- For the pressure resistance at least one of the CFD resistance results is outside of the uncertainty bound of the prediction in 8 of the 25 cases.
- For the viscous resistance at least one of the CFD resistance results is outside of the uncertainty bound of the prediction in 1 of the 25 cases.
- For the total resistance at least one of the CFD resistance results is outside of the uncertainty bound of the prediction in 5 of the 25 cases. At the highest speed (Fn = 0.3) the CFD result is only once outside the uncertainty bound of the prediction.
- In general, the uncertainty bound of the pressure resistance is larger than the uncertainty bound of the viscous resistance.
- The size of the uncertainty bound is in the order of 10% to 14% of the total resistance. At the same time the size of the actual error is typically in the order of 4% to 7% of the total resistance.

Based on these results the following conclusions are drawn.

- The pressure resistance component is more difficult to predict than the viscous component, most likely caused by the non-linearities in the relationship between the pressure resistance and the speed, as also described in Section 5.4.4.
- The model is not accurate enough to predict the pressure resistance for low prismatic values, approximately below 0.60.
- Still, in most of the cases the separate resistance components and also the total resistance can be estimated quite accurately, especially at the highest speed. The sizes of the errors seem acceptable to be used in the concept phase of ship design.

If the accuracy is not sufficient, a possibility is to use a multi-fidelity procedure to increase the accuracy of the kriging predictions. A good example is provided by MARIN [42], which combined cheap, low-fidelity CFD such as potential flow with expensive, high-fidelity RANS CFD. The correlation between the low- and high-fidelity resistance response surface are used to set up an additional prediction method that transforms the low-fidelity resistance results to high-fidelity resistance results. Since the low-fidelity CFD is computationally cheaper, more simulations can be done. Effectively, by using this multi-fidelity procedure one can obtain a lot more hull shapes with the accuracy from high-fidelity RANS. The amount of hulls in the CFD dataset would increase, which would increase the accuracy of the resistance predictions.

Next, validation of the conceptual design tool is done.

7.5 Validation of the design tool

The previous paragraphs have focused on verifying the results in the database. It was checked whether the tool is built right, and if the model behind the tool provides the right quantitative results. This paragraph focuses on checking if the right tool is built: validation. This is done by comparing the current concept of the design tool to the functional requirements which have been defined in

Chapter 3, which is described in Section 7.5.1. Implications of using this design tool for a future OPV CFD dataset are described in Section 7.5.2.

7.5.1 Comparison the concept with the requirements

Use and goals of the tool

It has been defined that the tool will be used to obtain first versions of the hull shape in the concept design phase. It should also provide a resistance prediction, hydrostatics and other relevant characteristics. The defined goals of the tool were (1) to increase the speed of the design process, (2) to get more insight in the design problem and (3) to be an integral platform such that fewer stakeholders are involved.

The current database has been filled with hull shapes which are all provided with a resistance prediction, hydrostatics and other relevant characteristics. The local sensitivity of the resistance to changes in the regression parameters has been assessed for each hull shape, providing insight in how the performance of a hull shape can be improved. The geometry is saved and can be used for exporting to other software. For providing insight several hull previews are saved, and scatter plots showing the selected hull in the design space of the CFD dataset are generated. Hence, all desired functionalities are being fulfilled by the design tool, such that the functional requirements are met.

It is estimated that the current database contains enough hulls to find a first hull shape in the concept design phase. More hull shapes can in theory by added by choosing a more fine input grid of morphing parameters. This does not have to be at the expense of computation time, as it can be significantly shorted.

It can be expected that this tool speeds up the current design process. D&P engineers will have the ability to get a hull shape right away, saving several hours on manual drawing or hull transformations, or even several days if other departments have to be consulted. Several days are also saved on the resistance prediction as often other departments are consulted for expert advice. These aspects also contribute to being an integral platform: the R&D department can manage the database and the D&P department can use the database at the same time, without actually being in contact with each other. Further validation of these goals can be done by actually letting test engineers use and review the tool.

