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Optimization of Ship Design for the Effect of Wind Propulsion

Timoleon Plessas[1,*] and Apostolos Papanikolaou[2]

ABSTRACT

International regulations as well as strong market demand for zero-emission transport call for a radical change in the shipping industry. One very promising zero-emission propulsion system for shipping is wind propulsion. In this context, the EU-funded Orcelle Wind project (https://cordis.europa.eu/project/id/101096673) aims at using wind as the main source of ship propulsion and to demonstrate the effectiveness and viability of Wind Assisted Propulsion Systems (WAPS) by a retrofitting and new building demonstrator. In this paper, we explore the effect of wing sails on the concept design of a VLCC tanker in the frame of a newly parametric ship design optimization procedure.

KEY WORDS

Ship Design; Parametric Optimization; Wind Propulsion; Wing Sails; WAPS; Case Study

INTRODUCTION

The International Windship Association (IWSA) has declared 2021-2030 the 'Decade of Wind Propulsion' and the European Maritime Safety Agency (EMSA) recently issued a related report (EMSA, 2023) concluding that "wind-assisted propulsion is considered to have potential for the shipping industry". Thus, the maritime industry seems to be returning to its roots by experimenting with Wind Assisted Propulsion Systems (WAPS) in its effort to drastically cut its carbon footprint. The numerous regulatory requirements related to Green House Gas (GHG) emissions (IMO 2022)and the increased costs and problems with logistics of *green* fuels make wind propulsion a promising alternative for achieving the required environmental goals, to comply with related regulations and to reduce operational costs. Wind as an energy source offers numerous advantages for the shipping industry: it is freely available and future-proof, independent from the supply and price fluctuations of combustible and of alternative fuels. In addition, wind is a predictable energy source with zero emissions, which does not require new shore infrastructures and associated logistic systems. It is also one of the few technologies potentially offering double-digit fuel and emission savings.

Numerous recent studies have focused on the modeling and the simulation of wind assisted propulsion systems (e.g, Rosander & Bloch 2000; Bentin et al 2018; Talluri et al 2018), while potential fuel savings have been demonstrated by 3-DOF (Viola et al 2015; Ma et al 2023) and 4-DOF (Tillig & Ringsberg 2019) simulation methods. Although the main focus has been given to the performance prediction of vessels equipped with Wind Assisted Propulsion Systems (WAPS), *the effect of WAPS on ship design optimization* has not been yet systematically examined, namely *traditional ship design concepts* are being equipped with WAPS in the way of retrofitting and their performance is examined/optimized, even if they are newbuildings.

[1] Ship Design Laboratory, National Technical University of Athens, Athens, Greece
[2] Ship Design Laboratory, National Technical University of Athens, Athens, Greece; ORCID: 0000-0001-7464-9476
* Corresponding Author: Timoleon Plessas <timplessas@naval.ntua.gr>

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In this paper we present the development of a parametric ship design optimization framework to identify possible differences in the main dimensions and characteristics of ships, when considering the effect of WAPS, starting with the concept design of ships with fitted wing sails. It is noted that until now, the fitting of WAPS to ships has been as a retrofitting to an existing design, even in cases of newbuildings. For this, we developed and implemented a new methodology in MATLAB (Mathworks, 2023). It enables the fast simulation of the effect of alternative WAPS on the design of ships of various types and sizes, the identification of trends for the main ship design characteristics (main dimensions, hull form, main engine and propeller characteristics), while using only few input parameters and while all pertinent major design constraints are taken in to account. The developed method and s/w tool are herein applied to the design of a VLCC tanker with WAPS (here: generic wing sails) to demonstrate the applicability and limits of the presented approach.

WIND POWERED SHIP PROPULSION SIMULATION MODEL

Focusing on the concept design of ships with WAPS, a simplified one degree of freedom (1-DOF) hydrodynamic/maneuvering simulation model is utilized to conclude on the effect of WAPS on ship design. The main differences between a 1-DOF model (surge, movement in longitudinal direction) and a 4-DOF model (surge, sway, yaw and roll movement) are the consideration of the hydrodynamic forces that occur due to the added rudder resistance to maintain the required course and the drift resistance, which is the added resistance due to the fact that the vessel sails at a drift angle which results in a non-symmetrical flow around the hull. Regarding the effect of roll motion, a simplified way to compensate for the lack of consideration of the roll movement in the simulation is to examine the caused heel angle hydrostatically, meaning that the static heel is estimated based on the generated sail side force. Also, the effect of the heel angle on the projected sail area and the height of the center of effort is considered. Of course, this is a simplified approach that ignores the dynamic phenomena of a complete maneuvering model of ship's hydrodynamics (Papanikolaou et al, 2016); thus, it needs to be used with caution in cases where large heel angles are expected and when the hydrodynamic effect of hull appendages (bilge keel, sideboards, bottom daggerboards etc.) is significant. Tillig and Ringsberg (2019) showed in a case study on the utilization of WAPS for a tanker operating on a route in the Baltic Sea (from Gothenburg to St. Petersburg) that the difference in estimating the fuel consumption for wind assisted vessels with 1 DOF model compared to a 4 DOF model ranges from 2% (for smaller sail areas – e.g. 300 m2) to 7% (for larger sail areas – e.g. 900 m2), with the 4 DOF model giving more conservative predictions in terms of savings.

Following this reasoning and for the purpose of optimizing ship's concept deign, a one degree of freedom (1-DOF), quasi-steady model has been developed and coded for simulating and optimizing a ship operating in a pre-defined route with available weather data information. The developed model takes into account the interaction between hull, propeller, engine and sail, simulates and balances all forces in surge direction and estimates the power and fuel consumption needed for completing a scheduled voyage. In addition, the developed model allows the communication (exchange of data) between MATLAB and NAPA software packages (Figure 1). This enables the conduct of a more detailed analysis for each generated design alternative, which includes lightship & loading conditions determination, intact stability criteria assessment, environmental regulations assessment (e.g., oil outflow compliance for tankers) and overall performance analysis. The user can choose if NAPA should be utilized during the optimization. Alternatively, simplified calculations can be conducted within MATLAB without the need of NAPA, which may provide less details but it significantly speeds up the optimization procedure. Indicatively, when calling NAPA a single simulation takes approximately 40 seconds, whereas computations using semi-empirical formulas within MATLAB take approximately 1 second on a conventional computer. The results presented in this study were conducted using only MATLAB internal routines.

