THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

A Generic Model for Simulation of the Energy Performance of Ships – from Early Design to Operational Conditions

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Abstract

Forecasts show a doubling of the world's transportation needs until 2050. Shipping today accounts for 90% of all freight transport. Simultaneously, shipping must become cleaner and more energy-efficient to meet the target to more than halve 2005 greenhouse gas emissions by 2050. To improve the energy efficiency of ships, we must be able to accurately predict and analyze the performance of ships not only in operation but also during the design of new ships as well as retrofitting of existing ships. Therefore, a practical and useful prediction method should not require prior measurements and should be applicable for an arbitrary ship.

The system "ship" is complex and composed by many components, which requires a structured- and component-based approach when analyzing and modelling this system. This thesis presents a generic ship energy systems model, which enables operational simulations and fuel consumption predictions of ships at sea with limited input parameters, i.e., without calibration or full-scale measurements. The simulation model consists of several empirical and semi-empiric methods to predict the performance of each component. To cover gaps where empirical methods were found unreliable, numerical standard propeller and hull series were developed.

Further on, the model was applied to two reference ships, one RoRo ship and one tanker, at four phases in the ship design process: (i) in the early phase, i.e., in the beginning of the ship design process when only the ship's main dimensions are available; (ii) when the hull design is finished; (iii) when information from calm water model tests are available; and (iv) when the complete ship design is finished. A thorough uncertainty analysis was done for each component of the model to specify design and method uncertainties and to find the total uncertainty of the fuel consumption prediction.

In several case studies, the usability of the model was shown in, e.g., main dimension variations, sea margin variations and speed profile optimizations, for a given route with realistic weather and sea conditions. It is shown that a systems perspective is crucial to capture the interaction of different parts of the energy system "ship".

The main conclusion of the work presented is that the developed generic energy systems model can predict the fuel consumption of an arbitrary ship at sea. Comparing fuel consumption prediction at design speed, it was found that the prediction with only the main dimensions available is within 5% of the prediction with model tests available. The comparison was done for the two reference ships and without calibration or prior measurements.

Keywords: fuel consumption; energy systems modelling; ship design; ship energy efficiency; ship operation; uncertainty analysis.

Preface

This thesis presents research work performed at the Division of Marine Technology, Department of Mechanics and Marine Sciences at Chalmers University of Technology, from November 2014 to May 2017. The work was partially funded by the Swedish Ship Owners' Association (through the Swedish Maritime Competence Center Lighthouse) and the Swedish Energy Agency.

Thanks to:

- My supervisors Jonas W. Ringsberg, Wengang Mao and Bengt Ramne for all the input, support and good discussions.

- Per Lindell and Robert Gustafsson for answering all my questions about propellers.

- My colleagues at the Division of Marine Technology for support and good chats at coffee breaks.

- My colleagues at the former Department of Shipping and Marine Technology for making this a nice place to work at.

- My family for the support.

- Ronja for being there.

Finally I want to give a special thanks to my main supervisor, Jonas W. Ringsberg, head of the Division of Marine Technology. Your tireless work to make this division a good place to work at and to bring us all forward is really impressive, much needed and appreciated. Thank you very much.

Gothenburg, May 2017

Fabian Tillig

Contents

List of appended papers

This thesis consists of a summary part and two appended papers, representing the research performed by the author during the years 2014-2017.

For all appended papers, the author of this thesis contributed to the ideas presented, planned the paper, did most of the modelling and programming work and wrote the majority of the manuscript.

Paper I Tillig, F., Ringsberg, J.W., Mao, W., Ramne, B. (2016). A generic energy systems model for efficient ship design and operation. *IMechE, Part M: Journal of Engineering for the Maritime Environment*. Doi: 0.1177/1475090216680672.

Paper II Tillig, F., Ringsberg, J.W., Mao, W., Ramne, B. (2017). Analysis of the reduction of uncertainties in the prediction of ships' fuel consumption – from early design to operation conditions. *To be submitted to the journal Ships and Offshore Structures.*

List of other published papers by the author

Paper A Tillig, F., Ringsberg, J.W., Mao, W., Ramne, B. (2015). Holistic ship energy systems modelling for efficient ship design and operation. In: *Proceedings of the RINA Efficient Ship Conference 2015 in Rotterdam, the Netherlands, November 4, 2015*. (Presenting author.)

1 Introduction

To decrease emissions and increase energy efficiency, the shipping industry needs generic methods to predict the energy consumption of ships during the whole life of a ship. This thesis presents an approach towards such a method by applying energy systems modelling to naval architecture problems. The result is a dynamic and generic ship energy systems model that provides accurate fuel consumption predictions, from early design through operation of ships.

1.1 Background and motivation

In 2015, the United Nations (UN) set up 17 goals to reduce climate change and end poverty, called the sustainable development goals (UN, 2017). One of them, goal 13, focuses on climate change and its impacts on the planet. The main objective of goal 13 is to reduce pollution and keep the total warmth of the earth below 1.5°C. Worldwide, transport stands for a share of about 20% of all CO_2 emissions (Worldbank, 2017). In Europe, the share is even larger with almost 25% (EU, 2017). Thus, achieving higher energy efficient transport must be one of the main objectives under UN goal 13.

With a global share of about 90% of all transport, shipping represents about 3% of the global CO_2 emissions, about 1-3% of SOx and more than 10% of NOx emissions (IMO, 2014). To further decrease emissions and increase the energy efficiency of ships, we must improve existing technologies, apply newly developed alternatives and develop new technologies. All of these options to increase the energy efficiency require that the system "ship" be completely understood and the impact of changes to the system be predicted accurately. Additionally, we have to learn to improve complete transport chains, which requires a reliable prediction of the fuel consumption and emission of all involved means of transport, including ships.

Following EU strategy to monitor and report the performance of ships (EU, 2017), multiple models and methods for performance monitoring and data collection have been developed, e.g., Leifsson et al. (2008), Pedersen & Larsen (2009) and Lu et al. (2015). These models and methods are useful to analyse, understand, and improve the operational performance of ships. Both the behaviour of the crew and the condition of the ship can be analysed and improved. However, these models are based on measurement data that were taken on board and therefore cannot be used for other ships or for reliable prediction of the impact of changes to the ship. More theoretic models were presented by Vinther Hansen (2011), Calleya (2014) and Cichowicz et al. (2015). All of these models are based on theoretic methods and can predict the behaviour of the ship's systems without full scale measurement data if sufficient input information is available. As reported in Vinther Hansen (2011), Calleya (2014) and Cichowicz et al. (2015), detailed information about the machinery systems and the hydrodynamics are required. The models can thus not be seen as generic models, which can be applied to a ship without detailed information other than the main dimensions. Additionally, subsystem models based on energy systems modelling are presented, e.g., the engine model published in Baldi (2016).

The shipping industry is lacking generic models and methods, especially for fuel oil consumption prediction of an arbitrary ship in transport chains. Additionally, such models are required for fleet planning and newbuilding projects as well as investigating retrofitting options of existing ships. A well-developed generic model could not only capture prediction for ships with a lack of available information but also be used as a performance monitoring and analysing model that does not require time consuming adjustment if applied to new ships or previous full-scale measurements.

1.2 Objective

This thesis contributes to the development of energy systems modelling for ships. The main objective is to develop a generic model to simulate the energy consumption of a ship at sea, from initial design through operation. According to the Cambridge dictionary, “generic” is defined as “applicable or referring to a whole class or group” (Cambridge University, 2017). For this study, the group is defined as cargo ships with conventional main engines, i.e., engines fuelled with bunker oil. With this definition, a generic ship energy systems model must be applicable to any ship in the above defined group, without calibration or changes in the model and without requiring detailed design information or calibration.

To reach the main objective and to prove the versatility and accuracy of the model, three sub-goals have been defined:

(1) Identify and compare suitable prediction methods for each part of the energy system of a ship. Suitable prediction methods are those that require only general input but provide an accurate prediction. This sub-goal includes identifying the couplings of different parts of a ship’s energy system.

(2) Identify, classify and quantify uncertainties in the energy consumption prediction.

(3) Demonstrate the usability and the strength of the generic model by applying the model to case studies from both ship design and operation. This includes demonstrating that operational analysis and predictions can be done using the generic model with only limited input information (i.e., the ship’s main dimension).

1.3 Outline of the thesis

Methodologies and details about the model are presented in Chapter 2, with the focus on parts of the model and the work that is not described in detail in the appended papers. A summary of the results presented in Paper I and Paper II is given in Chapter 3 followed by conclusions in Chapter 4. Future work, as well as areas of development and application are presented in Chapter 5. All abbreviations used in the thesis are defined in the nomenclature list in Chapter 6.

2 Methodology

In this chapter, basic methodologies that are used in the generic ship energy systems model are described. The main focus is on methods that were only briefly described in the appended papers. An introduction to the generic ship energy systems model and its system boundaries is given in Section 2.1. Section 2.2 presents the employed prediction, variation and optimization methods, followed by a description of the performed *CFD* computations in Section 2.3. An introduction to numerical hull and propeller standard series, which were developed by the author, is given in Section 2.4. Section 2.5 presents assumption and limitations of the current generic energy systems model.

2.1 Energy systems modelling

In Paper I and in Tillig et al. (2015), thorough introductions to energy systems modelling are provided. In general, an energy system, such as a ship at sea, consists of several components, which react on environmental conditions and interact with each other. Most components convert energy, e.g., from mechanical translation to heat in case of a frictional component. Model components are connected with non-directional energy domains. The energy flow in these domains is defined using through and across variables, e.g., the current and the voltage for electrical energy flows. A visual presentation of the full ship energy system, including the energy domains, is given in Figure 1. The main energy converters are the main and auxiliary engines (chemical to mechanical rotational) as well as the propeller (mechanical rotational to translational). In the generic ship energy systems model, four energy domains are used (across and through variables are in brackets): (i) mechanical rotational (n, Q_m); (ii) mechanical translational (v, F); (iii) thermal (T, Q_h), and electrical (U, I). For any model, it is important to define the systems boundaries and what type and how much energy is allowed to enter and to leave the system. For the generic ship energy systems model, the systems boundary is defined outside of the ship, with the model including all systems on board and the environment the ship is in, i.e., wind, waves, air and sea temperature. It is assumed that unlimited heat can be transferred from the ship to the surrounding sea and that unlimited chemical energy (fuel) exists within the system.

