Siri Helene Ludviksen Thorsen

Simulation Based Estimation of Power Consumption

Describing a simulation based methodology for predicting the power consumption of a vessel

Master's thesis in Marine Technology

Supervisor: Mehdi Zadeh

June 2019

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Preface

This thesis marks the final part of my Master of Science degree with specialization in Marine Systems Design at the Department of Marine Technology (IMT). The work has been carried out during the spring of 2019 at the Norwegian University of Science and Technology, and is equivalent to 30 credits. There have been weekly meetings with the project supervisor, professor Mehdi Zadeh, for a steady progress throughout the project.

The main objective is to study how a simulation based approach can be implemented in the ship design process, in terms of investigating a vessel's power consumption. The intention of the work behind this thesis is done in view of the greener focus that has been within the shipping industry the last years. The development of alternative fuel and innovative configurations have had an increased focus, and simulation has become an important tool for investigate these alternatives earlier in the vessel design process. A considerable part of the knowledge about hybrid systems and simulation based design was provided during fall 2018, related to the work of the project thesis.

I would like to thank primary supervisor Mehdi Zadeh for guidance, feedback and involvement in the work. I would also like to thank Torstein Bø and Kevin Kossup Yum from SINTEF, for providing me with information and data for the cargo vessel, in addition to professional discussion and helpful support with the simulation.

Trondheim, 2019-06-12

Siri Helene L. Thorsen

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Summary

During the last years have the maritime industry taken a significant interest in reducing their greenhouse gas emissions related to shipping. Strict emission regulations have taken effect and forced the ship designers to take immediate action for finding low-emission solutions for vessel design. In light of finding innovations that meets the new regulations, the urgency of improving the traditional design methods have sparked an interest among ship designers. Simulation and virtual testing has become important for the research of better design methodologies. This introduce a more accurate evaluation of the vessel model that includes more realistic operational conditions than the traditional methodology, which is limited to idealized conditions.

The methodology presented in this thesis uses simulation for estimating the power consumption of a general cargo vessel. The approach is based on the empirical method Hollenbach for resistance in calm water, and Wagnening-B screw series for estimating the open water efficiency. In addition will weather data be used for estimating resistance due to waves with the method STAWAVE-1, utilizing the location and time for the vessel in the GPS-data. Power consumption isn't necessarily available for the masses, unlike GPS-data which is easily assessed. The methodology is described in detail, including underlying methods and assumptions used. The method is programmed in MatLab with instructions on how to use it.

The results shows that there exist a great potential of using a simulation approach that is based on empirical methods and GPS-data for weather implementation. The methodology captures the impact of how calm water resistance and propeller efficiency affects the overall performance. On the other hand, there's still need for a deeper understanding of the underlying assumptions, to be able to create a precise model for real life operation. The resistance due to weather can profitably cover more aspects of the real life operation to estimate a more accurate prediction. The consumption at lower loading's is often neglected in the simulation, which give an imprecise visualization of the overall consumption. It should however be pointed out that the methodology still captures the advantage of implementing new information in the preliminary design stage, and allows the user to investigate the vessel performance without an iterative "try-and-error" approach.

Sammendrag

De siste årene har den maritime industrien fått en betydelig interesse for å redusere drivhusgass utslippene fra næringen. Strenge krav som har trådt i kraft har ført til at skipsbyggere har blitt tvunget til å handle raskt for å finne grønne løsninger på skipsdesignet. I lys av å finne innovasjoner som møter de nye reguleringene, har nødvendigheten av å forbedre de tradisjonelle designmetodene fanget interesse blant skipsbyggerne. Simulering og viriuell testing har blitt et viktig aspekt for utviklingen av metodene brukt innenfor skipsbygging. Dette muliggjør å kunne evaluere skipsmodellen under mer realistiske operasjonsforhold, enn den tradisjonelle metoden som kun forholder seg til ideelle forbehold.

