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Project Title:

Approaches of Optimizing Ships in Calm Water



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Contents

1. Introduction.....	4
1.1. General.....	4
1.2. Objectives	4
1.3. Research Overview	4
2. Selection of research area	5
3. LITERATURE REVIEW	5
4. CASE OF STUDY.....	7
4.1. Operation Profile	8
5. Parametric Modelling of Forebody	8
5.1. Partial Parametric Approach	8
5.2. Selection of Design Parameters	9
6. Computational Fluid Dynamics (CFD) Method	10
6.1. Use of GL Rankine Solver and Validation with Experimental Data.....	10
7. Optimization Process in Calm Water Condition	14
7.1. Single Objective Optimization.....	14
7.1.1. Design of Experiments(DoE)	14
7.1.2. Optimization Process.....	14
7.2. Single Objective Optimization Process with Weighted Functions	17
7.3. Multi-Objective Optimization.....	19
7.3.1. Optimization Process.....	19
8. Results.....	20
8.1. Selection of Optimal Model.....	20
9. Conclusion and Recommendations	22
9.1. Conclusion.....	22
9.2. Recommendations.....	22
10. References.....	23

List of Figures

Figure 1- Phases of product development.....	5
Figure 2-Knowledge accumulation and relevance for decision-making	6
Figure 3-Base Model Geometry in CAESES	8
Figure 4-Varying of bulbous bow shape by controlling design parameter	9
Figure 5-Sample unstructured mesh generated on the hull (mesh1)	11
Figure 6-Mesh Dependency for different Froude Numbers	12
Figure 7-Comparison of Wave Resistance Coefficients (C_w)	14
Figure 8-Single objective optimization process via SIMPLEX method for $V=20$ knots.....	15
Figure 9-Wave height comparison between Base model and Optimized model	15
Figure 10-Comparison of base model (left) and optimized (right) for R_T at 20knots	16
Figure 11-Single objective optimization process via SIMPLEX method for $V=25$ knots	16
Figure 12-Comparison of base model (left) and optimized (right) for R_T at 25knots	17
Figure 13-Comparison of Single objective optimization for 20kn and 25kn.....	17
Figure 14-Weighted function $\alpha = 0.25$	18
Figure 15-Weighted function $\alpha = 0.5$	18
Figure 16-Weighted function $\alpha = 0.75$	18
Figure 17-Weighted function. Comparison of all optimum designs regarding the R_T for both speed conditions.	18
Figure 18-general principle of a genetic algorithm.....	19
Figure 19-Multi-Objective Optimization Process with MOGA (Dakota).....	19
Figure 20-Wave pattern of the optimize and base hull form	21
Figure 21-Base model (left) and optimum design (right) forebody with pressure coefficient.	21
Figure 22-Base model (without mesh) and optimum design (with mesh) forebody longitudinal view	21

List of Tables

Table 1- Main Dimensions of DTC in Design Loading Condition.....	7
Table 2-Comparison of Main Parameters	8
Table 3-Variation of grid parameters.....	11
Table 4-Number of Panels for Different Froude Numbers	11
Table 5-Wave resistance coefficients for different mesh	12
Table 6-Results of resistance model tests	13
Table 7-Results of GL Rankine Simulations	13
Table 8-Comparison of Numerical results with experimental data.....	13
Table 9-Number of CFD runs and rel. resistance% to base model	20
Table 10-Geometry trend of the optimized bulbous bow	20

1. Introduction

1.1. General

Hull form optimization from a hydrodynamic performance point of view in calm water and in moderate sea states is an important aspect in preliminary ship design. In the optimization process, the SIMPLEX algorithm or genetic algorithm is linked to the computational method to obtain an optimum hull form by several geometrical constraints such as internal fitting, displacement and stability. The scope of this project will be focused on the total ship resistance in calm water.

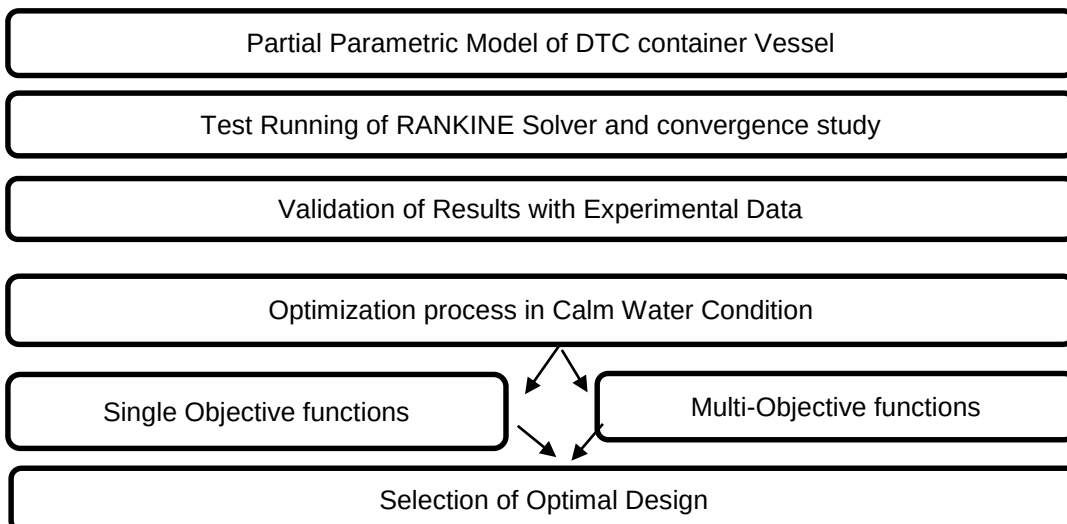
Therefore, ship optimization based on CFD simulation becomes the major factor of developing new optimal ship hull forms by minimizing ship resistance. In this project, the study will be carried out based on the FRIENDSHIP-Framework (FFW) software and RANKINE solver provided by DNV-GL.

1.2. Objectives

The main objective of this project is to study about the various approaches for the optimization of fore body of ship hull form for the container vessel based on the given technical specifications. The study of Rankine solver provided from DNV-GL has to be done and it is coupled to interface with the Friendship-Framework to check the resistances in both steady flow and seaway, as well as the seakeeping performances of the geometric hull form considering different sea-states of operating routes and different speeds. Furthermore, this work is motivated to understand which approach is particularly suited to compare different optimization approaches. The optimization process will be done with CAESES to get the optimized hull form that can be checked later for seakeeping behaviours with moderate sea states.

1.3. Research Overview

The whole project was performed as the following schemes.



2. Selection of research area

This project was prepared for student competition of TRAvision 2016 in research area of 'RA2:Vehicles & Vessels Technologies, Design and Production'. There are many reasons to choose this research area. Lots of effort have been put into the development of more environmental friendly devices for the transport of goods and people. The optimization applied on ship design process represents a potential benefit for environment. A vessel that is optimized, consumes less fuel, therefore it is better for the whole chain of the transportation system including the environment itself.

Ship hull form optimization offers several benefits: it increases a company's competitiveness in the way of:

- Better understanding of the design task (and the design space),
- Creating design with superior performance (and better trade-offs),
- Allowing shorter time-to-market (and faster response to market changes),
- Reducing risk (and building confidence),
- Saving costs (and avoiding expensive late changes).

Hull form optimization is conducted both for investigating new ideas and possibilities at the initial design stage and for fine-tuning of a given design at a later stage when only small changes are still acceptable, see Figure.1.