In the current state of the generic energy systems model, the main focus is on the propulsion unit, i.e., the main engine, propeller and resistance, including the influence of the environmental conditions on these components.

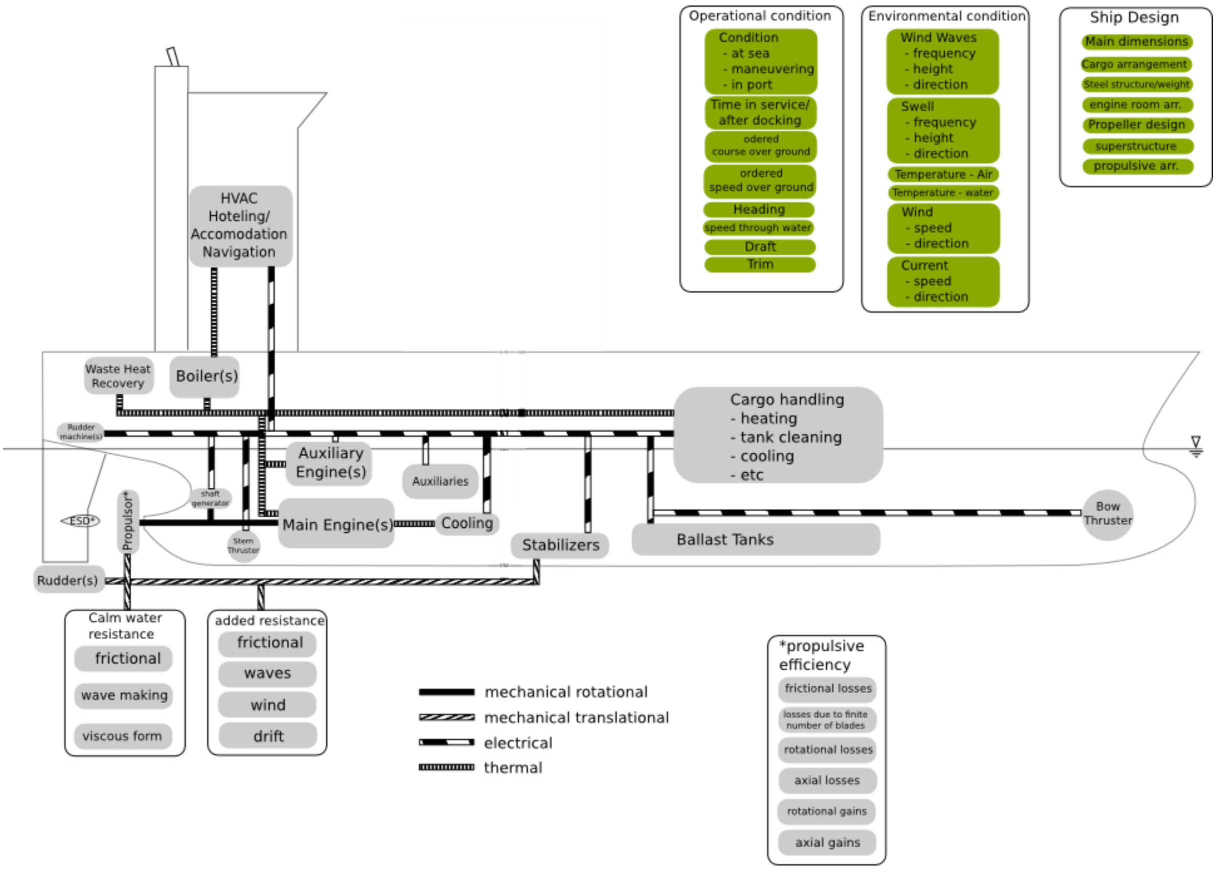

Figure 1: System boundaries, components and energy domains of the ship energy systems model.

The generic energy systems model is divided into two parts, one static power prediction part and one dynamic operational analysis part, and is divided into different components, as described in detail in Paper I. Figure 2 presents an overview of the ship energy systems model and its components, with boxes 1 through 8 representing the static part and box 9 representing the dynamic part.

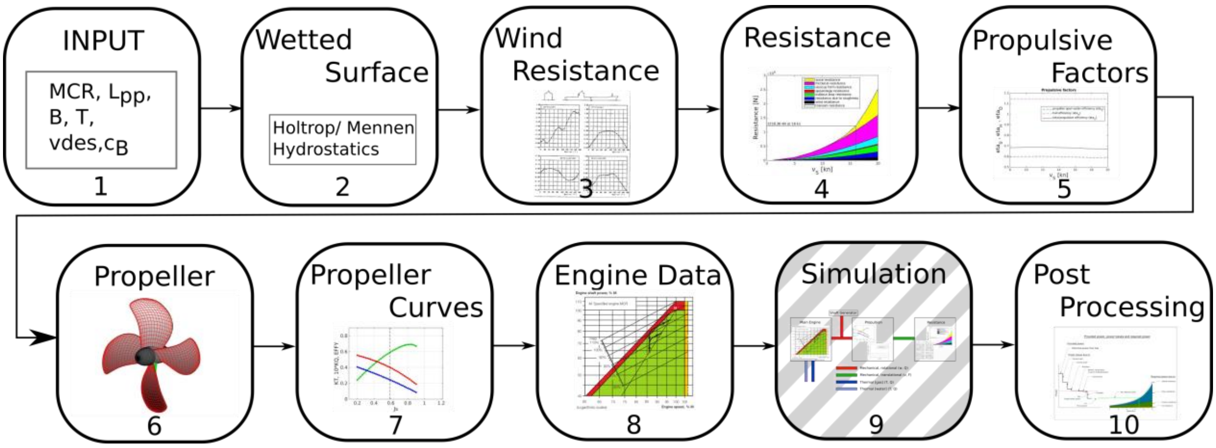

Figure 2: Flowchart of the generic energy systems model; see Paper I for details.

The static power prediction part is programmed in Matlab (Mathworks, 2017) and is used to provide power and fuel consumption prediction for one condition. Both calm water and operational predictions can be performed. The static part of the model consists of prediction methods for each component of the energy systems, e.g., the resistance and main engine specific fuel oil consumption. Depending on the available information about the ship (design and dimensions), different prediction methods can be used. Empirical methods or *CFD* computations of the standard series hulls (see Section 2.4.1) can provide results with very limited input information, i.e., only main dimensions. If available, model tests or *CFD* of the ship's hull form and propeller can be used in the model. Further information about the prediction methods are provided in Section 2.2.

Apart from the predictions, the static part provides the input to the dynamic part in terms of resistance curves in both calm water and sea, fuel consumption curves and propulsive efficiencies. The dynamic part is set up using the simulation environment Simscape (Mathworks, 2017), which is similar to the well-known Simulink but made for physical systems. The close coupling between Simscape and Matlab provides the opportunities to integrate the dynamic and the static parts. Simscape provides fast solutions of time dependent system simulations, such as a ship traveling along a route in changing weather.

The components in Simscape are mostly interpolation routines and are connected to each other with the earlier discussed energy domains. The employed *ode23t* solver iteratively converges to the equilibrium of all components using variable time steps. Naturally, the times steps are smaller in acceleration or deceleration phases as well as in points of time where the environmental conditions change. Several transfer functions were tested and applied to route simulations. In dynamical simulations, the damping becomes critical; too low damping will result in constant fluctuation, whereas too high damping results in slow convergence to the target value. Detailed information about the static and dynamic part as well as the transfer function are provided in Paper I.

Four different control values were applied: (1) the ship speed, (2) the engine rpm, (3) the engine power and (4) the engine torque. Studies performed in Paper I show that the ship speed is the most critical control value, which seems logical since the ship speed is controlled in the most indirect way.

A graphical overview of the parts of the dynamical model in Simscape is presented in Figure 3. Open connections like the thermal domain from the engine and the electrical domain from the shaft generator are supposed to be used once the model gets further developed and more components according to Figure 1 are included.

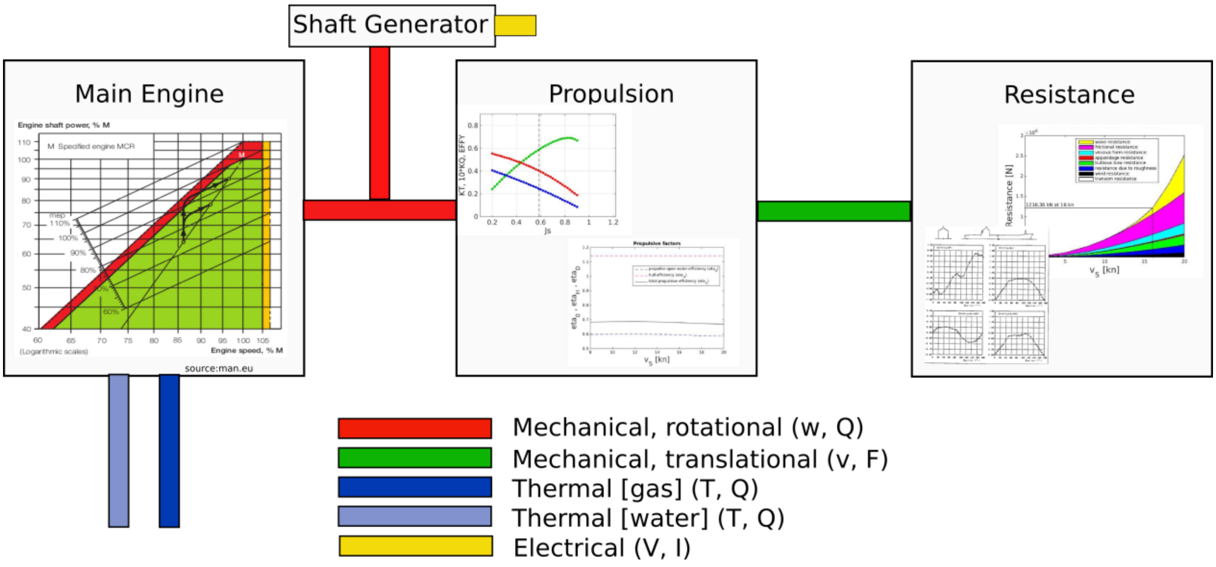

Figure 3: Overview of the components and the connections in the dynamic part.