Metoden som er presentert i denne oppgaven benytter simulering for å estimere effektforbruket for et lasteskip. Tilnærmingen baserer seg på den empiriske metoden Hollenbach for å beregne motstand i rolig sjø, og Wageningen-B skruserie for å estimere propellvirkningsgraden. I tillegg brukes værdata for å predikere bølgemotstand ved bruk av STAWAVE-1 metoden, gitt lokasjon og tid fra GPS-data til skipet. Fordelen med å bruke GPS-data er at det er lett tilgjengelig, i motsetning til historisk data for effektforbruket. Metoden er beskrevet i detalj, og inkluderer metoder og antagelser som ligger til grunn. Metoden er programmert i MatLab, med tilhørende instruksjoner om hvordan metoden skal implementeres.

Resultatene viser at det finnes et stort potensial med å bruke simulering basert på empiriske metoder og bruk av GPS-data til å kalkulere bølgemotstand. Metoden klarer å få frem innvirkningen motstanden i rolig sjø og propellvirkningsgraden har på det totale effektforbruket. Det er derimot nødvendig å utvikle en dypere forståelse for antagelsene bak reelle operasjonsforhold for å gjøre modellen mer presis. Bølgemotstanden kan fordelaktig bli mer nøyaktig ved å innføre flere reelle antagelser til modellen. Effekten som utgjøres ved lave forbruk, blir ofte neglisjert i simuleringen, hvilket gir et upresist bilde av det totale forbruket. Det må til gjengjeld påpekes at metoden fortsatt er i stand til å implementere informasjon tidlig i designprosessen, og lar brukeren estimere ytelsen til skipet uten en iterativ "prøv-og-feil" metode.

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Nomenclature

Acronyms

CFD Computational Fluid Dynamics

ECA Emission Controlled Areas

GHG Greenhouse gas

IDEAS Integrated Decision Support Approach for Ship Design

IMO International Maritime Organization

ITTC International Towing Tank Conference

MEPC Marine Environment Protection Committee

NOx Nitrogen Oxides

SFI Centres for Research-based Innovation

SOx Sulphur Oxides

ViProMa Virtual Prototyping of Maritime Systems and Operations

Greek Symbols

η_D Propulsion efficiency, [-]

η_H Hull efficiency, [-]

η_R Relative rotate efficiency, [-]

η_0 Open water efficiency, [-]

η_M Mechanical efficiency, [-]

η_T Overall efficiency, [-]

ρ Density of water, $[kg/m^3]$

ρ_a Density of air, $[kg/m^3]$

μ Viscosity of water, $[m/s^2]$

ψ Angle of attack, [degree]

θ Azimuth angle, [degree]

ζ_A Wave amplitude, [m]

ω Circular frequency of regular waves, [rad/s]

Lowercase

g Gravitational acceleration, $[m/s^2]$

k Form factor of the vessel, [-]

mwd Mean wave direction

n Propeller speed [rps]

swh Signinficant wave height

t Thrust deduction coefficient, [-]

w Wake fraction coefficient, [-]

Uppercase

A_E/A_O Blade area ratio, [-]

A_T Cross section area of the ship above the water, [m^2]

B Breadth, [m]

C_A Correlation coefficient, [-]

C_{AA} Air resistance coefficient, [-]

C_B Block coefficient, [-]

C_{BD} Base drag coefficient, [-]

C_D Drag coefficient, [-]

C_F Friction coefficient line, [-]

ΔC_F Roughness correction coefficient, [-]

C_P Prismatic coefficient, [-]

C_R Residual resistance coefficient, [-]

C_{TS} Total resistance coefficient, [-]

C_V Viscocity resistance coefficient, [-]

D Propeller diameter [m]

F_N Froudes number, [-]

H Roughness, [μm]

$H_{1/3}$ Significant wave height, [m]

J Advance number, [-]

K_Q Torque coefficient, [-]

K_T Thrust coefficient, [-]

L Length between perpendiculars, [m]

L_{BWL} Length from the bow to 95% of maximum breadth on the waterline, [m]

L_{fn} Froudes length, [m]

L_{OS} Length over surface, [m]

L_{WL} Length in waterline, [m]

N_{Boss} Number of bossings

N_{Brac} Number of brackets

N_{Rud} Number of rudders

N_{Thr} Number of side thrusters

P Pitch of propeller, [m]

P/D Pitch ratio, [-]

P_B Brake power of engine, [kW]

P_E Effective towing power, [kW]

