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MariData – Digital Twin for Optimal Vessel Operations Impacting Ship Design

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ABSTRACT

Energy efficiency is a key element for reduced shipping emission to meet future environmental regulations. Both design and operation play an important role to meet this goal and the perfection of the interplay between these aspects promises quick improvements to meet the requirements of short term emission standards. The MariData project [https://maridata.org] developed a forward-looking energy management and decision support system (DSS) for ship operation based on rational methods and data created during ship design and sets out to bridge the gap between design and optimized operation. The "digital performance twin" of a vessel, which is based on design data, is enhanced with lifecycle data covering the entire operational envelope and provides valuable feedback into design processes.

KEY WORDS

Simulation; Operational profile; Digital twin; Weather routing; Navigational support; Design Feedback.

INTRODUCTION

Shipping emissions are increasingly in the focus of public interest and political as well as regulatory attempts are being made to reduce such GHG emissions. While the majority of the maritime industry appears to concentrate on new generations of e-fuels to meet future emission standards, the question of sufficient availability and price is still uncertain. On the other hand, perfections of design and operational performance promise significant improvements of the energy efficiency of individual vessels and thus the whole of maritime operations, likely to meet emerging requirements for the 2030 emission goals. Departing from a vast experience of design improvements, the MariData project and its team members set out to develop a forward-looking energy management and decision support system (DSS) for ship operation based on rational methods and data created during ship design. In a first step, a digital twin of the vessel and its performance related properties is created, which can be derived from design data. Here, technologies from the EU HOLISHIP project (Papanikolaou, et al., 2022), (Papanikolaou, 2018) are applied to generate extensive surrogate models which cover the entire operational envelope including also degradation of the hull surface condition due to fouling which leads to increased resistance over time. This "digital design twin" is a fundamental prerequisite to determine optimal energy consumption during all phases of operation. In a second step a model of the engine / machinery system on board is created which provides another facet of the digital twin. In combination, these models allow to determine the total energy consumption on board for a large variety of operational conditions experienced during the lifetime of a vessel and form the basis for a continuous comparison of the target performance of the ship with actual data provided by comprehensive on-board data collection. Combining this energy model with advanced route planning is done on the basis

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of a combination of different geographic information and satellite weather data as well as weather forecasts. While ship safety is a key prerequisite, the information how the vessel will behave under projected environmental forecast data allows optimizing voyage planning using a variety of different target functions including minimal voyage time and / or fuel consumption or emissions. On the operational end, MariData presents planning and actual information to the ship crew through a dedicated advanced user interface, which allows for a permanent target performance comparison and decision support for corrective measures. By using advanced design data, MariData bridges the gap between modern design systems and operation. In one direction, the wealth of information created during design will be applied for optimized operation whilst in the other direction, statistical information obtained during – practical – operation will influence future designs.

DIGITAL TWIN FOR OPTIMAL VESSEL OPERATIONS

R&D Project MariData

The German national R&D project MariData (Comprehensive technologies for ship energy management) started in 2019 to explore the efficient use of energy during shipping operations. Energy efficiency has always been a key concern for both, shipbuilding and shipping. Whereas in the past it was mainly economic reasons that motivated the search for a low power requirement for a ship, nowadays ecological reasons and compliance with statutory regulations to reduce emissions are coming strongly to the forefront with at least equal weight. These concerns call for a consistent strategy of energy efficiency as well as a significant reduction of exhaust emissions not only in the construction but also substantially in the operation of ships.

The energy consumption of merchant ships is largely determined by their hydrodynamic characteristics and the systems onboard. In some cases, up to 90% of primary energy consumption is used for propulsion and must, therefore, be optimally managed. MariData's goal is to develop, improve and classify simulation-based modules for ship energy management based on information created during the design phase of a vessel.

Together with geospatial information and a DSS that brings together technical, environmental and economic data, energy consumption information is integrated into a platform that can be used both onboard the ship and shore-based by a shipping company. The platform provides on-line simulations for decision support to the ship's management, as well as assistance with short-, medium- and long-term forecasts and decisions related to ship operations.

A key element of the project's development is the energy model in form of a Digital Twin. Today, Digital Twins play an increasingly important role in the maritime industry: during design, production and operation of ships and other assets, they offer a large potential to improve the "product" in terms of (i) better understand the performance of the asset, (ii) study possible ways of improving it and (iii) predict and optimize operational behavior (e.g. with regard to scheduling maintenance, avoiding failure and improving energy efficiency). The concept applied in MariData is founded on a sophisticated and accurate simulation based energy which is in turn largely based on design data. This is accomplished with on-board measurements and allows to provide instant feed back for the operational optimisation. Although we consider the crew as part of the system, i.e. there will be no automatic manipulation of operational parameters, this concept can be regarded as a Digital Twin, though possibly not in the strict definition of the term. Rather than acquiring only measured operational data, often affected by sensor errors, the model is made up from large sets of simulations, e.g. for the energy requirements due to resistance and propulsion under various conditions of operation. This allows, together with reliable forecasts of environmental conditions, to plan and optimize voyages with increased reliability. The knowledge of all relevant parameters, wind, waves, currents etc. and the respective behavior of the vessel increases the accuracy of predictions and forecasts for the energy consumption during passages which in turn will yield a much higher accuracy in predicted and achieved fuel consumption for a planned voyage. This is a fundamental prerequisite for actual voyage optimization and makes fuel / energy savings accessible. The design contribution in this respect is that actual operational conditions are gathered and allow to produce more precise design briefs for similar or likewise ships in the future. The present system allows to feed experience gained from operation into detailed specifications for a new design brief which will be much improved by more precise weighting of different (operational) conditions and hence allow for a more specified design optimization, e.g. focusing more on the role of efficient behavior in waves, wind or other conditions which are typically considered to be "off design" at present.

Carl Büttner Tanker

Within the MariData project the main application is a tanker of 183 m length overall, 32 m maximum beam, 16 m depth, a design draft of 9.50 m (scantling draft of 10.5 m) and a cargo capacity of about 45 000 m3 (see Figure 1) is studied with regard to its energy consumption. The ship is an oil-chemical tanker, the CB Adriatic (called CBT for brevity), was built in 2019 after having been jointly optimized for an anticipated operational profile, i.e., for multiple speeds and drafts. The hull features an asymmetric stern, the propulsion system a tip rake propeller and the rudder a Costa bulb. Results from model tests showed a performance in the top of its class.

Figure 1: CB Adriatic (oil-chemical tanker, IMO 9851696), operated by Carl Büttner Shipmanagement

The project sets up a digital twin in order to compare consumptions as computed by means of simulations and as measured onboard and to suggest how to further improve energy efficiency. To this end, the ship's hydrodynamic performance needed to be simulated for many different operational scenarios, e.g. in calm water, in sea states representative of its operational profile, in both deep and shallow water, when maneuvering and when under the influence of heavy winds and current. As can be readily appreciated, this calls for suitable geometric representations of the ship hull, the propulsion system, appendages and the superstructure. Besides the tanker, also two heavy lift carriers have been equipped and investigated.

Data Acquisition

One cornerstone of our investigation was the acquisition of sensor-driven ship data alongside navigational data. To do this, custom-tailored hardware has been deployed on 6 ships of two fleets, representing a range of carrier vessel usages (tankers and heavy lift / project cargo vessels). The minimum specifications included access to navigational and performance-related data, such as Speed Over Ground (SOG) and Fuel Oil Consumption (FOC). To streamline data management and accessibility, a common interface has been established using the Navis Bluetracker Suite (Kaleris, 2024). This well-established platform, combining sensor and reporting data, serves as the backbone for data integration and pre-processing. In addition to this, a proprietary high-frequency data interface has been implemented to address the additional demands of model validation and onboard route monitoring. This interface supports archiving for historical analysis and facilitates local use, providing a robust foundation for real-time decision-making and continuous improvement of the digital twin. After initial sensor deployment, the acquired data on actual trips has been verified through plausibility checks and crew feedback, ensuring the reliability and practical relevance of the information obtained from sensor and onboard systems data.

Figure 2 illustrates the data flow within our system. The Navis Bluetracker Suite (B6, Figure 2) acts as the primary conduit for information, seamlessly integrating with the proprietary high-frequency data interfaces. On the shore side, this setup is enhanced by a proprietary server for geodata (e.g., environmental and navigational data; B3, Figure 2) and routing services. This architecture ensures a smooth and efficient flow of data from onboard sensors to centralized systems and back to the onboard decision support system (B1, Figure 2), enabling comprehensive monitoring and analysis. The visualization of this data provides valuable insights into vessel navigation and performance, empowering stakeholders to make informed decisions for enhanced maritime operations. Additionally, on shore side, extensive evaluation of recorded ship parameters for both system improvements and crew training is facilitated.

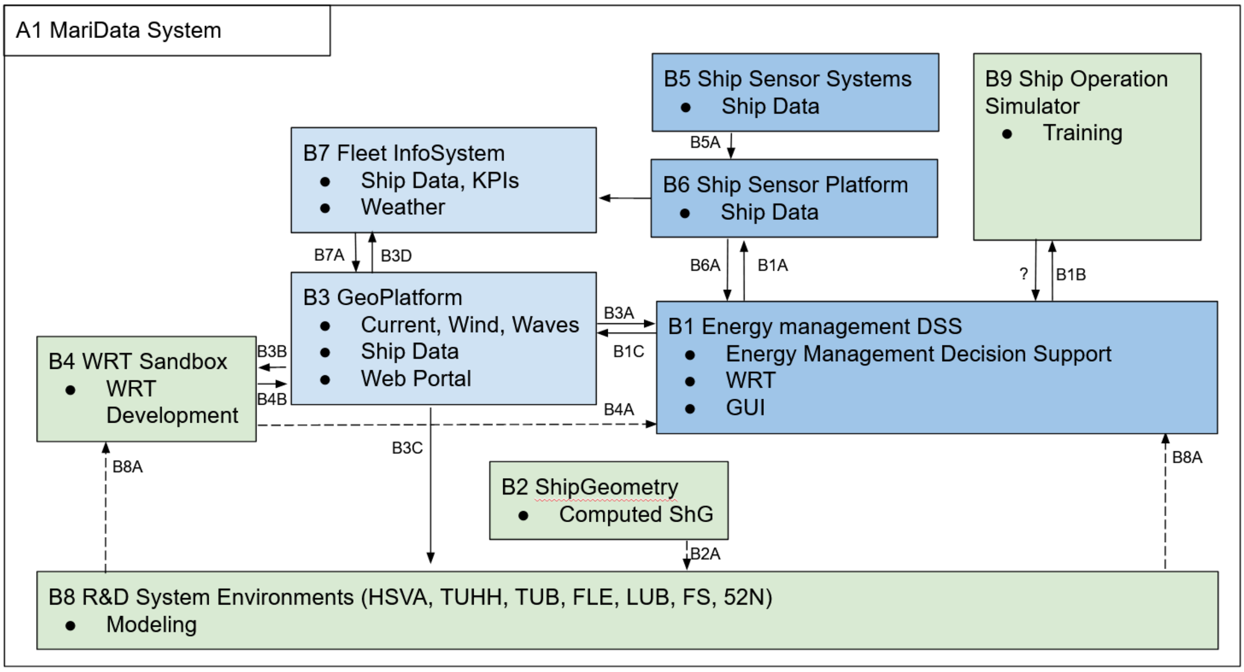
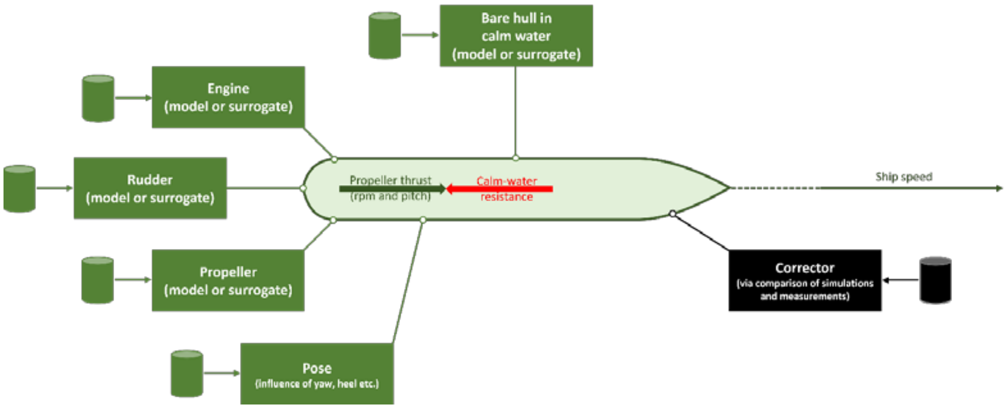