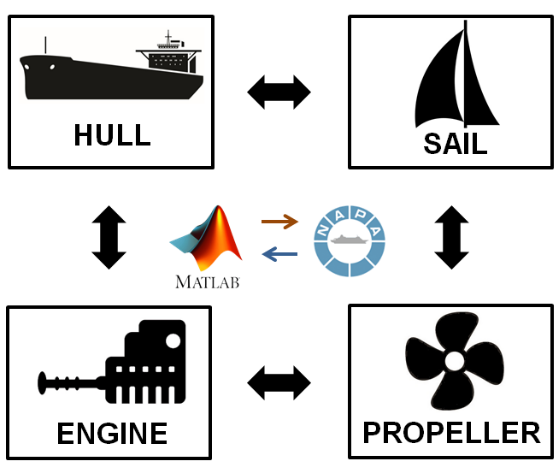

Figure 1. MATLAB code: Interaction between vessel modules

The developed simulation tool consists of three basic modules: “input creation”, “simulation” and “output”. The “Input creation” module is responsible for creating all the necessary input (power curves, engine curves, stability and weight relationships and calculations, etc.) while considering the input (selected) design variables (see subsection “Design Variables” for more information). Within this module it is possible to call NAPA for conducting more detailed weight, performance and stability calculations. Once all necessary input files are created, the “simulation” module estimates all acting hydrodynamic and aerodynamic forces and simulates the sailing of the vessel on the selected route considering the available weather information (wind and waves). Finally, the “output” module is responsible for printing the resulting figures and tables.

In the examined case study, the voyage is a typical tanker route between Corpus Christi (USA) to Rotterdam (Netherlands) (Figure 2). The voyage is subdivided into 12 legs and it is assumed that it is a round trip voyage, thus the vessel returns in ballast condition using the same route, therefore 24 voyage legs are considered in total (12 for laden condition and 12 for ballast condition). For each leg all ensuing parameters are estimated twice: once taking into account the effect of the wing sails and once as if the wing sails did not exist, for a fixed speed. This allows an instant comparison of the effect of wing sail on the required thrust to propel the ship and forms the foundation of the optimization process where the effect of the fitted wing sail on ship design is examined.

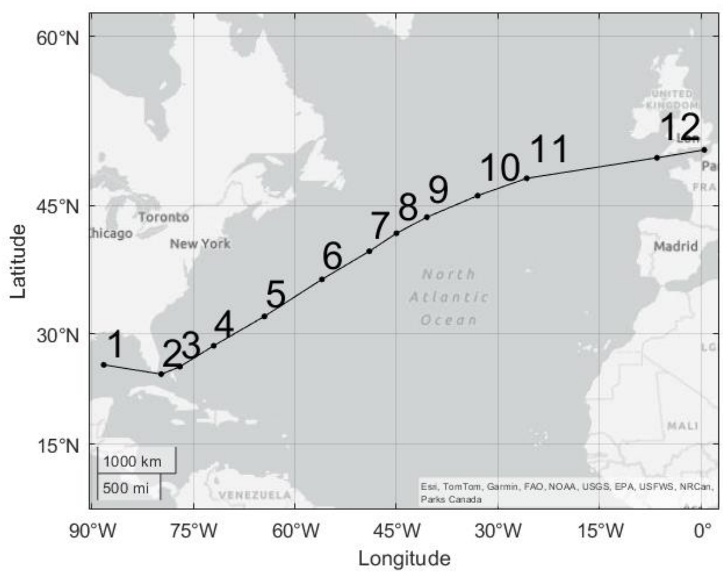

Figure 2. Selected Route

It is evident that the performance of fitted WAPS strongly depends on the route and the prevailing wind direction and strength, which are varying with location, time and season of the year. Thus, the shortest route between departure and arrival point is not necessarily the optimal one and traditional routing optimization procedures and software tools need to account for the best wind potential of the investigated route. An optimal routing methodology, which enables the operational energy savings to be assessed on various trading routes across the globe, has been developed by SSPA/RISE. The methodology considers the need for the vessel to fit into a logistics system regarding arrival time and lateness and considers European Centre for Medium-Range Weather Forecasts (ECMWF) weather data captured during the last decade (Werner 2021). This methodology is being utilized in the Orcelle project and supports the present study.

Wing Sail Characteristics

The main focus of the present methodology is development of tools in order to assess impact of WAPS on ship design in the frame of a design concept optimisation procedure. The herein examined wing sails system is based on a simplified, generic arrangement of symmetrical NACA airfoils (Abbott & Von Doenhoff 1959), which differs significantly from the *Orcelle Oceanbird* concept (Oceanbird 2024), whose sail consists of an optimized main wing and a controllable flap. This approach allows the development of the necessary WAPS simulation tools independently of the development and actual efficiency of the Oceanbird concept, which will be integrated into the developed simulation tools in the future, while it is expected that its efficiency in terms of generated lift (and thrust) will be significantly higher.

Based on the above reasoning, the herein examined WAPS consists of eight rigid wing sails of an approximate height of 80 m and average chord length of 23 m. The assumed wing profile is a NACA0015 airfoil with a modified trailing edge. Each sail has sail area 1,844 m^2, mean chord length of 23 m and aspect ratio of 3.47 (Malmek et al 2020). The developed MATLAB simulation code has the flexibility to ultimately consider a variation of the number of fitted wing sails, their arrangement, size and wing profile. Also, alternative WAPS (different types of wing sails and rotors) may be considered, assuming the availability of aerodynamic data for the estimation of the induced lift and drag forces.

In the present case study, some assumptions regarding the position and the interaction of the wing sails are made in order to simplify the problem, reduce computational time and reduce the parameters of the optimization problem. Sail position (longitudinally and crosswise) is crucial for maximizing the effectiveness of the wings. However, for the 1-DOF model the exact position of the sails is not examined, thus it is implied that there is a feasible/optimized sail arrangement that maximizes the generated wind thrust and minimizes the effect of drift angle and rudder resistance for maintaining the required course and complies with all necessary requirements (e.g. bridge visibility, ship structural strength etc.) (Bordogna et al 2018).

In cases where the generated sail force is sufficient to move the vessel at the desired speed (100% wind generated thrust), there are various options regarding the operation of the propeller such as windmilling, feathering or harvesting (Gypa, 2023). For the optimization problem, harvesting the energy of the rotating propeller is herein not examined and the added resistance from the windmilling/feathering propeller is not taken into account.

Estimation of Forces

The developed model simulates the longitudinal/surge forces, so the voyage is divided into legs with constant speed and environmental conditions and for each leg, equation [1] is solved to estimate the thrust of the propeller.

$$X_{CW} + X_{AW} + X_W + X_S + T = 0 \qquad [1]$$

where

X_{CW} is the calm water resistance (N) which is calculated using the Holtrop & Mennen method (Holtrop & Mennen 1982; Holtrop 1984), properly calibrated to predict the calm water resistance of the reference vessel.