Q Propeller torque, [Nm]

Q_0 Propeller torque in open water, [Nm]

R Calm water resistance, [N]

R_{AWL} Resistance due to waves, [N]

R_N Reynold's number

R_R Residual resistance, [N]

R_T Total resistance from calm water and resistance due to waves, [N]

R_{TS} Total resistance for calm water using Hollenbach, [N]

R_V Viscous resistance, [N]

R_{wave} Mean increase of resistance in regular waves, [N]

S Wetted surface, $[m^3]$

S_B Area of stern below waterline, $[m^3]$

S_η Frequency spectrum, $[m^2 s]$

T_{01} Mean wave period, [s]

T Propeller thrust, [N]

T_0 Propeller thrust in open water, [N]

T_A Draught at AP, [m]

T_F Draught at FP, [m]

T_{est} Theoretical propeller thrust, [N]

V Ship velocity, [knots]

V_A Velocity of advance, $[m/s]$

Z Number of blades

Chapter 1

Introduction

The focus on decreasing emission, has become an essential issue in almost every industry today, including the maritime industry. The increase of greenhouse gas (GHG) emissions is causing a climate change that is a well-known threat for our planet. This has resulted in stricter emission regulations, which calls for rapid action and greener innovations. In view of this, the possibility of investigating how innovative configurations and alternative fuel can affect the vessel performance early in the design process have sparked an interest among ship designers. The research of better design methodologies that utilize simulation and virtual testing are becoming more important, since the methodologies gives a more accurate prediction of the operational profile than traditional ship design methods.

The thesis investigates how GPS-data and the empirical methods Hollenbach for calm water resistance and Wagningen-B methodical series for open water efficiency, can be implemented for predicating fuel consumption of a vessel. The estimated consumption will be compared to historical GPS-data of a general cargo vessel. The GPS-data is provided from SINTEF, and is logged with a constant step interval within a given time period of sailing. The purpose is to analyze how vessel design and propeller characteristics can predict the power consumption, using input from GPS-data and the empirical methods mentioned. This can be implemented early in the design process, and opens up for evaluating new and innovative configurations. Data of power consumption doesn't exist for new configurations, and it's therefore desirable to find a simulation based approach that give accurate results for the power consumption.

1.1 Background

The rapid drop in oil price in 2014 led to an increased focus of cost savings and forced the shipdesigners to change focus from the oil and gas industry. The demand for these types of vessels plunged, causing the order books empty and the financial times in the maritime industry challenging. The change of focus and new vessel design led to a need of making the design process more efficient, since it was now a new set of requirements and demands that needed to be met. The research for finding better design methodology had taken an interest to keep up with the competition in the marked, and the focus on establishing improved methodology that are implementing the vessel performance early in the design stage was therefore becoming important. In the recent years has virtual testing and benchmarking schemes become highly relevant, and being rapidly evolved.

Increased greenhousegas emission has also changed the focus within the shipping industry, into taking a greener and more environment-friendly path. IMO's Marine Environment Protection Committee (MEPC) has been considering actions to address GHG emissions from ships involved in international trade, and the committee last met for its seventy-second session (MEPC 72) from 9 to 13 April 2018, at IMO Headquarters in London. Here, they adopted an initial strategy on how to reduce GHG emissions from ships, where they more specifically stated that the GHG emission should be reduced with at least 50% by 2050, compared to the emissions in 2008. This goal was first established in the report from IMOs third GHG study [26]. IMO is also responsible for developing the ship pollution rules, contained in the *International Convention on the Prevention of Pollution from Ships*, known as MARPOL 73/78. Here are regulations according to vessel pollution of nitrogen oxide NO_X, and sulphur oxides SO_x defined. Also, the definition of acceptable emission levels in the 'Emission Controlled Areas' (ECA) is defined in MARPOL 73/78, which is areas along coastlines with stricter requirements of these emissions [14]. The restrictions have contributed to design more fuel efficient power systems, and forced designers and engine manufactures to think innovative according to this.