In theory the tool also provides more insight in the design problem. The designer has the ability to directly see how a change in input affects the resistance, which is represented in the GUI mock-up. By adding more design aspects in modules even more insight can be gained. This goal can be further validated, by letting D&P engineers actually using the tool and checking if gained insights actually lead to better designs.

Other requirements

The non-functional requirements describe the criteria which can be used to assess the functioning of the tool. However, since the actual GUI has not been developed yet some of these requirements are not met yet. The most important requirements which have been met are that the hull geometries are sufficiently smooth and that the resistance prediction is assumed to be accurate enough for use in the concept design phase. Additionally, hull shapes are saved in formats which can be exported in Rhino, improving the workflow in the design process. Overviews of the working principles of models behind the tool are presented in this thesis, and can be integrated in the GUI for representation. Furthermore the current GUI can be adapted to other ship types.

Hence, the most important non-functional requirements have been met. After developing the GUI the rest of the requirements can be tested.

7.5.2 Application of the design tool to OPVs

The current proof-of-concept of the design tool has been developed by using a CFD dataset of double-ended ferries. However, the goal of this thesis is to set up a tool for rapid concept generation of hull shapes of Offshore Patrol Vessels. Exchanging the current CFD dataset by a dataset of OPVs is not trivial, but could have disadvantageous consequences which need to be addressed.

First, the hull shapes are significantly different. The hull shape of a DEF is a very simple shape compared to an OPV. The OPV might include a bulbous bow and tunnels in the aft ship. Additionally the OPV is not symmetrical with respect to the midship, such that half of the hull shape needs to be modelled instead of only a quarter. Therefore the amount of control points of an OPV will certainly be higher, and more rows of control points will be present. This could lead to more optional shapes to be created by morphing, of which a part will be undesired and unrealistic. These hull shapes should be analysed in order to define constraints that can be used during the filling process of the database, such all unwanted and infeasible hull shapes are filtered out. It can also be expected that the computation time per hull increases, as morphing loops over all control points. It is beneficial if the number of control points of the base and extreme OPV hulls is as little as possible.

The different shapes of these hull shapes will affect the resistance results as well. Specific design details such as the immersion of the transom or a bulbous bow will have a significant effect on the performance, mainly on the pressure resistance. They can be considered as additional design parameters and will make the resistance prediction more complex for sure. This thesis has not investigated if kriging models are suitable to capture the effects of applying these details. Nevertheless, procedures can be introduced which take into account different CFD datasets, i.e. one with hulls with a bulb and the other with hulls without a bulb. In that way the model and database can still be applied such that the resistance behaviour is correctly modelled.

These details also need to be addressed when setting up the morphing procedures. Using morphing for local and global deformations might not be possible, since the position of the local details is depending on the degree of morphing for the global deformation. The application of morphing for these local details should therefore be investigated thoroughly. It might be a good idea to create separate modules in the design tool which can be used to apply one of the local details, and in which morphing can be applied to investigate influence of the shape of the local detail on the performance of the hull.

Nevertheless, the principle of the database which is used by the GUI for loading hull shapes can certainly be applied to OPVs. Only setting up the methods used to create variations and provide a resistance prediction will certainly be a more complex task than for DEFs.

7.5.3 Conclusions

The current concept tool has been tested against the pre-defined requirements. It can be concluded that the tool lives up to all functional requirements and some of the non-functional requirements. The rest of the non-functional and the external interface cannot be tested until a working GUI is finished, which is not done in this thesis. Summarizing, the work which is done in this thesis meets the requirements.

The design tool can also be applied to other ship types, especially to OPVs. It is expected that OPV hull shapes will have more control points and local details such as tunnels and a bulbous bow. For creating the geometry additional constraints probably have to be added, separate modules for local details have to be included and computation time of morphing will increase. Also the resistance prediction will become more complex, but still it can be assumed that kriging can be used for predictions. In general it can be concluded that the preparations for filling a database will become more complex since OPVs have more complex hull shapes than DEFs, but the current concept of the design tool will still be appropriate.

As the most important requirements are met by this design tool, it can be concluded that the design tool will also satisfy the needs which have been defined in Section 2.4.2. It is, therefore, an effective tool to (1) speed up the design process, (2) provide insight to the designer and (3) be an integral platform such that fewer departments consults each other.