X_{AW} is the added resistance due to waves (N) which is calculated using the semi-empirical SNNM method (Liu & Papanikolaou 2020)

X_W is the wind resistance (N) of ship's superstructure, which is estimated according to ISO 15016 (International Organization for Standardization 2015)

X_S is the generated sail force (N) for the assumed wing sails, which is calculated from tabulated aerodynamic forces provided by RISE Research Institutes of Sweden (personal communication)

T is the propeller thrust (N)

Vessel performance comparison with and without sails

The developed tool is capable of simulating the whole voyage with detailed calculations for each leg and a direct comparison between the same design with and without sails. Below some indicative figures are presented that compare the results of the various modules (hull, engine, propeller and sail). The figures refer to the 4th leg of the selected voyage for the reference vessel (Figure 3).

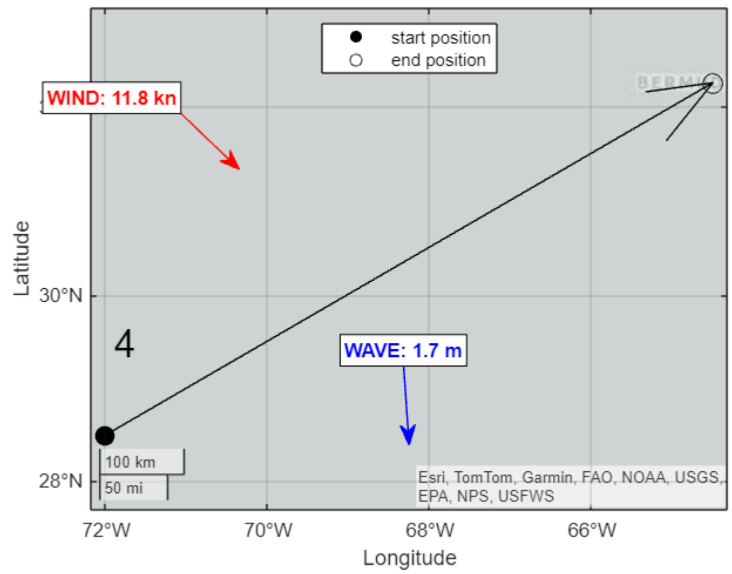

Figure 3. Leg 4

Forces

For each leg, all the forces are calculated (Figure 4) and the percentages of propulsion and resistance forces depicted in Figure 5.

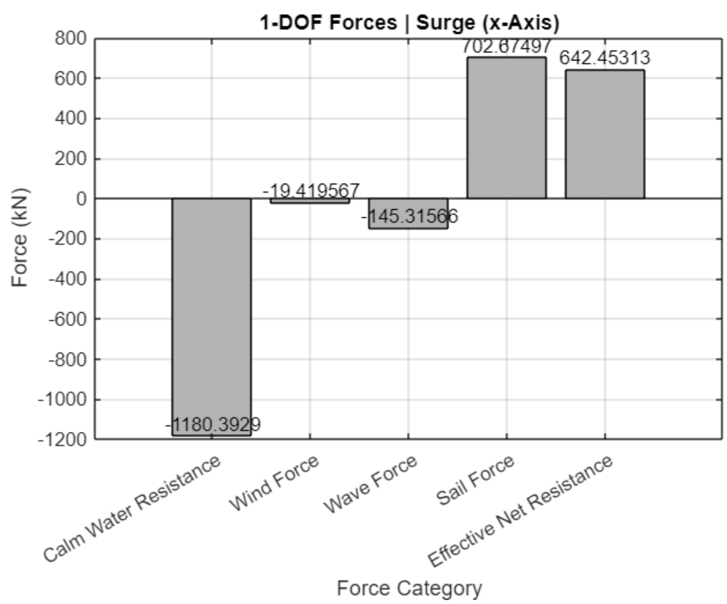

Figure 4. Estimated Forces for leg 4

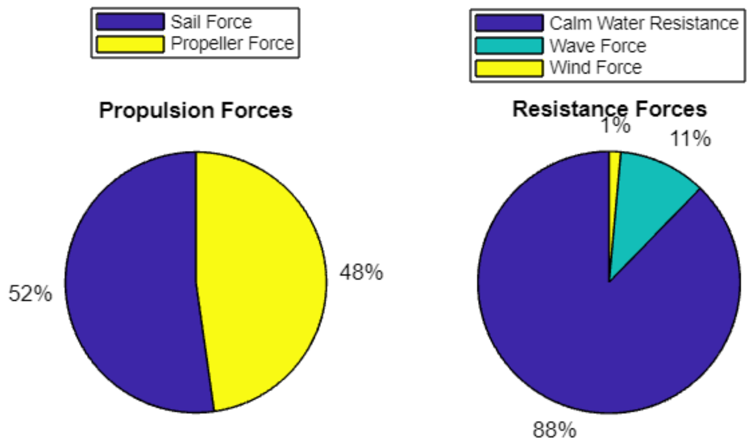

Figure 5. Force Percentages for leg 4

Hull

The calm water resistance of the vessel is plotted in Figure 6, along with the operational points. Speed is fixed to 12 knots.

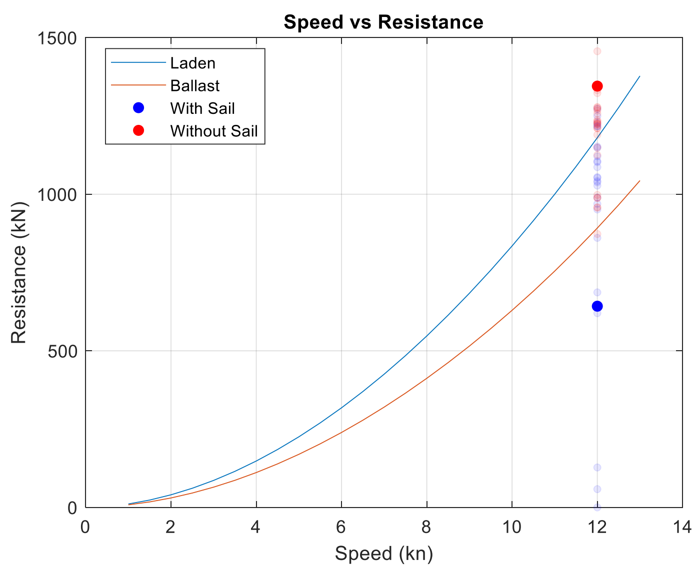

Figure 6. Speed vs Resistance
(Colored points refer to leg 4. Transparent points refer to the rest of the legs)

Main Engine

The engine layout diagram, along with the calculated operational points for all legs are shown in Figure 7 and the Specific Fuel Oil Consumption (SFOC) is shown in Figure 8. It should be noted that an assumption is made that the engine is always in operation (zero brake power is not allowed). In practice, operational points with very low engine loads (Reche-Vilanova et al 2023) need to be addressed with an operational strategy (e.g. increase vessel speed, trim sails etc.) in order to avoid operating at such low loads (and very high SFOC). During the herein conducted optimization, this is not taken into consideration because in the examined case study the majority of the operational points do not require very low engine loads, therefore the effect of an operational strategy for these cases does not have a significant impact on the optimization output.