The necessity of finding technological innovations has increased in line with the new regulations from IMO [26], [14]. Quite recently, a simulation based approach was starting to replace the traditional trial-and-error method for ship design. The conventional method does not take the accuracy of operational conditions in advance, and normally make simplifications based on a representative condition. Simulation allows new information to be implemented in an earlier stage in the design process, and make room for understanding how changes of the vessel design affects its performance. The interest among ship designers for improving the performance has increased in parallel with the new IMO regulations, and making the power systems more fuel efficient than earlier. The research of finding better design methodologies is therefore highly prioritized, since accurate predictions will give the designers technological and economical information in the preliminary stage of the design process.

The definition of simulation is to model the real world operation of a system over time, to create an artificial history of of the characteristics. [4] Simulation allows large amounts of information to be implemented without reducing the understanding of the system, and can be presented in a way that allows the user to see the performance clearly. Vessel design are complex, which makes individual testing and simulation important to see how it affects the system performance. Virtual testing gives an understanding of how dynamical changes as weather and design can affect the performance early in the design process, which opens up for investigating innovative design for greener shipping.

1.2 Literature Review

Previous work within the research of improving the design methodology and have also scoped the way for this thesis, is projects such as IDEAS [9], VISTA [7] and ViProMa [12].

The IDEAS project from 2012, short for 'Integrated Decision Support Approach for Ship Design,' worked on developing a simulation based benchmarking methodology for evaluation of ship design. The methodology is a combination of hydrodynamic calculations, hind cast weather data and a detailed mission profile, where the hydrodynamic calculations is for correct powering and speed values in waves. The object is to combing this in a simulation model and create an operational profile of real life operation of the vessel, replacing CFD calculations and model tests. [9]

In the paper from the 12th International Marine Design Conference in 2015 [3], the VISTA simulating complex marine operations work bench was presented. VISTA was developed for assessing operability of complex marine operations during design [7]. The primary objective of the project was to improve ship design through a development of methods and models, to receive a realistic simulation of the performances of vessels in operation. VISTA is a more detailed form of simulation than the discrete event, since this a system simulation that can be performed after an operational simulation like discrete event simulation. This will investigate more detailed how the components are affecting the vessel performance.

ViProMa presents an open virtual prototyping based on distributed co-simulation [12]. The platform allows testing within different areas, companies and simulation software, enabling everyone to contribute with their knowledge. The main objective of this platform, is to connect the different simulation based software that already exist for components and smaller system of the vessel, to be able to simulate the overall performance of the whole vessel.

SINTEF gave recently out a paper on using quasi static discrete event simulation for estimation of fuel consumption. The paper [24] was published in light of the drop in oil price in Norway in 2014 which caused a demand of rapid change to new types of industries, and challenged the Norwegian shipbuilders with a new set of requirements and demands. Virtual testing and simulation was highly preferred as this enables changes early in the design process. The method consist of using discrete simulation based models and historical weather for the vessels operational conditions, along with quasi static calculations for wave and wind calculations, to replicate a voyage of a general cargo from China to US. The purpose is to be able to compare and evaluate the accuracy with performance monitoring system measurements.

1.3 Objectives

The aim of this project is to estimate the fuel consumption of a general cargo vessel using a simulation based approach and GPS-data for position and velocity, in addition to weather conditions as significant wave height and mean wave direction. This will be compared to real-life operational data from the general cargo vessel. The purpose of this simulation is to evaluate whether a simulation based approach will give approximately same results as using measured operational GPS-data. Historical information of power consumption is not always available for the masses and a load profile can not always be easily generated. GPS-data is on the other hand easy assessed, and can therefore be applied as input in a simulation. Velocity will be used for calculation with the empirical method Hollenbach for calm water resistance, and for open water efficiency using the methodical propeller series Wageningen-B. The vessel's location coordinates will be used for calculating added resistance due to waves with STAWAVE-1 method. Weather data that consist wave direction and significant wave heights will be applied for the calculation.

The aim for this thesis is to build a simulation methodology, making it possible to simulate the power consumption of a vessel, by virtually creating an operating environment. The purpose of this methodology is to estimate the performance of the vessel in a more accurate way than is currently done by designers, at an early stage in the design process. This is achieved by utilize empirical methods that requires easily assessed input to quickly produce performance indicators based on simulated operating profiles.