2.2 Prediction, variation and optimization methods

This section presents a summary of prediction methods used in the static part of the model as well as an introduction to the variation and optimization methods used in Paper I and II.

2.2.1 Prediction methods

A selection of prediction methods for the resistance, added resistance and propulsive factors are discussed in Paper II. The complexity of a prediction of the fuel consumption (*FC*) of a ship at sea is presented in Equation 1. Values that must be estimated are shown in bold and summarized in Table 1. Most of these values are variable over the ship speed.

$$FC = \boldsymbol{sfoc} * \left(\boldsymbol{S_W} * \boldsymbol{c_T} * \frac{\rho_{SW}}{2} * v_S^2 + \boldsymbol{c_X} * \boldsymbol{A_T} * \frac{\rho_{Air}}{2} * v_{AW}^2 + \boldsymbol{R_{AW}}\right) / \boldsymbol{\eta_0} / \boldsymbol{n_h} * v_S \quad (1)$$

Table 1: Summary of the variables in fuel consumption prediction.

Symbol	Variable name
sfoc	Specific fuel oil consumption
S_W	Wetted surface of the hull
c_T	Calm water resistance coefficient
c_X	Wind resistance coefficient
A_T	Transversal area above the waterline
R_{AW}	Added resistance due to waves
η_0	Propeller open water efficiency
η_H	Hull efficiency

If model tests and engine data are available, the values in Table 1 can be derived from there. However, if only main dimensions are available, empirical or semi- empirical methods must be used. Paper II discusses which prediction methods are found to give the best accuracy. A short summary is given here.

- None of the tested empirical methods was found suitable to predict the wetted surface for a wide range of ships; thus, the standard series are used for that as a default.

- The calm water resistance, the effective wake and the added resistance in waves are obtained by using an average of multiple methods; see Paper II for details.
- The propeller efficiency is obtained using the OpenProp software (Epps et al., 2009) and the standard propeller series.
- The wind resistance is obtained from curves developed by Blendermann (1994), with superstructure areas derived from a standard deck height and an assumed number of decks for the ship type and size.
- The specific fuel oil consumption is obtained from an interpolation of engine data taken from MAN (2017) based on the design point of the engine (depending on the bore, the stroke and the number of cylinders) and the tuning.

CFD computations in calm water and in waves were performed for comparison and are a part of the calm water resistance prediction. A more detailed description of the performed *CFD* computations is given in Section 2.3. The mentioned standard hull and standard propeller series are further explained in Section 2.4.

2.2.2 Variation and optimization methods

In Paper I, parametric variation and optimization studies were performed, e.g., for the speed profile optimization, the propeller load variation and the main dimension variation. Automated variations were also used to study the design uncertainties in Paper II.

Matlab-based variations, e.g., the propeller design variation and the Monte Carlo simulation in Paper II, were performed using the random number generator in Matlab. For more complex variations and optimization, Matlab and SHIPFLOW (Flowtech, 2016) were coupled to the *CAE* software CAESES (Friendship-Systems, 2017), where variant creation and process administration were performed. A number of optimization and variation algorithms are available in CAESES. For the optimizations in Paper I, the single objective T-Search algorithm (Hilleary, 1966) was used, which proved to be a fast and robust local optimization algorithm. Since the T-Search is a local algorithm, a variation study should be performed prior to optimizations. For variations, the quasi-random algorithm Sobol (Bratley & Fox, 1988) was applied. Quasi random defines algorithms that cover the design space in a non-repetitive but reproducible pattern. Thus, contrary to studies with random numbers, a Sobol variation study can always be re-started since n^{th} variant of different studies with the same variables and boundaries will always be identical.

2.3 CFD computations

CFD computations were performed with three different objectives: (i) full scale predictions, (ii) variant comparisons, and (iii) prediction of the added resistance in waves. All computations were performed using the commercial software SHIPFLOW. The full-scale predictions (i) were performed using a global mesh for the viscous computations; i.e., the full hull was included. In contrast to this, the variant comparisons (ii) were done using a local approach, i.e., viscous computations were only performed for the aft body. Potential computations to obtain the wave pattern resistance were done for both the full-scale predictions and the variant comparisons. While full-scale prediction computations were performed at the full-scale Reynolds number (about 1.2×10^9), the variant comparisons were performed at a model scale Reynolds number (about 1×10^7). For full-scale predictions, the rudder was included as an overlaying grid. In all viscous computations, a refinement grid was put around the skeg to accurately capture vortices. The full-scale prediction grids had about 6 million cells, the variant comparison grids about 2.5 million. An impression of the aftbody of a standard hull with the overlapping rudder and refinement grid boundaries is given in Figure 4.

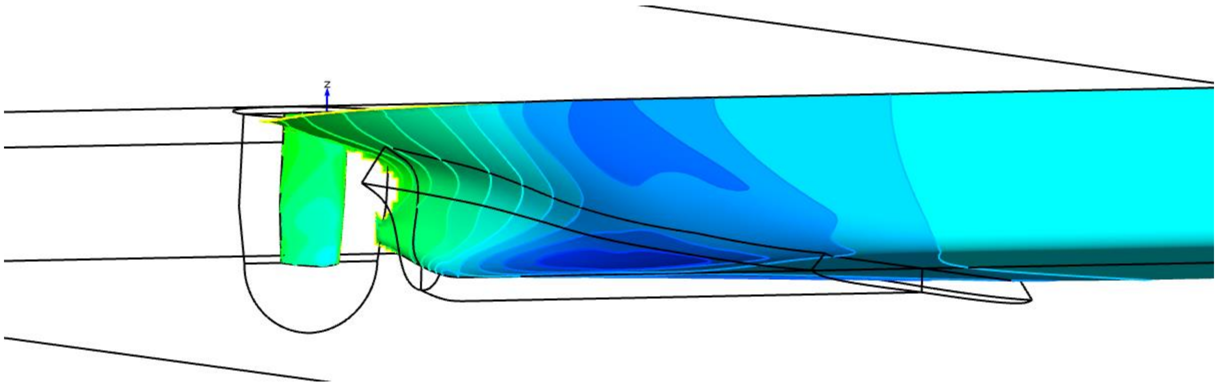

Figure 4: Impression of the aftbody with the boundaries of the overlapping grids for the rudder and the skeg refinement (sold lines).

The added resistance in waves predictions were performed using the fully nonlinear time dependent free surface flow solver SHIPFLOW Motions. The SHIPFLOW standard mesh with about 26000 panels was used. For the study in Paper II, computations in irregular waves were performed using the ITTC wave spectrum (ITTC, 2014). In the future, computations in regular waves could be combined with the empirical methods to adjust the empirical transfer functions.

2.4 Numerical standard series

In the early design phase, or when predicting operational performance of arbitrary vessels, detailed design features of the hull or propeller are unknown. Empirical methods and formulas can help to estimate parameters and characteristics, such as the wetted surface, resistance and propeller efficiencies, but often with varying accuracy. A better estimation and a better predictability of the uncertainties is obtained with standard series, traditionally with the Series 60 hulls or the Wageningen propeller series (Lewis, 1988). Standard series offer a possibility to obtain a hull or propeller design with very limited information about the vessel in question and with limited design effort. Traditionally, selected standard hulls were model tested, and results were then interpolated to obtain the results for the dimensions in question. However, the Series 60 hulls must be seen as outdated, and the usability of the results from these series can be questioned. Even though the Wageningen B-series propellers show open water efficiencies comparable to state-of-the-art designs, their geometry is rather old-fashioned and fixed; i.e., the pitch distribution is not adjusted to the expected wake.

Considering the above limitations of existing hull and propeller series, it was decided to build up new numerical standard series for both the hull and the propeller design. The numerical hull series offer both an accurate wetted surface prediction and the possibility to perform *CFD* computations for calm water resistance, self-propulsion and added resistance in waves. The propeller series provides an accurate prediction of the open water characteristics for a propeller with a geometry adjusted to the expected wake of the vessel.

The numerical hull series and the numerical propeller series are designed to represent an average, well performing hull and propeller. There will certainly be room for further improvement of the resistance and efficiency for all standard hulls and propellers, which might be applicable to some projects and not to others due to geometry constraints.

2.4.1 Numerical hull series

To date, numerical standard series for two ship types have been developed by the author of this thesis, (i) one for slender hulls with a wide stern, e.g., RoRo ships, container ships and ferries, and (ii) one for ships with higher blockage, e.g., tanker and bulker. The first series (i) is valid for ships with block coefficients between 0.55 and 0.71, while the second (ii) is valid for hulls with block coefficients of 0.73 to 0.85, assuming that the design speeds are selected to a reasonable value for the block coefficient, e.g., following the estimation given by Jensen (1994). The parametric model will create hulls outside of these boundaries, but the quality might not be as good as for hulls within the boundaries. Other coefficients, such as the length-to-beam and beam-to-draft ratio proved not to be as critical as the block coefficients. The input to both hull series are the main dimensions, i.e., length over all, beam, draft, displacement, propeller diameter, and the design speed. Missing main dimensions are obtained using empirical formulas, as shown in Table 2.

Table 2: Summary of empirical methods used in the numerical standard hull series.

Dimension	**Estimation**	**Reference**
Bulbous bow length	$c_{LPR} = 0.2642 * c_B * \frac{B}{L_{PP}} + 0.0046$	(Kracht, 1978)
Bulbous bow cross section coefficient[1]	$c_{ABT} = 40 * Fn - 3.5$ (%)	(Kracht, 1978)
Length of parallel midbody	$L_{PM} = 3 * \left(c_P - \frac{2}{3}\right) * L_{PP}$	(Jensen, 1994)
Waterline entrance angle	$i_E = 478.998 - 2048 * \sqrt{Fn} + 2343 * Fn - 2226 * Fn^3 + 3258 * Fn^5 - 2168 * Fn^7$	(Saunders, 1954)
Waterline area coefficient	$c_{WP} = 0.763 * (c_P + 0.34)$	(Bertram & Wobig, 1999)
Depth	$D = 0.087 * L_{PP}$	(Bertram & Wobig, 1999)
Main frame area coefficient	$c_M = 0.96845 + 0.095(c_B - 0.57)$	(Bertram & Wobig, 1999)

[1]*The cross section coefficient is even adjusted using a linear function over the block coefficient. The estimated value is taken as the value in the middle of the block coefficient range.*

The hull series are set up as highly flexible parametric geometry models in the CAESES software. In parametric modelling, hull surfaces are produced using basic geometry and property curves. Geometry curves are those that describe where the resulting surface will cut through, e.g., the flat of side and flat of bottom curves. Property curves are those that describe characteristics of the surfaces or the underlying curves (most often sections), e.g., the sectional area curve or the flare at the waterline curve. Figure 5 presents on overview of the most important geometry and property curves of the parametric models. All surfaces, except the skeg ending, are built up using x-constant sections and the CEASES surface type “Meta surface”, which is basically a surface loft over an infinite number of curves.

