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Scenario based optimization of a container vessel with respect to its projected operating conditions

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ABSTRACT: *In this paper the scenario based optimization of the bulbous bow of the KRISO Container Ship (KCS) is presented. The optimization of the parametrically modeled vessel is based on a statistically developed operational profile generated from noon-to-noon reports of a comparable 3600 TEU container vessel and specific development functions representing the growth of global economy during the vessels service time. In order to consider uncertainties, statistical fluctuations are added. An analysis of these data lead to a number of most probable upcoming operating conditions (OC) the vessel will stay in the future. According to their respective likeliness an objective function for the evaluation of the optimal design variant of the vessel is derived and implemented within the parametrical optimization workbench FRIENDSHIP Framework. In the following this evaluation is done with respect to vessel's calculated effective power based on the usage of potential flow code. The evaluation shows, that the usage of scenarios within the optimization process has a strong influence on the hull form.*

KEY WORDS: Ship design; Hull form optimization; Scenario; Operating conditions; Life-cycle analysis; Potential flow calculation.

INTRODUCTION

At least since the economical crisis the traditional way of designing ships is considered to be outdated. Operating ships at off-design conditions may appear as a good solution in times of a crisis and apparently leads to lower fuel consumption but there is a potential to save even more energy if the vessels would have been designed with respect to more operational conditions. But even without the crisis the process of designing a ship onto one operating condition had to be reconsidered, for the fact that both calculations or prognosis as done by Røe (2010) and analyses of operating profiles of real ships have shown that merchant vessels only operate at their respective design condition (e.g. at 85% Maximum Continuous Rating (MCR)) for a small amount of time.

Despite this fact, the knowledge of a vessels future operational profile is of great interest when it comes to environmental issues as a suboptimal ship design has a higher emission rate than an optimal one.

These problems necessitate a new approach which is capable to deal with future needs and uncertainties and which considers the vessels life-long operating situation. Keeping that in mind, scenario methods seem to be a suitable solution. By linking economical trend analysis with detailed operation profiles the usage of these methods offers the possibility to design ships which are not optimized to one or two particular operational conditions but will be significantly more efficient related to their overall operating time.

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LITERATURE REVIEW

The idea of using a complete operational profile as the basis for the development or optimization of a hull form instead of a single or only a few design points has been adapted within a few projects before. Two of them are in short presented in the following.

As an example, Temple and Collette (2012) have been using probability density functions in order to display the speed range of two vessels (DTMB-5145 naval combatant and KCS container ship) for a following multi-objective optimization of their hull forms. The optimization is done using a Multi-Objective Genetic Algorithm (MOGA) with the lifetime resistance being calculated from the integral over the speed dependant total resistance (estimated using the thin ship theory) multiplied by the Probability Density Function (PDF). The respective PDFs have been generated by applying a bimodal distribution with the two modes representing the vessel's endurance and mission speed in case of the DTMB-5145 and an unimodal distribution with the mode at the vessels design speed for the KCS. As far as the author is aware, those distribution functions are not based on statistics of existing vessels but on the author's consideration.

Statistically based probability distribution functions have been used by Eljardt (2010) in order to assess different vessel types, shipping routes or the commodity flow. Despite the speed distribution, he also considers environmental data such as seastate and wind conditions and other vessel specific data, e.g. the trim. Thereby, the respective distribution functions are taken from statistical analysis and / or prognosis. Within this work the distribution functions are used for sampling a sufficient number of ship operation conditions using the Monte Carlo Method in order to serve for example as the target function for an optimization of a ship's hull form and propulsion system. Although considering a wide range of parameters, this approach differs to the scenario based approach presented in this paper as it does not completely consider the coupled or correlated appearance of different parameters, which can lead to incorrect results in the target function (see next section for details).

GENERAL APPROACH

The basic idea of the scenario based approach is to predict the most probable operating conditions the designated vessel will stay in during its operating time in order to find the most suitable design variant. Fig. 1 shows the flow chart of the complete optimization process as presented in Wagner and Bronsart (2011).