7.6 Conclusion

The goal of this chapter is to answer the last two (6th and 7th) sub-questions, which are repeated below. The sixth question focuses on verification, while the seventh question focuses on validation. Effectively, this should say something about the trustworthiness of the results in the database, thus basically checking the research results.

> *How well does the approach perform in generating hull geometries and predicting the resistance of that new geometry?*

> *How effective is the conceptual design tool as an instrument for D&P engineers to satisfy their needs?*

Paragraphs 7.1 and 7.2 showed that the geometries in the database are sufficiently smoothed and well-faired to be used in the concept design phase. This has been done by examining various hull shapes at which high curvature is expected, and by looking up hull shapes from the database while varying individual parameters. However, offsets of certain parameters between the base and extreme hulls cause unwanted distortions in the creation of new geometry. As an effect, it cannot be pre-defined what the characteristics will be of the hull in the database. Nevertheless, the results in the database are useful, as the step size of parameters between hulls is sufficiently small.

For the resistance the Paragraph 7.2 showed that for changing individual parameters the kriging prediction provides logical results which can be physically explained. The behaviour of the model can be concluded to be correct. Thereafter, Paragraph 7.3 has learned us that the pressure prediction is more difficult to predict. For low values of the prismatic coefficient the pressure resistance component is incorrectly modelled. This can be improved by adding more hulls to the CFD dataset with low prismatic coefficients. Last, cross-validation (7.4) was done to see how the model behaves for smaller training sets and to compute numerical errors. Leave-one-out cross-validation confirms the results from Paragraph 7.3, and shows that the numerical errors are acceptable for use in the concept design phase.

Last, validation of the tool to the pre-defined requirements has been done in Paragraph 7.5. It is concluded that the tool meets most of the requirements. Some requirements are not met yet, as the GUI still has to be developed. It is concluded that the design tool is an effective measure to satisfy the needs that are present within Damen.

Effectively, the findings in this chapter have provided answers to the last two sub-questions. Hence, all research questions have now been answered, such that the main research question can be answered. This is done in the next chapter, Chapter 8, providing conclusions and recommendations as well.

8

Conclusions & Recommendations

After going through the analysis, solution development and verification & validation phases, the last phase is the closing phase. This chapter wraps up the thesis project by answering the research questions and checking whether the main research question is answered. Conclusions are drawn in Paragraph 8.1. Lessons-learned in this thesis are summarized in Paragraph 8.2, providing recommendations for further research and development.

8.1 Conclusions

The goal of this thesis report is to answer the **main research question**,

> *How can the efficiency of creating concept designs of Offshore Patrol Vessels be increased while using a brute-force approach for generating concepts?*

In order to answer the main research question seven sub-questions have been defined. The first sub-question aimed at finding the exact problems that that are present in the concept phase of the design process of OPVs, such that it is justified why the efficiency of that phase should be increased.

1. *Which problems are present in the current design approach of developing OPV concept designs?*

To answer this question the current design process of Damen has been thoroughly analysed in Chapter 2. It appears that bottlenecks are present in the form of the development of a hull shape and the first prediction of the resistance. They are the most important piece of information in the design process, and consequently additional attention is often given to these aspects. Due to the linear workflow, design mistakes and the general habit to go to another department for expert advice on these aspects, the whole concept design phase is often delayed. As an effect, more simplifications and assumptions are used, thus lowering the accuracy of the design, which on its turn increases the risk of project deviations. Consequently, there is a need to increase the efficiency of the concept design phase, meaning that (1) the speed needs to be increased, (2) the accuracy of concept designs need to be increase and (3) the risk of deviations of the project plan needs to be reduced.

In this thesis a conceptual design tool is developed to resolve these deficiencies and to satisfy these needs. This is done by populating a design space of hull shapes and resistance predictions with brute-force, such that this design space can be used for concept exploration in the design tool. For the development of this tool first requirements have been defined, which was the subject of the third sub-question.

