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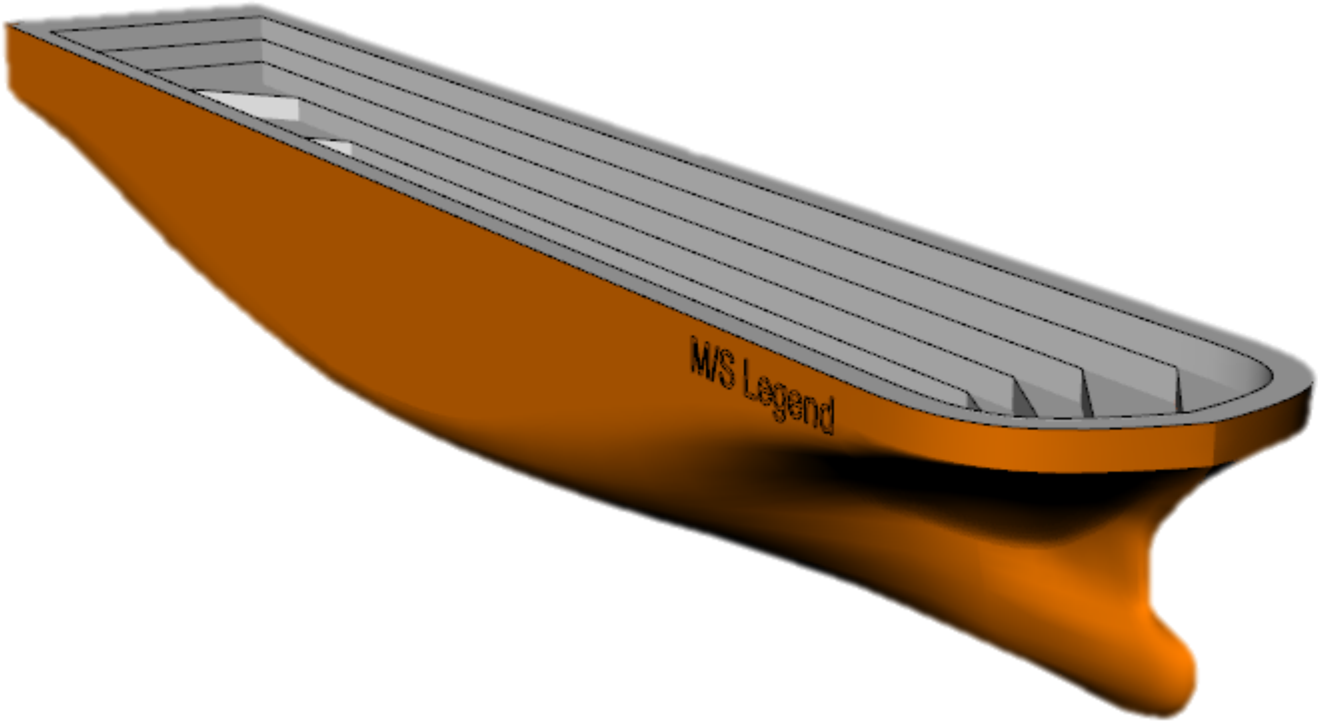


# Development and design of a ship model for use in education and research

Master's thesis in Naval Architecture and Ocean Engineering

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Department of Shipping and Marine Technology
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Gothenburg, Sweden 2016

Master's thesis 2016

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## Abstract

In this thesis a ship model for Chalmers University of Technology is developed. The model shall be used in research and education at the Department of Shipping and Marine Technology. The purpose was to develop a model that could compliment the courses thought at the maritime department at Chalmers, as well as the research.

SSPA is maritime consultant company, ship model manufacturer and a test facility located in Gothenburg, Sweden. Chalmers arrange yearly study visit to their test facilities as a part of the maritime educational program. These visits should complements the theoretical education and give the students hand-on experience. However, due to that most model tests are made confidential by the owner of the ship model, the students rarely get to participate in the model tests. For the same reason, the data from the tests are inaccessible and cannot be released to the students for further analysis. Therefor, Chalmers want to develop their own ship model.

The thesis examines and describes the concept development, design of the hull and the design of the model itself. The report has been divided in three parts. The first part address the development of several concepts. It covers the investigation of the need for a ship model at Chalmers and the desired features the model should obtain. One concept is chosen and further developed in the next parts. The second part consider the design of the hull, and the third part cover the development of the model itself.

The final result is 4.35 meter long ship model of a PCTC, which is specialised to do seakeeping and manoeuvring tests. In addition it has a large freeboard which makes it suitable to investigate intact stability.

## Preface

This report is submitted to fulfil the requirement to the degree of Master of Science in Naval Architecture and Ocean Engineering at Chalmers University of Technology. The work of the thesis was carried out during the spring of 2016. The scope of the project was developed in collaboration with our supervisors Senior lecture Per Hogström from Chalmers and Associate Professor Poul Andersen from DTU. The thesis is written by Kjartan Bauge and Emilie Voraa.

We would like to express our gratitude to our supervisors Per Hogström and Poul Andersen for their guidance and support during this thesis. We would also like to thank Gabrielle Mazza, Nicolas Bathfield and Jonny Nisbet at SSPA for sharing their knowledge and their patience during the completion of this thesis.

A special thank you to Fabian Tillig for highly appreciated guidance in the software Shipflow, your quality feedback and for the several hours of troubleshooting.

Last, we would like give our warmest gratitude to all the personnel and lecturers who willingly let us interview them for this thesis; Poul Andersen, Rickard Bensow, Per Hogström, Carl-Erik Janson, Olle Lindmark, Bengt Ramne, Jonas Ringsberg, Martin Schreuder, Jan Skoog and Linda de Vries. Your thoughts and knowledge have been of great value.

Göteborg, May 2016

Kjartan Bauge & Emilie Voraa

# Abbreviations

| | |
|---|---|
| CFD | Computational Fluid Dynamics |
| COG | Centre of Gravity |
| COB | Centre of Buoyancy |
| ConRo | Vehicle to carry Containers and Roll on Roll off |
| DNV GL | Det Norske Veritas Germanske Lloyd |
| DOF | Degrees of Freedom |
| DTC | Duisburg Test Case |
| DTU | Technical University of Denmark |
| IACS | International Association of Classification Sicieties Ltd. |
| IMO | International Maritime Administration |
| ITTC | International Towing Tank Conference |
| JONSWAP | Joint North Sea Wave Project |
| KCS | KRISO Container Vessel |
| KRISO | Korea Research Institute of Ships and Ocean Engineering |
| KVLCC | KRISO Very Large Crude Carrier |
| LCB | Longitudinal Centre of Buoyancy |
| LCF | Longitudinal Centre of Flotation |
| LCG | Longitudinal Centre of Gravity |
| MCT | Moment to Change Trim |
| MDL | Maritime Dynamics Laboratory |
| MPNAV | Master Programme in Naval Architecture and Ocean Engineering |
| NURB | Non-uniform rational Basis spline |
| PCC | Pure Car Carriers |
| PCTC | Pure Car Truck Carrier |
| PMM | Planar Motion Mechanism |
| PSS | Pre-Swirl Stator |
| RAO | Response Amplitude Operator |
| ROC | Rank Order Centroid Method |
| RoLo | Roll on/ lift off |
| RoPax | Cars and passengers |
| RPM | Revolutions per Minute |
| SAC | Sectional Area Curve |
| SEK | Swedish Kroner |
| STL | Stereo Lithography Trimesh |
| TCG | Transverse Centre of Gravity |
| TPC | Tonnes per centimetre immersion |
| ULCV | Ultra Large Container Vessel |
| VCG | Vertical Centre of Gravity |

# Nomenclature

| **Symbol** | **Unit** | **Designation** |
|---|---|---|
| a | $[\frac{m}{s^2}$ | Vertical acceleration |
| $a_{crit}$ | $[\frac{m}{s^2}$ | Critical vertical acceleration |
| B | [m] | Breadth of the vessel |
| $B_M$ | [m] | Breadth of the model |
| $C_B$ | - | Block coefficient |
| $C_P$ | - | Prismatic coefficient |
| $C_M$ | - | Midship section coefficient |
| $C_{WP}$ | - | Water plane area coefficient |
| D | [m] | Depth of the vessel |
| $D_{prop}$ | [m] | Diameter of propeller |
| $F_n$ | - | Froude number |
| g | $[\frac{m}{s^2}]$ | Gravitational forces |
| GM | [m] | Metacentric height |
| GZ | [m] | Righting lever arm |
| KG | [m] | Keel to center of Gravity |
| KB | [m] | Keel to center of Buoyancy |
| $L_E$ | [m] | Length of entrance |
| $L_M$ | [m] | Length of model |
| $L_R$ | [m] | Length of run |
| $L_P$ | [m] | length of parallel midbody |
| $L_{pp}$ | [m] | Length between Perpendiculars |
| $L_{oa}$ | [m] | Length Over All |
| $R_e$ | - | Reynolds number |
| $R_x$ | [m] | Radius of gyration, model x-dir. |
| $R_y$ | [m] | Radius of gyration, model y-dir. |
| $R_z$ | [m] | Radius of gyration, model z-dir. |
| t | - | Thrust deduction factor |
| T | [m] | Draft of the vessel |
| $T_p$ | [s] | Zero-upcrossing period |
| $\overline{T_p}$ | [s] | Mean of the zero-upcrossing period |
| $V_S$ | $[\frac{m}{s}]$ | Speed of the vessel |
| $V_M$ | $[\frac{m}{s}]$ | Speed of the model |
| w | - | Wake fraction |
| $W_n$ | - | Weber number |
| $X_g$ | [m] | Centre of gravity, model x-dir. |
| $Y_g$ | [m] | Centre of gravity, model y-dir. |
| $Z_g$ | [m] | Centre of gravity, model z-dir. |

| | | |
|---|---|---|
| $m_{0a}$ | $[\frac{m^2}{s^4}$ | Variance of the acceleration energy spectrum |
| $\Delta$ | [tonnes] | Mass displacement of the vessel |
| $\nabla$ | $[m^3]$ | Volume displacement of the vessel |
| $\eta$ | - | Efficiency |
| $\gamma$ | $[\frac{N}{m}]$ | Surface tension |
| $\rho$ | $[\frac{kg}{m^3}]$ | Density of the fluid |
| $\rho_d$ | $[\frac{kg}{m^3}]$ | Density H100 Divinycell |
| $S(\omega_e)$ | $[\frac{m^2}{rad/sec}]$ | Response energy spectrum |
| $S_\zeta(\omega_e)$ | $[\frac{m^2}{rad/sec}$ | Wave spectrum |
| $\zeta$ | [m] | Wave amplitude |
| $\phi$ | $^\circ$ | Heeling angle |
| $\omega_e$ | $[\frac{rad}{s}]$ | Encounter frequency |

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# 1 Introduction

There are mainly two ways of estimating a vessels performance before it is built: numerical calculations and with model testing. In the former method, the ship´s performance is investigated by using mathematical models. The latter method has a more practical approach.

The idea behind model testing is to make a scaled-down copy of the original vessel. The model can then be tested in a basin where the environment can be controlled. Forces, accelerations and other characteristics are measured on the model and then scaled up to represent the real vessel. This method is considered to be the most accurate way of predicting the vessels performance. The accuracy of numerical calculations have become better but is still not competitive with model testing. Numerical calculations are today used to estimate the performance of the ship and to optimise the ships geometry. However, model trials are needed to verify the calculations before the final ship geometry are decided. Due to its importance, model testing is a large part of the syllabus in most maritime educations.

In several of the courses thought at the Department of Shipping and Marine Technology at Chalmers the students have study visits to SSPA. During these visits, the students get an insight into model testing and an opportunity to observe what they have learnt in practice. However, due to that most model tests are made confidential by the owner of the ship model, the students rarely get to participate in the model tests. For the same reason, the data from the tests are inaccessible and cannot be released to the students for further analysis.

A study carried out at the Department of Psychology at the University of Chicago indicate that students better understand scientific concepts if they get to physically experience it. Through brain scans it was determined that the understanding of science concepts, such as torque and angular momentum, was aided by activation in sensory and motor-related parts of the brain (Kontra et al., 2015). It is assumed that allowing students to experience model testing would have some of the same benefits in terms of learning. This will increase the quality of the education at the Department of Shipping and Marine Technology at Chalmers.

The goal of this thesis is to develop a ship model to be used as a learning tool in the education and to support the research done at the department.

## 1.1 Report Outline

The thesis is divided into three parts; concept development, hull design and development of the model. Each chapter contain a description of the methodology used and the results obtained are presented and discussed. A conclusion is reached before the next chapter is started. An overall summary and conclusion is given at the end of the report, together with suggestions for future work.

The first part is to develop a concept that reflect the need at Chalmers. This is done by interviewing professors and experts at Chalmers and SSPA to identify what properties the model is desired to have. This information is processed and transformed into features and finally concepts. The second part consider the design of the hull, where the main dimensions and shape were set with regard to relevant literature, reference ships and empirical formula's. Part three consider the development of the model. This include scaling, design of the 3D model and implementation of the features from part one.

## 1.2 SSPA and model testing

SSPA is a maritime consultant company with their main office located in Gothenburg. Model testing of ship and maritime structures is one of their primary business area. For this, they have a towing tank, a large cavitation tunnel and a Maritime Dynamics Laboratory (MDL) (SSPA, 2016). The latter is a versatile facility used for seakeeping and manoeuvring analysis.

The towing tank is 260 meter long, 10 meter wide and 5 meter deep. The carriage has a speed range of 0-11 m/sec and can produce waves with a height up to 0.3 meters in head and following sea. In the towing tank the following tests are primarily done:

- Resistance test: The model is towed at a certain speed and the towing force is measured.
- Self-propulsion: The model is equipped with a engine, propeller and rudder. The model sails in a straight course at various speeds. The power necessary to maintain the speed are measured and used to derive the propulsion factors (w,t $\eta$). A dynamoeter is used to measure trust, torque and RPM.
- Flow visualisation: Tests to investigate the flow along the hull. Normal tests are paint test, tuft test and appendage alignment test.
- Wake-field: To investigate the flow into the propeller plane. This could be measured with a pitot tube mounted on the propeller shaft.
- Wave pattern: The models wave pattern is recorded on film. The wave elevation is measured.

The cavitation tunnel is divided in three interchangeable sections with different dimensions. Complete ship models can be installed in the tunnel. Tests in the cavitation tunnel includes cavitation observation, measurement of pressure fluctuations, erosion tests and measurement of propeller induced forces and noise.

The MDL basin is 88 meters long, 39 meters wide and 3.5 meters deep. The water depth can be regulated from 0 - 3.2 meters. Wave makers are installed in one of the long-sides and one of the short-sides of the basin. The remaining sides are equipped with wave dampers to minimise the reflection of the waves. The maximum wave height is 0.4 meters and wind speed up to 10 m/sec can be simulated. The model is self-propelled and free to move in all degrees of freedom (DOF). The following tests are primarily done in the MDL basin:

- Seakeeping test: The models seakeeping performance is investigated in different waves and headings. The following parameters are normally measured: roll damping, non-linear motion, slamming and local loads, green water and propeller emergence. Added mass can be investigated if a calm water resistance exist.
- Manoeuvring test: To assess the models manoeuvrability. Manoeuvring tests defined in IMO are carried out both at deep and shallow water (IMO, 2002). In addition, manoeuvring in channel and course stability can be investigated.
- Captive test: Used to derive the manoeuvring coefficients. This can be done by large amplitude

planar motion mechanism (PMM) tests and rotating arm tests.

- Depending on the model, the basin is also suitable for intact- and damage stability.

SSPA differ between two types of models; one used in the MDL basin and one used in the towing tank and cavitation tunnel. The latter model is larger then the former, which restrict a MDL model from being used in the towing tank, and vica versa.

# 2 Concept development

This chapter address the development of the initial concept of the ship model. The purpose is to establish a concept that is beneficial for as many stakeholders as possible. The methodology is first explained, then the results are presented and discussed. A single concept is chosen before the design of the ship is initiated in the next chapter.

## 2.1 Methodology

The first step was to establish who would have an interest in a ship model. The relevant persons were then interviewed. The information gathered form the interviews were processed in two steps. First the professors wishes where transformed into features. A feature is a specific thing the model should be able to do, i.e. be able to measure its resistance while towed through a basin. These features were then ranked according to how well they performed within certain conditions. Secondly, these features were sorted into concepts. In this context a concept is a collection of features that is possible to combine into one ship model.

The first step was repeated to decide which type of ship that should be used. Each feature was transformed into ship properties and ships that matched these properties were suggested for each feature. The ships were then ranked according to how well they fitted each feature. The ships grade, obtained from the ranking were then summed over the features in each concept to decide which ship type would suit each concept best.

The different concepts were then evaluated based on several factors and finally it was decided to proceed with one concept.

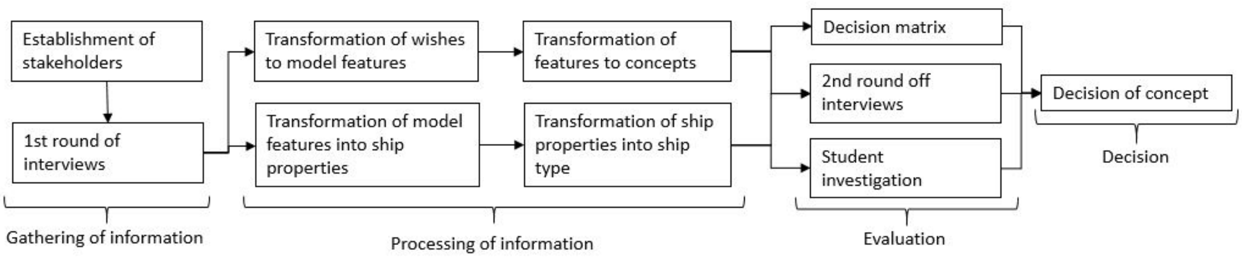



**Figure 1:** Work process, concept development

### 2.1.1 Gathering of information

The first step of the project was to establish the stakeholders to identify everyone who would benefit from having a ship model. It was found that the main stakeholders were students, lecturers and professors at the Department of Shipping and Marine Technology at Chalmers. Secondary stakeholders would be companies, universities and other research facilities within the maritime industry. This is due to that the results from research of this model would be freely published.

To assess the main stakeholders, the different course plans for the maritime educations at Chalmers where evaluated to decide where the model would be best utilised. It was found that a ship model would first of all be beneficial for students in Naval Architecture and Ocean Engineering, Maritime Management, Degree Course in Nautical Science, Marine Engineering and in various research at the institute. The next step was to interview the lecturers and course responsible of the above educations and research. The goal of the interview was to first determine if a ship model was needed and then which features the stakeholders wanted for the model.

Depending on the information desired to extract, there are several methods to carry out an interview. In this project, the interviews were carried out one-to-one in a semi-structured manner (Denscombe, 2014). The structure of an interview can be classified in three categories depending on how flexible the questions are asked. The categories are *structured-, semi-structured- and unstructured interviews*. In the semi-structured interviews, the researcher have a list of questions to ask and the interviewee have the possibility to navigate the answers in the desired direction. This way, the interviewee gets to address their interest without the researcher affecting the answer. The questions can be rearranged depending on the given answers in order to let the interviewee speak more widely about one topic. This way the interviewee can develop new ideas during the question and be able to end the string of thoughts before the next question is addressed. In a one-to-one interview you ensure that the answers from the interviewee is in fact the persons personal opinion. The opposite of one-to-one interviews are group interviews. In group interviews the interviewees are able to discuss upon each other's thoughts. There are pros and cons for both methods, but the interest of the researchers in this context was to get the lecturers personal opinion on their individual topic. Therefore a one-to-one interview were chosen.

The main structure of the interviews were similar for everyone. Some additional, and individual, questions were added for some lecturers to address their courses or field of research. The interviews started with an intro where the goal of the interview were thoroughly explained to the lecturer. The lecturers were asked to answer the questions with their courses and research in mind. Secondly to understand which type of features that would be most important for the model and which type of ship they believed would present these features best. The interviews opened with an easy question in order to make the interviewee relax and ended with an open question. In the open question, the lecturers were given the possibility to comment upon the model features with regard to other fields than their own. See Appendix A for the general interview form and Appendix J.3 for transcribed interviews. The professors gave consent to being recorded in advance and to use the information from their interviews for research in this thesis.

### 2.1.2 Processing of information

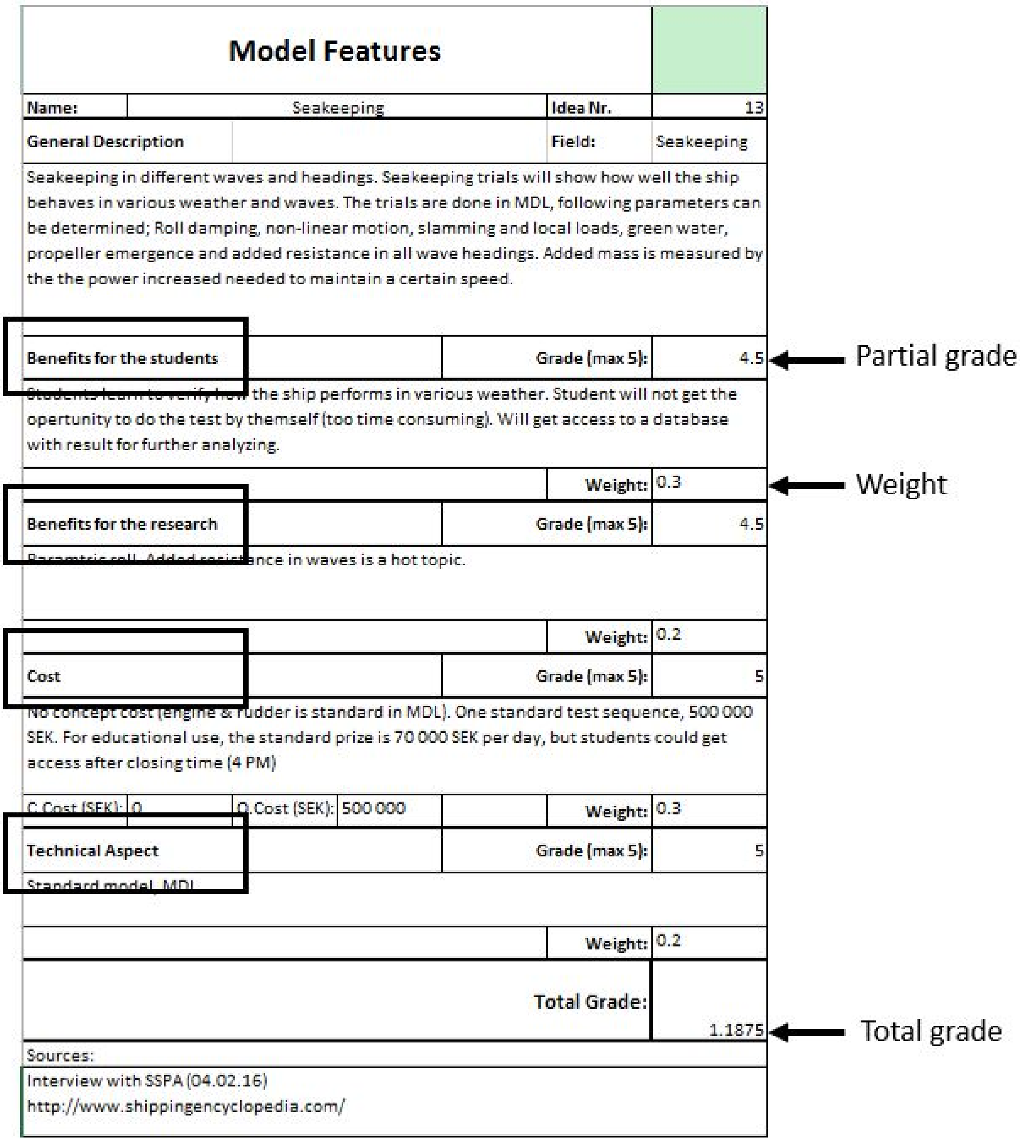
In this section the process of transforming the information obtained from the interviews to model concepts will be explained. The section is divided into two parts, the transformation of wishes into concepts, and the transformation of model features into ship type. The reader are referred to Appendix B and Appendix C, respectively, for details.

**Transformation of wishes to concepts**
Based on the interviews, the wishes and demands from the stakeholders were transformed into model features. The features were evaluated based on 4 conditions, *Benefits for the students*, *Benefits for research*, *Cost* and *Technical aspect*, see Figure 2. Each conditions were denoted a weight based on how

important it was believed that it was for the ship model. Table 1 show the definition of the condition and its respective weight. The benefits for the students was considered most important together with cost. This is because the model should be used as a support in the education and that the cost often are the limiting factor. The cost is divided in two; *Operational cost* and *Concept cost*. The former is the cost to operate the model, i.e one towing sequence. The latter is the cost of implementing the feature on the model, i.e making the model able to change parts.

**Table 1:** Overview of conditions and their weights

| Condition | Definition | Weight |
|---|---|---|
| Benefits for the students | How helpful the feature is in education of students | 0.3 of 1 |
| Benefits for research | How useful the feature is for research | 0.2 of 1 |
| Cost | How costly the feature will be to implement | 0.3 of 1 |
| Technical aspect | How technically challenging the feature is to implement | 0.2 of 1 |



**Model Features**

| Name: | Seakeeping | Idea Nr. | 13 |
|---|---|---|---|
| General Description | | Field: | Seakeeping |

Seakeeping in different waves and headings. Seakeeping trials will show how well the ship behaves in various weather and waves. The trials are done in MDL, following parameters can be determined; Roll damping, non-linear motion, slamming and local loads, green water, propeller emergence and added resistance in all wave headings. Added mass is measured by the the power increased needed to maintain a certain speed.

Benefits for the students — Grade (max 5): 4.5

Students learn to verify how the ship performs in various weather. Student will not get the opertunity to do the test by themself (too time consuming). Will get access to a database with result for further analyzing.

Weight: 0.3

Benefits for the research — Grade (max 5): 4.5

Parametric roll. Added resistance in waves is a hot topic.

Weight: 0.2

Cost — Grade (max 5): 5

No concept cost (engine & rudder is standard in MDL). One standard test sequence, 500 000 SEK. For educational use, the standard prize is 70 000 SEK per day, but students could get access after closing time (4 PM)

C.Cost (SEK): 0 — O.Cost (SEK): 500 000 — Weight: 0.3

Technical Aspect — Grade (max 5): 5

Standard model, MDL

Weight: 0.2

Total Grade: 1.1875

Sources:
Interview with SSPA (04.02.16)
http://www.shippingencyclopedia.com/



**Figure 2:** Explanation of grading of model features

A partial grade, between 1 and 5, was then decided for each condition based on how well the feature performed. The definition of the partial grades are found in Table 2. A total grade were calculated for each features as the summation of the weight multiplied with the partial grade for each condition.

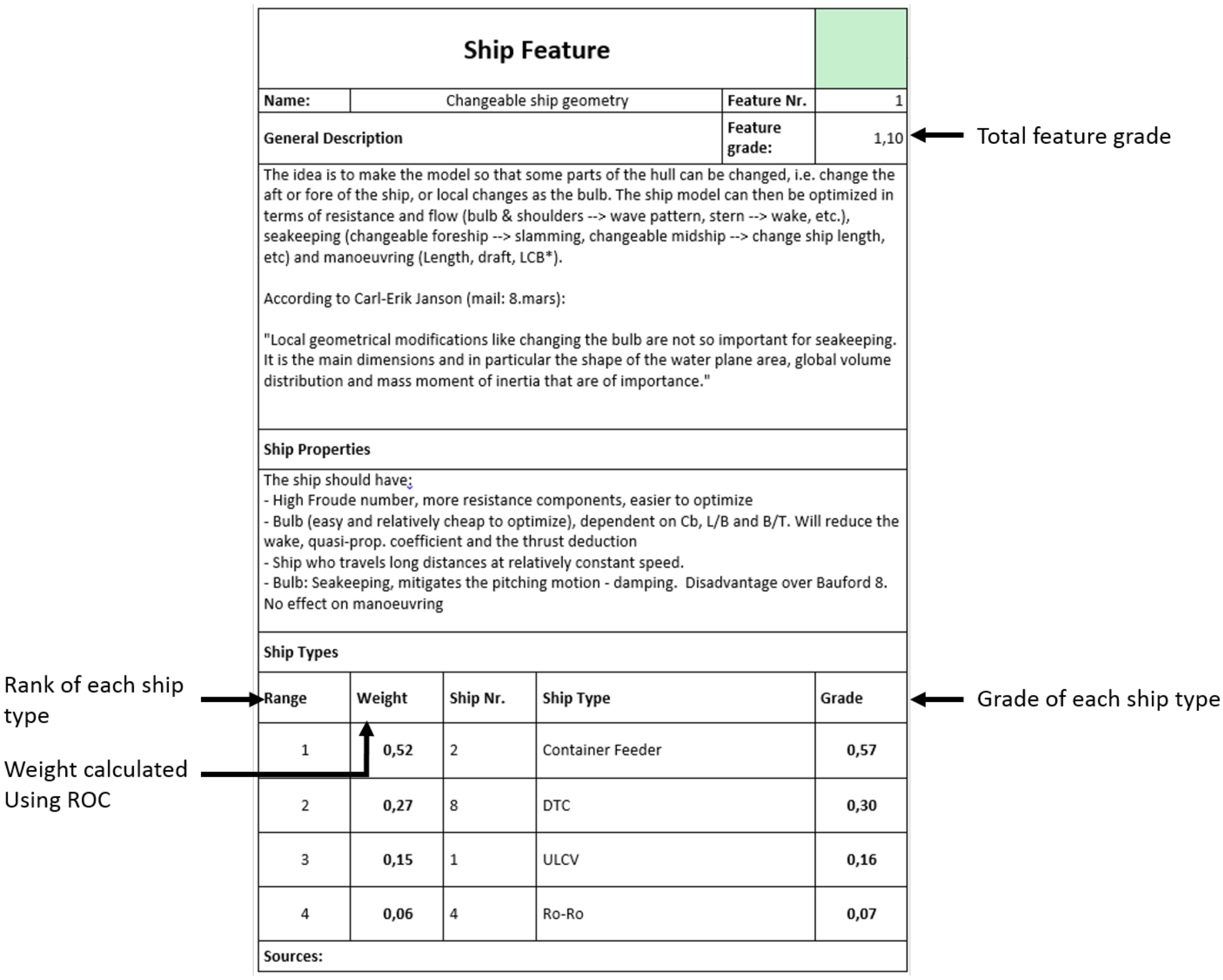
**Table 2:** Definition of different partial grades

| **Partial grade** | **Definition** |
|---|---|
| 5 | Excellent learning outcome for students. Highly beneficial for research. Zero cost and no technical difficulties. |
| 4 | Great learning outcome for students. Beneficial for research. Small cost and limited technical difficulties. |
| 3 | Some learning outcome. Some research capabilities. Medium (max 20% of standard cost) cost and some technical difficulties with implementation. |
| 2 | Low learning outcome. Limited research capabilities. High cost (max 50% of standard cost) and complicated to implement. |
| 1 | No learning outcome. No research. Very high cost (>50%) and very hard to implement. |

As it was challenging to only make one concept, several concept were developed, see section 2.2.1. Trough literature study and meetings with SSPA, an investigation was done to find which features that was applicable for each concept. A total grade was then calculated as a summation of the feature grades. This grade gives an indication on what concept is best, based on its number of (good) features.

**Transformation of model features to ship type**

Different types of ships have different properties such as bulb, high Froude number or large bow flare, that to a various extent can demonstrate the model features. In example, if it is interesting to investigate the wave pattern, the ship should have a high Froude number. It was important to select a ship that were able to illustrate most model features possible. Commercial vessels were mainly evaluated, from fast going and large container vessels to a medium sized tanker with a high block coefficient. Since only some of the model features are dependent on a specific ship property, only the relevant features were assessed. For each model feature, four different ship types were evaluated, see Figure 3.



**Ship Feature**

| | | | |
|---|---|---|---|
| Name: | Changeable ship geometry | Feature Nr. | 1 |
| General Description | | Feature grade: | 1,10 |

The idea is to make the model so that some parts of the hull can be changed, i.e. change the aft or fore of the ship, or local changes as the bulb. The ship model can then be optimized in terms of resistance and flow (bulb & shoulders --> wave pattern, stern --> wake, etc.), seakeeping (changeable foreship --> slamming, changeable midship --> change ship length, etc) and manoeuvring (Length, draft, LCB*).

According to Carl-Erik Janson (mail: 8.mars):

"Local geometrical modifications like changing the bulb are not so important for seakeeping. It is the main dimensions and in particular the shape of the water plane area, global volume distribution and mass moment of inertia that are of importance."

**Ship Properties**

The ship should have:
- High Froude number, more resistance components, easier to optimize
- Bulb (easy and relatively cheap to optimize), dependent on Cb, L/B and B/T. Will reduce the wake, quasi-prop. coefficient and the thrust deduction
- Ship who travels long distances at relatively constant speed.
- Bulb: Seakeeping, mitigates the pitching motion - damping. Disadvantage over Bauford 8. No effect on manoeuvring

**Ship Types**

| Range | Weight | Ship Nr. | Ship Type | Grade |
|---|---|---|---|---|
| 1 | 0,52 | 2 | Container Feeder | 0,57 |
| 2 | 0,27 | 8 | DTC | 0,30 |
| 3 | 0,15 | 1 | ULCV | 0,16 |
| 4 | 0,06 | 4 | Ro-Ro | 0,07 |

**Sources:**



**Figure 3:** Explanation of grading of ship type

Each ship type were given a weight. The weight was determined by using a rank based formula called *rank order centroid method* (ROC). The method uses the subjective given rank of each ship and converts it into a weight that illustrate how well the ship type fits the feature (Barron and Barrett, 1996). The rank is dependent on how many ships are rated and the order. The conversion from rank to weight are done using the following formula:

$$W = \frac{1}{n} \sum_{j=i}^{n} \frac{1}{j} \quad \text{where,} \quad i = 1, ..., n \tag{1}$$

Where $n$ is the number of ship types ranked for each feature and $W$ is the weight for each ship dependent on the given rank. In example, if only one ship type is applicable for a feature, the weight of the ship will be 1. If four types of ships are evaluated, the weights will be as shown in Table 3

**Table 3:** Example on calculation of weight using ROC

| Rank | Formula | Weight |
|---|---|---|
| 1 | (1 + 1/2 + 1/3 + 1/4)/4 | 0.52 |
| 2 | (1 + 1/2 + 1/3)/4 | 0.27 |
| 3 | (1 + 1/2)/4 | 0.15 |
| 4 | 1/4 | 0.06 |

To determine the grade of each ship type, the weight from the ROC method was multiplied by the total feature grade. This way the ship types were graded according to how well it fit the model features. The grade of each ship type was then summed together in a matrix. From the matrix it was possible to determine which ship would be most appropriate for each concept.

#### 2.1.3 Evaluation of concepts

After processing the information into distinct concepts, the next step was to evaluate which concept was most suitable for Chalmers. The concepts where evaluated through three instances:

- Interview with SSPA to evaluate if the concepts where achievable and to do a cost assessment.
- Interview with professors and lectures at Chalmers to get feedback on the concepts and decide which of them that would be most beneficial based on their opinion
- A questionnaire for the students. They were told to vote on the concept most favourable for them.

Both the meeting with SSPA and with the lecturers were carried out as a group interview. It was decided that this was the best technique to obtain the information needed. The attendants were first presented with the preliminary concepts, then a discussion was initiated. The interviewees were then able to defend their interest and get the perspective of the other lecturers.

In order to include the students in the process, a questionnaire was carried out for the students in Naval Architecture and Ocean Engineering. A questionnaire is a structured way of doing interviews and leave the interviewee with few answering possibilities (Denscombe, 2014). The preliminary concepts were posted in the common room for the MPNAV students, together with a voting sheet. The concepts were based on the decision matrices and was the same as the ones presented for the lecturers. The students were asked to rate the concepts with regard to what they believed would be most helpful in their education. The concepts were rated from 1-4, where 1 was the best. The ranks were converted into grades, where the rank 1 gave 4 points, 2 gave 3 points etc. The total grade was obtained by summing up the points for each concept.

## 2.2 Result

In this section, the results from the processing of information and evaluation of the concepts are presented. The former consists of a presentation and discussion of the derived concepts. The latter present the evaluation of the concepts through the instances from section 2.1.3 and the decision matrix.

### 2.2.1 Presentation of concepts

Being able to include all the features evaluated above into one ship model would have been the ultimate solution. For several reasons this is not achievable. In example, a towing tank model is too large for the MDL basin and a MDL model will give inaccurate result in the towing tank. SSPA has expressed that if the model will be made and operated by them, they want the result to be of a certain accuracy. It is extremely challenging to combine several features and at the same time keep the accuracy, i.e. damage stability in a towing tank model would be cumbersome as the hatches to flood the compartments could disturb the flow and thereby reduce the accuracy of the measured resistance. Some features become too expensive or technical challenging when combined with other features, i.e. a crane to demonstrate lifting of objects at sea, placed on a towing tank model, would need a capacity of several tens of kilos to be able to heel or trim the model. This would imply more steel, a large engine, and if the crane capacity is large enough, a license to be allowed to operate it.

Based on the above reasoning it was decided to make several concepts, where each concept had its own area of expertise. In the MPNAV program, there are basically five main areas who could benefit from having a ship model; resistance, seakeeping, manoeuvring, stability and structure. Resistance and flow analyses are done in the towing tank model, thus concept 1 were based on a standard towing tank model. Seakeeping and manoeuvring are done in the MDL basin, so concept 2 were based on a MDL model. Concept 3 is a hydrostatic stability model made for education. It is believed that if the features made to illustrate basic ship stability should have any value, the student had to do the trials themselves. This would not be the case if these features should have been included in concept 1 or 2. The last concept is the backbone model. The model has a great value for research and thus large demands for accuracy. Therefor it cannot be combined with other features, except maybe seakeeping and manoeuvring for educational purposes.

**Concept 1 – Resistance**
Concept 1 is based on a standard towing tank model. A standard towing tank model is approximately 7 meters long and weigh 3.5 tons. Figure 4 shows all the feature this model can do along with the grade and concept cost. The red columns to the right represent the additional features. These are features that the model can do, but that is not recommended. All the test for this model will be done in the towing tank and the cavitation tunnel. Apart from measuring the towing force necessary to drag the model through the towing basin, the model can by default do:

- Flow visualisation, i.e. tuft test, paint test and appendage alignment test.
- Wake-field measurement using a pitot tube.
- Wave pattern measurements and video recording

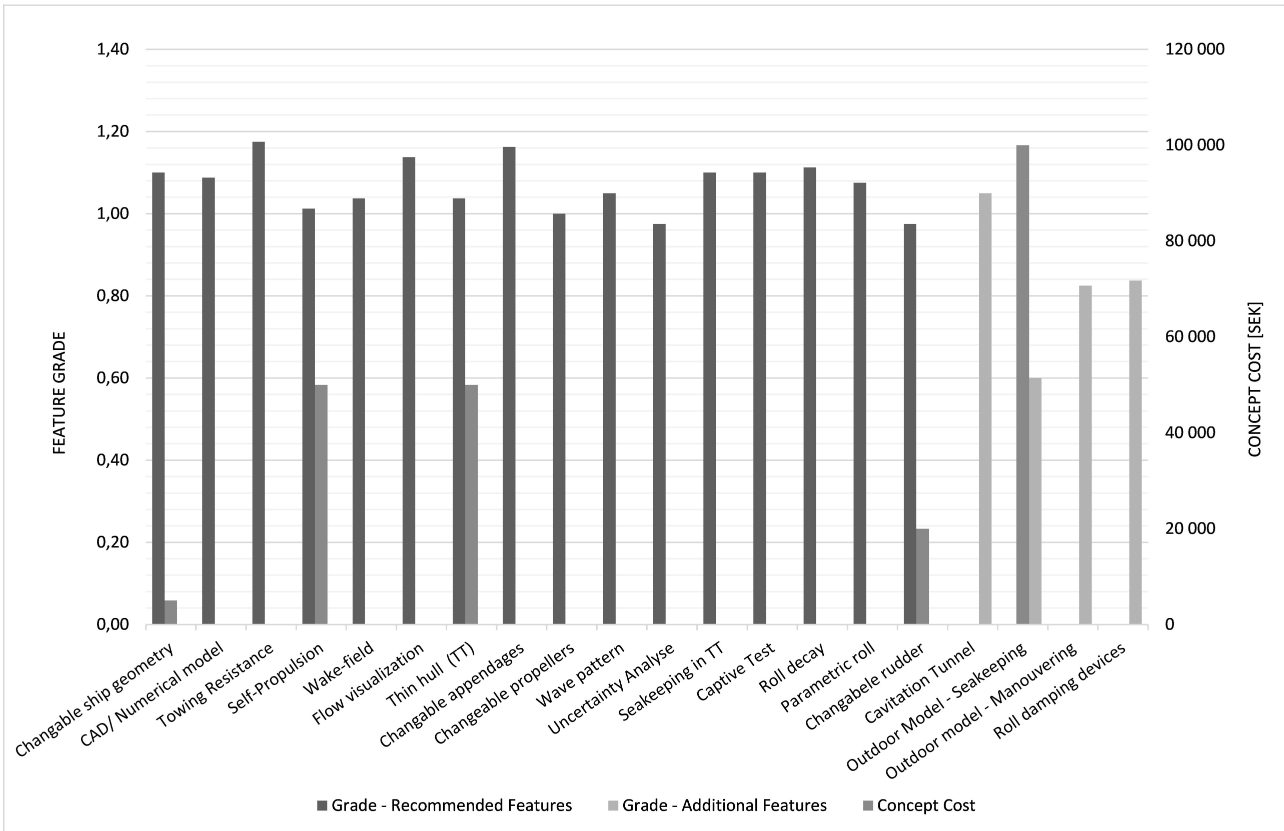



**Figure 4:** Feature grade for resistance concept

The same model can in addition be used in SSPAs cavitation tunnel, where the propeller performance with respect to cavitation can be investigated. With a cost of approximately 50 000 SEK the model can be self-propelled. Then it is possible to estimate the power needed at various speeds and derive the propulsion factors (w, t, $\eta$).

Of more unconventional features, the model can be prepared to change the geometry of the hull. It is suggested to build the model in three parts, an aft part, a midship section and a fore part. The idea is that these parts can be changed in order to optimise the flow around the hull and thereby lower the resistance. In addition, local changes can be done, i.e. only changing the bulb or parts of the stern. The cost of this feature depends on what to change, but is estimated to be between 20 000 – 50 000 SEK. In general, doing changes at the stern is most costly because of the engine shaft. The model can also be equipped with energy saving devices, as pre-swirl stator (PSS) and duct, to optimise the propeller wake. The cost of making these devices varies between 10 000 – 80 000 SEK. However, this cost could be lowered by using Chalmers 3D printers. It is also possible to manufacture new propellers for the model, but this is costly. An alternative can be to use stock propellers. These are propellers with different characteristic that SSPA have available for self-propulsion tests.

It is also suggested to make the model with thinner hull than an ordinary towing tank model. This can be done for an additional cost of 50 000 SEK. The extra cost is because the model have to be reinforced with fibreglass to be rigid enough. The advantage with a thinner hull is that it is possible to distribute the weights, with blocks of steel or chain, to get the correct centre of gravity and radii of gyrations. This is crucial when doing seakeeping tests, roll decay, parametric roll and captive test. If the ship has a bilge keel it has to be included in the three latter tests. Only head and following waves are available in the towing tank. In addition to a thinner hull, it is recommended that concept 1 is equipped to do self-propulsion. The cost of adding these two features is estimated to 100 000 SEK. It is a large investment, but expands the model usage considerably.

As additional features it suggested to equip the model with a rudder and remote control to be able to use it outdoor. However, there will be some practical problems with transportation of the 3.5 tons model and it may not be wise to let student drive a ship model with estimated price of 350 000 SEK outdoor on a lake. To make the model usable outdoor is considered as an additional feature.

Making the model able to do capsizing stability is considered not applicable. Since the model is larger then a MDL model, it is easier to place a floodable tank without conflicting with the measuring equipment. However, the functionality of MDL basin is needed to do proper capsizing stability tests.