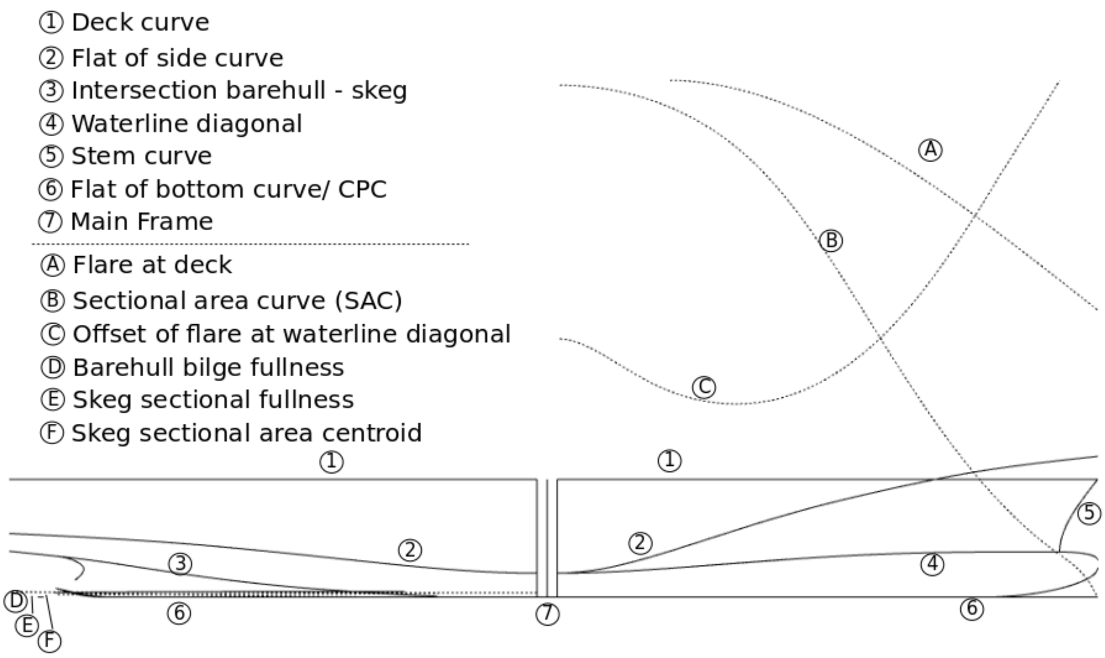

Figure 5: Basic geometry (1-7) and property (A-F) curves of the parametric model for the hull standard series.

Characteristics of the basic curves, which are not covered by the empirical formulas shown in Table 2, are obtained using interpolation curves between the values at lowest and highest block coefficient of the series, possibly with up to two intermediate points. The fullness of the sectional area curve of the forebody is obtained from the target displacement for the forebody, which depends on the target displacement of the hull and the obtained aftbody displacement. This ensures that the resulting hull form is within less than 1% of the desired displacement. Any difference between the resulting and the target displacement is resolved using Lackenby's method (Lackenby, 1950). The described procedure ensures that the standard hulls have unique hull design features, adjusted to their design speed and displacement, instead of being only distorted versions of a parent hull. This ensures well performing hulls over the whole range of the standard series. Figure 6 and Figure 7 present comparisons of body plans of three hulls of the slender hull series and the full block hull series, respectively.

To show the performance over the range of the standard series, a comparison of the wave pattern of hulls from the slender hull series with three different block coefficients at a speed of Fn = 0.19 is presented in Figure 8. The wake and the viscous resistance coefficents are rather constant over the block coefficient due to the similar aftbody skeg shape of all variants. Differences occur at the higher end of the block coefficent range, where the skeg becomes fuller, especially for the full block series. In Figure 9, the total resistance from *CFD* computations of the standard hull with c_B = 0.69 is compared to the results for the reference RoRo ship, presented in Paper II. It can be seen that the resistance is within 3% over the whole range of speeds with only about 0.5% difference at the design speed of Fn = 0.19.

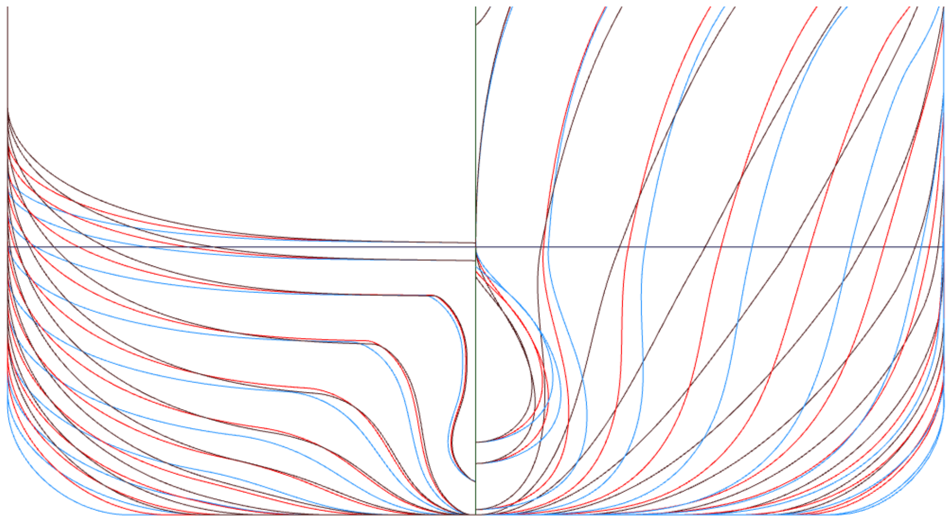

Figure 6: Comparison of three hulls of the slender standard hull series with c_B = 0.60 (black), c_B = 0.65 (red) and c_B = 0.70 (blue) and a design speed of Fn = 0.19.

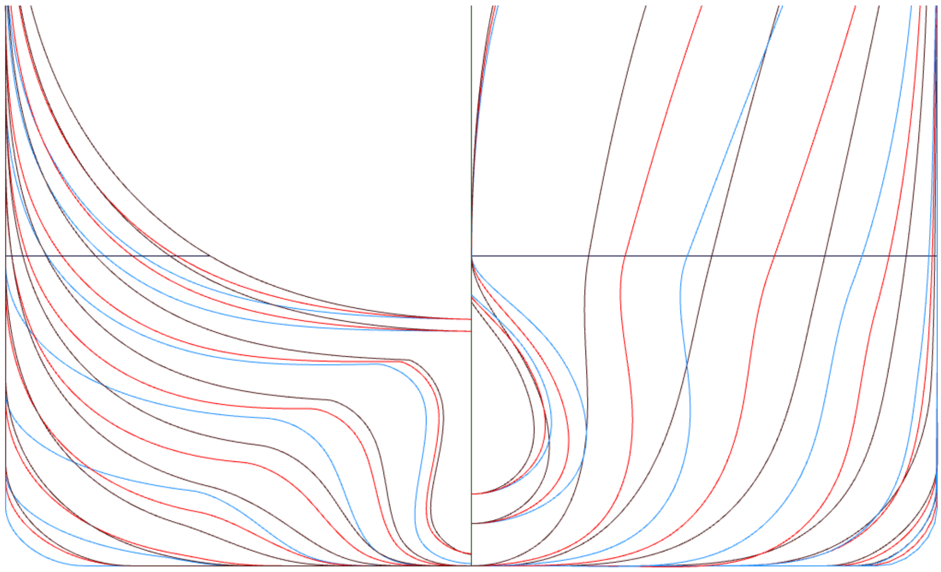

Figure 7: Comparison of three hulls of the high blockage standard hull series with c_B = 0.75 (black), c_B = 0.80 (red) and c_B = 0.85 (blue) and a design speed of Fn= 0.16.