The main objectives of this thesis can be summarized in following objectives:

1. Developing a theoretical model based on empirical methodology and GPS-data for prediction of propulsion power consumption

2. Investigate how simulation and GPS-data can replace traditional methods, utilizing historical data and real life operations for simulating a vessels power consumption

3. Investigate how simulation can be applied for designing innovative configurations

4. Conduct an evaluation of the model with comparison of measured operational data for the fuel consumption

1.4 Structure of the Report

Chapter 2 will first provide an introduction to ship design and simulation. The chapter will give an general introduction to simulation, and then in the view of how simulation is applied within ship design.

In chapter 3 will be introduced by presenting how the methodology will be implementing for calculating power consumption. Then will important condition parameters for vessel performance be described. Further on will the theoretical method that have been used, be presented in detail.

Chapter 4 gives a description of how the methodology is modeled in MatLab, and presented with the underlying assumptions for the methodology.

Chapter 5 contains the results from the thesis, in addition to a comparison to the measured operational data.

Chapter 6 provides a conclusion and recommendations for further work that should be included for improving the methodology.

Chapter 2

Simulation Based Approach in Ship Design

The stricter regulations and the increased interest of developing fuel efficient solutions for vessels have had a revolutionary turn the last years. This has caused a need of rapid solutions for implementing technological innovations in the maritime industry. Virtual testing and simulation based approaches have enchanted our understanding of the vessel performance at a early stage in the design process. This chapter will first present an introduction of how traditional ship design is being processed. Further on will an overview of the most common virtual testing and simulation based approaches used the last years be given. In addition will a description of the main segments of simulation be described.

2.1 Traditional Ship Design

Traditionally, ship design is evaluated based on how it performs in idealized conditions. This will lead to an uncertainty of capture the complete spectrum of real life operating conditions, as this evaluations usually base their operations on calm sea conditions. The task of designing a ship involves many disciplines, from hull design to machinery and structural engineering. The process is often described as a design spiral, where assumptions that are made for the final design, is evaluated for the current solution [8]. The spiral can be seen in figure 2.1

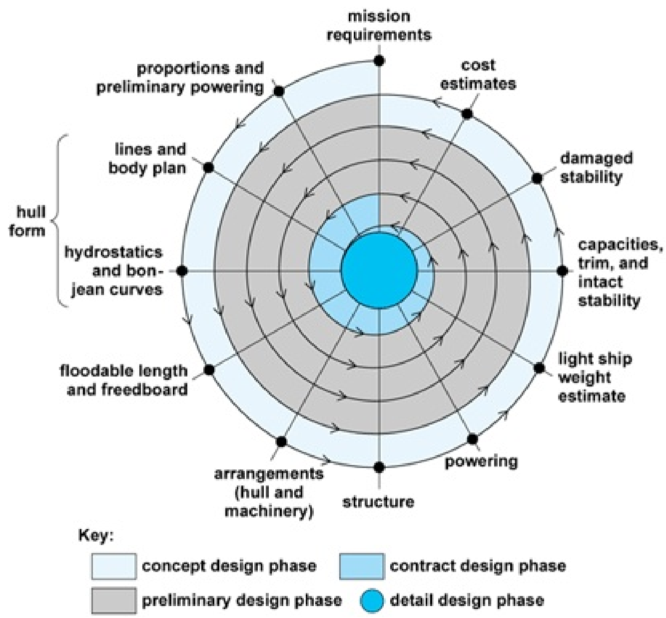

Figure 2.1: The Ship Design Spiral [19]

Information is added along the points at the curve for drawing details and engineering calculations. This gives new information that can be added to the assumptions made and to the design spiral. The design spiral will be repeated until the design is finished, making the design process sequential and iterative, having a "try - and - error" approach. The process is divided into stages, where a set of tasks is to be achieved in every stage. The tasks and stages are depending on how close they are to the center of the design spiral. The first stage is the concept design phase, where different designs are developed for further inspection and comparison against each other. The second phase is the preliminary design phase, where the project is being planned out and improves the major ship characteristics that are affecting cost and performance, and are not expected to change after this phase. The next stage is the contract design phase, and the specifications are settled. Also a costing for the project is being estimated. The final stage is the detail design stage that ends up the design spiral with drawings for the ship builder and documentation from classification societies. Compromises on cost, dimensions and specifications are continuous being made along the process, making the process iterative.