2. *What are requirements for a design tool that supports and improves the current design approach?*

Specific requirements for the design tool have been defined in Chapter 3, providing functional, non-functional and external interface requirements. The functional requirements are the most important, as they define what the desired behaviour between input and output is. Three main functionalities of the tool are to (1) provide a hull shape, (2) predict the resistance of that new hull shape and (3) to provide insight in the performance of a hull shape and how the input affects this performance. In this thesis the resistance is used as primary performance indicator of a hull shape. To provide this output a dataset of hull shapes is used for which accurate Reynolds-Averaged Navier-Stokes (RANS) Computational Fluid Dynamics (CFD) simulations were performed to obtain the resistance. This CFD dataset was only available for double-ended ferries and was provided by Damen. It is used because a similar dataset for OPVs has not come available within the timeframe in which this thesis is conducted. Therefore, the CFD dataset of DEFs is adopted, such that a proof-of-concept can actually be developed.

Next, focus was given to the generation of new hull geometry and resistance predictions based on the CFD dataset. This led to the following sub-questions.

3. *Which alternative hull generation method is the most promising to support the design approach in order to satisfy the need to acquire a hull shape much faster?*
4. *Which surrogate model is the most promising to predict the resistance of a new hull shape based on CFD results of parent hull shapes?*

In Chapter 4 the outcomes of literature research into these topics have been described. For a hull generation method various partial parametric modelling techniques have been analysed: (1) swinging & shifting, (2) free form deformation, (3) radial basis function interpolation, (4) morphing and (5) added patch perturbation. Based on pre-defined requirements and a quantitative comparison morphing is selected for application in this thesis, as it can be seamlessly connected to the CFD dataset, could also be used for local deformations and allows for extrapolation of hull shapes. A new shape is generated by linear superposition of a multiple parent hulls. Next, four promising regression-based surrogate models have been analysed: (1) polynomial regression models, (2) radial basis functions, (3) kriging and (4) support vector regression. Again, based on pre-defining requirements a quantitative comparison is made. Kriging is selected for three main reasons: (1) it is suitable for complex, non-linear functions, (2) it provides an uncertainty estimate and (3) case studies show that it is the most accurate predictor for similar problems. Kriging models the regression observations as a Gaussian process, and the prediction is equal to the mean of this Gaussian process.

Hereafter, Chapter 5 focuses on describing how the theory of these two methods can be used in practice to populate a design space for concept exploration. The aim is to answer the fifth sub-question.

5. *How can the chosen hull generation and resistance prediction methods be applied in practice to populate a design space of new hull shapes?*

Effectively, the answer to this question is a description of the model that populates the design space, which can be seen in Figure 8-1. These steps have been described in detail in Chapter 5.

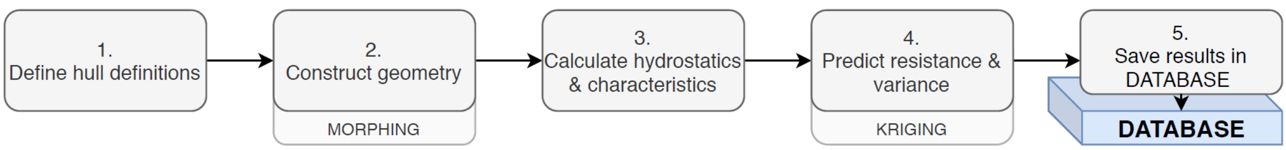

Figure 8-1: Strategy to populate the design space.

The end result is thus a database of hull shapes with corresponding resistance predictions, hydrostatics and other characteristics. It also contains the local sensitivity of the resistance to a change in the input parameters. The conceptual design tool loads results from this database and presents them to the designer in a Graphical User Interface (GUI).

To test this concept a proof-of-concept database of 245.005 hulls of double-ended ferries is generated in a few days on a laptop with good memory capabilities. Chapter 6 presents a summary of the database and a mock-up of the GUI that can be used to explore the concepts in the database. Next, verification and validation of the database results is done, which are the subjects of the last two sub-questions.

6. *How well does the design tool perform in generating hull geometries and predicting the resistance of that new geometry?*
7. *How effective is the design tool as an instrument for D&P engineers to satisfy their needs?*

Chapter 7 has described the answers to these questions. Assessment of the geometry in the database is done with a sensitivity study and inspection of specific hulls for which problems can be expected. It appears that the hull shapes created by morphing are smoothed and well-faired such they can be used in the concept design phase. It is concluded that the design tool will perform good in generating hull geometries.

