Application of Holistic Ship Optimization in Bulkcarrier Design and Operation

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Abstract The recent years have seen an evolution of traditional approaches in ship design. Raising fuel costs, tough and volatile market conditions, the constant societal pressure for a «green» environmental footprint combined with ever demanding international safety regulations pose a new challenge for today's Naval Architect. As a result of this current status of shipping commercial ship design is shifting towards new approaches where holistic approaches are deemed necessary. Apart from considering all the interrelationships between the subsystems that consist the vessel, lifecycle and supply chain considerations are the key in successful and «operator-oriented» designs. The paper presents a methodology within the parametric design software CAESES® for the optimization of the basic design of a new vessel and the operation of an existing one with regards to the maximization of the efficiency, safety and competitiveness of the final design. A case study with the design optimization was undertaken based on the simulation of the anticipated operation of a vessel engaged in the supply chain of Iron Ore. The target was the minimization of costs, fuel consumptions as well as of the Energy Efficiency Operating Index (EEOI) under conditions of uncertainty.

1 Introduction

For centuries the backbone of global trade and prosperity has been international shipping, with the vast majority of transportation of raw material as well as manufactured goods being transported by ships. While the 20th century saw the expansion of shipping in parallel with the industrial revolution, the first decade of the 21st posed a series of challenges for commercial shipping. The economic recession combined

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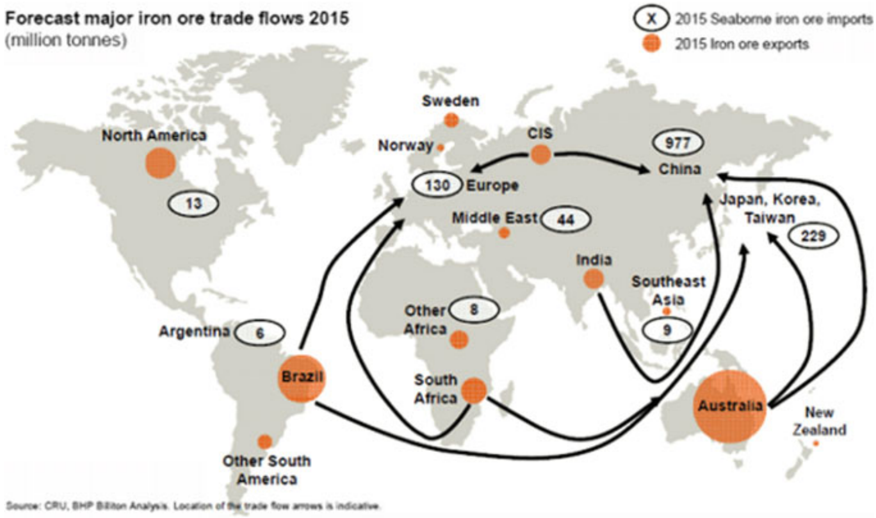

Fig. 1 Major iron ore trades

with a fall in freight rates (due to tonnage overcapacity as well as a global economic slowdown in terms of growth per capita) has threatened the financial sustainability of numerous companies. At the meantime, the Kyoto [1] protocol and the societal pressure for greener shipping, gave birth to a number of international environmental regulations that set the scheme for future ship designs. These are required to have a small carbon footprint and also incorporate ballast treatment systems to mitigate the risk of reducing biodiversity (especially in sensitive ecosystems such as reefs) due to the involuntary carriage of evasive species in the ballast water tanks.

Different cargoes have different main routes. Focusing on the seaborne trade of major bulk commodities such as iron ore or coal, the trade routes are very specific and shown in Fig. 1.

The rapid expansion of the Chinese economy created a constant demand for both iron and coal. The major iron ore exporters are located in South America (primarily Brazil) and Australia with million tons of exports per annum. The coal production is concentrated in Indonesia, Australia and Russia with 383, 301 and 314 million tons accordingly. The coal consumers are the Atlantic market consisted by Western European countries (mainly Germany and the UK) and the Pacific market, which consists of developing and OECD Asian importers, notably Japan, Korea and Chinese Taipei. The Pacific market currently accounts for about 57% of world seaborne steam coal trade. For the past half century global bulk shipping has focused on providing tonnage to serve the above trade with vessels of considerable size due to absence of significant size restrictions. The latter being the outcome of the ever expanding port terminals and the absence of physical restrictions (e.g. Panama Canal) on these routes. The present paper focuses on vessels intended for this trade which belong in the Capesize/Very Large Ore Carrier (VLOC) segment of the shipping market.

The design of bulkcarriers was focused during the last 7 years on the increase of efficiency by two means: increase of cargo carrying capacity and decrease of energy demands. In most cases the optimization is evolved around a single design point in terms of both speed and loading condition (draft and thus displacement). This paper provides a holistic methodology [2] intended for the optimization of the basic design of large bulkcarriers for their entire lifecycle, operational profile and supply chain. The speed and trading profile is simulated for the entire economic life of the vessel and the optimization focuses on the minimization of operating costs, maximization of income, minimization of internal rate of return (IRR) summarized by the Required Freight Rate (RFR) from one hand and from the other the minimization of the energy footprint of the vessel expressed by the Energy Efficiency Design Index (EEDI) and the simulated Energy Efficiency Operating Index (EEOI). In order to make sure that the produced designs will be also safe, the optimization targets on the minimization of the risk of structural failure without unnecessary increases the lightship weight.

2 Overview of the Holistic Methodology

Holism (from ὅλος holos, a Greek word meaning all, whole, entire, total) is the idea that natural systems (physical, biological, chemical, social, economic, mental, linguistic, etc.) and their properties, should be viewed as wholes, not as collections of parts. This often includes the view that systems somehow function as wholes and that their functioning cannot be fully understood solely in terms of their component parts. Within this context the authors have developed such methodologies in the Ship Design Laboratory of NTUA with the use of CAESES® [3] parametric design software or other similar tools [4, 5]. This approach has been applied in a variety of cases, e.g. to tanker design optimization [6] as well as to containership design [7].

The methodology is holistic in the sense that all the critical aspects of the design are addressed under a common framework that takes into account the lifecycle performance of the ship in terms of safety, efficiency and economic performance, the internal system interactions as well as the trade-offs and sensitivities. The workflow of the methodology has the same tasks as the traditional design spiral with the difference that the approach is not sequential but concurrent.

