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Ship Hull Form Optimization Using Scenario Methods

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Abstract

An operational profile for a post-panamax container vessel design, the Duisburg Test Case (DTC), operating in an Europe-Asia-Trade is developed. As the DTC is designed for benchmarking, no real service data are available. Therefore, shipping trades of similar ships and data from shipping companies are analyzed in order to derive operating conditions for the DTC in service.
A scenario program is applied to forecast a number of most probable upcoming operating conditions considering several operational aspects such as changing of transport demand, slow steaming decisions or speed reduction due to bad weather. To supply the forecasting program with reasonable input values is one aspect of this paper.
The forecasted ship specific operating conditions build the basis for the following scenario-based optimization. The optimization leads to a design best fitting its designated transportation tasks. Results of the hull form optimization are discussed. The benefits of a scenario based optimization are demonstrated.

Keywords

Ship Design; Hull Form Optimization; Scenario; Operating Conditions; Potential Flow Calculation

Introduction

Optimizing the ship economical performance with primary focus on its hull form resistance based on multiple design condition has gained considerable importance over the last years. Driving parameters are the increasing fuel cost and the need to reduce emissions. Usually design conditions for optimization are derived by analyzing the operational profile of existing ships on common shipping routes. Scenario based optimization however means to optimize based on forecasted operating conditions by adding a scenario for future needs. This offers the potential to save energy and leads to hull designs which are more robust against changing operational conditions. In the investigations of (Wagner et al., 2013) scenario based optimization was already realized. Compared to this study a distinctly advanced scenario approach is applied in the following. The basis for building up a scenario and the following forecasting process defines the operating data of a sailing ship, which is often not available. Therefore the aim of this study is to build the basis for a study on a scenario-based optimization for the DTC (el Moctar et al., 2012). Therefore a forecasting program is supplied with reasonable input values. The forecasting requires input in form of a variety of information regarding route, seaway and the development of the market conditions such as fuel oil price and transport demand. Also an optimization environment has to be built up.

Scenario Program

A scenario program is developed to forecast a number of most probable operating conditions. This section gives a short introduction to the functionality of the program and the information which are needed for its execution.
The forecasted operating conditions consists of draft, speed and seastate information in form of significant wave height and wave period. The scenario model is considering several operational aspects by implementation of influencing factors, development functions as well as global and local restrictions.
The draft of the ship is determined due to a specific draft-loading-function and is influenced by the function of the changing transport demand as well as global and local boundary conditions due to draft restrictions of the ship itself and restrictions along the route. The changing transport demand is a function of the development of the economic growth.
The speed of the ship is affected by

- a slow steaming function,
- a function of speed reduction due to bad weather,
- a function to regain lost time,
- and also by global and local boundary conditions.

The slow steaming function is controlled by the estimated development function of the fuel oil price: a slow steaming table determines the maximum speed according to the fuel oil price. The speed reduction due to bad weather conditions is also specific as a list, in which the maximum speed is a function of the wave height. If it is necessary to reduce the speed due to high waves the scenario program enables, if possible, to regain lost time in following route sectors. The speed restrictions of the ship itself and the restrictions during the voyage has to hold nevertheless.

As the development functions of the fuel oil price and the economic growth are basically unknown, uncertainties and even crises can be considered. Uncertainties are handled by a fluctuation function, whereas the crises is driven by the parameters occurrence frequency, average crisis duration, standard deviation of the crisis duration as well as the probability of rising fuel oil price or economic growth respectively.
All factors influencing the development of the scenario are called scenario parameters and are predefined by the user of the program. According to the chosen scenario parameters a scenario is developed on the basis of a route profile (Fig. 1).