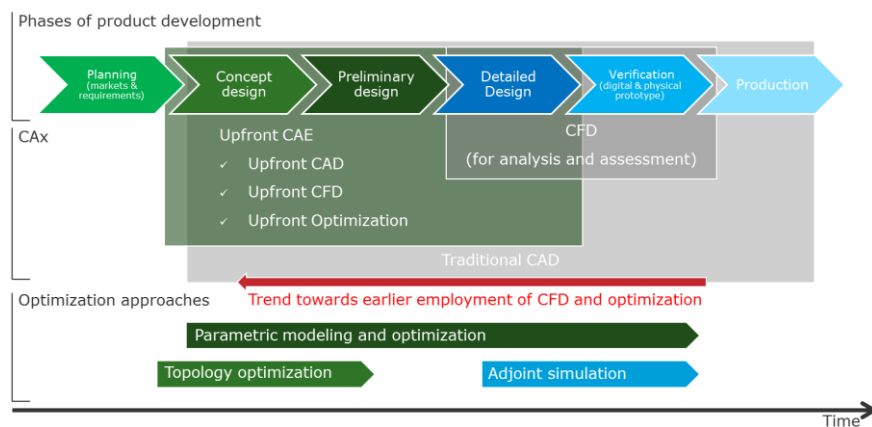


Figure 1- Phases of product development

3. LITERATURE REVIEW

The topic of this project concerns with numerous engineering studies such as optimization processes, study of hydrodynamic performances by the use of CFD solver, designing sea-states for operating routes and parametric modelling of the hull.

The time-to-market is constantly decreasing and to push the knowledge gained during the early design stages helps in all parties involved (shipyards, consultants, model basin, etc) and all team who contribute to the success of the design (managers, naval architects etc) to develop a better design, Harries 2007 [1].

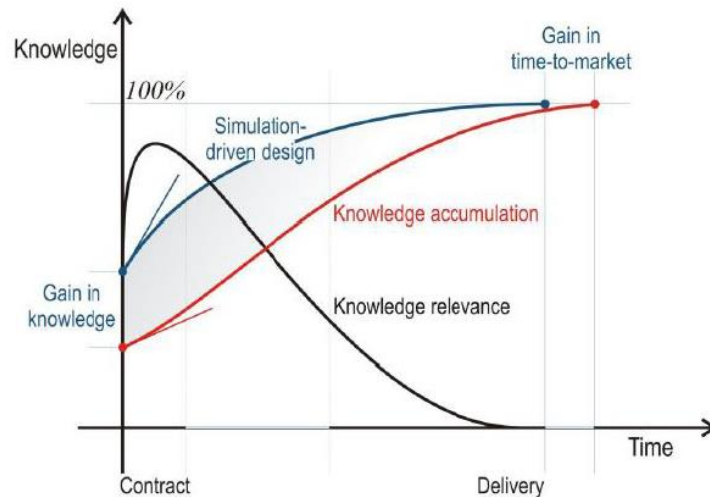


Figure 2-Knowledge accumulation and relevance for decision-making

Grigoropoulos and Chalkias (2009) [2] wrote a paper about “Hull-form optimization in calm and rough water”. Their work presents a formal methodology for the hull form optimization in calm and rough water using waves and selected dynamic responses, respectively. Parametric hull form modeling is used to generate the variant hull forms with some of the form parameters modified. Rankine-source panel method and strip theories are used for the hydrodynamic evaluation.

Kim (2009) [3] made a thesis about “Multi-objective optimization for ship hull form design”. His thesis covers the development of geometry modeling methods using NURBS representation and parametric representation for a complex geometry and to satisfy different design requirements, the development of various optimization algorithms. Both single- and multi-objective optimization algorithms are implemented. Several optimization algorithms are employed and compared with one another in various hull form optimization applications. Finally, a CFD module is developed to compute the flow field and evaluate the hydrodynamic performance of the new hull forms obtained during optimization cycles.

Heimann (2005) [4] wrote a thesis about ‘CFD based Optimization of the wave-making characteristics of ship hulls’ that covers a noble hull form optimization approach based on CFD evaluation of non-linear ship wave pattern and on wave cut analysis.

Due to the holistic ship design characteristic it is necessary to undertake multi-objective and multi-constrained optimization procedures. The generic ship design optimization problem and the basic elements are defined by Papanikolaou 2009 [5] as:

- Optimization criteria (merit functions, goals): This refers to performance/efficiency indicators that may be eventually reduced to an economic criterion.
- Constraints: This refers to a list of mathematically defined criteria resulting from safety, cost of materials or other case-specific constraints.
- Design parameters: refers to a list of parameters as ship's main dimensions
- Input data: This includes traditional owner's specifications/requirements, initial form etc.

- Output: This includes the entire set of design parameters for which the specified optimization criteria/merit functions obtain mathematically extreme values (minima or maxima); for multi-criteria optimization problems optimal design solutions are on the so-called Pareto front and may be selected on the basis of tradeoffs by the decision maker/designer.

There are a couple of reference works for optimization of hull forms for resistance and seakeeping behaviors, but there is no specific work for container ships considering the different operating routes and scenarios. So, this project will be more emphasized on this area and coupled the GL RANKINE CFD solver with the Friendship Frameworks.

4. CASE OF STUDY

The study relies on a DTC (Duisburg Test Case) container vessel. Duisburg Test Case (DTC) is a hull design of a modern 14000 TEU post-panamax container carrier, developed at the Institute of Ship Technology, Ocean Engineering and Transport Systems (ISMT). Table 1 shows main particulars in the design loading condition: length between perpendiculars L_{pp} , waterline breadth B_{wl} , draught amidships T_m , volume displacement V , block coefficient C_B , wetted surface under rest waterline without appendages S_w and design speed V_d .

	Model	Full Scale
L_{pp} [m]	5.976	355.0
B_{wl} [m]	0.859	51.0
T_m [m]	0.244	14.5
ϑ [°]	0.0	0.0
V [m ³]	0.827	173467.0
C_B [-]	0.661	0.661
S_w [m ²]	6.243	22032.0
v_d [knots]	3.244	25.0

Table 1- Main Dimensions of DTC in Design Loading Condition

A small area of the hull (bulbous bow) was selected to be optimized in hydrodynamic terms of total resistance of the vessel and concerning the actual operational condition of the ship. A partial parametric model is developed in CAESES and connected to GL Rankine set up in order to determine the calm water resistance at different speed range. The following figure shows the base model of DTC in CAESES.



Figure 3-Base Model Geometry in CAESES

Parameters	Design Data	Base Model Geometry Data
Lpp(m)	355	355
Bwl(m)	51	51
Tm(m)	14.5	14.5
Volume of Displacement(m ³)	173467	173216
Wetted Surface Area, S(m ²)	22032	22082
C _B	0.661	0.66

Table 2-Comparison of Main Parameters

Since the difference between design data and hydrostatic result obtained from CAESES of Base Model geometry is small, the CFD simulation will be done with the base model geometry.

4.1. Operation Profile

As this container vessel has not built yet and it is only in preliminary design state, the operating information of this vessel is not confirmed yet. Therefore, the realistic operating data of the similar vessel are considered as a sample.

After considering the ship operating routes, the ship is designed based on the following conditions at the draft of 14.5 m with zero trim;

In this project, the author will study at two different speeds of 20 knots and 25 knots which are the speeds used in experimental analysis in order to compare easily the numerical data with experiment results.