2.1 Design and Simulation Environment

The environment in which the methodology is programmed and is responsible for the generation of the fully parametric hullform is CAESES® which stands for “CAE system empowering simulation” [3]. It is a CAD-CFD integration platform which was developed for simulation-driven design of functional surfaces like ship hulls,

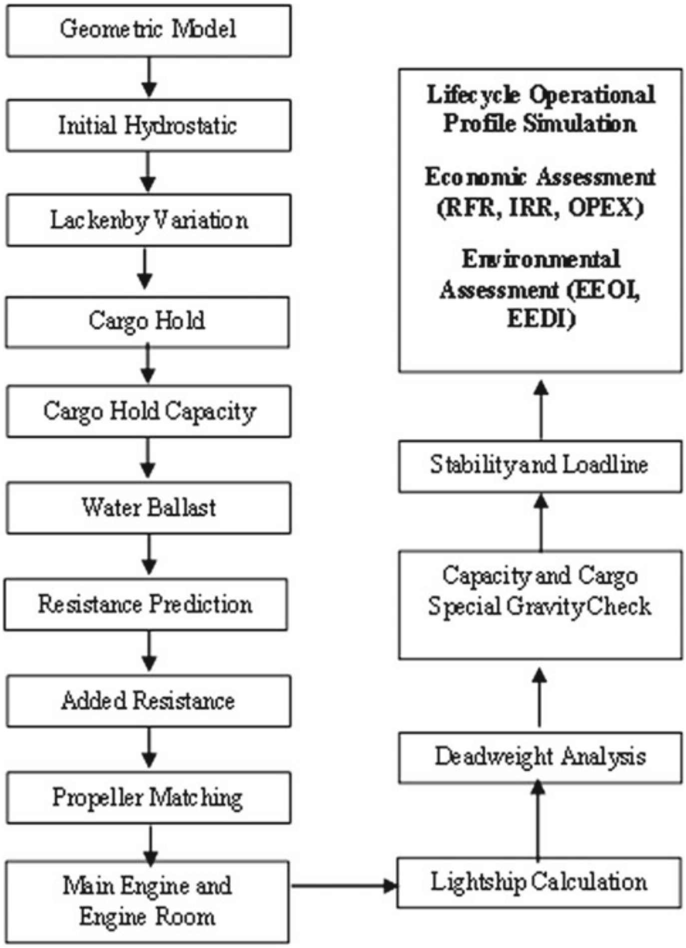

Fig. 2 Workflow of the proposed methodology

propellers and appendages. It may also be used for other applications like designing turbine blades and pump casings. It provides a wide range of functionalities like parametric modelling, integration of simulation codes, algorithms for systematic variation and formal optimization. These capabilities make it an ideal tool for the holistic ship design optimisation problem, where a parametric hullform should be generated and its performances should be assessed by different software tools. The holistic methodology proposed herein is depicted in Fig. 2 and will be analysed in the next paragraphs.

2.2 Geometric Core

The core of any holistic design optimisation method developed in a CAD/CAE system is the geometric model. For the ship hullform this poses unique challenges due to the fairness and shaping requirements for both the forward and the aft area e.g. the shape of the bulbous bow and the size of the transom respectively. In that respect, the more flexible is the modelling environment, the better and higher the resolution of the design space exploration would be. CAESES® offers such flexibility and this is why it was selected for the definition of the original hull. The surface of the hull was modelled as a group of parametric sub-surfaces.

2.3 Initial Hydrostatic Properties

The calculation of the hydrostatic properties is important for the verification of integrity of the design by its displacement, the block coefficient and the centre of buoyancy of the design. It is performed by an internal computation of CAESES®. For its execution a dense set of offsets (sections) is required as well as a plane and a mirror plane, defined by the user.

2.4 Lackenby Variation

In order to be able to generate the lines with the desired geometrical properties, the Lackenby [8] variation is applied. This variation is a transformation that is able to change the distribution of the enclosed volume longitudinally. Instead of applying quadratic polynomials as shift functions, fairness optimized B-Splines are used. This allows a better selection of the region influenced as well as smoother transition. The required input for the transformation is its extent and the target values for the block coefficient (Cb) and the longitudinal centre of buoyancy (LCB). In this case the extent was from the propeller's position to the fore peak. An example is shown in Fig. 3.

2.5 Cargo Hold Modelling

The cargo hold arrangement was generated on that resulting surface using a feature of CAESES® and the capacity of the various holds was calculated. The cargo hold surfaces and their respective parametric entity were realized within the CAESES®. The parameters/variables controlling this area were the positions of the bulkheads, the position of the Engine Room bulkhead, the frame spacing as well as some local

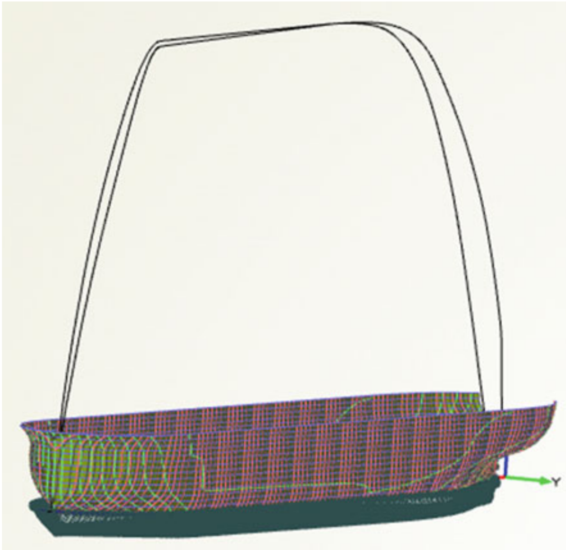

Fig. 3 Hullform after the application of Lackenby's variation

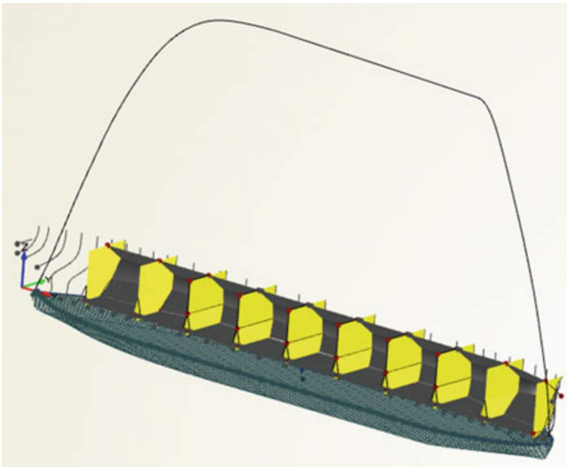

Fig. 4 Parametric cargo hold surfaces

variables such as the hopper width and angle, the topside tank dimensions (width and height), the lower stool height and length and double bottom height.