Figure 5 shows all the ships considered in this project and how well their properties satisfies concept 1. The three right most vessels in figure 5 are hulls used for research. A 3D model and a database with results from research are publicly available for these hulls, (Moctar et al., 2012, Larrson et al., 2003), See Appendix C for details. The suggested ships are all commercial vessel with a high Froude number. This is a specific wish from several of those interviewed. The wave making resistance for a vessel with high Froude number is a larger part of the total resistance than on ship with low Froude number. The wave resistance for a normal container ship account for 10% more of the total resistance than on a tanker (Larsson and Raven, 2010). The wave making resistance can be lowered by optimising the geometry of the ship, i.e. changing the shape of the bulb to optimise the wave pattern. A container feeder is suggested as the best alternative. This ship often have a rather rich body and operates at a high Froude number and therefor create some waves. This is interesting with respect to bulb optimisation.

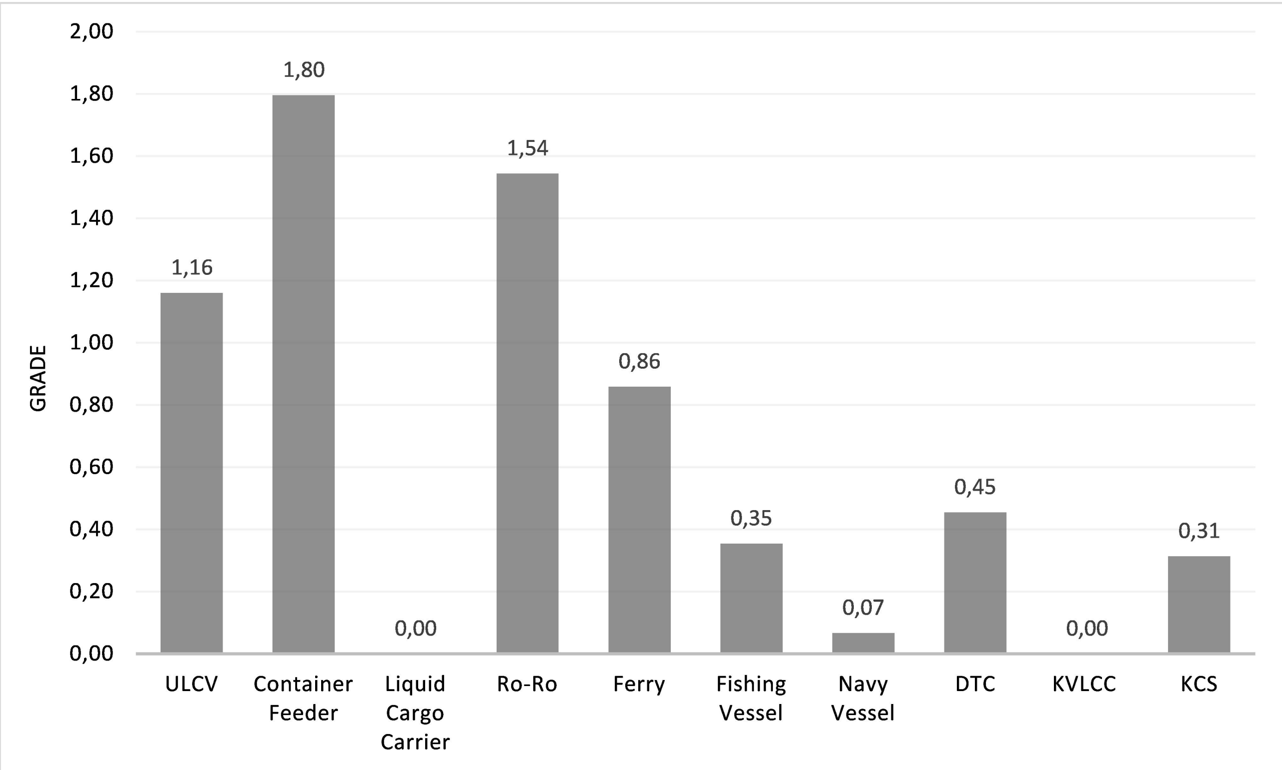



**Figure 5:** Graded ship types for concept 1

**Concept 2 – Seakeeping and Manoeuvring**
This concept is based on standard *Maritime Dynamics Laboratory* (MDL) model. The model is approximately 4-5 meters long and weighs about 1 ton. Figure 6 shows the feature grade and concept cost. This model have a thin hull by default, therefore the centre of gravity and radii of gyration can be properly modelled. The model can by default do:

- Seakeeping: Investigate how well the ship behaves in various weather and waves, i.e. roll damping, non-linear motion, slamming and local loads, green water and added resistance in all wave headings.

- Manoeuvring: How well the ship manoeuvre, turning circle, zig-zag test, stop test, etc.

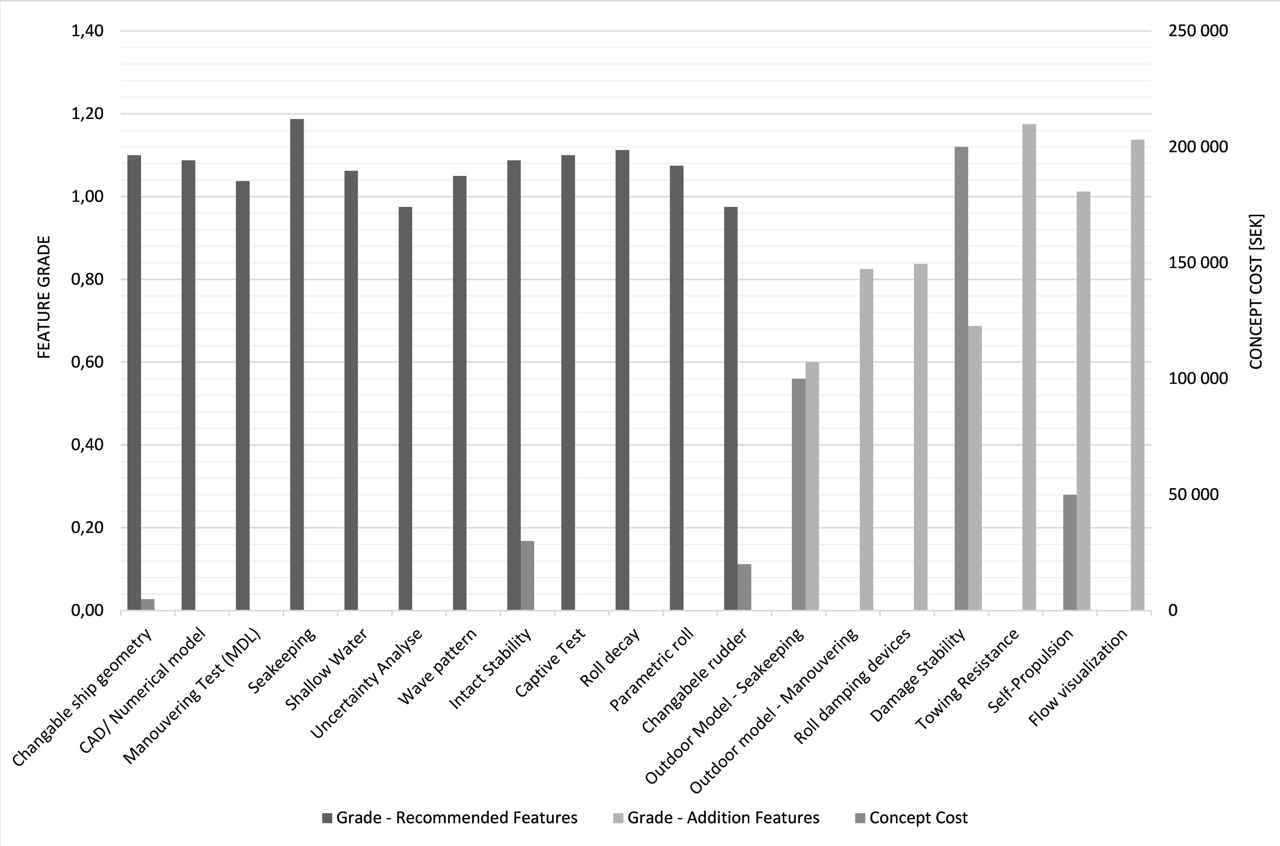



**Figure 6:** Feature grade for seakeeping and manoeuvring concept

The tests can also be done in shallow water for an additional cost of 30 000 SEK. The cost is for lowering the water level in the basin. An important feature with this model is that the MDL basin may be available for students after 4 PM for free or reduced cost.

Of the more unorthodox features, it is again suggested to prepare the model to be able to change parts. In most cases, the MDL model is smaller and contain more measuring equipment, therefore only local changes are possible. In examples, only the bulb would be changeable in the fore part of the ship.

This concept can be designed to be able to investigate intact and damage stability. Model trials with respect to intact and damage stability are often done to investigate the ships ability to withstand capsizing when exposed for an extreme environment. Damage stability is mainly done to determine the significant wave height that will cause the model to capsize (ITTC, 2005) . Intact stability is more about investigating phenomena leading to more sudden loss of stability, i.e. broaching, parametric rolling, pure loss of stability, typically on a wave crest and loss of stability due to cargo shift or other heeling moments (ITTC, 2005). For both intact and damage stability the ship models centre of gravity and radii of gyration has to represent the actual ship. The model has to be completed up to the weather deck and all appendages has to be installed. For damage stability, the model has to have a floodable compartment. This compartment has to be geometrically similar as the ship and the wall thickness should not be more than 4 mm (ITTC, 2005). According to SSPA, it is possible to make a model which can do both seakeeping, manoeuvring and damage stability, but it is challenging because of the limited space in a MDL model. The floodable compartment has to be removed to do the seakeeping and manoeuvring test. An additional cost of 200 000 SEK is estimated to implement damage stability. This is almost the same as the cost for a standard MDL model, and is considered too expensive. Therefore, it is recommended to only implement intact stability which has an estimated cost of 30 000 SEK for the increased freeboard. Damage stability can be simulated by loading the model to a heel and trim angle equal to what would be the case with a flooded compartment. Free surface effects would then be excluded.

The ship model can also be used in the towing tank for educational use. According to SSPA, using this small a model would give results with inadequate accuracy, because of scale effects. In addition it is challenging to trigger turbulent flow on such a small model. Although, the result is too poor for a commercial project, the students can still learn a lot with respect to optimisation of the ship geometry. For example, a bulb optimisation can still be done. The bulb can be optimised to improve the wave pattern and the lowered resistance would, even if it is not correct, give an indication if the new bulb design is better.

Outdoor model is in this concept also considered an additional feature. It is more applicable in this concept then concept 1, as this model is smaller and thus easier to handle. Less power is needed to propel the model. This is an advantage as the model normally are powered with an electric engine and thus a smaller battery package are needed. However, the model can already do manoeuvring in the MDL basin. The advantage of making the model able to run outdoor is to lower the operational cost. It is assumed that this benefit would not pay of as long as the students can use the MDL basin for a free/reduced price after 4 PM.

Figure 7 suggest to build a ship model of a RoRo ship. This is a commercial ship with high Froude number. This is interesting in terms of optimising the ship geometry to lower the resistance. In addition, RoRo ships often have some challenges with stability, especially damage stability. The ship will be designed to have a rather slim fore body and large flares in the fore and aft. This is, among other things, done to trigger parametric roll. As far as the researchers know there exist no publicly available RoRo hulls. Designing a new RoRo hull would therefore compliment the existing hulls made for research.

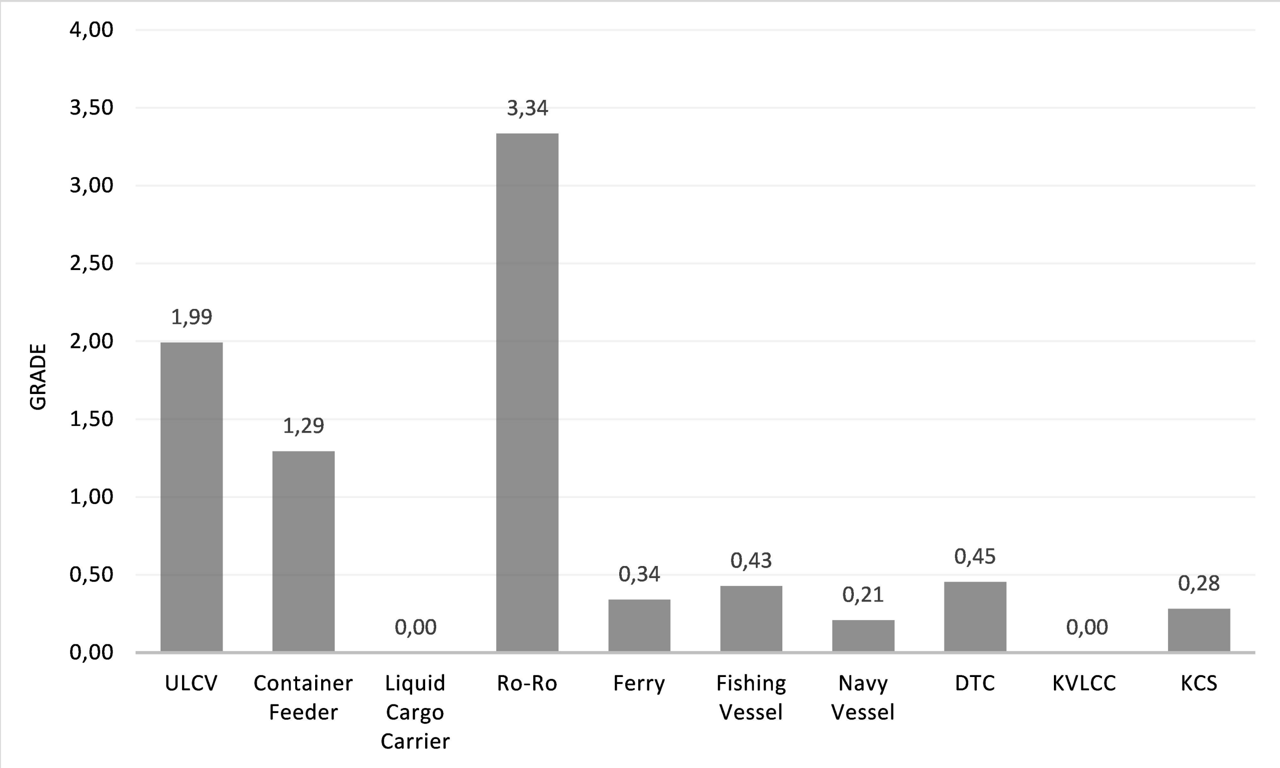



**Figure 7:** Graded ship types for concept 2

**Concept 3 – Stability**
Concept 3 is a hydrostatic stability model made entirely for education. It will have a length around 1 meter and several features which can be used to illustrate various stability phenomena, see Figure 8. It is based on a similar model made by Force Technology and used by the Technical University of Denmark (DTU).

The model will be equipped with the following features:

- Weights that can be moved transversely to do inclining tests.
- Weight that can be moved vertically to investigate the effect of raising the vertical centre of gravity.
- A crane to simulate lifting of objects at sea.
- A floodable compartment to investigate damage stability.
- Changeable plastic tanks with different features, i.e. different size to investigate free surface effects and passive anti-roll tanks.
- Sponsoons, to investigate how a change in the geometry in waterline affect the stability.
- Ballast tanks, so the students can ballast the ship model to proper trim (and heel).

Measurements of the heeling- and trim angle and the draft will be done with simple measuring equipment as electronic protractor and ruler. The student can get tasks like, find KG, do a limited KG analyse, find the Moment to Change Trim (MCT), do roll decay test with different plastic tanks, etc.

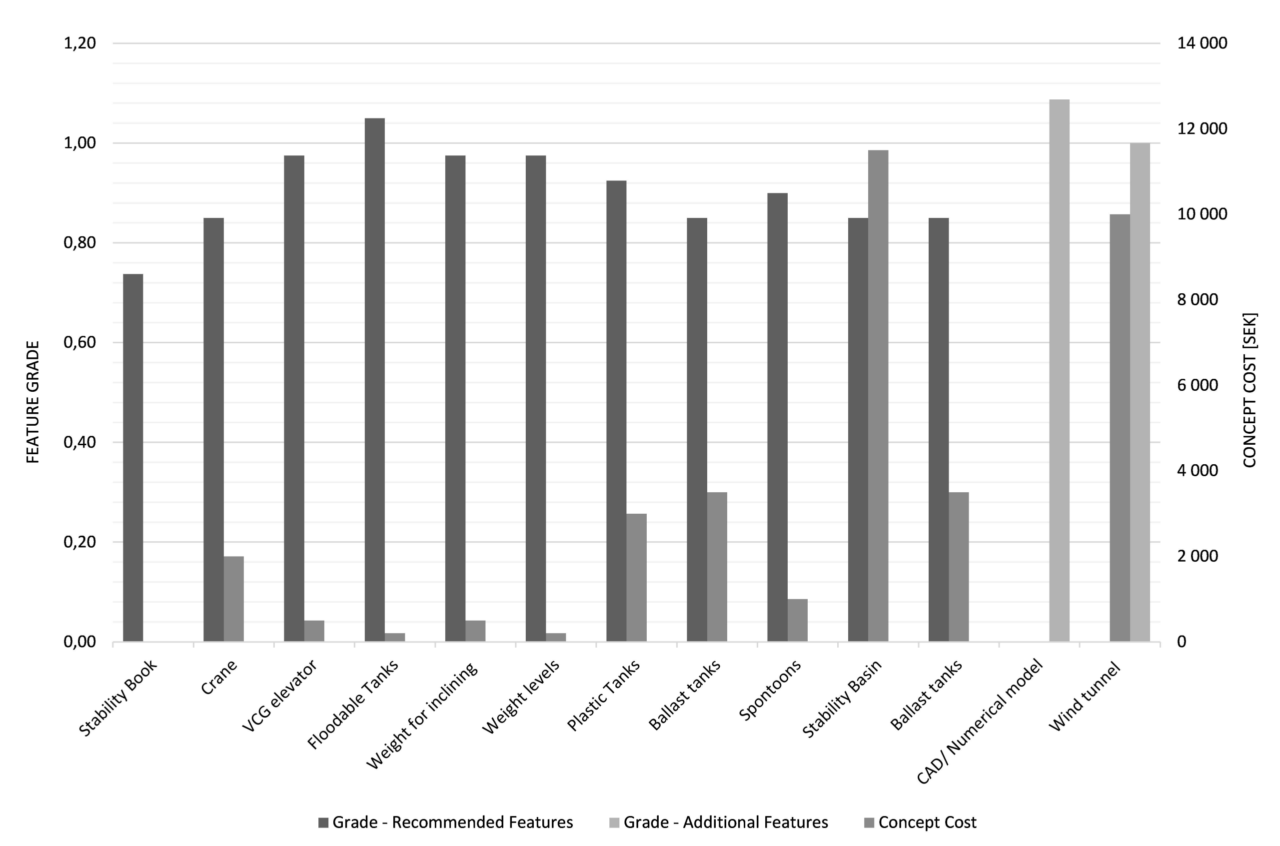



**Figure 8:** Feature grade for stability concept

To be able to do the test at the university and to lower the operational cost, it is suggested to build an own basin for this model. For an estimated cost of approximately 11 500 SEK, a basin of 2x3 meters and a height of 1.5 meters, can be build. The depth of the basin will be 45 cm. The basin will have an approximately weight of 2.8 tons including water. This cost covers only the material. A system to change the water or a hatch to seal the tank is not included. It is believed that the extra cost of such a basin will quickly pay of due to high operational cost at SSPA. However, using the MDL basin after 4 PM could be an alternative.

Chalmers has a closed circuit wind tunnel with test dimensions $3.0m \cdot 1.8m \cdot 1.25m$ and a speed range of $0-60m/s$ ("Wind tunnel", 2016). The high speed may be sufficient to trigger turbulent flow even if the model is only one meter long. The wind tunnel is equipped with balanced force measurements, hot wire anemometer for flow studies, optical- and pressure measurement equipment. The stability model could be used in the wind tunnel to visualise the flow around the hull and to measure wind forces on the air draft of the model. This will probably set more stringent requirement to the models surface finish. Thereby the estimated concept cost of 10 000 SEK for this feature. This feature would extend the area of use for the model, but is considered to be an additional feature until further investigations are done. In example, interference with the test section walls and if it would be possible to trigger turbulent flow.

The ship type for this concept is not important and therefore not considered.

**Concept 4 – Backbone**
The last concept is a segmented model, equipped with an elastic backbone. The model features is seen in Figure 9. The model can be used to find global loads as, bending moment, shear stress, torsions, and to investigate vibrations, such as whipping and springing. Segmented model means that the hull is divided into one or more segments by transverse cuts. The segments are connected with a backbone, typically an aluminium beam, placed midship, parallel to the longitudinal direction of the ship. The idea is that the global loads, caused by weight, hydrostatic – and hydrodynamics forces, etc., will be transferred through the segments to the backbone, where the structural response can be measured using i.e. strain gauges. The structural properties of the backbone has to represent the real ship.

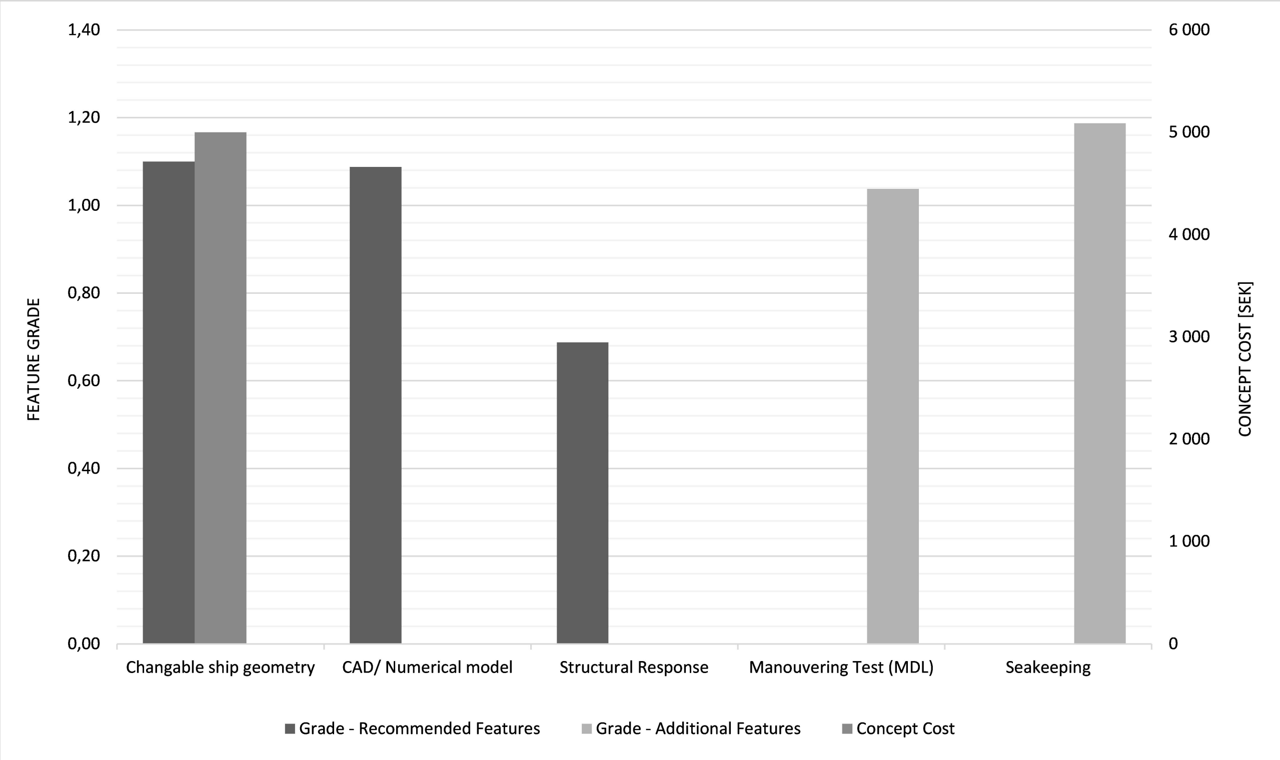



**Figure 9:** Feature grade for backbone concept

Several experiments have been done to measure the global loads of a ship model (Marón and Kapesenberg, 2014). ITTC has made recommendations on how to make the model and carry out the test (ITTC, 2011*a*). ITTC distinguishes between a hydro-structural model and a segmented model. The former is a ship model that is representative of the full scale ship down to the local structural level possible, even including hull plating. Such models have only been made a few times. The segmented model is more widely used. ITTC differs between a rigid segmented model and an elastic segmented model. The former has a rigid backbone; the backbone is rigid enough so that the model do not change shape on wave peaks or troughs. The elastic backbone is already briefly explained above. As an alternative to the elastic backbone, the model can be equipped with instrumented flexible connections at the segment break. An advantage with this system is that the connections can be made adjustable so that different resonance frequencies can be simulated. Which model type to build is mostly important for whipping experiments, as hydro-elasticity is of greater importance. This implies that a rigid segmentation should be avoided. Based on this, concept 4 is a segmented model with an elastic backbone.

Each segment in the segmented model must have the same inertial properties as the corresponding segment in the real ship. This implies that the ballasting of each segment must satisfy the weight and the inertial properties of that section, and at the same time the overall hull weight and ballast condition has to be satisfied. The backbone should, as close as possible, have the same structural properties as the real ship. The gap in the segmented model is usually between 5 and 10 mm. The model is made watertight by applying latex to seal the gap. The number of segments is decided based on what should be studied. For midship bending moment, one cut amidships is sufficient. For maximum shear, three cuts are needed. For dynamics loads and vibrations, more than five cuts are needed (ITTC, 2011*a*). Propulsion of the model should be done in a way to avoid that the thrust causes a longitudinal moment at the backbone. This can be done by channelling the trust through the geometric centroid of the beam.

It is believed that the model can be used for seakeeping for educational purpose. The effects of the gaps should not matter much in seakeeping trails and the fact that the model is elastic is believed to be an advantage as it represent a more realistic model. Manoeuvring could be challenging as the rudder would expose the backbone for horizontal moments and shear forces. The backbone already exist of several parts, so it should be possible to change the aft and fore ship quite easily.

According to Figure 10 an Ultra Large Container Vessel (ULCV) is recommended for this concept. These ships have structural challenges due to the length. Especially torsion is of concern. In addition they often have large flares which make them exposed for slamming, and therefore also whipping. Based on the economics of scale principle, it is assumed that even larger ship will be made in the future. Research on this kind of vessel is therefore highly relevant. The KVLCC, a 320 meter long crude carrier, was not chosen due to its low Froude number and rather bluff hull.

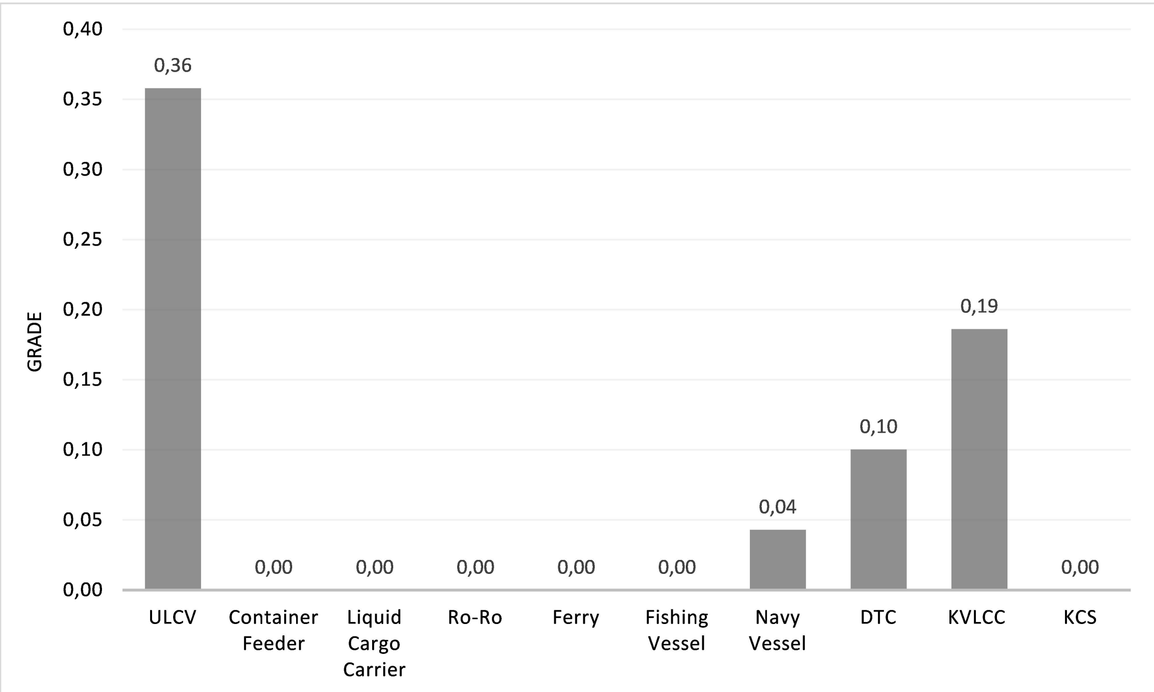



**Figure 10:** Graded ship types for concept 4

### 2.2.2 Decision of concept

In this section will the results from the evaluation of the concepts be presented. First, the results from the decision matrix, followed by the main conclusions from the second round of interviews with the lecturers. Last, the results from the student investigation.

**Results from decision matrix**
Figure 11 shows the total grade for each concept. The upper column represent the total grade of the additional features, while the lower column give the total grade of the recommended features. It could be seen that the resistance model was the most universal in terms of features. This model were able to do all resistance tests together with some seakeeping in head- and following waves. Second was the MDL model, third the stability model and last the backbone model. The grade from the decision matrix is just the summation of the grade of the features and represent only which of the concept that have most (good)features.

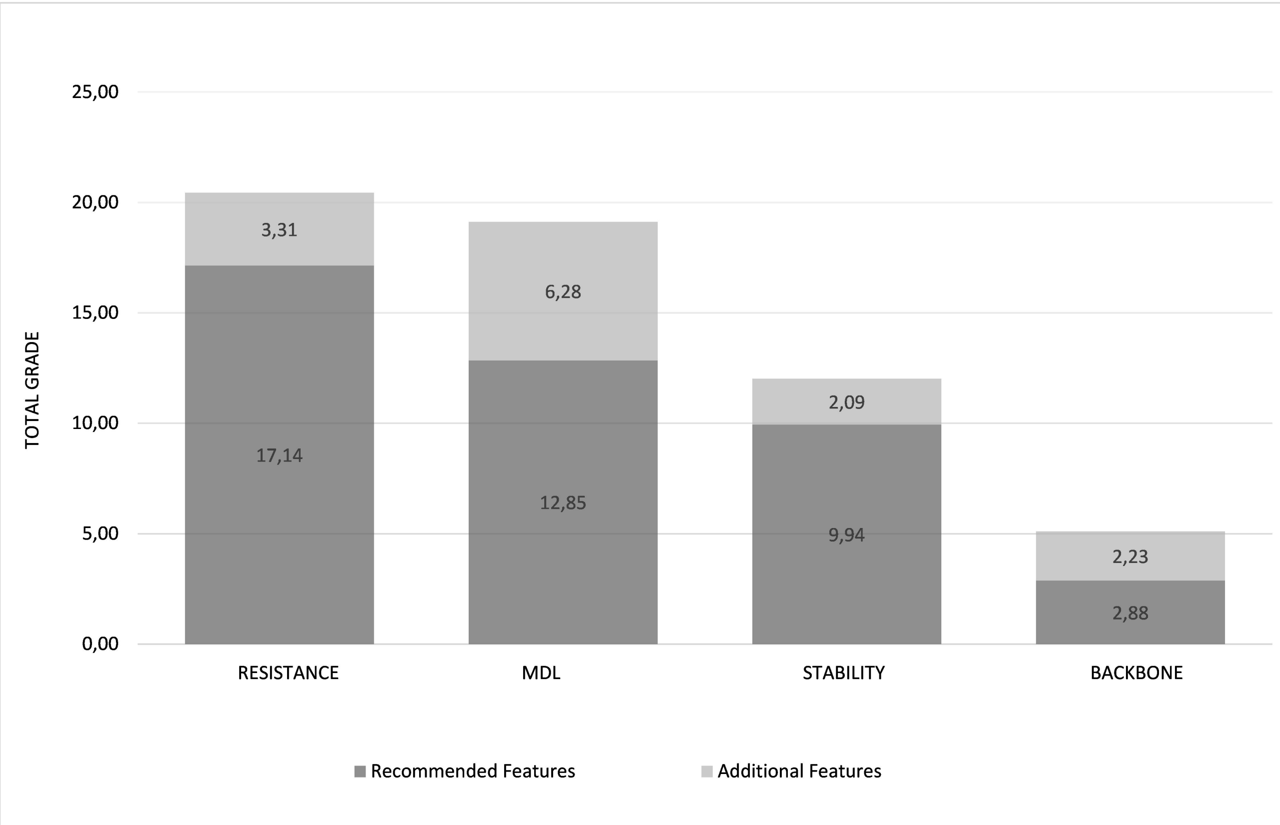



**Figure 11:** Total grade of concepts

Figure 12 shows the total cost for the four concepts. The lower column represent the standard cost for building a default model, the light grey column in the middle illustrate the cost for the recommended features. The upper column gives the cost for the additional features for each concept. It can be seen that the MDL model is the most expensive when all the features are included. However, it is less costly if only the recommended features are considered. The resistance model is the second cheapest all over, and when only the recommended features are included. The stability model is by far the cheapest model. This is due to that the model is smaller and simpler than the other models. The standard cost of the backbone model is higher than all the other concepts combined.

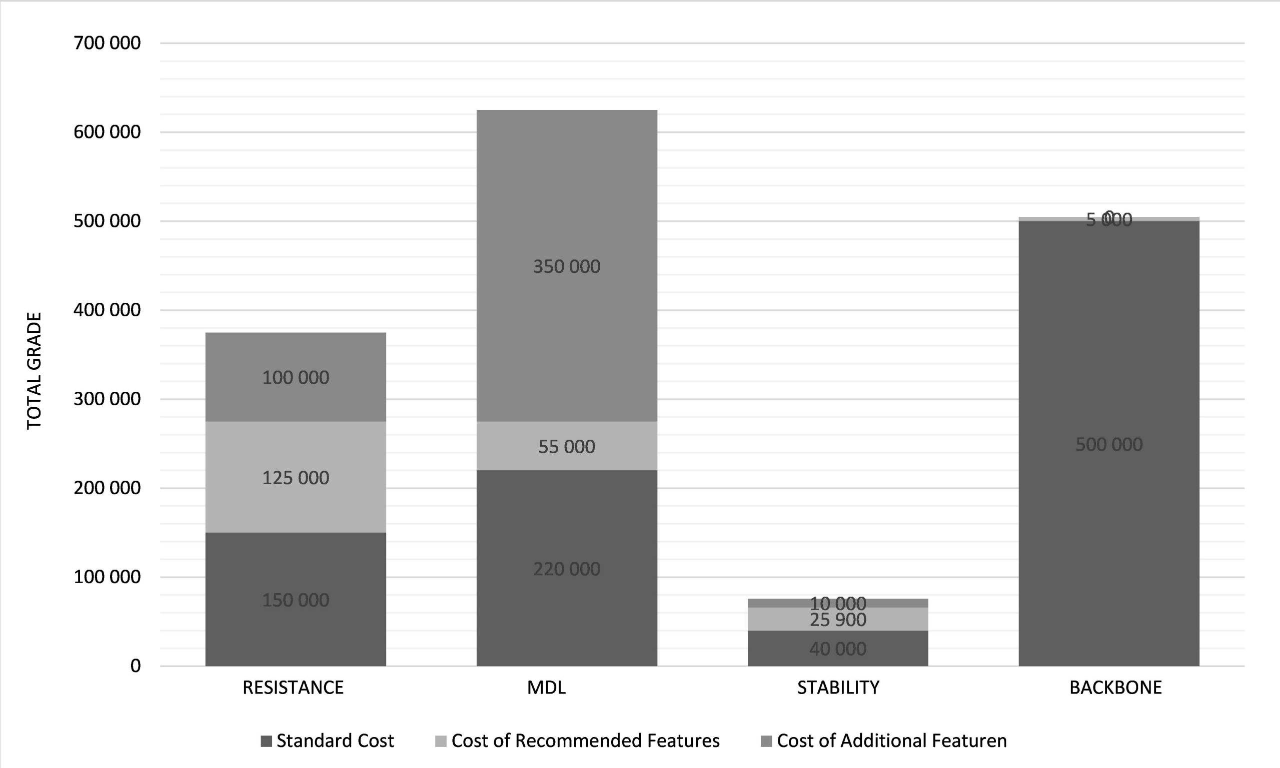



**Figure 12:** Feature cost

**Meeting with lecturers**
From the meeting with the professors, the following conclusion was established:

- The stability model was appreciated. It was suggested to develop it further as a student - or bachelor project.
- The backbone model was considered too advanced to be used as a learning tool.
- The MDL model was favoured over the resistance model for several reason that will be discussed in section 2.3.
- It was agreed that a RoRo vessel would be of interest for MDL concept. A length of 200 meters were suggested.

**Student investigation**
Figure 13 show the results from the student investigation. The total grade for each concept is given. In total, 25 students in the programme Naval Architecture and Ocean Engineering at Chalmers participated in the investigation. This corresponds to 35 % of the total number of students. The stability model was favoured with 31 % of the votes. The remaining concepts were fairly equally rated.

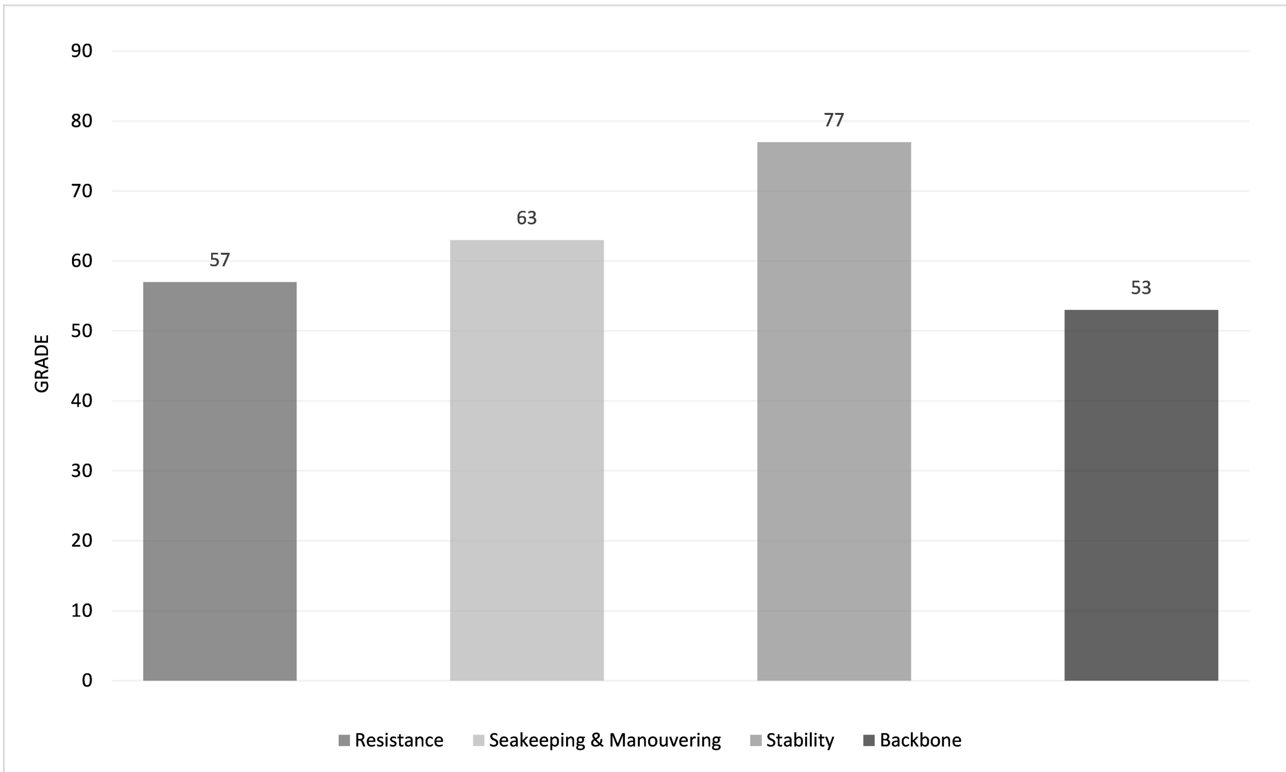



**Figure 13:** Results from student questionnaire

## 2.3 Discussion

Based on the grading seen in figure 11, the resistance model achieved the highest total grade. If this was directly convertible to being the best overall model was questionable. The lecturers agreed that the resistance model would be valuable in terms of education, but the fact that the general size of the model restricted it from running any tests in the MDL basin made it for them less universal. It is seen from figure 11 that including resistance features in the MDL model, almost makes it as universal as the resistance model. The stability model and backbone model are highly specialised, which can be seen from the low total grade. The two models would be more universal if the backbone model could be used in regular seakeeping and manoeuvring trials and the stability model could be used in the wind tunnel.

It is seen from figure 12 that the stability model is by far the cheapest to develop. In addition it has zero operational cost. The educational value of the stability model is considered high, due to that the basic stability course is thought in all the maritime educations. Since the cost is low and the learning outcomes substantial, this model is very beneficial compared to the other models. In total, the MDL model is the most expensive. Excluding the additional features, the cost of the MDL model and the resistance model are approximately the same. Compared to the other models, the backbone model would be extremely costly to produce.

A MDL model is able to operate in the MDL basin and give highly accurate results in seakeeping and manoeuvring tests. With some sacrifice of accuracy, it could also be used in the towing tank, but then only for education. Due to the small scale of the model, it would not be able to trigger turbulent flow, the results would therefore not be sufficiently accurate. The lecturers argued that the practical experience the students gets from doing the tests were valuable and regardless of the accuracy of the results, it would be valuable for the students to participate in carrying out the tests.

The resistance model would be able to run all resistance tests with high accuracy, as well as some seakeeping tests in head- and following sea. The MDL model can run all seakeeping tests in all headings. It can be argued that the resistance model is the best choice only in an educational perspective and that the seakeeping and manoeuvring tests are too complex for the general educations. But, for the more advanced educations, the value of getting a visual explanation of challenging concepts such as slamming, broaching and parametric roll would be very advantageous for the students.

Another concern of the lecturers were the cost. Not only the concept cost of the model, but also for the operational cost. From the commercial prices, the resistance model would be less costly to manufacture and also the tests would be less costly to run. But, if Chalmers were to rent a basin for a day, the cost would be in favour of the MDL basin: 70 000 SEK versus 100 000 SEK per day. This is due to that the MDL basin is only manned for 8 hours while the towing tank are manned for 12 hours a day. The MDL basin would also possibly be available for students to use after 4 PM for a lower cost. The importance of availability for the students were essential for the lecturers and another reason for favouring the MDL model.

The cost of one full seakeeping sequence is 500 000 SEK as opposed to a resistance test of 30 000 SEK. However, different trials could be carried out each year, resulting in a growing database. The students would then be able to watch one trial and do calculations with already existing results.

According to the lectures there are a limited publicly available databases for seakeeping tests. Since

Chalmers own the model, they are able to publish the results worldwide and compliment the seakeeping database. On the other hand, the need for a resistance model for research was low. At Chalmers, researchers do not look into different type of foreships on their own. The lecturers did not see the need for a resistance model in their research at the moment. The lecturers believed that the backbone model would be valuable for research, but that it probably was too complex to use in normal education. Due to the high cost of this model, it was rated lower than the other concepts from the lecturers point of view as well.

The student favoured the stability model most and the MDL secondly. However, the results should be analysed with a pinch of salt. It was not given any oral presentation of the different concept, leaving limited room for questions. The majority of the students were 4th graders. The 4th grades have not had any courses in seakeeping and manoeuvring at the time of the questionnaire, which may have affected their answers.

## 2.4 Conclusion

The stability concept was most favoured by the student, and is by far the cheapest concept. The lecturers also appreciated this concept. It was agreed that the model should be developed in the future, as a student - or bachelor project. The backbone model was too complex and expensive and should be developed as a separate project. The MDL model and resistance model both had desirable features, but the MDL model was chosen to further develop based on:

- The model is beneficial for research; a open database for seakeeping and manoeuvring is today not available and there are several hot topics for research w.r.t capsizing stability, i.e parametric rolling.
- The model is beneficial for the student as it can be used to illustrate phenomena that is challenging to grasp theoretically.
- With some loss of accuracy, the model can be used in the towing tank for educational use.
- The MDL basin will probably be available for the students after 4 PM

Based on the reasoning in section 2.2.1 and the interview with lectures it was decided that a RoRo ship with a length of 200 meters will suit this concept best. Since no publicly available hull for this type of vessel exist, the hull will be designed from scratch. When referring to the model in the continuing text this will be the MDL model.