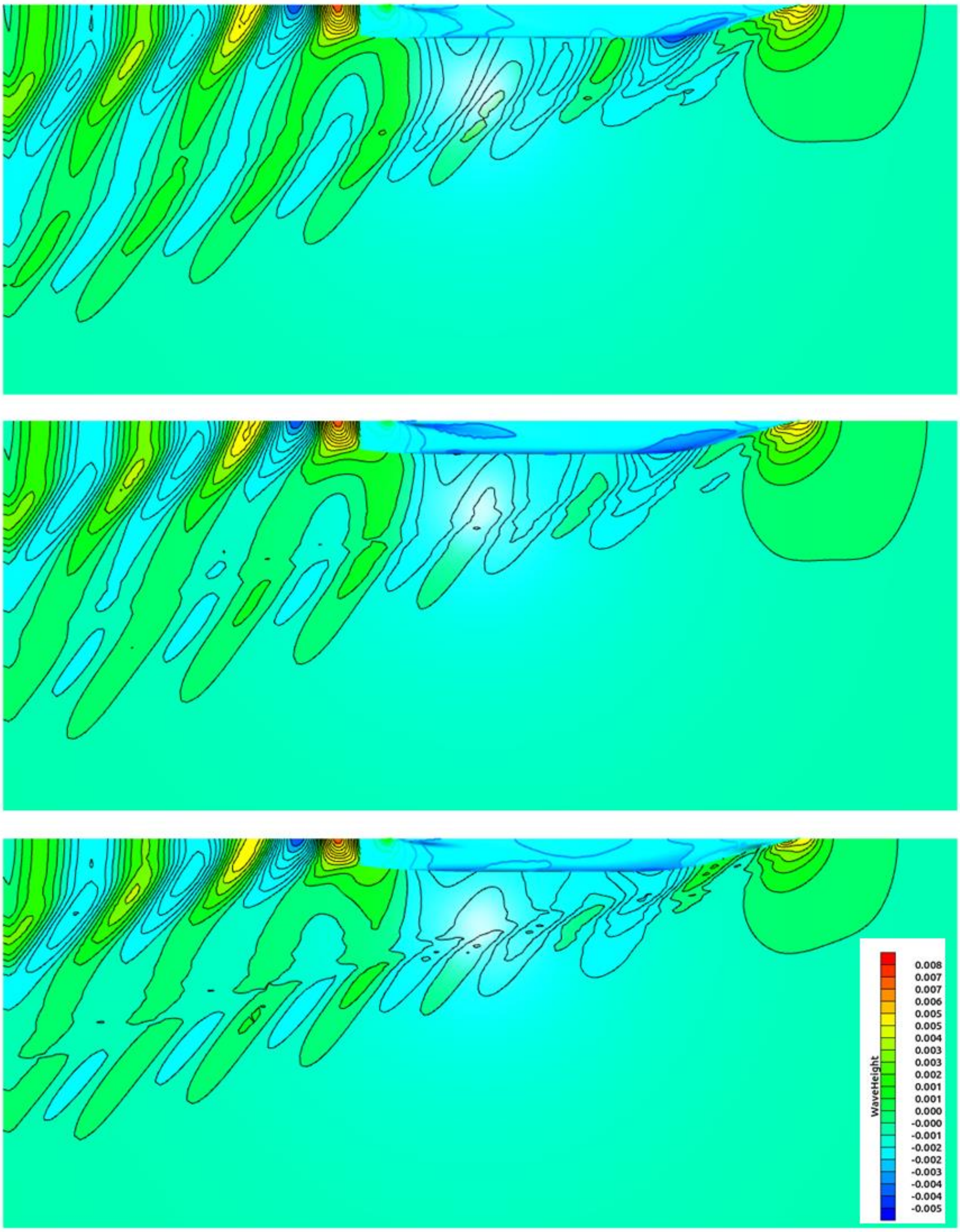

Figure 8: Comparison of wave patterns of the slender standard hulls with c_B = 0.60 (top), c_B = 0.65 (middle) and c_B = 0.70 (bottom) at a speed of Fn = 0.19.

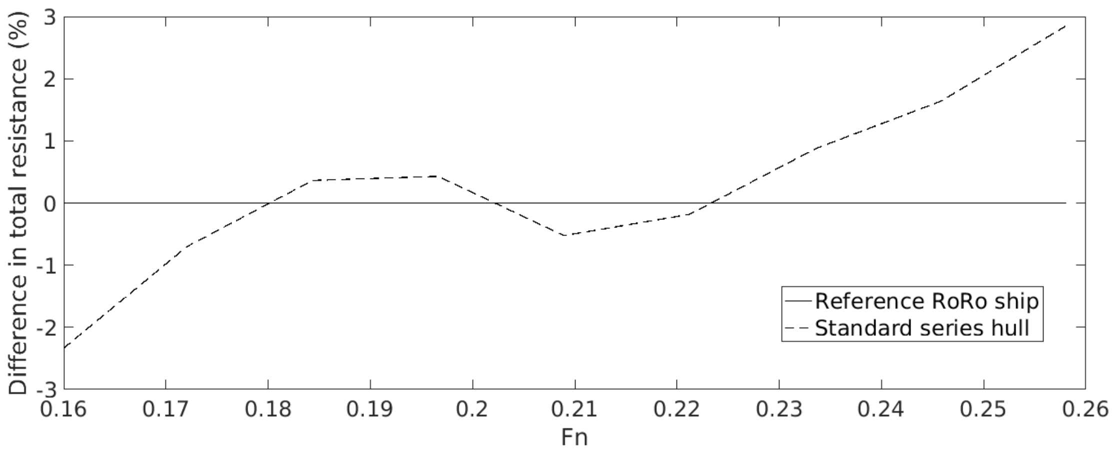

Figure 9: Difference in total resistance (%) between the reference RoRo ship and the standard series hull according to CFD.

2.4.2 Numerical propeller series

The well-known Wageningen B-series offers a quick estimation of the expectable open water efficiency with very limited input. However, the propeller geometry is not adjusted to the expected wake, and the designs are not according to today's standards. Therefore, a numerical standard propeller series is included in the ship energy systems model.

The pitch optimisation and the computation of the open water characteristics are performed using the OpenProp software. A circular wake field with axial velocity values ranging from 62% (at the hub) to 130% of the propeller inflow velocity (v_A) is used for the propeller design. Tangential velocity components are neglected. Methods for fixed pitch and controllable pitch propellers are available in the model and described in more detail below.

Fixed pitch propellers

The fixed pitch propeller series is designed to represent an average modern propeller. The propellers feature a higher tip loading and thus longer chord length in the tip region and a moderate skew. Compared to the Wageningen series, the profile thickness is chosen to be slightly higher. A hub diameter ratio of 0.16 is selected. In Table 3, the geometry characteristics of the fixed pitch propeller series are shown, including the normalized chord length (c/D_{norm}), the maximum profile thickness over the chord length (t/c) and the skew angle in degree. All values are shown for 10 normalized propeller radii (r/R). The normalized chord length is computed as (A_eA_0 as the area ratio and Z the propeller blade number):

$$c/D_{norm} = \frac{c/D}{A_e A_0 * Z} \tag{2}$$

Table 3: Geometry characteristics of the fixed pitch propeller series.

r/R	*c/D$_{norm}$*	*t/c*	*skew (deg)*
0.16	1.42	0.230	0.0
0.3	1.53	0.200	-4.9
0.4	1.60	0.170	-6.3
0.5	1.70	0.140	-6.2
0.6	1.81	0.110	-4.8
0.7	1.98	0.086	-2.2
0.8	2.11	0.061	1.8
0.9	2.00	0.038	6.7
0.95	1.60	0.025	9.2
1	0.01	0.003	11.7

To date, the propeller series has been applied to 3- and 4-bladed propellers. An impression of a standard propeller for the slender standard hull with a block coefficient of 0.69 is given in Figure 10. With the defined geometry, the standard propeller is well suited for ships with moderate propeller loading but might not be suitable for higher speed vessels with high propeller loading. Those ships would most likely require propellers with more tip unloading and higher skew angles. If those ships become of interest and large differences in efficiency between the standard series and actual designs become obvious, a second propeller series would be necessary.

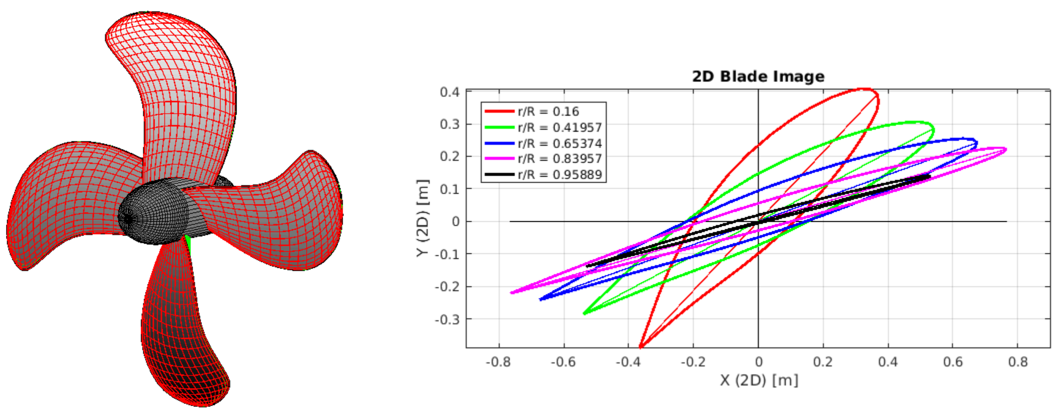

Figure 10: 3D impression and sectional drawings of a standard series propeller with an area ratio of 0.55, adjusted to fit the standard hull with c_B = 0.69.

A comparison of the standard propeller with a Wageningen B-Series propeller for the slender standard hull with c_B = 0.69 and a speed of Fn = 0.19 shows an open water efficiency at the design point of 0.640 for the standard propeller and 0.642 for the Wageningen B-Series propeller.

Controllable pitch propellers

Geometries of controllable pitch propellers (*CPP*) are much more difficult to parameterize than the geometries of fixed pitch propellers. Additionally, the methods used will result in distorted profile sections if a highly skewed propeller is computed at off-design pitch, with a simple rotation applied to the section. A realistic *CPP* propeller thus causes difficulties for the computation using software like OpenProp. To obtain good results, the sections have to be redefined for each pitch settings by rotating the propeller blades and obtaining new cylindrical cuts.

Using the operational performance and model test data available for the RoRo reference vessel in Paper II, two options were reviewed: (i) using the fixed pitch propeller series with a hub ration of 0.27, and (ii) using the curves available from the Wageningen C-series, see Dang et al. (2013). In option (i), the standard propeller would be used without any skew for the off-design pitch computations. Additionally, the chord length distribution is slightly adjusted to fit the larger hub ratio. For option (ii), results published in Dang et al. (2013) are only valid for a 4-bladed propeller with an area ratio of 0.40.

To apply the published efficiency curves of the Wageningen C-series propellers to propellers with other area ratios than 0.40, the efficiency has to be adjusted. Differences occur due to different Reynolds numbers and different aspect ratios A_R of the blades. The efficiency of a wing section can be written as (Abbot & Von Doenhoff, 1959):

$$\eta = c_L / c_D \tag{3}$$

with c_L as the lift coefficient and c_D the drag coefficient. The drag coefficient can be further decomposed into a frictional (c_F) and an induced part (c_{DI}):

$$c_D = c_F + c_{DI} \tag{4}$$

While the frictional coefficient can be obtained from the ITTC friction line (ITTC, 1999), the induced drag coefficient is dependent on the aspect ratio of the wing, A_R, which can be obtained from the expanded area ratio (A_e/A_0). Additionally, an average lift coefficient can be obtained from the propeller thrust (T) and the speed of the propeller sections, v_P. The speed of the propeller sections is obtained from the speed of advance (v_A) and the rotational speed at 75% of the propeller diameter.

$$c_{DI} = \frac{c_L^2}{\pi * A_R} \tag{5}$$

$$A_R = \frac{Z}{\pi} * \frac{A_0}{A_E} \tag{6}$$

$$v_P^2 = v_A^2 + (\omega_{0.75} * r_{0.75})^2 \tag{7}$$

$$c_L = \frac{T * \frac{v_A}{V_P}}{\frac{\rho}{2} * v_P^2 * A_E} \tag{8}$$

With the above equations, an adjustment of the efficiency for propellers with area ratios other than 0.40 becomes possible. It must, however, be noted that numerous assumptions are made. Most importantly, it was assumed that the lift is equally distributed over the blade. Considering different inflow velocities and sectional thicknesses, this is certainly not the case in reality.