Figure 2: Data Flow and System Map (excerpt; initial planning stage)

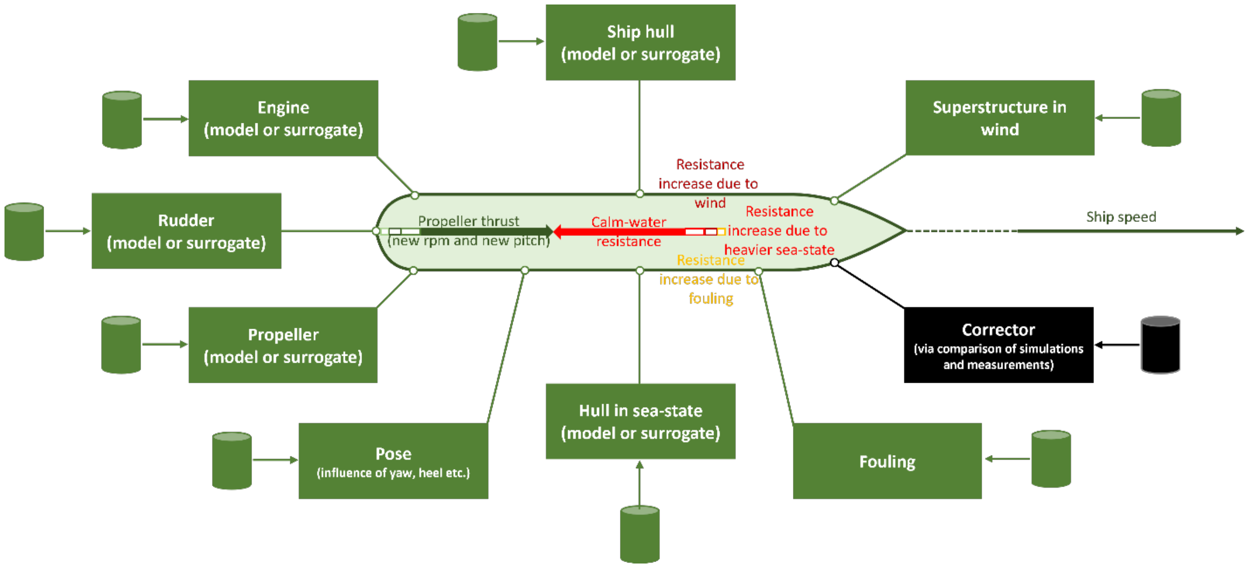
SIMULATIONS AND SURROGATES

Components

A ship traveling through water is influenced by many factors, all of which contribute to some extent to its total energy consumption. Assuming that interactions are sufficiently small in comparison to any component's direct contribution, a superposition ought to give reasonably good estimates. For the sake of simplifying the analysis often calm-water at infinite water-depth is considered, see Figure 3a, while the actual situation at sea comprises wind, waves, current, fouling along with possible effects from shallow water and/or canals, see Figure 3b. All components need to be suitably considered. Here, only the key contributors shall be discussed in some detail, namely calm-water resistance, added resistance in waves and propeller performance.



(a) Calm-water conditions (idealized)



(b) Conditions under the influence of wind, sea-state, restricted water conditions (e.g., shallow water), fouling etc. (realistic)

Figure 3: Components for which data are produced by simulations

Calm Water Resistance

Calm water resistance is typically the first and often foremost element of all hydrodynamic considerations. It is made up of two different components: (i) the pressure or form-related wave resistance and (ii) the viscous drag. The added resistance due to wind and waves is treated in the following section. The calm water contributions to the overall power requirements of a vessel typically amount to 70% of the overall power required on board. The pressure related component depends – besides speed and draft of the ship – on the hull form and hence is invariant over the lifetime. Viscous resistance however changes a lot over time due to increased hull roughness due to fouling. As the overall share of the viscous or frictional resistance can be large, especially for typical merchant vessel cases, this has to be taken into account not only during operational optimization but already during design as to make sure that the selected engine meets the requirements of increased water resistance over time.

For the surrogate model used in the digital twin of the CBT, a set of design predictions formed the basis. This concept follows an approach developed in the HOLISHIP project, see e.g. (Marzi, et al., 2018; Papanikolaou, 2018).

A first evaluation of the operational conditions of the tanker revealed that more draught and trim conditions than considered during design were required to cover the entire envelope. This meant that an extra set of predictions had to be performed. As the design predictions all were performed using a standard roughness according to ITTC guidelines, further analysis of additional hull roughness conditions was included in the data set which finally resulted in a model comprising more than 190 different conditions for the calm water resistance. This was considered sufficient for use during operational optimization. Predictions were performed using HSVA's in-house RANS code FreSCo$^+$ (Hafermann, 2007) using different roughness models. An example of the calm water predictions is shown in the following figure which illustrates also the complex wave formation at the bow of the ship.

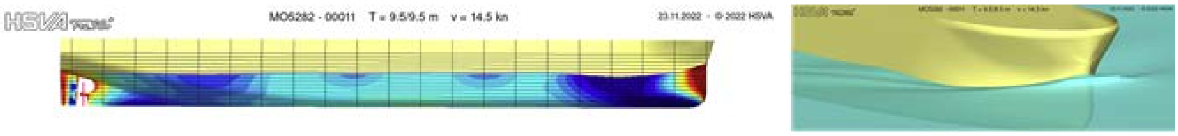


Figure 4: Example CFD prediction for the CBT – fully laden at design speed

The entire set of predictions resulted in a response surface shown in Figure 5 indicating total resistance as a function of speed and draft (even keel situation). Due to confidentiality, these and all following resistances are normalized with the calm water resistance $R_{calm,ref}$ at a ship speed of 13 kn and a draught of 9.5 m.

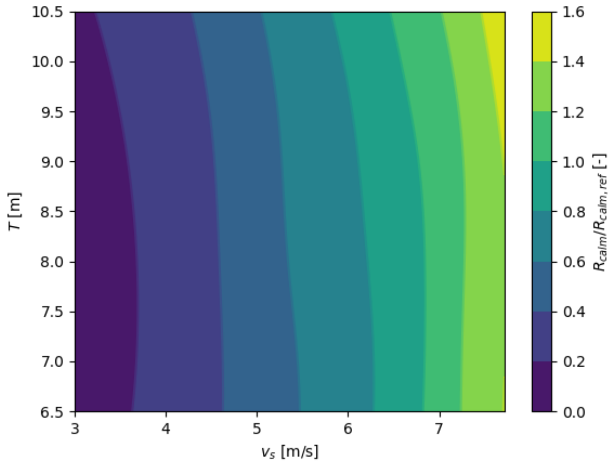


Figure 5: CBT calm water resistance as a function of speed and draft, even keel

The effect of hull roughness has been accounted for using a dedicated new wall function model in FreSCo+ developed in the MariData project. This allows to choose between different wall functions and even to specify local distributions of roughness based on a sand grain equivalent. The following Figure 6 indicates the effects of different distributions of roughness on the hull of the CBT: On the left, variable sand roughness distributions on tanker hull are indicated: from bottom to top: constant fouling, positive fouling gradient, negative fouling gradient and variable fouling fraction. On the right, friction coefficients on the hull and along hull center line are shown based on the different mean (spatially constant) sand roughness.

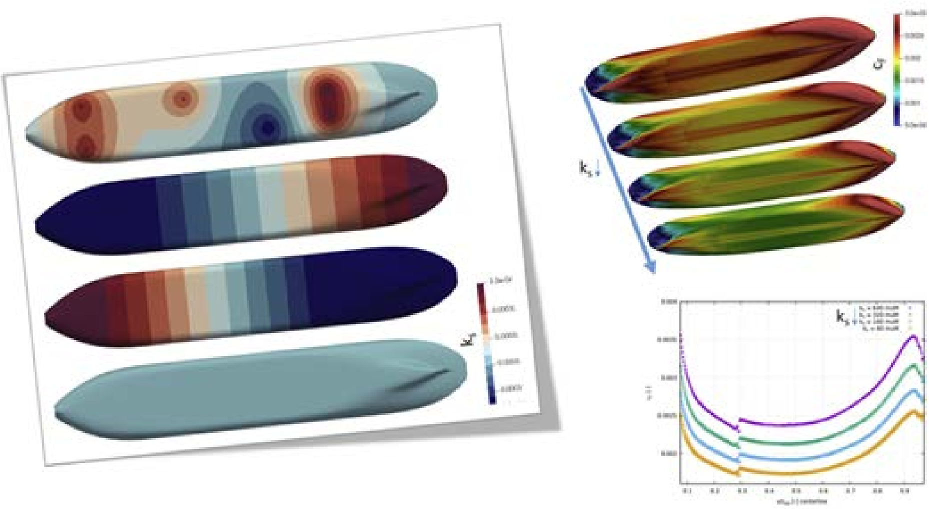


Figure 6: Effect of local roughness distribution on shear forces

Alternatively, roughness effects can of course also be modelled using the well-known ITTC roughness model. Figure 7 indicates the respective response surface for additional resistance according to roughness as a function of speed.

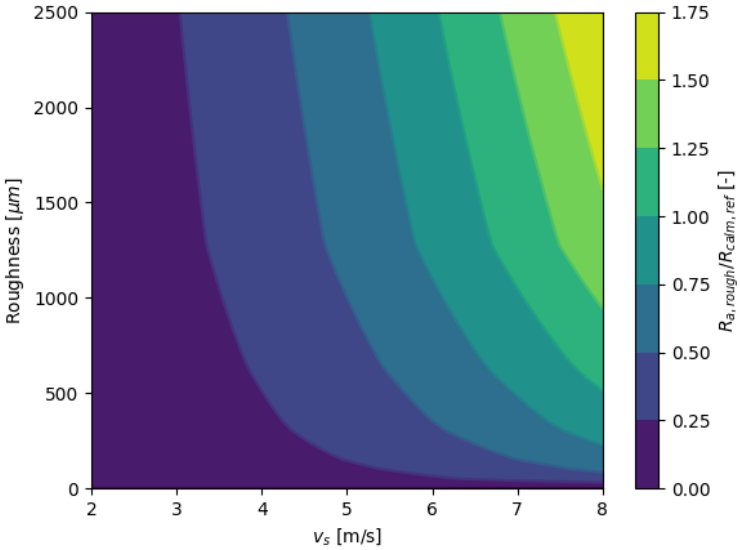


Figure 7: Added resistance due to hull roughness on CBT

Added Resistance in Waves

The contribution of added resistance in a seaway to the total resistance can be quite significant, depending on the ship type and weather conditions. To obtain a good estimate of the resistance, the following parameters must be considered:

- draught at aft perpendicular
- draught at forward perpendicular
- vertical position of center of gravity
- ship speed
- main direction of incoming waves
- peak period of wave spectrum
- significant wave height of incoming waves

Because of the number of relevant parameters, methods like RANSE-based simulations are not feasible to build the surrogate model. Instead, simulation methods based on potential flow theory are used. The 3D panel code NewDrift, developed at National Technical University of Athens (NTUA), was used in the scope of the MariData project to create large sets of training data. To generate penalizations for many different floating conditions, a process using the CAD environment CAESES was set up. About half of the generated dataset of approx. 6000 points is used to train the surrogate model using a Kriging approach. The remaining points serve as control set to check the model quality.