# 3 Hull design

This chapter address the design of a hull for the MDL model. The purpose is to design a hull with respect to the model features. The performance of the hull, with its hydrostatic & stability, resistance and seakeeping abilities should represent a real vessel, but with room for student optimisation. In this chapter, only the full scale hull will be considered.

## 3.1 Methodology

Figure 14 illustrates the work flow of this chapter. The main dimensions of a vessel are normally chosen with regard to limitations as port drafts or amount of cargo to carry. In this project, no such limitations exist. The dimensions were therefore chosen with regard to ship properties from chapter 2 and from relevant reference ships. The idea is that the main dimension of the hull should be relatively normal, so that the model would be representative for a real life vessel. From the previous phase, it was established that a RoRo-vessel with an approximate length of 200 meters were to be designed. Various types of RoRo vessels of 200 meters were evaluated and reference dimensions were selected. The dimensions were verified with different empirical formula's. The hull was then designed according to the derived dimensions. Then the hull's performance with respect to stability, resistance and seakeeeping were evaluated. The ship's performance with regard to manoeuvring was neglected in this project, due to limited time and that no rudder were designed.

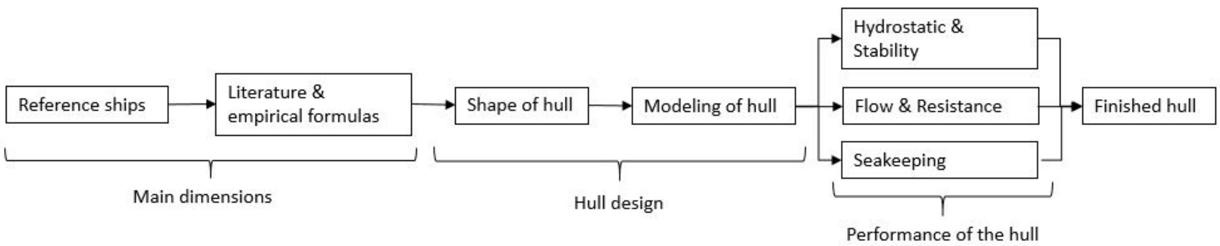



**Figure 14:** Work process, hull design

### 3.1.1 Reference ships

The first step when selecting the main dimensions was to determine which type of RoRo vessel to design. The different types were evaluated with regard to how well they can trigger the desired features. An approximately 200 meter long RoRo vessel was the first criterion. The hull should have a modern shape to best compliment the research and provide results that can be associated with today's RoRo fleet. Modern reference vessels recently built were therefore considered. Ships with a large bow flare are especially exposed to parametric roll, slamming and non-linear wave loads which are all desired features for the model to illustrate. The second criteria was therefore that the ship should have a large bow flare.

Another preferred feature was to have a slender ship with a high Froude number. For vessels with high Froude number, i.e in the region of a container ship, the residuary resistance represents a greater part of the total resistance, see Figure 15. The wave making would therefore be more interesting to investigate for the students.

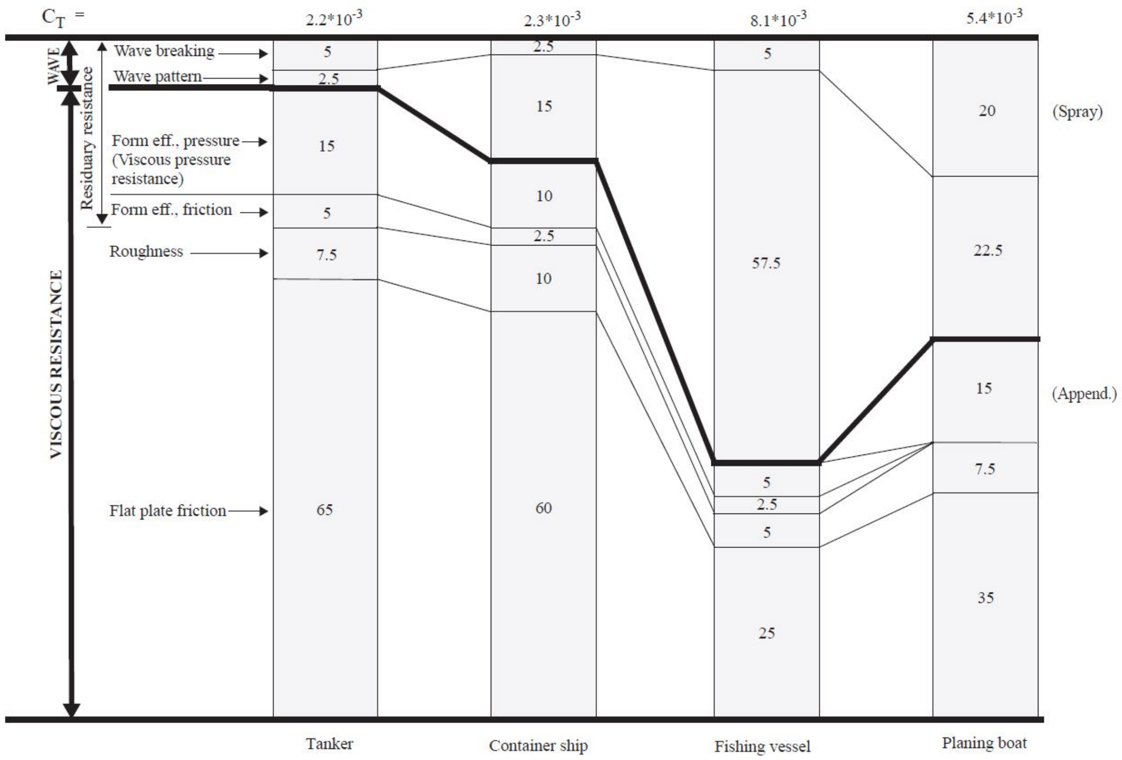



**Figure 15:** Resistance components for different types of vessels, Fig. 4.1 (Larsson and Raven, 2010)

Since RoRo is a quite wide term for a vessel designed to carry wheeled cargo, many different types of ships within this gender needed to be evaluated. Some of the types considered were ConRo, RoPax, RoLo, PCC and PCTC. A ConRo is a vessel that carry both containers and wheeled cargo. A RoPax carries wheeled cargo and passengers. The RoLo vessel can in addition to operate wheeled cargo, lift cargo on and off with installed cranes. A PCC is specialised vessel used to transport only cars and a PCTC transport both trucks and cars. By investigating the different vessels it was found that the PCTC had most of the desired features from phase one. The PCTCs generally have a large bow flare, slender body and run at a high Froude number.

The next step was then to establish the main dimensions of the full scale vessel. Ten different reference PCTCs of approximately 200 meters were evaluated with regard to beam, draft, speed and displacement. See section 3.2.1, table 5 for an overview of the results and figure 16 for the considered reference vessels.


**Figure 16:** Reference vessels

The reference vessels were found from the homepages of Wallenius ("Wallenius - fleet", 2016), Wilhelmsen ("Wilhelmsen - fleet", 2015) and Höegh ("Hoegh - fleet", 2014).

### 3.1.2 Literature and empirical formula's

Figure 17 illustrates the work flow when setting the main dimensions of the PCTC. Preliminary main dimensions were set with regard to the reference ships. Those dimensions were verified using literature and empirical formula's. Last, the remaining characteristics of the vessel were calculated.

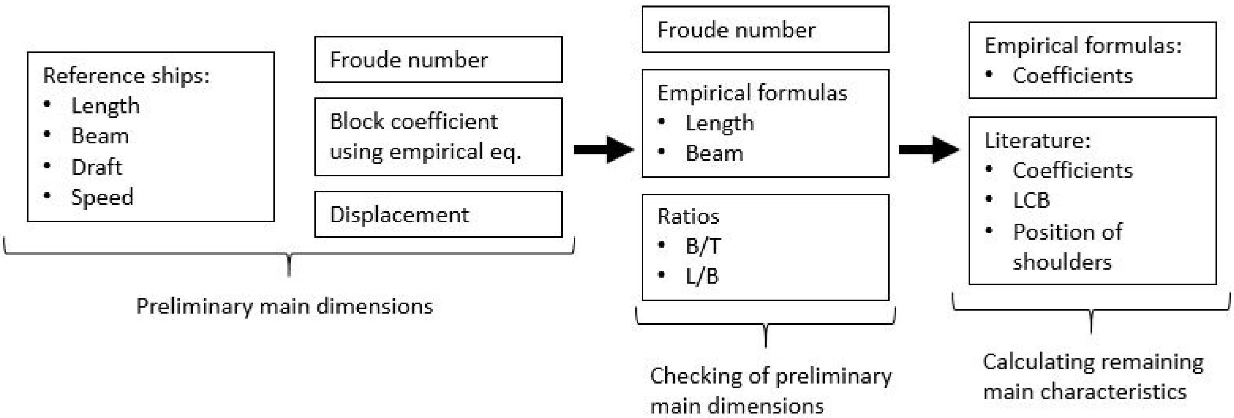



**Figure 17:** Process when determining the main dimensions of the full scale vessel

**Preliminary main dimensions**
From the reference ships the preliminary beam, draft and speed of the ship was determined. Using these dimensions, the Froude number, block coefficient and displacement were calculated. The block coefficient is defined as the ratio between the actual underwater hull volume of the ship at a given

draft and the volume of a rectangular prism. Since the displacement is unknown, empirical formula's proposed by (Jensen, 1994) and Bertram and Wobig (1999) were used as an estimation. Both the formula's are given as a function of the Froude number.

The empirical formula of Jensen (1994) for ships with Froude number in the region $0.1 < F_n < 0.4$ was given as

$$C_B = 2.179 - 9.675 \cdot \sqrt{F_n} + 18.633 \cdot F_n - 134 \cdot F_n^3 + 913 \cdot F_n^5 - 2274.852 \cdot F_n^7 \tag{2}$$

And Bertram and Wobig (1999) for $0.145 < F_n < 0.325$

$$C_B = -4.22 \cdot 27.8 \cdot \sqrt{F_n} - 39.1 \cdot F_n + 46.6 \cdot F_n^3 \tag{3}$$

**Checking of preliminary main dimensions**
To check whether the preliminary dimensions are feasible, the following investigations were performed

- The Froude number was compared with literature
- The length and beam were calculated using empirical formula's, based on the calculated Froude number, displacement and block coefficient.
- Common ratios were calculated and compared with literature.

In order to avoid humps in the wave making resistance curve, the Froude number should not be within $0.25 < F_n < 0.32$ (Schreuder and Tillig, 2015). Humps are the interference between two waves, where they intensify each other, which lead to an increase in the resistance. The contrast to humps are hollows, where the waves have a destructive interference, meaning they cancel each other out. A Froude number around 0.25 is in addition often unfavourable due to that considerable wave making may start at this point (Larsson and Raven, 2010).

To verify the preliminary length of the vessel, it was calculated as a function of the derived displacement, block coefficient and speed. Several empirical formula's exist to select the length of the vessel. They have been developed based on different criteria such as production cost or statistics of existing ships. Equation 4 gives an approximation of the length based on the lowest production cost.

$$L_{pp} = \Delta^{0.3} \cdot V^{0.3} \cdot C \tag{4}$$

Where $C = 3.2 \cdot \frac{C_B+0.5}{(\frac{0.145}{F_n})+0.5}$ for $C_B \neq \frac{0.145}{F_n}$. Where $V$ the speed in knots and the displacement $\Delta$ is given in tons (Schneekluth and Bertram, 1998).

Equation 5 below is in difference from equation 4 an iterative estimation of the length, based on statistics from existing vessels. The equation is recommended by Ayre (Schneekluth and Bertram, 1998).

$$\frac{L_{pp}}{\nabla^{\frac{1}{3}}} = 3.33 + 1.67 \cdot \frac{V}{\sqrt{Lpp}} \tag{5}$$

The minimum dimensions of the beam is usually determined from the requirements for sufficient stability, while the maximum value are normally restricted by topological limits of the route. The majority of the reference vessels had a beam of 32.3 meters, due to the former restrictions of the Panama Canal. This dimension was verified with two different formula's, both found in Schreuder and Tillig (2015).

Equation 6 recommended from Bertram and Wobig (1999) is a good approximation for build ships in the range $130m < L_{pp} < 410m$.

$$B = 0.175 \cdot Lpp - 2.5m \tag{6}$$

Equation 7 from Rawson and Tupper (1994) is an estimation of the beam for cargo ships

$$B = \frac{Lpp}{9} + 4.27m \tag{7}$$

The main requirements for the draft arises from the fitting of the propeller. If the model should be able to do self-propulsion tests, the model propeller diameter has to be of a certain size. It was therefore desired that the ship should have a large propeller as possible, within sensible limits. See Table 6 for the chosen draft and propeller diameter. The ballast draft was decided based on the draft necessary to keep the propeller and bulb submerged.

The normal ratios to evaluate are the length to beam ratio, beam to draft, length to depth and beam to depth. The two latter ones are not considered as the depth is not taken into account. This is because it depends on the load plan, which is not available in this thesis. The length to beam ratio is an indication of the slenderness of the ship and should be close to $6.25m$ for a container ship, according to Papanikolaou (2015). Since a container vessel and a PCTC have a relatively similar hull shape, the length to beam ratio for the PCTC should be close to this value. The same source recommend that the beam to draft ratio is close to $2.5m$. The value may deviate for ships with low draft or challenging stability, but is not to exceed $9.625 - 7.5 \cdot C_B = 4.672m$ (Schreuder and Tillig, 2015).

**Remaining main characteristic**
After checking and concluding on the main dimensions of the ship, the following parameters were calculated using empirical formula's and relevant literature:

- Coefficients
- Longitudinal centre of buoyancy (LCB)
- Length of entrance, run and parallel midbody

The main coefficients describing the hull form of a ship, in addition to $C_B$, are the midship section coefficient ($C_M$), the waterplane area coefficient ($C_{WP}$) and the prismatic coefficient ($C_P$).

The midship section area coefficient expresses the fullness of the midship section compared to a rectangle of the same width and height. The formula for the midship section area coefficient is given by Bertram and Wobig (1999) as,

$$C_M = 0.96845 + 0.095(C_B - 0.57) \tag{8}$$

And Jensen (1994),

$$C_M = 0.526 + 1.135 \cdot C_B - 0.683 \cdot C_B^2 \tag{9}$$

The value of $C_M$ for most vessels are usually very high. The water plane area coefficient $C_{WP}$ indicates the slenderness of the waterline, which affects both the wave making resistance from the hull and the stability of the vessel. The coefficient was found using the empirical formula given in Schreuder and Tillig (2015).

$$C_{WP} = 0.9811 \cdot C_B^{0.4824} \tag{10}$$

The prismatic coefficient was then found as the ratio between the block coefficient and the midship section area coefficient. The calculations of the optimum prismatic coefficient was verified using Figure 11.1 in Larsson and Raven (2010), Figure 18 below. The figure is based on results from different sources and shows the optimum prismatic coefficient on the y-axis and the Froude number on the x-axis.

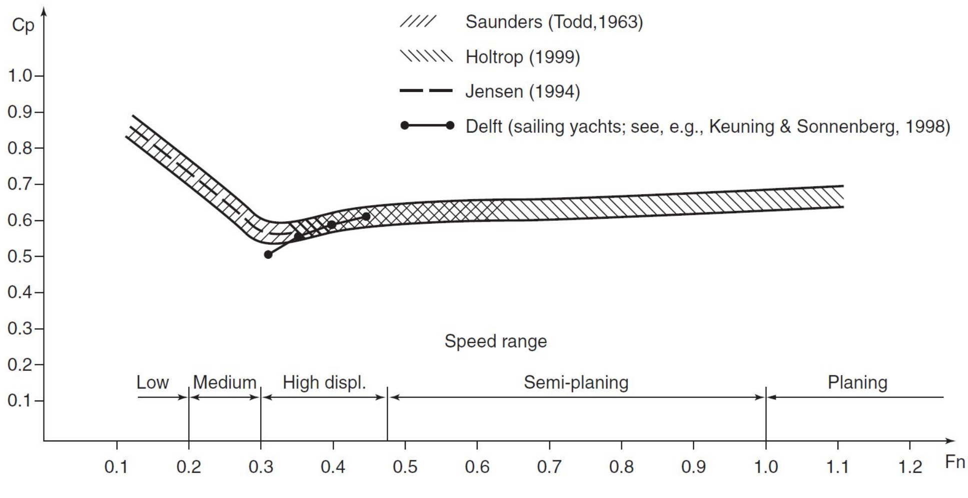



**Figure 18:** Prismatic coefficient versus Froude number, ref. Fig 11.1 (Larsson and Raven, 2010)

The positioning of the longitudinal centre of buoyancy (LCB) was then estimated. LCB is the longitudinal distance from the midship section to the centre of the displaced volume of water. Figure 19 shows the optimum position of the LCB versus the ships Froude number, given in percent of the length of the ship, $L_{pp}$.

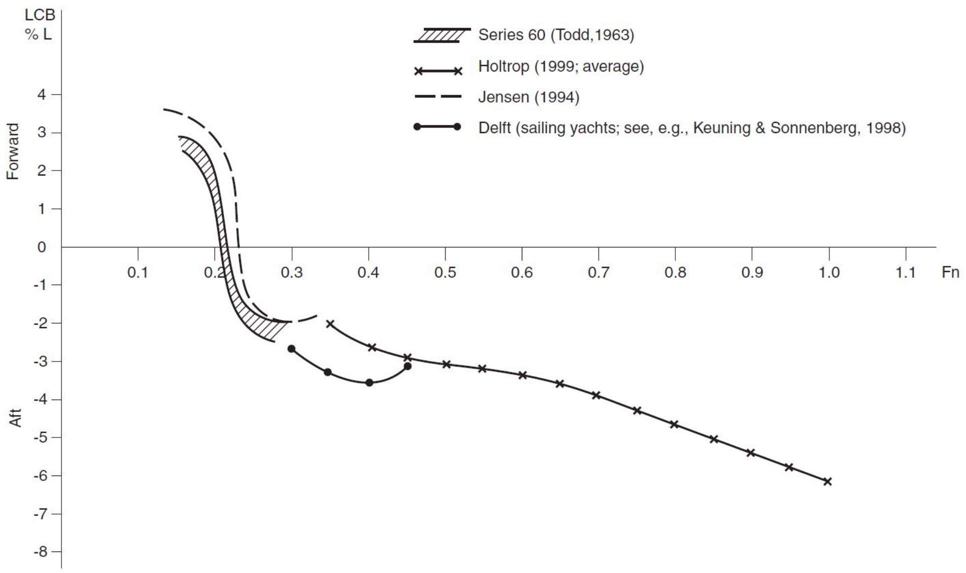



**Figure 19:** Optimum location of CoB vs Froude number, Fig. 11.2 ref (Larsson and Raven, 2010)

As seen from figure 19, at Froude number 0.15 - 0.25 there is a rapid shift in the location of the LCB from forward to aft. After a Froude number of approximately 0.3, the LCB is moved aftward more gradually. For medium displacement speed $0.2 < F_n < 0.3$ the wave resistance is a significant resistance component. To reduce the pressure peak that generates in a blunt bow, the fore is made more slender. Due to the thinner bow, the LCB is moved aft wards.

The position of the forward shoulder and the length of the parallel midbody was found from Fig. 3.7 in *Ship Design* (Papanikolaou, 2015), using the prismatic coefficient. The position of the forward shoulder affects the wave making resistance. A correct position will cause a favourable interference between the wave created at the bow and the shoulder, which in turn will decrease the resistance of the ship. The position of the aft shoulders were determined by the length of the mid section and have less influence on the total resistance. To find the correct positions, the ship can roughly be divided into three lengths $L_E + L_P + L_R = L_{pp}$. Where $L_E$ is the length of the entrance, $L_P$ is the length of the parallel midbody and $L_R$ is the length from the end of the parallel midbody to the aft perpendicular. These parameters determine the position of the forward and aft shoulders of the ship. Figure 20 shows the length of each sections as a fraction of the total length between the perpendiculars.

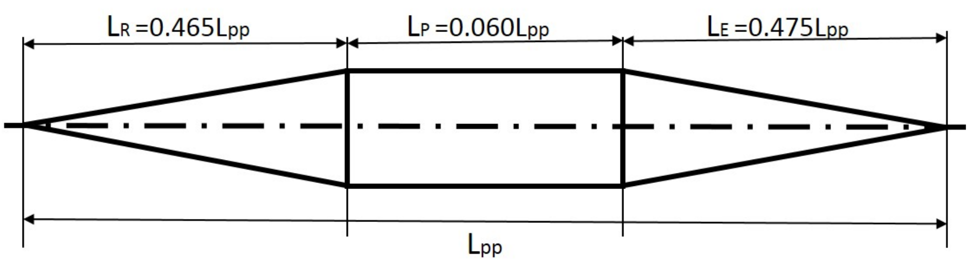



**Figure 20:** Fraction of entrance, midbody and run as a fraction of Lpp

### 3.1.3 Shape of the hull

After fixing the main dimensions, the next step is to investigate what shape the ship should have. The shape is limited by the ship's main dimensions and its sectional area curve (SAC), but there is still freedom to shape the lines. There exist a lot of literature on how a ship should be formed to obtain the best characteristic. In this section, relevant literature regarding the shape of the ship will be presented.

**Sectional area curve**
The SAC curve shows the area of each underwater section of the ship plotted against its length. It shows how the ship's volume is distributed and indicates the location of the LCB. The sectional area curve can be designed as a trapezium, see thin line in Figure 21. The maximum height of the trapezium is taken as the product of the breadth and depth of the ship. The trapezium in divided lengthwise into sections according to the length of the aft, fore and midship. The trapezium works as a skeleton for the actual SAC curve. Its final shape depends on the ship type. Typically for slender ship is a SAC curve with centroid aft midship and a s-shaped entrance as a result of the bulb (Larsson and Raven, 2010).

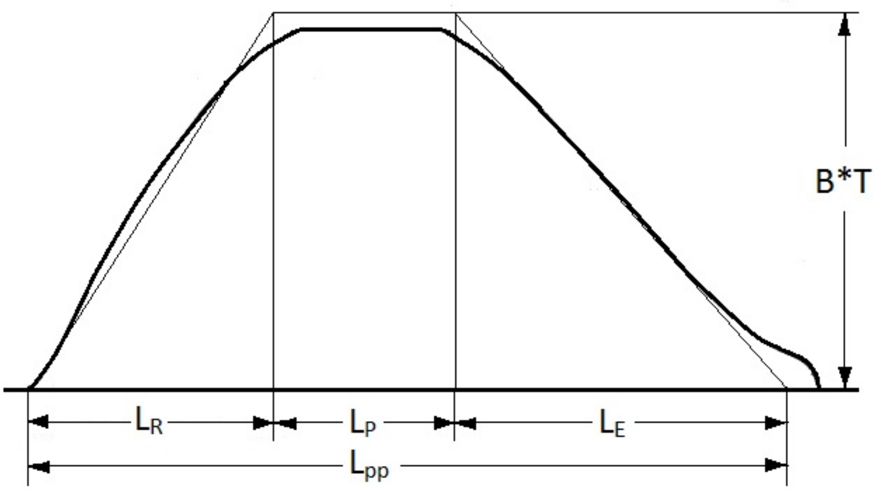



**Figure 21:** Design of a sectional area curve

**Fore ship**
When designing the fore part of the ship, the position of the shoulders, the design of the waterline, the shape of the sections and the shape of the bulb are important parameters. The importance of position of the shoulders are already emphasised in section 3.1.2. However, the final position and shape has to be determined by the use of potential flow methods.

For medium and high Froude number, Papanikolaou (2015) recommend that the entrance shape of the waterline should have a concave form, as illustrated in Figure 22. Based on formulas provided by Saunders (1957), the entrance angle of the waterline is calculated. See Appendix D.

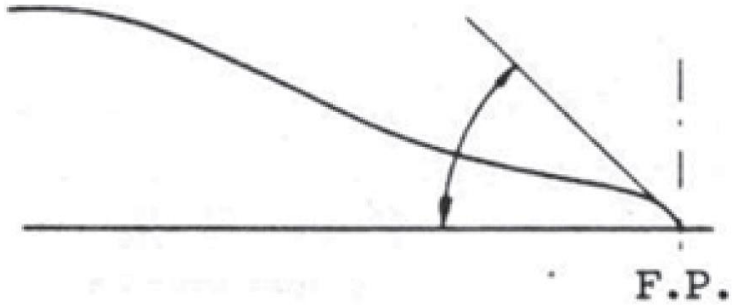



**Figure 22:** Entrance of waterline, Fig. 3.11 (Papanikolaou, 2015)

The shape of the ships forbody section depends on several factors, both concerning stability, hydrodynamic, construction and exploitation of space, etc. A V-shaped section is normally applied for fast ferries, while a U-shaped section is normal for tankers and slow going ships. For the PCTC in this project, a combination of less pronounced sections of U and V type are considered the best solution.

The vessels performance in seakeeping are often sensitive to the displacement and weight distribution. It is therefor an advantage if the model can operate at several drafts without the waterline being significantly changed. This is accomplished by making the bulb relatively small and positioned it far below the waterline. The size of the bulb is determined by the coefficients presented in Kracht (1978) and rendered in Figure 23 and Table 4. It is desired to make the lower part of the bulb's cross section V-shaped in order to avoid slamming.

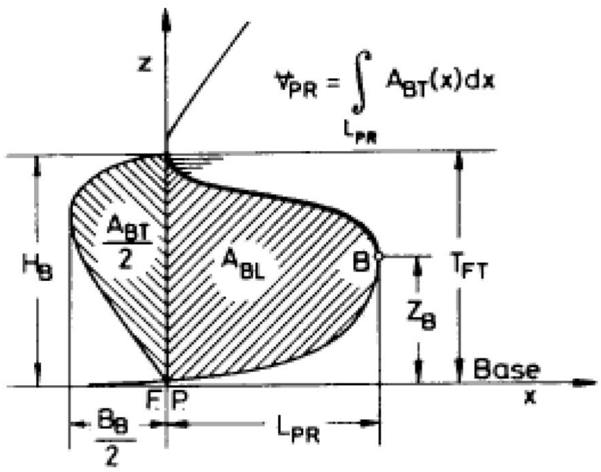



**Figure 23:** Sketch of bulb (Kracht, 1978)

**Table 4:** Minimum and maximum values of coefficients (Schreuder and Tillig, 2015)

| Coefficient | Explanation | Minimum | Maximum |
|---|---|---|---|
| $C_{BB} = B_B/B$ | Breadth | 0.170 | 0.200 |
| $C_{LPR} = L_{PR}/L_{PP}$ | Length | 0.018 | 0.031 |
| $C_{ZB} = Z_B/T$ | Height | 0.260 | 0.550 |

**Midship**
The midship sections are the part of the ship that are equal sectional wise. The midship section should be rectangular, with vertical sides and a constant bilge radius. It is important to have a large enough bilge radius in order to avoid separation. The radius is decided based on the formula from Schneekluth and Bertram (1998).

$$R_{bilge} = \frac{C_k}{(\frac{L_{pp}}{B+4}) \cdot C_B^2} = 3.615[m] \tag{11}$$

where $C_k$ were chosen as 0.5. According to table 2.17 in Schneekluth and Bertram (1998) a bilge radius for a common cargo ship normally lays between 2 and 2.7 meters. Since a PCTC is a large, fast cargo ship, the bilge radius calculated above were adjusted slightly down to 3.3 meters.

**Aft ship**
When designing the aft of the vessel, the aft shoulders, transom, propeller clearance and wake field is of most importance. Based on the reference ship a single screw arrangement was chosen for the model.

The aft shoulder cause wave system due to the convex curvature. This results in a low pressure area, where the pressure decreases towards the hull. The generated wave system will therefore start with a wave trough. The aft shoulder should be positioned at a longitudinal length along the hull, so that the generated wave system interfere nicely with the wave system generated from the forward shoulder and bulbous bow (Larsson and Raven, 2010).

Most commercial vessels today have a transom stern. When designing the transom, it was important to determine if it should be submerged or over the water line, dry. A dry transom is favourable with respect to resistance. The waterlines will follow the hull and leave the stern smoothly (Larsson and Raven, 2010). For a wet transom, the flow will move with the hull. This may result in turbulent flow behind the stern, which will increase the resistance. According to Schneekluth and Bertram (1998) it is recommended to have a dry transom for vessels with Froude number below 0.3, where some submergence of the stern during operation is expected. The drawback with a dry transom, is that the angle from the aft shoulder to the edge of the transom can become too large, which causes unfavourable flow and separation.

This angle is determined by the height from the baseline to the edge of the transom, which again is limited by the propeller diameter. The maximum angle has to be determined by flow calculations, but should normally not exceed 12 degrees. In addition to the propeller diameter, it should be a clearance between the propeller tip and the hull and the propeller tip and baseline. DNV (2000) recommend a clearance of $0.2 \cdot D_{prop}$ for the former, and $0.035 \cdot D_{prop}$ for the latter clearance. This gives a total minimum distance from the baseline to the hull of $1.235 \cdot D_{prop}$. The propeller base has to be located sufficiently far from the end of the ship to give space to the rudder. Due to the absence of the rudder dimensions, the distance from aft perpendicular to the propeller base is usually taken as $0.04 \cdot L_{pp}$, according to Schneekluth and Bertram (1998). These two distances form a point where the bottom line of the stern have to go through, see Figure 24. The goal is to keep the angle between the baseline and the stern sufficiently small and at the same time have a dry transom.

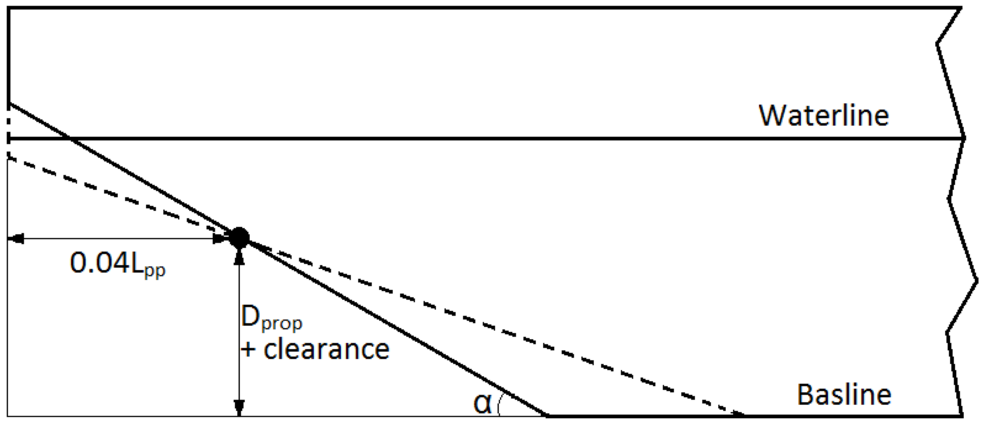



**Figure 24:** Propeller clearance, obtained from DNV recommendations for single screw vessels

For slender vessels at relatively high speed, the stern wave making is a considerable factor in the total resistance. In order to decrease the resistance, the hull should be designed so that the flow lines are as straight as possible. A relatively flat afterbody with a concave last part towards the stern was desired in order to reduce transverse waves from the ship that may be generated on wide transom sterns, as for a PCTC.

For vessels with a slender afterbody fitted with a single-screw, the wake is less homogeneous than the wake of a more full body form (Larsson and Raven, 2010). It is therefore especially important to optimise the flow into the propeller for this kind of vessel. The bulb shaped stern, as opposed to a V-shaped stern, is favoured for slender hull forms. This is mainly because the deep wake peak in the top of the propeller disk are reduced due to that the lines above the propeller become more slender, which gives a more uniform flow into the propeller. In addition, the vortex get stronger due to the curvature of the bilge. See Figure 25 for the desired shape of the stern.

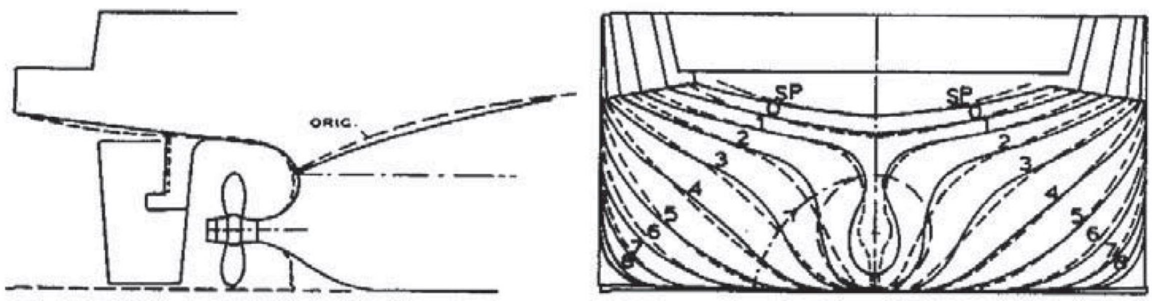



**Figure 25:** Desired bulb shaped stern, ref. Fig 11.20 (Larsson and Raven, 2010)

### 3.1.4 Modeling of the hull

*MaxSurf Modeller* was used to model the hull. This is a three-dimensional surface modelling system created to design marine constructions (Bentley, 2015*a*). In this subsection, the basic features in *MaxSurf*, along with some practical modelling techniques, are elaborated.

**Modeling of surfaces**
*MaxSurf* uses *Non Uniform Rational B-spline (NURB)* surfaces to create a model. The shape of a NURB surface is calculated based on the position and weight of a number of control points and a given surface stiffness in transverse and longitudinal direction. The control points are distributed in a net of control points with four corner points, see Figure 26. Any number of rows and columns of control points can be added to obtain the desired surface.

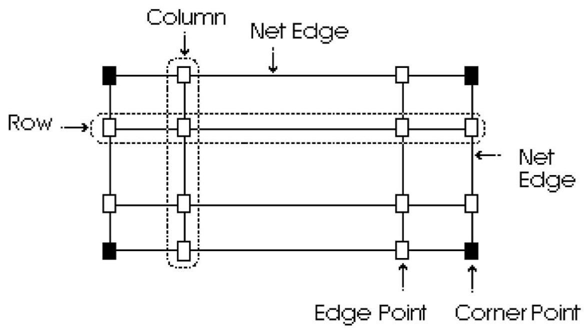
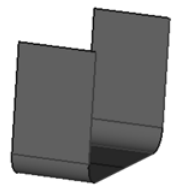


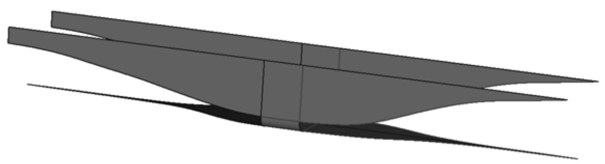

**Figure 26:** Net of control points used to define a surface (Bentley, 2015*a*)

In *MaxSurf*, it is distinguished between two type of NURB surfaces, namely *B-spline* and *NURB*. The latter differ from the former as it is possible to change the weight of the control points from unity. In practical ship design, the *NURB* surfaces are only used to model precise conic shapes, i.e. the bilge. The stiffness of the surface can be increased from 2 - linear, 3 - flexible, up to 10 which represent a stiff plate. The stiffness of the surface decide the "amount of curvature" between the control points, i.e a stiffness of 2 would mean that a straight line is created between two control points. What degree of stiffens to choose depends on the shape that should be modelled, but a good start according to *MaxSurf User Manual* (Bentley, 2015*a*), is a longitudinal stiffness of 5 and transverse stiffness of 4. The degree of stiffness has to be equal or lower then the number of rows or columns with control points.

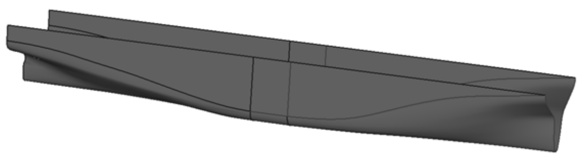
**Designing the hull**
Several surfaces are needed to successfully design a hull. This ship is designed by the stepwise procedure illustrated in Figure 27. First the midship section is designed (fig. 27a). Then the part of the bow and stern that consist of flat plates are made (fig. 27b). After that, the curved plates between the flat side and bottom plate are designed (fig. 27c) and finally, the bow and stern are made (fig. 27d). The surfaces are bonded, which means that the surfaces share the control points along their edge. This ensure a nice transition between the surfaces. To be able to bond surfaces, the surfaces has to have the same stiffness and number of control points. The geometry of the curved plates are mainly shaped through the sectional view, while the flat plates are modelled in the side view. Smaller modifications are done in all views to ensure smooth lines.



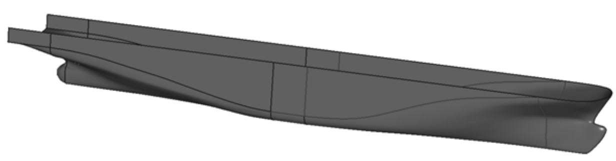
**(a)** Midship



**(b)** Midship including flat plates



**(c)** Ship excluding bow and stern

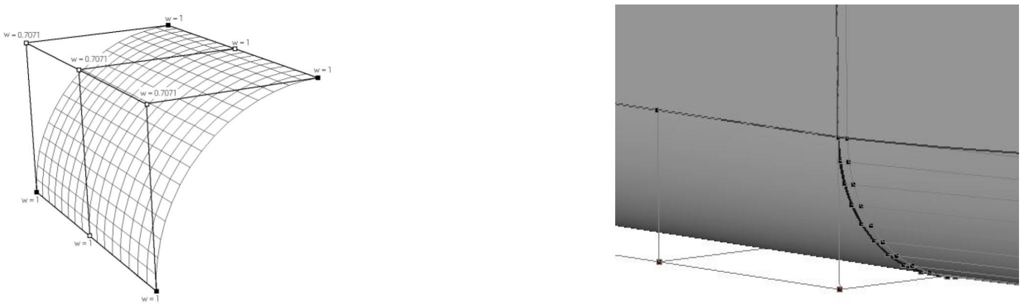


**(d)** Complete ship

**Figure 27:** Methodology of modelling a ship

The bilge is modelled as a perfect quarter circle. This is done by using a NURB surface with three control points for each column and a order of 3 in stiffness, see Figure 28a. If the distance of the control points are kept equal, the weight of the centre point can be calculates as, $w = \cos(\frac{\theta}{2}) = cos45° = 0.7071$. Since more than three rows with control points are needed to model the curved section between the flat plates (fig. 27c), this surfaces can not be bonded with the bilge. It is not possible to make these two quarter circles perfectly equal. This is not critical as a watertight geometry can be obtained at a later stage using Stereo Lithography Trimesh (STL) meshing. A close enough match between the two surfaces can be obtained by calculating the transverse and vertical position of each control points using trigonometric functions, sinus and cosinus, which ensure that the control points are placed at the bilge arc, see Figure 28b. This is done with a accuracy of 3 decimals.

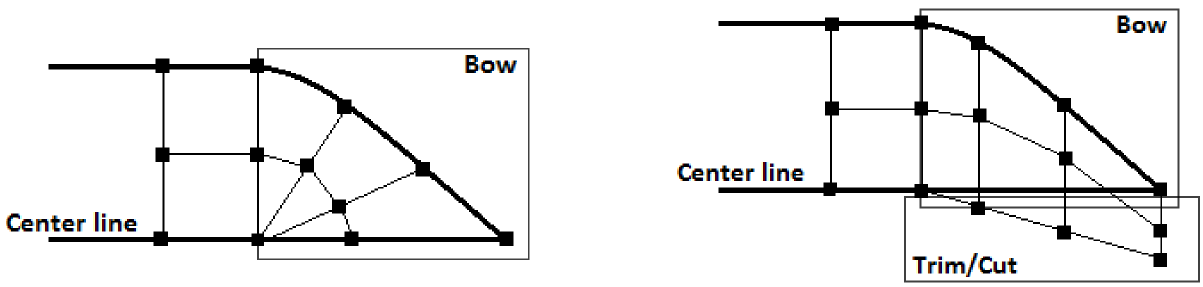
An additional row or column with control points has been added close to the the end of each surface. These additional control points have the exact same position, in two of the directions, as the end points. This can be seen in Figure 28b. This is done to ensure that the tangent of the curve is zero across the two bonding surfaces. Thus, a nice transition is ensured.



**(a)** Modeling of bilge (Bentley, 2015*a*) **(b)** Connection to bilge

**Figure 28:** Modelling of bilge

The stern and bow is challenging to model because the ship is closed in these regions and the geometry are often complex. To close the ship, the waterlines has to be manipulated, while in order to shape the bow and stern, the buttocks have to be manipulated. There are two normal approaches to accomplish this; the fan shaped distribution of control points (fig. 29a) and the distribution of control point beyond the centre line (fig. 29b). In the former method the control points are distributed in fan shaped pattern. This gives good control of the buttocks. The latter method distribute the control points sectional-ways, as with the rest of the ship, but extends the end points beyond the centre line. The surface that crosses the centre line has to be trimmed away when the desired shape is obtained. This method gives good control of the waterline. As the shape of the bow and stern are to be changed by the students, it is chosen to use the method with fan shaped distribution of control points, both for the stern and bow.




**(a)** Fan shaped distribution of control points **(b)** Distribution of control point beyond centre line

**Figure 29:** Modelling of bow/stern

**Faring**

Faring of the hull is the process of making the hull as smooth as possible. The goal is to remove every unnecessary curvature or knuckles from the hull lines. This is important, as these knuckles creates pressure variations and thus larger resistance. It is impossible to make a perfectly fair hull as this demands straight lines or lines with a constant curvature. This counteract with the ship geometry. Thus, fairing is an optimisation problem between fair lines and obtaining the desired shape.

Faring is carried out after the main shape of the hull is finish. But a fair hull strongly depends on how the model is build. The general rule is to use as few control points as possible. A NURB curve with few control points would return a fair curve, with few variations in curvature. However, few control points means reduced control of the shape of the curve. In example the bilge is modelled with the minimum of three control points and is completely fair, but it is impossible to make the curved plate discussed above (fig. 27c) with three points. The distribution of the control points is also important to obtain a fair hull. The fairness of the net of control points represent the fairness of the under-laying surface (Bentley, 2015*a*). This correlates to two important properties with the NURB curve; the NURB curves always start and end with the same slope as the accompanying net and the curve is guaranteed not to extend outside the area, highlighted in grey in Figure 30, limited by its control points. This means that rows and columns with control points should not intersect with neighbouring rows and columns, if this can be avoided.

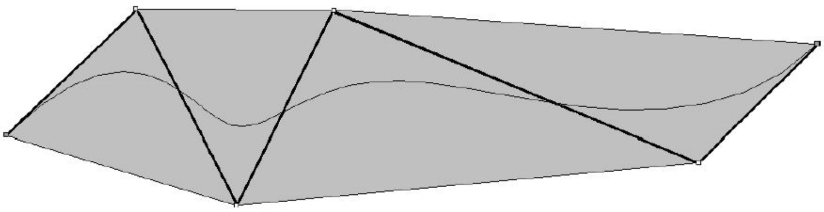


**Figure 30:** Behaviour of the NURB curve (Bentley, 2015*a*)

There are several techniques used to investigate the fairness of the hull. The simplest one is to rotate the hull around different axis, with different lightning and study how the light change along the hull. The parts of the hull where the change in light is rather small is considered fair. Of more advanced techniques, *MaxSurf* have a command which shows the *Porcupines* perpendicular to the surface contours and different types of rendering.

The *Porcupines* can be displayed using the *Show Curvature* command in *MaxSurf*. The length of the porcupines is inversely proportional to the square root of the radius of curvature at that point on the curve (Bentley, 2015*a*). The longer the porcupines is, the smaller the radius which means more curvature. This is a handy tool to investigate how smooth the change in curvature is on, i.e. the waterlines. Figure 31 shows the porcupines displayed on a waterline. The valley between the two tops indicate that the curvature at this point is in the opposite direction, something which is unfavourable and should be adjusted if possible.