Both options, the adjusted Wageningen curves and the standard series, were applied when analyzing the performance data of the reference RoRo ship in Paper II. Figure 11 presents a comparison of the journey analyses using both methods, the standard series (i) to the left and the modified Wageningen curves (ii) to the right. Compared to the results with the standard series, the results obtained with the modified Wageningen curves show less peaks but a larger deviation toward the end of the journey. In Paper II, it is argued that the deviations towards the end of the journey are likely due to measurement errors. For most of the data points, the obtained propeller efficiency with the Wageningen curves is about 3% lower than the efficiency obtained with the standard series propellers, except for the end of the analyzed journey. It must also be noted that large variations of the relative differences are observed over the time, especially in the beginning of the journey.

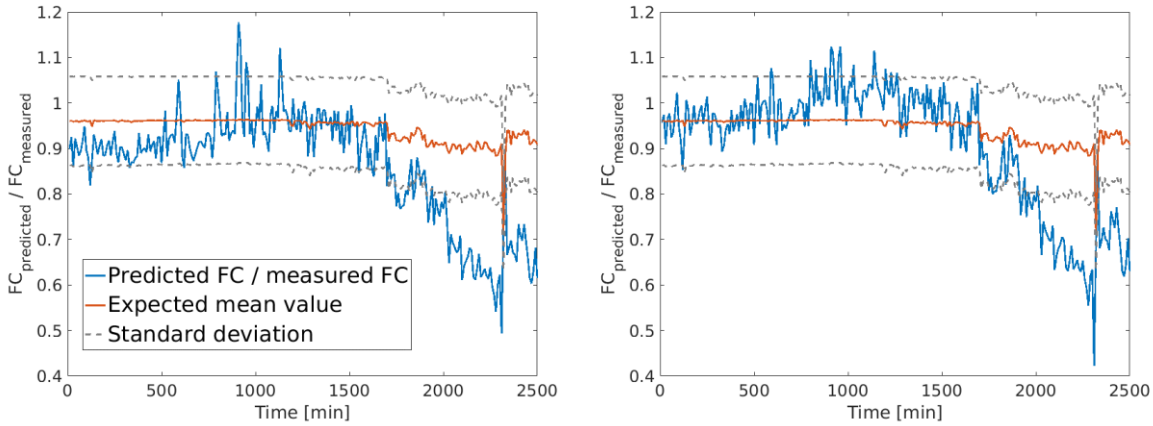

Figure 11: Comparison of the operational analysis using the standard series propeller (left) and the modified Wageningen curves (right) over the time of the journey.

It can be concluded that the prediction of off-design pitch performance of controllable pitch propellers is difficult. None of the two available methods seem to capture all effects, but the modified Wageningen C-Series curves seem to capture the level of open water efficiency better. However, none of the presented methods is obviously better in the performance analysis. For future works, it seems best to develop a dedicated *CPP* standard series and a method to make reliable off-design pitch predictions for these propellers using OpenProp.

2.5 Assumptions and limitations

The developed model is called a generic ship energy systems model, which implies that it can be applied to any ship and cover the whole energy system "ship". Naturally, there are limitations in both, the range of ships that the model is valid for and parts of the ship that are included in the model. Further limitations are the validity of the employed methods and the accuracy of the prediction, as discussed in the appended papers and Section 2.2.

(i) Generic model – range of application

First of all, it must be clarified that the model is intended to be used for analyzing and predicting a ship's energy efficiency; thus, it is thought to be used for analyzing the propulsion performance of conventional cargo ships traveling along a route in moderate weather. Conventional cargo ships are those that are designed in a common way, e.g., no special asymmetric single skeg designs, and travel at a common speed for the ship type. Further on, only conventional propulsion units, i.e., main engines fueled with bunker oil, can be modeled with the current version of the model. The engine model is based on interpolation curves and only covers the fuel consumption and exhaust gas temperature. For more detailed analyses of the engine behavior or changes to the engine system, a more sophisticated engine model must be included. Moderate weather is defined as sea states and wind conditions where the ship can operate in its usual way; i.e., no survival conditions can be modeled. The dynamic part of the model does not consider voluntary speed losses. The employed empirical added resistance methods seem to work very well in sea state 4 (2 m wave height) and sufficiently in sea state 6

(4 m wave height), as discussed in Paper II. In higher waves, the methods seem not to be accurate, and the model should not be applied in those conditions. The time scales and the inertia settings in the dynamic part are currently made in a way to simulate ships traveling along a route; i.e., normal de- and acceleration phases can be simulated but not the maneuvering in a harbor. In the current version of the model, only the propulsion unit is modelled. Any other consumers, e.g., hoteling and cargo handling, are disregarded.

(ii) Validity of the methods used in the model

The validity of employed methods must be specified for empirical or semi-empirical methods, as used in the resistance prediction in calm water and the added resistance prediction. All employed methods, apart from the *CFD* computations using the standard hulls, are based on regression analysis of model test results. Due to this fact, these methods might introduce interpolation errors. It can also be questions of quality and the representativeness of the fleets that the methods are based on. Further on, these methods are based on model tests, which introduces new uncertainties. The results of the prediction within each component are only tested on two ships in Paper II; thus, it must be mentioned that the methods are not calibrated and that the range of possible applications is not clearly defined yet.

(iii) Uncertainties of the prediction

Uncertainties in prediction are discussed and presented in detail in Paper II. It was shown that the uncertainty can be significantly reduced with more information and more sophisticated methods available. Depending on the application, the level of uncertainty that is acceptable must be defined and the methods must be selected accordingly. Further on, it must be mentioned that uncertainty analysis is based on theoretical analysis; if more reference ships become available, the results might be changed. Until now, the model has not been calibrated, which would be possible with more reference ships available and would increase the accuracy.

3 Results

This chapter provides a brief summary of the most important results presented and discussed in the two appended papers. Detailed information about methods and results can be found in the papers.

3.1 Summary of Paper I

In Paper I, “A generic energy systems model for efficient ship design and operation”, a flexible and generic energy systems model was introduced. The differences, advantages and disadvantages compared to other existing energy system models for ships are discussed. Aside from the description of the structure, the components and the employed methods, four case studies were performed on an Aframax tanker:

(i) a speed profile optimization for a route with changing wind and sea state,
(ii) a main dimension variation,
(iii) a propeller design point variation, and
(iv) a sea margin and main engine size variation.

Results from the speed profile optimization are shown in Figure 12. Four different possible speed and power settings were identified and tested: (a) constant torque, (b) constant target speed, (c) constant average speed and (d) constant rpm. It can be seen from Figure 12that the constant target speed setting resulted in the lowest fuel consumption for both the journey with an average speed of 13 kn and the journey with 15.5 kn average speed. As discussed in Paper I, it must be kept in mind that the methods used, especially the added resistance in waves prediction, were not fully developed in the time of the study. The accuracy of the prediction has been significantly improved during the study for Paper II. In Figure 13, the results from a main dimension variation for an Aframax tanker are shown. The variation was done for two scenarios, (a) a constant displacement for all variants and (b) a block coefficient fixed for all variants. The results are shown as the fuel consumption along the route over the deadweight of the ship. In Paper I, how the deadweight is obtained from the variants displacement and dimensions is discussed. It can be seen that the longer the ship, the lower the fuel consumption for both scenarios. However, the influence of the beam seems much lower.

Results from the propeller design point variation and from the main engine size and sea margin can be found in Paper I. In summary, it was shown that the fuel consumption can be reduced if the propeller design thrust and the sea margin are chosen to be as low as possible, whereas the main engines should be as large as possible.

Apart from the findings of the case studies, the most important result was that it could be shown that the developed generic energy system can be used in different phases of a ship’s life. Unlike the existing energy systems model, the presented model does not require detailed input or measurements to study the influence of design or operational changes on the fuel consumption of ships along a route with variable weather.