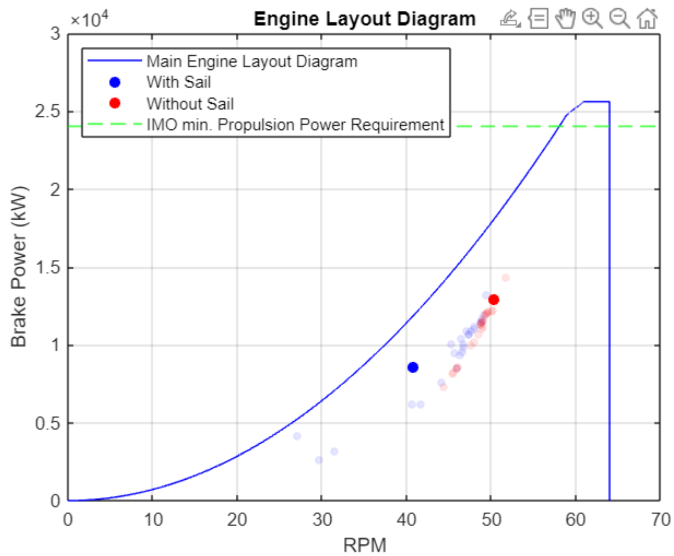

Figure 7. Engine layout diagram
(Colored points refer to leg 4. Transparent points refer to the rest of the legs)

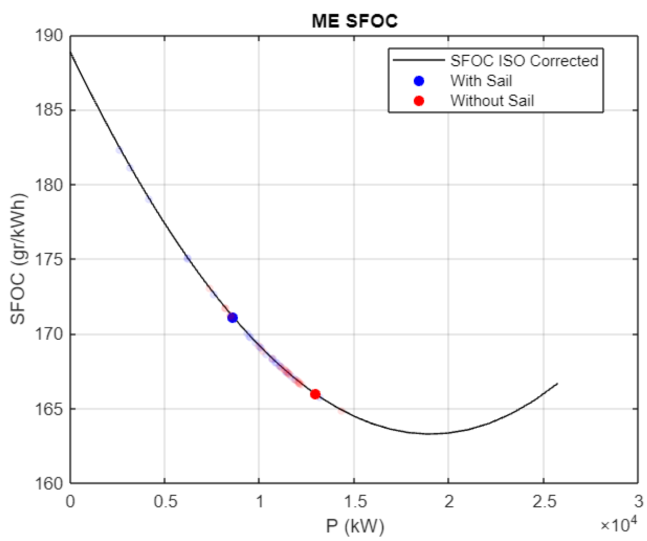

Figure 8. Power vs Specific Fuel Oil Consumption (SFOC)
(Colored points refer to leg 4. Transparent points refer to the rest of the legs)

Propeller

The examined Fixed Pitch Propeller (FPP) is modeled based on the polynomials of the Wageningen B-series (Lammeren et al 1969 and Oosterveld & Van Oossanen 1975). Propeller efficiency is estimated for the various operating points (Figure 9) and a check is conducted to ensure that we do not have extensive cavitation (Figure 10)

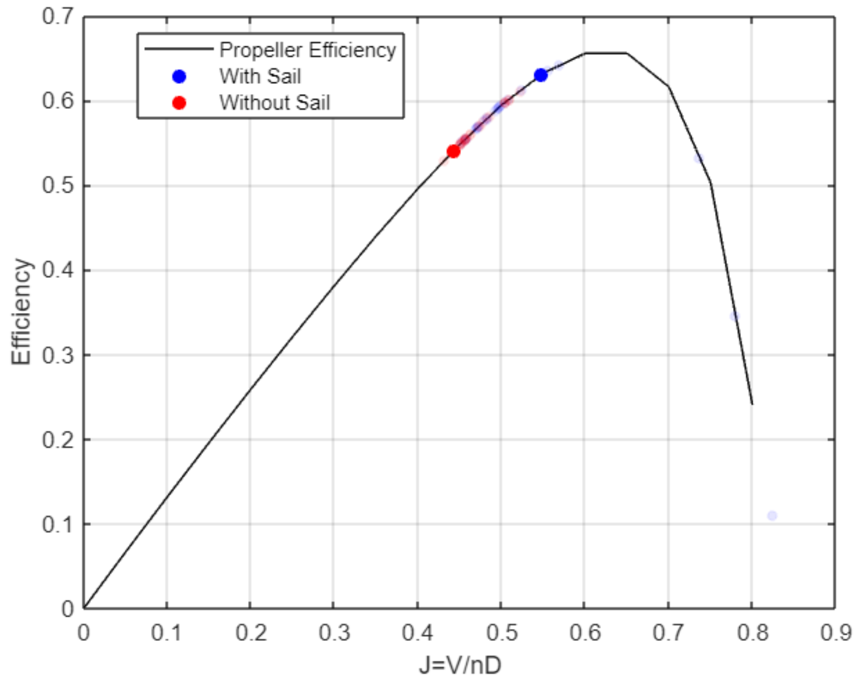

Figure 9. Propeller Efficiency
(Colored points refer to leg 4. Transparent points refer to the rest of the legs)

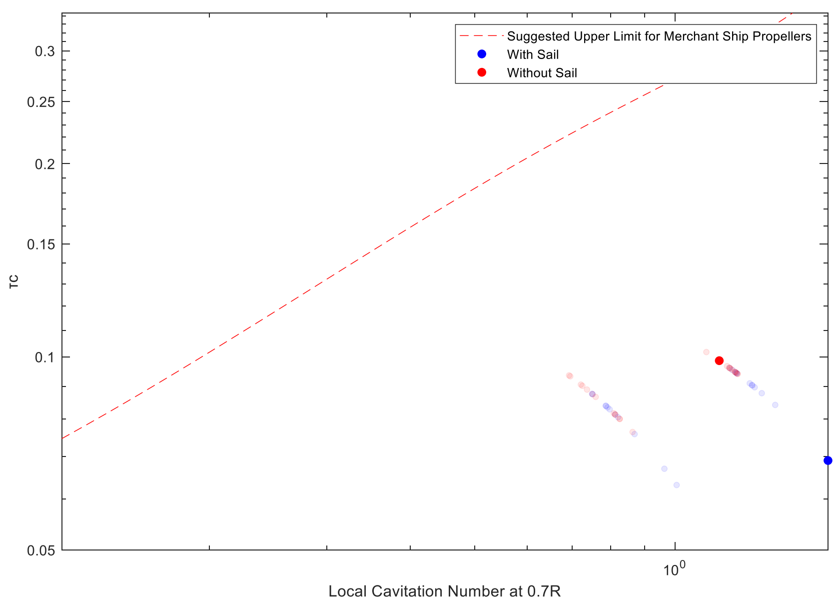

Figure 10. Checking for cavitation (Carlton 2007)
(Colored points refer to leg 4. Transparent points refer to the rest of the legs)