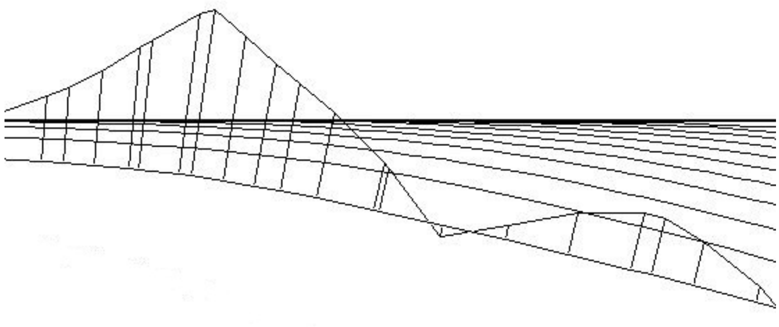


**Figure 31:** The porcupines displayed on a waterline

*MaxSurf* has the following rendering options made to investigate fairness; Gaussian curvature, longitudinal curvature, transverse curvature and convexity. The most useful of these is the longitudinal curvature. It display the curvature of each longitudinal parametric curve, taken perpendicular to the surface at each point along the hull. The goal is to obtain an even graduation of colour along the hull. Inflections can be detected by looking for sudden changes from blue, positive curvature, and red, negative curvature.

It is a challenge itself to design a ship with nice lines and high degree of fairness. In addition the ship has to fulfil requirements as correct displacement and a sensible LCB. These parameters are assessed in the next section.

### 3.1.5 Hydrostatic & stability

*Maxsurf Stability* has been used to evaluate the hydrostatic properties of the ship and its performance with respect to stability. The hydrostatic properties are calculated for a selection of drafts between ballast draft and $T = 12m$. There has not been developed any load plan for the ship, thus the centre of gravity is unknown. To assess the stability, a limiting KG analyse has been carried out. This analysis calculates the highest vertical position of the centre of gravity (maximum KG) for which the selected stability criteria are just passed. At each displacement, several GZ-curves are calculated for different KGs. The centre of gravity is increased until one of the stability criteria fails. The criteria evaluated is those defined in IMO MSC 267 (IMO, 2008). In a addition a GZ-curve is calculated for the design draft. The centre of gravity is given by the maximum VCG from the limited KG analyse and LCG equal to LCB. TCG is set to zero.

### 3.1.6 Resistance & flow

The software *Shipflow* was used to investigate the performance of the ship. Shipflow is a numerical program used to solve hydrodynamic problems. The program consists of five major modules; *XMESH, XPAN, XBOUND, XGRID* and *XCHAP*, which are partly interacting with each other. A short introduction of the modules are given below.

XPAN is used to calculate the wave resistance and wave pattern. The program uses the potential flow theory, thereby excluding the viscosity of the fluid and only taking the pressure forces into account. The mesh used in XPAN are generated in the module XMESH. The wave resistance is calculated based on the energy-flux of the far-field waves generated by the ship. As an equal amount of energy has to be supplied by the ship, the wave resistance equals the energy flux divided by the ships speed. The results from XPAN are used to execute the program XBOUND.

In XBOUND the thin turbulent boundary layer is computed together with the skin friction and limiting streamlines. The module can also compute the transition to turbulent boundary layer for simple cases when a stagnation point (the local velocity is zero) is clearly defined (Flowtech, 2016). The database file generated from XBOUND was used in the module XCHAP.

XCHAP was used to obtain the viscous effects. XCHAP solves the Reynolds averaged Navier-Stokes equations, using several turbulence models. From this the turbulent quantities, pressure and velocity field were acquired. The grid used for the viscous computations in XCHAP can either be imported from external grid generators or generated in the module XGRID. XGRID calculates the grid around a ship. The program can handle bulbous bows and transom sterns, but not appendages.

Several analysis were run in *Shipflow* for the design draft and speed of the vessel. It is common practice to do the initial CFD calculations for model scale. The model scale ensures a smaller Reynolds number, resulting in a thicker boundary layer with more room for mesh cells. *Shipflow* automatically scale the ship based on the Reynolds number. The hull was revised with regard to entrance angle, placement of shoulders and stern until a satisfactory result was achieved. The goal was to obtain a fairly good stern and a fore part with room for optimisation for the students. More effort was put into optimising the stern as it is more expensive and challenging to modify when the model is finished. A decent initial performance was therefore important. When reasonable results for model scale were achieved, the CFD calculations were run with full scale Reynolds number.

The full scale resistance from the CFD calculations was verified using the resistance coefficients obtained from the model scale CFD simulation and the ITTC'78 procedure, specified in Larsson and Raven (2010). The result was also verified using *Maxsurf Resistance*. The program considers different algorithms, depending on the hull type, to estimate the resistance. The Holtrop algorithm was chosen as the most suitable for the designed PCTC. The slender body method was used to estimate the energy in the free-surface wave pattern generated by the hull. This was used to calculate the wave resistance of the vessel. The program compute the total resistance by adding the wave resistance from the slender body method to the viscous resistance estimated from ITTC'57 (Bentley, 2015*c*). The results can be obtained from section 3.2.5, figure 45.

### 3.1.7 Seakeeping

*Maxsurf Motion* is used to assess the seakeeping abilities of the hull. *Maxsurf Motion* uses linear strip theory to calculate the vessels response in heave and pitch (Bentley, 2015*b*). Roll response is calculated assuming that the vessel behaves as a simple, damped, spring/mass system, and that the added inertia and damping are constant with frequency. The other degrees of freedom can be calculated using the *panel method*, but only for zero speed.

Strip theory consider the vessel to be made up of a finite number of transverse sections which are rigidly connected to each other. The sections are transformed into circles using conformal mapping. *Maxsurf* uses Lewis mapping which is able to map a large range of ship-like sections (Bentley, 2015*b*). The coefficients in the equation of motion are then calculated and integrated over the length of the vessel to obtain the global coefficients. Finally, the coupled equation of motion are solved.

The result is presented as response amplitude operators (RAO), which gives the motion amplitude of the ship as a function of encounter frequency. The RAOs describe how the ship behave when exposed to one unit wave amplitude (or slope). To assess the ship behaviour in a irregular seastate, one has to do a spectral analyse. In a spectral analyse, the RAOs are treated as sort of filter that transfer the motion of the waves into ship motions. The ship motions are represented by a response spectrum. The irregular waves are represented by wave energy spectres, which gives the wave energy as a function of wave frequency. By assuming that the ship motion responses are linearly proportional to the wave amplitude, the response spectrum for a particular wave spectrum can be derived by multiplying the square of the RAO with the wave spectrum, for each wave frequency (Nielsen, 2010):

$$S(\omega_e) = RAO(\omega_e)^2 \cdot S_\zeta(\omega_e) \tag{12}$$

*Maxsurf* does this automatically, and can even calculate the velocity and acceleration spectrum (by differentiation) at any location of the ship (Bentley, 2015*b*). Based on these spectra one can calculate several useful statistical quantities which in turn can be used to calculate the probability for exceeding certain limiting criteria, such as maximum vertical accelerations, propeller emergence, slamming, etc. However, the goal of this analyse is to derive the ships RAOs and the significant vertical accelerations at different locations on the ship. The computed accelerations are compared with the limiting vertical acceleration derived from *section 4 - Design load* in the DNV standard, *Hull structural design - Ships with length 100 metres and above* (DNV, 2016). The calculations of the acceleration from DNV are available in Appendix G.

For the headings which gives the largest accelerations, the probability of exceeding the DNV limit (eq. 13) and the occurrence per hour (eq. 14) is calculated based on the following formula's (Bentley, 2015*b*):

$$prob(a > a_{crit}) = exp(\frac{-a_{crit}^2}{2 \cdot m_{0a}}) \tag{13}$$

$$N = \frac{3600}{\overline{T_p}} \cdot prob(a > a_{crit}) \tag{14}$$

Where $a_{crit}$ is the critical vertical acceleration, $m_{0a}$ is variance of the acceleration energy spectrum, $N$ is the number of occurrence per hour, and $\overline{T_p}$ is the mean of the zero-upcrossing period of the spectrum.

To set up the analyse the following parameters are defined:

- The draft is set to the design draft and the trim to zero. The speed of the vessel is set to design speed of 21 knots.
- The number of transverse sections is set to 25 to ensure an accurate prediction of the ship motions.
- The order of conformal mapping is set to 12 to ensure that the hull shape is represented accurately.
- The VCG is set to 15 meters, which is close to the maximum value calculated in the limited KG analyse done in section 3.1.5.
- The radius of gyration is set equal to $0.25 \cdot L_{pp}$ for pitch and yaw, and equal to $0.35 \cdot B$. This is in accordance with the ITTC procedure 7.5-02 07-02.1 (ITTC, 2011*b*).
- Roll damping largely depend on viscous effects which are not accounted for in *Maxsurf* and therefor have to be defined by the user. It is defined by a damping coefficient, which for most

vessel are between 0.05 and 0.1. The lower value is typical for ships without roll suppression devices and is chosen here (Bentley, 2015*b*).

- There are several option to correct the result obtained from strip theory for different vessel. In this case a transom stern is accounted for and the added resistance is estimated by the method of Salvesen (Bentley, 2015*b*).

- 5 headings are defined; head sea (180°), bow quartering sea (135°), beam sea (90°), stern quartering sea (45°) and following sea (0°).

- Three points are defined to calculate acceleration: $Aft_{top} = [10, 15, 32]m$, $Fore_{top} = [190, 15, 32]m$ and $CoG = [100.17, 0, 15]m$.

- A Jonswap spectrum is used with a significant wave height of 11.5 meters and a zero-upcrossing period of 11.5 s. The wave height chosen represent the mean height of seastate 8 as defined by the World Meteorological Organisation, reprinted in Bentley (2015*b*). The period chosen represent the most likely period for the particular wave height according to the North Atlantic scatter diagram ("Wave Data", 2001).

## 3.2 Results

In this section, the results from part 2 are presented. First the vessel's dimensions and parameters obtained from the investigation in section 3.1.1 and 3.1.2 are presented. Then the results from the design of the ship, and finally the result of the stability-, seakeeping- and resistance analysis of the ship is given.

### 3.2.1 Reference Ships

The result from the study of the reference vessels is presented below. The main dimensions of the vessels in section 3.1.1, Figure 16 are listed in the Table 5, together with the average dimensions of all the vessel.

**Table 5:** Results from reference vessels

| **Ship** | **Length [m]** | **Breadth [m]** | **Draft [m]** | **Speed [kn]** |
|---|---|---|---|---|
| Höegh Target | 200 | 36 | 10.3 | 16 |
| MV Mignon | 227 | 32.3 | 11 | 19 |
| MV Morning Chorus | 199.9 | 32.3 | 10 | 20 |
| MV Otello | 199.9 | 32.26 | 9.5 | 19 |
| MV Tosca | 199.9 | 32.3 | 11 | 19 |
| Silverstone Express | 180 | 30 | 9.2 | 20 |
| Viking Adventure | 200 | 32 | 10.5 | 18 |
| MV Tombarra | 199.9 | 32.26 | 11.5 | 20 |
| MV Tongala | 199.9 | 32.26 | 11 | 19 |
| MV Morning Concert | 199.9 | 32.26 | 11 | 21 |
| **Average** | **200.64** | **32.39** | **10.50** | **19.10** |

### 3.2.2 Main dimensions

In Table 6, section 3.1.2, the preliminary main dimensions found from the reference study and the empirical formula's are given. In the last column, the achieved dimensions for the PCTC are listed. The dimensions are a combination of the values found from the reference ships and the empirical formula's. The calculations of the empirical formula's can be found in Appendix E.

**Table 6:** Parameters found from study of reference ships, empirical formulas and modeling of the hull

| Parameter | Reference vessels | Empirical | Achieved value |
|---|---|---|---|
| Length ($Lpp$) | 180 - 227 m | 208 - 220 m | 200 m |
| Breadth (B) | 30 - 36 m | 26 - 33 m | 32.3 m |
| Draft (T) | 9 - 11.5 m | - | 11 m |
| Speed (V) | 19 - 21 knots | - | 21 knots |
| Displacement ($\Delta$ | - | 47 000 - 49 000 tons | 47 971 tons |
| Ballast draft | - | - | 9 m |
| Propeller diameter | - | - | 6.5 m |
| Froude number ($F_n$) | 0.244 | - | 0.244 |
| Block Coefficient ($C_B$) | - | 0.65 - 0.67 | 0.654 |
| Midship section Coefficient ($C_M$) | - | 0.97 | 0.990 |
| Water plane Area Coefficient ($C_{WP}$) | - | 0.77 - 0.8 | 0.843 |
| Prismatic Coefficient ($C_P$) | - | 0.67 - 0.69 | 0.661 |
| Length to Beam ratio | - | 6.2* | 6.25 |
| Beam to Draft ratio | - | 4.7** | 2.9 |
| LCB | - | 0 - 2 % aft | 0.2 % aft |

*Normal for container vessels

**Maximum value

### 3.2.3 Hull design

In this section the designed hull will be presented and its shape will be compared with the review of the literature in section 3.1.3. The lines drawings are presented in Figure 32 and a 3D view of the hull is showed in Figure 33. A larger version of the line drawings are available in Appendix F. From these figures it is seen than the waterline is S-shaped with a low entrance angle. The bulb is small and located well below the design waterline. The ship have large bow - and stern flares. The transom are dry, the stern angle is low and the aft buttocks are relatively straight. The skeg is well integrated in the hull with a cross section shaped like a pear. This is to force water to the upper part of the propeller plane and thereby achieve a more uniform wake.

The hull's SAC curve is presented in Figure 34. The shape is similar to the one presented in figure 21 that represent a typical SAC curve for slender ship. Table 7 compare values from the literature reviewed in section 3.1.3, against the one obtained from the hull. It is seen that all values are within the range of optimum values, except the breadth of the bulb, which is relative slender.

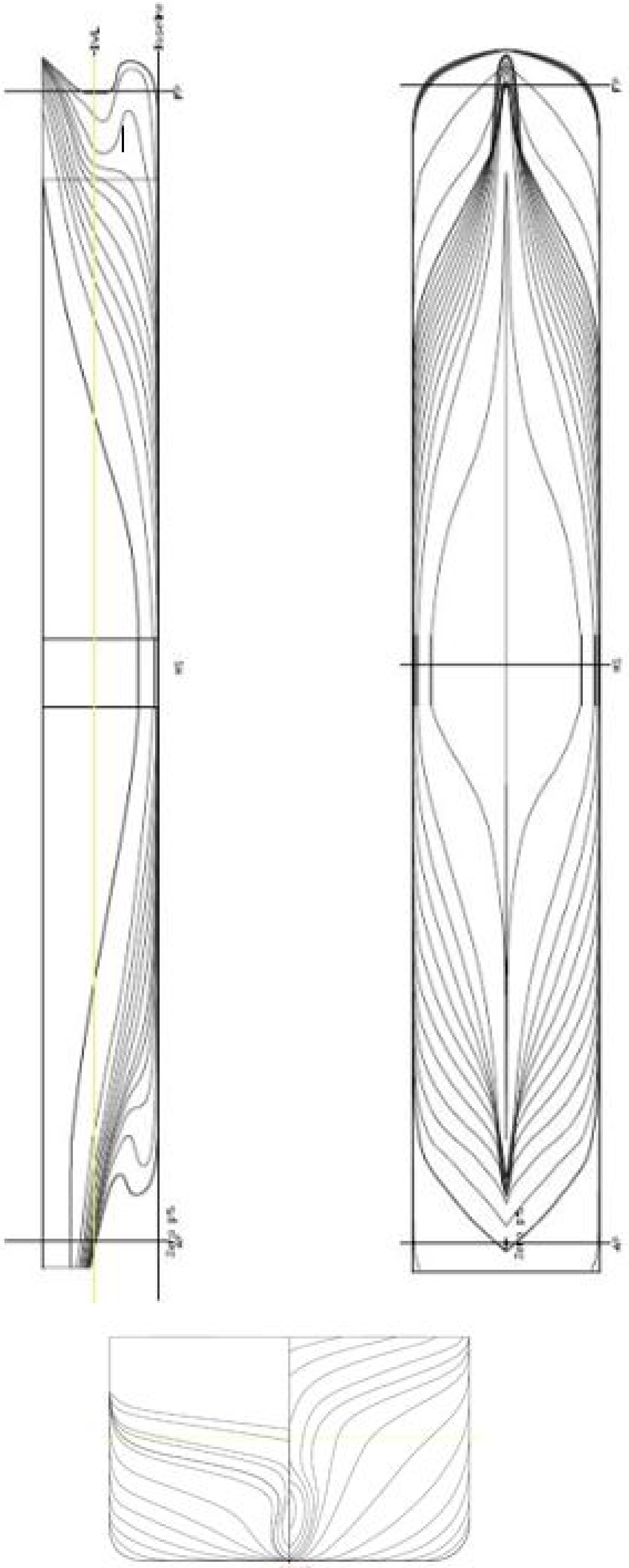


**Figure 32:** Lines drawings of the hull

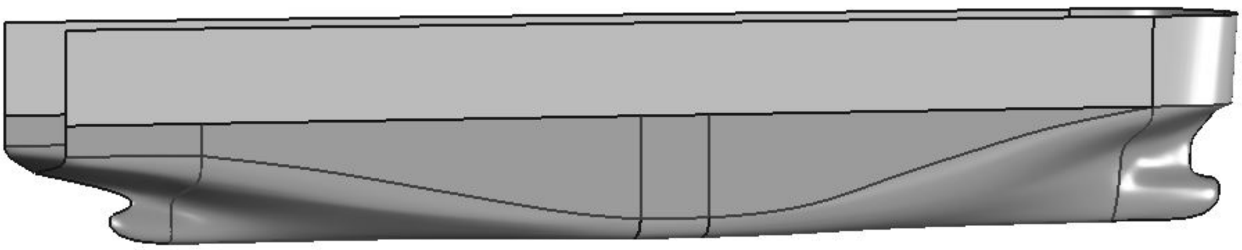


**Figure 33:** 3D view of the hull

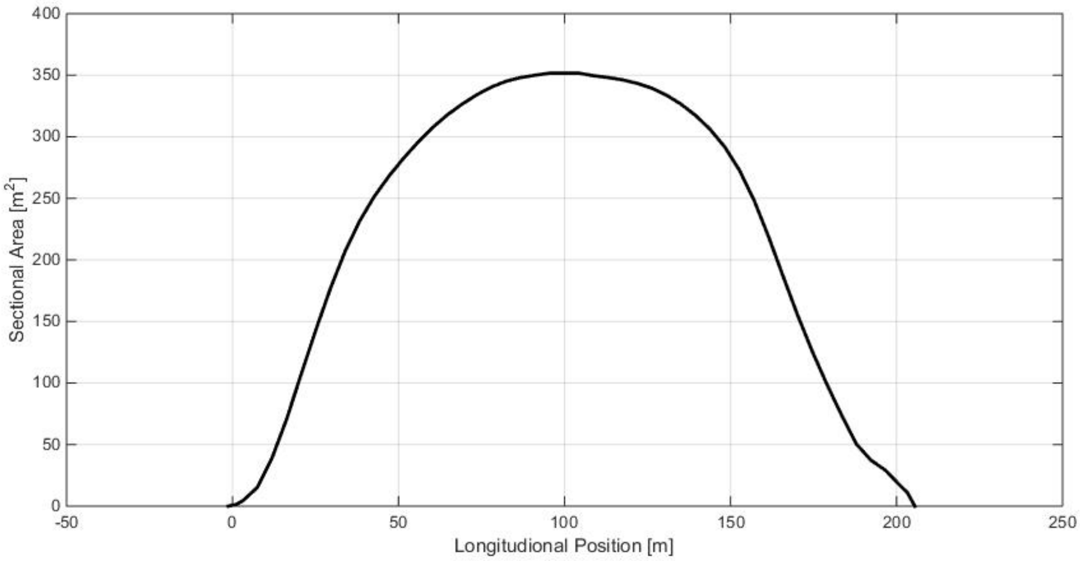



**Figure 34:** Sectional area curve of the hull

**Table 7:** Comparison of the hull against the optimum values of hull shape elaborated in 3.1.3

| Parameter | Optimum value(s) | Achieved value |
|---|---|---|
| Entrance angle of waterline | 6.4°- 17.1° | 12° |
| Breadth of bulb | 5.49 m - 6.46 m | 3.5 m |
| Length of bulb | 3.60 m - 6.20 m | 5.4 m |
| Height of bulb | 2.86 m - 6.05 m | ca. 5 m |
| Bilge radius | 2.7 m - 3.6 m | 3.3 m |
| Angle between baseline and stern | 10°- 15° | 13° |

### 3.2.4 Hydrostatic & Stability

Figure 35 - 37 shows several hydrostatic properties of the ship as a function of draft. The LCB and LCF decreases with draft indicating that the ship gets less voluminous in the fore when the draft increases. The tonnes per centimetre immersion (TPC) and the moment to change trim one centimetre (MTC) increase with the draft and the corresponding increase in water plane area. KB increases with an increase in submerged volume.

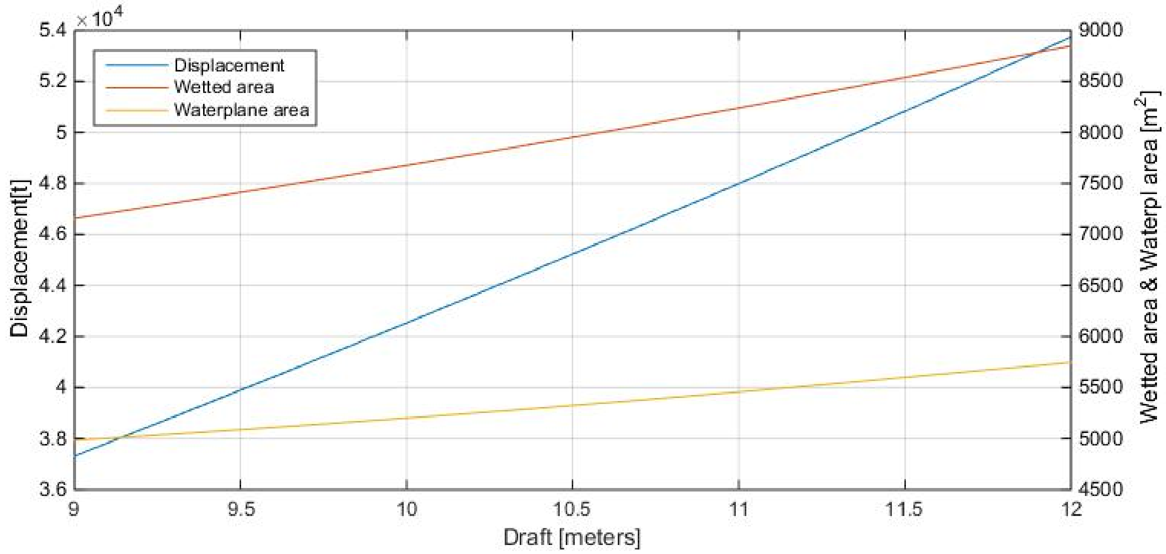



**Figure 35:** Displacement, wet surface area and water plane area as a function of draft

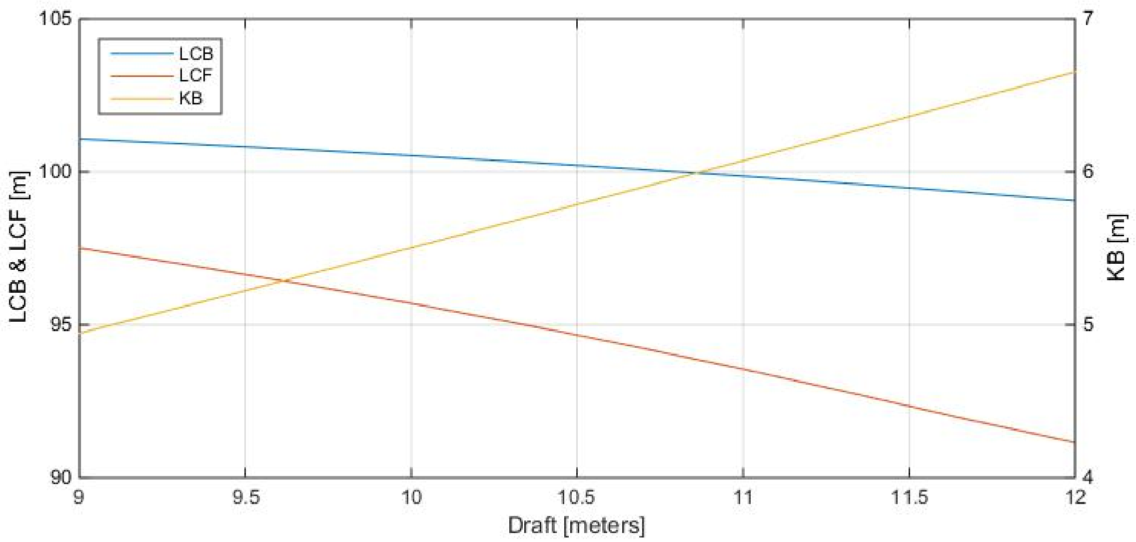



**Figure 36:** KB, LCB and LCF as a function of draft

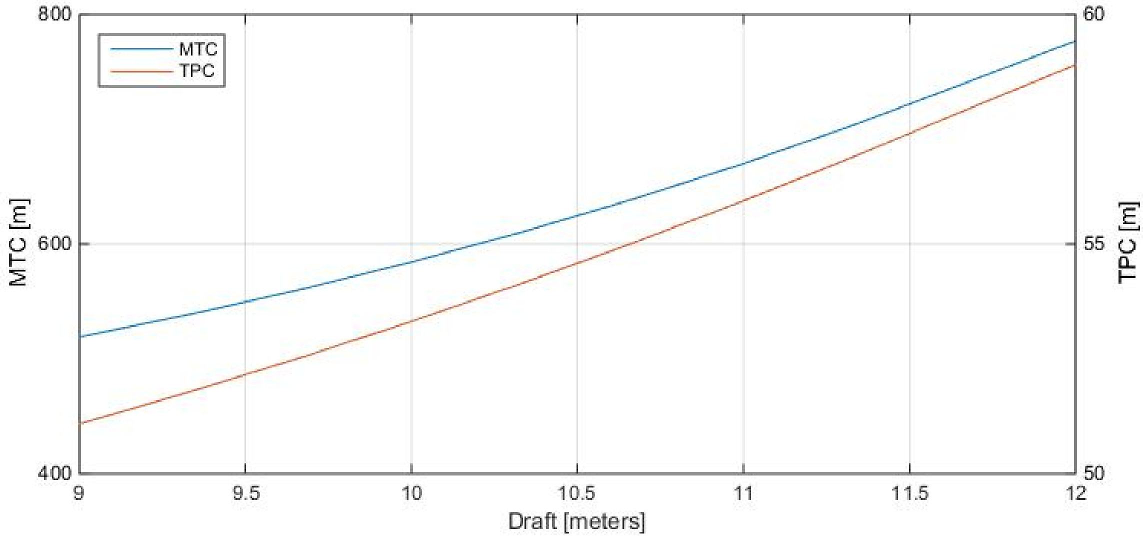



**Figure 37:** TPC and MTC as a function of draft

The limiting KG analyse in Figure 38 shows that the vessel is nearly equally stable for the displacements which are analysed. A minimum KG can be observed at a displacement of 44 670 tons, which correspond to a draft of 10.4 meters. The criteria that failed for all the displacements were the initial GM. This should be larger then 0.15 meters according to IMO (2008).

Figure 39 shows the GZ-curve for the design draft of 11 meters, a VCG of 15 meters and a LCG which is equal to the vessel's LCB. The GZ-curve has no angle of vanishing stability, meaning that the vessel will always turn the right way when the heeling moment is removed. At least, as long as the CoG is not changed (i.e. as a result of loose cargo).

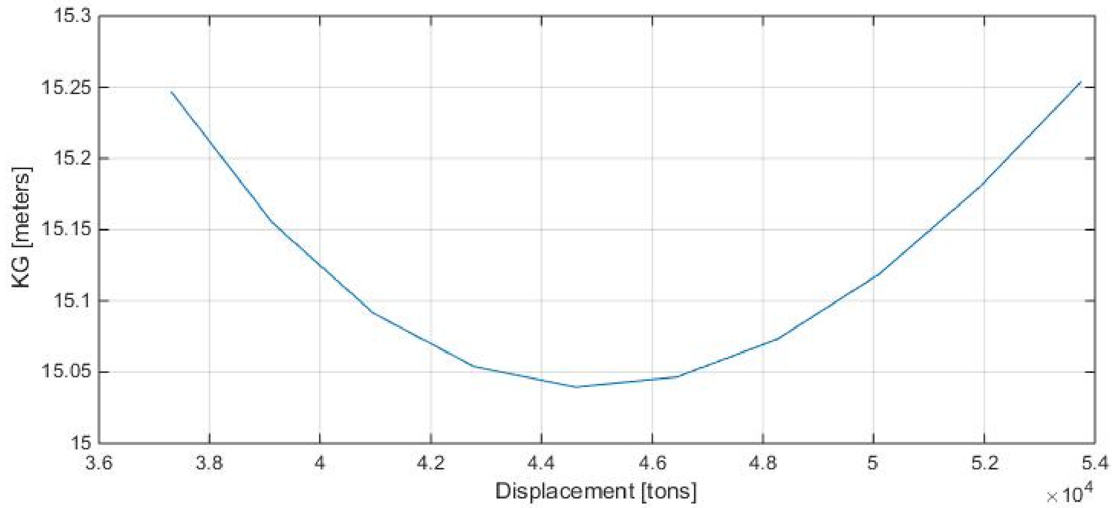



**Figure 38:** Result from the limiting KG analyse

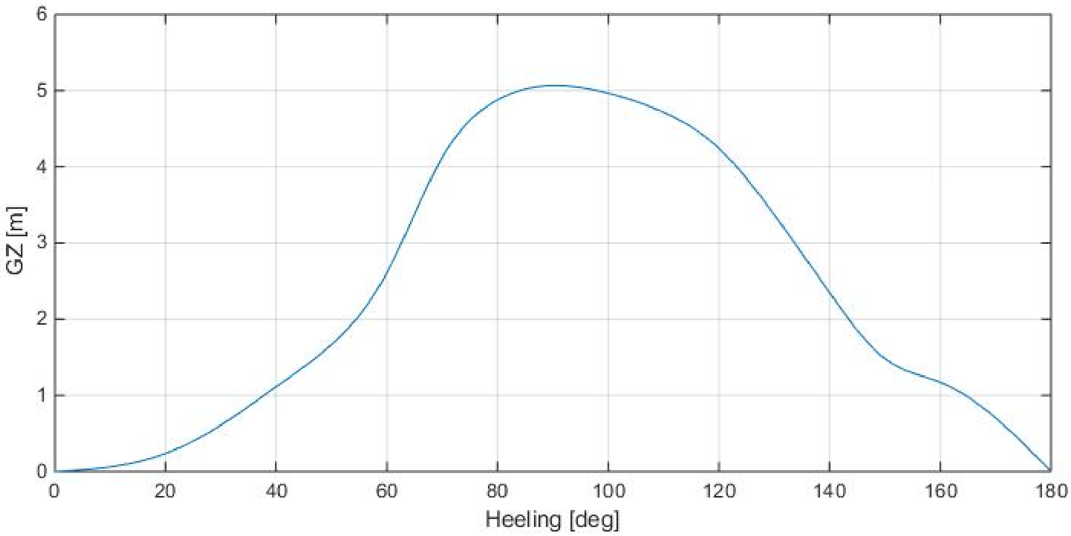



**Figure 39:** GZ-curve for $T = 11m$, $VCG = 15m$ and $LCG = LCB$

### 3.2.5 Resistance & flow

The results from the full scale simulations in *Shipflow* will be presented in this section. The figures displaying the wave pattern, pressure distribution and wake have been extracted from *Shipflow* and short comments are given here.

Table 8 shows the different resistance coefficients and the form factor for model - and full scale. The wave coefficient is independent of viscosity and do not change. The total resistance obtained from the model scale CFD calculations, scaled with ITTC'78 is approximately equal to the resistance obtained directly from full scale. As the Reynolds number differ, the viscous resistance coefficients varies significantly between model and full scale. The from factor for full scale is almost twice as large as the one obtained from model scale simulations.

**Table 8:** CFD results for model scale and full scale

| **Parameters** | **Model scale** | **Full scale** |
|---|---|---|
| Reynolds number | $8.781 \cdot 10^6$ | $1.818 \cdot 10^9$ |
| $C_{Tm}$ | $4.52 \cdot 10^-3$ | $2.824 \cdot 10^-3$ |
| $C_{Fm}$ | $2.97 \cdot 10^-3$ | $1.472 \cdot 10^-3$ |
| $C_{Pm}$ | $0.493 \cdot 10^-3$ | $0.295 \cdot 10^-3$ |
| $C_{Wm}$ | $1.057 \cdot 10^-3$ | $1.057 \cdot 10^-3$ |
| k | 0.129 | 0.242 |
| $R_{Ts}$ | 1423 kN* | 1419 kN |

*Scaled using the ITTC'78 procedure and obtained results from the model scale CFD ($C_{Tm}$ and k). See Appendix H

Figure 40 shows the wave elevation along the hull seen from above. The wave making and wave resistance are related to the hull form. According to Larsson and Raven (2010), high pressure mainly occur near stagnation points and where there is a concave stream-wise curvature. Low pressure occur when the acceleration is directed outwards as for convex curvature. A small region of high-pressure can be seen at the bow. The high pressure occur due to the location of the stagnation point, where the velocity of the fluid is zero. This agrees with Bernoulli's law, saying that low velocity correspond to a high pressure and vica versa. The plot shows that it is room for improvement of the interference between bow and foreward shoulder. The interference with the aft shoulder and stern are quite decent, leaving a relatively low shoulder wave. This is confirmed in the plot of the wave pattern in Figure 42.

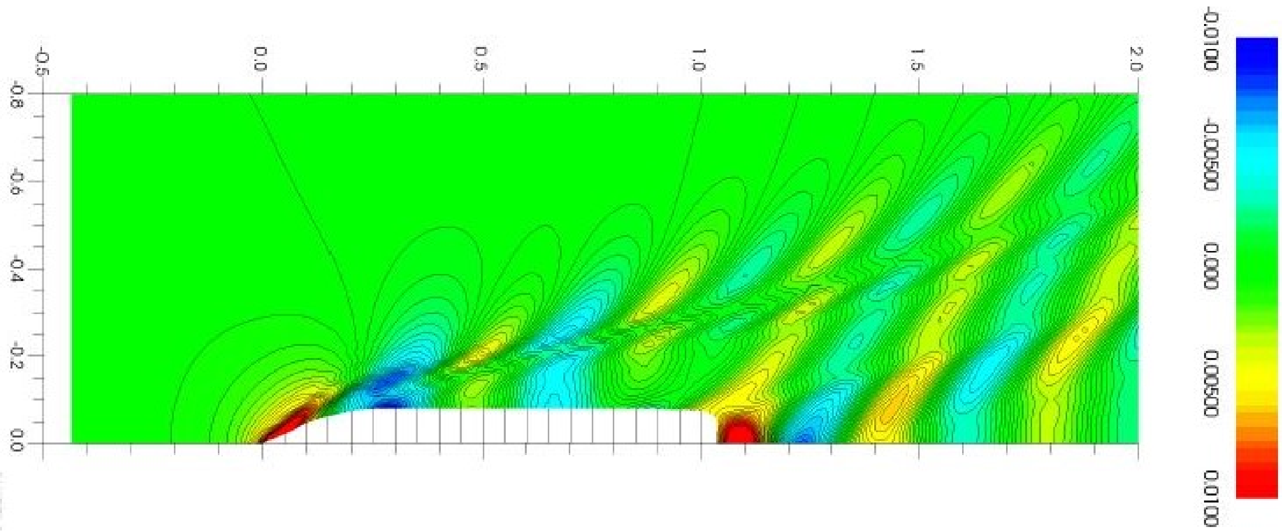



**Figure 40:** Wave and interference with free surface elevation colour map

Figure 41 shows the pressure distribution and wave elevation from the side. It is seen that waves are mainly generated from the curvature in the bow, fore- and aft shoulder and the stern. This corresponds good to the theory stated above. An elevation in the pressure occurs close to the waterline in the forebody. This is due to the concave curvature in this region. Moving backwards, a low pressure region occur at both the fore- and aft shoulder. The low pressure is caused by the convex curvature. The change in pressure along the midbody is a result of the waves generated in the forebody, and not due to curvature of the hull. The streamlines visible in figure 41 shows that they are curving down under the ship in the foreward part, and curves up towards the stern in the end as supposed.

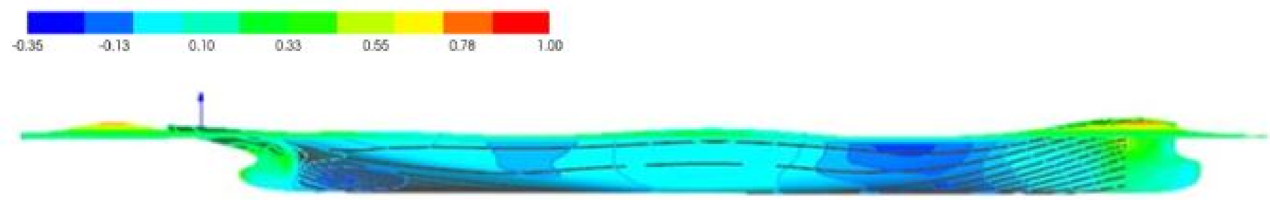



**Figure 41:** Pressure distribution (Cp) along the hull

In Figure 42 a plot of the near-field disturbance and wave system along the hull is illustrated. Comparing the plot from figure 42 and the ones above, it can be seen that there is a fairly direct relationship between the pressure distribution and the wave making along the hull. It is seen that the bulb has almost zero affect on the wave. This may be due to that the bulb is submerged so far that it no longer affects the wave generated on the surface. The maximum wave amplitude was found in the bow to approximately 3 meters. This is relatively high, but assumed reasonable for a fast-going vessel like this.

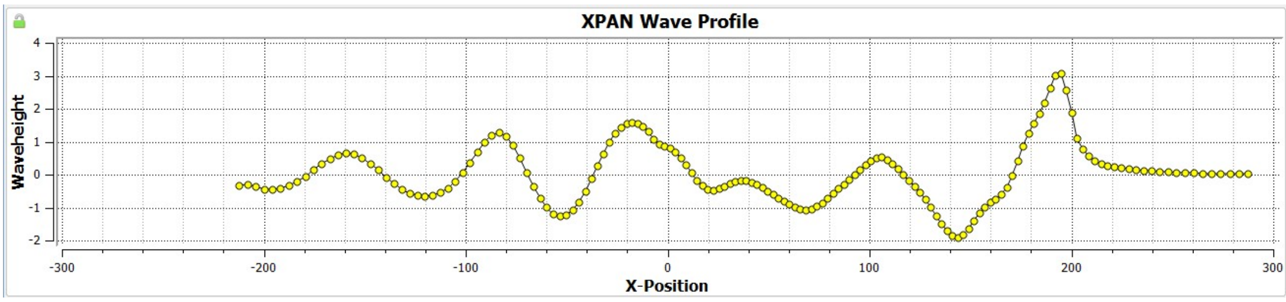
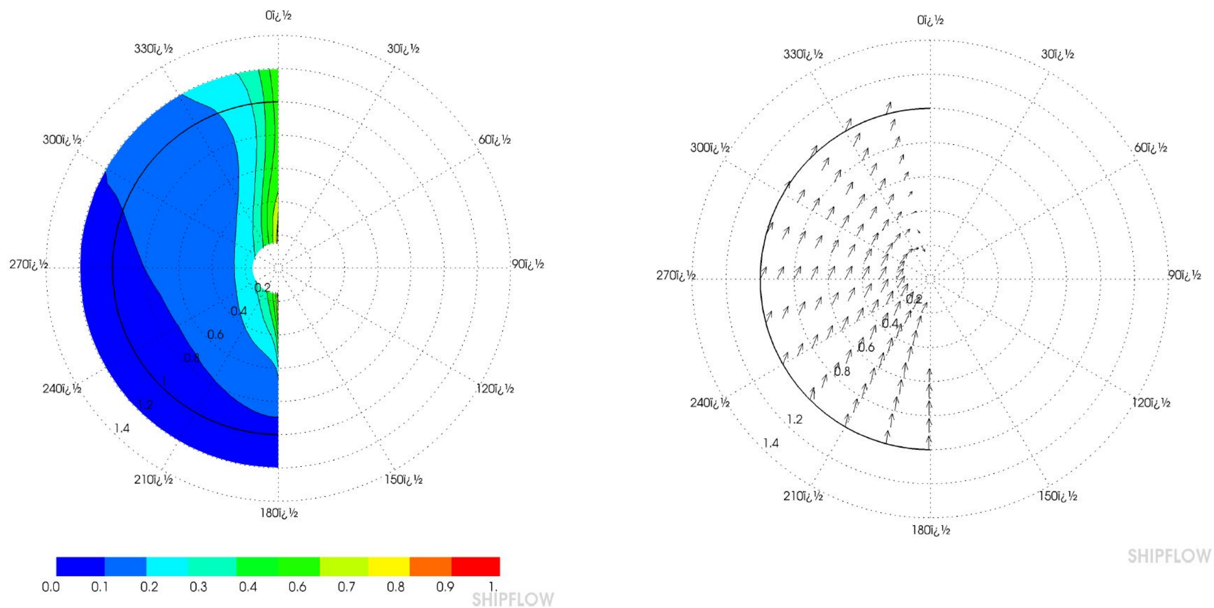



**Figure 42:** Wave pattern obtained from *Shipflow*

In Figure 43 the wake fraction distribution into the propeller plane is shown. It is seen that the flow into the propeller plane is quite uniform, satisfying the desired features mentioned in section 3.1.3. A friction wake is generated, meaning that it is affected by the growth of the boundary layer, taking the shape of the hull just in front. No separation are detected in the stern of the ship.




**(a)** Total wake fraction in propeller disc

**(b)** Transversely velocities in propeller disc

**Figure 43:** Propeller wake

Figure 44, illustrates the velocity distribution in the aft part of the vessel. At approximately half draft, it can be seen that the flow diverge slightly. The lines above the propeller shaft is slender, forcing the flow down to the top of the propeller blade. The concave shape of the stern increase the velocity of the flow into the propeller disk.

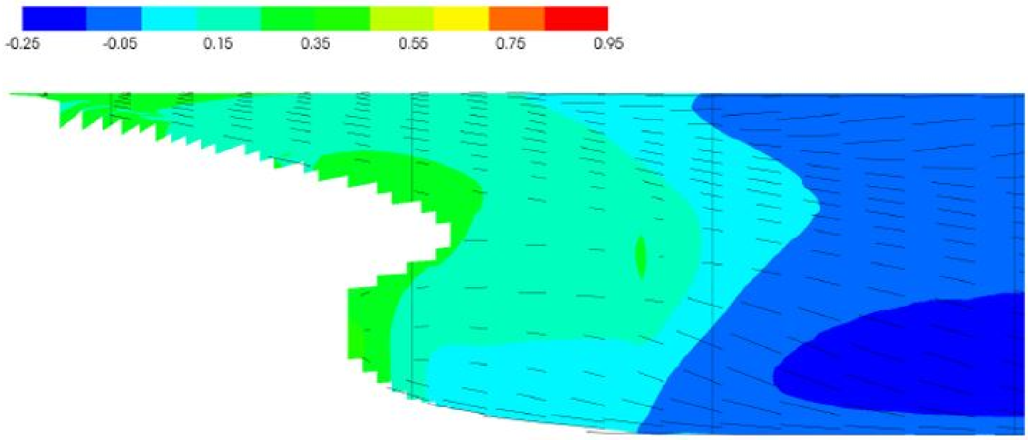



**Figure 44:** Pressure (Cp) distribution and velocity flow into the propeller

Figure 45 shows a plot of the ships resistance as a function of the speed. The total resistance obtained from the full scale CFD computations can be seen with the red circle in the graph. The black full line indicates the resistance versus speed obtained from the Holtrop algorithm explained in section 3.1.6. The Holtrop algorithm estimates the resistance to approximately 1400 kN, while the full scale CFD gives a total resistance of 1419 kN. The total resistance from the CFD simulation is slightly higher than what the Holtrop method predicts at the same design speed.