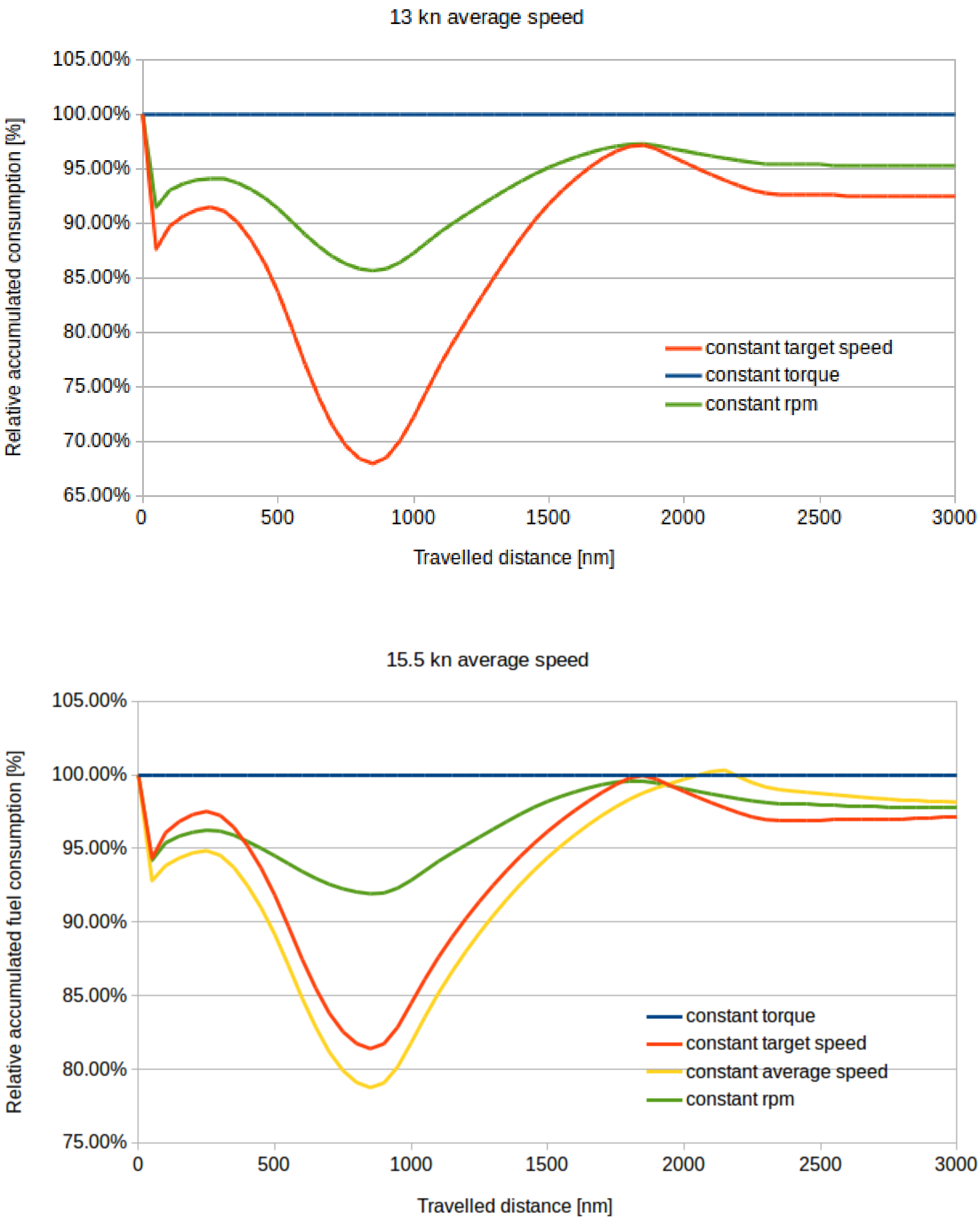

Figure 12: Results from a speed profile optimization for an Aframax tanker at sea.

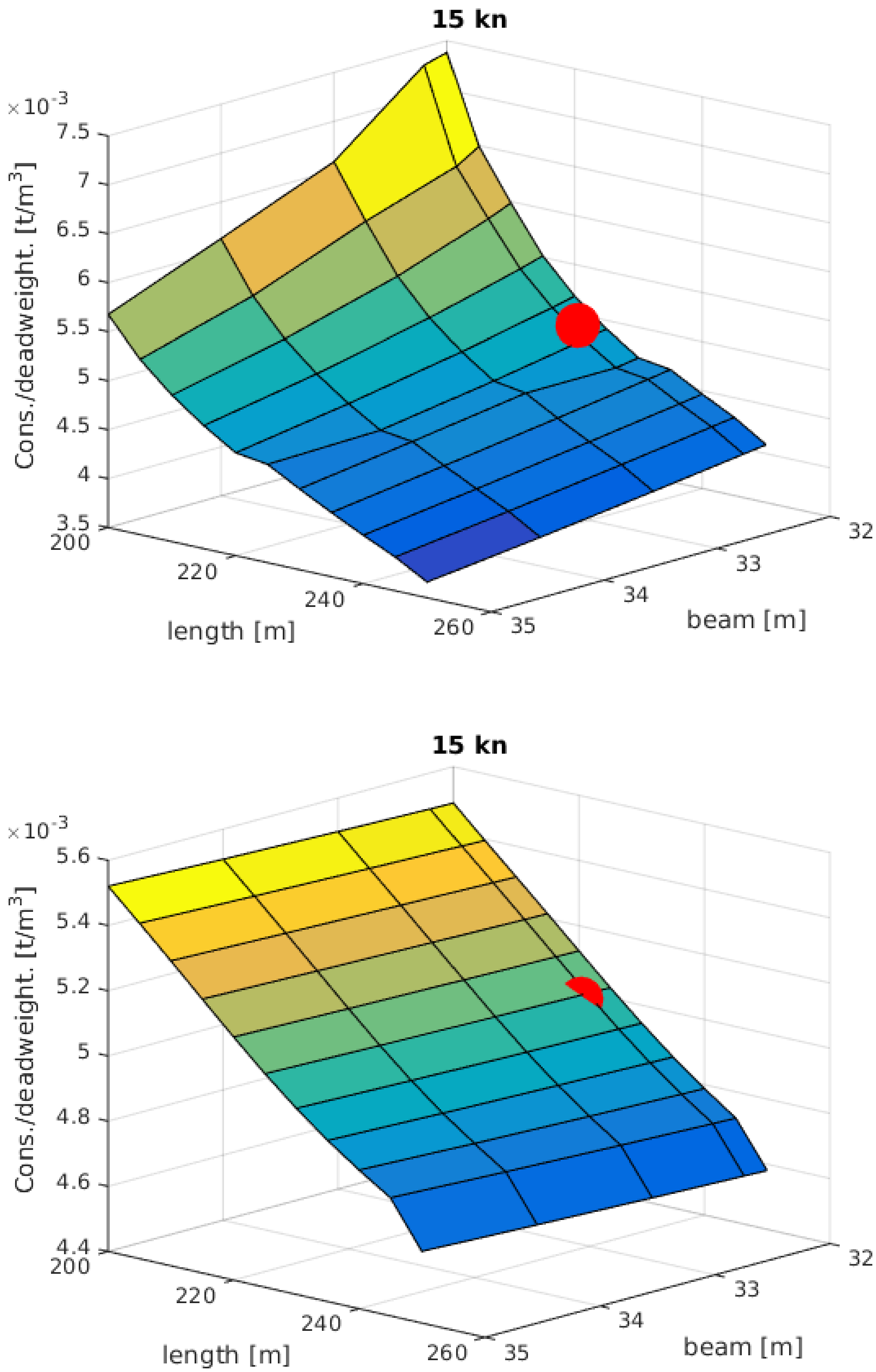

Figure 13: Results from the main dimension variations for an Aframax tanker with constant displacement (upper) and constant block coefficient.

3.2 Summary of Paper II

Based on the work presented in Paper I, the generic energy systems model was further developed. The main target of the development was to increase the accuracy of the prediction throughout the life of the ship, i.e., with different amounts of information available. Two main improvements were made: (i) The Hollenbach empirical method (Hollenbach, 1998) for calm water resistance prediction was implemented, and (ii) three newer, more sophisticated empirical methods for the prediction of added resistance in waves were included. The methods for (ii) were the STAWAVE 2 (ITTC, 2014), the method developed by Liu & Papanikolaou (2016) and an improved version of this method as presented in Liu et al. (2016). Further information and motivation for the use of the above methods are given in the appended paper. Apart from the implementation of new methods, decisions were made to use the average of multiple methods in various components, e.g., wake prediction, calm water prediction and added resistance prediction.

In Paper II, each component of the static power prediction part of the model was investigated to find the uncertainty of prediction in four design phases; (I) only main dimensions are known, (II) the hull and propeller design are finished, (III) calm water model test results are available, and (IV) the design of the whole ship is finished. Uncertainties were divided into two groups: (a) methods uncertainties and (b) design uncertainties. Method uncertainties are those that arise from prediction errors and differences between methods and exist in design phases but might have different values. Design uncertainties exist only in the design phases where the final shape of the component is not defined; i.e., the properties of the component must be predicted empirically.

Two existing, i.e., build and in operation, ships were used as reference ships, one RoRo ship and one tanker. In Figure 14 and Figure 15, the results of the uncertainty analysis are shown for the tanker and the RoRo ship, respectively. The results of the study show an uncertainty of fuel consumption prediction in operational conditions of about 12% in design phase I. This value is reduced to about 4% in design phase IV. The largest increase in accuracy is obtained between design phase II and III, i.e., when model test results are available. Further analysis showed that the main factor for increased accuracy was the prediction of the effective wake and thrust deduction. A comparison of the mean values showed that the mean value of design phase 1 was within 3% of the mean value of design phase IV for the tanker case. For the RoRo ship, larger deviations of the mean values were found, especially at lower speeds. It was found that differences appear in the open water and hull efficiency. Further on, the reference ship has a significant bulb effect at lower speeds, which was not captured by empirical methods.

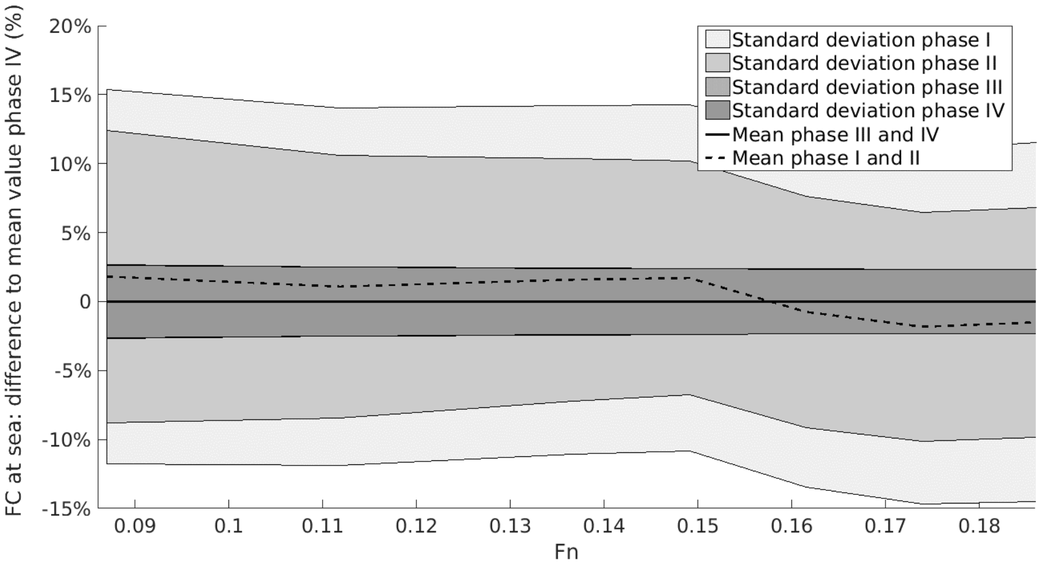

Figure 14: Comparison of the mean value and the standard deviation in different design phases for the tanker.