Wing Sail

Regarding the wing sail, the forces are calculated based on the apparent wind speed, apparent wind angle and lift/drag characteristics of the ensuing wing profile (Figure 11).

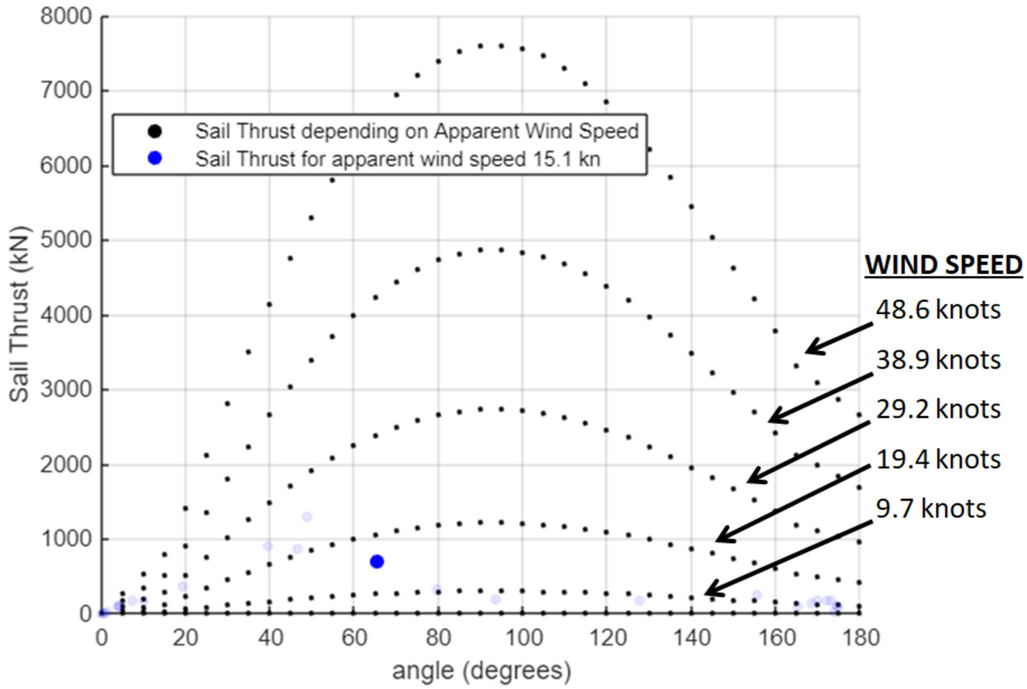

Figure 11. Wing Sails Thrust (8 Wing Sails) depending on wind angle and wind speed

DESIGN OPTIMIZATION METHODOLGY

A customized optimization problem for the design of ships with WAPS has been defined and appropriate methodology developed to handle the wind assisted propulsion problem. The output of the optimization process is the optimum combination of hull, engine and propeller that minimize the objective function, while including the effect of the examined WAPS. The MATLAB coded optimization module is capable of conducting both single- and multi-objective optimization studies and the main optimization process is sketched in Figure 12. The herein presented study focuses on a single-objective optimization problem. Below, some details regarding the optimization process are briefly mentioned.

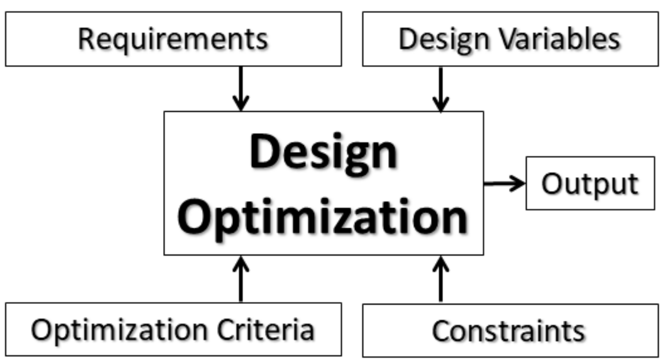

Figure 12. Generic design optimization process (Papanikolaou, 2014)

Optimization Algorithm Selection

Due to the nonlinear nature of the problem, a combination of optimization algorithms is utilized, both heuristic (genetic algorithm) and deterministic (sequential quadratic programming), in order to ensure that convergence to a global optimum solution and avoid possible local minimal solutions.

Design Space Exploration

In order to ensure that we have explored the design space sufficiently, a large number of initial designs is populated using the SOBOL sequence (Bratley & Fox 1988). A SOBOL sequence is a probabilistic sampling scheme that covers the design space more evenly compared with a pseudorandom number source. It increases the diversity of the population and leads to better optimization results (Agushaka & Ezugwu 2022). In the examined case study 5,000 designs are generated and the best 50 feasible designs are used as initial population in the genetic algorithm.

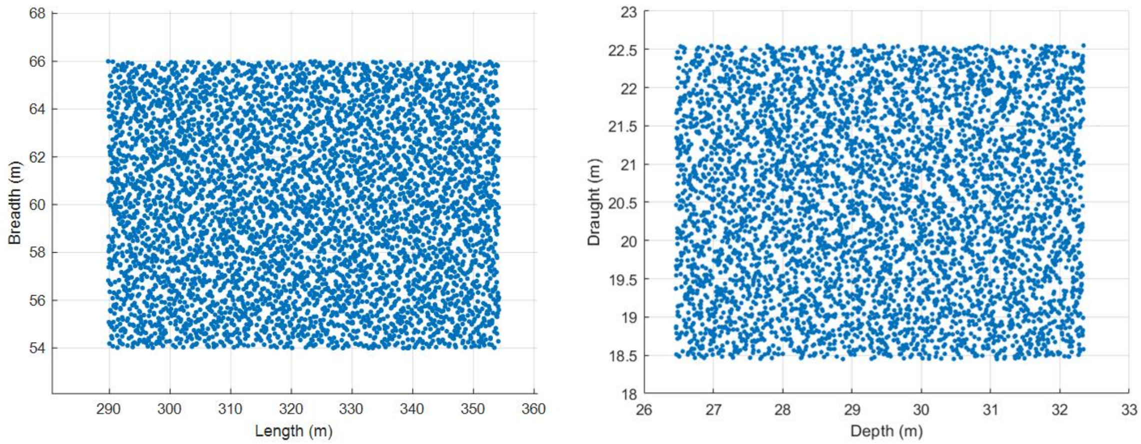

Figure 13. 5,000 Initial Designs Using Sobol Sequence

Heuristic Optimization Algorithm

The global optimization algorithm that is utilized is the genetic algorithm (Mathworks 2023). We optimize for 500 generations with each generation containing 50 individuals. The 50 "fittest" designs from the design space exploration process are used as initial population.