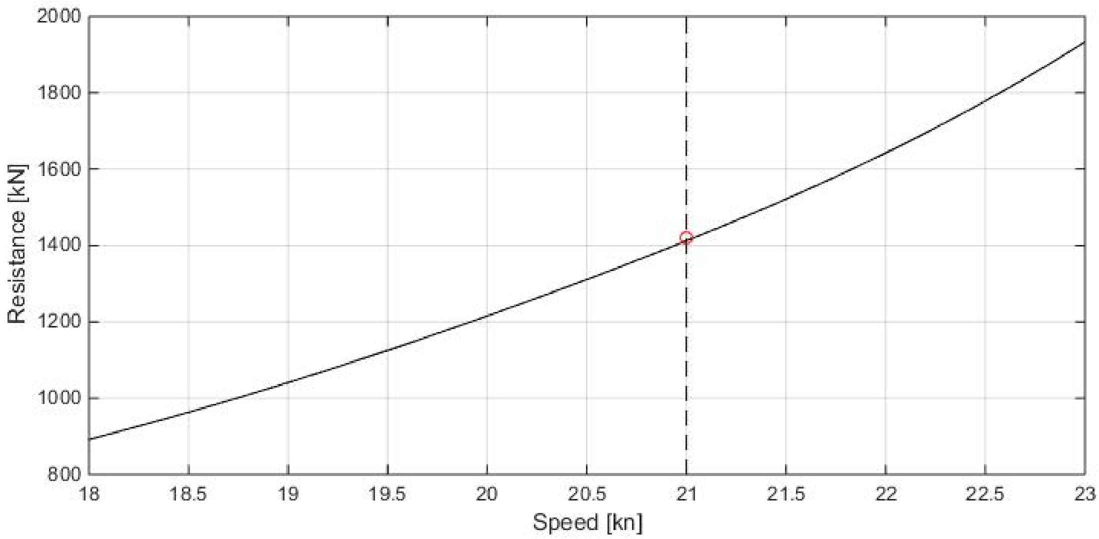
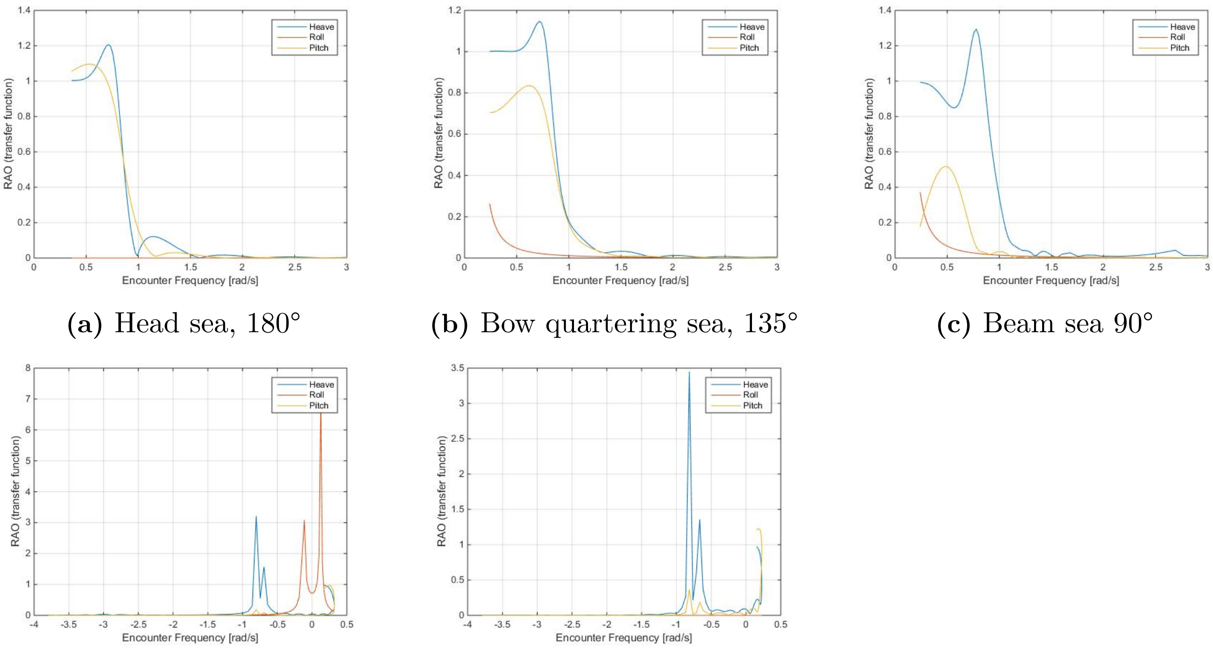



**Figure 45:** Speed-resistance curve

### 3.2.6 Seakeeping

Figure 46 shows the vessel's transfer functions or RAOs in different headings. By studying the heave curve in Figure 46a to 46c it is seen that it tend to unity at low frequency. This is when the ship simply move up and down with the waves. At larger frequency it is seen that the response approaches zero. This is due to the effect of many small waves cancelling each other out over the length of the ship. The heave curves in the three figures have a distinct peak. This peak is due to resonance between the wave period and the vessels natural period. An RAO value greater then unity means that the ship response is greater then the wave amplitude or slope. The same analogy goes for pitch and rolling, but is not that easily seen on the RAOs. The largest value of the RAOs are observed for roll at a heading of 45 °and an encounter frequency off $\omega_e = 0.125 rad/s$. In general the response from following - to stern quartering sea seems significant severe than head - to beam sea, having values much larger then unity.




**(a)** Head sea, 180°

**(b)** Bow quartering sea, 135°

**(c)** Beam sea 90°

**(d)** Stern quartering sea, 45°

**(e)** Following sea, 0°

**Figure 46:** The ships RAO in heave, roll and pitch

Figure 47 shows the significant acceleration amplitudes at different headings and locations at the ship. The black line illustrate the maximum vertical accelerations defined by DNV. All accelerations are within the limit. The largest accelerations occurs at head - and bow quartering sea. This contradict with what is observed in the RAOs. However, the ship motions in irregular sea also depends on how the wave energy are distributed over the frequencies. If the RAOs and the wave spectrum has a large value at particular frequency, one could except large ship motions at this frequency, and vica versa. Table 9 gives the probability of exceeding the critical acceleration defined by DNV and the number of occurrence per hour for head sea. The calculations are only done for head sea, as this is the most server heading according to figure 47.

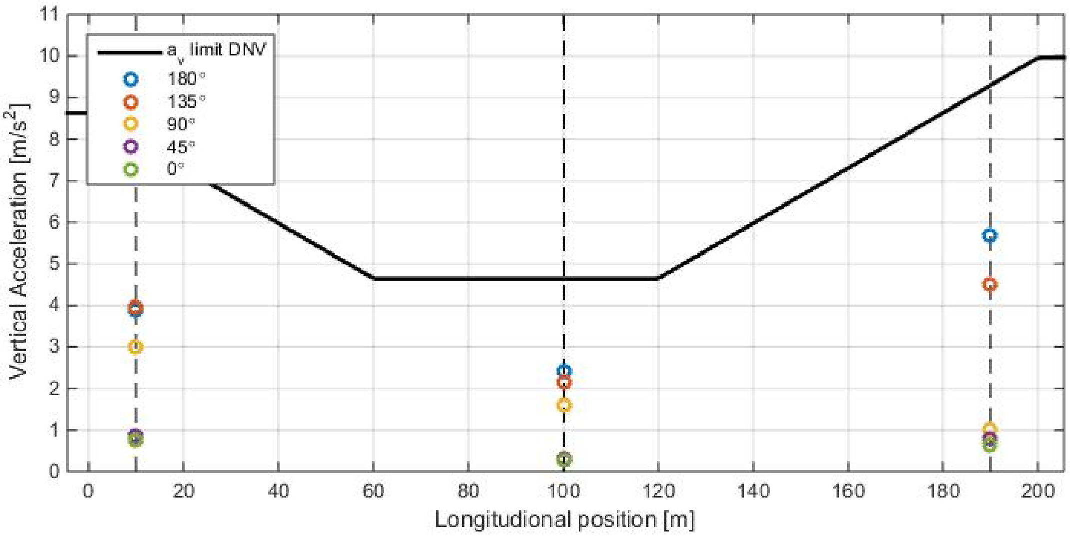



**Figure 47:** Significant acceleration amplitudes at remote locations on the ship

**Table 9:** Probability of exceeding the critical acceleration and the number of occurrence per hour for head sea

| Location [m] | $a_{crit}[m/s^2]$ | $m_{0a}[m^2/s^4]$ | $\overline{T_p}$ | $prob(a > a_{crit})$ | $N$ |
|---|---|---|---|---|---|
| $x = 10$ | 8.0 | 3.78 | 8.29 | 0.02% | 0.09 |
| $x = 100.7$ | 4.6 | 1.45 | 8.72 | 0.07% | 0.28 |
| $x = 90$ | 9.3 | 8.12 | 8.94 | 0.49% | 1.95 |

## 3.3 Discussion

In this section, the selection of the main dimensions along with the shape and performance of the hull will be discussed.

### 3.3.1 Main dimensions

The determination of the main dimensions was carried out as an iterative procedure, in order to find the optimum relations. To have a reasonable starting point, the length of the full scale vessel was decided by the lecturers in the first round of interviews to 200 meters. Using empirical formula's, it was found that at the given speed, the length of the vessel could be increased to some extent. The length of the vessel was, despite the empirical formula's, set to 200 meters. This was mainly due to the request of the lecturers and the wish to design a vessel close to the reference vessels.

It was a desired feature from the lecturers to have a vessel with a high Froude number. As seen in figure 15, section 3.2.1, the wave resistance increase with the Froude number. In the finished model, the students will be limited to do local changes. Therefore, it will be challenging to optimise with regard to the viscous resistance, such as wetted surface. It was therefore important to make the wave resistance as dominant as possible, so that the results from the students optimisation would represent a larger reduction of the total resistance. However, it was important that the Froude number was outside the limits mentioned in section 3.1.2. It can be seen that the value is close to the lower limit for where the humps in the wave making resistance curve begins. It could therefore be discussed if the speed should be reduced slightly in order to get more clearance to this limit. This will be a trade-off between the students learning outcome and the performance of the vessel for use in research.

All the reference vessels had approximately the same beam, around 32.3 meters. These dimensions are probably set with regard to the former restrictions of the Panama Canal of 32.3 meters. Since the maximum width of the Panama Canal have been increased recently, it was discussed whether the beam of the new model should be made wider. According to the empirical formula's, the beam was recommended to be within 26 - 33 meters, which indicated that a larger beam would not be beneficial. The draft of the PCTC was set to the upper limit of the reference vessels, in order to fit a large propeller. A large propeller is favourable if the model should be used in self-propulsion trials. This will be discussed further in section 4.3.

According to Table 2.6 in Papanikolaou (2015), the length to beam ratio for fast seagoing cargo ships should be within 5.7 - 7.8. From Table 6 the ratio was calculated to 6.2, which is nicely within the given range. According to (Schreuder and Tillig, 2015) the $\frac{L}{B}$ ratio should be approximately 6.25 for container vessels. Since a container vessels usually have a lower Froude number than the PCTCs, this is coherent with a slightly higher length to beam ratio.

In order to reduce both the residuary- and the frictional resistance of the hull, it was desired to have a beam to draft ratio value around 2.5. From table 6, the beam to draft ratio were calculated to 2.9. This value is a bit high compared to other fast going vessels, but still within the limit mentioned in section 3.1.2. It was assumed that the downside by the slightly low $\frac{B}{T}$ ratio was compensated by the higher draft, which allowed a larger propeller and a dry transom.

The coefficients calculated in table 6 gives an indication of the hull shape of the vessel. As expected for a slender fast going ship, it can be seen that the midship section coefficient is quite large, close to 1. The prismatic block coefficient on the other hand is relatively small, which generally indicates that the vessel have slender ends and that the displacement is mainly concentrated around the midship section. This corresponds quite well to the large midship area coefficient. The block coefficient is relatively low, indicating that the vessel have a slender hull form.

The longitudinal centre of buoyancy (LCB) of the ship is within recommended limits. It is close to zero, indicating that the volume is equally distributed between the fore and aft of the ship. According to Papanikolaou (2015), a parallel midship section are mainly recommended for vessels with a low Froude number, below 0.24. The PCTC design is therefore in the limit for having a parallel body at all. It was desired to preserve the parallel body in order to keep the possibility to increase the length of the model. An increased length will affect the ships seakeeping performance. This will be discussed in section 4.1.3.

### 3.3.2 Shape of the hull

The obtained shape of the hull correspond relatively good to the desired shape elaborated in section 3.1.3. The breadth of the bulb is rather slender compared to recommendations. It is chosen to neglect this parameter to better integrate the bulb in the hull. The cross-section of the bulb ended up as a modified O-type bulb (Kracht, 1978). The lower part of the bulb were designed more slender to achieve the good seakeeping abilities of the $\nabla$-type bulb.

### 3.3.3 Performance of the hull

Over the years, the PCTCs have become more optimised towards maximising the cargo capacity and minimising the fuel consumption. Since the length and breadth of the vessels are often restricted, the depth have increased in order to meet the escalating demand for cargo. The increased depth drives the vertical centre of gravity up. Based on the limiting KG analyse, the PCTC is stable as long as the VCG is below 15 meters. As some of the reference vessels have a depth up to 45 meters, this may indicate that the calculated VCG of 15 meters may be too low to be realistic. However, it is assumed sufficient for the model.

The results from the CFD analyse shows that the stern have a descent design. There are no sign of separation and the stern wave is relatively low. From figure 43 it can be seen that the wake is somewhat uniform, except in the most upper part of the propeller disc, which is normal. The bow wave is rather large. Work can be done to improve the interference between the bow and the shoulder waves.

As seen from table 8, the form factor in full scale is almost two times as large than for model scale. The form factor is Reynolds dependent and increase with an increasing Reynolds number, but exactly how much is not clear. According to Larrson et al. (2003), the form factor for the full scale research hull KRISO VLCC, increased with up to 50 % compared to model scale. The form factor was predicted by different numerical methods. However, by using the form factor from model scale and the ITTC'78 procedure, the same total resistance was obtained as for the full scale CFD results. The total resistance also correspond well to the one predicted by the Holtrop method.

As seen from figure 47 the ship performs well within the limitation from DNV. The probability of exceeding this limit are low for all positions considered. The accelerations from DNV are given as design loads to be used in structure analyses of ships. It could be discussed if these are too large to be used as a critical accelerations. The analyse have only been done for one seastate and features as, the probability of slamming, propeller emergence and motion sickness, has not been evaluated. However, the goal of the analyse was to get an indication of the seakeeping abilities of the ship. The performance is good considered that the analysed seastate is relatively rough.

## 3.4 Conclusion

A modern PCTC is designed with the desired ship properties elaborated in chapter 2. The ship has a large bow flare and operates at a high Froude number. The shape of the vessel and its main dimensions correspond well to the reference ships and the literature.

The vessel perform good in the tested seastate and is stable as long as the VCG is below 15 meters. The maximum VCG is relatively low, but should not be of high importance for the model. The design of the stern is decent. This was desired, as the cost of changing the stern of the model after it is build is considerable. The wave pattern of the ship can be further optimised, both with respect to lowering the bow wave or improving the interference with the shoulder waves. This is as intended. The fore part of the ship is designed to make room for student optimisation.

# 4 Development of the model

The goal of this part of the project was to further develop the concept decided on in chapter 2 based on the hull from chapter 3. This would be a standard MDL model with the following extra features:

- The model should be able to change parts
- The model should be able to be used to investigate intact stability

It is also evaluated how the MDL model perform in the towing tank and if it can be used to investigate added resistance. Damage stability and the outdoor model is not further investigated due to the complexity and cost.

## 4.1 Methodology

The scaling factor is the ratio between the full scale and model scale. The scale of the model is the main parameter that decide the tests the model are able to perform. In example, a large scale will result in a small model that is not functional in the towing tank. The choice of the model scale, the mass properties of the model and the method for changing the parts are elaborated in this chapter.

### 4.1.1 Scaling of the model

When scaling the model, there are several aspects that needs special attention. Even if it is fairly obvious that the geometry of the model and full scale vessel should be similar, there are other aspects that may not be so obvious. In addition to being geometrical similar, the model shall have both kinematic- and dynamic similarity to the full scale ship. Kinematic similarity means that the streamlines around the hull shall be similar in full scale and model scale and that the velocities in the x- and y direction have the same ratio. Dynamic similarities ensures that the ratio between the forces in the flow are the same. To ensure that the similarity requirements are fulfilled, the non-dimensional numbers of Froude, Reynolds, Weber and Euler have to be equal for both model and full scale. The numbers are given by equation 15 to 17.

The equality in the Froude number assures that the gravity force are correctly scaled. Since the waves occurring on the surface are driven by the gravity force, this will ensure that the scaling of the wave forces and wave resistance are correct. The Froude number is therefore only important when there is a free water surface.

If the Reynolds number are kept constant for model and full scale, correctly scaling of viscous forces would be achieved. The Reynolds number has in practice an influence on all the hydrodynamic flows of interest due to its presence in the Navier-Stokes equations (Larsson and Raven, 2010). The Reynolds number will therefore affect all flows governed by these equations.

The Euler number determines the absolute pressure level in the fluid. This number is normally not considered in the towing tank, due to that cavitation seldom occur in the flow around the hull. This is not the case if the propeller should be tested in the cavitation tunnel. Then equality in the Euler number is of higher importance. Last, the Weber number must be scaled correctly in order to obtain the correct effect of the surface tension and inertia forces.

$$F_n = \frac{V}{\sqrt{g \cdot L}} \quad (15) \qquad R_e = \frac{V \cdot L}{\nu} \quad (16) \qquad W_n = \frac{\rho V^2 L}{\gamma} \quad (17)$$

$\nu$ is the viscosity of the fluid the vessel or model is operating in and $\gamma$ is the surface tension. $\rho$ is the density of the fluid.

In reality, it is not practically possible to satisfy the equality of all the numbers above simultaneously. When scaling the speed of the vessel using both the Reynolds number and the Froude number, this is easily seen. Equation 18 shows the scaled velocity of the model using equality of the Reynolds number, while equation 19 use equality in Froude number.

$$V_{MReynolds} = V_S \cdot \frac{L_S}{L_M} \cdot \frac{\nu_M}{\nu_S} \quad (18) \qquad V_{MFroude} = V_S \cdot \frac{\sqrt{L_M}}{\sqrt{L_S}} \quad (19)$$

The equations above are contradicting. The model speed would have to be lower than the ship speed in order to obtain a correct Froude number, but higher than the ship speed to achieve correct Reynolds number. Due to practical reasons, the models are normally tested at a lower speed than the full scale vessel. As can be seen from equation 17, the Weber number becomes very small when the velocity is low. An erroneous scaling of the Weber number will therefore have the smallest effect on the resistance and flow. When the equality of the Weber number is disregarded, the question is which of the Froude- or Reynolds number to keep constant during scaling. This is a dilemma as both have a large impact on the resistance and flow around the hull. The required speed of a model scaled with similarity of the Reynolds number would be very large. The most convenient solution to this dilemma is thus to scale the model using a constant Froude number while correcting for the *scale effect* occurring due to the the wrong Reynolds number. This is done using the frictional resistance coefficient – ITTC 1957 model-ship correlation line, which gives the friction coefficient as a function of the Reynolds number (ITTC, 2002).

The scale effect is the designator of the error between the scaled results from the model test and the full scale performance. This error is not only affected by the underestimation of the flow due to viscous effects, but a too low Reynolds number may also result in laminar flow around the hull. An increase in the the size of the model, means an increased Reynolds number and improved accuracy of the measured results (it is easier to measure larger quantities accurate). This is specially important for the models used to measure the resistance and in self-propulsion tests. For the MDL model, this phenomena is less important, due to that the motions are mainly affected by the gravity. The Reynolds number therefore has less influence on the results. The MDL model can therefore in theory be smaller than the model used in the towing tank. Nonetheless, in order to have a realistic model it is preferred that the model is as large as possible in both basins. The main limitations are therefore the dimension of the test basin, waggon capacity and requirements for interference between the walls of the basin and the model. These limitations are given by SSPA and defined by ITTC. Some of them are listed in Table 10. See Appendix I for calculations.

**Table 10:** Limitations of the model size

| **Limitations** | | **Comment** | **Reference** |
|---|---|---|---|
| Depth | 0.5 m | Limited by the height of the wagon, so that the model won't crash with the wagon during seakeeping trials. | (SSPA, 2016) |
| Displacement | $\Delta < 1ton$ | Maximum weight for the wagon. | (SSPA, 2016) |
| | $400 < \Delta < 600kg$ | Normal range for MDL models | |
| Wave height | $0 < \zeta < 0.4m$ | Possible wave height in MDL basin | (SSPA, 2016) |
| | $0 < \zeta < 0.25m$ | Recommended wave height in MDL basin | |
| Wave length | $0.2 < \lambda < inf$ m | Possible wave lengths in MDL basin | (SSPA, 2016) |
| Wave frequencies | 0 - 3 Hz | Possible wave frequency in MDL basin | (SSPA, 2016) |
| Wagon speed | 0 - 10 m/s | Speed range of wagon | (SSPA, 2016) |
| Propeller diameter | 0.15 - 0.30 m | Recommended diameter of propeller for self-propulsion test | (ITTC, 2011*c*) |
| | minimum: 0.18 m<br>recommended: 0.20 m | Minimum and recommended diameter for self-propulsion test | (SSPA, 2016) |
| Tank interference | $\frac{B_{basin}}{L_M} > 4$ | Else, the model speed and wave frequencies are limited in order to avoid interference | (SSPA, 2016) |
| | $\frac{H_{basin}}{T_M} > 4$ | To avoid shallow water effects | (ITTC, 2008*a*) |
| Test speed | $V_m < 0.5(g \cdot H_{basin})^{1/2}$ | To avoid shallow water effects | (ITTC, 2008*a*) |
| | 3 m/s | Maximum model speed | (SSPA, 2016) |

Different scaling factors were considered in order to find an accurate scale of the model to satisfy the above criterion's.The investigation ended in two scales which gave the model different desired characteristics.

### 4.1.2 Mass properties of the model

For ship models used in seakeeping and manoeuvring test, the centre of gravity and radii of gyrations has to be correctly modelled. This is done by ballasting the model with weights, often by using solid steel cubes in different sizes. To be able to make a load plan - a plan of where to place the ballast, some characteristic of the model has to be known:

- The radius of gyrations of the model stripped for equipment
- LCB at different draft so that the model's centre of gravity can be chosen to obtain zero trim (if this is wanted).
- The maximum VCG with respect to stability, so the model do not capsize.
- The model's lightweight mass properties.

The radius of gyration should represent the real ship. If the weight distribution of the real ship is not known, ITTC recommend to use $0.25 \cdot L_{pp}$ in pitch and yaw, and $0.35 - 0.40 \cdot B$ in roll (ITTC, 2011*b*). The LCB and maximum VCG is scaled to model scale from the result in figure 35-39. To find the lightship mass properties of the model, a solid model is made in *Rhinoceros*. *Rhinoceros* is a advanced 3D modelling program which also have the capability of calculating the volume and radius of gyration of the 3D model.

The ship model is designed to fit SSPA's building procedure. SSPA build their models by gluing layers of divinycells together to a rough representation of the ship geometry. Then the outside of the models are milled to achieve the proper shape. This leaves the inside of the model with a clear layer-by-layer structure. The divinycell used at SSPA has a thickness of $6cm$. Therefor, this is commonly used as a standard wall thickness for the models. The divinycells SSPA uses is denoted *h100* and has a density of $\rho_d = 100kg/m^3$ ("DURO Divinycell", 2016). The models are often equipped with bulkheads made of divinycells, to ensure that it is rigid enough.

### 4.1.3 Changeable parts

It was desired that the students should be able to change parts of the hull. The idea is that the student can optimise the the vessel to some criteria, analyse the design using numerical models and then verify the result by model testing. This was regarded to have a high education value. Local changes is often sufficient to observe changes in the resistance. In example, the bulb can be changed and different energy saving devices can be mounted. For seakeeping, the local changes will have less influence on the hulls performance. The seakeeping abilities of a vessel are mainly affected by the main dimensions and in particular the shape of the water plane area, global volume distribution and radius of gyrations. The length can be changed by enlarging the midship section. The other main dimensions are challenging to change. The shape of the waterline can be modified by changing the entire foreship. This is also interesting in terms of slamming. The global weight distribution is independent of the geometry.

As the model is made of divinycells, it is fairly easy to change parts. A new part is installed by cutting off the old one and gluing/screw on a new part. The gap between the model and the new part are filled with spackle to obtain a fair hull. This implies that basically all the parts of the hull can be changed. During trials, the model is equipped with an engine, a steering unit and different measurement equipment. Moving the equipment during trials is very time consuming and costly. It is therefore desirable that modifications of the model's hull is done without affecting the position of the equipment. If the length of the hull is to be enlarged, it is an advantage to place the equipment outside the modified region. When the model is stored it is emptied for all equipment. This is good opportunity to do larger changes on the model. In example, the foreship could be changed prior to storage or immediately after.

## 4.2 Results

In this section the results from the scaling of the model, and the model characteristics are given. In the results, the model scaled with a factor $\lambda = 36$ will be referred to as model 1, while the model scaled with a factor $\lambda = 46$ is referred to as model 2.

### 4.2.1 Scaling of the model

The results from the scaling explained in section 4.1 are presented in Table 11.

**Table 11:** Dimensions of full scale and two different model scales

| Properties | Unit | Full scale | Model 1 | Model 2 |
|---|---|---|---|---|
| Length, $L_{pp}$ | [m] | 200 | 5.56 | 4.35 |
| Breadth, B | [m] | 32.3 | 0.897 | 0.702 |
| Model Depth, D | [m] | 35 | 0.5* | 0.5* |
| Draft, T | [m] | 11 | 0.31 | 0.24 |
| Displacement, $\Delta$ | [ton] | 47 989 | 1.00 | 0.44 |
| Speed, V | [kn] | 21 | 1.8 | 1.59 |
| Reynolds number, $R_e$ | - | $1.818 \cdot 10^9$ | $8.78 \cdot 10^6$ | $6.08 \cdot 10^6$ |
| Propeller diameter, $D_{prop}$ | [m] | 6.5 | 0.18 | 0.14 |
| Heeling angle, $\phi$ | - | - | 23° | 37° |
| Seastate | - | - | 7** | 8** |
| Resistance*** | [N] | $1.42 \cdot 10^6$ | 47.4 | 22.7 |

*Maximum height to waggon

**According to World Meteorological Organisation

***Resistance from CFD calculations for full scale and the two different model scales

The maximum roll angle for model 1 are given in equation 20 and in equation 21 for model 2.

$$\phi = tan^{-1}(\frac{2 \cdot (D_{M1} - T_{M1})}{B_{M1}}) = 23° \quad (20)$$

$$\phi = tan^{-1}(\frac{2 \cdot (D_{M2} - T_{M2})}{B_{M2}}) = 37° \quad (21)$$

Based on the numbers from the table above, scale $\lambda = 46$ was chosen. Arguments for the selection are discussed in section 4.3

### 4.2.2 Mass properties of the model

Figure 48 show the finished 3D model and Figure 49 shows the model seen from above. The typical layer-by-layer structure of divinycells is clearly seen in both figures. Table 12 show the mass properties of the model. Figure 50 show the LCB and limiting VCG as a function of draft for the ship model. To ensure that the model is sufficiently stable and have zero trim, these values should not be exceeded.

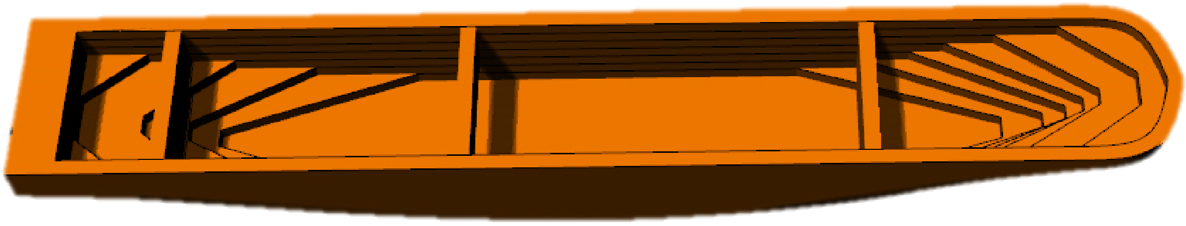


**Figure 48:** 3D view of ship model

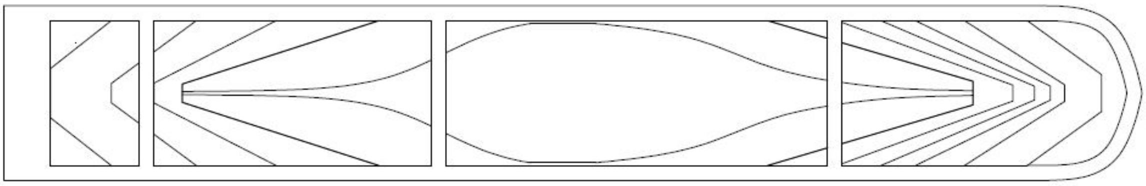


**Figure 49:** 3D view of ship model

**Table 12:** Mass properties of the ship model

| Parameter | Value |
|---|---|
| Weight, m | 42.90 kg |
| Centre of gravity, $X_g$ | 2.05 m |
| Centre of gravity, $Y_g$ | 0 m |
| Centre of gravity, $Z_g$ | 0.23 m |
| Radius of Gyration, $R_x$ | 0.29 m |
| Radius of Gyration, $R_y$ | 1.27 m |
| Radius of Gyration, $R_z$ | 1.29 m |

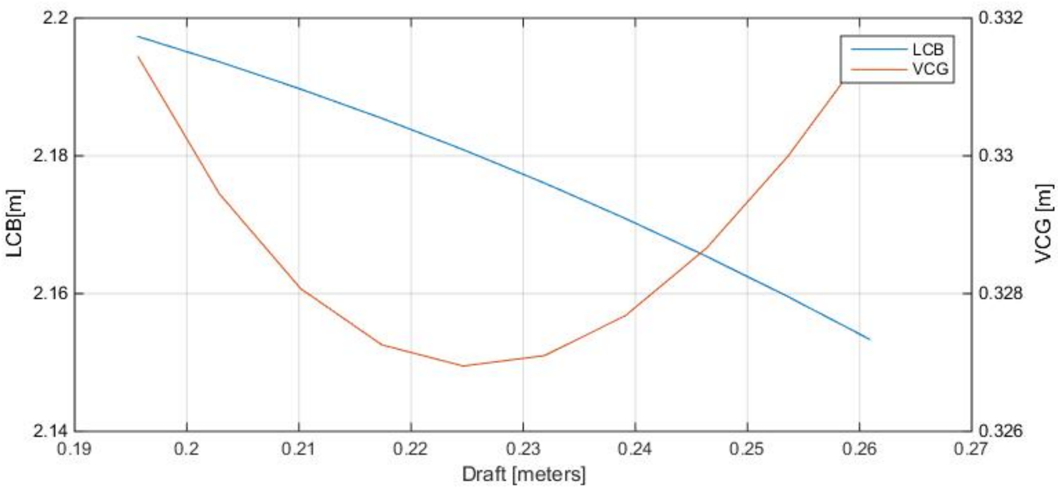



**Figure 50:** LCB and limiting VCG as a function of draft for model scale, $\lambda = 46$

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### 4.2.3 Changeable parts

Figure 51 illustrate how the model could be divided. Since, in theory, all parts of the hull can be changed during the storing of the model, the only limiting factor is the position of the bulkheads. When replacing the foreship, a transverse cut is made just in front of the bulkhead. Then the bulkhead can be used as support when the new forship is installed. Based on this, the forward bulkhead is placed behind the shoulders so that the students are able to adjust the location of the shoulders.

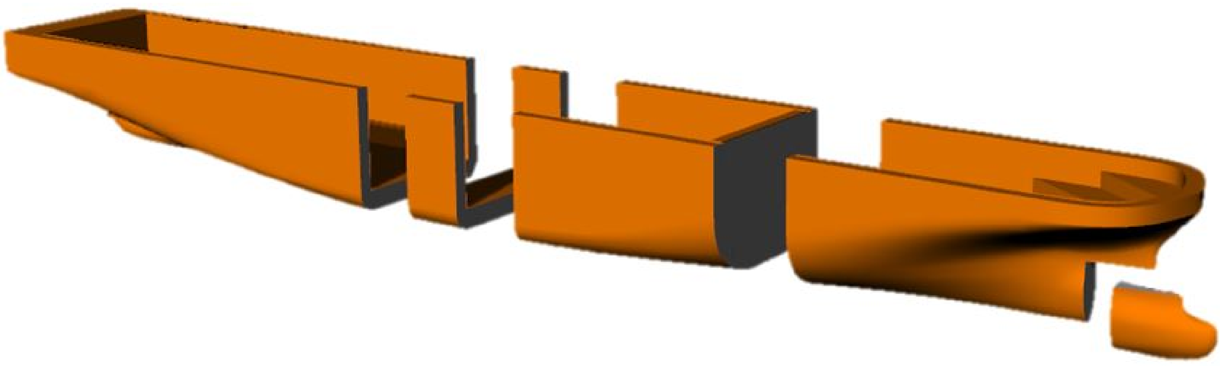

**Figure 51:** Illustration on how the model could be divided
.

## 4.3 Discussion

The model was scaled with several scales to investigate how it performed in the different tests. The investigation favoured two scales, the pros and cons are discussed below.

From the first round of interviews, the lecturers desired that the model should be able to illustrate parametric roll. From ITTC (2008*b*), it was found that the relationship between the length of the basin and model should be $L_{basin} > 25L_M$ to be able to perform tests for both parametric roll and broaching. The MDL basin is too short for both models. ITTC (2008*b*) recommend that the width of the basin is larger than the models tactical diameter, which according to IMO (2002) should not exceed $5 \cdot L_M$. The towing tank is long enough, but not wide enough to carry out a broaching test. This excluded the examination of the broaching phenomena for the model. It was found that parametric roll could be simulated in the towing tank or at zero speed by constraining the model with soft springs ("Illustration of parametric roll", 2010). Since large roll angles over 30 degrees can occur during parametric roll, it was important to investigate if the model had sufficient freeboard. The depth of the models at SSPA is restricted to 0.5 meters. From equation 20 it can be seen that with model 1 only a 23° heeling angle could be obtained. For model 2, a heel angle of 37° can be achieved. Model 2 was therefore favoured with regard to parametric roll and intact stability in general.

On the other hand, model 2 will be considerably smaller than model 1, which means that the scale effects will be larger. To reduce the scale effects, which are important in resistance trials, it is beneficial to have a large model as possible. Model 2 will in this case yield less accurate results than model 1. However, since both models are significantly smaller than a normal resistance model, the results would nonetheless only be accurate for educational purposes. According to SSPA (2016), the model needs a sufficiently large propeller to do a self-propulsion test. See table 10 for limitations. From table 11 it is seen that model 1 has a propeller diameter of 18.1 cm. This is at the limit of what SSPA accept in order to avoid large scale effects. The propeller diameter of model 2 is only 14.1 cm, which is too small. From a self-propulsion point of view, model 1 would be beneficial. On the other hand, the model itself is too small to yield accurate result in terms of resistance, so the achieved results from the test would be incorrect.

If the model should be able to give results for added resistance, a calm water resistance is required. As stated above, a model that is large enough to achieve accurate results for resistance is often too large to run in the MDL basin. Therefore, it is necessary to have two models to obtain accurate results. This exclude tests for added resistance for the model in this assignment since only one model is being manufactured. But, for educational purposes the added resistance could be estimated by measuring the difference in trust in calm and wavy water. Then it would be beneficial to have a large propeller as possible.

When the models become sufficiently large, interference between the model and tank walls can become a challenge. When investigating this phenomena, it was found that both models were far from the limit where tank interference occur. ITTC have not defined a value for the width of the basin, but the MDL basin is much larger than the maximum tactical diameter of the model, and should be sufficient. The scale effect in manoeuvring tests are not fully understood (ITTC, 2008*b*). It is therefore recommended to keep the model scale as large as possible within this requirement. The weight of the model was an important limitation to consider when the scales was evaluated. Model 1 has a displacement of 1000 kg, which is the maximum limit that SSPA can handle. This makes the model more challenging to handle and time consuming to ballast. Model 2 has a displacement in the lower range of what is normal at SSPA.

Last, it was desired that the model should be able to simulate seastate 8, which is the maximum seastate tested at SSPA. From table 11 it can be seen that the maximum wave height for model 1 corresponds to 9 meters for the full scale ship. This only equals seastate 7 according to World Meteorological Organisation. Model 2 can simulate a wave height of 11.5 meters, which corresponds to average wave height in seastate 8. Since this is a MDL model, the ability to illustrate the higher seastate played a large role when the scale was decided.

The ship model is designed based on guidelines from SSPA. It is assumed that the model would be sufficiently rigid by following their recipe; a wall thickness of $6cm$ and 2-3 bulkheads. It could be discussed if a strength analyse should be done. ITTC recommend a maximum deflection of 2 mm midship in hogging/sagging (ITTC, 2011*c*) and due to the model's open sections, it is probably vulnerable to torsion.

The seakeeping and manoeuvring performance of the ship depends to a large extent on the model's weight distribution. Investigating how changes in the weight distribution affects the ship performance are interesting both in terms of research and education. Figure 50 in section 4.2.2, which show the LCB and limiting VCG as a function of draft, should be of great help when setting up different load cases.

The lightweight mass properties of the model were given in table 12. The weight in that table is the weight of the divinycells and do not include surface treatment or possible reinforcements. Strictly speaking, the lightweight of the model should also include all the standard items that always are attached to the model, i.e. engine, rudder servo, dynamometer and rails for attachment to the waggon. These weights are not accounted for due to lack of information. The radius of gyration for the model are rather large compared to ITTC, being approximately 15% larger in pitch and yaw and 3% larger in roll. This means that the ballast has to be positioned closer to the centre of gravity. This is a good thing as it is relatively much space there.

## 4.4 Conclusion

Two scales that yield different model properties were evaluated, see section 4.2.1. Model 1 ($\lambda = 36$) is considered more universal than model 2 ($\lambda = 46$), due to its better performance in resistance and self-propulsion tests. However, model 2 was chosen because:

- It was desired to use the model for research, therefore a sufficient freeboard was needed, together with the possibility of simulating seastate 8
- The dimensions of the model are within the regular limits set by SSPA.
- The model is easier to handle and faster to ballast
- Lecturers and in particular SSPA, recommended to design a model specialised in one segment, not a "half-baked" one.

Table 13 shows which of the initially desired features the model are able to conduct. The model can do all the recommended features, but few of the additional ones.

**Table 13:** Feature performance

| **Feature** | **Ability** | **Comment** |
|---|---|---|
| Seakeeping | ✓ | Very good performance |
| Manoeuvring | ✓ | Very good performance |
| Shallow water | ✓ | Basin feature |
| CAD/ numerical model | ✓ | Independent of model |
| Changeable ship geometry | ✓ | Relatively good performance |
| Uncertainty analyse | ✓ | Independent of model |
| Wave pattern | ✓ | Only for visualisation |
| Intact stability | ✓ | Relatively good performance, no broaching |
| Captive test | ✓ | Coefficients can be derived from manoeuvring test |
| Roll decay | ✓ | Good performance |
| Parametric roll | ✓ | Possible to do with the model, basin limitations |
| Changeable rudder | ✓ | Good performance |
| Roll damping devices | ✓ | Bilge keel possible, otherwise restricted by space |
| Flow visualisation | ✓ | Laminar flow may occur |
| Outdoor model | ✗ | Not applicable as long as basin is available after 4 PM |
| Damage stability | ✗ | Not further evaluated, too expensive |
| Towing resistance | ✗ | Possible, but low performance |
| Self-propulsion | ✗ | Too small propeller |

Table 14 shows how the model can be utilised in the different courses thought in Naval Architecture and Ocean Engineering (MPNAV). The model is not usable in the other maritime educations at Chalmers.

**Table 14:** Courses in MPNAV

| Course | Ability | Comment |
|---|---|---|
| Waveloads and Seakeeping [SJO745] | 🙂 | Good in seakeeping and manoeuvring tests. Verify numerical calculation methods. Parametric roll and extreme motion responses. |
| Ship Geometry and Hydrostatics [MMA136] | 😐 | Intact- and damage stability in waves. No flooding, only cargo shift or water tanks. Some stability can be assessed, i.e inclining experiments and roll decay, however the stability model would do this better. |
| Ship Resistance and Computational Hydrodynamics [MMA161] | 😐 | The model can be used in resistance, self-propulsion and added resistance, but will yield inaccurate results. Decent flow visualisation, laminar flow can be a challenge. |
| Marine Structural Engineering [MMA167] | 🙁 | Very limited area of use. Can be used to evaluate local loads, i.e slamming. |
| Marine Propulsion Systems [SJO740] | 🙁 | Possible to measure wake and investigate flow into the propeller. Different propellers/ stock propellers could be tested, but with low accuracy. |

Technically, this model represent a basic MDL model. There are no special features deviating from what is normal or easily implemented. On the other hand, both the ship and the model are designed to fit the need at Chalmers. The model do this to a large extent. As desired the model performs well in seakeeping and manoeuvring tests, both in terms of education and research. The model is highly usable to investigate intact stability phenomena as parametric roll and can be used for educational purposes in the towing tank, but then with a low accuracy. The ship are able to illustrate the desired features and the shape and performance of the ship are similar to an ordinary PCTC.

# 5 Summary and conclusion

The project started by investigating the need for a ship model at Chalmers together with the demands and desired features the model should have. The gathering of information was done in form of interviews with the relevant instances. Based on the collected information, four different concepts were derived. The concepts differs in terms of operability, where the first concept is intended to use in the towing tank, concept 2 for seakeeping and manoeuvring, concept 3 for stability and the fourth concept was intended to use for obtaining the structural responses of the vessel. The four concepts were rated, and it was decided to continue with development of the MDL model.

In the second phase of the project, the hull of the ship was designed. A PCTC was chosen as the most appropriate vessel to illustrate the desired features found in the first phase. Based on reference vessels, literature and empirical formula's the main dimensions were established. The performance of the vessel was then investigated. The ship has a decent performance in terms of resistance, stability and seakeeping. It is left openings for the students to improve the performance of the hull, then especially with regard to the foreship.

In the last phase, the designed hull was scaled down to model scale and the special features of the model were implemented. The finished model is similar to a basic MDL model in terms of operability, but with a hull form designed to fit the demands and wishes from Chalmers. The cost of this model will be approximately 255 000 SEK, based on the cost assessment from chapter 2.

Even though the model is especially designed to fit the need at Chalmers, it is not specialised enough to justify the cost. The researchers of this project recommend Chalmers to investigate the possibility to inherent an old model from one of their associated companies. This model could probably be modified to achieve a lot of the same features as the model in this project, but at a considerably lower cost. The researches also recommend that the stability model is further developed and build. The educational value of this model is considered to be high. It is less costly to build and operate, and could be used in many of the courses thought at the department. If the model could be used in the wind tunnel, it would be applicable in the resistance courses as well.

# 6 Future Work

If it is decided to further develop this model, it is recommended to take the following things into consideration:

- A strength calculation should be done to ensure that the model is rigid enough. This could be done by ballasting the model to design draft and calculating the net load (weight subtracted from buoyancy) by using *Maxsurf Stability*. The radius of gyrations has to be accounted for to get a realistic weight distribution. The net load could be imported into *ANSYS Workbench* and the deflection midship could be calculated using a beam element with the same structural properties as the midship section. This will probably give a close enough estimation of the models rigidity.

- As discussed in section 3.3.3 the seakeeping analyse could be improved. More seastates should be included in the analyse and features as slamming, propeller emergence and sea sickness could be evaluated.

- A rudder need to be designed and the manoeuvring abilities of the model need to be analysed.

- A propeller has to be chosen for the model. A stock propeller should be sufficient. However, calculations are needed to find what stock propeller to use. After the propeller is chosen, the total power demand can be calculated, and it can be determined what engine is suitable.

- The proper lightweight mass properties of the model has to be calculated. This includes the weight of the engine, rudder servo, dynamometer, etc.

- A final cost assessment of the model should be done.

In addition the following topics could be interesting to investigate further:

- It would be interesting to quantify the error of using the MDL model in the towing tank. This is challenging to assess before the model is build as the scale effects are determined by interpreting the result from the towing test and comparing it with other tests of similar ships. However, an estimation of the scale effects could possible be done running CFD simulations at different scales. After the model is build it could be experimented with different types of turbulent simulators to achieve a sufficiently turbulent flow.

- A plan of how the model should be used in education should be developed. This would be a description of the tests, how the student should be involved, and what the students should do with the result. This should be done in close cooperation with the relevant teachers and within a realistic budget.