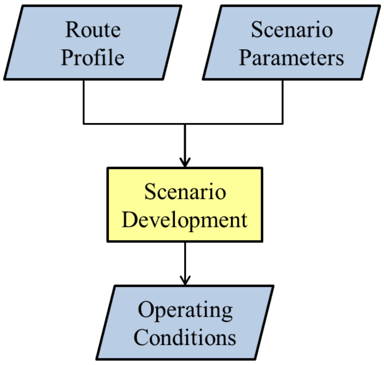

Figure 1. Scenario Model

A route profile consists of a list of route segments and contains the description of the trade and the amount of goods to be transported accompanied by local constraints. For the description of the trade, information have to be given about the distance of the route segment, the weather condition, the initial speed of the ship, the lay time and the type of the port. The weather condition is specified by a sea area ID according to the scatter table of global seaway statistics obtained by (Söding, 2001). The port type is defined specifically indicating the additional services in of port operations like docking or refueling. Information about the number of full and empty containers (TEUs) are necessary to calculate the draft of the vessel via the ship specific loading-draft function.
For calculating the probability distribution of the operating conditions the Monte Carlo method is applied. The scenario program uses all given input to run through a specific number of life cycles creating randomly varying vessel lives, intendedly in the end covering all future developments of the specified descriptors and their respective combinations being possible. All operating conditions appearing within these runs will be clustered according to user-given constraints and then summed up respective their weightings.

Route Profile

The previous section gave a brief description of the information which is included in the route profile, as it is one main input for the scenario program. As no real service data of the DTC exist, shipping trades of similar ships are used. Hence in this paper, the route profile is derived based on 13 800 TEU vessels of the Thalassa Hellas series. The data available are from bringing into service until the end of 2014 and is limited to Europe-Asia-trades.
One single round trip of the specific vessel Thalassa Hellas is selected to generate the route profile for the DTC. On the journey with a duration of about 73 days 12 ports are called (Fig. 2).

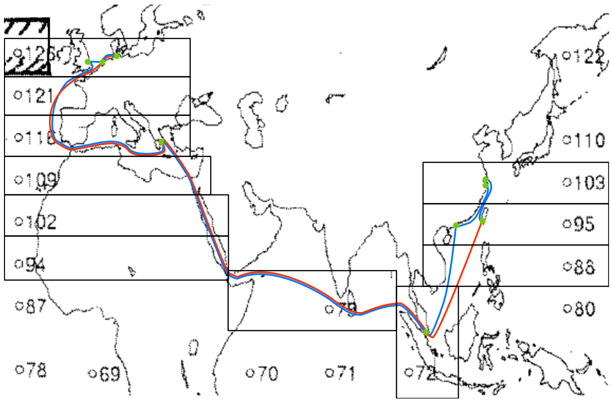

Figure 2. Voyage of the Thalassa Hellas on the wave statistic map from Söding

The specific route is divided into route segments, each representing one part of the trade with constant characteristics. The trip between two ports consists of at least five route segments: port (two times), estuary trading (two times) and transit. On the comparatively long transit changes of weather conditions (Sea Area ID) and speed due to crossing the Suez Canal lead to the necessity of accordingly additional route segment.
The received operational data only contains information about the time of arrival and departure. To determine the initial speed of the vessel v_{ini} for each route segment, distances between two ports as well as distances at the the port areas and rivers are based on the data found on the website (SeaRates, 2015). Assumptions for vessel speeds in port areas and on rivers are made to correct the real transit time and complement the route profile. The zoning of the wave statistic map from Söding helps to estimate the distances of constant weather conditions and to define the sea area ID for each route segment (Fig. 2).
For the port route segments the lay time t_{port} and the port type are derived. The lay times are directly taken from the data of the Thalassa Hellas. The port type as well as local constraints $v_{min,l}$, $v_{max,l}$ and $T_{max,l}$ are determined.The received data also contain information about the ratio of full and empty containers. These values are used for the calculation of full and empty TEUs respectively.
To get an impression how in the derived route profile looks like, a section for the voyage between Rotterdam and Hamburg is shown in Table 1.

Table 1. Route profile between ports of Rotterdam and Hamburg.

distance $[sm]$	sea area ID [-]	v_{ini} $[kn]$	t_{port} $[h]$	port type [-]	TEU_{full} [-]	TEU_{empty} [-]	$v_{min,l}$ $[kn]$	$v_{max,l}$ $[kn]$	$T_{max,l}$ $[m]$
0	126	0	53.33	4	5683	1933	0	0	17.5
2.4	126	6.3	0	0	1804	1698	0	10.0	0
276.8	126	19.5	0	0	1804	1698	0	0	0
3.5	126	6.3	0	0	1804	1698	0	10.0	0
0	126	0	57.5	5	1804	1698	0	0	15.1