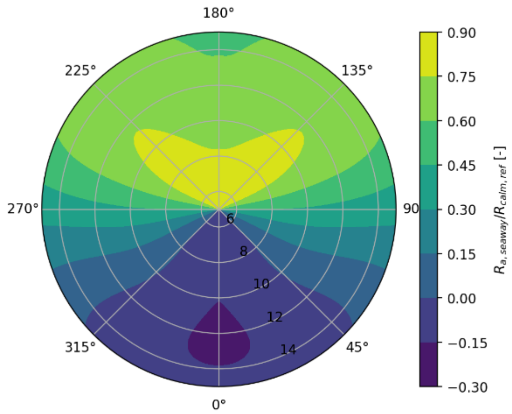


Figure 8: Added resistance due to seaway in $T_p = 9.5\ s, H_s = 2\ m$

Propeller Performance

Simulations were performed in the panel code panMARE (Hundemer, 2005) developed at the Institute of Fluid Dynamics and Ship Theory. A grid study resulted in a blade discretization with 20 panels in chord wise direction and 25 panels in radial direction, shown in Figure 9.

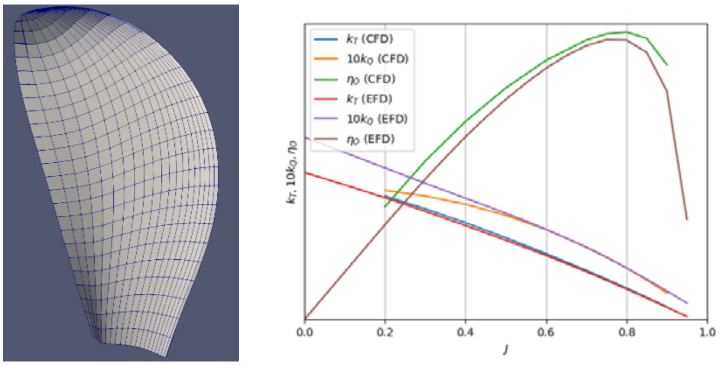
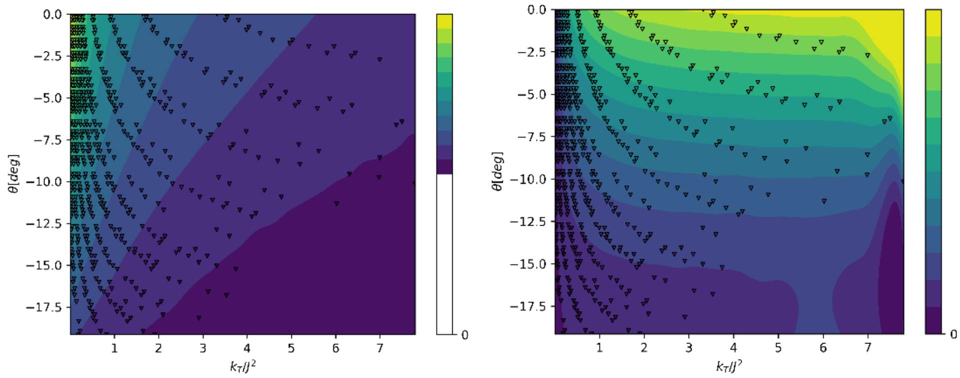


Figure 9: CBT propeller blade panel grid and open water comparison of simulated and measured results

A Sobol sequence was used for the sampling in parameter space of rotation rate and blade pitch θ. Only operating conditions from the first quadrant were simulated until the absolute of the second statistical moment of thrust coefficient, torque coefficient and open water efficiency fell below 1E-4. 736 operating conditions remained for the generation and testing of the two surrogate models under the condition $c_{Th} < 10$. The models are designed to determine the advance coefficient J and torque coefficient k_Q from the ship loading curve coefficient k_T/J^2 and θ, see Figure 10 for the resulting response surfaces.



a) Advance coefficient **b) Torque coefficient**

Figure 10: CBT propeller surrogate model response surfaces

Various Additional Components

Environmental factors not only introduce parts to the added resistance but can also introduce transversal forces as well as yaw moments. The reaction of the ship to these components in form of drift motion and necessary rudder angle to neutralize yaw moments is modeled with a set of maneuvering coefficients. These also contain parts for the longitudinal force due to sway motion and rudder angle.

Aerodynamic Resistance

For the wind influence, forces were determined through hybrid RANS/LES simulations for two geometries, a detailed geometry and a simplified one regarding deck and deckhouse superstructure. The difference in longitudinal and transversal force for the two versions in apparent wind angles of 0°, 45° and 90° were between –5% and 8% of the force on the detailed version. The surrogate model was built with a coefficient-based interpolation approach with ship speed, wind speed, wind angle, draught and material properties of the air as input parameters,

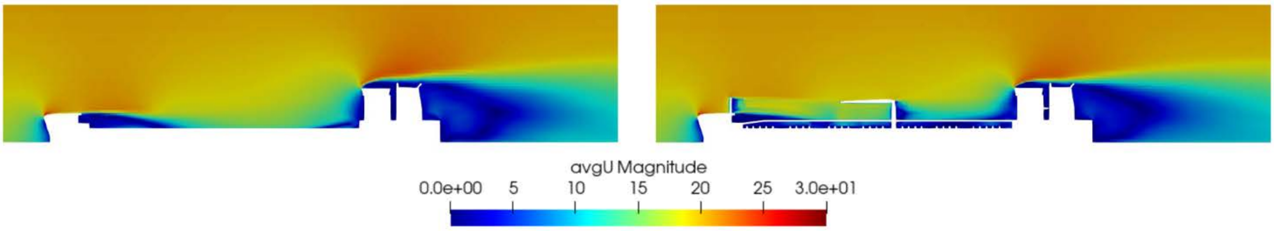
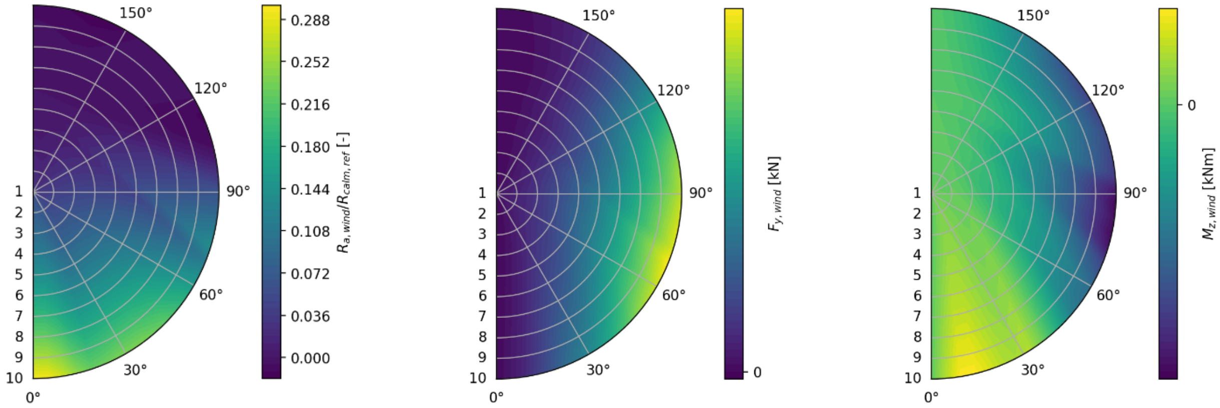


Figure 11: Air velocity distribution on midship plane for two geometry detail levels



a) Added resistance **b) Side force** **c) Yaw moment**

Figure 12: CBT wind force surrogate model results for 5 m/s ship speed as a function of apparent wind angle and wind speed

Added Resistance in Shallow Water

Simulations with the CBT hull in restricted water depths were carried out using a Finite-Volume method. The results were used as training data for a Kriging-based surrogate model, as previously published e.g. in (Harries, et al., 2019) and (Harries, et al., 2017) for the added resistance due to shallow water with the parameters water depth, ship speed and draught. Exemplary results of this model are shown in Figure 13.

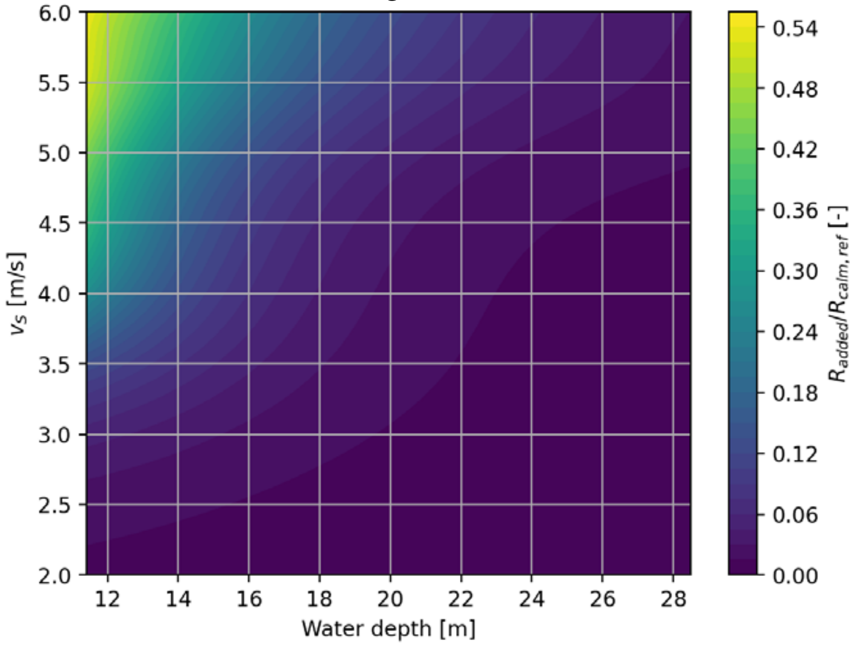


Figure 13: Added resistance due to shallow water effects for CBT at T=9.5m

Uncertainty considerations and analysis

Given the complex structure and interdependencies between different elements of the overall MariData development, it is evident that here are several sources of errors, causing uncertainty. Prominent sources of uncertainty are:

- Simulations: System behavior is only approximated by simulations which themselves are sufficiently converged numerical solution to chosen mathematical model that describe the physics of interest. In some cases certain phenomena are deliberately neglected to be able to undertake simulations with reasonable effort, e.g., potential theory for sea-keeping analyses in which viscous effects are not taken into account.
- Interactions: Assuming that various resistance components can be superimposed linearly omits any interaction between them. For instance, hull fouling not only changes calm-water resistance but might change the wake field into the propeller.
- Surrogates: The various components are captured by means of surrogates, i.e., meta-models that are fed with simulation data and which interpolate (or approximate) these data, yielding quantitative results for system behavior where no simulation actually took place. Previous work has shown good accuracy for surrogates representing calm-water resistance (±1% difference between the approximation and the simulations) and added resistance in waves (uncertainty of ±2.5%), see Harries et al. (2019) and Harries et al. (2017), respectively.
- Biofouling: This component has a huge impact on ship resistance while its assessment is often rather difficult. Without regular inspections, the amount and location of biofouling can only guessed by the crew while in port. In the present case timely and well documented hull inspections were available which allowed to determine a fairly accurate level of hull roughness increase during the periods for which historic voyages were analyzed.
- Representation: The geometry of various components is not taken into account as built but as designed, causing additional uncertainty in the simulation set-ups.

There are further uncertainties which are related to the weather fore- and/or hindcast as well as in the sensors installed on board. These will be briefly addressed in the sections below.
Ideally, a through analyses of the error propagation would be undertaken. This, however, was beyond the scope of the project and is certainly beyond the scope of this paper. Still, an attempt was made to develop an appreciation of the influence of uncertainty by assuming ±5% of change in calm-water resistance, independent of its origin, and ±20% of change in added resistance in waves. Further investigations would be needed.