- A parametric model of the hull could be developed. A parametric model differ from a surface model as its geometry is decided by mathematical relations. In example, the bulb shape could be determined as a function of the bulb length. The advantage of this is that it is easy to investigate the effect of modifying the hull, whether speaking about changing the length of the vessel or the shape of the waterline. The parametric model should made with regard to what is physically possible to change on the model and what is relevant in the different courses.

- It would be interesting to investigate if the model could be used to do damage stability. The ability to do damage stability depends, among other, on the size of the model. After the measuring equipment are placed and the model is ballasted, it has to be sufficient space for floodable tanks. There are strict requirements for the wall thickness of the floodable tanks. This is to proper simulate the water jet that occurs when the model is damaged. This means that the floodable part of the model has to be removed when it is used for seakeeping and manoeuvring tests. This could be solved by having a changeable midsection denoted to damage stability.

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# A General Interview

**Goal**: Investigate if the model is necessary, and what properties are needed/wanted for the ship model.

**Interview plan**: Semi-structured, one-to-one. The interview will be carried out as a discussion with the following guiding questions.

**Intro**: We are going to develop and design a ship model for Chalmers for use in research and education. The idea is that the model shall be used as a learning tool in the different maritime courses thought at Chalmers. The project will be carried out together with SSPA. The goal of this interview is to gather information from you to be able to decide what features the model should have.

**Questions**:

1. How could the ship model be of use in your course/subject?
   (Goal: Establish if a model is needed)

2. Which features do you think would be important for such a model in your course/subject?
   (Goal: Find specific areas the model can be used)

3. Suggestion on how to implement such features?
   (Goal: Help to transform wishes into features)

4. Which type of ship?
   (Goal: Help to transform model features into ship type)

5. Other comments regarding the model features and the project in general?
   (Goal: give the interviewee a chance for final comments)

# B Decision matrix 1

## INFO

*FEATURES:*
Each features are evaluated in a seperate excel sheet, #[number]. They are evaluated based on their peformance w.r.t: the student (*Benefit for the students),* to research *(Benefits for research),* to cost (*Cost)* and the difficulity to implement it (*Thechnical Aspect).* A grade (score x weight) is given based on their performance multiplied with their respectiv weight. The weight represent how important the subjects are relative to each other. For weigth see sheet *Weight.*

*CONCEPT:*
The concept is based on a ship model made for one porpose, *Concept [number]* . A list of possible additional features is provided for each concept. The final features of the ship model should be decided based on their grade and possibly the cost. Each concept is assigned a grade. This grade is just the summation of the grade of the features and represent only which of the concept that have most (good) features. The decison of the concept should be based on what Chalmers University of Technology need and wants.

*PRICES:*
All prices in this document represent commercial prices at SSPA. Some discount for Chalmers is expected.

OTHER:
See report for more information

## Terms & Expressions

**O.Cost:** Operational Cost, the cost of using the model, i.e one series of towing trials.
**C.Cost:** Concept Cost, the additonal cost of implementing a feature to the model.
**Standard Price:** The cost of one standard model (concept) stripped for features.
**Education Stability**: Featrues made for student to learn stability
**Research Stability:** Features made to do research w.r.t stability.
**NaN:** Not applicable number.
**Day Price:** Rent of basin per day; Towing tank = 100 000 SEK (12h), Cavitation tunnel and MDL = 70 000 SEK (8h).

## Score

The meaning of the scores:
**5** - Excellent learning outcome for students. Highly beneficial for research. Zero cost and no technical difficulties.
**4** - Great learning outcome for students. Beneficial for research. Small cost and limited technical difficulties.
**3** - Some learning outcome. Some research capabilities. Medium (max 20 % of standard prize) cost and some technical difficulities with implementation.
**2** - Low learning outcome. Limited research capabilities. High cost (max 50 % of standard prize) and difficult to implement.
**1** - No learning outcome. No research. Very high cost (>50%) and very hard to implement.

| Name | Description | Weight |
|---|---|---|
| Benefits for student | How good the model will suit the student w.r.t learning. How well the model will support the lecturer in his/her subject. | 0.3 |
| Benefits for research | How useful the is in research. | 0.2 |
| Cost | How much the feature would cost | 0.3 |
| Technical Aspect | How difficult the feature is to implement | 0.2 |
| | **Total (Should equal 1):** | 1.0 |

| Name: | Resistance | | | | |
|---|---|---|---|---|---|
| Concept Nr: | 1 | | | Total Grade: | 20.45 |
| **Description:** | | | | | |
| This concept is based on a standard towing tank model with features and additional features listed below.<br><br>Features: No education stability because of the size of the model. No research stability because of the limited seakeeping abilities in the TT basin. | | | | | |
| | | | Standard cost: | 150 000 | |
| | | | Features cost: | 225 000 | 936 000 |
| **Features:** | | | | | |
| **Idea Nr.** | **Name:** | **Grade:** | **Field:** | **C.Cost (SEK)** | **O.Cost (SEK)** |
| | **Recommended Features** | | | | |
| 1 | Changable ship geometry | 1.10 | Hydro | 5 000 | 50 000 |
| 2 | CAD/ Numerical model | 1.09 | General | 0 | 0 |
| 5 | Towing Resistance | 1.18 | Hydro | 0 | 30 000 |
| 6 | Self-Propulsion | 1.01 | Hydro | 50 000 | 33 000 |
| 7 | Wake-field | 1.04 | Hydro | 0 | 40 000 |
| 8 | Flow visualization | 1.14 | Hydro | 0 | 25 000 |
| 9 | Thin hull (TT) | 1.04 | Seakeeping | 50 000 | Day Cost |
| 11 | Changable appendages | 1.16 | Hydro | 0 | 80 000 |
| 22 | Changeable propellers | 1.00 | Propeller | 0 | 75 000 |
| 25 | Wave pattern | 1.05 | Hydro | 0 | 3 000 |
| 27 | Uncertainty Analyse | 0.98 | General | 0 | 0 |
| 29 | Seakeeping in TT | 1.10 | Hydro | NaN | Day Cost |
| 32 | Captive Test | 1.10 | Manouvering | 0 | 300 000 |
| 33 | Roll decay | 1.11 | Seakeeping | NaN | Day Cost |
| 34 | Parametric roll | 1.08 | Seakeeping | NaN | Day Cost |
| 28 | Changabele rudder | 0.98 | Manouvering | 20 000 | Day Cost |
| | **Additional Features** | | | | |
| 10 | Cavitation Tunnel | 1.05 | Hydro | 0 | 300 000 |
| 23 | Outdoor Model - Seakeeping | 0.60 | Seakeeping | 100 000 | 0 |
| 36 | Outdoor model - Manouvering | 0.83 | Manouvering | NaN | 0 |
| 35 | Roll damping devices | 0.84 | Seakeeping | NaN | Day Cost |

| Name: | MDL | | | | |
|---|---|---|---|---|---|
| Concept Nr: | 2 | | | Total Grade: | 19.13 |
| **Description:** | | | | | |
| This concept is based on a standard seakeeping & manouvering (MDL) model with features and additional features listed below.<br><br>Features: Education stability better, but still no real value. Self propulsion not possible because the propeller is to small. Only local (small parts) can be changed becuase of all the measuring equipment in the MDL model. Wave patteren is only for visualization. Outdoor model as it is cheaper to do outside.<br><br>The MDL basin can be availible for students after work hour (4 PM) | | | | | |
| | | | Standard cost: | 220 000 | |
| | | | Features cost: | 505 000 | 1 271 000 |
| **Features:** | | | | | |
| **Idea Nr.** | **Name:** | **Grade:** | **Field:** | **C.Cost (SEK)** | **O.Cost (SEK)** |
| | **Recommended Features** | | | | |
| 1 | Changable ship geometry | 1.10 | Hydro | 5 000 | 50 000 |
| 2 | CAD/ Numerical model | 1.09 | General | 0 | 0 |
| 12 | Manouvering Test (MDL) | 1.04 | Manouvering | 0 | 300 000 |
| 13 | Seakeeping | 1.19 | Seakeeping | 0 | 500 000 |
| 14 | Shallow Water | 1.06 | Seakeeping | 0 | 30 000 |
| 27 | Uncertainty Analyse | 0.98 | General | 0 | 0 |
| 25 | Wave pattern | 1.05 | Hydro | 0 | 3 000 |
| 26 | Intact Stability | 1.09 | Stability | 30 000 | Day Cost |
| 32 | Captive Test | 1.10 | Manouvering | 0 | 300 000 |
| 33 | Roll decay | 1.11 | Seakeeping | NaN | Day Cost |
| 34 | Parametric roll | 1.08 | Seakeeping | NaN | Day Cost |
| 28 | Changabele rudder | 0.98 | Manouvering | 20 000 | Day Cost |
| | **Additional Features** | | | | |
| 23 | Outdoor Model - Seakeeping | 0.60 | Seakeeping | 100 000 | 0 |
| 36 | Outdoor model - Manouvering | 0.83 | Manouvering | NaN | 0 |
| 35 | Roll damping devices | 0.84 | Seakeeping | NaN | Day Cost |
| 21 | Damage Stability | 0.69 | Stability | 200 000 | Day Cost |
| 5 | Towing Resistance | 1.18 | Hydro | 0 | 30 000 |
| 6 | Self-Propulsion | 1.01 | Hydro | 50 000 | 33 000 |
| 8 | Flow visualization | 1.14 | Hydro | 0 | 25 000 |

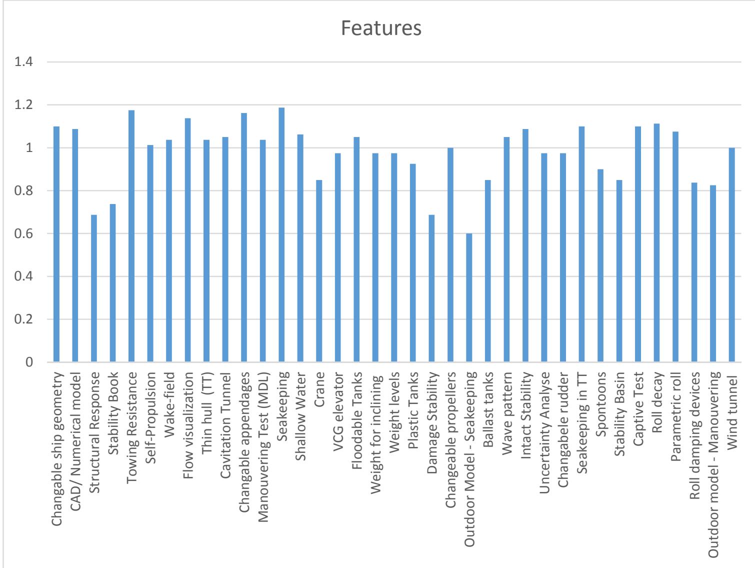
| | | | | | |
|---|---|---|---|---|---|
| **Name:** | Stability | | | | |
| **Concept Nr:** | 3 | | | **Total Grade:** | 12.025 |
| **Description:** | | | | | |
| Small stability model as the one at DTU placed at Lindholmen. Students responsible for running the test. | | | | | |
| | | | | **Standard cost:** | 40 000 |
| | | | | **Features cost:** | 35 900 | 0 |
| **Features:** | | | | | |
| **Idea Nr.** | **Name:** | **Grade:** | **Field:** | **C.Cost (SEK)** | **O.Cost (SEK)** |
| **Recommended Features** | | | | | |
| 4 | Stability Book | 0.74 | Stability | 0 | 0 |
| 15 | Crane | 0.85 | Stability | 2 000 | 0 |
| 16 | VCG elevator | 0.98 | Stability | 500 | 0 |
| 17 | Floodable Tanks | 1.05 | Stability | 200 | 0 |
| 18 | Weight for inclining | 0.98 | Stability | 500 | 0 |
| 19 | Weight levels | 0.98 | Stability | 200 | 0 |
| 20 | Plastic Tanks | 0.93 | Stability | 3 000 | 0 |
| 24 | Ballast tanks | 0.85 | Stability | 3 500 | 0 |
| 30 | Spontoons | 0.90 | Stability | 1 000 | 0 |
| 31 | Stability Basin | 0.85 | Stability | 11 500 | 0 |
| 24 | Ballast tanks | 0.85 | Stability | 3 500 | 0 |
| **Additional Features** | | | | | |
| 2 | CAD/ Numerical model | 1.09 | General | 0 | 0 |
| 37 | Wind tunnel | 1.00 | Resistance | 10 000 | 0 |

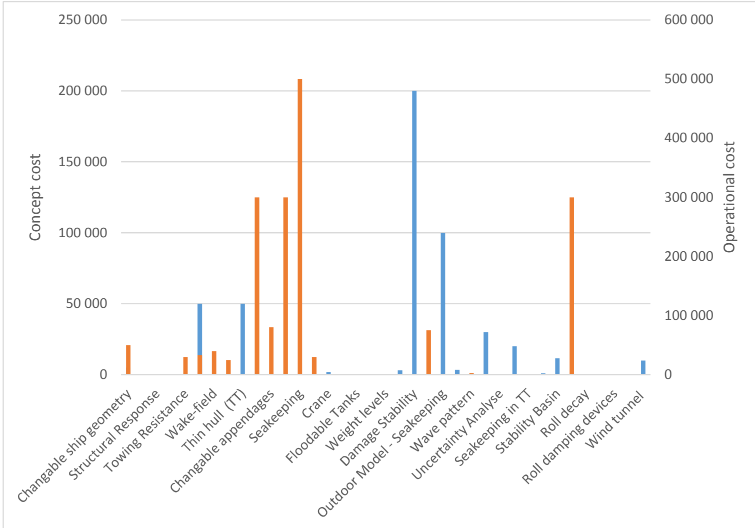
| | | | | | |
|---|---|---|---|---|---|
| **Name:** | Backbone | | | | |
| **Concept Nr:** | 4 | | | **Total Grade:** | 5.1 |
| **Description:** | | | | | |
| Segemented model with a backbone to measure global loads.<br><br>Features: Resistance not applicable due to the gaps between the segments and the small scale of a MDL model. | | | | | |
| | | | **Standard cost:** | 500 000 | |
| | | | **Features cost:** | 5 000 | 850 000 |
| **Features:** | | | | | |
| **Idea Nr.** | **Name:** | **Grade:** | **Field:** | **C.Cost (SEK)** | **O.Cost (SEK)** |
| **Recommended Features** | | | | | |
| 1 | Changable ship geometry | 1.10 | Hydro | 5 000 | 50 000 |
| 2 | CAD/ Numerical model | 1.09 | General | 0 | 0 |
| 3 | Structural Response | 0.69 | Structure | 0 | Day Cost |
| **Additional Features:** | | | | | |
| 12 | Manouvering Test (MDL) | 1.04 | Manouvering | 0 | 300 000 |
| 13 | Seakeeping | 1.19 | Seakeeping | 0 | 500 000 |

## Model Features

| Idea Nr. | Idea Name | Grade | C.Cost (SEK) | O.Cost (SEK) | Field | Status |
|---|---|---|---|---|---|---|
| 1 | Changable ship geometry | 1.1 | 5 000 | 50 000 | Hydro | |
| 2 | CAD/ Numerical model | 1.0875 | 0 | 0 | General | |
| 3 | Structural Response | 0.6875 | 0 | Day Cost | Structure | |
| 4 | Stability Book | 0.7375 | 0 | 0 | Stability | |
| 5 | Towing Resistance | 1.175 | 0 | 30 000 | Hydro | |
| 6 | Self-Propulsion | 1.0125 | 50 000 | 33 000 | Hydro | |
| 7 | Wake-field | 1.0375 | 0 | 40 000 | Hydro | |
| 8 | Flow visualization | 1.1375 | 0 | 25 000 | Hydro | |
| 9 | Thin hull  (TT) | 1.0375 | 50 000 | Day Cost | Seakeeping | |
| 10 | Cavitation Tunnel | 1.05 | 0 | 300 000 | Hydro | |
| 11 | Changable appendages | 1.1625 | 0 | 80 000 | Hydro | |
| 12 | Manouvering Test (MDL) | 1.0375 | 0 | 300 000 | Manouvering | |
| 13 | Seakeeping | 1.1875 | 0 | 500 000 | Seakeeping | |
| 14 | Shallow Water | 1.0625 | 0 | 30 000 | Seakeeping | |
| 15 | Crane | 0.85 | 2 000 | 0 | Stability | |
| 16 | VCG elevator | 0.975 | 500 | 0 | Stability | |
| 17 | Floodable Tanks | 1.05 | 200 | 0 | Stability | |
| 18 | Weight for inclining | 0.975 | 500 | 0 | Stability | |
| 19 | Weight levels | 0.975 | 200 | 0 | Stability | |
| 20 | Plastic Tanks | 0.925 | 3 000 | 0 | Stability | |
| 21 | Damage Stability | 0.6875 | 200 000 | Day Cost | Stability | |
| 22 | Changeable propellers | 1 | 0 | 75 000 | Propeller | |
| 23 | Outdoor Model - Seakeeping | 0.6 | 100 000 | 0 | Seakeeping | |
| 24 | Ballast tanks | 0.85 | 3 500 | 0 | Stability | |
| 25 | Wave pattern | 1.05 | 0 | 3 000 | Hydro | |
| 26 | Intact Stability | 1.0875 | 30 000 | Day Cost | Stability | |
| 27 | Uncertainty Analyse | 0.975 | 0 | 0 | General | |
| 28 | Changabele rudder | 0.975 | 20 000 | Day Cost | Manouvering | |
| 29 | Seakeeping in TT | 1.1 | NaN | Day Cost | Hydro | |
| 30 | Spontoons | 0.9 | 1 000 | 0 | Stability | |
| 31 | Stability Basin | 0.85 | 11 500 | 0 | Stability | |
| 32 | Captive Test | 1.1 | 0 | 300 000 | Manouvering | |
| 33 | Roll decay | 1.1125 | NaN | Day Cost | Seakeeping | |
| 34 | Parametric roll | 1.075 | NaN | Day Cost | Seakeeping | |
| 35 | Roll damping devices | 0.8375 | NaN | Day Cost | Seakeeping | |
| 36 | Outdoor model - Manouvering | 0.825 | NaN | 0 | Manouvering | |
| 37 | Wind tunnel | 1 | 10 000 | 0 | Resistance | |

## Summary Features



## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Changable ship geometry | **Idea Nr.** | 1 |
| **General Description** | | **Field:** | Hydro |

The idea is to make the model so that some parts of the hull can be changed, i.e. change the aft or fore of the ship, or local changes as the bulb. The ship model can then be optimzed in terms of resistance and flow (bulb & shoulders --> wave pattern, stern --> wake, etc. ), seakeeping (changable foreship --> slamming, changable midship --> change ship length, etc) and manouvering (Length, draft, LCB*).

According to Carl-Erik Janson (mail: 8.mars):

*"Local geometrical modifications like changing the bulb are not so important for seakeeping. It is the main dimensions and in particular the shape of the water plane area, global volume distribution and mass moment of inertia that are of importance."*

| | | |
|---|---|---|
| **Benefits for the students** | **Grade (max 5):** | 5 |

Students can optimize the ship geometry using CAD & CFD tools and then do model test with the new geoemtry. Poul Andersen report that students get very engaged in their model with changable bulb at DTU. Students get to do both the CFD optimization and verify with model results (as done in the industry).

**Weight:** 0.3

| | | |
|---|---|---|
| **Benefits for the research** | **Grade (max 5):** | 4.5 |

To change part of the ship make the model more flexible and enlarge the chance to perform research. Can be used for CFD validation. However, the midsection is default and the changeable part will always (in some degree) depend on this, i.e. you cant make a new ship.

**Weight:** 0.2

| | | |
|---|---|---|
| **Cost** | **Grade (max 5):** | 4 |

Cost depends on what part of the model you change. Cost range form 10 000 - 50 000 SEK dependent on the part. The cost could be lowerd if students do the work. Approx 5000 to make the model fit for changes.

| | | | | | |
|---|---|---|---|---|---|
| C.Cost (SEK): | 5 000 | O.Cost (SEK): | 50 000 | **Weight:** | 0.3 |

| | | |
|---|---|---|
| **Technincal Aspect** | **Grade (max 5):** | 4 |

According to SSPA, is no problem to implement. Common to do this for clients. It is an advantage to prepare the model for changable part when building the model.

**Weight:** 0.2

**Total Grade:** 1.1

Sources:
Interview with Poul Andersen (12.02.16), SSPA (04.02.16) & SSPA (19.02.16). *Manouvering: http://www.sciencedirect.com/science/article/pii/S0029801806001247

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | CAD/ Numerical model | **Idea Nr.** | 2 |
| **General Description** | | **Field:** | General |

Develop a numerical model which can be used in calculations before the model tests are performed and for visualization of flow and seakeeping phenomens. The model should be made so that certain features are easy to change, i.e. the bulb. CASES and parametric modifications can be a option.

| | | |
|---|---|---|
| **Benefits for the students** | **Grade (max 5):** | 4.5 |

Some sort of numerical model has to be availible for the students. The results from model testing could be used in the numerical model - simulation of parametric roll etc can be visualized.

**Weight:** 0.3

| | | |
|---|---|---|
| **Benefits for the research** | **Grade (max 5):** | 3.5 |

Optimization of the hull.

**Weight:** 0.2

| | | |
|---|---|---|
| **Cost** | **Grade (max 5):** | 5 |

No direct cost.

| | | | | | |
|---|---|---|---|---|---|
| C.Cost (SEK): | 0 | O.Cost (SEK): | 0 | **Weight:** | 0.3 |

| | | |
|---|---|---|
| **Technincal Aspect** | **Grade (max 5):** | 4 |

Time consuming to develope a numerical model with many different features. The numerical model should consider both hydro & FEM model.

**Weight:** 0.2

**Total Grade:** 1.0875

Sources:
Email Bengt Ramne (8.02.16), SSPA meeting (19.02.16)

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Structural Response | **Idea Nr.** | 3 |

**General Description** — **Field:** Structure

The model is segmented and equiped with a backbone. The model can then be used to find bending moment, shear stresses, whipping - and springing, etc. caused by waves. The model can probably be used in normal seakeeping trails as welll. Normally a seakeeping model is rigid, but a flexible model with the correct stiffnes should yield a more realistic result. Manouvering could be a bit more cumbersome as a the backbone will be subjected to a horisontal bending moment (when turning the rudder). Then the backbone needs to have a correct horisontal stiffnes (which they do not always have).

**Benefits for the students** — **Grade (max 5):** 3.5

Compare results obtained by calculation with the one obtained from the tests. Student get the possiblity to study relevant problems (i.e. springing, whipping, slamming loads). Has to be done by professional personal. Students are probably allowed to watch a limited amount of trials, but will be given access to a database with results. The model is only applicable for students taking advanced seakeeping course or doing master thesis in this topic. Could be used in structural engineering, relability analysis & probablity and waveloads & seakeeping.

**Weight:** 0.3

**Benefits for the research** — **Grade (max 5):** 5

Highly relevant for research. The model could be used to investigate and capture seakeeping phenomens such as springing and whipping (hot-topic) on a more realisticly behaving model. These phenomens are non-linear and difficult to simulate with a numerical model, thus a real model is needed.

**Weight:** 0.2

**Cost** — **Grade (max 5):** 1

Very expensive model, however the model will probably have a higher budget since it is already an ongoing project - SSPA and Chalmers.

| | | | | | |
|---|---|---|---|---|---|
| C.Cost (SEK): | 0 | O.Cost (SEK): | Day Cost | **Weight:** | 0.3 |

**Technincal Aspect** — **Grade (max 5):** 2

Difficult model to make. SSPA has limited experience. DTU/Force has bad experience with accuarcy. But several model has been made with different degree of success. ITTC has a set of recomendation and a thorough article of a design of segmented container ship can be found in *Design of a ship model for hydro-elastic experiments in waves* (Marón & Kapsenberg, 2014). Limited tests can be performed with this model due to accuracy. Complex testing which take a long time.

**Weight:** 0.2

**Total Grade:** 0.6875

Sources:
Interview with Poul Andersen (12.02.16) , SSPA (04.02.16), Jonas Ringsberg (02.02.16). Recomendation form ITTC. Design of a ship model for hydro-elastic experiemnts in waves (Marón & Kapsenberg, 2014).

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Stability Book | **Idea Nr.** | 4 |

**General Description** — **Field:** Stability

Make a stability book for the model so students can use this book in operational situations, i.e load handling experiments.

**Benefits for the students** — **Grade (max 5):** 2.5

The captains can use the book together with the model i.e load handling simulations. The naval architects can develop the book as a part of their education. However, the captains have good computer simulators that do the same (and maybe better).

**Weight:** 0.3

**Benefits for the research** — **Grade (max 5):** 1

No research

**Weight:** 0.2

**Cost** — **Grade (max 5):** 4

The development of the book could cost a bit, but incling test etc. could be done by students as a part of learning.

| | | | | | |
|---|---|---|---|---|---|
| C.Cost (SEK): | 0 | O.Cost (SEK): | 0 | **Weight:** | 0.3 |

**Technincal Aspect** — **Grade (max 5):** 4

No problem to make. Could be done as a student project. For the book to be intersting to use, the model has to be equipped with some form of cargo handling, i.e. tanks for cargo and ballast.

**Weight:** 0.2

**Total Grade:** 0.7375

Sources:
Interview with Jan Skoog (02.02.16) and Olle Lindmark (16.02.16).

## Model Features

| | | | | |
|---|---|---|---|---|
| **Name:** | Towing Resistance | | **Idea Nr.** | 5 |
| **General Description** | | | **Field:** | Hydro |
| Normal towing test. Resistance, sinkage & trim, wave elevation, boundary layer and the nominal wake are measured in the towing basin. Load cells are used to measure forces. Rotative potentiometers used to measure the fore and aft displacement in sinkage & trim. Tested at different speeds, giving the same Froude number as for full scale. Wave elevation measured with pictures. Nominal wake measure the flow into the propeller using pitot tubes. The model should be tested in two conditons; with and without appendages. | | | | |
| **Benefits for the students** | | | **Grade (max 5):** | 5 |
| Traditional test which all Naval Architects should learn about. The students can scale the model result using ITTC and compare it with computed result (both emperical and CFD). Sinkage and trim can be seen and measured and analysis of head waves can be done. Students get hands-on experience. The student could learn alot of planning the test procedure. | | | | |
| | | | **Weight:** | 0.3 |
| **Benefits for the research** | | | **Grade (max 5):** | 3.5 |
| Limited research. Verification of CFD models. | | | | |
| | | | **Weight:** | 0.2 |
| **Cost** | | | **Grade (max 5):** | 5 |
| Additonal cost if the model are not standard, i.e. high speed. | | | | |
| C.Cost (SEK): 0 | O.Cost (SEK): 30 000 | | **Weight:** | 0.3 |
| **Technincal Aspect** | | | **Grade (max 5):** | 5 |
| Standard model. | | | | |
| | | | **Weight:** | 0.2 |
| | | | **Total Grade:** | 1.175 |
| Sources: | | | | |
| Methodology TT: http://www.iihr.uiowa.edu/wp-content/uploads/2013/06/TR421.pdf | | | | |

## Model Features

| | | | | |
|---|---|---|---|---|
| **Name:** | Self-Propulsion | | **Idea Nr.** | 6 |
| **General Description** | | | **Field:** | Hydro |
| Self-propulsion test are done to estimate ship power at various speeds and to derive propulsion factors, (w,t,eta). A dynometer is used to measure trust, troque and RPM. Can not be done in the MDL basin because the propeller becomes to small. | | | | |
| **Benefits for the students** | | | **Grade (max 5):** | 4.5 |
| Traditional test which all naval architect learn about. Students get hands-on experience. Result can be compared with result from CFD - or emperical calculations. | | | | |
| | | | **Weight:** | 0.3 |
| **Benefits for the research** | | | **Grade (max 5):** | 4 |
| Verification of CFD models. Relevant for propeller research. | | | | |
| | | | **Weight:** | 0.2 |
| **Cost** | | | **Grade (max 5):** | 3 |
| Extra cost for engine and propeller in TT basin. Could use stock propellers which are free of charge. A custom made propeller cost 75 000 SEK | | | | |
| C.Cost (SEK): 50 000 | O.Cost (SEK): 33 000 | | **Weight:** | 0.3 |
| **Technincal Aspect** | | | **Grade (max 5):** | 5 |
| Standard model. Make it more difficult to have a changable stern (#1) in TT basin | | | | |
| | | | **Weight:** | 0.2 |
| | | | **Total Grade:** | 1.0125 |
| Sources: | | | | |
| Interview with SSPA (04.02.2016) | | | | |

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Wake-field | **Idea Nr.** | 7 |
| **General Description** | | **Field:** | Hydro |
| The boundary layer increase in thickness with its distance from the bow, meaning it is thickest at the stern. In addition, the ship displaces water, which causes wake waves fore and aft. This will cause the propeller behind the hull to work in non-uniform water. Therefore tests are performed to optimize the flow to the propeller. Can be measured in cavitation tunnel and towing tank. The wake field is dependent on the ship type, each ship have a unique wake field. | | | |
| **Benefits for the students** | | **Grade (max 5):** | 3.5 |
| Students get hands on experience from seeing the problem. Easier to understand the flow charecteristic when you see it in reality than analysing CFD results. The students get pictures/ video to analyse after the tests. Verification of CFD. | | | |
| | | **Weight:** | 0.3 |
| **Benefits for the research** | | **Grade (max 5):** | 3 |
| Verification of CFD result. Investigate different wake optimizing devices: vortex generator, etc. | | | |
| | | **Weight:** | 0.2 |
| **Cost** | | **Grade (max 5):** | 5 |
| Standard test (4 radii & 15 deg) | | | |
| C.Cost (SEK): 0 | O.Cost (SEK): 40 000 | **Weight:** | 0.3 |
| **Technincal Aspect** | | **Grade (max 5):** | 5 |
| Under water TV. No additional features for the consept. | | | |
| | | **Weight:** | 0.2 |
| | | **Total Grade:** | 1.0375 |
| Sources: | | | |

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Flow visualization | **Idea Nr.** | 8 |
| **General Description** | | **Field:** | Hydro |
| Flow visualization by paint test, tuft test & appendage alignment test. Three basic types of visualization: Adding foreign material, optical techniques, adding heat and energy. | | | |
| **Benefits for the students** | | **Grade (max 5):** | 4.5 |
| Traditional tests. Show the streamlines along the hull. Compare with CFD. Interesting for students to see the flow charcteristic. Paint test is the most common. Evaluate the flow into the propeller. | | | |
| | | **Weight:** | 0.3 |
| **Benefits for the research** | | **Grade (max 5):** | 3.5 |
| Research of flow around different part of the hull. Verify new theory or model. | | | |
| | | **Weight:** | 0.2 |
| **Cost** | | **Grade (max 5):** | 5 |
| No concept cost. But some operational cost. | | | |
| C.Cost (SEK): 0 | O.Cost (SEK): 25 000 | **Weight:** | 0.3 |
| **Technincal Aspect** | | **Grade (max 5):** | 5 |
| Tests are time consuming. Can be sufficiently shown by CFD. Bad position of the appendages results in higher resistance and separations may occur. | | | |
| | | **Weight:** | 0.2 |
| | | **Total Grade:** | 1.1375 |
| Sources:<br>Fluid flow visualization: http://cfd.spbstu.ru/agarbaruk/c/document_library/DLFE-7706.pdf<br>SSPA (19.02.16) | | | |

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Thin hull (TT) | **Idea Nr.** | 9 |
| **General Description** | | **Field:** | Seakeeping |

To be able to have control of the VCG, LCG & the radius of gyration the wall of the model has to be thinner than on a ordinary resistance model. By doing this the model would be able to do captive test (VCG), roll decay (VCG) and seakeeping in head waves (LCG and radius of gyration in pitch), and parametric roll (CoG, and radius of gyration).

Captive test: measurement of forces to find manouvering coefficients.
Roll decay: roll damping found by heeling the model and measuring the amplitudes of roll damping. Could only be done with zero speed in TT.
Parametric Roll: Rolling of ship cause by head or following waves. Ship has large flares, flat aftership, slim fore and aft body, i.e. large container ship. Its difficult to obtain parametric roll. SSPA have no experience with it.

| | | |
|---|---|---|
| **Benefits for the students** | **Grade (max 5):** | 5 |

By making the hull thinner, the students can do more experiments and see more phenomens.

**Weight:** 0.3

| | | |
|---|---|---|
| **Benefits for the research** | **Grade (max 5):** | 3.5 |

Can be used in manouvering simulators (captive test). Parametric rolling is a hot topic, difficult to trigger. In general, the model is more flexible with the thin hull.

**Weight:** 0.2

| | | |
|---|---|---|
| **Cost** | **Grade (max 5):** | 3.5 |

The hull has to be made thinner to be able to do the weight distribution properly. The cost varies between 20 000-50 000 SEK (wall thickness).

| | | | | | |
|---|---|---|---|---|---|
| C.Cost (SEK): | 50 000 | O.Cost (SEK): | Day Cost | **Weight:** | 0.3 |

| | | |
|---|---|---|
| **Technical Aspect** | **Grade (max 5):** | 4.5 |

The bilge keel (if the ship has one) has to be included for captive test and roll decay. For roll decay it is important to have correct VCG and radius of gyration in roll. Seakeeping; correct radius of gyration in pitch. To ensure that the model is rigid enough, the model has to be reinforced with glas fiber. SSPA has experience with similar models.

**Weight:** 0.2

**Total Grade:** 1.0375

Sources:
Interview: SSPA (04.02.16 & 19.02.16) & Martin Schreuder (16.02.16)

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Cavitation Tunnel | **Idea Nr.** | 10 |
| **General Description** | | **Field:** | Hydro |

Cavitation tests are performed in a cavitation tunnel using a dummy afterbody model and simulated full-scale wake-field or a full model. At SSPA the entire model is used. Tests include cavitation observation, measurement of pressure fluctuations, erosion tests and measurement of propeller-induced forces and noise.

| | | |
|---|---|---|
| **Benefits for the students** | **Grade (max 5):** | 3 |

Students get to see the effect of cavitation, noise and vibrations . Student can make a hypothesis and verify the results. Can be a bit out the scope of the courses thought at Chalmers, too complex in education. Could be used in master thesis projects.

**Weight:** 0.3

| | | |
|---|---|---|
| **Benefits for the research** | **Grade (max 5):** | 4 |

Optimization of propellers w.r.t cavitation etc. and research on the inflow to the propeller.

**Weight:** 0.2

| | | |
|---|---|---|
| **Cost** | **Grade (max 5):** | 5 |

Same model as used in the towing tank. No additional concept cost. One standard series cost 300 000 SEK, included two propeller loading condtion.

| | | | | | |
|---|---|---|---|---|---|
| C.Cost (SEK): | 0 | O.Cost (SEK): | 300 000 | **Weight:** | 0.3 |

| | | |
|---|---|---|
| **Technical Aspect** | **Grade (max 5):** | 5 |

No technical aspect.

**Weight:** 0.2

**Total Grade:** 1.05

Sources:
Interview: SSPA (04.02.16) & Rickard Bensow (18.02.16)
http://www.shippingencyclopedia.com/term/cavitation-tests

## Model Features

| Name: | Changable appendages | Idea Nr. | 11 |
|---|---|---|---|
| **General Description** | | **Field:** | Hydro |

Different appendages which can be fixed at the hull, i.e. energy saving device (see below), bilge keel etc.

Different energy saving device; pre-swirl stator (PSS) (a device mounted on the the boss designed to make pre-swirl flows which improves propeller efficiency), duct, vortex generator etc. Mainly used to enhance the flow into the propeller to increase propulsion efficiency as well as reduce energy loss.

| **Benefits for the students** | **Grade (max 5):** | 4.5 |
|---|---|---|

The student can design and place the device on the hull and then verify the CFD result. Easy for students to see if the device improve the overall performance. May be too time consuming/ difficult to implement in the courses. Relevant for master thesis.

**Weight:** 0.3

| **Benefits for the research** | **Grade (max 5):** | 5 |
|---|---|---|

Hot topic with energy saving devices. Model to be used for verification of computer results.

**Weight:** 0.2

| **Cost** | **Grade (max 5):** | 5 |
|---|---|---|

Small concept cost (set to zero): one mounting system (energi saving device fixed to a small part of the ship geometry which is installed on the ship model). Operational cost of 15 000 - 80 000. Operational cost could be lowered by using 3D printer at Chalmers.

| C.Cost (SEK): | 0 | O.Cost (SEK): | 80 000 | | **Weight:** | 0.3 |
|---|---|---|---|---|---|---|

| **Technical Aspect** | **Grade (max 5):** | 4 |
|---|---|---|

Easy additonal feature to implement as long as the scale of the model is sufficient large. The appendages can be made by SSPA which using milling as production technique OR by using Chalmers 3D printer. The 3D printer at Chalmers have a print area of 200 x 200 x 200 mm and can handle the folowing material: PLA, ABS, MABS, Nylon, PETT (T-glase), TPE, PC, Laywood, Laybrick, PVA and HIPS.

**Weight:** 0.2

**Total Grade:** 1.1625

Sources:

SSPA research:
http://www.sspa.se/sites/www.sspa.se/files/field_page_files/From_Highlights_no51.pdf

ESD - Duct:
https://www.ihi.co.jp/var/ezwebin_site/storage/original/application/d9ef7ca9ee68bc504d13b6d3fa4a2e0e.pdf

3D printer:
http://www.chalmersrobotics.se/wiki/3D-printer#Features

## Model Features

| Name: | Manouvering Test (MDL) | Idea Nr. | 12 |
|---|---|---|---|
| **General Description** | | **Field:** | Manouvering |

Manouvering test are perfomed for verification of the ships maneuverability. The free running test are carried out in the MDL basin. Manouvering in channel is also availible (to a higher cost).

| **Benefits for the students** | **Grade (max 5):** | 3.5 |
|---|---|---|

Students learn to verify how good a ship is to manouver. Student will not get the opertunity to do the test by themself. Maybe one of the simulators at Chalmers will do the job better.

**Weight:** 0.3

| **Benefits for the research** | **Grade (max 5):** | 3 |
|---|---|---|

Manouverbility in different weather and to find manouvering coefficents to use in i.e. simulators.

**Weight:** 0.2

| **Cost** | **Grade (max 5):** | 5 |
|---|---|---|

No cost (engine & rudder is standard in MDL)

| C.Cost (SEK): | 0 | O.Cost (SEK): | 300 000 | | **Weight:** | 0.3 |
|---|---|---|---|---|---|---|

| **Technical Aspect** | **Grade (max 5):** | 5 |
|---|---|---|

Standard model

**Weight:** 0.2

**Total Grade:** 1.0375

Sources:

Interview with SSPA (04.02.16) & SSPA (19.02.16)

Slides from NTNU about the different test:
http://www.ivt.ntnu.no/imt/courses/tmr7/lecture/ship_model_testing.pdf

## Model Features

| | | | | |
|---|---|---|---|---|
| **Name:** | Seakeeping | | **Idea Nr.** | 13 |
| **General Description** | | | **Field:** | Seakeeping |

Seakeeping in different waves and headings. Seakeeping trials will show how well the ship behaves in various weather and waves. The trials are done in MDL, following parameters can be determined; Roll damping, non-linear motion, slamming and local loads, green water, propeller emergence and added resistance in all wave headings. Added mass is measured by the the power increased needed to maintain a certain speed. However, to be able to measure added resistance the calm water resistance is needed, which only can be obtained in the towing tank. To assess added resistance, two models are needed.

| | | |
|---|---|---|
| **Benefits for the students** | **Grade (max 5):** | 4.5 |

Students learn to verify how the ship performs in various weather. Student will not get the opertunity to do the test by themself (too time consuming). Will get access to a database with result for further analyzing.

**Weight:** 0.3

| | | |
|---|---|---|
| **Benefits for the research** | **Grade (max 5):** | 4.5 |

Paramtric roll. Added resistance in waves is a hot topic.

**Weight:** 0.2

| | | |
|---|---|---|
| **Cost** | **Grade (max 5):** | 5 |

No concept cost (engine & rudder is standard in MDL). One standard test sequence, 500 000 SEK. For educational use, the standard prize is 70 000 SEK per day, but students could get access after closing time (4 PM)

| | | | | | |
|---|---|---|---|---|---|
| C.Cost (SEK): | 0 | O.Cost (SEK): | 500 000 | **Weight:** | 0.3 |

| | | |
|---|---|---|
| **Technical Aspect** | **Grade (max 5):** | 5 |

Standard model, MDL

**Weight:** 0.2

**Total Grade:** 1.1875

Sources:

Interview with SSPA (04.02.16)

http://www.shippingencyclopedia.com/

## Model Features

| | | | | |
|---|---|---|---|---|
| **Name:** | Shallow Water | | **Idea Nr.** | 14 |
| **General Description** | | | **Field:** | Seakeeping |

The shallow water tests are done to investigate the propulsion characteristics of ships as well as the (low speed) manoeuvring behaviour in shallow water. Different tests that can be performed are: Manouvering tests, resistance and self-propulsion, seakeeping with motion measurment, added resistance in waves (self-propelled), wave loads, beaching (with waves), oscillation tests, restrained model in waves to get hydrodyn. coeff., moored and fixed objects to determine motions, forces and loads due to waves.

| | | |
|---|---|---|
| **Benefits for the students** | **Grade (max 5):** | 4.5 |

The students get to see the consequenses of shallow water. Many tests can be performed in this condition. Easy for students to evaluate and see the results. Database could be made from each year (new tests can be run to compliment the existing database).

**Weight:** 0.3

| | | |
|---|---|---|
| **Benefits for the research** | **Grade (max 5):** | 5 |

Used for concept development of new design and how it operates in shallow water.

**Weight:** 0.2

| | | |
|---|---|---|
| **Cost** | **Grade (max 5):** | 3 |

No concept costs, the MDL model can be used directly. High operational cost, the basin needs to be partly drained. 30 000 SEK approx. for draining the basin + normal operational cost for testing.

| | | | | | |
|---|---|---|---|---|---|
| C.Cost (SEK): | 0 | O.Cost (SEK): | 30 000 | **Weight:** | 0.3 |

| | | |
|---|---|---|
| **Technical Aspect** | **Grade (max 5):** | 5 |

Standard model, MDL.