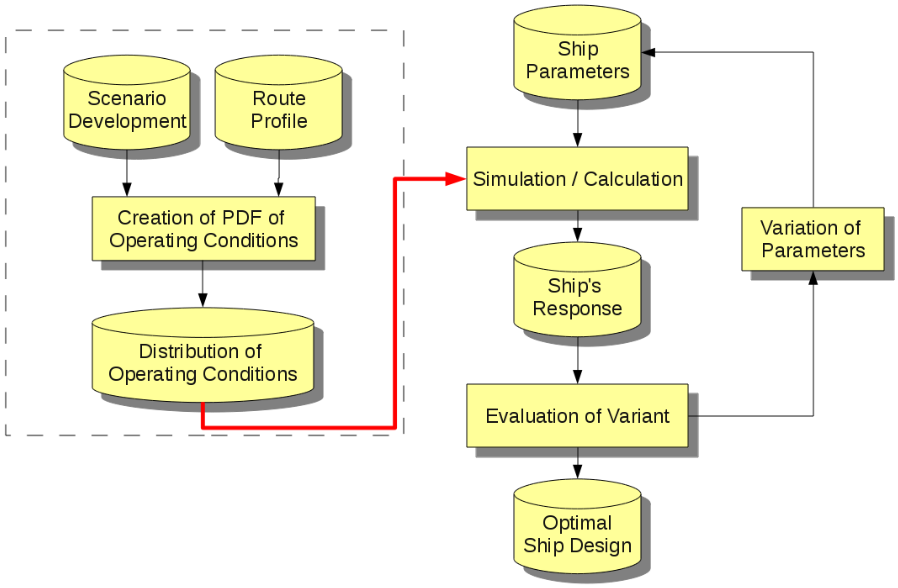

Fig. 1 Flow chart of optimization process.

It can be seen, that the general procedure can be divided into two stages. The first stage consists of the development of a probability density function of operating conditions on the basis of a given route profile and specific scenario development functions. Based on this distribution a target function can be derived, which consecutively will be handed over to stage two - a traditional hull form optimization process chain - in order to evaluate an optimal design variant. As the methodology of the second stage can be considered to be well known, this paper mainly focuses on the part of the scenario creation.

In order to meet the claim of developing a distribution of operating conditions and subsequently from this deriving the target function, a basic operational profile consisting of a chronological sequence of ship operating parameters will be projected into the future by reiterating it several times. This leads - as a simplified example only considering one unspecific parameter - to the picture given in Fig. 2.

To represent constantly changing surrounding parameters one or more development functions are added to the reiterated data. Continuing the above example and with a constant linear development function indicated by the dotted line the picture given in Fig. 3 develops.

Fig. 2 Scenario development, step 1.

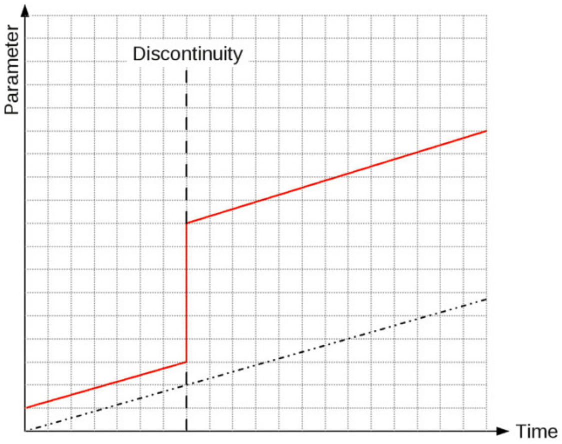

Fig. 3 Scenario development, step 2.

As the forecasted development functions normally are afflicted with insecurity, gradually increasing uncertainties in form of a normal distribution of probabilities will be added to the sequence. In Fig. 4 it can be seen, that at this point the probability of any possible value of a parameter P can be determined at any certain point in time T, allowing to sum up the respective probabilities of all operating situations the vessel will possibly stay in during its life-time.

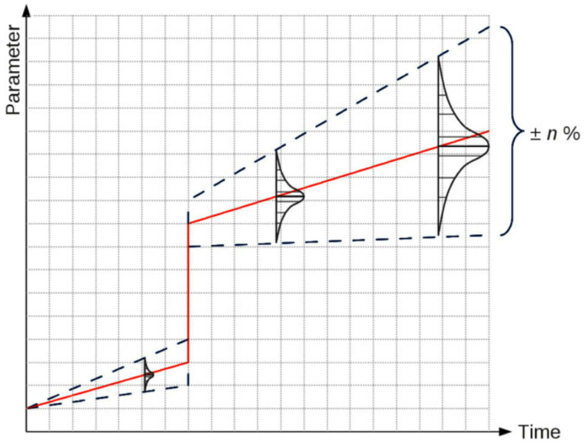

Fig. 4 Scenario development, step 3.

From the resulting Frequency Distribution (FD) of operating conditions the most probable ones can be chosen in order to serve as a basis for an optimization considering more than just one operating condition.