Table 4. Speed reduction due to bad weather conditions

$H_{1/3}$ $[m]$	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5
$v_{max,H_{1/3}}$ $[kn]$	22.8	20.6	18.4	16.2	14	11.8	9.6	7.4	5.2	3	0.8

Table 5. Parameters of the fuel oil price development

development function	$t \leq 8765.82:\ FOP_{ini} = 275 - 50 \cdot (t/8765.82)$
	$t > 8765.82:\ FOP_{ini} = 225 + 50 \cdot (t/8765.82 - 1)$
fluctuation per day	$1.5\,\$$
occurrence frequency	$40\,\%$
average crisis duration	$4382.91\,h$ (0.5 years)
standard deviation of crisis duration	$4382.91\,h$ (0.5 years)
probability of rising	$50\,\%$

Scenario Parameter

As an additional input to the forecasting program scenario parameters are necessary.
First of all the vessel characteristics and the forecasting horizon must be defined. They are listed in Table 2.

Table 2. Scenario and vessel characteristics

time horizon	$87\,658.2\,h$ (10 years)
$T_{min,g}$	$10\,m$
$T_{max,g}$	$15.5\,m$
$v_{min,g}$	$0\,kn$
$v_{max,g}$	$25\,kn$
LDF	$7.8136 + ((n_{TEU,f} \cdot 11.85$ $+ n_{TEU,e} \cdot 2.0) \cdot 6e^{-5}$
dry-docking interval	$43\,829.1\,h$ (5 years)
dry-docking time	$504\,h$

The minimum draft of the vessel $T_{min,g}$ (no trim assumed) is limited by the requirement that the propeller should be fully submerged under all conditions. The maximum draft $T_{max,g}$ is assumed $1\,m$ above the design draft, assuming that the scantling draft and all safety criteria do allow this. The maximum speed of the vessel $v_{max,g}$ is equal to the design speed of the DTC.
The ship specific loading-draft-function (LDF) is determined based on the data of the Thalassa Hellas vessels. With help of these data the average values of the mass of full and empty containers were calculated resulting in $11.85\,t$ for a full container and $2\,t$ for an empty container. Based on values for the numbers of full and empty TEUs and the related drafts a linear regression is derived which is used as the loading-draft-function. For the determination of the dry-docking intervals and time information in personal communication with shipping company are applied. In the course of the investigations the shipping company also provides information about questions in the scope of the forecasting approach.
For the slow steaming function assumptions are made as shown in Table 3). According to explanations of the shipping company no standard concept exists on slow steaming criteria.

Table 3. Slow steaming effect: max speed dependend on FOP

FOP [\$]	$v_{max,FOP}$ $[kn]$
550	20
600	18
700	16

The speed reduction due to bad weather conditions is provided by the University of Duisburg (Table 4) which is based on investigations to determine operational conditions in seaways for the DTC.
The applied parameters of fuel oil price and economic growth development are listed in Tables 5 and 6 respectively. The assumptions are made with the help of the “Review of Maritime Transport 2015” (UNCTAD, 2015) and experiences of a shipping company. For the eco-

nomic growth development the progress of the container transport demand is analyzed.

Table 6. Parameters of the economic growth development

development function	$E_{ini} = 0.05 \cdot (t/8765.82)$
fluctuation per day	$0.5\,\$$
occurrence frequency	$13.33\,\%$
average crisis duration	$8765.82\,h$ (1 year)
standard deviation of crisis duration	$1460,97\,h$ (2 months)
probability of rising	$25\,\%$

Forecasted Operational Profile

Considering the scenario parameters an operational profile is forecasted by the scenario program based on the developed route profile. Here the chosen range width for the ship speed is taken to $0.5\,kn$ and for the draft to $0.5\,m$. The following Table 7 lists the seven most frequent operating conditions (OC) and their respective fraction of the total profile w:

Table 7. Operating conditions of the forecasted profile

OC	v [kn]	T [m]	w	$w_{cum,n}$
1	22.5	15.5	0.1277	0.1277
2	19.5	15.5	0.0709	0.1986
3	16	15.5	0.064	0.2626
4	19	14	0.0561	0.3187
5	18	15.5	0.0552	0.3739
6	22.5	13.5	0.0413	0.4152
7	19.5	15	0.0348	0.45