**Weight:** 0.2

**Total Grade:** 1.0625

Sources:

http://www.marin.nl/web/Facilities-Tools/Basins/Shallow-Water-Basin.htm

## Model Features

| Name: | Crane | Idea Nr. | 15 |
|---|---|---|---|
| **General Description** | | **Field:** | Stability |
| A motorised crane to illustrate how the stability is affected by moving weights | | | |
| **Benefits for the students** | | **Grade (max 5):** | 4 |
| Illustrate the challanges by lifting objects at sea. Students can operate the crane by them self. | | | |
| | | **Weight:** | 0.3 |
| **Benefits for the research** | | **Grade (max 5):** | 1 |
| No | | | |
| | | **Weight:** | 0.2 |
| **Cost** | | **Grade (max 5):** | 4 |
| Small concept cost: Engine: 200-500 SEK, Material: 300 SEK, Radio control (?). No operational cost. | | | |
| C.Cost (SEK): 2 000 | O.Cost (SEK): 0 | **Weight:** | 0.3 |
| **Technical Aspect** | | **Grade (max 5):** | 4 |
| Possible to make. | | | |
| | | **Weight:** | 0.2 |
| | | **Total Grade:** | 0.85 |
| Sources: | | | |
| Study visit to DTU/Force (12.02.2016).<br><br>Possible suppliers of parts:<br>http://www.modelshipmaster.com/products/Remote-control-ship-model/Remote-control-cruise-ship-oasis-of-the-seas.htm<br>http://www.harbormodels.com/site08/pumps.htm | | | |

## Model Features

| Name: | VCG elevator | Idea Nr. | 16 |
|---|---|---|---|
| **General Description** | | **Field:** | Stability |
| A rod with a weight that can be moved vertically to change the VCG. | | | |
| **Benefits for the students** | | **Grade (max 5):** | 5 |
| Student can do a limiting KG analyse: find the highest vertical position of CoG before vanishing stability. | | | |
| | | **Weight:** | 0.3 |
| **Benefits for the research** | | **Grade (max 5):** | 1 |
| No | | | |
| | | **Weight:** | 0.2 |
| **Cost** | | **Grade (max 5):** | 4 |
| Small concept cost. No operational cost | | | |
| C.Cost (SEK): 500 | O.Cost (SEK): 0 | **Weight:** | 0.3 |
| **Technical Aspect** | | **Grade (max 5):** | 5 |
| Easy to implement. | | | |
| | | **Weight:** | 0.2 |
| | | **Total Grade:** | 0.975 |
| Sources: | | | |
| Study visit to DTU/Force (12.02.2016) | | | |

## Model Features

| | | | | | |
|---|---|---|---|---|---|
| **Name:** | Floodable Tanks | | | **Idea Nr.** | 17 |
| **General Description** | | | | **Field:** | Stability |
| Hatches which can be removed to simulate flooding of compartment. | | | | | |
| **Benefits for the students** | | | | **Grade (max 5):** | 5 |
| Student can simulate damage stability. | | | | | |
| | | | | **Weight:** | 0.3 |
| **Benefits for the research** | | | | **Grade (max 5):** | 1 |
| No | | | | | |
| | | | | **Weight:** | 0.2 |
| **Cost** | | | | **Grade (max 5):** | 5 |
| Small concept cost. No operational cost | | | | | |
| C.Cost (SEK): | 200 | O.Cost (SEK): | 0 | **Weight:** | 0.3 |
| **Technical Aspect** | | | | **Grade (max 5):** | 5 |
| Easy to implement. Model has to be made of material that withstand a capsize, i.e. glasfiber. | | | | | |
| | | | | **Weight:** | 0.2 |
| | | | | **Total Grade:** | 1.05 |
| Sources: | | | | | |
| Study visit to DTU/Force (12.02.2016) | | | | | |

## Model Features

| | | | | | |
|---|---|---|---|---|---|
| **Name:** | Weight for inclining | | | **Idea Nr.** | 18 |
| **General Description** | | | | **Field:** | Stability |
| Horisontal weights placed on a rod to do inclining test | | | | | |
| **Benefits for the students** | | | | **Grade (max 5):** | 5 |
| Student can easily do a inclining test | | | | | |
| | | | | **Weight:** | 0.3 |
| **Benefits for the research** | | | | **Grade (max 5):** | 1 |
| No | | | | | |
| | | | | **Weight:** | 0.2 |
| **Cost** | | | | **Grade (max 5):** | 4 |
| Small concept cost. No operational cost | | | | | |
| C.Cost (SEK): | 500 | O.Cost (SEK): | 0 | **Weight:** | 0.3 |
| **Technical Aspect** | | | | **Grade (max 5):** | 5 |
| Easy to implement | | | | | |
| | | | | **Weight:** | 0.2 |
| | | | | **Total Grade:** | 0.975 |
| Sources: | | | | | |
| Study visit to DTU/Force (12.02.2016) | | | | | |

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Weight levels | **Idea Nr.** | 19 |
| **General Description** | | **Field:** | Stability |
| Different levels to place weights on to vary the CoG | | | |
| **Benefits for the students** | | **Grade (max 5):** | 4 |
| Student can see the concequences of different CoG. | | | |
| | | **Weight:** | 0.3 |
| **Benefits for the research** | | **Grade (max 5):** | 1 |
| No | | | |
| | | **Weight:** | 0.2 |
| **Cost** | | **Grade (max 5):** | 5 |
| Small concept cost. No operational cost | | | |
| C.Cost (SEK): 200 | O.Cost (SEK): 0 | **Weight:** | 0.3 |
| **Technical Aspect** | | **Grade (max 5):** | 5 |
| Easy to implement | | | |
| | | **Weight:** | 0.2 |
| | | **Total Grade:** | 0.975 |
| Sources: | | | |
| Study visit to DTU/Force (12.02.2016) | | | |

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Plastic Tanks | **Idea Nr.** | 20 |
| **General Description** | | **Field:** | Stability |
| Different plastic tanks which can be fitted inside the hull. The tanks can have different properties, such as floodable (hevert prinsippet), free surface effects, roll damping tank (?) | | | |
| **Benefits for the students** | | **Grade (max 5):** | 5 |
| Student can see the concequences of i.e free surface effects | | | |
| | | **Weight:** | 0.3 |
| **Benefits for the research** | | **Grade (max 5):** | 1 |
| No | | | |
| | | **Weight:** | 0.2 |
| **Cost** | | **Grade (max 5):** | 4 |
| Small concept cost (depends on the amount of tanks). No operational cost | | | |
| C.Cost (SEK): 3 000 | O.Cost (SEK): 0 | **Weight:** | 0.3 |
| **Technical Aspect** | | **Grade (max 5):** | 4 |
| Easy to implement | | | |
| | | **Weight:** | 0.2 |
| | | **Total Grade:** | 0.925 |
| Sources: | | | |
| Study visit to DTU/Force (12.02.2016) | | | |

## Model Features

| | | | | |
|---|---|---|---|---|
| **Name:** | Damage Stability | | **Idea Nr.** | 21 |
| **General Description** | | | **Field:** | Stability |

Damage stability is mainly done to determine the significant wave height that will cause the model to capsize. Apart from test in *irregular* waves with different characteristic, the models equilibrium propeties in calm water are tested for verification. The models roll period are also tested.

| | | |
|---|---|---|
| **Benefits for the students** | **Grade (max 5):** | 3.5 |

The students get can observe how the ship model behavies in damaged condtion. At least in calm water the behaviour can be compared to calculated result

**Weight:** 0.3

| | | |
|---|---|---|
| **Benefits for the research** | **Grade (max 5):** | 5 |

Relevant for research as damage contidion in waves are hard to model with computers.

**Weight:** 0.2

| | | |
|---|---|---|
| **Cost** | **Grade (max 5):** | 1 |

Concept cost for a own damage stability model is approx the same as a MDL model, 200 000 SEK. How much the cost would be for integrating a damage and MDL model is unknown. Shift of cargo (load instead of flooding) could simulate damage stability without free surface effects (0 SEK)

| | | | | | | |
|---|---|---|---|---|---|---|
| C.Cost (SEK): | 200 000 | O.Cost (SEK): | Day Cost | | **Weight:** | 0.3 |

| | | |
|---|---|---|
| **Technical Aspect** | **Grade (max 5):** | 2 |

To simulate the damage stability properly, the model has to have the following features:
1) Adequate strength & stiffnes properties.
2) Min model scale of 1:40. Min length 3m.
3) The model should represent the ship up to the main deck (may also include the superstructure).
4) The floodable compartments should be geometrically simular as the ship. Wall thickness maximum 4mm
5) All appendages should be included
6) The radii of gyrations should correspond to the ship.
It should be possible to combine with a MDL model. The tank has to be removed for seakeeping & manouvering.

**Weight:** 0.2

**Total Grade:** 0.6875

Sources:
Interview with Martin Schreuder (16.02.16), SSPA (19.02.16) and recomendation from ITTC.

## Model Features

| | | | | |
|---|---|---|---|---|
| **Name:** | Changeable propellers | | **Idea Nr.** | 22 |
| **General Description** | | | **Field:** | Propeller |

Change the propeller to see different effect in terms of required trust, torque & RPM. Use in cavitation tunnel to see caviation and errosion. A system can be fitted where different propulsors can be tested.

| | | |
|---|---|---|
| **Benefits for the students** | **Grade (max 5):** | 4 |

Students can design their own propeller and verify the CFD analyse. Probably too complex for the students to implement in the courses. Relevant for master thesis. Student can compare the performance of different stock propellers.

**Weight:** 0.3

| | | |
|---|---|---|
| **Benefits for the research** | **Grade (max 5):** | 4 |

Easy to verify CFD results of propellers in model testing. Much research done. Can develope different types of propellers: flaps on propeller for energy saving.

**Weight:** 0.2

| | | |
|---|---|---|
| **Cost** | **Grade (max 5):** | 4 |

No concept cost. 75 000 to make the propeller + the cost of the test. Free to use different stock propellers (education).

| | | | | | | |
|---|---|---|---|---|---|---|
| C.Cost (SEK): | 0 | O.Cost (SEK): | 75 000 | | **Weight:** | 0.3 |

| | | |
|---|---|---|
| **Technical Aspect** | **Grade (max 5):** | 4 |

No problem to make. Not possible to 3D print because the plastic is to flexible

**Weight:** 0.2

**Total Grade:** 1

Sources:
Interview with Per Hogström (15.02.16) and SSPA (19.02.16).

## Model Features

| | | | | |
|---|---|---|---|---|
| **Name:** | Outdoor Model - Seakeeping | | **Idea Nr.** | 23 |
| **General Description** | | | **Field:** | Seakeeping |

Outdoor model with the following extra features: wave rader or buoy to measure the wave characteristic, acceleration measurments and remote controll. Specific model that can be used both in MDL and outside.

Regarding seakeeping it can be difficult to find a place with large enough waves and still have control of the model. Really difficult to control the environment.

| | | |
|---|---|---|
| **Benefits for the students** | **Grade (max 5):** | 4 |

Student can do seakeeping outdoors. The waves may be too small to give any interesting results outdoor.

| | | |
|---|---|---|
| | **Weight:** | 0.3 |
| **Benefits for the research** | **Grade (max 5):** | 1 |

No research - no control of the environment.

| | | |
|---|---|---|
| | **Weight:** | 0.2 |
| **Cost** | **Grade (max 5):** | 2 |

Need some extra quite expensive features.

| | | | | | |
|---|---|---|---|---|---|
| C.Cost (SEK): | 100 000 | O.Cost (SEK): | 0 | **Weight:** | 0.3 |

| | | |
|---|---|---|
| **Technical Aspect** | **Grade (max 5):** | 2 |

Mini buoy availible (but still proffesional). Probably really expensive. Wave rader in small scale not found. The model has to be equipped with engine, propeller, rudder & remote control. Acceleration measurements no problem. Power supply for a large TT or MDL model could be a problem as this is normally solved with cable through the towing wagon. Could be solved with batteries. A large MDL/TT model will probably be so large that the waves availible outside, would be to small to be able to observe anything of interest. SSPA recommend a small, high speed model for this to be a valid feature.

| | | |
|---|---|---|
| | **Weight:** | 0.2 |
| | **Total Grade:** | 0.6 |

Sources:

Mini Buoy: http://axystechnologies.com/products/triaxys-mini-directional-wave-buoy/

## Model Features

| | | | | |
|---|---|---|---|---|
| **Name:** | Ballast tanks | | **Idea Nr.** | 24 |
| **General Description** | | | **Field:** | Stability |

Equip the model with ballast tanks (maybe cargo tanks) so the student can practice cargo handling. The tanks will be equipped with some sort of pump system.

| | | |
|---|---|---|
| **Benefits for the students** | **Grade (max 5):** | 4 |

The students can practice cargo handling. Mainly for captains. The feature can also be used to illustrate stability. The captains already have a computer simulator which may do the job better.

| | | |
|---|---|---|
| | **Weight:** | 0.3 |
| **Benefits for the research** | **Grade (max 5):** | 1 |

No research

| | | |
|---|---|---|
| | **Weight:** | 0.2 |
| **Cost** | **Grade (max 5):** | 4 |

Some cost for tanks and pump system

| | | | | | |
|---|---|---|---|---|---|
| C.Cost (SEK): | 3 500 | O.Cost (SEK): | 0 | **Weight:** | 0.3 |

| | | |
|---|---|---|
| **Technical Aspect** | **Grade (max 5):** | 4 |

Have to find a supplyer of a small scale pump systems or make it by our self. A hand pump may be sufficient. A system with pipes and valves could quite esily be made (with 1-2 cm plastic or copper pipes). A plexiglass window can be made to indicate the liquid level. Tanks has to be made in glasfiber.

| | | |
|---|---|---|
| | **Weight:** | 0.2 |
| | **Total Grade:** | 0.85 |

Sources:

Interview with Olle Lindmark (16.02.2016)

Supplier of pump: http://www.harbormodels.com/site08/pumps.htm
Supplier of valves: http://cnlvke.en.alibaba.com/product/1513733064-218365409/pvc_white1inch_water_valve_small_water_valve.html

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Wave pattern | **Idea Nr.** | 25 |
| **General Description** | | **Field:** | Hydro |
| The wave pattern shows the disturbance of the water around the hull due to the ships motion. Two types of waves are created; divergent ('backward') and transverse waves. The wave pattern can be seen when running the model in waves, could be difficult to model accurately. | | | |
| **Benefits for the students** | | **Grade (max 5):** | 4 |
| Study wave pattern and added resistance when the model is operating in waves. See the difference in wave pattern at various speeds and displacements. | | | |
| | | **Weight:** | 0.3 |
| **Benefits for the research** | | **Grade (max 5):** | 2.5 |
| Complex to get accurate results. Interesting to verify CFD results. | | | |
| | | **Weight:** | 0.2 |
| **Cost** | | **Grade (max 5):** | 5 |
| No additional concept cost. 3000 SEK for video | | | |
| C.Cost (SEK): 0 | O.Cost (SEK): 3 000 | **Weight:** | 0.3 |
| **Technical Aspect** | | **Grade (max 5):** | 5 |
| No additional features for the model. | | | |
| | | **Weight:** | 0.2 |
| | | **Total Grade:** | 1.05 |
| Sources: | | | |
| http://www.steelnavy.com/WavePatterns.htm | | | |

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Intact Stability | **Idea Nr.** | 26 |
| **General Description** | | **Field:** | Stability |
| Intact stability test are normally carried out to investigate the ships behaviour in extreme condtions (capsizing). This include phenomens as:<br>- Pure loss of stability, typically on a wave crest<br>- Paramtric rolling<br>- Cargo shift or other heeling moments<br>- Broaching<br>- etc | | | |
| **Benefits for the students** | | **Grade (max 5):** | 4.5 |
| Interesting for students to see these phenomens, which can be quite difficult to grasp theoretically. | | | |
| | | **Weight:** | 0.3 |
| **Benefits for the research** | | **Grade (max 5):** | 5 |
| All these phenomens are interesting in terms of research | | | |
| | | **Weight:** | 0.2 |
| **Cost** | | **Grade (max 5):** | 4 |
| Thin Hull needed for TT model. The model need to be water proof (floodable). And an sufficient freeboard is necessary. | | | |
| C.Cost (SEK): 30 000 | O.Cost (SEK): Day Cost | **Weight:** | 0.3 |
| **Technical Aspect** | | **Grade (max 5):** | 4 |
| The CoG and the radii of gyration has to represent the ship. The model has to be completed up to the weatherdeck (depends a bit on ship type). Appendeges should be installed. | | | |
| | | **Weight:** | 0.2 |
| | | **Total Grade:** | 1.0875 |
| Sources: | | | |
| ITTC procedure. Interview with Martin Schreuder (16.02.16). | | | |

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Uncertainty Analyse | **Idea Nr.** | 27 |
| **General Description** | | **Field:** | General |

Students make an uncertainty analyse (check if their estimate corresponds to the result). This is normally done for all tests. This can be done on a backbone model used for resistance (the student can estimate the effect of the gaps).

| | | |
|---|---|---|
| **Benefits for the students** | **Grade (max 5):** | 4 |

Student can estimate the expected magnitude of the errors that will occur in the model test, caused by i.e the gaps on the backbone model.

**Weight:** 0.3

| | | |
|---|---|---|
| **Benefits for the research** | **Grade (max 5):** | 1 |

Normally always done before a test. Beneficial to have an idea about the accuracy of the results.

**Weight:** 0.2

| | | |
|---|---|---|
| **Cost** | **Grade (max 5):** | 5 |

No additional cost.

| | | | | | |
|---|---|---|---|---|---|
| C.Cost (SEK): | 0 | O.Cost (SEK): | 0 | **Weight:** | 0.3 |

| | | |
|---|---|---|
| **Technical Aspect** | **Grade (max 5):** | 5 |

No technical aspect.

**Weight:** 0.2

**Total Grade:** 0.975

Sources:

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Changabele rudder | **Idea Nr.** | 28 |
| **General Description** | | **Field:** | Manouvering |

The rudder can be changed to investigate the effects on manouvering. Both by optimizing the rudder for the particular ship and to try different types of rudder (Spade, semi-spade, balanced rudder, rudder bulb).

| | | |
|---|---|---|
| **Benefits for the students** | **Grade (max 5):** | 4 |

It interesting for the students to see the effect of different rudder types and designs on manouvering.

**Weight:** 0.3

| | | |
|---|---|---|
| **Benefits for the research** | **Grade (max 5):** | 3.5 |

New rudder types.

**Weight:** 0.2

| | | |
|---|---|---|
| **Cost** | **Grade (max 5):** | 4 |

Pretty cheap as it is easy to change and fairly easy to manufacture

| | | | | | |
|---|---|---|---|---|---|
| C.Cost (SEK): | 20 000 | O.Cost (SEK): | Day Cost | **Weight:** | 0.3 |

| | | |
|---|---|---|
| **Technical Aspect** | **Grade (max 5):** | 4 |

Easy to change rudders

**Weight:** 0.2

**Total Grade:** 0.975

Sources:

## Model Features

| Name: | Seakeeping in TT | Idea Nr. | 29 |
|---|---|---|---|
| **General Description** | | **Field:** | Hydro |

Some seakeeping tests can be done in the TT using headwaves and following waves, such as added resistance and measuring of the different accelerations. See feature #13.

| **Benefits for the students** | **Grade (max 5):** | 4 |
|---|---|---|

If a resistance model is chosen, the students will still be able to see and get results from some seakeeping tests. The students can see how waves affect the resistance and how the ship behaves in head- and following waves.

**Weight:** 0.3

| **Benefits for the research** | **Grade (max 5):** | 3.5 |
|---|---|---|

Same research as for seakeeping (#13), limited to head- and following waves.

**Weight:** 0.2

| **Cost** | **Grade (max 5):** | 5 |
|---|---|---|

No additional concept cost.

| C.Cost (SEK): | NaN | O.Cost (SEK): | Day Cost | **Weight:** | 0.3 |
|---|---|---|---|---|---|

| **Technical Aspect** | **Grade (max 5):** | 5 |
|---|---|---|

The wave heights are small in the TT, need a small enough model so the waves give reasonable results. Thin hull (#9) needed. Easy to measure added resistance.

**Weight:** 0.2

**Total Grade:** 1.1

Sources:

## Model Features

| Name: | Spontoons | Idea Nr. | 30 |
|---|---|---|---|
| **General Description** | | **Field:** | Stability |

A device which gives extra bouyancy and/or stability. The spontoons can be placed around the ship to see how they influence the stability.

| **Benefits for the students** | **Grade (max 5):** | 4 |
|---|---|---|

Students can easily see how a change in the geometry at the WL affect the stability performance of the ship.

**Weight:** 0.3

| **Benefits for the research** | **Grade (max 5):** | 1 |
|---|---|---|

No

**Weight:** 0.2

| **Cost** | **Grade (max 5):** | 4 |
|---|---|---|

Low concept cost. The spontoons will be made in the same material as the hull and do represent only a small concept cost.

| C.Cost (SEK): | 1 000 | O.Cost (SEK): | 0 | **Weight:** | 0.3 |
|---|---|---|---|---|---|

| **Technical Aspect** | **Grade (max 5):** | 5 |
|---|---|---|

Quite easy to implement.

**Weight:** 0.2

**Total Grade:** 0.9

Sources:

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Stability Basin | **Idea Nr.** | 31 |
| **General Description** | | **Field:** | Stability |
| Own basin for small stability model placed at Lindholmen. | | | |
| **Benefits for the students** | | **Grade (max 5):** | 5 |
| Student can do their own stability test and observe the result directly. | | | |
| | | **Weight:** | 0.3 |
| **Benefits for the research** | | **Grade (max 5):** | 1 |
| No benefits | | | |
| | | **Weight:** | 0.2 |
| **Cost** | | **Grade (max 5):** | 3 |
| 18 m HUP 100x100x5 : 6750 SEK, 12 m L 50x50x5: 905 SEK, PL 8 mm: 200 SEK, Pleksiglass 6m^2: 2628 SEK, Other stuff (bolts,nuts,etc): 1000 SEK. | | | |
| C.Cost (SEK): 11 500 | O.Cost (SEK): 0 | **Weight:** | 0.3 |
| **Technical Aspect** | | **Grade (max 5):** | 4 |
| Easy to make. Total weight: 414 kg, with water: 2400 + 414 = 2814 kg. 2x3 meter w/ total height of 1.5 meters. | | | |
| | | **Weight:** | 0.2 |
| | | **Total Grade:** | 0.85 |
| Sources: | | | |

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Captive Test | **Idea Nr.** | 32 |
| **General Description** | | **Field:** | Manouvering |
| Captive test is done to obtain the manouvering coefficients. The model is subjected to forced motions and the applied forces are measured. This is done in the TT basin at SSPA. | | | |
| **Benefits for the students** | | **Grade (max 5):** | 4 |
| The students can derive the manouvering coefficients and use them in manouvering equations. | | | |
| | | **Weight:** | 0.3 |
| **Benefits for the research** | | **Grade (max 5):** | 4 |
| The manouvering coefficients can be used in ship simulators. | | | |
| | | **Weight:** | 0.2 |
| **Cost** | | **Grade (max 5):** | 5 |
| Quite costfull to execute all the manouvering tests. No additional concept cost | | | |
| C.Cost (SEK): 0 | O.Cost (SEK): 300 000 | **Weight:** | 0.3 |
| **Technical Aspect** | | **Grade (max 5):** | 4.5 |
| Bilge keel (if the ship has one) has to be included. The hull of the model has to be thin to be able to a propper weight distribution - so eiter feature #9 Thin hull or a standard MDL model. | | | |
| | | **Weight:** | 0.2 |
| | | **Total Grade:** | 1.1 |
| Sources: | | | |
| PPT NTNU: *Ship model testing.* SSPA meeting (19.02.16) | | | |

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Roll decay | **Idea Nr.** | 33 |
| **General Description** | | **Field:** | Seakeeping |

Roll damping is found by heeling the model and measuring the amplitudes of roll damping. Could only be done with zero speed in TT.

| | | |
|---|---|---|
| **Benefits for the students** | **Grade (max 5):** | 4.5 |

Relatively easy for the students to obeserve. Student could probably execute the tests by themself. The stability of the ship and ships ability to righten are measured.

**Weight:** 0.3

| | | |
|---|---|---|
| **Benefits for the research** | **Grade (max 5):** | 3 |

Test different appendages that increase/ decrease the roll period of the model.

**Weight:** 0.2

| | | |
|---|---|---|
| **Cost** | **Grade (max 5):** | 5 |

A thinner hull is needed, which will have some concept cost (accounted for under Thin hull).

| | | | | | |
|---|---|---|---|---|---|
| C.Cost (SEK): | NaN | O.Cost (SEK): | Day Cost | **Weight:** | 0.3 |

| | | |
|---|---|---|
| **Technical Aspect** | **Grade (max 5):** | 5 |

.

**Weight:** 0.2

**Total Grade:** 1.1125

Sources:
Interview: SSPA (04.02.16) & Martin Schreuder (16.02.16)

## Model Features

| | | | |
|---|---|---|---|
| **Name:** | Parametric roll | **Idea Nr.** | 34 |
| **General Description** | | **Field:** | Seakeeping |

Rolling of ship cause by head or following waves. Ship has large flares, flat aftership, slim fore and aft body, i.e. large container ship. Its difficult to simulate parametric roll. SSPA have no experience with it. The MDL basin is too short to do parametric roll. Both it can be done at zero speed by mooring the model with soft springs. The towing tank could probably also be used.

| | | |
|---|---|---|
| **Benefits for the students** | **Grade (max 5):** | 4 |

Interesting phenomen for some kind of ships. See how the impact of different types of waves on the ships performance.

**Weight:** 0.3

| | | |
|---|---|---|
| **Benefits for the research** | **Grade (max 5):** | 5 |

Hot topic. Interesting to investigate at what state parametric roll happens for the model and methods to prevent it.

**Weight:** 0.2

| | | |
|---|---|---|
| **Cost** | **Grade (max 5):** | 5 |

The hull has to be made thinner to be able to do the weight distribution properly (#9 Thin hull or MDL)

| | | | | | |
|---|---|---|---|---|---|
| C.Cost (SEK): | NaN | O.Cost (SEK): | Day Cost | **Weight:** | 0.3 |

| | | |
|---|---|---|
| **Technical Aspect** | **Grade (max 5):** | 3 |

Very difficult to trigger parametric roll. SSPA had no experience with it. Very time consuming and requiers a long wave history. SSPA recommend to use model results from seakeeping trials in a CFD program to illustrate parametric roll.

**Weight:** 0.2

**Total Grade:** 1.075

Sources:
Interview: SSPA (04.02.16) & Martin Schreuder (16.02.16). Soft springs: https://www.youtube.com/watch?v=ewqaRMGv2mE. Model test on intact stability (ITTC, 2008).

## Model Features

| | | | | | |
|---|---|---|---|---|---|
| **Name:** | Roll damping devices | | | **Idea Nr.** | 35 |
| **General Description** | | | | **Field:** | Seakeeping |
| The model could be equiped with different roll damping devices, as bilge keels, roll damping tanks (both passive and active), finns, | | | | | |
| **Benefits for the students** | | | | **Grade (max 5):** | 4 |
| Investigate roll damping devices effect on roll period (and seakeeping in general). | | | | | |
| | | | | **Weight:** | 0.3 |
| **Benefits for the research** | | | | **Grade (max 5):** | 4 |
| The effect of roll damping devices could be investigated. | | | | | |
| | | | | **Weight:** | 0.2 |
| **Cost** | | | | **Grade (max 5):** | 2.5 |
| Depends on what roll damping system that is chosen, a passive system, i.e. bilge keel or roll damping tanks would be fairly cheap. A active system would be considarble more expensive. No cost assesment is done because the cost varies too much between the systems. | | | | | |
| C.Cost (SEK): | NaN | O.Cost (SEK): | Day Cost | **Weight:** | 0.3 |
| **Technical Aspect** | | | | **Grade (max 5):** | 3 |
| The active system would relativly difficult to implement. The passive system, on the other hand, is achiveable. | | | | | |
| | | | | **Weight:** | 0.2 |
| | | | | **Total Grade:** | 0.8375 |
| Sources: | | | | | |

## Model Features

| | | | | | |
|---|---|---|---|---|---|
| **Name:** | Outdoor model - Manouvering | | | **Idea Nr.** | 36 |
| **General Description** | | | | **Field:** | Manouvering |
| The idea is the same as for feature #21, but the model should only be used for manouvering. | | | | | |
| **Benefits for the students** | | | | **Grade (max 5):** | 4 |
| Student can do free running manouvering test by them self. Great learning and fun for students controlling the boat | | | | | |
| | | | | **Weight:** | 0.3 |
| **Benefits for the research** | | | | **Grade (max 5):** | 2 |
| Limited research. Maybe manouvering in a environment with waves and wind. But impossible to control the environment | | | | | |
| | | | | **Weight:** | 0.2 |
| **Cost** | | | | **Grade (max 5):** | 3 |
| The model would need a battery pack and remote control in addition. | | | | | |
| C.Cost (SEK): | NaN | O.Cost (SEK): | 0 | **Weight:** | 0.3 |
| **Technical Aspect** | | | | **Grade (max 5):** | 4 |
| Possible to make. The challange would be to fit a sufficiently large batteri pack inside the model. | | | | | |
| | | | | **Weight:** | 0.2 |
| | | | | **Total Grade:** | 0.825 |
| Sources: | | | | | |

# Model Features

| | | | | |
|---|---|---|---|---|
| **Name:** | Wind tunnel | | **Idea Nr.** | 37 |
| **General Description** | | | **Field:** | Resistance |
| The stability model could be used in Chalmers windtunnel to investigate the flow around the ship. | | | | |
| **Benefits for the students** | | | **Grade (max 5):** | 4 |
| Student can use the model to study the flow around the hull. The flow characteristic is easier to see than in a water tank. | | | | |
| | | | **Weight:** | 0.3 |
| **Benefits for the research** | | | **Grade (max 5):** | 4 |
| Interesting in terms of flow visualization and boundary layer (as the Reynolds number would be larger). | | | | |
| | | | **Weight:** | 0.2 |
| **Cost** | | | **Grade (max 5):** | 4 |
| Increased cost for surface finish. Lower operational cost as its Chalmers own tunnel. | | | | |
| C.Cost (SEK): 10 000 | O.Cost (SEK): 0 | | **Weight:** | 0.3 |
| **Technical Aspect** | | | **Grade (max 5):** | 4 |
| Chalmers windtunnel is a closed circuit tunnel with test dimensions 3.0 x 1.8 x 1.25 [m] and a speed range of 0-60 m/s. It is equipped with balances force measurements, hot wire anemometry for flow studies, optical measurments equipment and advanced pressure measurment equipment. The surface finish of the stability model has to of higher quality than the ordinary model. Wind tunnel has advantages like a the opertunities to operate at a higher Reynolds number giving more accurate result and are also less time consuming than towing tests. | | | | |
| | | | **Weight:** | 0.2 |
| | | | **Total Grade:** | 1 |

Sources:

Wind tunnel Chalmers:
https://www.chalmers.se/SiteCollectionDocuments/Tillämpad%20mekanik/Forskning/Forskningsresurser/Chalmers%27%20Wind%20tunnels.pdf

Info from Force:
http://forcetechnology.com/en/maritime-industry/cargo-vessels/aerodynamic-test

# C Decision matrix 2

| Concept | 1 | | Features | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ship Nr | Ship Type | | 1 | 3 | 5 | 7 | 12 | 13 | 21 | 24 | 25 | 26 | 34 | 35 | SUM |
| 1 | ULCV | 1 | 0,16 | 0,36 | 0,07 | 0,00 | 0,28 | 0,32 | 0,00 | 0,00 | 0,07 | 0,30 | 0,30 | 0,56 | 1,16 |
| 2 | Container Feeder | 2 | 0,57 | 0,00 | 0,61 | 0,06 | 0,00 | 0,17 | 0,00 | 0,00 | 0,55 | 0,00 | 0,00 | 0,00 | 1,80 |
| 3 | Liquid Cargo Carrier | 3 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,64 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 4 | Ro-Ro | 4 | 0,07 | 0,00 | 0,17 | 0,28 | 0,54 | 0,62 | 0,42 | 0,00 | 0,15 | 0,66 | 0,58 | 0,29 | 1,54 |
| 5 | Ferry | 5 | 0,00 | 0,00 | 0,32 | 0,54 | 0,15 | 0,00 | 0,19 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,86 |
| 6 | Fishing Vessel | 6 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,07 | 0,00 | 0,00 | 0,28 | 0,00 | 0,07 | 0,00 | 0,35 |
| 7 | Navy Vessel | 7 | 0,00 | 0,04 | 0,00 | 0,00 | 0,06 | 0,00 | 0,08 | 0,00 | 0,00 | 0,00 | 0,00 | 0,07 | 0,07 |
| 8 | DTC | 8 | 0,30 | 0,10 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,16 | 0,45 |
| 9 | KVLCC | 9 | 0,00 | 0,19 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,21 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 10 | KCS | 10 | 0,00 | 0,00 | 0,00 | 0,15 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,12 | 0,16 | 0,00 | 0,31 |

| Concept | 2 | | Features | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ship Nr | Ship Type | | 1 | | 5 | 7 | 12 | 13 | 21 | 24 | 25 | 26 | 34 | 35 | SUM |
| 1 | ULCV | 1 | 0,16 | 0,36 | 0,07 | 0,00 | 0,28 | 0,32 | 0,00 | 0,00 | 0,07 | 0,30 | 0,30 | 0,56 | 1,99 |
| 2 | Container Feeder | 2 | 0,57 | 0,00 | 0,61 | 0,06 | 0,00 | 0,17 | 0,00 | 0,00 | 0,55 | 0,00 | 0,00 | 0,00 | 1,29 |
| 3 | Liquid Cargo Carrier | 3 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,64 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 4 | Ro-Ro | 4 | 0,07 | 0,00 | 0,17 | 0,28 | 0,54 | 0,62 | 0,42 | 0,00 | 0,15 | 0,66 | 0,58 | 0,29 | 3,34 |
| 5 | Ferry | 5 | 0,00 | 0,00 | 0,32 | 0,54 | 0,15 | 0,00 | 0,19 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,34 |
| 6 | Fishing Vessel | 6 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,07 | 0,00 | 0,00 | 0,28 | 0,00 | 0,07 | 0,00 | 0,43 |
| 7 | Navy Vessel | 7 | 0,00 | 0,04 | 0,00 | 0,00 | 0,06 | 0,00 | 0,08 | 0,00 | 0,00 | 0,00 | 0,00 | 0,07 | 0,21 |
| 8 | DTC | 8 | 0,30 | 0,10 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,16 | 0,45 |
| 9 | KVLCC | 9 | 0,00 | 0,19 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,21 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 10 | KCS | 10 | 0,00 | 0,00 | 0,00 | 0,15 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,12 | 0,16 | 0,00 | 0,28 |

| Concept | 3 | | Features | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ship Nr | Ship Type | | 1 | 3 | 5 | 7 | 12 | 13 | 21 | 24 | 25 | 26 | 34 | 35 | SUM |
| 1 | ULCV | 1 | 0,16 | 0,36 | 0,07 | 0,00 | 0,28 | 0,32 | 0,00 | 0,00 | 0,07 | 0,30 | 0,30 | 0,56 | 0,00 |
| 2 | Container Feeder | 2 | 0,57 | 0,00 | 0,61 | 0,06 | 0,00 | 0,17 | 0,00 | 0,00 | 0,55 | 0,00 | 0,00 | 0,00 | 0,00 |
| 3 | Liquid Cargo Carrier | 3 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,64 | 0,00 | 0,00 | 0,00 | 0,00 | 0,64 |
| 4 | Ro-Ro | 4 | 0,07 | 0,00 | 0,17 | 0,28 | 0,54 | 0,62 | 0,42 | 0,00 | 0,15 | 0,66 | 0,58 | 0,29 | 0,00 |
| 5 | Ferry | 5 | 0,00 | 0,00 | 0,32 | 0,54 | 0,15 | 0,00 | 0,19 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 6 | Fishing Vessel | 6 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,07 | 0,00 | 0,00 | 0,28 | 0,00 | 0,07 | 0,00 | 0,00 |
| 7 | Navy Vessel | 7 | 0,00 | 0,04 | 0,00 | 0,00 | 0,06 | 0,00 | 0,08 | 0,00 | 0,00 | 0,00 | 0,00 | 0,07 | 0,00 |
| 8 | DTC | 8 | 0,30 | 0,10 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,16 | 0,00 |
| 9 | KVLCC | 9 | 0,00 | 0,19 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,21 | 0,00 | 0,00 | 0,00 | 0,00 | 0,21 |
| 10 | KCS | 10 | 0,00 | 0,00 | 0,00 | 0,15 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,12 | 0,16 | 0,00 | 0,00 |

| Concept | 4 | | Features | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ship Nr | Ship Type | | 1 | 3 | 5 | 7 | 12 | 13 | 21 | 24 | 25 | 26 | 34 | 35 | SUM |
| 1 | ULCV | 1 | 0,16 | 0,36 | 0,07 | 0,00 | 0,28 | 0,32 | 0,00 | 0,00 | 0,07 | 0,30 | 0,30 | 0,56 | 0,36 |
| 2 | Container Feeder | 2 | 0,57 | 0,00 | 0,61 | 0,06 | 0,00 | 0,17 | 0,00 | 0,00 | 0,55 | 0,00 | 0,00 | 0,00 | 0,00 |
| 3 | Liquid Cargo Carrier | 3 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,64 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 4 | Ro-Ro | 4 | 0,07 | 0,00 | 0,17 | 0,28 | 0,54 | 0,62 | 0,42 | 0,00 | 0,15 | 0,66 | 0,58 | 0,29 | 0,00 |
| 5 | Ferry | 5 | 0,00 | 0,00 | 0,32 | 0,54 | 0,15 | 0,00 | 0,19 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| 6 | Fishing Vessel | 6 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,07 | 0,00 | 0,00 | 0,28 | 0,00 | 0,07 | 0,00 | 0,00 |
| 7 | Navy Vessel | 7 | 0,00 | 0,04 | 0,00 | 0,00 | 0,06 | 0,00 | 0,08 | 0,00 | 0,00 | 0,00 | 0,00 | 0,07 | 0,04 |
| 8 | DTC | 8 | 0,30 | 0,10 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,16 | 0,10 |
| 9 | KVLCC | 9 | 0,00 | 0,19 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,21 | 0,00 | 0,00 | 0,00 | 0,00 | 0,19 |
| 10 | KCS | 10 | 0,00 | 0,00 | 0,00 | 0,15 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,12 | 0,16 | 0,00 | 0,00 |

| Ship Type | | | | | |
|---|---|---|---|---|---|
| **Name:** | ULCV | | | **Ship Nr.** | 1 |

**General Description**

Ultra Large Container Vessel. 10-18 000 TEU. Large ships have a larger natural periods in bending and torsion, they generally go faster --> more high-frequency wave loads, larger bow flares --> more nonlinear wave loads. It is generally limited experience with large containerships.


**Features**

**Large bow flare** (larger than 40 deg are challenging), **small B/L ratio**, relatively **fast** going (25 knots), **flat bottom** (spec. twin scre) which results in aft slamming. This phenomen creates an increased sagging moment. Important to define the hull girder loads. The ship is very **flexible** due to the lengt of it, this may lead to **vibrations** --> whipping and springing. Bulb.

**Main Dimensions (Typical)**

| L [m] | B [m] | T [m] | Disp. [t] | Fn | Cb |
|---|---|---|---|---|---|
| 360 | 49 | 15,5 | - | ~ 0.22 | - |

**Sources**

ULCV:http://commons.wmu.se/cgi/viewcontent.cgi?article=1279&context=all_dissertations
Merchant ship: http://www.marin.nl/web/ShipsStructures/Merchant-vessels-Work-boats.htm

| Ship Type | | | | | |
|---|---|---|---|---|---|
| **Name:** | Container Feeder | | | **Ship Nr.** | 2 |

**General Description**

Container feeder used for short distances. Specialized in the transport of containers from small ports to feeder ports and the other way around. Small or medium sized ships, starting at 200 TEU.


**Features**

Small sized vessel, relatively high speed: 18 knots. Rich body (Ref. Poul Andersen), relatively high Fr. Commonly has a bulb. A research vessel with approxmately the same dimensions called Hamburg Test Case (HTC) already exist.

**Main Dimensions (Typical)**

| L [m] | B [m] | T [m] | Disp. [t] | Fn | Cb |
|---|---|---|---|---|---|
| 150 | 21,8 | 7,2 | - | 0,24 | ~0.65 |

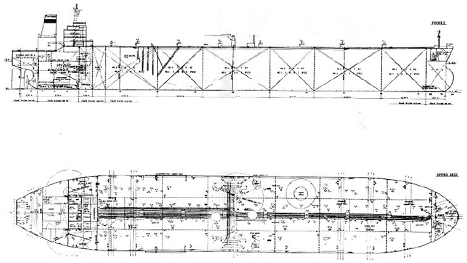
Ship Knowledge, Klas Van Dokkum, 5th edition 2008.
Source: http://products.damen.com/en/ranges/container-feeder

# Ship Type

| Name: | Liquid Cargo Carrier | Ship Nr. | 3 |
|---|---|---|---|

**General Description**

A merchant vessel built to carry liquid cargo, from the oil field to the rafinery.



**Features**

High block coefficient, slow going, stable. Usually single screw. Important to avoid separations in the stern. Large holds.

**Main Dimensions (Typical)**

| L [m] | B [m] | T [m] | Disp. [t] | Fn | Cb |
|---|---|---|---|---|---|
| 245 | 34 | 20 | 80 000 | ~0,15 | - |

**Sources**

Ship Knowledge, Klas Van Dokkum, 5th edition 2008.
Lars Larsson, Ship Resistance and Flow, 2010.

# Ship Type

| Name: | Ro-Ro | Ship Nr. | 4 |
|---|---|---|---|

**General Description**

Ro-ro: Wide term for a vessel designed to carry cargo that can roll on/ off by it self. Many different categories and sizes, ro-ro is the general description. RoPax, ConRo, RoLo, PCTC, PCC in example.



**Features**

Large open car decks (exposed for flooding). Exaggerated bow flare (to provide form stability) and distinct transom stern (parametric rolling). Slender underwater body and high VCG. Ship is optimized for low resistance and maximum cargo capacity, bad manouverability.

**Main Dimensions (approx.)**

| L [m] | B [m] | T [m] | Disp. [t] | Fn | Cb |
|---|---|---|---|---|---|
| 200 | 32,2 | 9,5 - 11 | - | 0,18 - 0,24 | - |

**Sources**

Ship Knowledge, Klas Van Dokkum, 5th edition 2008.

## Ship Type

| Name: | Ferry | Ship Nr. | 5 |
|---|---|---|---|

**General Description**

Perform well over a wide range of speeds and conditions, and have good manouvering and seakeeping capabilities. Relatively wide term, all from RoPax ferries to small river ferries.

**Features**

Centre of Buoyance relatively far aft (approx. 3.5%-5 %). Goose neck bulbs are usually used. Straight water lines. Mostly twin-screw arrangement, and flat stern. Propeller is placed in front of the pod in order to minimize noise and vibrations. High speed vessel, supported by the dynamic lift from the high pressure bottom. Some deadrise required from a seakeeping point of view.

**Main Dimensions (Typical)**

| L [m] | B [m] | T [m] | Disp. [t] | Fn | Cb |
|---|---|---|---|---|---|
| - | - | - | - | ~0.25 | 0.6 - 0.65 |

**Sources**

Lars Larsson, *Ship Resistance and Flow,* 2010.

## Ship Type

| Name: | Fishing Vessel | Ship Nr. | 6 |
|---|---|---|---|

**General Description**

The purpose of the vessel is to locate, catch and perserve fish while at sea. The vessels are design, constructed and equiped based on area of use. Many different designs.

**Features**

Stable, relatively fast going. Wave resistance is the largest component. Blunt hull. Needs large refrigerated volumes for fish holds (stability). High engine power for trawlers.

**Main Dimensions (Typical)**

| L [m] | B [m] | T [m] | Disp. [t] | Fn | Cb |
|---|---|---|---|---|---|
| 23 | 7 | 2,5 | - | 0,3 | - |

**Sources**

Ship Knowledge, Klas Van Dokkum, 5th edition 2008.

# Ship Type

| Name: | Navy Vessel | Ship Nr. | 7 |
|---|---|---|---|

**General Description**

Navy vessels include; Aircraft carriers, Cruisers, Destroyers, Frigates and Corvettes. Frigates are considered here. Vessel used for defence.


**Features**

Fast going and stable. High demand of controllability, i.e. the steering ability and ship & platform motions. Workability, loads and operation in extreme weather are important. Interesting to inverstigate damaged) stability aspects. Fast stop.

**Main Dimensions (Typical)**

| L [m] | B [m] | T [m] | Disp. [t] | Fn | Cb |
|---|---|---|---|---|---|
| 130 | 16,1 | 7,3 | 4 900 | 0.4 - 0.5 | |

**Sources**

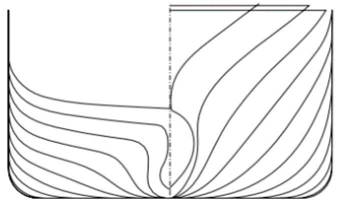
Ship Knowledge, Klas Van Dokkum, 5th edition 2008.

# Ship Type

| Name: | DTC | Ship Nr. | 8 |
|---|---|---|---|

**General Description**

Duisburg Test Case (DTC) is a hull design of a typical 14 000 TEU container ship (post-panamax) , developed by Ship Technology, Ocean Engineering and Transport Systems (ISMT).



**Features**

Bulbous bow, large bow flare, large stern overhang and a transom.

**Main Dimensions (Typical)**

| L [m] | B [m] | T [m] | Disp. [t] | Fn | Cb |
|---|---|---|---|---|---|
| 355 | 51 | 14,5 | 173 467 | 0,218 | 0,661 |

**Sources**

http://www.simman2008.dk/KVLCC/KVLCC2/tanker2.html

## Ship Type

| **Name:** | KVLCC | **Ship Nr.** | 9 |
|---|---|---|---|

**General Description**

Very large crude carrier made by Korea Research Institute of Ships and Ocean Engineering - KRISO.

**Features**

KVLCC 1: V-shaped stern
KVLCC 2: U-shaped stern

Tanker with bulb bow and stern. Two stern variants were designed: KVLCC1 has barge type stern frame-lines with a fine stern end bulb i.e. relatively V-shaped frame-lines, while KVLCC2 has more U-shaped stern frame-lines.