The capacity of each tank was calculated by creating offsets for each one of the tank surfaces and joining them together. The calculation of the tanks' hydrostatics was performed then and the total capacity was checked. A calibration factor which derived from the parent hull was applied to account for the volume losses due to the structural frames inside the cargo holds. A similar factor was used for the estimation of the Bale and Grain capacities. The result of the parametric tank modelling is shown in Fig. 4.

2.6 Resistance Prediction

2.6.1 Calm Water Resistance

The resistance prediction of this model uses a hybrid method and two different approaches, depending on the optimization stage.

Initially, during the design of experiment (DoE) and the global optimization phase, where a large number of variants is created there is a need for a fast procedure. For this particular reason Holtrop's [9] approximate powering prediction method is used. It derives from the statistical analysis of model tests and is well-known for its very good accuracy-to-computational cost ratio. Especially for bulkcarriers it is more accurate as the wave making and the viscous pressure resistance are very small fractions of the total resistance. It is the frictional resistance (directly related to the wetted surface) that dominates the total resistance due to their small Froude number. The entire Holtrop's method was programmed within CAESES®. Thus, the actual data from the geometric model (e.g. entrance angle, prismatic coefficients etc.) are used, making the process more precise for the specific design.

An innovative feature of the methodology developed is that the parameters from Holtrop's statistical method were systematically calibrated in order for the programmed methodology to match the speed-resistance and speed-power curves of the parent vessel as derived from its model tests. The calibration was performed by a systematic optimization approach. The optimization variables were the coefficients used in Holtrop's methodology with a small margin of variance. Then the methodology would be applied for each speed/point of the model tests and the difference in powering would derive. The minimization of this difference is the optimization target of this particular sub-problem. As 9 different speeds (from 12.5 to 16.5 knots) were assessed the applied algorithm for the optimization was the NSGA II [10], while 900 variants were produced. The result was an average difference of 1.5% with the Holtrop results being more conservative (over estimation) than the model tests.

At a later stage, in the optimization post processing, where local hullform parameters are considered, the CFD code package STAR CCM+ is used in order to validate the trends in terms of propulsion efficiency for the Pareto front designs. However, the results of Holtrop are generally conservative and on the safe side compared with CFD analysis while there are no discrepancies regarding the ranking of the designs in terms of hull efficiency. Under these assumptions, the use of Holtrop's method at the preliminary design stage can be considered a prudent choice since the results cannot be considered to be distorted and any errors are systematic and they do not bias the results. Given the systematic calibration for the same «family» of hullforms it argued that this is a sound strategy for both accuracy and computational efficiency.

2.6.2 Main Engine and Engine Room Dimensioning

With the propeller dimensioned, the RPM and required power of the main engine are determined. A margin for adverse weather conditions and fouling is considered on the basis of 15% as per industry standard. A further 5% is also considered for derating the main engine and ensuring smaller SFOC.

For the final requirements the main engine is matched with the existing G-Type, ultra-long stroke, engines available from MAN [11]. An internal iterative procedure ensures that the engine will have sufficient light running margin and that the layout point on the diagram is close to the L2L4 line corresponding to larger torque/MEP margins and smaller SFOC values.

From the above, the final SFOC curve from 50 to 100% is produced and corrected for the actual engine layout.

The Diesel Generator output is calculated from an electrical balance while the boiler output is based on the exhaust gas amount of the main engine in order to be also sufficient for the steam production for the onboard heating of the fuel tanks.

2.6.3 Lightship Weight Prediction

The lightship calculation follows the traditional categorization in three weight groups, the machinery weight, the outfitting weight and the steel weight.

Machinery Weight

The machinery weight calculation is based on the average of two methods: the Watson-Gilfillan formula and the calculation based on the Main Engines weight respectively.

The machinery weight estimation is based on a empirical formula due to Watson-Gilfillan [12]:

$$Wm = Cmd * Pb^{0.89} \tag{1}$$

The average is used to balance out any extreme differences, and the coefficients of the Watson-Gilfillan formula are calibrated for low speed, two stroke engines based on statistic data available for a fleet of bulkers.

Outfitting Weight

The outfitting weight is also based on the average of two independent calculations. The Schneekluth method [12] is the first one and the use of empirical coefficients for sub-groups of that particular weight group is the other.

Steel Weight

During the initial design stages, and the selection of optimal main dimensions, it is necessary to identify the effect of the change of the principal dimensions of a reference ship on the structural steel weight. Thus, at first, an accurate calculation of the steel weight of the reference ship is conducted. Following this, the "Schneekluth Lightship Weight Method" was applied [12]. Given that the steel weight for the parent vessel was available as derived from summing the individual steel block weights (from the shipbuilding process) a TSearch algorithm [3] was employed in order to vary the values of the statistical coefficients and constants of subject methodology with the objective of the minimization of the difference between the actual and calculated values for the steel weight. The results have an accuracy of 0.3% which is more than acceptable within the scope of basic/preliminary design.

2.7 Deadweight Analysis

The deadweight of the vessel is comprised by subgroups such as the consumables, the crew weight and the deadweight constant. The deadweight analysis predicts the payload of the vessel based on the calculation of the consumables.

As mentioned before, the consumables for the machinery is calculated, namely the Heavy Fuel Oil for the main engines, and diesel generators, the Lubricating Oils of the engines and generators.

Furthermore, based on the number of the crew members (30), the fresh water onboard is calculated as well as the supplies and the stores of the vessel.

2.8 Stability and Loadline Check

The initial intact stability is assessed by means of the metacentric height of the vessel (GM). The centre of gravity of the cargo is determined from the capacity calculation within the framework while the centre of gravity for the lightship and consumables is determined from non-dimensioned coefficients (functions of the deck height) that derive from the information found in the trim and stability booklet of the parent vessel. All the above are calculated according to the requirements of the IMO Intact Stability Code [13].