Engine Model

The main engine model was supplied by project partner AVL and predicts the fuel oil consumption based on engine operational data as shown in Figure 14.

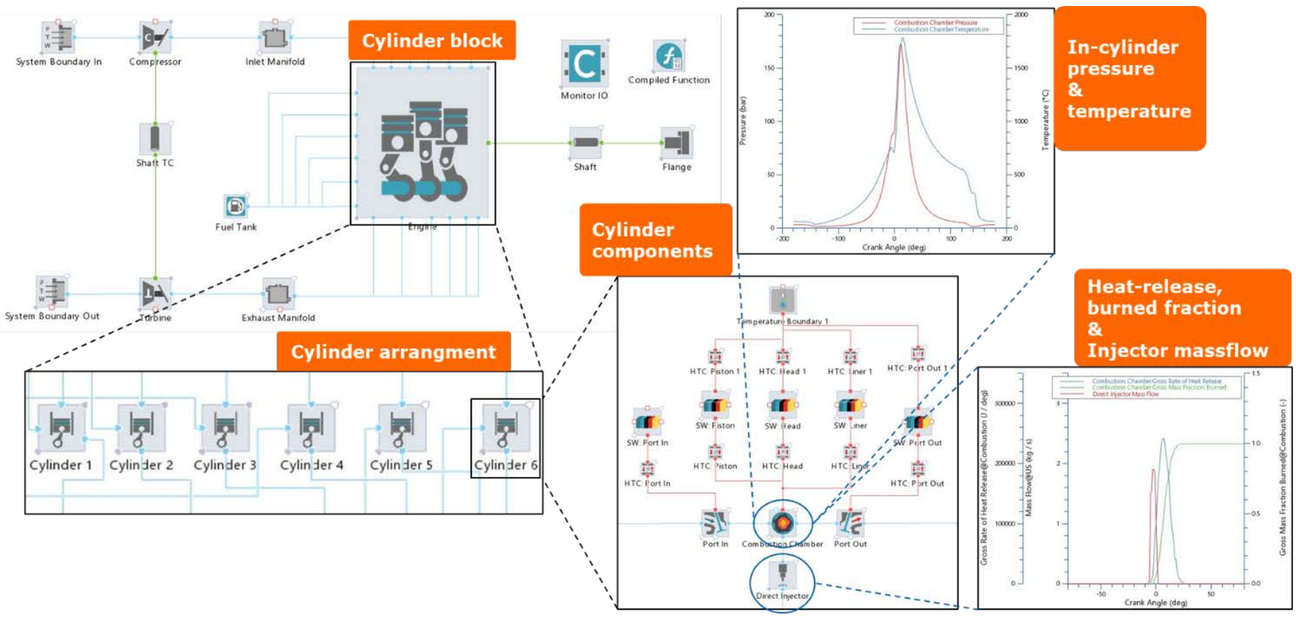


Figure 14: Detailed main engine model derived from design data

The core of the model consists of six cylinders, which in turn are divided into a combustion chamber and an integrated injector model. All geometric design parameters have already been considered in the model parameterization. The model can calculate and output both transient, i.e. time-resolved, engine variables (e.g. total engine power, fuel consumption, engine speed, etc.) and traces resolved via crank angle position (e.g. cylinder pressure curve, heat release rate, etc.). Combustion and heat release in the combustion chamber are approximated using the empirical vibe model. The calorific value of the fuel was stored using the fuel tool integrated in the AVL CRUISE M tool and is used as the basis for calculation in combustion modeling.

The injector model receives a variable injection mass flow as a transient target value as an actuator signal and distributes the corresponding fuel quantity during the conversion between the time/crank angle domain in accordance with the stored injection profile via a working cycle. The engine shaft, which is mechanically coupled to the cylinder bank, can be operated both speed-controlled and torque-controlled. Depending on the set mode, either the applied speed or the applied torque can be applied directly as a control variable. The transient response of the motor model after the manipulated variables have been changed can be checked for plausibility using the calculated engine power, consumption, and speed.
A turbocharger has been added to the main engine model, which means that charge air conditioning and energy recovery from the engine exhaust are considered in the model. A simplified representation without operating maps for the compressor and turbine was selected: the turbine component is equipped with an internal wastegate sub model, which adjusts the wastegate opening depending on the power requirement.

In addition, two auxiliary blowers were added to the main engine model. The pressure increase that the intake air experiences as it flows through the blowers is taken into account using adapted maps. These are used to maintain charge air control even at low engine loads, where the turbocharger alone cannot achieve the desired compression on the intake side. With the implementation of the turbocharger and the auxiliary fans, the gas path representation of the main engine is complete.

Due to the limited measurement data available, which does not allow a detailed comparison of the internal cylinder condition with detailed combustion curves over a working cycle, no changeover was made to a predictive combustion model with detailed, phenomenologically based parameterization. Instead, an empirical Vibe combustion model was used and its parameters were adjusted as part of the parameter variation plan so that the simulation results approximate the consumption/power and torque figures in the data sheets with sufficient accuracy. The purpose of the Vibe function is to reproduce the typical S-shaped profile of the integrated heat release of combustion engines (Stiesch, 2003). The start of combustion and the combustion duration in the cylinder were defined as load point-dependent parameters of the Vibe model. The shape factor used was also represented as a function of the load point. It was possible to achieve a high level of agreement between the simulation results and the characteristic values from the data sheets by taking the above-mentioned measures when parameterizing the Vibe model. The accuracy was examined over five stationary operating points: 25%, 50%, 75%, 100% load and then at 10% overload. Table 1 shows the resulting model reference deviation for absolute fuel consumption (FOC) and power-specific fuel consumption (BSFC). Depending on the selected operating point, the deviation ranges between 0.3% and 0.98%.

Table 1: Deviation of the simulated fuel consumption over five reference load points

Load Points	25	50	75	100	110
Deviation percentage FOC	0.594	0.332	0.886	0.269	0.745
Deviation percentage BSFC	0.522	0.299	0.983	0.167	0.622

WEATHER ROUTING

Weather Data

To evaluate the simulations – i.e. by comparison with measured data – and to perform route optimization for historical and planned routes, we need to know the physical state of the atmosphere and the ocean at the time of travel. The in-situ data from the sensors deployed on the ships are not sufficient as they do not cover all necessary variables and provide only information about the current state. Today, multiple operational forecast and reanalysis systems exist which can fill this gap. For oceanographic data we use two products, “Global Ocean Waves Analysis and Forecast” (EU Copernicus Marine Service Information (CMEMS). Marine Data Store) and “Global Ocean Physics Analysis and Forecast” (EU Copernicus Marine Service Information (CMEMS). Marine Data Store) and for atmospheric data we use the Global Forecast System (National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of

Commerce, 2015). The data come in different spatial and temporal resolutions. Table 2 shows an overview of those variables expected as input for our fuel consumption model.

Table 2: Overview of the environmental variables downloaded from CMEMS and GFS

Variable	Platform	Space	Time
Wind speed u-component[1]	GFS	1/4°, global	3 h, 10 days-forecast
Wind speed v-component[1]	GFS	1/4°, global	3 h, 10 days-forecast
Air pressure reduced to mean sea level	GFS	1/4°, global	3 h, 10 days-forecast
Air temperature at water surface	GFS	1/4°, global	3 h, 10 days-forecast
Spectral significant wave height	CMEMS	1/12°, global	3 h, -1 Y to 10 days-forecast
Wave period at spectral peak	CMEMS	1/12°, global	3 h, -1 Y to 10 days-forecast
Mean wave direction from	CMEMS	1/12°, global	3 h, -1 Y to 10 days-forecast
Total[2] surface sea water zonal velocity (u)	CMEMS	1/12°, global	1 h, -2 Y to 10 days-forecast
Total[2] surface sea water meridional velocity (v)	CMEMS	1/12°, global	1 h, -2 Y to 10 days-forecast
Sea surface salinity	CMEMS	1/12°, global	1 h, -2 Y to 10 days-forecast
Sea water potential temperature	CMEMS	1/12°, global	1 h, -2 Y to 10 days-forecast

[1] available at 10 m, 20 m, 30 m, 40 m, 50 m, 70 m, 100 m height above ground
[2] Eulerian + Waves + Tide

As the system being developed in the MariData project aims at providing decision support in real time, the focus is on actual forecast data. However, for the evaluation of the models we also need historical data. The CMEMS products include analysis data for the last 1-3 years and thus also cover the period for which we collected data on the ships. For GFS, analysis data is not available. Instead, we use the archived forecasts from the temporarily closest forecast cycle.
In addition to the temporarily varying environmental data, we also use static data on water depth from the ETOPO 2022 15 Arc-Second Global Relief Model with a 30 arc second resolution (NOAA National Centers for Environmental Information).

Routing

A variety of algorithms has been explored in the past to optimize time and/or fuel consumption during sea journeys for a given weather scenario (Walther, Rizvanolli, Wendebourg, & Jahn, 2016). Due to the large interdisciplinarity of the MariData consortium, it is not only possible to investigate the performance of individual algorithms in the project context but also to elaborate on the interplay between the respective hydrodynamic simulations for power and fuel consumption on the one hand and the weather routing tool (WRT) on the other hand. In this paper, the measured power consumptions for historical routes traveled by a CBT are compared to routes provided by the routing tool as a general proof of concept. In addition, the effect that different weights on added resistances have on the simulation of power consumption for a specific historical route as well as on the routing procedure will be investigated.

The routing algorithm which has been utilized in this paper is an 'isofuel' algorithm – i.e. it provides routes that are optimized for fuel consumption – based on the concept of the modified isochrone method by Hagiwara (1989). Similar to the latter, the routing is performed in individual routing steps. For every step, it is calculated how far the ship can travel in different directions with a fixed amount of fuel considering the respective weather conditions and properties of the environment. All environmental variables listed in Table 2 are considered in this process. Tides are only considered as part of the overall ocean currents. Water depth is assumed to be static based on bathymetry data. At present the ship is assumed to sail at constant speed and fore and aft draught for the full route. Adaptations will be considered in the next step. Weather conditions are considered to be constant for every individual routing step.

The optimization is achieved by grouping routes according to their courses and selecting only the route segment per group for the next routing step that maximizes the travel distance. Using this concept, a wide angular range is scanned systematically for optimal routes as it can be seen in Fig. 15. The algorithm considers constraints by landmasses and shallow water by eliminating routes that cross the latter from the optimization process. Thereby, shallow waters are defined as areas with a water depth below the sum of the ship's draught and an under keel clearance of 20 m.
Due to the nature of the algorithm choices in an early routing step might lead to an overall worse fuel consumption later. This is partially mitigated by scanning a large number and wide range of angles and by using many groups in the

selection process thus keeping a sufficient number of segments for the subsequent routing step. In the future, it is planned to evaluate algorithms which consider always the complete route like genetic algorithms.

Uncertainty of environmental data

Further uncertainties in the model evaluation and the route optimization are related to the environmental data. The reanalysis and forecast data used to feed the power and fuel consumption models represent average values for a coarse grid where one grid cell covers an area in the order of tens to hundreds of square kilometers and time periods from 1 to 3 hours. In contrast, a ship experiences conditions at a specific position in space and time which might vary significantly from the average values. Moreover, the reanalysis and forecast models come with their own uncertainties.