The resistance predictions are assessed with a sensitivity study, leave-one-out cross-validation and comparison with the parent hulls. They are sufficiently accurate for use in the concept design phase, but applicability is limited for low prismatic coefficients ($C_p < 0.60$) as the pressure resistance prediction becomes inaccurate. Adding hulls with low prismatic coefficients to the CFD dataset could significantly improve this behaviour. In other regions of the design space the model shows more accurate results for the pressure resistance, and thus also for the total resistance. For the viscous resistance there are no issues, as it is easier to predict due to less non-linearities.

Last, the effectiveness of the tool is assessed by comparing the concept of the tool to the requirements from Chapter 3, in order to answer the seventh sub-question. As the GUI has not been developed and tested in this thesis, not all requirements are met yet. However, it can be concluded that all of the functional requirements have been fulfilled by realisation of the contents of the database. It can consequently be assumed that the developed concept of the design tool, after actually realising and testing of the GUI, will satisfy the needs that are present within Damen.

Having searched for, developed, and tested a solution, we arrive at the main research question again: ***How can the efficiency of creating concept designs of Offshore Patrol Vessels be increased while using a brute-force approach for generating concepts?***

In this thesis a conceptual design tool is developed to increase this efficiency, by providing a platform for fast hull concept exploration. Key of the design tool is that time-intensive design aspects are pre-computed, such that the most critical design activities are done before starting the design process. By using the CFD dataset in combination with a partial parametric modelling technique (morphing) and a surrogate model (kriging) it becomes possible to use a brute-force approach for filling a design space. The conceptual design tool uses that design space for concept exploration of hull shapes in the beginning of the concept design phase.

The tool seems very promising to actually improve the efficiency of the concept design phase, as it (1) reduces time pressure in the design process significantly, (2) provides insight in how the resistance is affected by main dimensions of the vessel, and (3) reduces the number of departments which is actively involved in the design process. When further optimizing the model and employ more powerful computational resources, it seems possible to actually generate all possible hull shapes.

The next section describes recommendations for further research and development. Possible improvements are presented as well.

8.2 Recommendations

8.2.1 Further research

In Paragraph 5.4 the kriging settings have been tuned, in order to find the settings which have the lowest computation time and the highest accuracy. While doing so it was found difficult to find a model that performs well at all 4 Froude numbers for which CFD was done: selecting another setting provided better results at one speed but worse results at another speed. This is not strange, as it can be seen in Appendix F.3 that the non-linearities of the resistance (especially the pressure component) become higher for increasing speeds. It is, therefore, expected that a set up in which a kriging model is selected and tuned for each prediction separately provides more accurate overall results. This would not result in an increase in computation time, as the number of predictions remains equal. It would only result in more preparations, as more models have to be selected and tuned. Further research into the application of different kriging models and settings for different speeds and resistance components is consequently recommended.

For application of the used models to the CFD dataset of OPVs some consequences have been described in Paragraph 7.5, stating that in that case additional design parameters would be a bulbous bow and tunnels in the aft ship. It is interesting to investigate how the combination of morphing and kriging can be applied in the case when local deformations should be taken into account as well. To do so, it is recommended to first conduct research into the possibility of setting up a set of base and extreme hulls which can be used for both local and global deformations at the same time. It is advantageous if this is possible, as it would not be necessary to create two parallel databases for one design parameter (e.g. one database with bulb and one database without bulbs). In both cases it would also be interesting to investigate automated design of the tunnels or bulbous bows, for example based on sizing of the hull. Additionally, the application of surrogate models for the cases with tunnels and bulbous bows is an interesting research topic. It is recommended to investigate how kriging or an alternative surrogate model should in that case be used to correctly predict the resistance, for hulls with and without these design features.