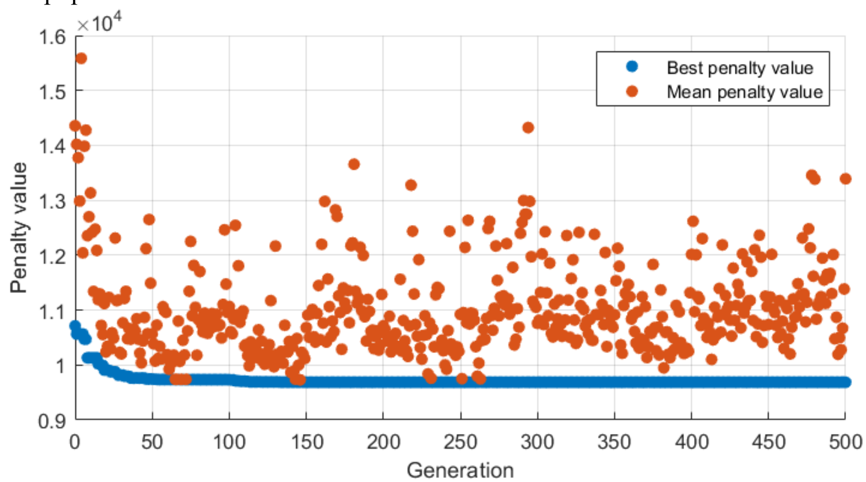

Figure 14. Genetic Algorithm Progress Example

Deterministic Optimization Algorithm

After the global optimization algorithm finishes, a deterministic optimization algorithm is utilized, namely Sequential Quadratic Programming (SQP). The initial value of the deterministic optimization algorithm is the output of the Heuristic Algorithm, thus optimizing further the design.

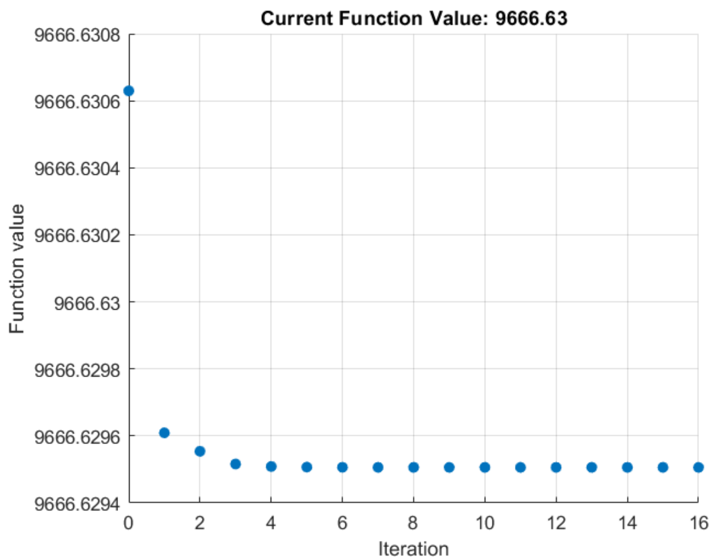

Figure 15. SQP Optimization Algorithm Iterations Example

IMPLEMENTATION

The developed WAPS simulation tool is implemented within the earlier defined design optimization methodology to approach the wind-assisted design optimization problem holistically (Figure 15). Some details regarding the implementation of the methodology are briefly outlined below.

Design Variables

In the herein presented application study, we consider 8 ship design variables: Length (L), Breadth (B), Depth (D), Draft (T), Block Coefficient (CB), Engine BHP/type (selected from a list), propeller pitch ratio (P/D) and propeller expanded area ratio (A_E/A_0). Due to the nature of the employed genetic algorithm that is used for optimization, it is more efficient to handle all design variables as integers (discrete optimization). For L, B, D and T we keep 2 decimals, thus $L_{integer} = L \cdot 100$, $B_{integer} = B \cdot 100$ etc. and for CB, P/D and A_E/A_0 we keep 3 decimals $CB_{integer} = CB \cdot 1000$ etc. The engine selection parameter is also an integer number that defines which engine has been selected from the provided engine list. This technique significantly speeds up the optimization process and allows a wider examination of the design space.

Once the genetic algorithm has completed the optimization process, the deterministic optimization algorithm uses the optimum result of the genetic algorithm to conduct a continuous optimization process, thus no longer treating the design variables as integers. This is due to the nature of the employed continuous optimization algorithm and allows the fine-tuning of the already optimized design by a genetic algorithm.

Objective Function

The objective function used in the present case study is the minimization of annual fuel oil consumption of the main engine (and indirectly of the associated GHG emissions). The fuel consumption per roundtrip is estimated for the provided weather conditions and then the annual consumption is estimated taking into consideration the activity of the reference vessel (yearly percentage of laden and ballast sailing time) and the number of roundtrip voyages that can be achieved yearly. It is noted that there is no restrictions in the implemented optimisation method and code to include more objective functions (multi-objective optimization possible)

Constraints

The set design optimization problem considers 15 constraints, which ensure that the derived results are feasible. More specifically, the constraints include limits for the DWT, limits for the form coefficients and main dimension ratios in order to ensure that the generated designs are meaningful and do not much deviate from relevant data of existing vessels (Papanikolaou 2014), they ensure that the propeller operates within engine limits with minimum cavitation (Burrill &

Emerson 1978), and the compliance with regulations regarding freeboard (IMO 1966) and minimum propulsion power (IMO 2021). A minimum metacentric height (GM) of 3 meters is also required as an initial check of the intact stability of the vessel. It should be noted that the EEDI constraint (IMO 2022) is herein excluded due to lack of information regarding the calculation of the possible reduction factor for the installed WAPS (presently under consideration at IMO).