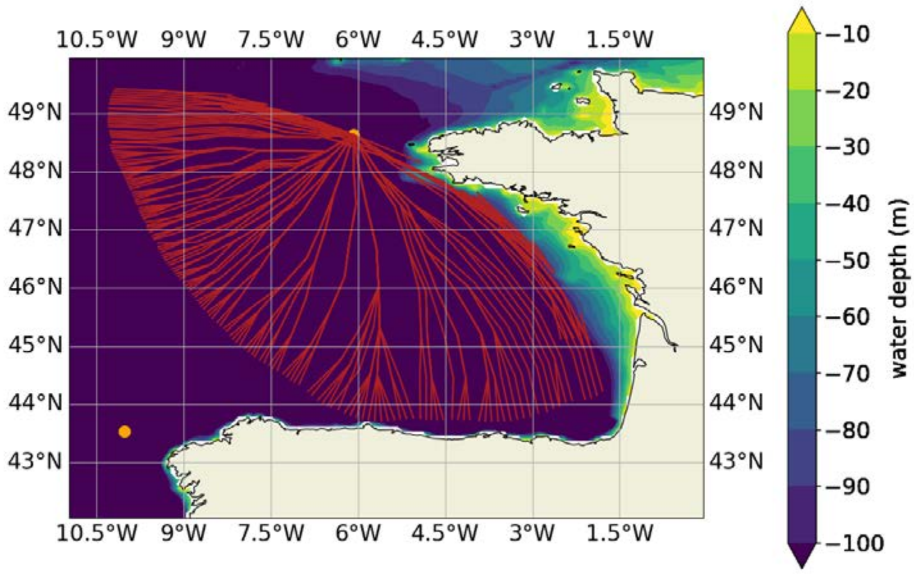


Figure 15: Visualization of route segments at an intermediate routing step of the Isofuel algorithm for a CBT traveling in the Bay of Biscay

SYNTHESIS AND SHIP OPERATIONS

Synthesis

It would be rather resource-intensive – if not prohibitively expensive – to compute the performance of a ship by means of direct simulation, i.e., by computing the behavior of all components at full-scale and bringing them into the correct balance of total resistance encountered and thrust delivered, providing the engine power and fuel oil consumption for any given speed in any environmental condition. As shown in Fig. 2 the approach taken here is to subdivide the overall system into manageable components. This follows the approach developed in HOLISHIP (Papanikolaou, 2018), and used for design synthesis. Based on (many) upfront simulations, realized via Design-of-Experiments, the various contributions are captured in surrogates that provide quantitative results within split-seconds for any condition of interest.

A python module called mariPower was implemented that connects all described surrogates for (added) resistance components and propulsion to consider every factor during the power and fuel consumption prediction. It takes loading conditions along a route specified by a discrete trajectory and ship speeds and determines the encountered weather from a forecast or hindcast for all points along the route. Then, it iterates the unknown ship motion parameters (propeller rotation rate, drift angle and rudder angle), continuously updating the surrogate model results as their inputs change. After convergence or the maximum number of iterations is reached the fuel oil consumption is estimated from the resulting engine power and rotation rate.

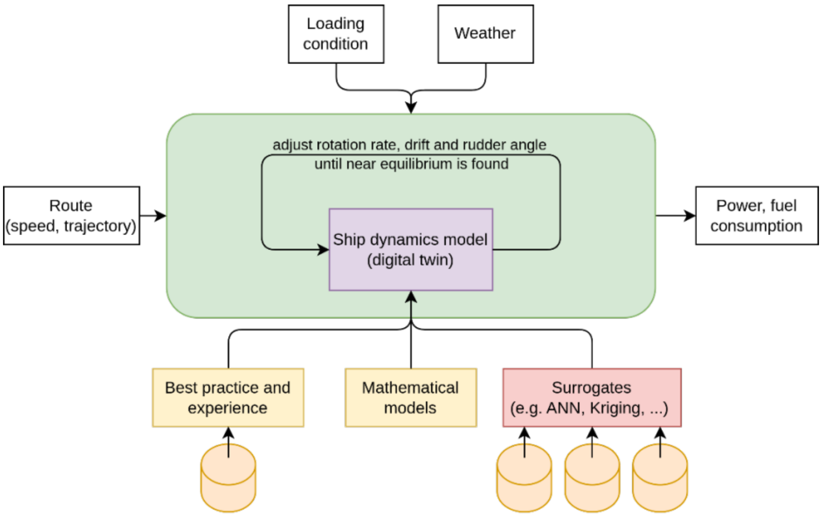


Figure 16: Process flow within mariPower

Ship Operations via mariPower

The described module mariPower was implemented as a general framework to take into account various environmental factors in the prediction of necessary engine power. In the current state, it is able to consider additional forces due to wind, seaway, fouling and shallow water. In the latter three cases also wake fraction changes can be included. The base class in the module implements the functionality to iterate the ship and engine motion state. It updates the added forces in longitudinal and transversal direction as well as the yaw moment of all available sources iteratively and estimates a drift and rudder angle to keep its course based on maneuvering coefficients. The total required thrust and forward velocity through water are used as inputs to the propeller model which predicts the resulting rotation rate and torque. This continues until an equilibrium of longitudinal forces is found or the maximum number of iterations is reached. Its child classes allow the connection to individual user-defined surrogate models for the added forces and wake fraction changes due to each of the described environmental factors. Those only need to comply with the defined input and output parameters and units. The code uses vectorized functions where possible to increase efficiency.

STATISTICAL ANALYSES

Data Lake

Within the research project MariData extensive measurements of onboard data with high sampling rate were performed. Those data were used to find predominantly encountered weather conditions as well as periods where the operating conditions were steady with a certain tolerance.

For the latter, the sensor data was synchronized first and resampled to a frequency of 1Hz to ensure a shared time stamp before filtering with a minimum ship speed and several other conditions regarding draught and engine load to remove sections before and after berthing. This combined data was then separated into voyages whenever a pause of more than two hours was found. Since this could also happen due to technical issues with the sensors, the endpoints of resulting routes are not necessarily near ports of call. Each voyage data is then evaluated regarding the standard deviation on rolling windows of 30 minutes compared to an individual tolerance for each sensor. If all tolerances are met, the window is marked as steady. In a second step, the slope of this evaluation result is calculated to determine starts and ends of steady intervals. Finally, all values in between stops and starts are marked as unsteady as well as those values between starts and stops where the time difference is less than the window length. The results are then resampled to a period of one hour and enriched with hindcast weather data.

To determine the representative operating conditions used in the following chapter, histograms were calculated from the operational data and manually analyzed.

Representative Operating Points

Two representative weather situations were picked from available operational data of seven months. For a ship speed of 6 m/s (11.7 kn) at a draft of 9.5 m on even keel the calm water case was selected having a low wind speed of 2 m/s with the rough weather case set at 12 m/s wind speed. Since no onboard wave measurements were available the seaway was approximated using a Pierson-Moskowitz spectrum for the two wind speeds (see Table 3). Water and air temperature were chosen as 293 K and the air pressure at 101350 Pa. The roughness of the hull was assumed to be hydraulically smooth in this case.

Table 3: Wind and seaway conditions for representative operating points

Weather	calm	rough
Wind speed	2 m/s	12 m/s
Significant wave height	0.09 m	3.25 m
Peak period	1.5 s	9 s

INFLUENCES IN REPRESENTATIVE OPERATING POINTS

Resistance Components

The digital twin was simulated in both weather conditions from all directions. In calm weather, the added resistance due to seaway is almost zero. The wind forces cause some yaw especially for crosswinds while the added resistance is highest for the frontal wind directions. Still, the maximum total added resistance is only around 3% of the calm water resistance. For rough weather, the added resistance due to seaway causes a drastic rise of the total added resistance, contributing 50% and more of the calm water resistance. The wind forces cause maximum drift angles of around 4° while increasing the total added resistance in head wind by another 30% to a total of 80% of the calm water resistance.

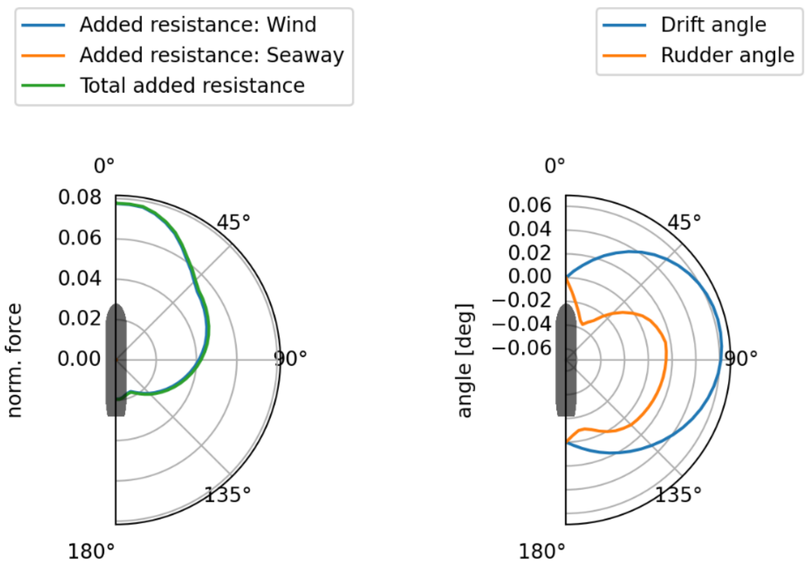


Figure 17: Added resistance components and drift and rudder angle in calm condition (forces normalized by calm water resistance)

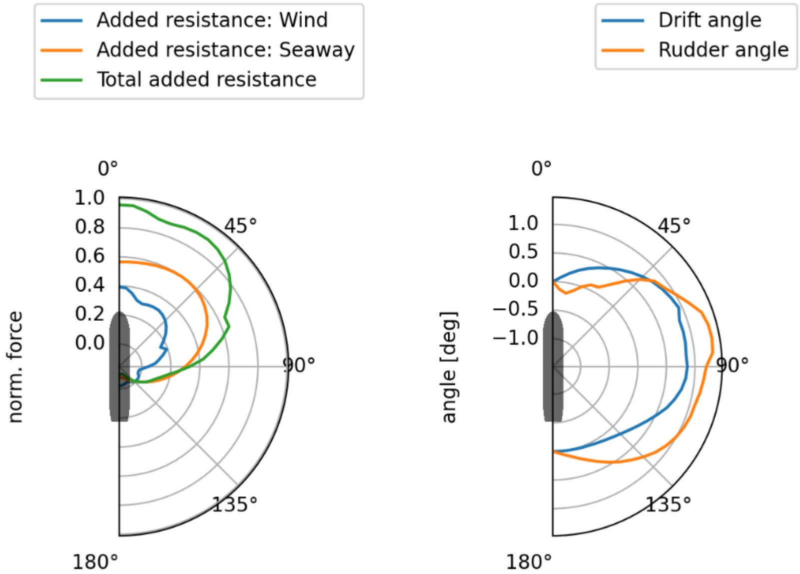
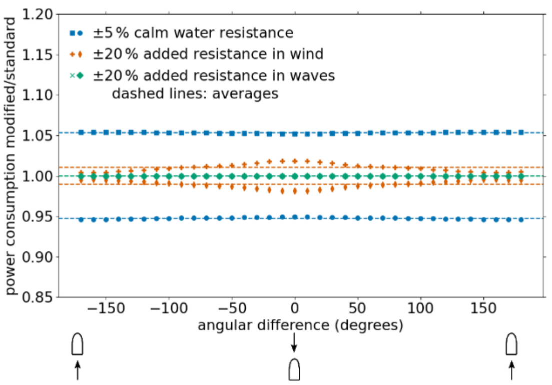


Figure 18: Added resistance components and drift and rudder angle in rough condition (forces normalized by calm water resistance)

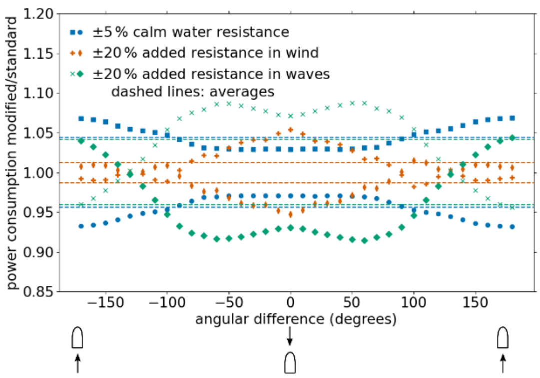
Hypothetical Variation of Resistance Components

In the following, the effect of adding weights to the calm water resistance as well as the added resistances for waves and sea state on the power consumption is investigated. By these manipulations, it is possible to mimic imperfect hydrodynamic simulations and study the respective differences of the power prediction. As in the previous paragraph, angles between wind and waves on the one hand and the ship's course on the other hand are scanned in steps of ten degrees for two weather scenarios. The ratio of the power consumption calculated for the modified resistances over the results for the original settings is visualized. The results for changing the calm water resistance by +-5%, the added resistance for wind by +-20% and the added resistance for waves by +-20% can be seen in Figure 19.