Although the scenario program is capable to also output the seaway conditions for the various operating conditions, in the following optimization the seastate is not considered. The reason for this approach is that previous calculations have shown that neglecting the wave resistance for each design variant in the optimization process, specially for large vessels like the DTC, but performing the resistance calculation for calm water conditions has principally no impact on the result, the optimal design variant.
The cumulated weightings $w_{cum,n}$ are simply calculated using equation 1 and give an idea of the increasing coverage of the operational profile while consideration more operating conditions.

$$w_{cum,i} = \sum_{i=1}^{n} w_i \qquad (1)$$

The seven most frequent conditions sum up to $45\,\%$ of the total forecasted operating profile. They are characterized by a spreading of the vessel's speed between 16 and 22.5 kn. The drafts cover a range from 13.5 to 15.5 m, of which the maximum draft of $15.5\,m$ is of largest significance. With an increasing number of operating conditions the specific weightings do not differ considerably, see also Fig. 3 in which the weigthings are shown as function of draft and speed. Form the figure it becomes obvious that it is almost impossible to identify the number of operating conditions to be chosen for the hull form optimization.

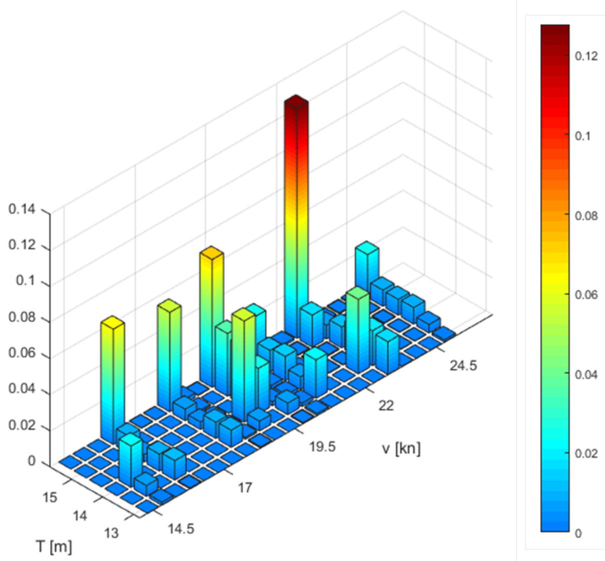

Figure 3. Forecasted operational profile

Parametric Hull Form Model

To automatically modify the ship hull form in the optimization process, a parametric model of the DTC is defined based on a STL-representation. In a first step only the bulbows bow is parametrically remodeled. The midship and the aft sections remain constant and equal the original form. The parametric modeling is performed with the software CAESES/FFW. In accordance to Kracht (Kracht, 1978) the following five parameters are introduced to modify the bow (Fig. 4):

- ΔL_B: parameter for the change of length of the bulbous bow
- ΔZ_B: parameter for the change of height of the bulbous bow
- P_x, P_y, P_z: parameters for the change of breath of the bulbous bow

The implementation of the parameters is done using the *Surface Delta Shift* transformation which allows modifications of the local hull form surface in the direction of a specified axis whose delta values are given by surface coordinates (Friendship Systems, 2016). The transformations for the change of length and height of the bulbous bow are controlled by the parameters ΔL_B and ΔZ_B respectively, in which the values of these parameters dedine the actual transformation. The change of breath of the bulbous bow is controlled by the coordinate values of a specific point P_x, P_y and P_z. The transverse modification of the bulbous bow is illustrated on the left in Fig. 4. It shows the transformation of the initial bow (light blue) due to the *Delta Shift Surface* (dashed area) to the new design (dark blue).