2.2 Simulation - Basic Terms

Simulation is widely used to analyze stochastic systems, where the outcome is based on the probability over time, and includes one or more random variables. [23] Some of the basic terminology used are:

1. *Entity*: Component in a system, with a given property called *attribute*. An example is a vessel driving along the west coast of Norway, where the vessel is the entity and its cargo capacity is an attribute.

2. *System*: A collection of entities

3. *System state*: A collection of variables that will describe the system at a specific time.

4. *Event*: A change in the system. This can for example be the arrival of the vessel mentioned.

5. *Model*: Representation of the system, which is necessary to describe the relations between the events, variables, entities and attributes. The model representation is further divided into different categories that are based on the characteristics. One model description is discrete - or continuous event model, based on the variables. If the variables are defined at particular times it is discrete event, and continuous if the variables are defined all the time. A model can also be deterministic or stochastic, depending on the results of the simulation. If the results can be predicted ahead given a set of variables, the model is deterministic. If there are several uncertain outcomes with a given probability to it, then the model is stochastic. A model can also be static or dynamic, depending on whether the system is changing over time. In general, most computer simulation models are continuous-time, discrete-state, probabilistic and dynamic. [23]

Simulation are used in a wide range of purposes and projects, ranging from details in products to large transportation logistic systems. Simulation is not always the most beneficial choice of problem solving, and it demands someone who understands how to read the outcoming results. Figure 2.2 shows different types of problem solving, and can be used to evaluate when simulation based approach is most beneficial.

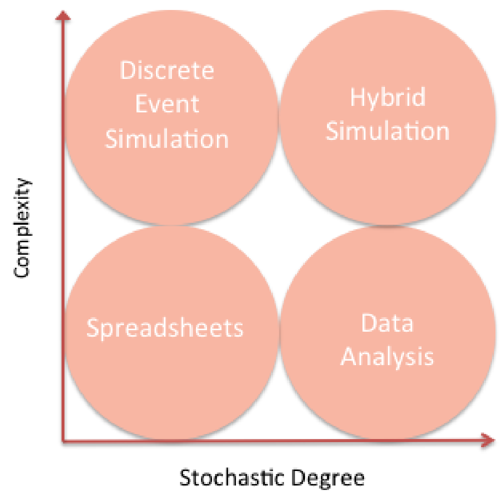

Figure 2.2: Problem solving illustration [29]

From the figure, it can be shown that use of simulation is depending on the degree of complexity, and are not necessary for all types of problems. Problem solving by using a spread sheet might be more efficient when all the variables are known, and data sheet when sufficient sets of data for the problem is available. When the level of complexity is decreasing, the more interesting it is to use simulation based models for solving. Discrete event simulations can handle multiple subsystems and inputs with uncertainty. If one wants to handle both discrete and continuous events into same model, a hybrid simulation approach need to be used.

2.3 Simulation in ship design

For marine operations, the virtual testing and bench marking schemes have been developed the recent years. This section will review some of the different virtual tools that are being used in the maritime industry until today.

2.3.1 Integrated Decision Support Approach for Ship Design (IDEAS Project)

The IDEAS project from 2012, is short for 'Integrated Decision Support Approach for Ship Design', and worked on developing simulation based bench-marking methodology for evaluation of ship design. The methodology is a combination of hydrodynamic calculations, hind-cast weather data and a detailed mission profile, where the hydrodynamic calculations is for correct powering and speed values in waves. The object is to combing this in a simulation model and create a operational profile of real life operation of the vessel, and replacing CFD calculations and model tests. [9]

The paper are describing a case with two different vessels with similar ship design, but where the second design have an improved bow design. The intention is to capture the differences in performance between these two, using simulation with the software ShipX and weather data from Met-Ocean Data. Operations where a simple round trip with the same fixed deadweight, and a similar speed- and power policy were applied for both, to be able to maintain the variability as low as possible. The simulations are run for two industrial cases; the first one are the vessels non stop operating under different load conditions, and the second one similar to a deep sea transportation, where also the cargo handling capacities in ports were bench-marked.