For the calm-weather scenario, the effect of the modifications for the added resistances for wind and sea state are negligible while a +-5% modification of the calm-water resistance directly translates into a +-5% deviation for the power consumption. For the rough-weather scenario, the effect of the modifications for the added resistances for wind and sea state are most significant if wind and waves are coming from the front. In these cases, a 10% deviation for wind and 5% deviation for waves is reached. Due to the significant contribution from the added resistances for wind and sea state in this scenario, the modifications of the calm water resistance have a smaller effect (~3%) on the overall power consumption if wind and waves are coming from the front.



a) Calm weather

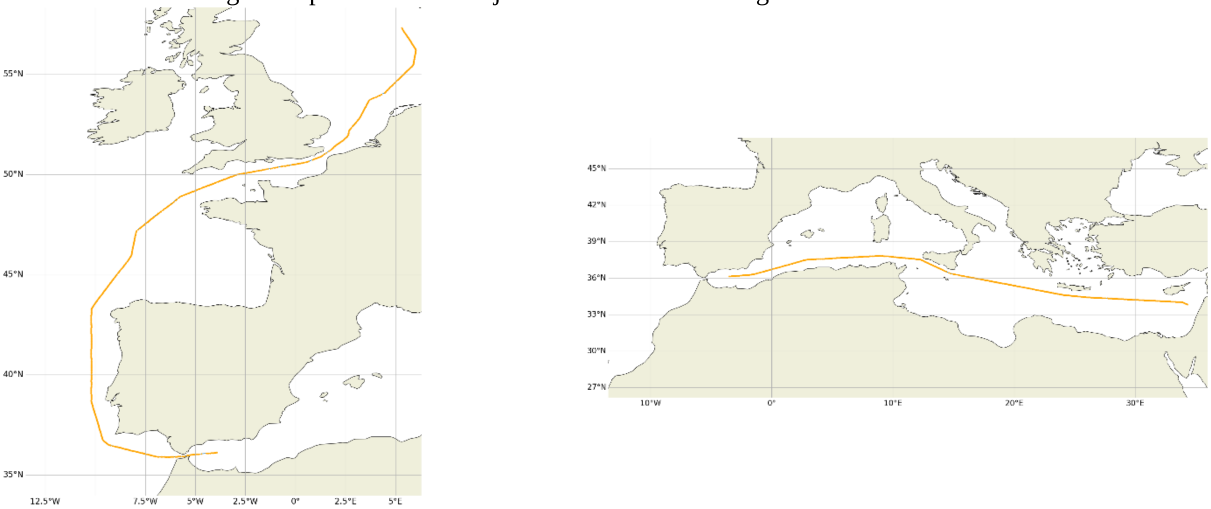


b) Rough weather

Figure 19: The ratios for simulations of the power consumptions for manipulated resistances over those for standard settings in dependence of the angular difference between the CBT's course and the directions of winds and waves in ideal weather

INFLUENCES IN REAL CONDITIONS

Two routes have been selected from the analyzed operational data of one of the tankers in 2023. They were chosen based on long periods of quasi-steady ship motion and operation as well as being different regarding the severity of the weather conditions encountered during those periods. Their trajectories are shown in Figure 20.



a) British channel **b) Mediterranean sea**

Figure 20: The historical routes traveled by a CBT which have been selected for investigations on the simulated power consumption in real weather conditions

Comparison of Operations and Simulations

When comparing predicted and measured engine power in Figure 21 the surrogate models clearly are able to predict the power with a certain error (RMS error across all routes in 2023 was 6.5%). Correlation coefficients showed that the main cause for the apparent fluctuations in the predicted power between all input parameters was the speed through water with a correlation coefficient of -0.657. The measured propeller pitch was usually above 98%, so the error due to predicting the propeller operating point for the maximum pitch only is assumed to introduce little error. Since the response surfaces of all surrogate models shown in previous chapters are continuous, we suspect the measured speed through water or the engine power to have some kind of measurement error.

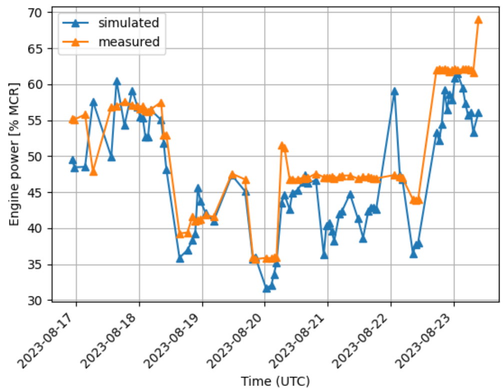
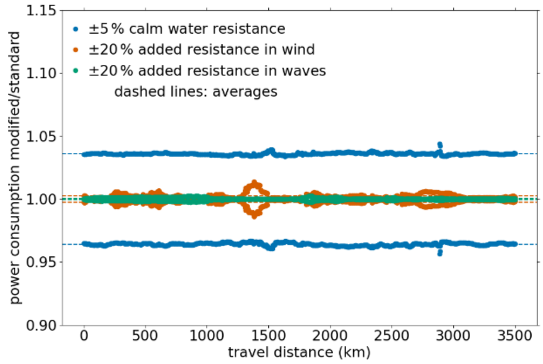


Figure 21: Predicted and measured engine power along "Mediterranean sea" route

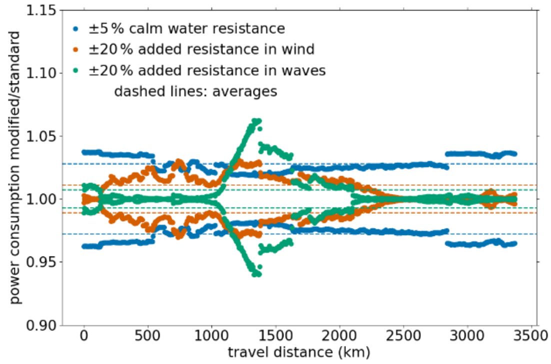
Hypothetical Variation of Resistance Components

To investigate the effect of manipulated resistances on realistic routes, the power consumption has been simulated for historical routes traveled by a CBT under real weather conditions. In addition to the simulations for the standard settings, the calm water resistance as well as the added resistances in wind and waves have been varied by the same values as for the previous investigations for the representative operating points. The routes that have been selected pass the Mediterranean Sea as shown in Figure 20a and the British Channel as shown in Figure 20b. While the weather conditions are mild in the Mediterranean Sea, the route through the British Channel traverses a low-pressure region roughly at the middle of the full travel distance.

The results for both routes are provided in Figure 22. It can be found that for the rough weather conditions in the British-Channel scenario, the modifications of the added resistances for wind and waves have a more significant effect than for the calmer conditions in the Mediterranean-Sea scenario. In contrast, the effects of the manipulations of the calm water resistance are more significant in the Mediterranean-Sea scenario than in the British-Channel scenario.



a) Mediterranean-Sea scenario



b) British Channel scenario

Figure 22: The ratios for simulations of the power consumption for manipulated resistances over those for standard settings in dependence of the travel distance for historical routes traveled by the CBT

Routing in Actual Weather

In this section, it shall be demonstrated that the WRT of the MariData DSS provides alternatives to historical routes that reduce the overall fuel consumption. In addition, the effect of manipulations of the resistances on the routing procedure will be elaborated.

Naturally, the effect of the routing will be most significant in regions where restrictions like water separation zones or danger areas are rare. This is why two segments from the Mediterranean and the British-Channel scenario that meet these conditions have been selected for the investigations. The corresponding areas are displayed in Figure 23 and Figure 24 and shall be referred to as the Biscay and the Crete scenario.

For the routing procedure, the constant speed of the tanker is set to the average speed of the historical route. The inputs for fore and aft draught are averaged over the full historical route. In addition, the settings for the hull roughness are adapted to those which were found to describe the measured power consumption best (see Sec. 21).

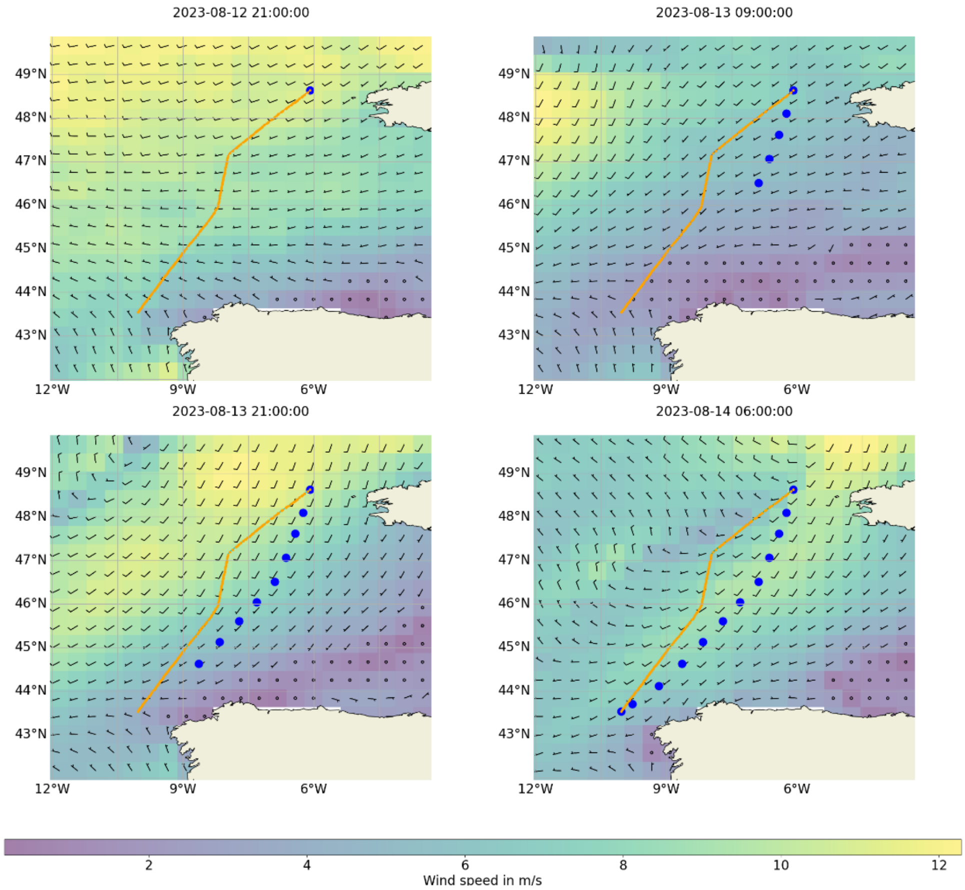


Figure 23: Trajectories of reference (orange) and optimized (blue) routes in the Biscay scenario for four snapshots. The background map shows wind speed and wind direction as heat map and wind barbs.