In case of more than one observed parameter one advantage of this approach against for example the Monte Carlo sampling of distribution functions of single parameters as done in Eljardt (2010) exists in the consideration of coupled appearances of different parameters. Fig. 5 shows the coupled exemplary distribution of speed (1 to 3) and draught (a to c) values of a vessel with the main peak at speed 1 and draught b, followed by speed 2 and draught b. Deriving the single parameter distribution results in the diagrams given in Fig. 6. It can be seen, that - when sampling these two diagrams - the designer would most probably come to the wrong conclusion, that the main operating condition is the combination of speed 2 and draught b. Although this problem can be solved for the Monte Carlo Method by the identification of correlations and the implementation of conditional probabilities, this approach can become time consuming, especially with a further increasing number of parameters. With an increasing complexity of the system, the direct modeling of the scenario approach becomes comparatively easier and will in most cases also be more accurate.

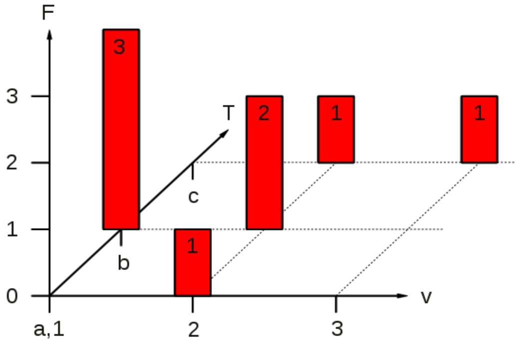

Fig. 5 Coupled speed / draught frequencies.

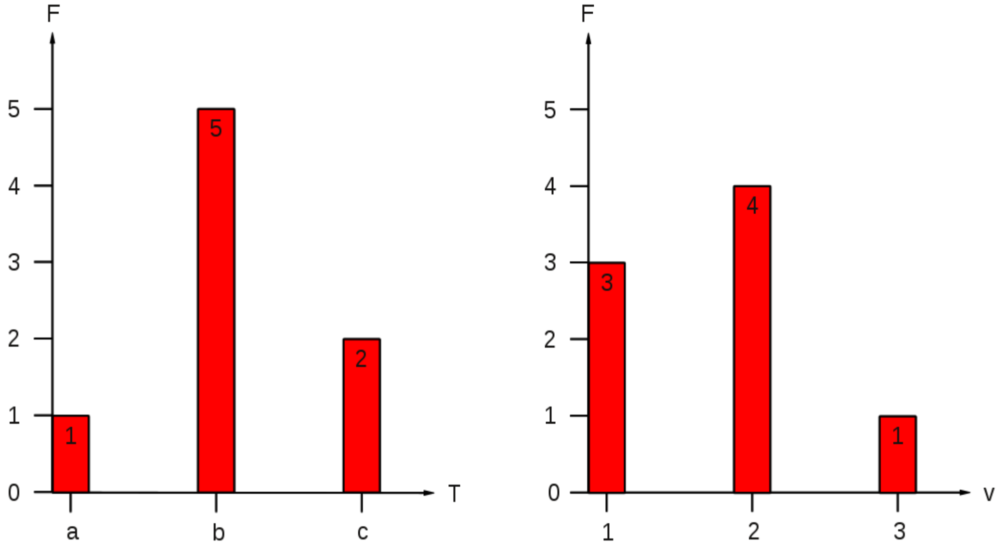

Fig. 6 Single draught and speed frequencies.

In the following the functionality of this optimization approach is presented using the example of the bulbous bow of the KCS.

BASIC DATA

To have a realistic basis to start with, the log-data of an existing comparable 3600 *TEU* container vessel of a German ship owning company have been analyzed. Data for this vessel were available from April 2008 to January 2012. Among other data the draught and speed of the vessel has been monitored and reported at any change in the vessels floating condition and additionally every twelve hours during transit resulting in 2329 data sets. It has to be noted, that for convenience all data sets concerning port times and pilotage area have been filtered out. Furthermore - as the observed vessel has slightly larger main dimensions as the KCS - the draught values have been scaled down by the factor 0.92.

As it covers approximately a time span of three years and eight months including the beginning of the economical crisis this data have been considered to represent a typical picture of today's vessels operating situation. When choosing bin sizes of 1 knot for the vessels speed and 0.5*m* for the draught the histogram given in Fig. 7 can be developed presenting the frequencies of the respective parameter combinations on the z-axis (note: for clarity reasons all images have been cut to the most relevant speed and draught ranges). It can be seen, that the vessel only spends a short amount of its operating time at its designated design conditions (v = 21.5*kn*, T = 10.8*m*). In fact, the actual percentage accounts for less than 1%.