The set constraints for the VLCC tanker considered in the following are summarized below:

1. Min. DWT ≥ 270000 tons
2. Max. DWT ≤ 330000 tons
3. Engine Limit Constraint
4. Less than approximately 5% cavitation at the propeller
5. 0.79 ≤ CB ≤ 0.88
6. 0.992 ≤ CM ≤ 0.996
7. 0.88 ≤ CWL ≤ 0.94
8. 0.835 ≤ CP ≤ 0.855
9. 5.1≤ L/B ≤ 6.8
10. 2.4 ≤ B/T ≤ 3.2
11. 10.5 ≤ L/D ≤ 14
12. IMO Minimum Power Requirement
13. Freeboard Constraint
14. GM ≥ 3 m
15. 0.2·T ≤ Propeller Diameter ≤ 0.55·T

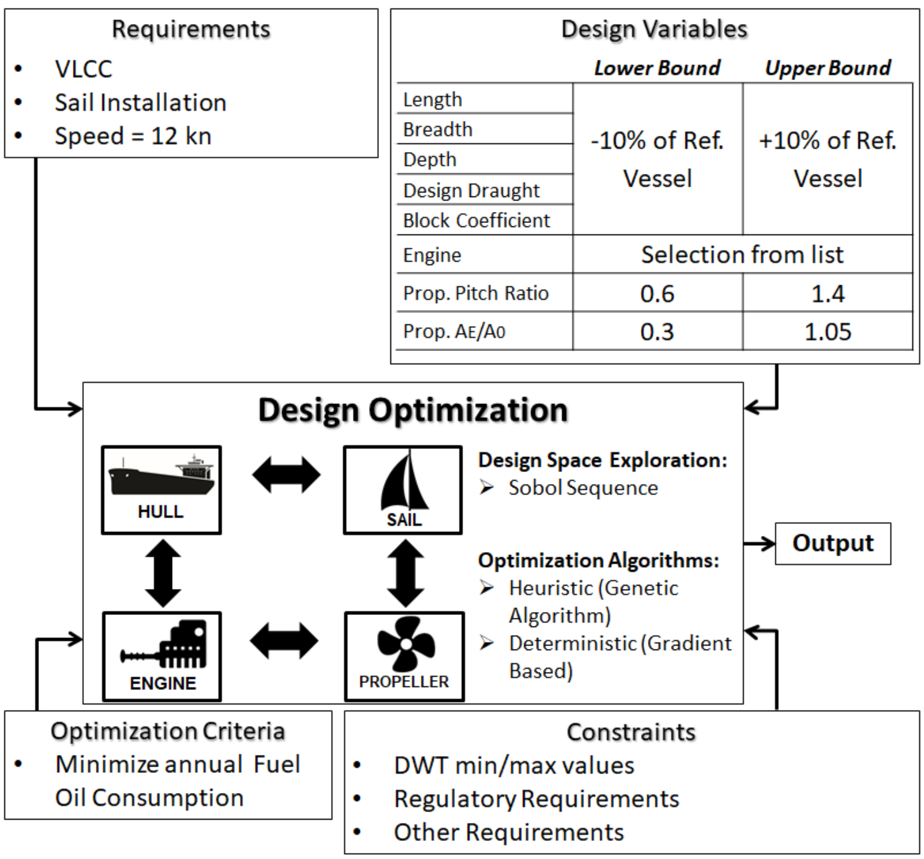

Figure 16. WAPS optimization process for VLCC case study

CASE STUDY

Reference Vessel

The reference vessel is an existing VLCC tanker. The main particulars of the reference vessel are presented in Table 1.

Table 1. Main particulars of reference vessel

Length B.P.	322.00 m
Breadth Mld.	60.00 m
Depth Mld.	29.40 m
Design Draught	20.50 m

Selected route and weather characteristics

The selected route for the case study is a common route from Corpus Christi (USA) to Rotterdam (Figure 2). The weather characteristics per leg were provided by the ORCELLE partner StormGEO and contain ERA5 data from 1980 to 2022. ERA5 (Hersbach et al. 2020) is the fifth generation atmospheric reanalysis of the global climate, produced by the Copernicus Climate Change Service (C3S) at ECMWF. In Table 2 the mean values of the provided data are presented. Seasonal changes in weather can also be taken into consideration but for the examined case study the weather information is herein considered constant.

Table 2. Weather information for the selected route

leg	Latitude	Longitude	TWS (kn)	TWA (deg)	Wave Height (m)	Wave Period (s)
1	26	-88.25	11.5	277.4	1.1	5.8
2	24.75	-79.75	11.0	276.6	0.9	5.4
3	25.75	-77	11.3	285.1	1.2	8.2
4	28.5	-72	11.8	310.7	1.7	8.7
5	32.25	-64.5	13.4	44.5	1.8	8.7
6	36.75	-56	16.3	64.4	2.5	9.2
7	40	-49	16.9	70.3	2.8	9.7
8	42	-45	17.8	75.3	3.0	9.8
9	43.75	-40.5	18.0	73.6	3.1	10.0
10	46	-33	18.1	70.0	3.3	10.3
11	47.75	-25.75	17.9	72.7	3.3	10.5
12	49.75	-6.5	15.7	86.2	2.5	10.4

It should be noted that the possible fitting of WAPS goes hand in hand with weather routing optimization, thus the examined conventional route (not optimized for prevailing winds) significantly underestimates the potential savings (Werner et al 2023).

Results

The results from the optimization algorithm are presented in Table 3 and a comparison of the main dimensions of the initial population (feasible and infeasible), the reference vessel (with and without sails) and the optimum vessel is presented in Figure 17

Table 3. Optimization Results

	Reference Vessel (without sail)	Optimized Vessel (with sail)	Difference (%)
L (m)	322	338.4	+5%
B (m)	60	54	-10%
D (m)	29.4	32.23	+10%
T (m)	20.5	22.12	+8%
CB	0.796	0.78	-2%
Main Engine MCR (kW)	25600	26437.61	+3%
Main Engine RPM at MCR (RPM)	60.9	63.5	+4%
Prop. P/D	0.803	0.787	-2%
Prop. AE/A0	1.05	0.459	-56%
Disp. (m3)	315264	315264	0%
DWT (t)	276902	276902	0%
Estimated Annual Main Engine Fuel Cons. (t)	13003	9666.6	-26%