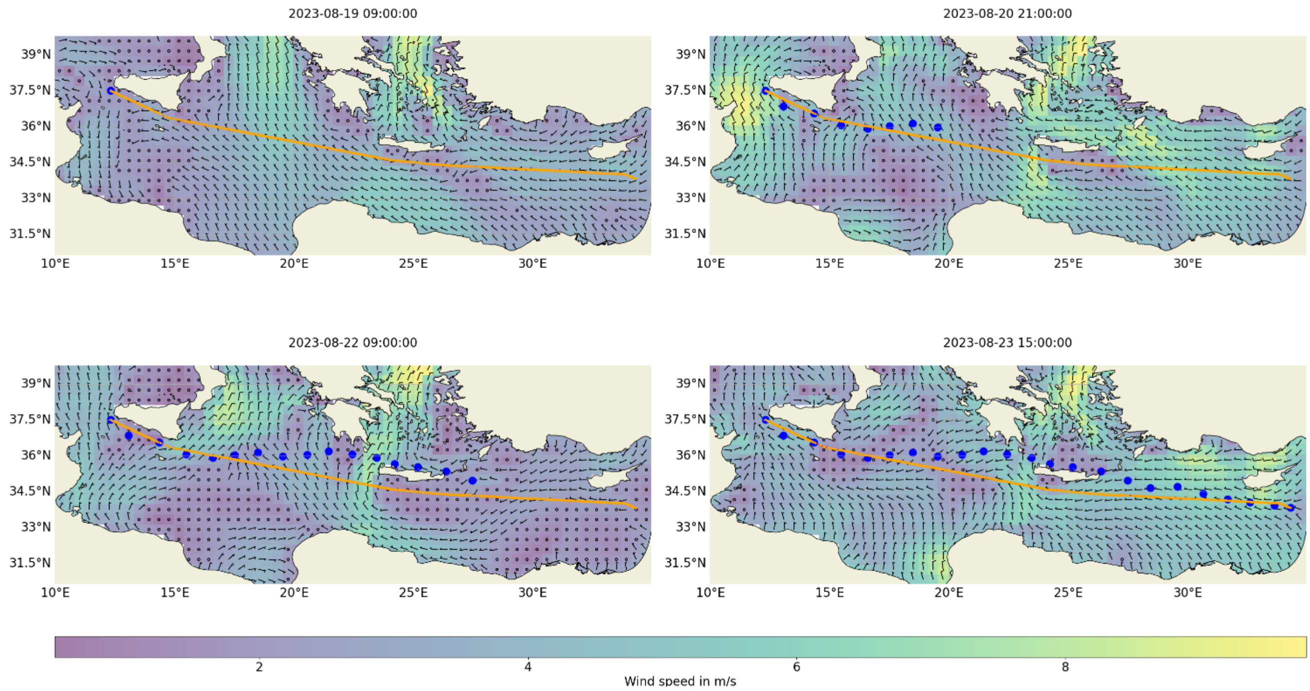
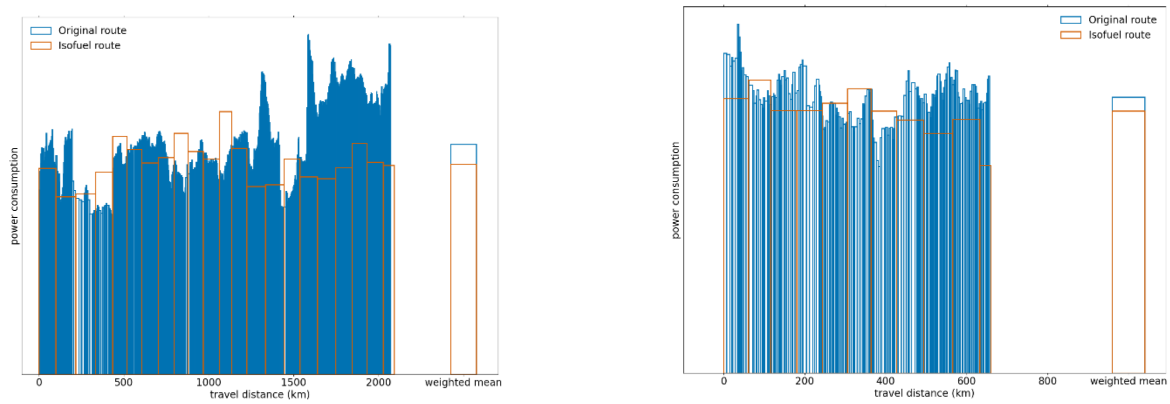


Figure 24: Trajectories of reference (orange) and optimized (blue) routes in the Crete scenario for four snapshots. The background map shows wind speed and wind direction as heat map and wind barbs.

The alternative routes for both scenarios are compared to the historical routes in Figure 23 and Figure 24. The differences between the historical routes and the routes from the WRT are significant. In the Biscay scenario, the WRT tanker travels farther east than the historical route and in the Crete scenario, the WRT tanker passes by Crete on the northern side, while the historical CBT is traveling on the southern side. Looking at the corresponding weather conditions, these differences are plausible as in both scenarios, the wind speed and wave heights are more suitable for the routes selected by the WRT. In particular, both wind speed and wave heights are decreasing from west to east in the Biscay scenario making routes that reach farther to the east more fuel-efficient. In the case of the Crete scenario, the WRT tanker traveling on the northern side of Crete experiences stronger tail wind than the original CBT tanker traveling on the southern side.



a) "Crete" b)"Biscay"

Figure 25: Power consumption of reference and optimized routes in two scenarios

Figure 25a and Figure 25b compare the resulting power consumptions for the historical and the WRT routes. For both scenarios, a smaller mean power consumption can be observed for the WRT routes which, in particular, results from a significantly smaller power consumption towards the end of both routes. Considering the absolute values and differences with respect to the historical route for travel time, travel distance and fuel consumption provided in Table 4 and Table 5, the WRT routes tend to be slightly longer, they reach the destination in roughly the same travel time (differences are smaller than an hour) and they spare about 8.7 % (Crete scenario) and 6.4 % (Biscay scenario) of the total amount of fuel that has been consumed for the historical routes.

Similar to the previous sections we investigate how a variation of individual resistances influences the routing process. We selected only the Biscay scenario as the effects are more significant here due to rougher weather. Figure 26 shows how the proposed routes differ geographically for variations of added resistance in wind. Table 4 and Table 5 summarize the key characteristics of travel distance and time and accumulated fuel consumption for both routes. Here, also values for variations of added resistance in waves and calm water resistance are included.

Generally, it can be observed that with a higher resistance ships can travel less far in each routing step and vice versa for lower resistances. Higher and lower resistances also naturally result in a different accumulated fuel consumption along a given track. However, the optimized routes also tend to travel in different areas to the originally proposed route without variation. If the added resistance in wind is 20 % higher, the ship can save fuel by traveling farther in the east where wind speeds decrease. For the last few waypoints, the opposite effect can also be observed when resistance is 20 % smaller. The specific behavior of the routing algorithm depends on a multitude of factors, so one has to be cautious with drawing specific conclusions from the given examples. In particular, the temporal evolution of the weather conditions can smear definite effects by the resistance variations. As a general conclusion, varying resistance components can not only change the overall consumption but also the track proposed by a routing optimization tool itself.

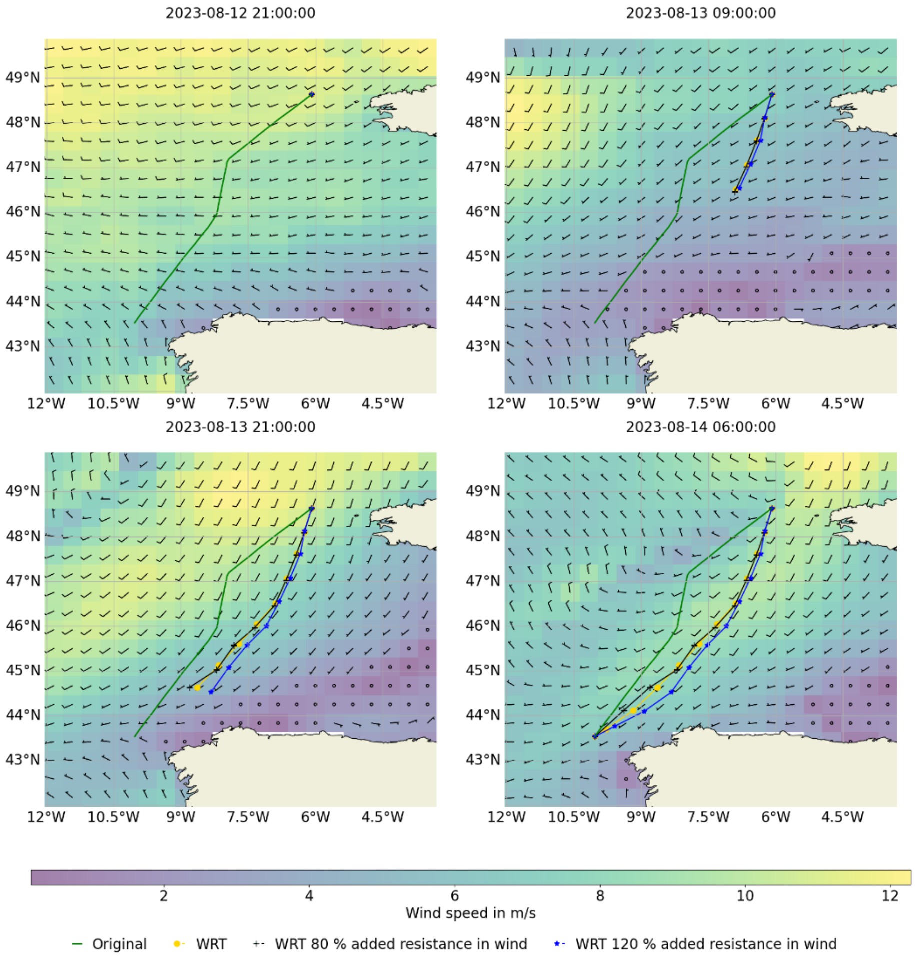


Figure 26: Trajectories of optimal routes found by varying the added resistance in wind by +-20 %

Table 4: Key characteristics of the routes in the Crete scenario

Route	Fuel consumption difference	Travel distance	Travel distance difference	Travel time	Travel time difference
Original	-	2071 km	-	4 days, 03:14:36	-
WRT	8.7 % less	2092 km	21 km (1.0 %) more	4 days, 04:10:15	00:55:39 (0.9 %) more

Table 5: Key characteristics of the routes in the Biscay scenario

Route	Fuel consumption difference	Travel distance	Travel distance difference	Travel time	Travel time difference
Original	-	657 km	-	1 day, 7:35:23	-
WRT	6.4 % less	660 km	3 km (0.5 %) more	1 day, 7:35:07	00:00:16 (0.0 %) less
WRT (120% Wind)	4.6 % less	670 km	13 km (2.0 %) more	1 day, 8:06:09	00:30:46 (1.6 %) more
WRT (80% Wind)	10.1 % less	660 km	3 km (0.5 %) more	1 day, 7:37:31	00:02:08 (0.1 %) more
WRT (120% Wave)	4.1 % less	661 km	4 km (0.6 %) more	1 day, 7:38:53	00:03:30 (0.2 %) more
WRT (80% Wave)	10.5 % less	659 km	2 km (0.3 %) more	1 day, 7:33:57	00:01:26 (0.1 %) less
WRT (105% Calm)	3.4 % less	661 km	4 km (0.6 %) more	1 day, 7:38:16	00:02:53 (0.2 %) more
WRT (95% Calm)	11.3 %	665 km	8 km (1.2 %) more	1 day, 7:49:58	00:14:35 (0.8 %) more

NAVIGATIONAL SUPPORT

Defining the relevant operational points is critical for custom-tailored ship design as currently practiced. According to our research, there is a high variance in how these operational points are defined. Making a digital twin of the prototype available at design time, we want to engage in a discourse on the differentiation of an optimization project or making compromises transparent and discussable at the design stage. The role of virtual prototyping (VP) and related concepts in ship design has been identified as crucial in the highly individualized field of ship design, with even sister ships having significant design variations (Hassani, et al., 2016). Effective VP requires an interdisciplinary effort, covering hydrodynamics, machinery and power systems, structural engineering, navigation, and control. Current contributions in the field focus on methodological innovation in the design processes (Dodero, Bertagna, Braidotti, Marinò, & Bucci, 2022), the discourse on Human-Centered Digital Twins (Preuss, et al., 2023), and review the “clean” integration of Digital Twins (DT) in Marine Engineering (Mauro & Kana, 2023) or industry in general (Sharma, Kosasih, Zhang, Brintrup, & Calinescu, 2022). This paper aims to contribute to and expand upon the framework relating virtual Prototyping/Digital Twins and Ship Design.