As it is intended to not only consider the past but also the future, the existing data have been put into a loop covering a time span of approximately eleven years. In order to consider a possibly changing transport task due to changing economical conditions, assumptions regarding the possible future development of the global economy have to be done. For convenience reasons constant linear growths for all loops have been chosen as follows:

- Loop 1: -0.5% per year (decrease).
- Loop 2: 0% per year (stagnation).
- Loop 3: 0.5% per year (increase).

Subsequent a translation of these surrounding conditions to the floating condition of the vessel has to be done. In order to keep the model simple, the growth of global economy has been converted at its face value to the vessels draft.

In order to represent the insecurity of the above predictions a constantly increasing, normally distributed uncertainty of 0.5% per year has been added to the respective draught and speed values. From these operations the histogram given in Fig. 8 arises.

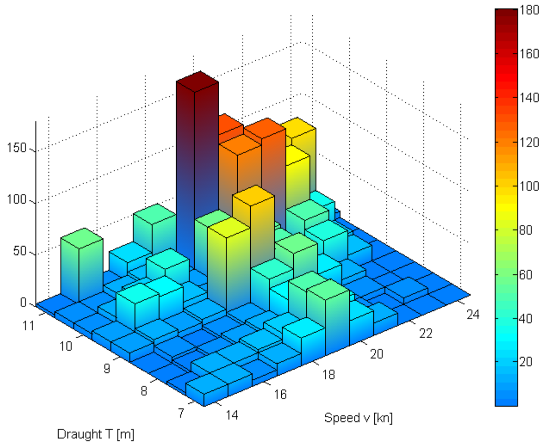

Fig. 7 Histogram of operating conditions of 3,600*TEU* container vessel (scaled 0.92).

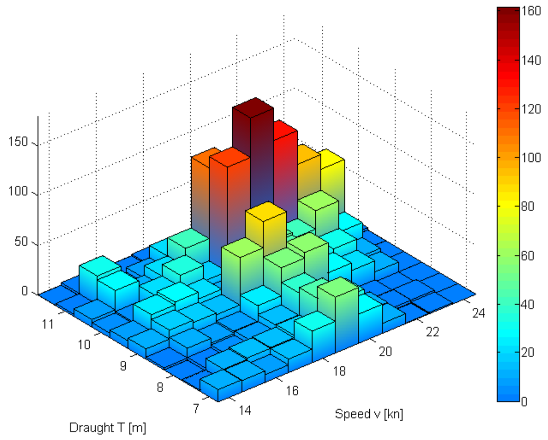

Fig. 8 Histogram of operating conditions after scenario development.

Despite the fact, that the whole profile has been flattened, it can be seen, that the major peak originally located at T = 10.5*m* and v = 18*kn* moved over to a higher speed value of v = 20*kn*. Furthermore the draught of 12*m* - not notably appearing within the histogram of the original operating conditions - comes up mainly due to the raising uncertainty. As this also leads to draughts higher than the maximum draught of the KCS (T_{max} = 12*m*), the frequency of these values have been allocated onto the maximum possible draught.

It has to be noted, that the chosen uncertainty can be considered to be very small value when it comes to economic predictions, but as it can be seen in Fig. 9, higher uncertainties strongly flatten the operational profile and therefore cause problems indentifying the major peak operating conditions.