5. Parametric Modelling of Forebody

5.1. Partial Parametric Approach

In traditional CAD-based geometric modelling, shapes are generated in terms of mathematically defined curves and surfaces by means of graphical user interface (GUI). The global parameters such as length, breadth and depth are set up first and the local parameters such as bulbous bow length, width, bulb keel elevation, waterline entrance angle, etc. are considered for the variation of hull

shape to analyse the hydrodynamic performance in calm water conditions and in moderate sea states.

In order to optimize the vessel, a few parameters has to be defined. In this case, only the bulbous bow part of the ship is to be optimized thus, some parameters are selected to control the changes on the selected area of the geometry. The selection of parameters was based on an extended study of the influence of each variable regarding it optimization improvement i.e. the “capability” of each parameter on reducing the wave resistance and total resistance of the vessel.

First, the initial geometry of the DTC container vessel is imported to CAESES as a STL mesh format [see in Fig-3]. The surface delta shift method is used to get partial parametric model in order to get different bulb shape by changing selected design parameters.

5.2. Selection of Design Parameters

The number of design parameters should be as minimum as possible in order to be more efficient in the optimization process. The large number of design variables can lead to the very large amount of designs while combining all parameters. The design of experiments (DoE) study provides information to classify the design variables in order of influence to the resistance reduction.

- (a) **Dx Bulb** –The variation range for the longitudinal position of bulb tip from base design is from -2 m to +2 m.
- (b) **Dy Bulb**– The variation range for the half width of the bulb from base design is from -1 m to +2 m.
- (c) **Dz Bulb**– The variation of bulb tip elevation from the original base design is from -1.5m to 1.5m.
- (d) **Bulb top tangent at FP**– It is the inclination of the after part of the bulb that connects it to the hull. It ranges from -5 degree to 11 degree.
- (e) **Bulb keel fullness** –changing the fullness of keel elevation which alters the shape of lower part of bulb in longitudinal direction, ranging from -0.2 to 0.2.
- (f) **Entrance Angle DWL** – changing the angle of DWL at forward perpendicular at design waterlines, ranging from -1 degree to 1 degree (zero degree for base design).
- (g) **DWL Fullness**– changing the fullness of design waterline from FP to the end of flat of bottom, ranging from -0.1 to 0.1 (zero for base design).

As above, there are 7 design parameters for optimization process. In Fig-4, the examples of the effect of design parameters on changing the shape of hull form are illustrated.

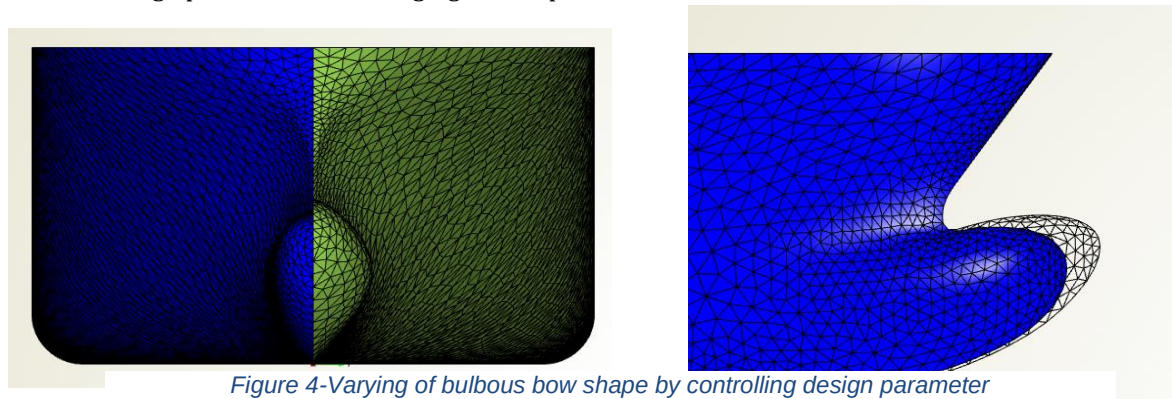


Figure 4-Varying of bulbous bow shape by controlling design parameter

Appendix A1 will show the study of each variable parameter affecting on the wave resistance and total resistance of the ship by using Direct Search Method. From the results shown in Appendix A1, it can be seen that design variables named DWL fullness and Bulb keel fullness have no influence on the resistance. Finally, only 5 design variables were used in order to continue optimization process.

6. Computational Fluid Dynamics (CFD) Method

Determination of the wave pattern and the resistance of the ship moving with a constant speed either in calm water or in sea states is the objective study of ship hydrodynamics. In assessment of ship hydrodynamics and optimization, CFD solvers play an important role to compute the flow fields for different operation conditions and to evaluate objective functions. It is necessary to be accurate, fast, reliable, and automatic for their usage in optimizing process and also to communicate with the other components in the chain. At present, there are a lot of effective, reliable and fast CFD tools that are available to evaluate the numerical solution of wave flows. The solvers for inviscid potential flow are using widely for different ship types and flow cases.

RANSE CFD solvers can obtain very accurate results. But, for variety of loading conditions, various ship speeds and numerous wave periods and directions, these tools require too much computational time. Therefore, at early design stage, potential flow code solvers are utilized practically. CFD solvers based on nonlinear free surface Rankine panel method are widespread for semi-automated or fully-automated hull shape improvement. These free surface Rankine methods are straightforward in handling, fast and generate reliable results in terms of detailed flow information for a variety of applications. In this project, potential flow code GL Rankine developed by DNV-GL is used to calculate the wave resistance and total resistance in steady flow computation and added resistance in waves for seakeeping analysis.

6.1. Use of GL Rankine Solver and Validation with Experimental Data

In the first part, the variation of C_w coefficients in base model for the speeds given by Froude numbers of 0.174, 0.200 and 0.218 will be checked for different hull grids. While changing the hull grid parameters, only the grid length at the bow, mid and aft region will be changed. The variation of the height of panel grid above the waterline at bow and aft region should be careful since it is proportional to stagnation height, $z = V^2/2g$ for non-linear steady simulation. The other parameters such as relaxation factor and wave damping factor that effect on convergence of the iteration will be kept as default values. For the free surface mesh, all the default parameters based on forward speed will be used for structured rectangular grids.

In the second part, the CFD simulation will be done by potential flow solver GL Rankine for the final selected panel hull at different speeds from 20 knots to 25 knots. After that, the comparison of CFD simulation results in calm water resistance with experimental data will be done.

Results:

Part 1: Convergence study on the base model for mesh dependency on numerical results

In this part, the convergence of the wave resistance coefficient (C_w) in base model is checked by varying the different grids for three different Froude Numbers.

Froude Number	Velocity (knots)
0.174	20
0.200	23
0.218	25

While changing the grid parameter for the hull surface, only the grid length at the aft, mid and bow region will be changed manually as shown in the following tables. The other parameters of panel generation of the hull and free surface mesh parameters will be kept as defaults.

Parameters	mesh 1	mesh 2	mesh 3	mesh 4	mesh 5
LMid	5	4	4	3.5	3
LBow	3	3	2.5	2.5	2
LAft	3	3	2.5	2.5	2

Table 3-Variation of grid parameters

According to GL Rankine user manual, $ZAft = \min(0.3z, LAft)$ and $ZBow = \min(0.5z \text{ to } 1.0z, LBow)$, where $LAft$ = approximate grid length at aft region, $LBow$ = approximate grid length at bow region and $z = V^2/2g$. According to the variation of $ZAft$ and $ZBow$ for different Froude Numbers, the number of panel generated of the hull is also different as shown in Table-4.