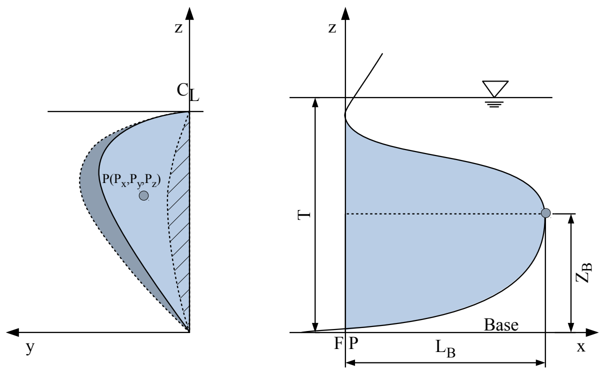

Figure 4. Parameters of bulbous bow modifications

All transformations are applied on a *Image Trimesh*, which is directly used for calculation of the resistance in the optimization process. Table 8 shows the boundary conditions of the parameters are utilized to define the design space: The values of ΔL_B and ΔZ_B ensure, that the bulbous bow never pierces the waterline. The values are also chosen in order to guarantee that no unrealistic bow forms occur. Applying the initial values results in the original hull form.

Table 8. Parameter boundaries

Parameter	lower bound	initial value	upper bound
ΔL_B $[m]$	-4	0	5
ΔZ_B $[m]$	-5	0	4
P_x $[m]$	345	355	365
P_y $[m]$	-3	0	4
P_z $[m]$	2	7.75	12

Optimization

The optimization target is to reduce the fuel oil consumption based on the minimized effective power. Here the assumption is made that the propulsion parameters are not influenced by the hull form modifications in the most forward hull form region. Additionally no dependance on the draft and speed is assumed. A varying number of operating conditions of the forecasted operational profile is considered:

$$P_{e,w}(w_{cum,j}) = \sum_{i=1}^{j} R_{T,i} \cdot v_i \cdot \frac{w_i}{w_{cum,i}} \quad (2)$$

The optimization of the DTC bulbous bow region is performed with the software CAESES/FFW, in which the calculation of the total resistance $R_{T,i}$ for the respective operating conditions is done with the potential flow code GL Rankine. The total resistance is calculated to:

$$R_{T,i} = (1 + k) \cdot R_{F,i} + R_{W,i} \quad (3)$$

Here the k-factor is taken to be constant for all operating conditions with $k = 0.145$. Investigations of the University of Duisburg support this assumption, even though this can be specifically problematic in case of larger variations in e.g. draft. The frictional resistance $R_{F,i}$ is determined according to the ITTC 57 formula. The wave resistance $R_{W,i}$ results from the pressure distribution in the potential flow.
To cover the whole design space (Table 8) 600 quasi-random design variants are generated using a Sobol Algorithm. For each of these variants the resistance is calculated for any operating condition listed in Table 7 to determine the effective power according to the number of considered conditions $P_{e,w}(w_{cum,j})$. The design variant causing the minimum effective power represents the optimal hull form under the specified conditions. This conclusion could be justified by further optimization with help of a Nelder-Mead-Simplex method: in all cases the "Sobol solution" could not be further improved.

Optimization Results

The variation of the form parameter with the Sobol Algorithm leads to optimal design variants as shown in Table 9. Irrespective of the number of operating conditions accounted for the optimal bulbous bows are longer compared with the base model (BM): ΔL_B always positive. While increasing the number of considered operating conditions the width trends to become smaller, a fact which is known form hull form investigations based on multiple operating conditions. For the parameters P_x and P_z no clear tendencies can be identified.

Table 9. Optimal design variants as function of number of operating conditions

OC	ΔL_B $[m]$	Δz_B $[m]$	P_x $[m]$	P_y $[m]$	P_z $[m]$
1	1.85	1.98	364.6	0.21	5.07
1-2	1.90	0.91	345.6	-0.59	5.44
1-3	2.26	-0.71	351.7	-0.76	11.14
1-5	1.68	-1.64	360.6	-1.89	11.59
1-7	1.36	-0.76	358.8	-1.59	7.64

The improvements gained by the form variations become apparent by the comparison with the initial hull form (Table 10). The weighted effective power considering $45\,\%$ of all conditions of the operational profile can be reduced by about $1.23\,\%$.
The diagrams in Fig. 5 show the results of the form variation considering the first seven operating conditions. The weighted effective power is plotted over different design parameters. Clear limit curves with tendencies are formed for the parameter ΔL_B, Δz_B and P_y. The optimal design is located on the bottoms of these limit curves.