2.9 Operational Profile Simulation

This module is an integrated code within the methodology that simulates the actual operating conditions of the vessel for its entire lifecycle. Two trade routes are considered, the Brazil to China and the Australia to China roundtrips. Each voyage is split into legs depending on distinctive sea areas.

Input Data

For each one of the legs (given distance in nautical miles) the average speed and added resistance curves are input as well as the loading of the generators and the manoeuvring time. If the leg includes discharging, loading or bunkering port the corresponding time in hours is also used. Based on this profile, the voyage associated costs together with the fuel costs are calculated on a much more accurate and realistic basis. The predictions of this module have been verified by actual data from real ships.

Added Resistance

In order to be consistent with the need for the simulation driven design it is necessary to include a consideration for the added resistance in waves. Thus, a module has been herein developed that utilizes Kwon's method for the calculation of added resistance in waves [14, 15].

Kwon's added resistance modelling is an approximate method for the prediction of loss of speed due to added resistance in rough weather condition (irregular waves and wind). The advantage of this method is the prediction of the involuntary loss of speed due to the effect of weather loading on an advancing displacement type of ship with a limited number of input data. The module is described by Eqs. (2) and (3).

$$\frac{\Delta V}{V_1} * 100\% = C_\beta * C_U * C_{Form} \tag{2}$$

$$V_2 = V_1 - \left(\frac{\Delta V}{V_1} * 100\%\right) * \frac{1}{100\%} * V_1 = V_1 - \left(C_\beta * C_U * C_{Form}\right)\frac{1}{100\%} * V_1 \tag{3}$$

where:

V_1 Design (nominal) operating ship speed in calm water conditions (no wind, no waves), given in m/s

V_2 Ship speed in the selected weather (wind and irregular waves) conditions, given in m/s

$\Delta V = V_2 - V_1$, Speed difference, given in m/s.

C_β Direction reduction coefficient, dependent on the weather direction angle (with respect to the ship's bow) and the Beaufort number BN (Bft), as shown in Table 1

C_U Speed reduction coefficient, dependent on the ship's block coefficient b. The loading condition and the Froude number n, as shown in Table 2

Table 1 Direction reduction coefficient CB due to weather direction

Weather direction	Direction angle (with respect to the ship's bow) (deg)	Direction reduction coefficient $C_ß$
Head sea (irregular waves) and wind	0	$2C_ß = 2.0$
Bow sea (irregular waves) and wind	30–60	$2C_ß = 1.7 - 0.03 * (BN-4)^2$
Beam sea (irregular waves) and wind	60–150	$2C_ß = 0.9 - 0.06 * (BN-6)^2$
Following sea (irregular waves) and wind	150–180	$2C_ß = 0.4 - 0.03 * (BN-8)^2$

Table 2 Speed reduction coefficient CU due to Block coefficient Cb

Block coefficient Cb	Ship loading conditions	Speed reduction coefficient C_U
0.8	Loaded or normal	$2.6–13.1 \cdot Fn-15.1 \cdot Fn^2$
0.85	Loaded or normal	$3.1–18.7 \cdot Fn+28 \cdot Fn^2$
0.8	Ballast	$3.0–16.3 \cdot Fn-21.6 \cdot Fn^2$
0.85	Ballast	$3.4–20.9 \cdot Fn+31.8 \cdot Fn^2$

Table 3 Ship form coefficient CForm due to ship categories and loading condition

Type of ship	Ship form coefficient C_{Form}
Full hull in laden condition	$0.5 \cdot BN+(BN^{6.5})/(2.7 \cdot \nabla^{2/3})$
Full hull in ballast condition	$0.7 \cdot BN+(BN^{6.5})/(2.7 \cdot \nabla^{2/3})$

C_{Form} Ship form coefficient, as shown in Table 3.

The above formulas for speed loss need to be combined for all the sea states and weather angles of each of the stages of the determined voyage legs (see Sect. 2.10) in order to include all the in service considerations. The derived reduced speed from the Kwon calculation is in combined with Holtrop's resistance for the powering prediction. This results to four different Added Resistance–Speed curves, depending on the weather angle (0–30, 30–60, 60–150 and 150–180 as in Fig. 5). Then, in the operational simulation module (Sect. 2.10) for each stage and voyage leg, the computation of these four curves is performed for Beaufort numbers of the following groups: (0,2], (2,4], (4,6], (6,8].

For each stage of each leg, the probability of both the weather encountering heading as well as the Beaufort number range is set as input. At the end, a probabilistic additional Propulsion Power given the known stage/leg average speed is derived. Using this requirement, the engine load is estimated.

The developed methodology calculates the Operational Expenditure (OPEX), the Capital Expenditure (CAPEX), the Required Freight Rate (RFR), the Internal Rate of Return (IRR) as well as the IMO Energy Efficiency Operational Index (EEOI). All

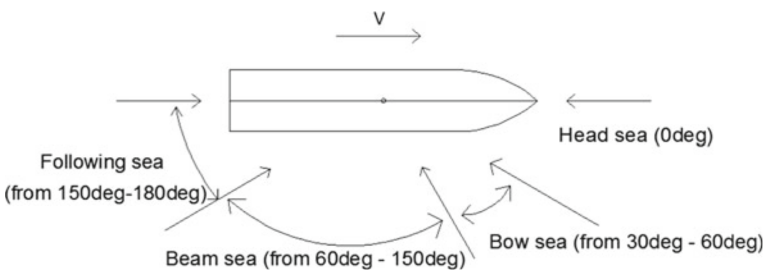

Fig. 5 Vessel heading directions

the calculations are made under two uncertainties: Fuel Price and Market Condition (expressed by the Baltic Dry Index and USD per ton of cargo paid as charter that is translated into TCE afterwards). This is another key point of this methodology, as it allows the optimization of the vessel's design under uncertainty as the produced designs correspond to a more realistic scenario and the dominant variants of the optimization have a more robust behaviour over a variety of exogenous governing market factors. The derived probabilistic values of RFR and the deterministic value of the EEOI are the functions/targets used in the optimization sequence later.