	Number of panels				
Fn	Mesh 1	Mesh 2	Mesh 3	Mesh 4	Mesh 5
0.174	2204	2965	3383	3888	5374
0.200	2312	3008	3424	3943	5527
0.218	2299	3048	3409	4004	5527

Table 4-Number of Panels for Different Froude Numbers

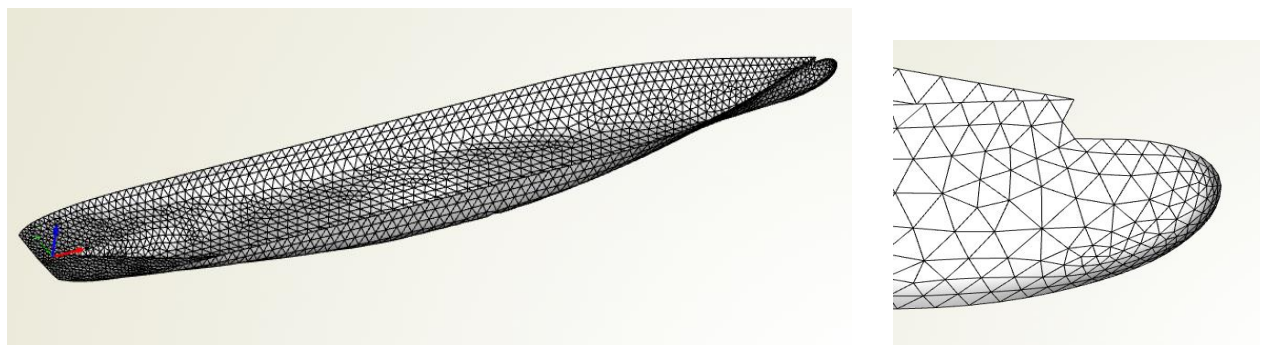


Figure 5-Sample unstructured mesh generated on the hull (mesh1)

The free surface mesh are generated by default parameter according to different forward speed. The free surface mesh around the hull for resistance calculation is generated as the structured rectangular mesh.

Cw x e4(-)	mesh1	mesh2	mesh3	mesh4	mesh5
Fn=0.174	1.3668	1.4863	1.4530	1.2277	1.2864
Fn=0.200	1.3753	1.3065	1.4516	1.2307	1.1362
Fn=0.218	1.8082	1.8784	2.1613	1.9535	1.4200

Table 5-Wave resistance coefficients for different mesh

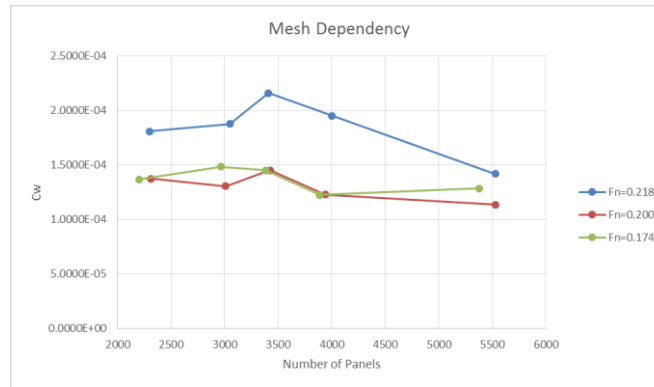


Figure 6-Mesh Dependency for different Froude Numbers

While changing the mesh parameters, it should be noted that the maximum number of panels generated below waterline is 10000 as default. Table-5 and Figure-6 show the wave resistance coefficient for different mesh at $Fn = 0.174, 0.200, 0.218$. It can be seen that the mesh dependency is quite sensitive to the numerical results of wave resistance.

For panelization of the model, it should be nice to follow the standard recommendation such as 1% of LPP of ship for panel size in middle section and 0.7% for that in forward or aft section.

As summary of the first part, the final mesh of hull panel generation is chosen for **mesh 3** with **L_{Aft}, L_{Bow} = 0.7% of LPP = 2.5 m** and **L_{Mid} = 1% of LPP = 4m** [approximately 3500 panels on hull, approximate computation time= 15 minutes for each simulation in Intel® Core™ i5-3230M CPU @ 2.60GHz, RAM 4GB].

Part 2: Validation of Numerical Results with Experimental Data

The set-up file is done after trying and adjusting the parameters for different situations and finally, the simulations for different speeds for both steady flow computation are finished with the reasonable results. But in order to explore the accuracy of the results that come out from GL Rankine solver, they are validated with the experimental results that are done in in the model test basins SVA Potsdam (resistance and propulsion tests), Nietzschmann (2010), and HSVA (roll decay tests), Schumacher (2011).

A: Description of Experiment

Resistance was measured at six forward speeds, corresponding to Froude numbers from 0.17 to 0.218 and full-scale advance speeds V_s from about 20.0 to 25.0 knots. The hull was ballasted at the design draft 14.5 m with zero trim, and was free in trim and sinkage. Tests were carried out at water kinematic viscosity = $1.09E-06 \text{ m}^2/\text{s}$ and density 998.8 kg/m^3 .

Table- 6 shows the experimental results referring to the model scale, including model speed V_m [m/s], Froude number, Reynolds number, total resistance R_T [N] and its non-dimensional

coefficient C_T , frictional resistance R_F [N] and its non-dimensional coefficient C_F , and non-dimensional wave resistance coefficient C_W .

$$C_{Tm} = \frac{R_{Tm}}{0.5 \times \rho m \times S_m \times V_m^2}$$

$$C_{Fm} = \frac{0.075}{\log(Re_m - 2)^2}$$

$$C_{Wm} = C_{Tm} - (1 + k)C_{Fm}$$

The form factor k was found from a RANSE-CFD simulation for a double-body flow at the model scale as $k = 0.094$ (for reference, RANSE-CFD computed form factor for the full scale is $k = 0.145$). By Froude number similitude, the coefficients of the residual resistances of the model scale and full scale are the same and therefore, C_w for full scale is obtained. By following the same procedure as the model scale, the total resistance coefficient of the full scale ship (C_{TS}) is achieved.

Vs (knots)	Vm (m/s)	Fmm	Re m	Ctm x e3(-)	Cfm x e3(-)	Cw x e4(-)	RTm(N)	Rwm(N)
20	1.335	0.174	7.3198E+06	3.6606	3.1695	1.9316	20.34	1.0733
21	1.401	0.183	7.6816E+06	3.6049	3.1423	1.6714	22.06	1.0228
22	1.469	0.192	8.0545E+06	3.5880	3.1160	1.7907	24.14	1.2048
23	1.535	0.200	8.4164E+06	3.6019	3.0919	2.1935	26.46	1.6113
24	1.602	0.209	8.7837E+06	3.6231	3.0687	2.6590	28.99	2.1276
25	1.668	0.218	9.1456E+06	3.6695	3.0471	3.3594	31.83	2.9141

Table 6-Results of resistance model tests

B. Calculations and Comparisons of Result values

For the range of Froude numbers used in experimental data, the CFD simulations in GL Rankine for the final mesh panel hull and free surface are performed to compute non-dimensional resistance coefficients (C_T , C_F and C_W). The results are as follow in Table- 7.