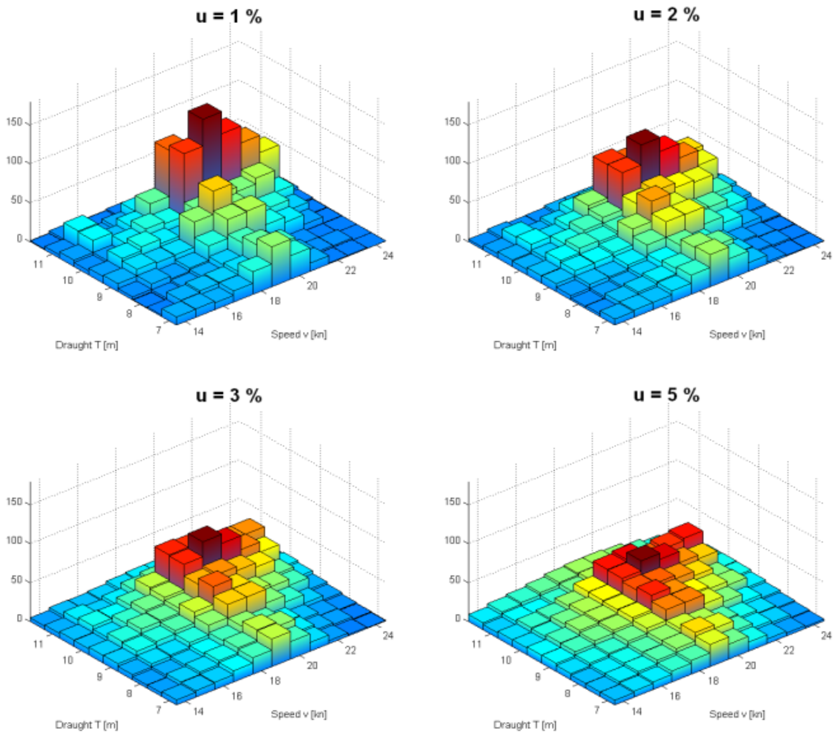

Fig. 9 Uncertainty influence onto operational profile.

In order to derive the optimizations objective function the four major peaks covering about 20% of the vessels total operating time have been chosen to represent the KCS' operational profile (Table 1).

Table 1 Operational profile.

	OC1	OC2	OC3	OC4
T [*m*]	10	10	10	10.5
v [*kn*]	20	21	19	19
Frequency [-]	161.4	129.1	121.8	110.5
Percentage of total OP [%]	6.19	4.95	4.67	4.23
Weighting w_{OCk} [%]	30.87	24.69	23.30	21.39

The first three conditions share a draught of T = 10*m*, distributed over different speed values (v = 19 to 21*kn*) while OC4 shows a increased draught of 10.5*m* at a speed of 19*kn*. Based on their respective weightings w_{OCk} (meaning their percentage of the four chosen operating conditions) those conditions are handed over to the *FRIENDSHIP Framework* to be used as part of the objective function.

MODEL

The parametric Model of the KCS is build based on the IGS-file offered by the SIMMAN 2008 workshop. Whilst the midship and the stern section have not been touched the stem has been parametrically remodeled. To do this, in compliance with Kracht (1978) the following four parameters have been introduced:

- ΔL_B: change of length of bulbous bow.
- ΔZ_B: change of height of bulbous bow.
- PB_y, PB_z: change of breadth of bulbous bow.

The implementation of the first two parameters has been done using the *Delta Shift* functions of the *FRIENDSHIP Framework*. Being comparable to the *Lackenby Approach* they allow defining Translations in *x* and *z* direction of the original bulbous bow based on shift functions which are controlled by the two mentioned parameters. The parameters PB_y and PB_z are used to define a *Surface Delta Shift* that works similar to the before mentioned function but with a distorted 3D surface instead of a 2D function. With these two parameters the shape of the enlargement of the bulbous bow can be controlled. An illustration of the parameters is given in Fig. 10.

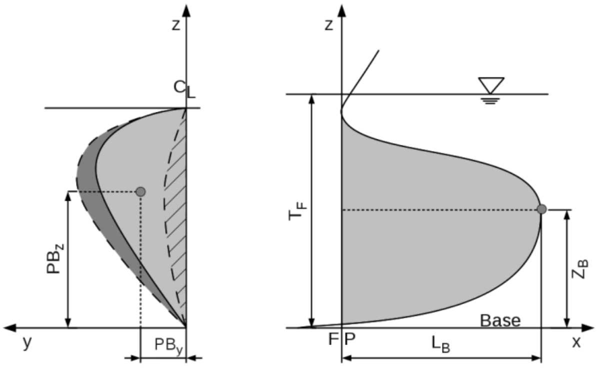

Fig. 10 Parameters of bulbous bow.

On the left side of this figure the (shaded) *Surface Delta Shift* controlled by PB_y and PB_z can be seen, which transforms the initial (light grey) bow into the new (dark grey) variant. It has to be noted, that the values of these parameters do not comply with the actual shifting of the bulbous bow.

In order to define the design space the boundaries of the mentioned parameters have been chosen as follows:

Table 2 Parameter boundaries.

Parameter	Lower bound	Initial value	Upper bound
ΔL_B [*m*]	-2	0	1
ΔZ_B [*m*]	-1	0	2.5
PB_y [*m*]	-5	0	4
PB_z [*m*]	-5	6	10

Those values reflect the idea, that the bulbous bow should neither emerge the prow nor pierce the waterline. In case of PB_y and PB_z the chosen boundaries ensure a correct resistance calculation. Using the initial values leads to the original KCS hull form.

It has to be noted that in order to verify an accurate resistance calculation, the meshing of the bulbous bow has also been done as a function of the parameters ΔL_B and PB_y.