2.10 Energy Efficiency Design Index Calculation

The Energy Efficiency Design Index (EEDI) is calculated according to the formula proposed in the IMO resolution MEPC.212(63) [16], using the values of 70% deadweight and 75% of the MCR of the engines and the corresponding reference speed:

$$EEDI = \frac{\left(\prod_{j=1}^{M} fj\right)\left(\sum_{i=1}^{nME} PME(i) * CFME(i) * SFCME(i)\right) + (PAE * CFAE * SFCAE)}{fi * Capacity * Vref * fw} + \frac{\left\{\left(\prod_{j=1}^{M} fj * \sum_{i=1}^{nPTI} PPTI(i) - \sum_{i=1}^{neff} feff(i) * PAEeff(i)\right) * CFAE * SFCAE\right\} - \left(\sum_{i=1}^{neff} feff(i) * Peff(i) * CFME * SFCME\right)}{fi * Capacity * Vref * fw} \quad (4)$$

The minimization of this index is one of the primary objectives of the conducted optimization. The engine power is directly related to the resistance of the hullform, while the deadweight is also related to both the hullform in terms of displacement and to ship's lightship weight.

3 Design Concept

3.1 Large Bulkcarrier Market

The focus of the present study lies within the large bulkcarrier segment dominated in numbers by Capesize ships as well as Very Large Ore Carriers (VLOCs). During the last decade a new class of vessels has emerged, known as Newcastlemax as they are the largest vessels that can enter and load in the Coal Terminal of Newcastle in Australia.

3.2 Baseline Vessel—208k Newcastlemax

It is imperative in a ship design optimization case study that a baseline is set in the form of a parent vessel used as a primary source of reference as well as calibration for the methodology and all the formulas/computations applied in the latter. For this particular reason it is necessary to have as complete data as possible for the parent vessel in order to achieve a better degree of accuracy as well as being able to make proper comparison during the analysis of the dominant variants of the optimization front.

The vessel chosen for this study belongs to the new category segment of Newcastlemax Bulkers and is a newly delivered vessel. The baseline parametric geometry has been adapted to fit the hull lines available. Its model test results were used to calibrate Holtrop's prediction for resistance and powering. The principal particulars of the vessel can be found in Table 4.

3.3 Proposed Design Concept Characteristics

A low Froude number (slow speed) and full hullform is herein proposed as the base hull for the global optimization. The absence of a bulbous bow is evident as it is a recent trend in bulkcarrier design. It results from the understanding that such a geometry assists in the reduction of the vessel frictional resistance (primary resistance component) while the wave making resistance is not increased. The effect of the bulbous bow on the above as well as the added resistance were investigated in depth in a separate study. Furthermore, the decision to limit the selection of the Main Engine to only electronically controlled types was taken and no Energy Saving Devices (wake equalizing duct, pre-swirl fin, bulbous rudder etc.) are considered since there

Table 4 Baseline vessel principal particulars

Baseline vessel principal particulars	
Length over all	299.98
Length between perpendiculars	294
Beam	50
Scantling draft	18.5
Deck height	25
Cb	0.8521
Main engine specified MCR (kW)	17494 @ 78.7 RPM/MAN B&W 6G70ME-C9.2
Deadweight (tons)	Abt 208,000
Lightship weight (tons)	26,120
Cargo hold capacity (m^3)	224,712.1

is no such device installed on the parent vessel. The improvements achieved by such devices can be considered at a later stage.

3.3.1 Simulation Driven Design, Choice of Hullform Parameters

The assessment of the design is derived from the simulation of the operational, economic and trading profile. In other words, instead of using only one design point (in terms of draft and speed) multiple points are used derived from actual operating data of a the baseline vessel.

3.3.2 Newcastlemax Design Concept

The maximum allowable dimensions (Length Over All and Breadth) in order to load in the port Newcastle in Australia set the constraints for this optimization case study.

4 Optimization Studies

4.1 Optimization Target/Goals

The generic targets or objectives in this optimization problem were:

4.1.1 Competitiveness

The market and economic competitiveness of a design is the core of any optimization as a vessel will always be an asset (of high capital value). This can be expressed by the following indices:

1. *Required Freight Rate*

The required freight rate is the hypothetical freight which will ensure a break even for the hypothetical shipowner between the operating costs, capital costs and its income based on the annual voyages as well as collective cargo capacity and is such expressed in USD per ton of cargo.

2. *Operating Expenditure (OPEX)*

The operating expenditure expressed on a daily cost includes the cost for crewing, insurance, spares, stores, lubricants, administration etc. It can indicate apart from the operator's ability to work in a cost effective structure, how the vessel's design characteristics can affect. The lubricant cost is based on actual feed rates used for subject engines as per the relevant service letter SL2014-537 of MAN [17].

3. *Capital Expenditure (CAPEX)*

The CAPEX is a clear indication of the cost of capital for investing and acquisition of each individual design variant. The acquisition cost is calculated from a function derived from actual market values and the lightship weight for vessels built in Asian shipyards, and more specifically in China.

4.1.2 Efficiency

The merit of efficiency is herein expressed by the IMO EEOI index. Although on the design basis in practice the IMO Energy Efficiency Design Index is used as a KPI and measure of the merit of efficiency in new design concepts as well as for any newbuild vessel, in this study the calculated Energy Efficiency Operating Index is used instead. The reason for this change is the use of the Operational Profile simulation module which contains from a wide statistical database of a bulker operator the daily average speed per each stage of each voyage leg (see Sect. 2.10) thus given the cargo capacity calculation (see Sect. 2.4) the EEOI can be accurately derived, which can depict more accurately the efficiency of the design given the fact that it takes into account all operating speeds (instead of one design speeds) and all operating drafts (instead of the design draft) thus expressing the actual transport efficiency of each variant by a simple ratio of tons of CO_2 emitted (direct function of the tons of fuel consumed) to the tons of cargo multiplied by the actual distance covered (in nautical miles). In addition to the above, each operational practice such as slow steaming is taken into account, also considering side implications (for example the use of two diesel generators in the normal sea going condition instead of one in order to cover the blower's electrical load).

4.2 Design Variables

The design variables used are shown in Table 5. They can be categorized in three groups; principal dimensions, hullform characteristics (Cb, LCB, Parallel Middle-body) and cargo hold arrangement parameters. The more detailed design variables of the hullform arrangement for the detailed shape of the bulbous bow (if any), flair and stem shape as well as stern shape are going to be assessed in a separate optimization study with the use of integrated CFD codes.