Parameters	Base Model simulation with mesh 3					
Vs(knots)	20	21	22	23	24	25
Lmid	4	4	4	4	4	4
Lbow	2.5	2.5	2.5	2.5	2.5	2.5
Laft	2.5	2.5	2.5	2.5	2.5	2.5
Zbow	2.5	2.5	2.5	2.5	2.5	2.5
Zaft	1.62	1.78	1.96	2.14	2.33	2.5
no. of panels	3383	3339	3346	3424	3323	3409
FS no. of panels	2503	2142	1809	1504	1296	1058
Trim(deg)	0.056	0.065	0.074	0.083	0.09	0.1
Sinkage(m)	-0.235	-0.262	-0.292	-0.322	-0.355	-0.389
Wetted surface(m2)	22077	22078	22084	22087	22097	22109
Cw	1.4530E-04	1.2799E-04	1.3522E-04	1.4516E-04	1.5874E-04	2.1613E-04
Cfs	1.3937E-03	1.3883E-03	1.3832E-03	1.3784E-03	1.3713E-03	1.3667E-03
Cts	1.5390E-03	1.5162E-03	1.5185E-03	1.5235E-03	1.5295E-03	1.5828E-03

Table 7-Results of GL Rankine Simulations

		Experimental Data			GL Rankine		
Vs(knots)	Fn	RTm(N)	Rwm(N)	Cw x e4(-)	Rws(kN)	Rwm(N)	Cw x e4(-)
20	0.174	20.34	1.0733	1.9316	174	0.8299	1.4530
21	0.183	22.06	1.0228	1.6714	169	0.8061	1.2799
22	0.192	24.14	1.2048	1.7907	196	0.9349	1.3522
23	0.200	26.46	1.6113	2.1935	230	1.0970	1.4516
24	0.209	28.99	2.1276	2.6590	274	1.3069	1.5874
25	0.218	31.83	2.9141	3.3594	405	1.9317	2.1613

Table 8-Comparison of Numerical results with experimental data

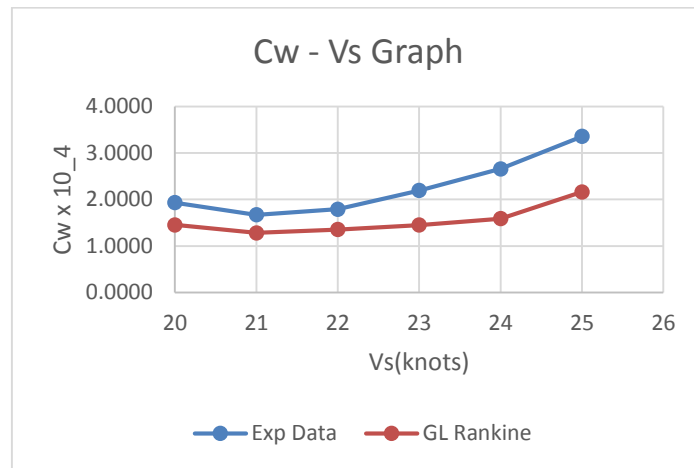


Figure 7-Comparison of Wave Resistance Coefficients (Cw)

The comparison of the numerical results simulated by GL Rankine and the experimental results performed by HSVA are described accordingly in figure 7. It can be seen that the numerical simulation was done for 6 different forward speeds and its curve shows the same curvature as experimental data.

At two extreme speeds, the total resistance at 20 knots has the decrement of 7% in numerical results compared to that in experimental results, while the total resistance at 25 knots is reduced 10% in simulation.

7. Optimization Process in Calm Water Condition

Years ago, optimization is a long and costly experiment test with limited number of designs. Nowadays, with the numerous optimization methods, thousands of designs can be simulated and optimized with effective algorithms in a short time without doing any experiments and it is cost effective. The efficiency of algorithm is depending on the types of constraints, number of objectives, and function of the problem to solve, time required for the process and accuracy of the objectives.

7.1. Single Objective Optimization

7.1.1. Design of Experiments(DoE)

The optimization processes applied on this project consist, as first step, to perform a study of the design space. Usually the Design of Experiments (DoE) is driven by a random or quasi-random process (SOBOL in CAESES). Appendix A2 shows the sampling of design space obtained from SOBOL with 100 designs in order to get the feasible design with all ranges of design variables. With these results from design of experiment, the best design can be selected and on it, the optimization method performed.

7.1.2. Optimization Process

For single objective optimization process, SIMPLEX (Downhill Simplex Method of Nelder and Mead) was used starting from the initial design selection from Design of Experiments.

1st Case -Objective: minimize total resistance at V=20knots at design draft of 14.5m
The Figure 8 presents the results for the optimization process together with the designs obtained on the DoE study, displayed by their indexes (order of creation) and in the ordinate is the total resistance.

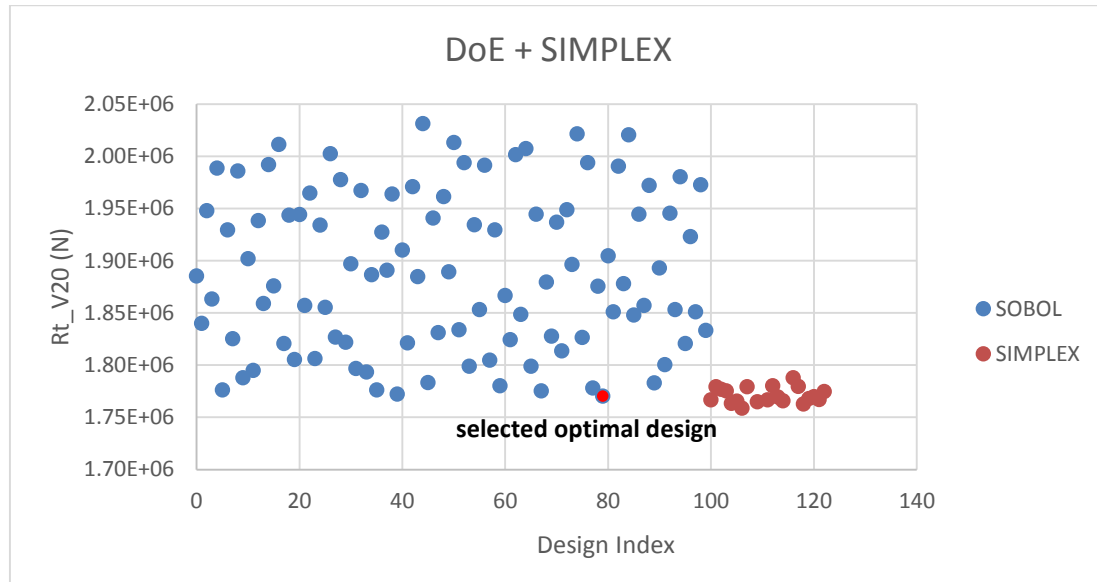


Figure 8-Single objective optimization process via SIMPLEX method for V=20 knots

The optimized model for the speed of 20 knots has a wave resistance reduction of 41%, an expressive result. However, regarding the total resistance, where the viscous effects are estimated from GL Rankine, the reduction is of 4% related to the base model.