OPTIMIZATION

The optimization of the KCS' stem section has been done with respect to the vessels weighted effective Power $P_{E,w}$ which is calculated for all four operating conditions by the help of the potential flow code *ν-SHALLO*. Thereby the calculation of the total resistance coefficient c_T is done using Eq. (1).

$$c_T = c_R + c_{F_{ITTC}} = c_{VD} + c_W + (1 + k_{Friction})c_{F_{ITTC}} \tag{1}$$

Here c_R is the residual resistance coefficient, $c_{F,ITTC}$ the frictional resistance coefficient due to ITTC 57, while c_{VD} is the viscous drag coefficient, which is an estimation of the viscous drag forces acting on the aft body of the hull form due to the thicker boundary layer. It is calculated by determining the fraction of resistance due to the viscous pressure while taking into account the maximum c_p on the aft body. c_W is the wave resistance coefficient and $k_{Friction}$ a ν-SHALLO internal form factor accounting for the change in the wetted surface area and the inhomogeneous velocity distribution (Marzi et al., 2010).

The weighted effective power then results from Eq. (2).

$$P_{E,w} = \sum_{k=1}^{4} R_{T,OC_k} v_{OC_k} w_{OC_k} \tag{2}$$

Thereby $R_{T,OCk}$ is the total resistance, v_{OCk} the speed and w_{OCk} the weighting of the respective operating conditions.

In a first step a *Sobol Algorithm* has been used to generate 200 quasi-random design variants covering the whole design space in order to find five starting variants that should help to indentify the global instead of a local optimum. As can be seen in Fig. 11 and 9, despite a few outliers caused by numerical errors some first trends can be spotted. The results indicate a dependency of the weighted total resistance on the length (ΔL_B) and the breadth (PB_y) of the bulbous bow. The variation of ΔZ_B and PB_z does not seem to have a major influence. Fig. 9 furthermore shows, that numerical errors are mainly caused by variants with a PB_y higher than 2.5*m*.

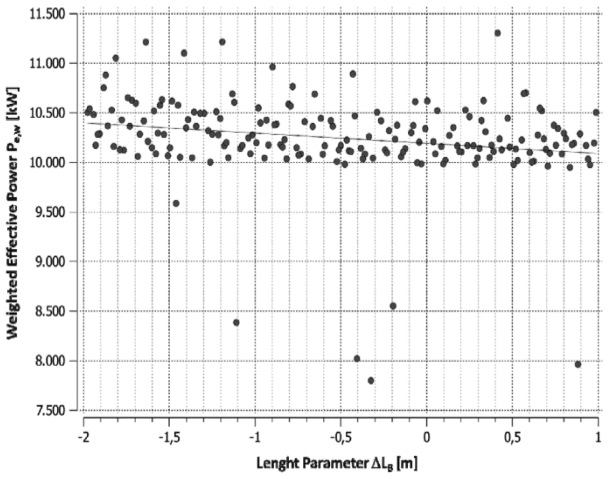

Fig. 11 Influence of ΔL_B variation on weighted effective power.

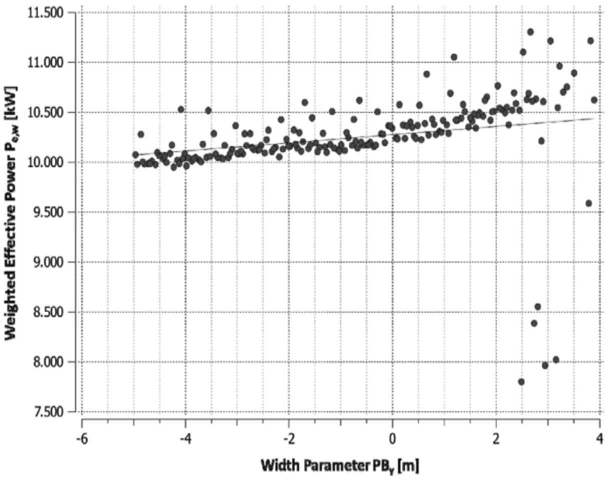

Fig. 12 Influence of PB_y on weighted effective power.

The final optimization of the five chosen starting variants has been done using the *Nelder Mead Simplex* of the *FRIENDSHIP Framework.*

RESULTS

The optimization leads to a design variant with the parameters given in Table 3.

Those values acknowledge the trends gained from the *Sobol Algorithm* as the newly developed bulbous bow is longer and smaller than the original one. Furthermore the tip of the bow rises as well as the point of its maximum breadth. This leads to an overall improvement in the weighted effective power $\gamma_{Pe,w}$ of approximately 2.7*%* in comparison to the ν-SHALLO calculations of the initial hull form.

Table 3 Optimal design parameters.