4.3 Optimization Procedure

The optimization procedure applied for this study is depicted in Fig. 6.

Table 5 List and range of design variables of the optimization problem

Design variable	Lower boundary	Upper boundary
Length between perpendiculars	290	299
Length overall	298	300
Beam	48	50
Draft	18	19
Deck height	24	27
Hopper length	8	11
Hopper breadth (m)	3	6
Topside height (m)	8	14
Topside breadth (m)	9	13
Inner bottom height (m)	2.4	3
Block coefficient Cb	0.84	0.87
LCB (% Lbp)	0.49	0.53
Beginning of parallel midbody (Aft % Lbp)	0.35	0.45
End of parallel midbody (Fore % Lbp)	0.65	0.8
Stem overhang (% Lbp)	0	0.02

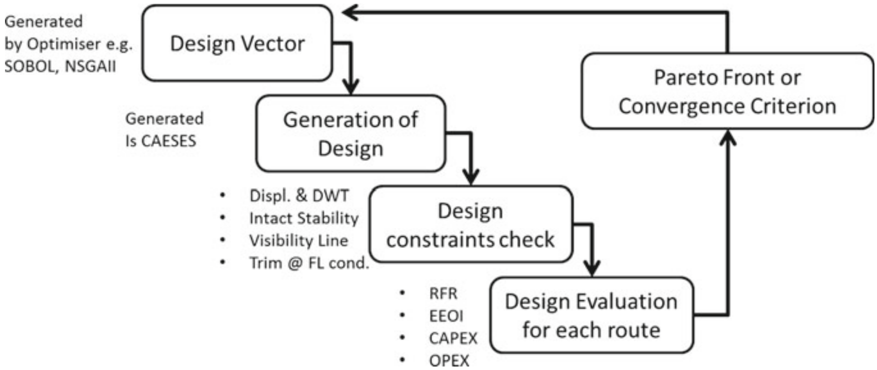

Fig. 6 The optimization loop applied

In each iteration the design variables receive their input values from the "design engine" i.e. CAESES®. The design engine can either be a random number generator, a design of experiments procedure or an optimization algorithm depending on the optimization stage. The generated values trigger the creation of a new design from the parametric model. The design's performance, in the form of the calculated values of the Design Objectives, is logged and assessed accordingly and the Design Constraints imposed are checked for compliance. The Design constraints chosen for this study were the calculated values for Deadweight, Cargo Specific Gravity and the Stability Criteria of the 2008 Intact Stability Code. The size restrictions (in terms of vessel's dimensions) were not used in constraints given the fact they were taken into account in the applied range of the Design Variables.

The optimization procedure described in this paper can be described as a multi stage one. At first, it is necessary to explore and fully understand both the design space (potential for improvement with given constraints) as well as the sensitivity of the methodology by a Design of Experiments (SOBOL) procedure. The sensitivity analysis is a very important, preparatory step in which it is ensured that no major, unreasonable manipulations occur. Furthermore, it is important to see that the results are realistic both on a quantitative and qualitative basis, with the latter in need of particular attention since the design ranking and selection is the essence of optimization (the absolute value of a design is not important than the relationship with all the other produced designs).

During the next stage a formal optimization is performed using a genetic algorithm technique (NSGA II algorithm). The formal optimization runs involve the determination of the number of generations and the definition of population of each generation to be explored. The generated designs are ranked according to a number of scenarios regarding the preference of the decision maker. One favoured design is picked to be the baseline design of the next optimization run, where the same procedure is followed. When it is evident that there little more potential for improvement the best designs are picked using the same ranking principles with utility functions, and are exported for further analysis.

Both the SOBOL and NSGA II algorithms as well as a plethora of other variant generation and optimization algorithms are fully integrated and available within the CAESES®.

4.4 Design of Experiment

The Design of Experiment has the primary purpose of calibration, test and sensitivity check of the methodology from one hand as well as the investigation for the optimization margin. In this case study, it was evident that there is a strong scale effect that dominates this particular optimization problem. This effect is very common in ship design were the largest vessels usually dominate the smaller since the increase of cargo capacity does not trigger an equivalent increase in the powering requirements or the vessel's weight.

In addition to the scaling effect it was observed as in the formal optimization algorithm that there was a strong linear correlation between the Required Freight Rate (RFR) and the EEOI, which was expected since both functions use cargo capacity.

The feasibility index was in a very high level (above 90%). In total 250 designs were created.

4.5 *Global Optimization Studies*

In this stage the formal, global design optimization with the NSGA II algorithm was utilized. The latter is a genetic, evolutionary algorithm that is based on the principles of biological evolution [18]. As in the biological evolution each design variant is an individual member of a population of a generation. Each individual of the population is assessed in terms of the Optimization Objectives, as well as its relation to the desired merits. For the application in ship design optimization it is usual to apply a large population for each generation with an adequate number of generations. The large population combined with a high mutation probability ensures that the design space is properly covered, while the number of generations ensures that there is a push towards the Pareto frontier for each case of objective combination. For this particular application a combination of 10 generations with 100 variants population each was selected.

The results of this run can be seen in Figs. 7, 8 and 9. In Fig. 7 the relation of the RFR to the EEOI is depicted and is quite evident that their relationship as already explained is strongly linear. The reason is the direct correlation to the cargo capacity for both indices. It is interesting to note that the baseline vessel is in the middle and towards the lower part of the range meaning that although it belongs to the better performers it is away from dominant variants.