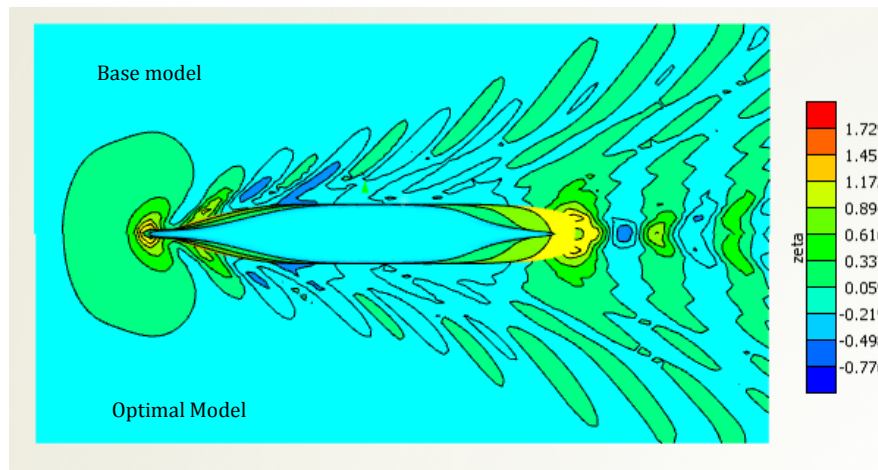


Figure 9-Wave height comparison between Base model and Optimized model

The optimized geometry has a shorter and narrower bulb as can be observed in Figure 10. Furthermore, the bulb tip elevation becomes higher and the entrance angle becomes a bit narrower than the base model.

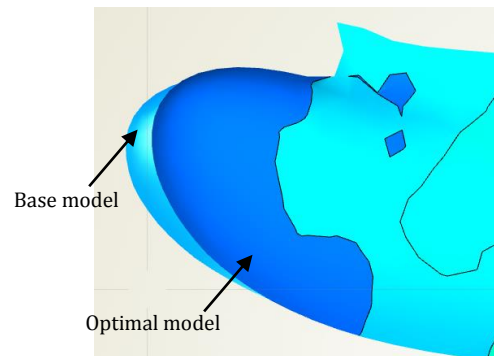


Figure 10-Comparison of base model (left) and optimized (right) for R_T at 20 knots

Finally, the same process, single objective SIMPLEX optimization, is done for a second operational case.

2nd Case -Objective: minimize total resistance at $V=25$ knots at design draft of 14.5m

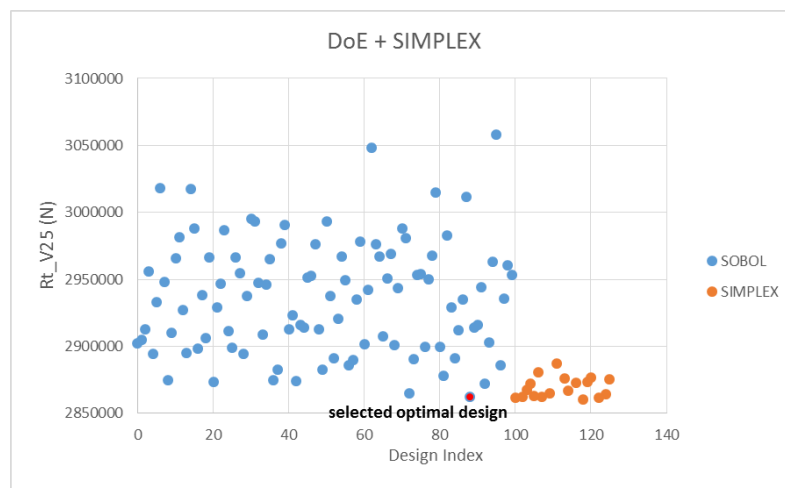


Figure 11-Single objective optimization process via SIMPLEX method for $V=25$ knots

The optimized model for the speed of 25 knots has a wave resistance reduction of 27%, an expressive result. However, regarding the total resistance, where the viscous effects are estimated from GL Rankine, the reduction is of 3.5% related to the base model. The optimized geometry has a bit longer and wider bulb as can be observed in Figure 12.

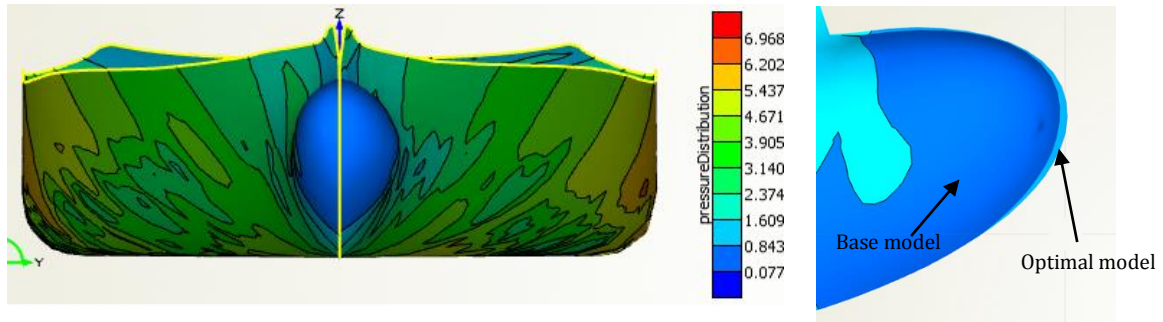


Figure 12-Comparison of base model (left) and optimized (right) for RT at 25knots

When comparing both models, optimized for V1 and V2 in both conditions, the results can be observed in a seesaw behaviour of the vessel when changing condition in Figure 13.

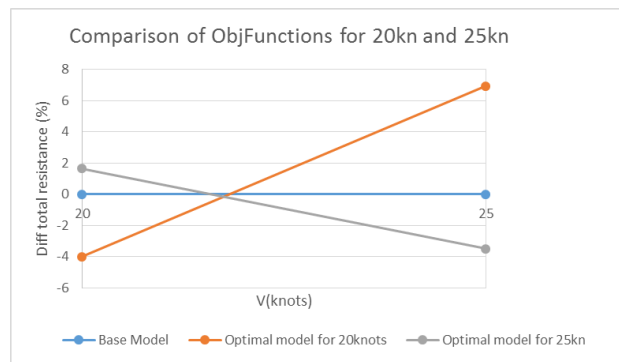


Figure 13-Comparison of Single objective optimization for 20kn and 25kn

7.2. Single Objective Optimization Process with Weighted Functions

Multi-objective optimization can be performed by using the weighted function in the single objective optimization functions. For the consideration of two different operational conditions as objective function on the optimization process, several techniques were used where the conditions are defined by the variation of the velocity ($V_1 = 20$ knots and $V_2 = 25$ knots). A single objective optimization method was performed in each case by SIMPLEX method and the multi-objective function (MoF) is defined as following:

$$\text{MoF} = \alpha * R_{TV1} + (1-\alpha) * R_{TV2}$$

Where, R_{TV1} and R_{TV2} are total resistance at the speeds of $V_1 = 20$ knots and $V_2 = 25$ knots and α is the weight function coefficient ($0 < \alpha < 1$). Three different values for the weight coefficients were considered: i. $\alpha = 0.25$, ii. $\alpha = 0.50$ and iii. $\alpha = 0.75$.

The weight of 0.25 means that 25% for the objective function is due to the resistance of the vessel at velocity V_1 and 75% related to the resistance of the vessel at velocity V_2 . It can also be observed that in both operational conditions the total resistance is reduced by the weighted method where both are considered in the optimization process.