Our goal is to provide early-stage information to operators on how a ship might behave in future scenarios and inform ship design by how operators will actually conduct the vessel—and in which typical range of environmental conditions. On one hand, we used this constant comparison of virtual ship operation and actual journeys to inform and validate model construction. On the other hand, having the DTs and actual environmental data available during design-time enables designers and operators to compare the performance of design variants, including current ships, all performing under the same conditions. In this project, we derived actual typical operational points from previous journeys, combined them with actual trips and environmental conditions encountered, and enabled operators to drive the digital representations of existing ships and prototypes in a highly realistic ship simulator in identical conditions, e.g., actual weather data. Repeated with design variants, this enables a much more detailed look into, e.g., added resistance (e.g., wind, wave and even hull fouling effects), resulting in requirements analysis of unprecedented depth, matching the custom-tailored approach to carrier vessel design aimed for today to ensure peak energy efficiency.

Ship design is always a compromise. Designers today already account for added resistance, but can seldom base calculations on detailed data of, e.g., how often a ship will actually face specific conditions. In this project, a broad parameter space is explored, including the analysis of a crew’s decision-making between avoiding and confronting weather situations in simulator runs where, on historical routes with actual weather data, and equipped with a next generation energy efficient operational decision support system developed in this project, future operators determine the sweet spots informing design decisions. Gathering these data during design time enables addressing operational aspects during simulations (e.g., prioritizing cargo space upfront in the ship, even if it negatively impacts seakeeping resistance). Additionally, our system allows for the detailed exploration of future propulsion systems, such as diesel-electric drives, with the ability to connect multiple engines to an electrical power supply, and its design implications, when existing ships on established routes are to be replaced.

Supporting this virtual prototyping and test-driving, a novel Onboard-Decision Support System (DSS) for navigational and operational support was designed and implemented (Schwarz, et al., 2023), enabling differentiated control over route optimization processes. A novel module allows for the inspection of simulation data quality (i.e., uncertainties), pertaining to chart accuracy, up-to-date weather, and model fitness for the current operational point, among others. This digital-twin powered tool also enables logging and evaluating user actions (Zoubir, et al., 2023), again driving the optimization process in the ship design phase. Factors considered in the DSS include Requested Time of Arrival as multiple distinct windows (i.e., encouraging slow steaming to match external conditions in tide waters, ship lock operational times or port arrival time frames), CO_2e emissions, and energy efficiency, enabling the analysis of crew decisions in specific contexts. The DSS hereby interacts with the DT for route optimization, realistic simulation, and simultaneously feeds and optimizes the DT. Insofar, the DSS functions as both a research vessel and an outcome.

Figure 27: Photograph of Crew Member System Use During Navigational Task "Enroute Re-Planning"

FEEDBACK FOR DESIGN

Ship operational patterns have changed drastically over the past decades. On the one hand enhanced digital systems on board support the crew in operating the vessels leading to a large amount of data which are often only used for optimizing part of the operation. Often based on purely data driven and machine learning algorithms these are also prone to errors resulting from erroneous data collection and sensors if not properly validated. On the other hand, vessels are – still – often designed for a limited range of operational conditions while in practice they encounter all conceivable conditions during their life-cycle often not considered during the early stages of vessel design. This is often due to the fact that a number of operational constraints are not known a priori and may change over time. This may have economic, environmental or even political reasons which are barely predictable at the beginning of a 25 + years lifecycle of a new ship. Present striking examples being the situations around the two major canals, Suez and Panama which call for significant changes of operational patterns, due to different causes but having similar effects. A digital twin in turn which uses all available information from design stages onwards helps to optimize operations and provides valuable feedback to ship design in that collected data will both improve the quality of design data and will form the basis for more holistic considerations of future designs.

During design, predictions of operational and environmental performance are traditionally based on a forecasted, limited range of environmental conditions. Due to limited resources, a design team always needs to decide where to put a focus and hence resources for further improvements and where an existing solution would be sufficient. Similarly, it is important to understand if an improvement at design stage will actually show during operations and to which extent. In

the present example for a medium-size tanker all components which contribute to resistance at representative trim and draft conditions and in specific weather conditions so as to maintain certain speeds were studied. The composition of total resistance followed the classic approach in naval architecture of superposing calm-water resistance, added resistance in waves, wind resistance, resistance due to fouling, resistance when sailing with (small) yaw angles at non-zero rudder angles while keeping the course and, finally, resistance increases in shallow and/or restricted waters. It was generally assumed that secondary influences are negligible, for instance, that mean wind resistance does not change with ship motions in heavy seas. Furthermore, added drag due to openings such as bow thrusters, sea chests, sacrificial anodes, potential asymmetries from production etc. were not accounted for.
There are several findings that this study suggests, some of which are not surprising while others may indicate that further attention should be given in the future:

- Calm-water resistance, unsurprisingly, is the governing component. A decrease or increase of resistance yields similar improvements or drawbacks, respectively, provided the propulsive efficiency is not determinately affected. At least for the tanker design at hand and for the routes considered any improvement – independent of where it comes from – leads to reductions in fuel oil consumption to almost the same extent.
- The increase of resistance due to hull and propeller fouling has very tangible effects. While maintaining good conditions is controlled by the operator the design team may be able to contribute to the ease of cleaning the wetted surface.
- Wind resistance turns out to be a component that deserves more attention. Even though air is considerably less dense than water (factor around 800) the air resistance is non-negligible and should be considered when designing superstructures for higher energy-efficiency.
- Added resistance in waves naturally also contributes to overall resistance. However, tangible increases lead to less severe drawbacks in fuel oil consumption and, vice versa, tangible decreases – while being hard to realize when keeping the main dimensions constant – also do not show considerable effects.

While these findings are based on the current example it is evident that the concept of a design based Digital Twin for energy efficient operation can yield equivalent conclusions also for other ships and ship types. Using the complete design information collected in the surrogate models introduced in the Resistance chapter, the Digital Twin allows analyzing the effect of any special focus in form of a “What if?” analysis once weighted changes to either factor influencing the performance are introduced. This feedback will allow designers to more efficiently decide on the focus for further improvements. In the future this will particularly apply to so-called green ships, for which the use of alternative fuels or energy sources (e.g. wind propulsion) introduces additional constraints not addressed in traditional design processes.

CONCLUSIONS

The MariData project developed a simulation based digital twin for improved energy management of ships, based on available design information which was further enhanced using the same concepts as during design to cover the broader range of operational conditions encountered during the life-cycle so far. As an example, a medium sized tanker was investigated in a white-box approach for its major resistance components and its propulsion system, comprising the propeller, the rudder and the main engine. All components were simulated with appropriate and validated numerical methods for large sets of representative conditions. The data were captured in dedicated surrogates equivalent to those already applied during design optimization for a fast and repetitive look-up. Subsequently, a simulation tool was established that takes environmental conditions – wind, waves, currents and bathymetry – along with the ship’s loading – draft and trim – into account and computes the fuel-oil consumption for any given speed. Uncertainties in each of the modelling and simulation steps have been considered, This allows running routing optimizations in which all important contributors are considered. For each leg along a certain route the simulation tool thus determines the expected FOC.

Comparing onboard measurements for several routes, primarily along Europe’s Atlantic coast and in the Mediterranean, with the white-box simulations fed with the weather and bathymetry encountered and the speed (through water and over ground) measured on the ship has shown realistic accuracy. Nevertheless, some erratic differences which are visible when comparing simulated and measured engine power could not be resolved yet. The question whether these relate to the reliability of acquired sensor data from onboard measurements needs to be solved in the final phase of the project. An uncertainty is also introduced in the comparison of simulations as local weather phenomena could still have been slightly different to the hindcasts interpolated from the European weather grid. The surrogates which represent the digital twin of the ship are smooth and, therefore, cannot be held responsible for higher frequency variations of the solution. While the simulations may not always yield results that are accurate in absolute terms, they indicate clear tendencies. Looking at the relative FOC for various routes gives confidence that the major elements which determine overall energy consumption were well captured. The system combining weather routing and FOC was further utilized to check sensitivities regarding hypothetical changes of various resistance components. Those changes are representative of two scenarios: (i) What should a design team focus on when spending resources on improving a ship and (ii) which components need to be captured accurately to yield reliable suggestions for safe, economic and environmentally friendly routes. To this end, hypothetical changes to three resistance components were undertaken: (i) What if calm-water resistance, i.e., the lion's share of resistance, could be improved by 5% and vice versa. This is typical of many hull form optimization campaigns that often yield three to seven percent of improvements over good baselines. (ii) What if added resistance in waves is under- or overestimated by 20%. Of course, added resistance in waves cannot be influenced so easily at the design stage, save for modifying main dimensions which, however, are often more or less fixed. Yet, for routing, unless a rather high-fidelity seakeeping code is employed, the accuracy of the predictions, at least in many routing routines, might only be within that range, see Harries et al. (2023). (iii) What if the estimate for wind resistance is +-20%, wind resistance not being considered often at the design stage with more than reasonable estimates.

As expected, though not often shown, changes in calm-water resistance are fully apparent, i.e., any improvement leads to a reduction in energy consumption of almost the same amount. Added resistance in waves and wind resistance often being substantially smaller than calm-water resistance do not influence the FOC to the same extent. Yet, they affect the optimal route by avoiding detrimental and by taking advantage of favorable conditions. Therefore, it appears questionable if a routing algorithm can produce reliable predictions for energy savings if the underlying models are too simple, e.g., if calm-water resistance is merely taken from series data via the input of a handful of main dimensions, see Harries et al. (2022) for additional discussion.

Consequently, for design work it seems fair to still focus on calm-water performance as has been done in the past. However, aerodynamics should no longer be simply estimated. While this might be obvious for ships that should be retrofitted with wind-assisted propulsion systems (WASPs) or new buildings that shall benefit from WASPs from the start this may well be worthwhile to consider for ships in service and for new buildings, especially in view of retro-fit options which can offer reductions in aerodynamic resistance for a range of vessels (Voß & Marzi, 2020).

While here a white-box model for the simulation of FOC was used it should not be forgotten that there are black-box models, too. They are trained on data measured onboard a ship over considerable periods of time without building on any physics-based simulations or using low fidelity models. Black-box models may potentially be more accurate regarding actual FOC, in particular when applying machine learning on large data sets. However, from black box models it is likely more difficult to understand which components contribute how much to the overall performance, making them less valuable for designers. In the future, a hybrid approach may show benefits, i.e., as suggested in the synthesis model presented here, see Fig. 2, the major contributors are determined from a white-box while deviations could be captured from a black-box. This, however, is subject to additional research. Based on the experience made here, one should be cautious with data from onboard measurements. They should not be used without supervision and intelligent filtering.

Naturally, it needs to be kept in mind that the study presented here only covers a single ship. It stands to reason, however, that similar influences could be seen for other ships. For smaller ships, for instance, the effect of added resistance in waves might be more important since they experience larger motions. For ships with sizeable loads on and above deck, meanwhile, the impact of wind resistance might have greater importance. Additional work is needed to quantify which components show an especially strong influence on both energy consumption as considered at the design stage and routing recommendations as made for efficient ship operation.

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