ΔL_B [*m*]	0.89
ΔZ_B [*m*]	0.95
PB_y [*m*]	-4.27
PB_z [*m*]	8.00
$P_{e,w}$ [*kW*]	9946.1
$\gamma_{Pe,w}$ [*%*]	-2.67

Table 4 Detailed optimization results and comparison to initial hull form.

	OC1		OC2	
v [*kn*]	20		21	
Fn [-]	0.217		0.227	
T [*m*]	10		10	
w_{OC} [-]	0.3087		0.2469	
∇ [m^3]	23374	-0.25%	23374	-0.25%
c_W [-]	4.81E-04	-12.89%	5.15E-04	-4.44%
$c_{F,ITTC}$ [-]	1.39E-03	0.00%	1.38E-03	0.00%
$k_{Friction}$ [-]	6.70E-02	-0.26%	7.11E-02	1.72%
c_{VD} [-]	5.90E-05	-8.14%	5.76E-05	6.35%
c_T [-]	2.02E-03	-3.66%	2.05E-03	-0.91%
c_R [-]	6.33E-04	-10.81%	6.71E-04	-2.73%
R_T [*kN*]	978.0	-3.75%	1094.4	-1.01%
R_R [*kN*]	306.3	-10.90%	358.1	-2.83%
P_e [*kW*]	10061.8	-3.75%	11821.7	-1.01%

	OC3		OC4	
v [*kn*]	19		19	
Fn [-]	0.206		0.206	
T [*m*]	10		10.5	
w_{OC} [-]	0.233		0.2114	
∇ [m^3]	23374	-0.25%	24869.1	-0.23%
c_W [-]	5.16E-04	-4.87%	4.57E-04	-8.47%
$c_{F,ITTC}$ [-]	1.40E-03	0.00%	1.40E-03	0.00%
$k_{Friction}$ [-]	6.54E-02	-2.00%	6.11E-02	-0.47%
c_{VD} [-]	5.95E-05	-39.46%	5.39E-05	-17.60%
c_T [-]	2.06E-03	-3.15%	1.99E-03	-2.65%
c_R [-]	6.67E-04	-9.14%	5.96E-04	-8.34%
R_T [*kN*]	901.1	-3.25%	904.7	-2.75%
R_R [*kN*]	291.2	-9.23%	270.7	-8.43%
P_e [*kW*]	8806.7	-3.25%	8842.4	-2.75%

The detailed results presented in Table 4 show decreasing power values for all four operating conditions. The biggest reduction of 3.75% is achieved in OC1, mainly caused by the decreased wave resistance coefficient (-12.89%). This seems to be reasonable due to the higher weighting of this operating condition. In OC2 the smallest reduction (-1%) is achieved. This could be an allusion to the fact, that the initial KCS hull form has been designed to operate on higher speeds. This statement is also supported by the speed-power diagrams at T = 10*m* and T = 10.5*m* given in Figs. 13 and 14, where the (dotted) power curves of the optimized hull in both cases cross the (dashed) ones of the initial hull at a speed of approximately 21.5*kn*. The difference between the two power curves is indicated by the continuous line.

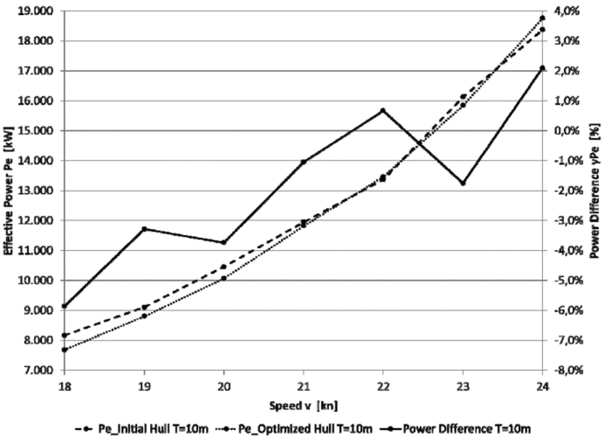

Fig. 13 Speed-power diagram (T = 10*m*).

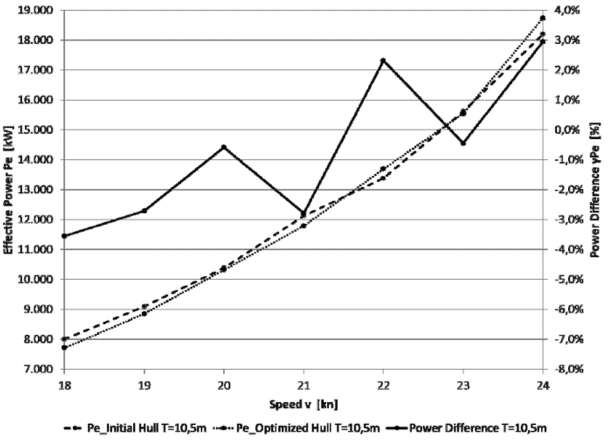

Fig. 14 Speed-power diagram (T = 10.5*m*).