The models applied for this simulation, is a combination of logistic model, Met-ocean data and a vessel model into a bench marking tool. Included in the logistic model is the routes sailed and the cargo quantity, the weather conditions is provided by Met-data and the vessel model includes the geometry for the vessel and the engine- and power configuration. For the vessel model is MARINTEKs numerical software ShipX applied for the hydrodynamics, calculating the vessels motions and resistance in waves using strip theory formulation [10] [22]. ShipX is also used for processing information about the vessels propeller and engine. The simulation begins with selecting a route, and estimations for the amount of cargo and the time spent are being done. In every sailing, iterations are being done over waypoints and collects weather data at grid points, which includes wave heights, wave period and the wave heading. With this data and the ShipX calculations for powering and speed loss, the interpolation of speed requirement for the ship in current conditions can be done. Once a route is finished, a new route is selected, and this process is repeated until the simulation is finished. A flow chart of IDEAS project is given in figure 2.3.

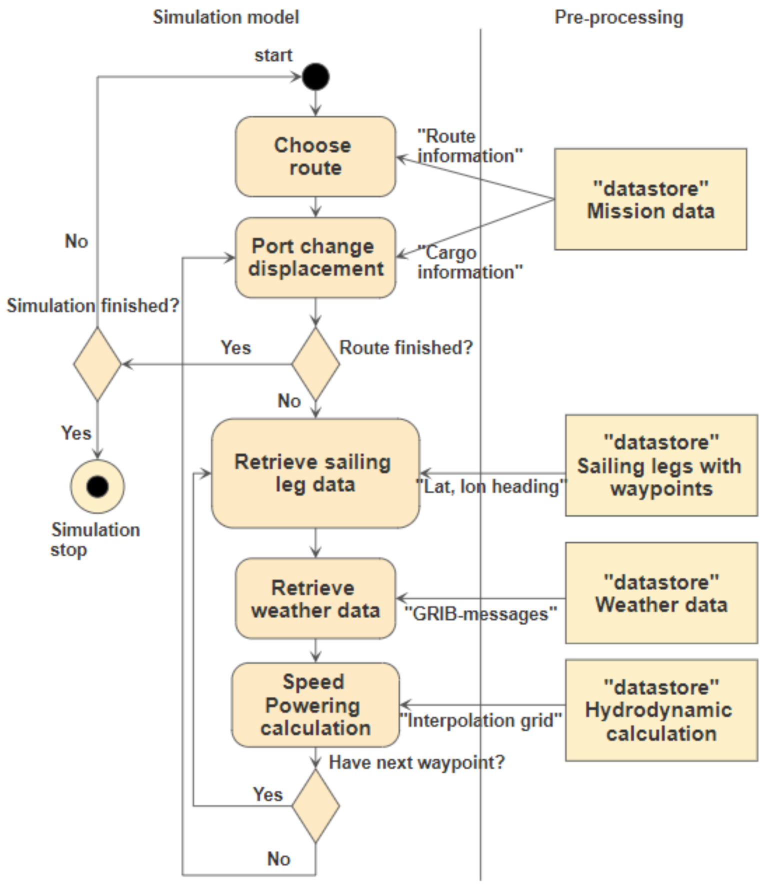

Figure 2.3: Flow chart used in simulation model to IDEAS project [9]

2.3.2 Discrete Event Simulation

SINTEF gave recently out a paper on using quasi static discrete event simulation for estimation of fuel consumption. The paper [24] was published in light of the drop in oil price in Norway in 2014 demanding a rapid change for new types of industries, which challenged the Norwegian shipbuilders with a new set of requirements and demands. Virtual testing and simulation was highly preferred as this enables changes early in the design process. The method consist of using discrete simulation based models and historical weather for the vessels operational conditions, along with quasi static calculations for wave and wind calculations, to replicate a voyage of a general cargo from China to US. The purpose is to be able to compare and evaluate the accuracy with performance monitoring system measurements.