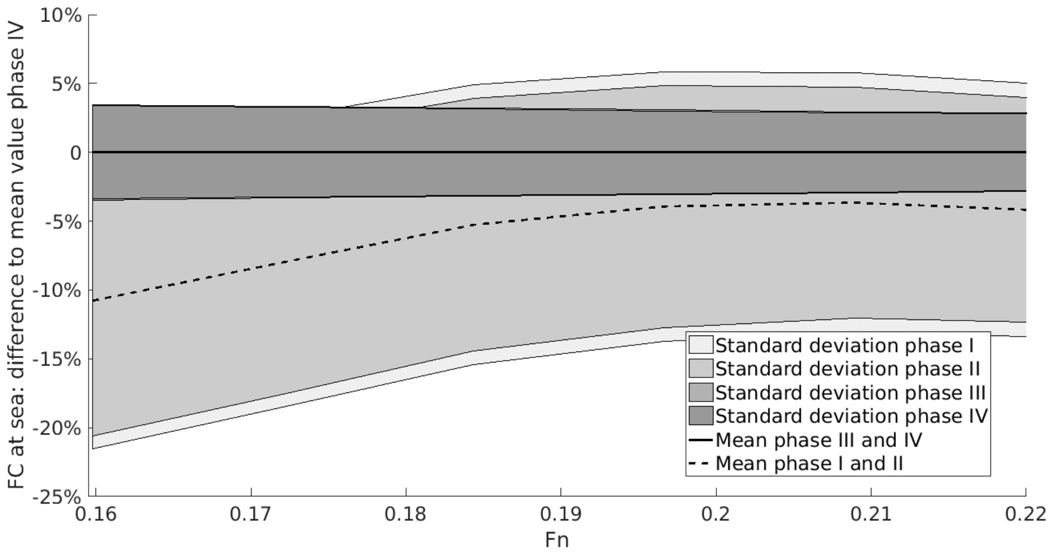

Figure 15: Comparison of the mean value and the standard deviation in different design phases for the RoRo ship.

Further demonstration of the usability of the generic model was done by means of an analysis of available operational data for the reference RoRo ship. The results of the analysis are shown in Figure 17. The predicted fuel consumption was obtained using methods and information that would be available in design phase 1; i.e. the operational data was analysed using only the main dimensions of the ship. It became clear that measurement uncertainties must be analysed and quantified in future work.

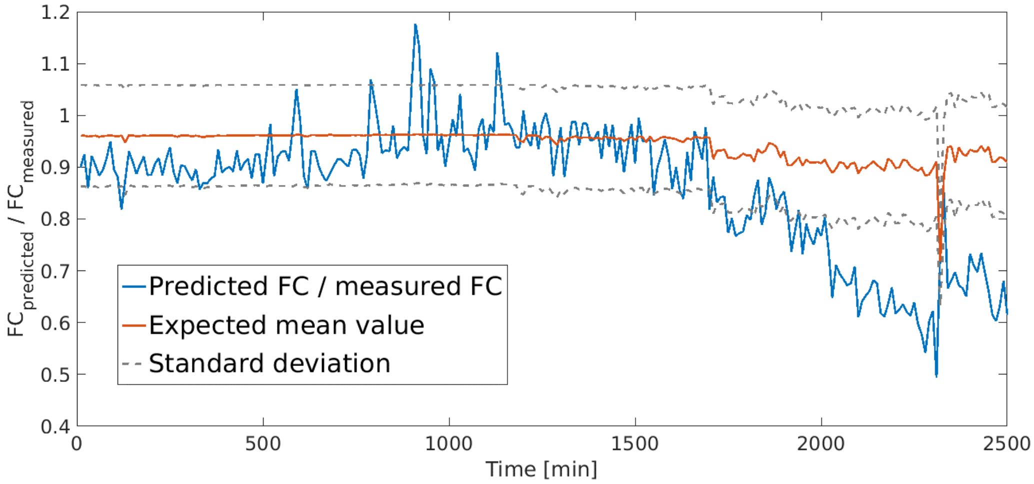

Figure 16: Relative fuel oil consumption (predicted over measured) for a journey of the reference RoRo ship over the times of the journey.

In this study, the achievable accuracy of fuel oil consumption was discussed for different phases in the life of a ship, from early design through operation. A thorough analysis of the uncertainties in each component shows ways to improve the prediction and can be used as a guideline of which information must be made available as soon as possible. Further on, it was shown that the operational performance can be predicted with only the main dimensions available.

4 Conclusions

A new generic and dynamic ship energy systems model was presented in this thesis. A strong focus was placed on the hydrodynamics of the ship and on the behaviour of the propulsion system in different sea and weather conditions. The model is designed with a naval architecture point of view with the target to provide reliable predictions during the design and operation of ships. In different case studies from the design and operation of ships, it was shown that it is important to simulate the whole energy system instead of only single components, e.g., the main engine. It was shown that the model can be applied to a wide range of ship energy efficiency problems with very limited input information, i.e., only the main dimensions and the ship type. Thus, it can be concluded that the presented model is generic for the defined group of conventional cargo ships. For two reference ships, it was shown that fuel consumption prediction performed with only the main dimensions available is within 5% of the prediction with model tests available, compared at design speed. The predictions are made without any calibration and without prior measurements.

It was found that the highest accuracy can be achieved when combining different empirical methods and substituting these methods by values obtained with newly developed standard hull and propeller series, if possible. Combinations of empirical methods are used for calm water resistance, added resistance in waves and effective wake prediction. It was found that the prediction of the thrust deduction is complicated; thus, the hull efficiency is estimated directly.

A thorough uncertainty analysis showed that the standard deviation of the fuel consumption prediction is expected to be about 14% when only main dimensions are available. It was shown for two reference ships that the uncertainty can be reduced to about 4% with the model test results available. The prediction of the propulsive coefficients was identified to be the most crucial to achieve a higher accuracy.

From a full-scale operational analysis, it can be concluded that measurement errors and uncertainties must be identified and quantified before those measurements can be used to validate and calibrate the model. Without a thorough analysis of the full-scale measurements, it cannot be concluded if the differences in prediction and measurements are due to modelling or measurement errors.

5 Future work

Three main areas of future work were identified, (i) further development of the existing parts of the model, (ii) development and inclusion of new parts of the energy system and (iii) application of the model. The first area, (i), will contribute to further improve the accuracy and reliability of the prediction. Area (i), together with area (ii), contributes to the inclusion of more ships into the group for which the model is applicable, as defined in Section 1.2. The third area of future work, (iii), will contribute to validation and calibration of the model and thus increase the accuracy of the prediction.

The first area (i) is about both, including new prediction methods and developing the existing methods for each component. One of the components that should be developed first is the main engine model. The underlying curves for the fuel consumption and exhaust gas temperature are obtained from one engine manufacturer and are in the current state based on the mean effective pressure. This method must be improved if more analysis of the main engine or changes to the main engine system shall be performed. It must be investigated how detailed an engine model must be and how detailed it can be to still keep the simulation time low. Further adjustment can be done in calm water power prediction, especially for the propulsive coefficients; more reference ships with model tests would be needed for such work. For added resistance, a combined method of the current empirical method and *CFD* in regular waves could be realised. In such a method, the empirically generated transfer function could be adjusted using *CFD* results in, e.g., two wave lengths.

The second area (ii) is about expanding the model to include more than just the propulsion unit and to make the propulsion prediction more complete. For the latter, a method to predict the biofouling on the hull over the time is missing. For the first named, the expansion of the model, one would most likely start with integrating waste heat recovery systems and boilers, i.e., components that are depending on the main engine. Also, the main engine itself can be developed to capture different fuels and new engine types. The dynamic part could be modified to even capture manoeuvring. Further on, new techniques could be included, such as hybrid propulsion systems and wind assisted propulsion. Including more parts of the energy system can raise the systems perspective even more and show more couplings between different parts. This will result in more accurate predictions and in increased opportunities to apply the model, especially in retrofitting projects.

The last area (iii), application of the model, is about finding real life problems to solve with the help of the model. It was shown in Paper I and Paper II that the generic energy systems model can be very useful in design and operational improvement studies. It can help to linearize the design process since all relevant information (i.e., fuel consumption at sea) is available at all times. Further on, the model can be applied to logistics problems and can represent the part "ship" in a simulation of transport chains. It can also be of help for ship owners in the charter market that face the daily problem to decide which ship to send to which cargo. The model can be a tool to increase the energy efficiency of ships but only if applied to real life problems and not only to academic case studies. The application to real ships and logistic problems will also provide data to calibrate and further develop the model toward the needs of the shipping industry.

6 Nomenclature

A_e	Expanded area (propeller) [m^2]
A_eA_0	Expanded area ratio (propeller)
A_0	Propeller disc area [m^2]
A_L	Longitudinal area above the waterline [m^2]
A_R	Aspect ratio
c/D	Chord length over diameter
c/D_{norm}	Normalized chord length over diameter
c_{ABT}	Bulbous bow cross section coefficient
CAE	Computer aided engineering
c_B	Block coefficient
c_D	Drag coefficient
c_{DI}	Induced drag coefficient
c_F	Frictional drag coefficient
CFD	Computational fluid dynamics
c_L	Lift coefficient
c_{LPR}	Bulbous bow length coefficient
c_M	Main frame area coefficient
c_P	Prismatic coefficient
CPP	Controllable pitch propeller
c_T	Total resistance coefficient
c_{WP}	Waterplane area coefficient
c_X	Wind resistance coefficient
D_h	Depth
EU	European Union
F	Force [N]
FC	Fuel consumption [t/nm,t/h]
Fn	Froude number
I	Current [A]
i_E	Waterline entrance angle [º]
L_{PM}	Length of the parallel midbody [m]
L_{PP}	Length between perpendiculars [m]
n	Rotational speed [s^{-1}]
Q_m	Torque [Nm]
Q_h	Heat flow [W/m^2]
R_{AW}	Added resistance in waves [N]
r/R	Normalized radius
$SFOC$	Specific fuel consumption [kg/kWh]
S_W	Wetted surface
T	Temperature [K]
T_P	Propeller thrust
t/c	Thickness over chord length
U	Voltage [V]
UN	United nations
v	Translational speed [m/s]
v_A	Propeller speed of advance [m/s]
v_{AW}	Apparent wind speed [m/s]
v_P	Propeller sectional speed [m/s]
v_S	Ship speed [kn]
Z	Number of blades (propeller)
η_H	Hull efficiency
η_0	Open water propeller efficiency
ρ_{Air}	Air density (1.25 kg/m^3)
ρ_{SW}	Sea water density (1025 kg/m^3)

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