The above figures furthermore indicate that the initial KCS has been designed with respect to higher draughts. A comparison between the power curves for the two draughts at speed values below 21*knots* shows that for the initial variant the weighted effective power $P_{E,w}$ at T = 10*m* is always lower than $P_{E,w}$ at a draught of 10.5*m*. In case of the optimized variant the opposite applies, due to the high weightings of T = 10*m*.

Looking closer on OC1 the comparison of the pressure distribution of the initial and the optimal bulbous bow at this operating condition (Fig. 15) as well as the respective comparison of the wave elevation (Fig. 16) give an explanation for the reduction in needed effective power.

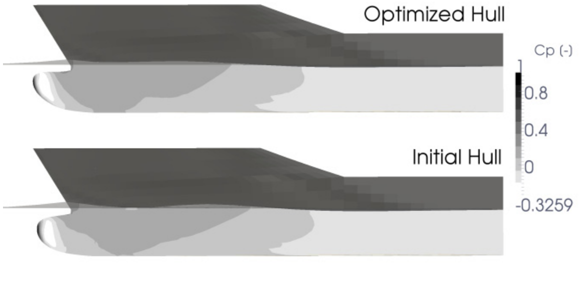

Fig. 15 Comparison of pressure distribution at OC1.

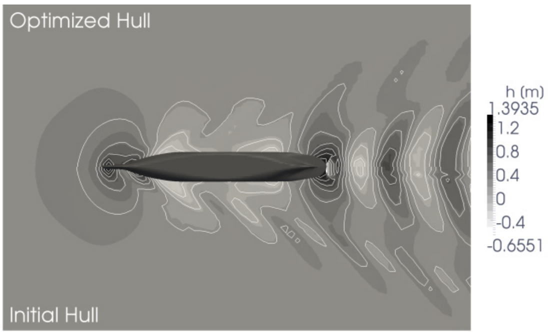

Fig. 16 Comparison of wave elevation at OC1.

The stagnation point at the tip of the optimized bulbous bow is smaller than its initial counterpart due to its decreased breadth. As a result of the uplifting the underpressure area at the top of the bow has become bigger leading - in conjunction with the slightly forward shifted area of overpressure - to a smaller bow wave elevation.

This effect is reflected in the comparison of the wave elevations, which shows a significant reduction within the vessels wake caused by the more advantageous wave interferences of the optimized hull form.

In general, the achieved results comply with the outcome of other related studies on the topic of hull form optimizations based on more than one operating condition. As an example Ernst and Hollenbach (2011) come to the conclusion that a multi-objective hull form optimization typically leads to reduced, less distinctive bulbous bow.

CONCLUSIONS AND OUTLOOK

The presented method for the scenario based optimization of parametrically modeled hull forms has shown to be reliable and to achieve reductions in the needed effective power. In order to validate the method more and especially more comprehensive optimizations have to be done as the achieved results seem to be dependent on many factors.

At first, the data taken as basic input to the scenario development is of great importance. It should be taken care of, that the data cover a sufficiently long period of time and can be considered to be complete. Furthermore they should belong to a comparative vessel operating on a comparable or the same route.

The second point aims at the uncertainties. As shown in Fig. 9 the consideration of higher uncertainties results in flattened operational profiles, which leads to the need of considering more than four operation conditions within the objective function. In the course of this it should be analyzed, whether the consideration of a higher coverage of the selected operating conditions leads to better results.

Despite those factors there are some other possibilities for increasing the approaches accuracy. One exists in reducing the bins, allowing it to optimize onto more specific operating conditions. On the other hand and in accordance to the increase of uncertainties reduced bins would raise the need for considering a higher number of operating conditions in order to achieve a certain coverage. It has to be noted, that not only the size but also the bins' position has a notable influence on the objective function.

Other possible improvements can be done by using RANSE instead of potential flow code or a more sophisticated model with more parameters that make it possible to control the complete hull form instead of only the bulbous bow.

The next steps in developing the scenario based optimization approach primarily focus on the implementation of more features into the scenario development. As an example future versions should be able to predict and consider weather conditions and should come with an enhanced objective function. The latter will be capable of executing life-cycle analyses taking into account economic parameters like for example constantly developing fuel oil prices.

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