Table 10. Comparison of optimal design variant to initial hull form

	$P_{e,w,1}\,[kW]$	$P_{e,w,2}\,[kW]$	$P_{e,w,3}\,[kW]$	$P_{e,w,5}\,[kW]$	$P_{e,w,7}\,[kW]$
base model	32455	28364	24404	22456	22945
optimum	32089	28210	24315	22252	22663
δ	-1,13 %	-0,54 %	-0,36 %	-0,91 %	-1,23 %

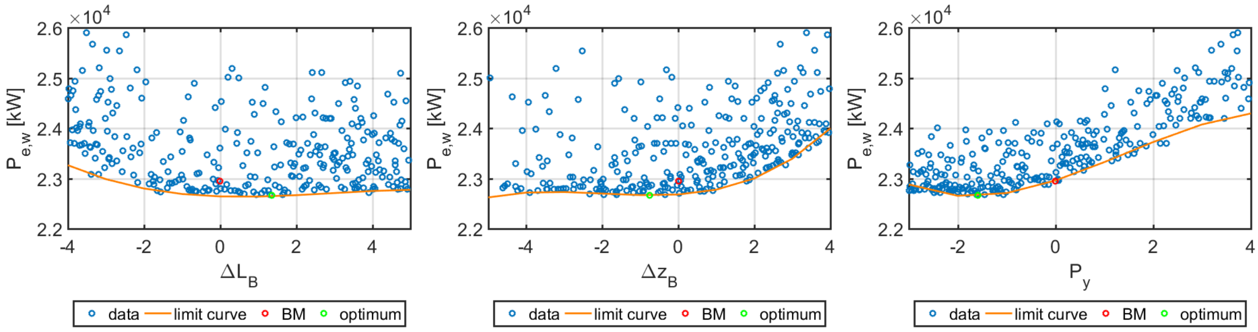

Figure 5. $P_{e,w,7}$ as a function of the design parameters ΔL_B, Δz_B and P_y (BM for Base Model)

The calculations reveal that the courve progressions are independent of the number of considered operating conditions.
To investigate the sensitivity of results according to the number of considered operating conditions the different values of weighted effective power are normalized to the weighted effective power of seven conditions, see Eq. 4 in which the variable 'OptiForm()' represents the related optimal variant.

$$P_{e,norm}(w_{cum,i}) = \frac{P_{e,w}\left(\text{OptiForm}(w_{cum,i}) \Rightarrow w_{cum,7}\right)}{P_{e,w}\left(\text{OptiForm}(w_{cum,7})\right)} \quad (4)$$

In Fig. 6 the normalized effective power is plotted over the cumulated weightings. An asymptotic trend can be identified: with an increasing number of considered operating conditions an optimal design with respect to the overall operational profile can be found. The optimal design, considering only one operation condition leads to about 3 % more power with respect to the design considering seven conditions, in the latter case covering 45 % of the vessel's forcasted speed and draft combinations.

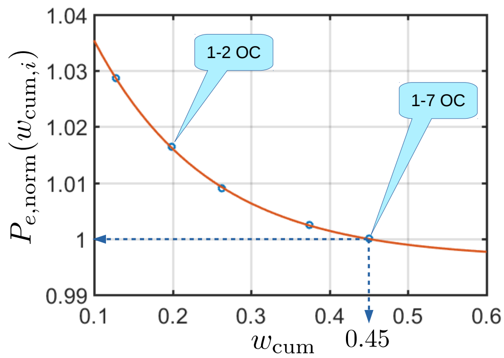

Figure 6. Normalized effective power according to the number of considered operating conditions, see Table 7

Conclusion and Outlook

The presented method for a scenario based optimization of a parametrically modeled hull form shows how to achieve reductions of the effective power in order to gain savings of fuel oil and costs. It is shown that the consideration of seven conditions, representing 45 % of the total operational profile, leads to a design that is almost optimal for satisfying the designated transportation task.
For the introduced scenario approach reasonable input values are found to determine a operational profile for the DTC. Therefore simplified assumptions are made mainly due to the lack of information. To improve the optimization RANSE-methods could be used instead of potential flow code for determine more precise resistance results. Also the expansion of the parametric model with additional form parameters controlling the complete hull form could be interesting for continuing studies. The validation of the scenario method with real case studies should the the focus for the next steps.

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