When it comes to the relationship between the CAPEX and RFR (see Fig. 9) we can see that there is a contradicting requirement since the acquisition cost is calculated with a linear function of the lightship weight, while the larger vessels

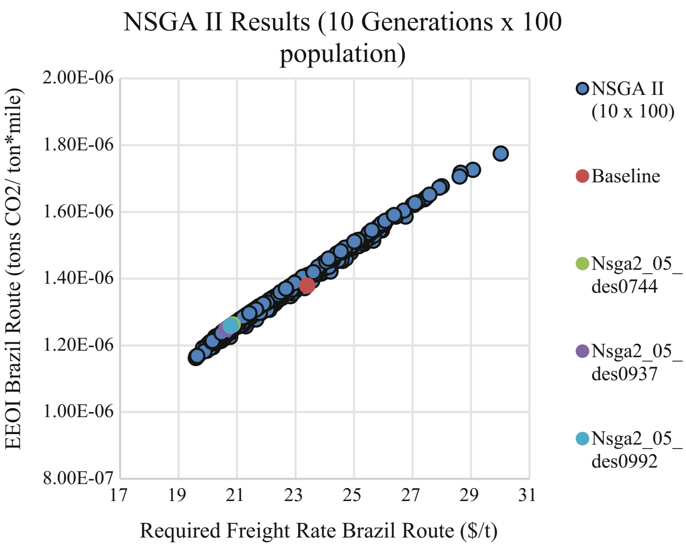

Fig. 7 NSGA II run: RFR versus EEOI

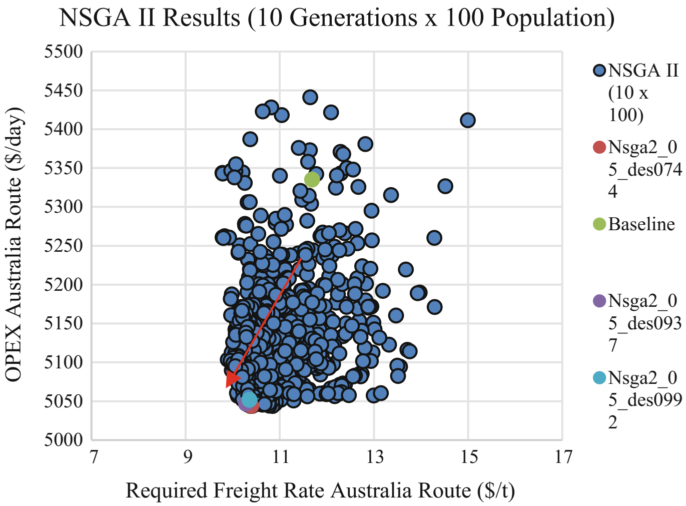

Fig. 8 NSGA II results: OPEX versus RFR

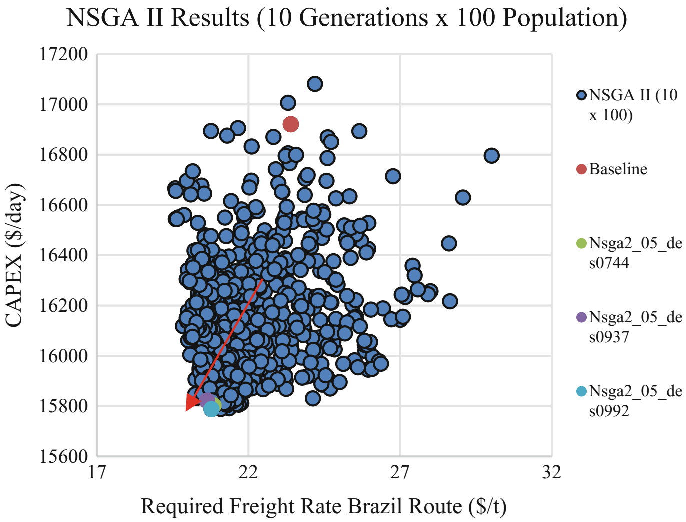

Fig. 9 NSGA II results: RFR versus CAPEX

boast a greater profitability and thus better RFR. A small area like a Pareto front is created, however again there is a localized peak that dominates the majority of the generated designs. The same relationship is also observed between the OPEX and RFR values of the generated design (see Fig. 8).

4.6 Dominant Variant Ranking

One of the most critical steps during optimization of any system is the selection and the sorting of the dominant variants. For this particular reason it is necessary to follow a rational, rather than an intuitive, approach in order to consider in an unbiased way all trade-offs that exist. One such method is utility functions technique.

The optimum solution in our case would dispose the minimum EEOI, RFR, OPEX and CAPEX values. Instead of using fixed weights for the set criteria in the evaluation of the variants, we rather assume a utility function as following

$$U = w_{EEOI} \cdot u_{(EEOI)} + w_{RFR} \cdot u_{(RFR)} + w_{CAPEX} \cdot u_{(CAPEX)} + w_{OPEX} \cdot u_{(OPEX)} \quad (5)$$

The maximization of this utility function is the objective now, and the dominant variants of those 10 most favourable with respect to the 4 defined utility scenarios (Table 6) resulting in the identification and sorting of 40 designs with best performance according to each utility scenario.

From the above ranking (Figs. 10, 11, 12 and 13) it is very interesting to observe that there is a certain repetition in the top three dominant variants from the ranking procedure. Furthermore, for scenario U3 where there is an equal weight for all objectives, the three top dominant variants are the ones from scenario's U1 and U2. All the above illustrate that the peak on the observed Pareto front is strong and apart from that, the dominant variants that can be selected (e.g. 744, 937, 992) perform better in a robust way under different assumptions and weights from the decision maker point of view. The characteristics of these three variants can be found in Table 7.

5 Discussion of the Results—Future Perspectives

From Table 8 it is apparent that a 10–11% average improvement in the required Freight Rate has been achieved, while the OPEX and CAPEX values have been

Table 6 Weights used for the utility functions

Maximum objective weight	U1	U2	U3	U4
RFR_Brazil	0.2	0.1	0.125	0.1
RFR_NMAX	0.2	0.1	0.125	0.1
EEOI_Brazil	0.1	0.1	0.125	0.1
EEOI_NMAX	0.1	0.1	0.125	0.1
OPEX_Brazil	0.1	0.1	0.125	0.2
OPEX_NMAX	0.1	0.1	0.125	0.2
CAPEX_Brazil	0.1	0.2	0.125	0.1
CAPEX_NMAX	0.1	0.2	0.125	0.1