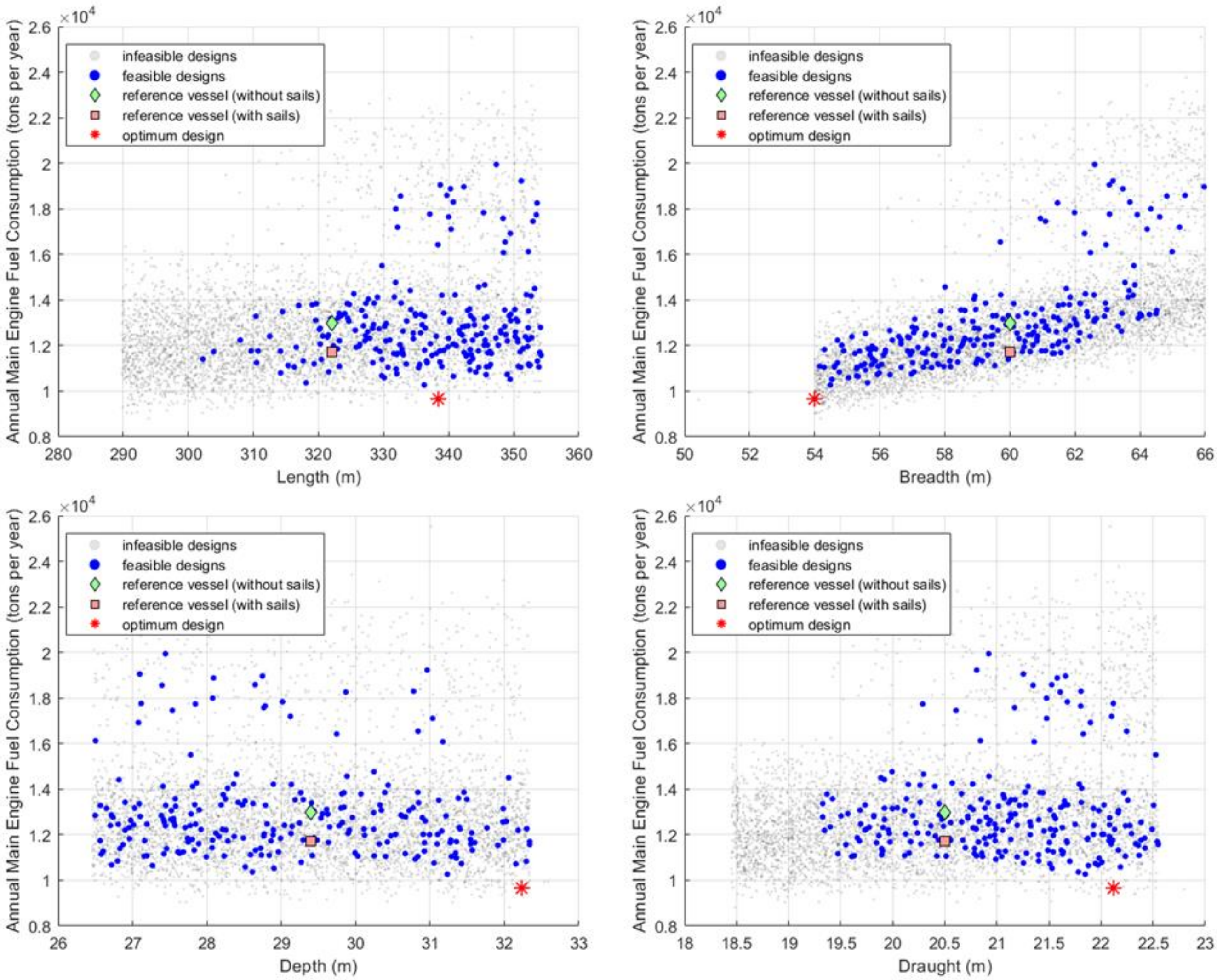

Figure 17. Comparing Main Dimensions of Explored Designs

In Figure 17 It can be observed that during the design exploration phase, a large number of infeasible designs is generated (grey points), which emphasizes the effect of the set constraints and the need of a sufficiently large and evenly-distributed initial population in order to ensure that the optimization algorithm converges to the global optimum. In Table 3, it can be observed that the conducted optimization resulted in a vessel with the same DWT but longer, with smaller breadth and larger draught. The reduction of the annual fuel consumption compared to the reference vessel is about 26%. It is also interesting to note that if the present wing sail system were installed at the reference vessel (retrofitting), the estimated annual Main Engine consumption would be 11728 tons, thus we would have still a reduction of 17.5% that is attributed to the changed design characteristics. It should be finally noted that the effect of WAPS on ship's main dimensions can be expected to be more drastic for other ship types and sizes, considering that the wind potential may be assumed the same for all ships operating on the same route, but its effect on ship's propulsion and motions is directly dependent on ship's size (displacement) and on the magnitude of the generated wind thrust compared to ship's hydrodynamic (and air) resistance.

SUMMARY & CONCLUSIONS

In the present paper, we developed a new simulation tool for the assessment of the performance of ships equipped with WAPS, allowing the exploration of the effect of the wing sails on the concept design of ships with wing sails in the frame of a multi-parametric ship design optimisation procedure. The developed simulation tool has been applied to a VLCC tanker design case study. Several useful conclusions maybe drawn from the conducted research:

1. There are numerous ship design and operational parameters that have major effect on ship design, when the ship is fitted with WAPS, such as ship's main dimensions, engine and propeller characteristics, route, speed, size/number/arrangement of wing sails, logistics, WAPS alternatives etc. and all of them need to be included in a ship design optimization procedure.
2. The main characteristics of the resulting optimized VLCC tanker with WAPS significantly differ from those of traditional VLCC designs w/o WAPS. It may be expected that differences will be more pronounced for smaller vessels and other ship types (volume vs. deadweight carriers).
3. The predicted fuel saving and associated reduction of GHG emission of 26% for a VLCC tanker are remarkable. These savings may appear too optimistic, because of the limited accuracy of the employed 1DOF hydrodynamic modeling. However, using an optimized route with respect to wind potential, instead of the shorted root and advanced technology wing sails, like the Oceanbird concept, instead of the herein used NACA wing profiles, it may be expected that the encouraging outcome of this study is fully justified.
4. Way ahead: further investigation of the effect of WAPS by
    a. proceeding to ship's preliminary design (by use of, e.g., the NAPA® naval architectural software platform)
    b. applying the present concept design approach to other ship types and sizes
    c. using more advanced hydro- and aero dynamic models (3 and 4DOF maneuvering models, inclusion of Oceanbird wing sail characteristics, effect seakeeping on the sails and on the resistance/thrust estimations).

It seems evident only a holistic approach to the wind-assisted ship design process will reveal the true and full potential of wind assisted propulsion in shipping and facilitate its acceptance by the maritime industry.

CONTRIBUTION STATEMENT

TP: Conceptualization; data curation, methodology; writing – original draft. **AP:** conceptualization; supervision; writing – review and editing.

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