**Main Dimensions (Typical)**

| L [m] | B [m] | T [m] | Disp. [t] | Fn | Cb |
|---|---|---|---|---|---|
| 320 | 58 | 20,8 | 312 622 | 0,142 | 0,8 |

**Sources**

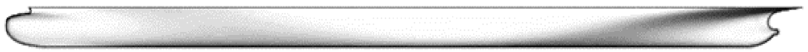
http://www.simman2008.dk/KVLCC/KVLCC2/tanker2.html

## Ship Type

| **Name:** | KCS | **Ship Nr.** | 10 |
|---|---|---|---|

**General Description**

Modern containership with bulb bow made by Korea Research Institute of Ships and Ocean Engineering - KRISO.



**Features**

Large bulb, slender stern and relatively short midsection.

**Main Dimensions (Typical)**

| L [m] | B [m] | T [m] | Disp. [t] | Fn | Cb |
|---|---|---|---|---|---|
| 230 | 32,2 | 10,8 | 52 030 | 0,26 | 0,651 |

**Sources**

http://www.simman2008.dk/KCS/container.html

## Ship Feature

| | | | |
|---|---|---|---|
| **Name:** | Changable ship geometry | **Feature Nr.** | 1 |
| **General Description** | | **Feature grade:** | 1,10 |

The idea is to make the model so that some parts of the hull can be changed, i.e. change the aft or fore of the ship, or local changes as the bulb. The ship model can then be optimzed in terms of resistance and flow (bulb & shoulders --> wave pattern, stern --> wake, etc. ), seakeeping (changable foreship --> slamming, changable midship --> change ship length, etc) and manouvering (Length, draft, LCB*).

According to Carl-Erik Janson (mail: 8.mars):

"Local geometrical modifications like changing the bulb are not so important for seakeeping. It is the main dimensions and in particular the shape of the water plane area, global volume distribution and mass moment of inertia that are of importance."

**Ship Properties**

The ship should have:
- High Froude nr., more resistance components, easier to optimize
- Bulb (easy and relatively cheap to optimize), dependent on Cb, L/B and B/T. Will reduce the wake, quasi-prop. coeff and the thrust deduction
- Ship who travels long distances at relatively constant speed.
- Bulb: Seakeeping, mitigates the pitching motion - damping. Disadvantage over Bauford 8. No effect on manouvering

**Ship Types**

| Range | Weight | Ship Nr. | Ship Type | Grade |
|---|---|---|---|---|
| 1 | **0,52** | 2 | Container Feeder | **0,57** |
| 2 | **0,27** | 8 | DTC | **0,30** |
| 3 | **0,15** | 1 | ULCV | **0,16** |
| 4 | **0,06** | 4 | Ro-Ro | **0,07** |

**Sources:**

## Ship Feature

| | | | |
|---|---|---|---|
| **Name:** | Structural Response | **Feature Nr.** | 3 |
| **General Description** | | **Feature grade:** | 0,69 |

The model is segmented and equiped with a backbone. The model can then be used to find bending moment, shear stresses, whipping - and springing, etc. caused by waves. The model can probably be used in normal seakeeping trails as welll. Normally a seakeeping model is rigid, but a flexible model with the correct stiffnes should yield a more realistic result. Manouvering could be a bit more cumbersome as a the backbone will be subjected to a horisontal bending moment (when turning the rudder). Then the backbone needs to have a correct horisontal stiffnes (which they do not always have).

**Ship Properties**

Springing is due to waves with the natural frequency of the ship. Whipping is a result of slamming. Slamming occours at ship with flat bottom (like barges and supertankers) or ships with large bow flares (i.e container ships). Long ships are more exposed for springing.
Other loads (as bending moment and shear) is also of interest. Especially torsion for container ships.
In general container ship are of most interest w.r.t this phenomens, and then espesially ULCS:
- Larger natural periods in bending and torsion
- Often higher speed, thus more high-frequency wave loads
- Large bow flare, more nonlinear wave loads

**Ship Types**

| Range | Weight | Ship Nr. | Ship Type | Grade |
|---|---|---|---|---|
| 1 | **0,52** | 1 | ULCV | **0,36** |
| 2 | **0,27** | 9 | KVLCC | **0,19** |
| 3 | **0,15** | 8 | DTC | **0,10** |
| 4 | **0,06** | 7 | Navy Vessel | **0,04** |

**Sources:**

## Ship Feature

| Name: | Towing Resistance | Feature Nr. | 5 |
|---|---|---|---|
| **General Description** | | **Feature grade:** | 1,18 |

Normal towing test. Resistance, sinkage & trim, wave elevation, boundary layer and the nominal wake are measured in the towing basin. Load cells are used to measure forces. Rotative potentiometers used to measure the fore and aft displacement in sinkage & trim. Tested at different speeds, giving the same Froude number as for full scale. Wave elevation measured with pictures. Nominal wake measure the flow into the propeller using pitot tubes. The model should be tested in two conditons; with and without appendages.

**Ship Properties**

The ship should:
- Have a high Froude number
- Initial bulb to optimize
- Large wave resistance for the studentds to optimize

**Ship Types**

| Range | Weight | Ship Nr. | Ship Type | Grade |
|---|---|---|---|---|
| 1 | **0,52** | 2 | Container Feeder | **0,61** |
| 2 | **0,27** | 5 | Ferry | **0,32** |
| 3 | **0,15** | 4 | Ro-Ro | **0,17** |
| 4 | **0,06** | 1 | ULCV | **0,07** |

**Sources:**

## Ship Feature

| Name: | Wake-field | Feature Nr. | 7 |
|---|---|---|---|
| **General Description** | | **Feature grade:** | 1,04 |

The boundary layer increase in thickness with its distance from the bow, meaning it is thickest at the stern. In addition, the ship displaces water, which causes wake waves fore and aft. This will cause the propeller behind the hull to work in non-uniform water. Therefore tests are performed to optimize the flow to the propeller. Can be measured in cavitation tunnel and towing tank. The wake field is dependent on the ship type, each ship have a unique wake field.

**Ship Properties**

The ship should:
Wake fields (for extremes)
- U shape aftbody (single screw bulk carrier) the bilge vortex dominates the flow in the thwart-ship plane of the propeller disc.
- V shape aftbody (single screw, fast going) a high-speed axial flow field exists for much of the propeller disc except the top dear centre location, where the flow is relatively slow (may even reverse in dir.).
- Twin-screw (Ex. ferry) - specific attention to the design of the shaft support.

**Ship Types**

| Range | Weight | Ship Nr. | Ship Type | Grade |
|---|---|---|---|---|
| 1 | **0,52** | 5 | Ferry | **0,54** |
| 2 | **0,27** | 4 | Ro-Ro | **0,28** |
| 3 | **0,15** | 10 | KCS | **0,15** |
| 4 | **0,06** | 2 | Container Feeder | **0,06** |

**Sources:**

https://books.google.se/books?id=F1oWVQpvyw4C&pg=PA57&lpg=PA57&dq=wake+field+ship&source=bl&ots=EMUFqMJmpd&sig=_2GdJvJwAXa1VCd70Nm0WA6b9RM&hl=no&sa=X&ved=0ahUKEwjL2frVsZDLAhUrBnMKHaMlB44Q6AEISzAJ#v=onepage&q=wake%20field%20ship&f=false

## Ship Feature

| Name: | Manouvering Test (MDL) | Feature Nr. | 12 |
|---|---|---|---|
| **General Description** | | **Feature grade:** | 1,04 |

Manouvering test are perfomed for verification of the ships maneuverability. The free running test are carried out in the MDL basin. Manouvering in channel is also availible (to a higher cost).

**Ship Properties**

The effect of some ship parameteres on its manoeuvrability characteristic (Pérez & Clemente, 2006)
- Decreasing length has a positv effect on the turning manouvarbility, but affect the Zigzag tests negatively.
- The increase of beam & reduction of length reduce the advance and the tactical diameter, but increase the overshoot angle.
- The effect of changing draft alone is not clear and depand on other parameteres.
- Displacing the LCB position forward affect the turning manouver positivly. The effect of the Zigzag test is small.

Manouvering of a container ship is challenging because of its great length (i.e. turning circle) and high speed (i.e. safety). Navy ships often has to have good manouverability (in all weather at high speed) because of their misson. Manouverability of ships which travel short distances (has much harbour time) is important. RoRo vessel usually have bad manouverability due to the large wind area above waterline.

**Ship Types**

| Range | Weight | Ship Nr. | Ship Type | Grade |
|---|---|---|---|---|
| 1 | **0,52** | 4 | Ro-Ro | **0,54** |
| 2 | **0,27** | 1 | ULCV | **0,28** |
| 3 | **0,15** | 5 | Ferry | **0,15** |
| 4 | **0,06** | 7 | Navy Vessel | **0,06** |

**Sources:**

## Ship Feature

| Name: | Seakeeping | Feature Nr. | 13 |
|---|---|---|---|
| **General Description** | | **Feature grade:** | 1,19 |

Seakeeping in different waves and headings. Seakeeping trials will show how well the ship behaves in various weather and waves. The trials are done in MDL, following parameters can be determined; Roll damping, non-linear motion, slamming and local loads, green water, propeller emergence and added resistance in all wave headings. Added mass is measured by the the power increased needed to maintain a certain speed. However, to be able to measure added resistance the calm water resistance is needed, which only can be obtained in the towing tank. To assess added resistance, two models are needed.

**Ship Properties**

- Large ships generally have lower motions (relative size in waves)
- Heavier ship will have lower motions (lower accelerations)
- A stable ship follow the wave profile better (higher acc. but lower amplitudes of motion)
- higher freebord = less likely to immerse the deck (green water)

**Ship Types**

| Range | Weight | Ship Nr. | Ship Type | Grade |
|---|---|---|---|---|
| 1 | **0,52** | 4 | Ro-Ro | **0,62** |
| 2 | **0,27** | 1 | ULCV | **0,32** |
| 3 | **0,15** | 2 | Container Feeder | **0,17** |
| 4 | **0,06** | 6 | Fishing Vessel | **0,07** |

**Sources:**

## Ship Feature

| Name: | Damage Stability | Feature Nr. | 21 |
|---|---|---|---|
| **General Description** | | **Feature grade:** | 0,69 |

Damage stability is mainly done to determine the significant wave height that will cause the model to capsize. Apart from test in irregular waves with different characteristic, the models equilibrium propeties in calm water are tested for verification. The models roll period are also tested.

**Ship Properties**

In general there is two forms of damage stability, sinkage as a result of loss of bouyancy and capcising as a result of loss of transversal stability. Damage stability in waves are a hot-topic for research.

Especially RoRo vessel are of concern because of their large compartments, which flooded would give huge free-surface effects. Water on deck is also a concern. For passenger vessel, i.e. RoPax, there is stricter requirement for survailability w.r.t stability.

**Ship Types**

| Range | Weight | Ship Nr. | Ship Type | Grade |
|---|---|---|---|---|
| 1 | **0,61** | 4 | Ro-Ro | **0,42** |
| 2 | **0,28** | 5 | Ferry | **0,19** |
| 3 | **0,11** | 7 | Navy Vessel | **0,08** |
| 4 | **Error** | | | **NaN** |

**Sources:**

## Ship Feature

| Name: | Ballast tanks | Feature Nr. | 24 |
|---|---|---|---|
| **General Description** | | **Feature grade:** | 0,85 |

Equip the model with ballast tanks (maybe cargo tanks) so the student can practice cargo handling. The tanks will be equipped with some sort of pump system.

**Ship Properties**

A tanker is suitable for cargo handling due to the large amount of tanks. Also interesting to investigate ballasting of other vessels. A pump system would be beneficial.

In the Cargo Operetion Studio (COS) this can be done with sufficient accuracy using computers.

**Ship Types**

| Range | Weight | Ship Nr. | Ship Type | Grade |
|---|---|---|---|---|
| 1 | **0,75** | 3 | Liquid Cargo Carrier | **0,64** |
| 2 | **0,25** | 9 | KVLCC | **0,21** |
| 3 | **Error** | | | **NaN** |
| 4 | **Error** | | | **NaN** |

**Sources:**

## Ship Feature

| Name: | Wave pattern | Feature Nr. | 25 |
|---|---|---|---|
| **General Description** | | **Feature grade:** | 1,05 |

The wave pattern shows the disturbance of the water around the hull due to the ships motion. Two types of waves are created; divergent ('backward') and transverse waves. The wave pattern can be seen when running the model in waves, could be difficult to model accurately.

**Ship Properties**

The ship should have a high Froude number and preferably a full body and a bulb. The wave resistance should be a considerable part of the total resistance.

**Ship Types**

| Range | Weight | Ship Nr. | Ship Type | Grade |
|---|---|---|---|---|
| 1 | **0,52** | 2 | Container Feeder | **0,55** |
| 2 | **0,27** | 6 | Fishing Vessel | **0,28** |
| 3 | **0,15** | 4 | Ro-Ro | **0,15** |
| 4 | **0,06** | 1 | ULCV | **0,07** |

**Sources:**

## Ship Feature

| Name: | Intact Stability | Feature Nr. | 26 |
|---|---|---|---|
| **General Description** | | **Feature grade:** | 1,09 |

Intact stability test are normally carried out to investigate the ships behaviour in extreme condtions (capsizing). This include phenomens as:
- Pure loss of stability, typically on a wave crest
- Paramtric rolling
- Cargo shift or other heeling moments
- Broaching
- etc

**Ship Properties**

Examples of situations leading to capsizing as a result of loss of intact stability: Pure loss of stability, typically in a wave crest (1), Parametric Rolling (2), Cargo shift or other heeling moments (3) and Broaching (4) (Blome & Krueger, Unknown).

**Ship Types**

| Range | Weight | Ship Nr. | Ship Type | Grade |
|---|---|---|---|---|
| 1 | **0,61** | 4 | Ro-Ro | **0,66** |
| 2 | **0,28** | 1 | ULCV | **0,30** |
| 3 | **0,11** | 10 | KCS | **0,12** |
| 4 | **Error** | | | **NaN** |

**Sources:**

## Ship Feature

| Name: | Roll decay | Feature Nr. | 33 |
|---|---|---|---|
| **General Description** | | **Feature grade:** | 1,11 |

Roll damping is found by heeling the model and measuring the amplitudes of roll damping. Could only be done with zero speed in TT.

**Ship Properties**

The slender shape of a modern ship hull, exhibits a roll motion that is, in contrast to heave and pitch motion, submitted to large amplitudes and weak damping (Piehl & Moctar, 2013). The slender shape represent a ship with relative high Froude number.

**Ship Types**

| Range | Weight | Ship Nr. | Ship Type | Grade |
|---|---|---|---|---|
| 1 | **0,52** | 4 | Ro-Ro | **0,58** |
| 2 | **0,27** | 1 | ULCV | **0,30** |
| 3 | **0,15** | 10 | KCS | **0,16** |
| 4 | **0,06** | 6 | Fishing Vessel | **0,07** |

**Sources:**

## Ship Feature

| Name: | Parametric roll | Feature Nr. | 34 |
|---|---|---|---|
| **General Description** | | **Feature grade:** | 1,08 |

Rolling of ship cause by head or following waves. Ship has large flares, flat aftership, slim fore and aft body, i.e. large container ship. Its difficult to simulate parametric roll. SSPA have no experience with it. The MDL basin is too short to do parametric roll. Both it can be done at zero speed by mooring the model with soft springs. The towing tank could probably also be used.

**Ship Properties**

Parametric rolling in head/following sea is a phenomen that occours at certain wave condtions (relative to the vessels main dimenisons). The ship starts rolling and angles up to 35 deg. can occour. Large container ship with the following characteristic is tyically exposed:
- large flare in the fore and aftship
- flat aftership
- slim fore and aft body
- righting arm varies significant with draft
- Wavelength approx equal to ship length

Could also happen for other type of ship with the same characteristic, i.e. Ro-Ro or Navy ships. In general following sea and quartering sea are most critical.

**Ship Types**

| Range | Weight | Ship Nr. | Ship Type | Grade |
|---|---|---|---|---|
| 1 | **0,52** | 1 | ULCV | **0,56** |
| 2 | **0,27** | 4 | Ro-Ro | **0,29** |
| 3 | **0,15** | 8 | DTC | **0,16** |
| 4 | **0,06** | 7 | Navy Vessel | **0,07** |

**Sources:**

# D Shape of a PCTC

Main Dimensions:

$L_{ref} := 200$ $A_m := 350.619$

$B_{ref} := 32.3$

$T_{ref} := 11$

$v_{ref} := 21$

$\Delta_{ref} := 47971$

$rho := 1.026$

$C_{bref} := 0.654$

$$Fn := \frac{v_{ref} \cdot 0.5144}{\sqrt{9.81 \cdot L_{ref}}} \qquad Fn = 0.244$$

Design of waterline:

$C_{WP} := 0.9811 \cdot C_{bref}^{\,0.4824}$ $C_{WP} = 0.799$ [Bogemann, 1982]

Entrance angle of DWL:

$E_{min} := 438 - 1909 \cdot \sqrt{Fn} + 2218 \cdot Fn - 2261 \cdot Fn^3 + 3624 \cdot Fn^5 - 2721 \cdot Fn^7$ $E_{min} = 6.372$

$E_{max} := 402.387 - 1521 \cdot \sqrt{Fn} + 1503 \cdot Fn - 211.936 \cdot Fn^3 + 2428 \cdot Fn^5 + 4461 \cdot Fn^7$ $E_{max} = 17.054$

$E_{opt} := 478.998 - 2048 \cdot \sqrt{Fn} + 2343 \cdot Fn - 2226 \cdot Fn^3 + 3258 \cdot Fn^5 - 2168 \cdot Fn^7$ $E_{opt} = 9.431$

Design of bulb:

Overall design is based on a "Goose-neck" shaped bulb, see p. 177 in Lars Larsons book

The size of the bulb is based on the following coefficients from Fabians paper

$B_{bulb} := (0.17 \;\; 0.2) \cdot B_{ref}$ $B_{bulb} = (5.491 \;\; 6.46)$

$L_{bulb} := (.018 \;\; 0.031) \cdot L_{ref}$ $L_{bulb} = (3.6 \;\; 6.2)$

$H_{bulb} := (0.260 \;\; 0.550) \cdot T_{ref}$ $H_{bulb} = (2.86 \;\; 6.05)$

$A_{cross} := (0.064 \;\; 0.112) \cdot A_m$ $A_{cross} = (22.44 \;\; 39.269)$

$A_{long} := (0.068 \;\; 0.0146) \cdot A_m$ $A_{long} = (23.842 \;\; 5.119)$

# E Calculations of the ship's main dimension

Reference Ship:

Based on a study of relevant reference ship, the prelminary dimension are chosen:

$L_{ref} := 200$

$B_{ref} := 32.2$

$T_{ref} := 11$

$v_{ref} := 21$

$D_{ref} := 35$

$rho := 1.026$

$\Delta_{ref} := 48000$

$C_{Mref} := 0.98$

$$C_{bref} := \frac{\frac{\Delta_{ref}}{rho}}{L_{ref} \cdot B_{ref} \cdot T_{ref}} \qquad C_{bref} = 0.66$$

$$Fn_{ref} := \frac{v_{ref} \cdot 0.5144}{\sqrt{9.81 \cdot L_{ref}}} \qquad Fn_{ref} = 0.244$$

Not in between 0.25 < Fn < 0.32 --> Avoid humps

Block Coefficient, Cb:

$$C_{b1} := 2.179 - 9.675 \cdot \sqrt{Fn_{ref}} + 18.633 \cdot Fn_{ref} - 134.501 \cdot Fn_{ref}{}^{3} + 913.261 \cdot Fn_{ref}{}^{5} - 2274.852 \cdot Fn_{ref}{}^{7}$$

$C_{b1} = 0.665$ [Jensen, 1994]

$$C_{b2} := -4.22 + 27.8 \cdot \sqrt{Fn_{ref}} - 39.1 \cdot Fn_{ref} + 46.6 \cdot Fn_{ref}{}^{3}$$ [Bertram & Wobig, 1999]

$C_{b2} = 0.649$

Displacement:

$\Delta_1 := L_{ref} \cdot B_{ref} \cdot T_{ref} \cdot C_{b1} \cdot rho \qquad \Delta_1 = 4.837 \times 10^4$

$\Delta_2 := L_{ref} \cdot B_{ref} \cdot T_{ref} \cdot C_{b2} \cdot rho \qquad \Delta_2 = 4.717 \times 10^4$

Length:

$$L_1 := 7.25 \cdot \left( \frac{v_{ref}}{v_{ref} + 2} \right)^2 \cdot \Delta_{ref}{}^{\frac{1}{(3)}} \qquad L_1 = 219.652$$ [Schneekluth, 1957 - fastgoing]

$$L_2 := \Delta_{ref}{}^{0.3} \cdot v_{ref}{}^{0.3} \cdot \left( 3.2 \cdot \frac{C_{bref} + 0.5}{\frac{0.145}{Fn_{ref}} + 0.5} \right) \qquad L_2 = 214.566$$ [Schneekluth & Bertram, 1998]

$$\frac{L_3}{\left(\frac{\Delta_{ref}}{rho}\right)^{\frac{1}{3}}} := 3.33 + 1.67 \cdot \frac{v_{ref}}{\sqrt{L_3}}$$ [Schneekluth & Bertram, 1998]

Solved seperatly, and gives a length of $L_3 := 207.7$

Beam:

$B_1 := 0.175 \cdot L_{ref} - 2.5$ $\quad B_1 = 32.5$ [Bertram & Wobig, 1999]

$B_2 := \frac{L_{ref}}{9} + 4.27$ $\quad B_2 = 26.492$ [Rawson & Tupper, 1994 - Cargo ships]

$B_3 := \frac{L_{ref}}{7.5} + 1.98$ $\quad B_3 = 28.647$ [Rawson & Tupper, 1994 - Cargo ships]

Depth, D:

$D := 0.087 \cdot L_{ref}$ $\quad D = 17.4$

$T := 0.065 \cdot L_{ref} - 0.68$ $\quad T = 12.32$ Not valid for containership

Ratio:

$\frac{L_{ref}}{B_{ref}} = 6.211$ 6.25 for container ships

$\frac{B_{ref}}{D_{ref}} = 0.92$

Not so relevant for PCTC as the freeboard is especially large. B/D - 1.3 to 2 & L/D - 10 -15

$\frac{L_{ref}}{D_{ref}} = 5.714$

$\frac{B_{ref}}{T_{ref}} = 2.927$ Should not exceed, $9.625 - 7.5 \cdot C_{bref} = 4.672$ [Roseman, Gertler, Kohl, 1974]

Coefficients:

$C_{M1} := 0.96845 + 0.095 \cdot (C_{bref} - 0.57)$ $\quad C_{M1} = 0.977$ [Bertram & Wobig, 1999]

$C_{M2} := 0.526 + 1.135 \cdot C_{bref} - 0.683 \cdot C_{bref}^2$ $\quad C_{M2} = 0.978$ [Jensen, 1994]

$C_p := \frac{C_{bref}}{C_{Mref}}$ $\quad C_p = 0.674$ Good value according to p.161 (Larsson,2010)

$C_{WP1} := 0.981 \cdot C_{bref}^{0.4824}$ $\quad C_{WP1} = 0.803$ [Bogemann, 1982]

$C_{WP2} := 0.763 \cdot (C_p + 0.34)$ $\quad C_{WP2} = 0.774$ [Bertram & Wobig, 1999]

Bilge Radius:

$C_K := 0.5$

$R_{bilge} := \frac{B_{ref} \cdot C_K}{\left(\frac{L_{ref}}{B_{ref}} + 4\right) \cdot C_{bref}^2}$ $\quad R_{bilge} = 3.615$

Forward body & parallel midbody

See table in Ship Design

LCB:

$LCB_{min} := -972.8 + 3523 \cdot \sqrt{C_{bref}} - 3374 \cdot C_{bref} + 1597 \cdot C_{bref}^3 - 1136 \cdot C_{bref}^5 + 368.2 \cdot C_{bref}^7$

$LCB_{min} = -0.582$ $\quad LCB_{min} \cdot \frac{L_{ref}}{100} = -1.165$

$LCB_{max} := 226.626 - 656.693 \cdot \sqrt{C_{bref}} + 447.969 \cdot C_{bref} + 15.422 \cdot C_{bref}^3 - 120.733 \cdot C_{bref}^5 + 63.666 \cdot C_{|}$

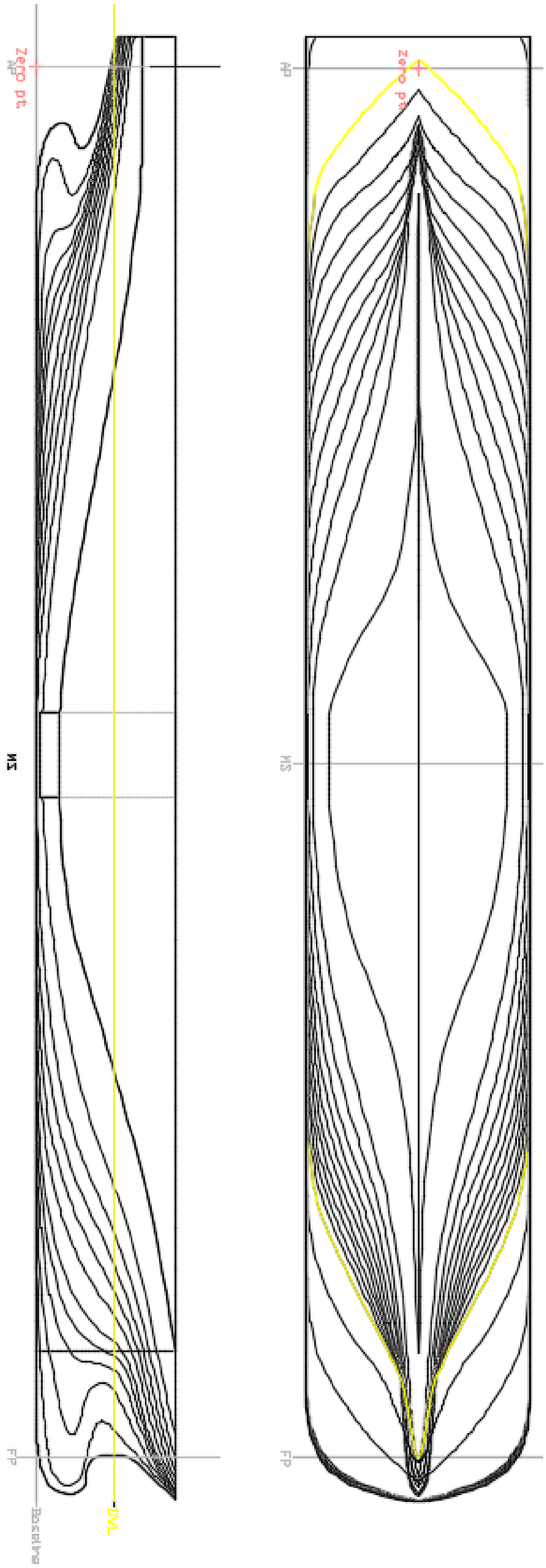
$LCB_{max} = -18.433$ $\quad LCB_{max} \cdot \frac{L_{ref}}{100} = -36.866$ [Saunders, 1957]

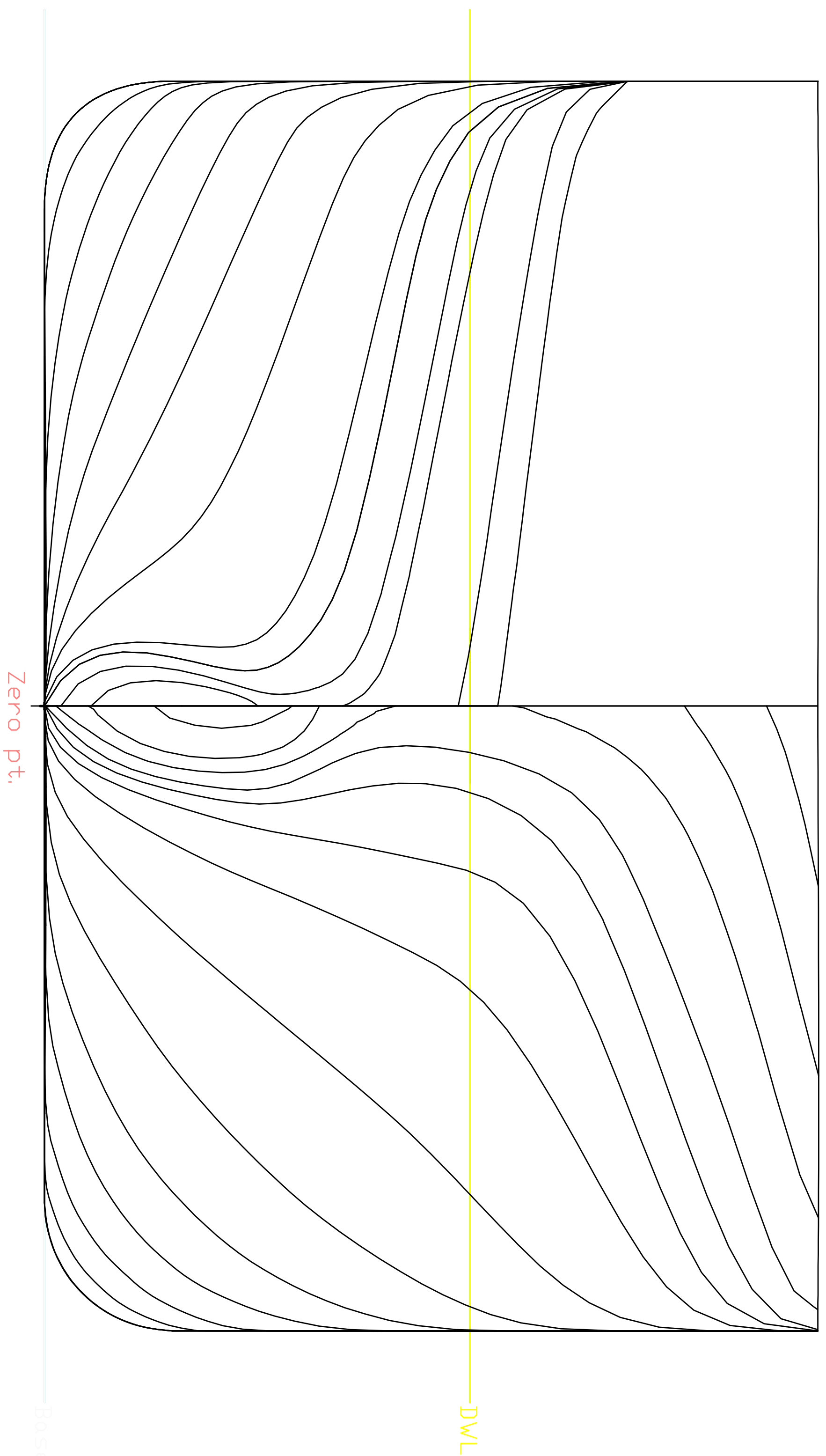
Weird answer. According to fig. 3.4 in ShipDesign LCB should between 0 - 2% ahead off Lpp/2

Stability:

$KB_1 := T_{ref} \cdot (0.9 - 0.36 \cdot 0.851)$ $\quad KB_1 = 6.53$

# F Line drawings of the hull




Zero pt.
DWL
Baseline

# G Design loads from DNV hull structural design

Main dimensions of the ship:

$L_{pp} := 200$ $\quad g_0 := 9.81$

$B := 32.3$ $\quad D := 35$

$T := 11$ $\quad VCG := 15$

$V := 21$ $\quad LCG := 99.8$ (Equal to LCB)

$C_B := 0.654$

Intermediate calculations:

Wave Coefficient, B201: $C_W := 10.75 - \left(\frac{300 - L_{pp}}{100}\right)^{\frac{3}{2}} = 9.75$

Coefficient 1, B203, $C_V := \frac{\sqrt{L_{pp}}}{50} = 0.283$ $\quad C_V := 0.2$ (Max value: 0.2)

Coefficient 1, B203, $C_{V1} := \frac{V}{\sqrt{L_{pp}}} = 1.485$ (Min value: 0.8)

Acceleration parameter, B203, $a_0 := \frac{3 \cdot C_W}{L_{pp}} + C_V \cdot C_{V1} = 0.443$

Accelerations:

Surge acceleration, B301, $a_x := 0.2 \cdot g_0 \cdot a_0 \cdot \sqrt{C_B} = 0.703$ [m/s$^2$]

Combined sway/yaw acceleration, B302, $a_y := 0.3 \cdot g_0 \cdot a_0 = 1.304$ [m/s$^2$]

Heave acceleration, B303, $a_z := 0.7 \cdot g_0 \cdot \frac{a_0}{\sqrt{C_B}} = 3.764$ [m/s$^2$]

Roll radius of gyration, B402, $k_r := 0.40 \cdot B$ for ships with even transverse distribution of mass

Metacentric height in m., B402, $GM := 0.07 \cdot B$ in general

Actual GM with a VCG=15 equals, $GM := 0.218$

Period of roll, $T_R := \frac{2 \cdot k_r}{\sqrt{GM}} = 55.343$ [s] (Max value: 30)

Coefficient, B401, $k := 1.2$, for ships without bilge keels.

Coefficient, B401, $c := (1.25 - 0.025 \cdot T_R) \cdot k = 0.6$ $\quad T_R := 30$

Roll angle, B401, $\phi := \frac{50 \cdot c}{B + 75} = 0.28$ [rad]

The distance from the base line to the roll axis of rotation could be taken equal to the smallest of $\frac{D}{4} + \frac{T}{2} = 14.25$ [m] and $\frac{D}{2} = 17.5$ [m]. Thus $z := \frac{D}{4} + \frac{T}{2} = 14.25$ [m]

The distance from the centre of mass to the axis of rotation, $R_R := VCG - z = 0.75$

Tangential roll acceleration (w/o gravity), B403, $a_r := \phi \cdot \frac{2 \cdot \pi}{T_R} \cdot R_R = 0.044$ [m/s$^2$]

The radial roll acceleration may be neglected, B404.

Pitch angle, B501, $\theta := 0.25 \cdot \frac{a_0}{C_B} = 0.169$ [rad]

The pitch period, B502, $T_p := 1.8 \cdot \sqrt{\frac{L_{pp}}{g_0}} = 8.127$ [s]

Distance between pitch axis and CoG in longitudional direction, $x_{pitch} := LCG - 0.45 \cdot L_{pp} = 9.8$ [m] and in vertical directions it equals z defined B403, thus the distance from CoG to the pitch axis of rotation is, $R_p := \sqrt{x_{pitch}^2 + z^2} = 17.295$ [m]. Angle equals $\varphi_{Rp} := \tan\left(\frac{z}{x_{pitch}}\right)^{-1} = 0.117$

Tangential pitch acceleration, $a_p := \theta \cdot \left(\frac{2 \cdot \pi}{T_p}\right)^2 \cdot R_p = 1.751$ [m/s$^2$]

The radial pitch acceleration is normally neglected (B504), the total pitch acceleration is given by,

B503, $a_P := 120 \cdot \theta \cdot \frac{R_p}{L_{pp}} = 1.758$ [m/s$^2$]

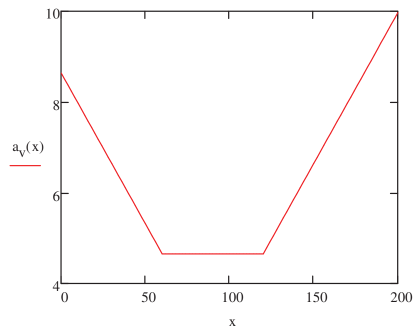
Combined accelerations:

Combined vertical accelerations,B601:

$x := 0, 0.01 \cdot L_{pp} .. L_{pp}$

$$k_v(x) := \begin{cases} 1.3 & \text{if } x = 0 \\ 1.3 - \frac{1.3 - 0.7}{0.3 \cdot L_{pp}} \cdot x & \text{if } x > 0 \wedge x \le 0.3 \cdot L_{pp} \\ 0.7 & \text{if } x > 0.3 \cdot L_{pp} \wedge x \le 0.6 \cdot L_{pp} \\ 0.7 + \frac{1.5 - 0.7}{0.4 \cdot L_{pp}} \cdot (x - 0.6 \cdot L_{pp}) & \text{if } x > 0.6 L_{pp} \wedge x < L_{pp} \\ 1.5 & \text{otherwise} \end{cases}$$

$a_v(x) := \frac{k_v(x) \cdot g_0 \cdot a_0}{C_B}$




The transverse component of $a_r$ equals the vertical projection of $R_R$, B701, $a_{ry} := 0$ [m/s$^2$] , since the COG is placed at the centre of the ship transveresely.

Combined transverse acceleration, B701, $a_t := \sqrt{a_y^2 + (g_0 \cdot \sin(\phi) + a_{ry})^2} = 3.005$ [m/s$^2$]

The longitudional component of pitch acceleration, B801, $a_{px} := \cos(\varphi_{Rp}) \cdot a_p = 1.739$

Combined longitudinal accelerations, B801, $a_l := \sqrt{a_x^2 + (g_0 \cdot \sin(\theta) + a_{px})^2} = 3.466$

# H Scaling of resistance

$\lambda := 46$

Main dimensions from the full scale vessel:

$L_S := 200$

$B_S := 32.3$

$T_S := 11$

$V_S := 21 \cdot 0.5144 = 10.802$

$D_S := 35$

$\Delta_S := 48000$

$S_S := 8400$

$C_B := 0.657$

$A_T := B_S \cdot (D_S - T_S) = 775.2$

$\rho_S := 1025$

$\nu_S := 1.18831 \cdot 10^{-6}$

$$F_n := \frac{V_S}{\sqrt{g \cdot L_S}} = 0.244 \frac{s}{m^{0.5}}$$

$$R_{Ns} := \frac{V_S \cdot L_S}{\nu_S} = 1.818 \times 10^9$$

Main dimensions of model:

$$L_M := \frac{L_S}{\lambda} = 4.348$$

$$B_M := \frac{B_S}{\lambda} = 0.702$$

$$T_M := \frac{T_S}{\lambda} = 0.239$$

$$V_M := V_S \cdot \frac{\sqrt{L_M}}{\sqrt{L_S}} = 1.593$$

$$S_M := \frac{S_S}{\lambda^2} = 3.97$$

$$\Delta_M := \frac{\Delta_S}{\lambda^3} \cdot \frac{\rho_M}{\rho_S} = 0.481$$

$$D_M := \frac{D_S}{\lambda} = 0.761$$

$\rho_M := 999$

$\nu_M := 1.13902 \cdot 10^{-6}$

$$R_{Nm} := \frac{V_M \cdot L_M}{\nu_M} = 6.08 \times 10^6$$

$$D\_prop := \frac{6.5}{46} = 0.141$$

Resistance Calculations ITTC-78

$C_{Tm} := 4.52 \cdot 10^{-3}$

$k := 0.129$

# I Main dimensions of the ship model

Main dimensions from the full scale vessel:

$L_S := 200 \cdot m$

$\rho_M := 999 \cdot \frac{kg}{m^3}$

$\lambda := 36$

$B_S := 32.3 \cdot m$

$T_S := 11 \cdot m$

$\rho_S := 1026 \cdot \frac{kg}{m^3}$

$V_S := 21 \cdot knot$

$D_{propS} := 6.5 \cdot m$

$D_S := 35 \cdot m$

$\Delta_S := 48000 \cdot ton$

$S_S := 8400 \cdot m^2$

$F_n := \frac{V_S}{\sqrt{g \cdot L_S}} = 0.244$

Dimensions of the basin:

$L_{basin} := 88 \cdot m$

$B_{basin} := 39 \cdot m$

$H_{basin} := 3.2 \cdot m$ (Actual draft of basin equals 3.5 m)

Requirments:

- $\Delta$ < 1 tonn (SSPA)
- Wave height 0 m < $2\delta_a$<0.4 m (SSPA)
- Wave length 0.2 m < $\lambda_w$< inf m (SSPA)
- Wave frequencies 0 Hz < f < 3 Hz (SSPA)
- Speed 0 - 10 m/s (SSPA)
- Max hog/sag at fully loaded is 2 mm (ITTC 2011a)
- The propelle diamater should normally be between 0.15-0.30 meters (ITTC 2011a)
- Wavelengths for seakeeping should be between 0.5*Lpp - 2.0*Lpp.
- Wavelengths for broaching should be between 0.6*Lpp - 2.3*Lpp.
- Wavelengths for parametric roll should be between 0.8*Lpp - 1.5*Lpp.
- For free running models, the GM should have accuracy of 5% compared to full scale (ITTC 2008a)
- For intact stability models, 2% (ITTC 2008c)
- Model scale w.r.t manouvering should be as large as possible due to unknown scale effects (ITTC 2008a).
- Minimum length of 2 meter for intact stability (ITTC 2008c). Scale ship so that bilge keel is larger than 7 mm.
- According to several ITTC procedure, the model should be manufactured up to the weatherdeck.

Main dimensions of model:

$L_M := \frac{L_S}{\lambda} = 5.556\,m$ (SSPA recomends length of 5 m)

$B_M := \frac{B_S}{\lambda} = 0.897\,m$

$T_M := \frac{T_S}{\lambda} = 0.306\,m$

$D_M := \frac{D_S}{\lambda} = 0.972\,m$ (Max 0.5 m. Note that the entire depth do not have to be modeled)

$\Delta_M := \frac{\Delta_S}{\lambda^3} \cdot \frac{\rho_M}{\rho_S} = 908.757\,kg$ (Max 1 tonn, but SSPA recomends around 500-600 kg)

$S_M := \frac{S_S}{\lambda^2} = 6.481\,m^2$

$V_M := V_S \cdot \frac{\sqrt{L_M}}{\sqrt{L_S}} = 1.801\,\frac{m}{s}$ Max 2.8 m/s [ITTC] & Max 3.0 m/s [SSPA]

$D_{propM} := \frac{D_{propS}}{\lambda} = 0.181\,m$ (Normally between 0.15 - 0.30 meter (ITTC), SSPA recomends D=20 cm, but can handle D>18 cm )

$\phi := 24 \cdot deg$

$D_{pre} := T_M + \tan(\phi) \cdot \frac{B_M}{2} = 0.505\,m$

$D_{modeled} := D_{pre} \cdot 1.1 = 0.556\,m$

Wave characteristic:

$H_w := (0 \cdot m \;\; 0.25 \cdot m) \cdot \lambda = (0 \;\; 9)\,m$

$\lambda_w := \left(0.2 \cdot m \;\; L_{basin}\right) \cdot \lambda = \left(7.2 \;\; 3.168 \times 10^3\right) m$

$f_w := (0 \cdot Hz \;\; 3 \cdot Hz) \cdot \frac{1}{\sqrt{\lambda}} = (0 \;\; 0.5)\,\frac{1}{s}$ $T_{wMax} := \frac{1}{0.5} = 2$

Checking of main dimension:

Maxium frequency at which tank interference occurs in head waves (ITTC 2011b):

$\frac{B_{basin}}{L_M} = 7.02$ $\omega_{max} := \frac{0.245}{F_n \cdot \sqrt{\frac{L_M}{g}}} = 1.334\,\frac{1}{s}$ $f_{max} := \frac{\omega_{max}}{2} = 0.667\,\frac{1}{s}$

Ratios to ensure that shallow effects are avoided (ITTC 2008a):

$\frac{H_{basin}}{T_M} = 10.473$ (Min value H/T=4)

$V_{Mmax} := 0.5 \cdot \sqrt{g \cdot H_{basin}} = 2.801\,\frac{m}{s}$ (Maximum value)

Broaching test, intact stability (ITTC 2008c):

$L_{basinMin} := 25 \cdot L_M = 138.889\,m$ (For parametric roll the basin should preferebly be even longer)

$B_{basinMin} := 5 \cdot L_M = 27.778\,m$ (Maxium alowed length of a tactical diameter equals 5*Lpp)

Wave lengths (ITTC):

$\lambda_{Broaching} := (0.6 \;\; 2.3) \cdot L_M = (3.333 \;\; 12.778)\,m$

$\lambda_{ParametricRoll} := (0.8 \;\; 1.5) \cdot L_M = (4.444 \;\; 8.333)\,m$

$\lambda_{Seakeeping} := (0.5 \;\; 2.0) \cdot L_M = (2.778 \;\; 11.111)\,m$

# J Various result available electronic

The following appendages can be found electronically.

## J.1 Decision matrix 1 (DM1.xlsx)

## J.2 Decision matrix 2 (DM2.xlsx)

## J.3 Transcribed interviews

## J.4 Shipflow full scale

## J.5 Shipflow model scale

## J.6 Maxsurf modeler design file

## J.7 DXF AutoCad model

## J.8 IGES model

## J.9 Maxsurf stability report

## J.10 Maxsurf seakeeping report