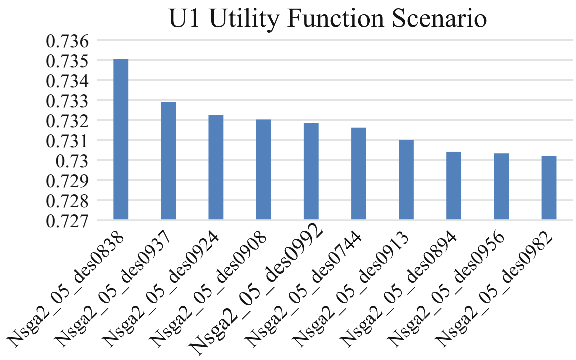

Fig. 10 Ranking of dominant variants with U1 scenario

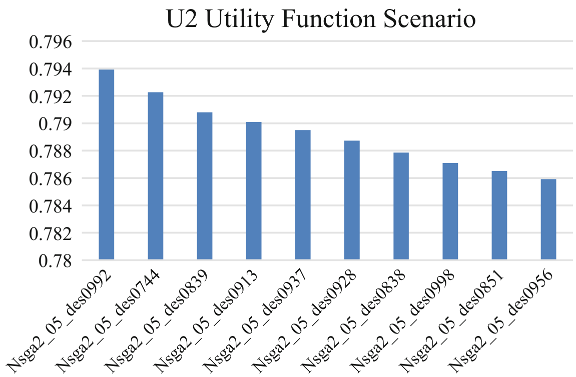

Fig. 11 Ranking of dominant variants with U2 scenario

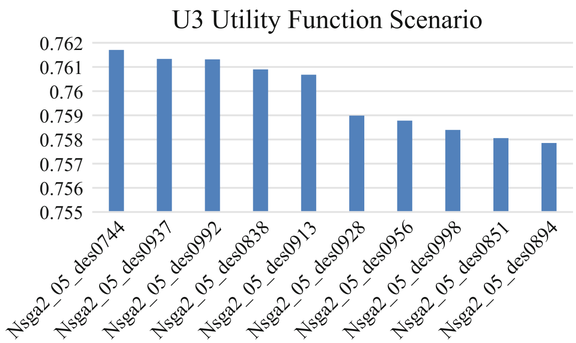

Fig. 12 Ranking of dominant variants with U3 scenario

reduced in a lesser extent by approx. 6.5%. This can be justified by the reduction of generally vessel size primarily in terms of beam and length (beam given the fact that these vessels are not stability limited) and thus the reduction of the initial capital cost, while in the meantime the cargo capacity has increased, boosting in this way the Required Freight Rate. It is also interesting to observe that although beam has

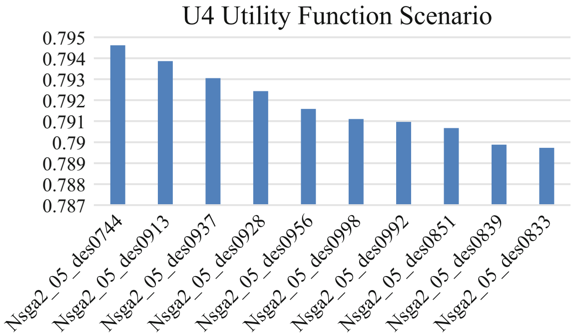

Fig. 13 Ranking of dominant variants with U4 scenario

Table 7 Comparison between the baseline and the three variants geometric properties

Particulars	Baseline	ID744	ID937	ID992
Lbp (m)	294	290.24926	290.26683	290.26464
Beam (m)	50	48.01819	48.07337	48.09241
Deck height (m)	25	26.98824	26.87828	26.98750
Cb	0.8538	0.86535	0.86533	0.86301
LCB	0.51986	0.52203	0.51169	0.51145
LOA (m)	299.98	299.15743	299.04591	298.07306
Draft (m)	18.5	18.00232	18.00220	18.03555
Topside breadth (m)	12	9.11792	11.36893	12.87433
Topside height (m)	9	9.09700	8.30011	8.20636
Hopper height (m)	10	8.56892	8.53816	9.56466
Hopper breadth (m)	4	3.30607	3.22715	3.08890
Double bottom height (m)	2.5	2.82176	2.82140	2.51971
Bow overhang (% Lbp)	0.01	0.00098	0.00120	0.00107
Beggining parallel midbody (% Lbp)	0.42	0.43373	0.40859	0.36219
End parallel midbody (% Lbp)	0.72	0.73976	0.74282	0.76179

reduced the draft has been increased in order to facilitate and balance the decrease in deadweight.

From the above discussion we can conclude that the novel methodology herein proposed for the simulation driven design with lifecycle, supply chain and the actual

Table 8 Design objectives of the baseline versus the dominant variants

Particulars	Baseline	ID 744	Diff%	ID 937	Diff%	ID 992	Diff%
RFR_Brazil	23.40	20.86	−10.86	20.64	−11.80	20.78	−11.17
RFR_Australia	11.69	10.40	−11.07	10.29	−11.99	10.36	−11.38
EEOI_Brazil	0.00	1.26E−06	−8.46	1.25E−06	−9.46	1.26E−06	−8.74
EEOI_Australia	0.00	1.16E−06	−8.49	1.15E−06	−9.49	1.16E−06	−8.78
OPEX_Brazil	5198.09	4911.06	−5.52	4913.97	−5.47	4918.75	−5.37
OPEX_Australia	5335.02	5043.68	−5.46	5046.64	−5.41	5051.42	−5.32
CAPEX	16920.61	15802.94	−6.61	15821.74	−6.49	15788.05	−6.69

operating in service parameters can successfully trigger a reduction in the RFR and EEOI via systematic variation and advanced optimization techniques. However, this is a preliminary work restricted only into illustrating the applicability and potential of this method. The following work is planned for the next steps:

1. Integration of the STAWAVE 2 methodology for added resistance prediction.
2. Refinement of the statistical data for in service conditions.
3. Investigation of larger bulker concepts for the iron ore supply chain by waving the restrictions of the Port of Newcastle and thus scaling up to the VLOC segment while also utilizing dual loadline characteristics.
4. Optimization of the in service operating profile of the vessel. For the baseline vessel, given the results of a pending trim optimization study (with use of STAR CCM+) the in service speeds and trims (trims only for the ballast leg) are going to be re-assessed in a rational way with systematic variation while taking into account exogenous factors such as Port Congestion as well as trade route supply and demand functions.
5. Local Hullform optimization of Bow and Stern Area. Three different bow types (ledge bow, bulbous and semi bulbous) are considered and further optimized for the baseline vessel.

Finally, given the developed library of modules for several calculations in «feature format» in the CAESES® the operational, supply chain and lifecycle simulation is going to be expanded for the case of a containership where the optimization problem is far more challenging due to the slender hullform and the inherent stability limitations.

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