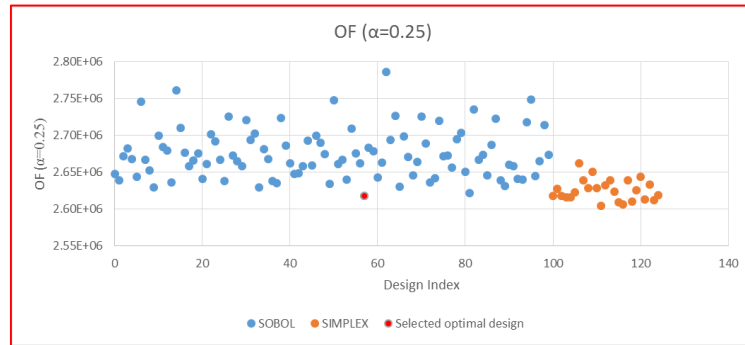


Figure 14-Weighted function $\alpha = 0.25$

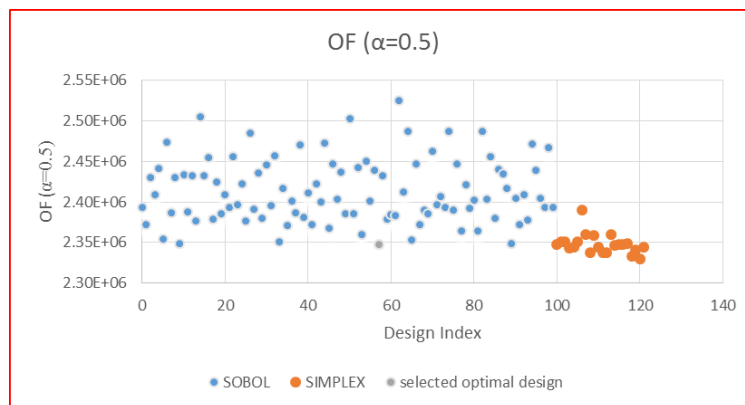


Figure 15-Weighted function $\alpha = 0.5$

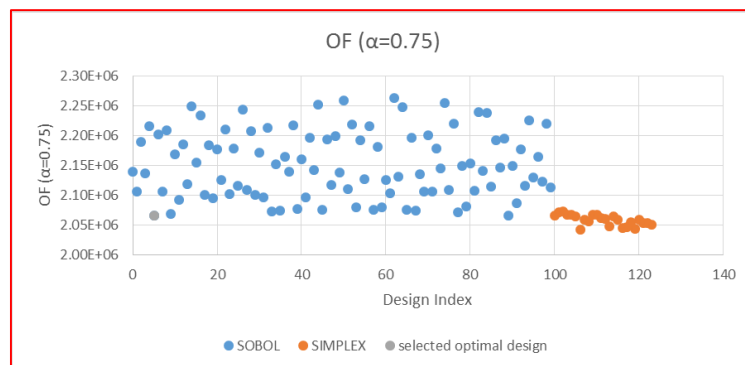


Figure 16-Weighted function $\alpha = 0.75$

It can be observed on Figure 17 that the trade-off characteristic is presented. As expected, when varying the weight, once for higher the weight better is the improvement regarding R_{tV1} . In addition, the weighted method possibility the optimization of the vessel for multiple objectives (Min R_{tV1} and R_{tV2}), as the vessels is optimized for both V_1 and V_2 conditions, and yet using the single objective SIMPLEX method.

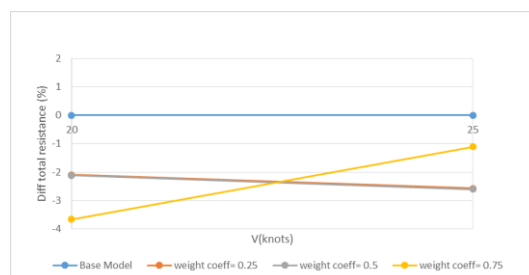


Figure 17-Weighted function. Comparison of all optimum designs regarding the R_T for both speed conditions.

7.3. Multi-Objective Optimization

In general, there is no design in which all the functions are minimal as there is no unique optimum design to a multi-objective optimization problem. However, there is a set of points that represents the best compromise between the various objectives called Pareto Frontier. Genetic algorithms are used to perform multi-objective optimization. Coming from the evolution theory the general principle of a genetic algorithm can be represented by:

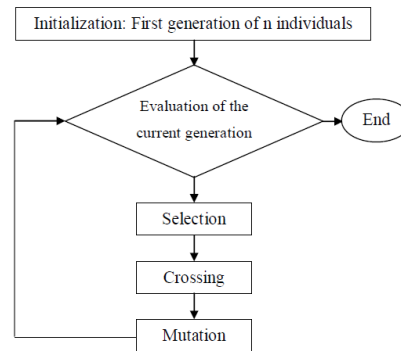


Figure 18-general principle of a genetic algorithm

7.3.1. Optimization Process

The algorithm chosen for the multi-objective optimization process is the Dakota MOGA (multi-objective genetic algorithm). The results presented a low percentage of designs in which both results R_T for V_1 and V_2 were achieved.

In optimization process, 300 unique designs were created and evaluated; the process took 4 days approximately running in a local machine. However, only 165 designs are feasible designs with the results of the total resistance for both V_1 and V_2 .

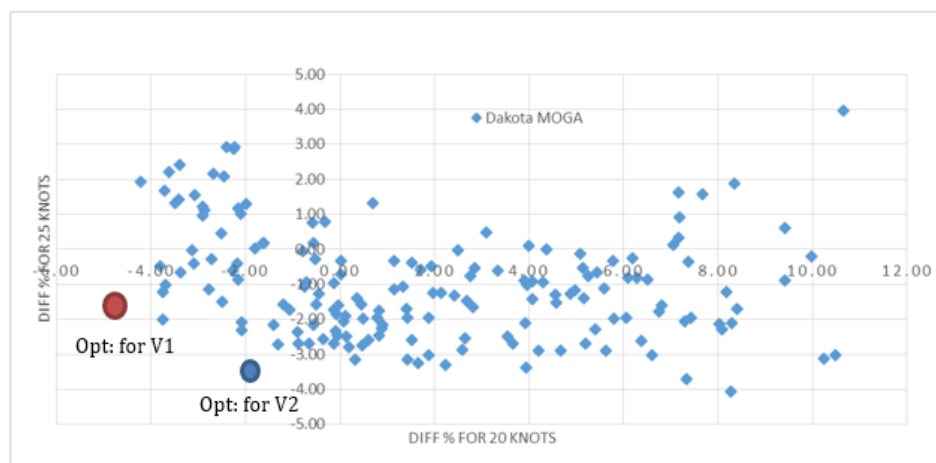


Figure 19-Multi-Objective Optimization Process with MOGA (Dakota)

From figure 19, it can be seen that two optimal design can be chosen. In 'Opt: for V_1 ', the reduction of total resistance is 4.75% for $V_1=20$ knots and 1.6% for $V_2=25$ knots. In 'Opt: for V_2 ', the reduction of total resistance is 1.9% for $V_1=20$ knots and 3.5% for $V_2=25$ knots.

8. Results

In Table 9, the number of CFD runs necessary to perform the optimization for each method and final performance obtained relative to the total resistance of the base model are presented.