As appeared from the testing of the design tool in Chapter 7, the current error between CFD and kriging predictions is in the order of 4% to 7% of the total resistance. If this accuracy is not sufficient, it could be improved by employing multi-fidelity procedure. A correlation between low-fidelity and high-fidelity response surfaces can then be used to compute high-fidelity resistance results. Effectively, the amount of hulls in the CFD dataset can be increased, such that the accuracy of the kriging prediction increases as well as there are more observations. Therefore, another recommendation is to investigate whether multi-fidelity procedures can be used to increase the accuracy of the resistance predictions in the database.

8.2.2 Improvements to the hull geometry model

As has been described in Section 7.2.1 there are small offsets in hull dimensions between the base and extreme hulls. This causes some small deviations in the main dimensions of the resulting hull shapes. It is desired that if a parameter is changed, that all the other parameter which should not change actually remain unchanged. Therefore, it is recommended to improve this issue for further use of morphing: every extreme hull should have exactly the same characteristics as the base hull, except for the parameter of which the hull is the extreme.

Additionally, for parameterizing the base hull only parameters should be used which describe the dimensions of the hull directly in 1D or 2D. For example, the block coefficient is a parameter that should not be used for variation, but only as an output parameter. By varying the other parameters the block coefficient will always change, disabling the option to individually change a parameter without changing others. Together with the abovementioned issue, this makes it impossible to define on beforehand which hulls will be generated. Thus, it is recommended to only choose parameters for dimensionalizing which directly affect the hull dimensions.

8.2.3 Improvements to the resistance prediction model

For obtaining more accurate results for the resistance predictions some improvements are possible. First, as written in Section 5.3.2 the wetted surface has been calculated by using an empirical formula. The result will, therefore, never be as accurate as the actual wetted surface of a hull shape. It is recommended to exactly calculate the wetted surface by integrating the arc lengths of all frames over the length of a hull. This would result in a more accurate resistance prediction, as the wetted surface is used to dimensionalize the resistance coefficient obtained by kriging.

Additionally, it is recommended to do extra verification of the resistance results by running CFD for a few randomly selected hull shapes from the database. These hull shapes should then be well spread over the design space of the database, and should not be close to hulls which are in the CFD dataset. These resistance results can subsequently be added to the training data of the kriging model, such that the resistance results in the database are updated and potentially become more accurate.

An important conclusion for the resistance prediction from Chapter 7 has been that the model provide inaccurate results for hulls with low prismatic coefficients. This can simply be improved by adding more hulls with low prismatic coefficients to the CFD dataset. Nevertheless, this should only be done when the hull type would actually possibly have such low prismatic coefficients. It is recommended to always verify the distribution of the prismatic coefficient, as it has shown to be an important parameter for regression of the pressure resistance. Additionally, for OPVs it might be beneficial to also use the longitudinal centre of buoyancy (LCB) as regression parameter, as this parameter also has a good correlation with the pressure resistance.

8.2.4 Improvements to the design tool

For improving the design tool the most important recommendation is to actually built the GUI and let D&P engineers test the tool. Feedback should be gathered and used to improve the design tool for OPVs.

Additionally, it is recommended to not plot and save the figures in the database. Only saving the hulls is sufficient: the resistance curves and geometry previews can then be generated specifically for the GUI. This would save computation time, such that more hulls can be generated. It would also save on consumed space, probably making it faster to load the actual database. Another recommendation for developing a GUI is to investigate which search procedure is most optimal for using an inverse design approach. The ultimate goal is to have a pre-defined strategy with the 'open' and 'fixed' parameters (defined in Sections 6.2 and 6.3) in which the resistance can be varied at specific speeds, after which the design tool returns a specific hull shape.

Last, some recommendations are given about the use of the design tool. In Section 3.1.3 some concerns were raised which focused on the prevention of a black-box effect. A first recommendation is to provide options in the GUI to view overviews of how the model. This is a simple but accessible method to show the working principle of the model to the user. A second recommendation is to invest some of the expected gained time to the front of the first design iteration. This time should be used to assure that the input provided to the tool is correct. If the input is incorrect, the output of the tool is incorrect as well, and thus useless. This is recommended, as a possible black-box effect might cause that mistakes are only later noticed. Currently, these mistakes would already be noticed when a hull geometry is manually created or while doing a resistance prediction.

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