		Objective Functions	CFD run(DoE+Opt)	Performance	
				20knot	25knot
Single Objective	DoE+ SIMPLEX	OF: V_1	122	-4.00%	2.00%
		OF: V_2	125	7.00%	-3.50%
Multi-Objective	Single Objective with weighted function	OF: $0.25*V_1+0.75*V_2$	124	-2.12%	-2.57%
		OF: $0.5*V_1+0.5*V_2$	121	-2%	-2.5%
		OF: $0.75*V_1+0.25*V_2$	123	-3.66%	-1.11%
	Dakota MOGA	OF: V_1 and V_2	167	-4.75%	-1.62%
		OF: V_1 and V_2	167	-1.94%	-3.50%

Table 9-Number of CFD runs and rel. resistance% to base model

When comparing the optimum designs obtained by the several optimization processes some trends of the form characteristics are observed in Table-10.

Objective Functions	Bulbous bow geometry characteristics								
	Length		Width		Height		bulb tangent at top (0 deg for Base)	Entrance Angle	Diff in Final Volume
OF: V_1	-76.56%	shorter	-64.84%	narrower	32.81%	higher	5.6 deg	-1.50%	-0.12%
OF: V_2	35.94%	longer	70.70%	wider	-4.69%	lower	4.375	-14.00%	0.22%
OF: $0.25*V_1+0.75*V_2$	78.13%	longer	-48.44%	narrower	65.63%	higher	-4.25	34.37%	-0.03%
OF: $0.5*V_1+0.5*V_2$	78.13%	longer	-48.44%	narrower	65.63%	higher	-4.25	34.50%	-0.03%
OF: $0.75*V_1+0.25*V_2$	25%	longer	-62.50%	narrower	-25%	lower	1	-75%	-0.07%
OF: V_1 and V_2	29.81%	longer	-59.93%	narrower	-37.31%	lower	0.0753502	42.50%	-0.06%
OF: V_1 and V_2	14.80%	longer	-21.78%	narrower	-62.64%	lower	10.6704	-84%	-0.005%

Table 10-Geometry trend of the optimized bulbous bow

The analysis is performed by the relative value of the design variable that defines the geometry. For example, the bulbous bow for the first case presents a value 76.56% shorter which means that the parameter that controls the length of the bulb is in between the mean value (base model) and the lower bound, in 76.56% of that range. The optimized bulbous bow for every case is narrower than the bulb of the base model and mainly longer bulbs are observed.

8.1. Selection of Optimal Model

Considering the good performance of the design obtained from different optimization process, the optimal model obtained from Dakota MOGA for $V_1=20$ knots was chosen as a final design model. This model has the reduction of total resistance is 4.75% for $V_1=20$ knots and 1.6% for $V_2=25$ knots. In Figure 20, the wave pattern of the base model, in top, and of the optimum design, bottom, are presented for the velocity condition one ($V_1 = 20$ Knots).

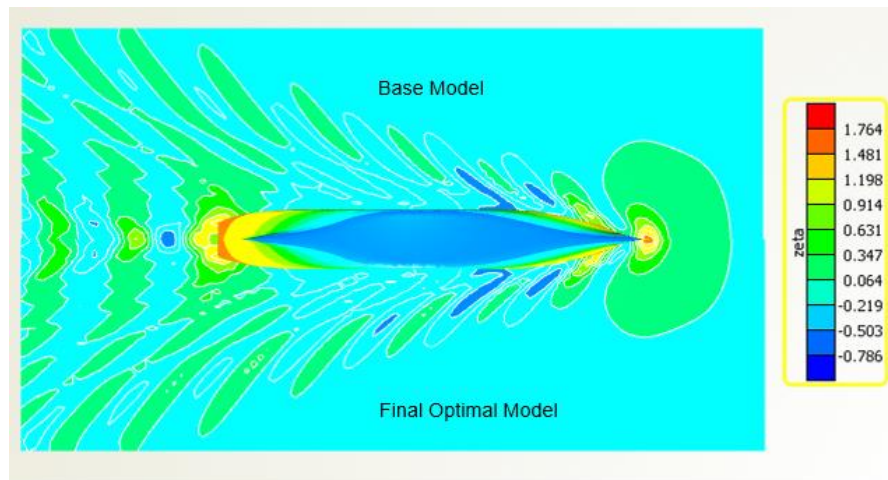


Figure 20-Wave pattern of the optimize and base hull form

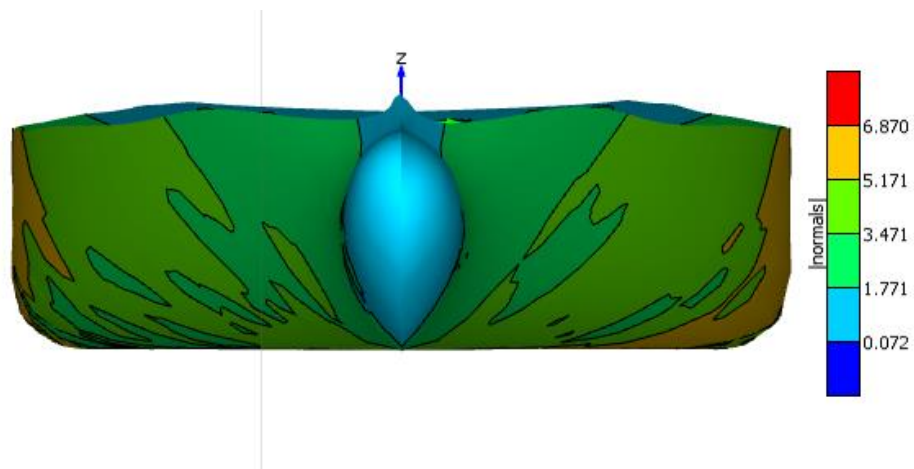


Figure 21-Base model (left) and optimum design (right) forebody with pressure coefficient.

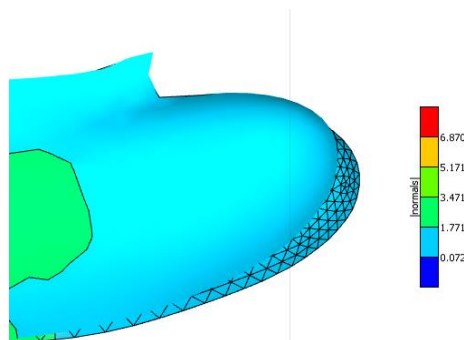


Figure 22-Base model (without mesh) and optimum design (with mesh) forebody longitudinal view

9. Conclusion and Recommendations

9.1. Conclusion

In summary, the single objective method leads to a very good improvement for the condition set as objective. The optimization with different objective conditions included in the objective function by a weight presented a very low degree of improvement. In addition, it can also be concluded that, as expected, the weight is an efficient way to move the objective from one condition to another in a smooth way. The multi-objective optimization by means of genetic algorithm, MOGA, considering the high number of necessary designs leads to a very expensive method with high cost/benefits. The higher number of designs could lead to more problematic designs which can compromise the optimization process. In conclusion, the proper selection of the optimization method for each case of study proves to be a key factor in order to achieve good results.

9.2. Recommendations

An adequate optimization method should be selected for each case of study; tests with simplified analyses should be performed for the selection. For the optimization processes it is important to have a good initial design that can be obtained via DoE (e.g. SOBOL method). While doing optimization process, the operation profile of the vessel should be considered for the robustness and sensitivity analysis. This project was performed only for the optimization of bulbous bow in calm water condition. The seakeeping performance of the vessel at different sea states should also be considered during optimization process.

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