The simulation based workbench that are used is GYMIR, developed in the research project SFI Smart Maritime. One of the inputs to determine the simulator actions is choice of speed policy, which in this case a constant speed policy is being applied. For added resistance, quasi static estimates are being done in GYMIR, and there are typically three contributions to this. The first one is from calm water, that value will be calculated calm water resistance curves from towing test. The second is due waves, using strip theory or pressure integration to solve it [1]. The third one is due wind, using ShipX database to find the drag coefficients needed. A figure of the flow chart is given in figure 2.4.

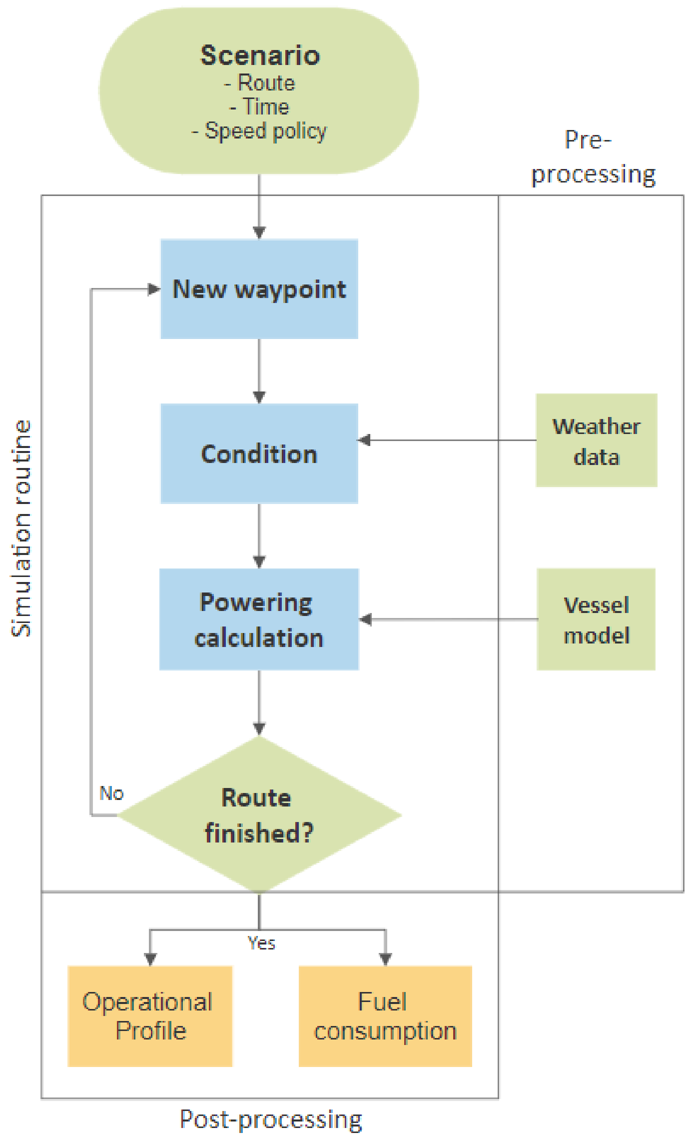

Figure 2.4: Flowchart of discrete event simulation, used by SINTEF [24].

In the conclusion it's pointed out how the assumed simplifications gave a too low fuel consumption compared to the realistic model. A reason for this is the assumption of constant speed policy. In the real life operation, a constant RPM was applied. This causes an involuntary speed reduction in harsh weather, but protects the engine from wear and tear in addition to limited fuel consumption. It's recommended for next simulation to increase knowledge about the vessels performance, including speed policy, the weather - speed relationship, hull degradation and fuel curves that take engine performance into account. It should also be done more research on different routes, vessel types and seasons as input for the power consumption, to get a more accurate solution.[9]

2.3.3 Virtual sea trial (VISTA)

The paper from the 12th International Marine Design Conference in 2015 [3], the VISTA simulating complex marine operations work bench is presented. This is an industry project that aimed to develop a workbench that uses multiple disciplines to develop a more exact model of the real life performance for a complete ship system over its operational life cycle. The primary objective of the project is to improve ship design through development of methods and models to get a realistic simulation of the performances of vessels in operation. VISTA is a more detailed form of simulation than the discrete event, since this a system simulation that can be performed after an operational simulation like discrete event simulation. A system simulation will investigate more detailed how the components are affecting the vessel performance. The architecture of the components of VISTA project is in figure 2.5.

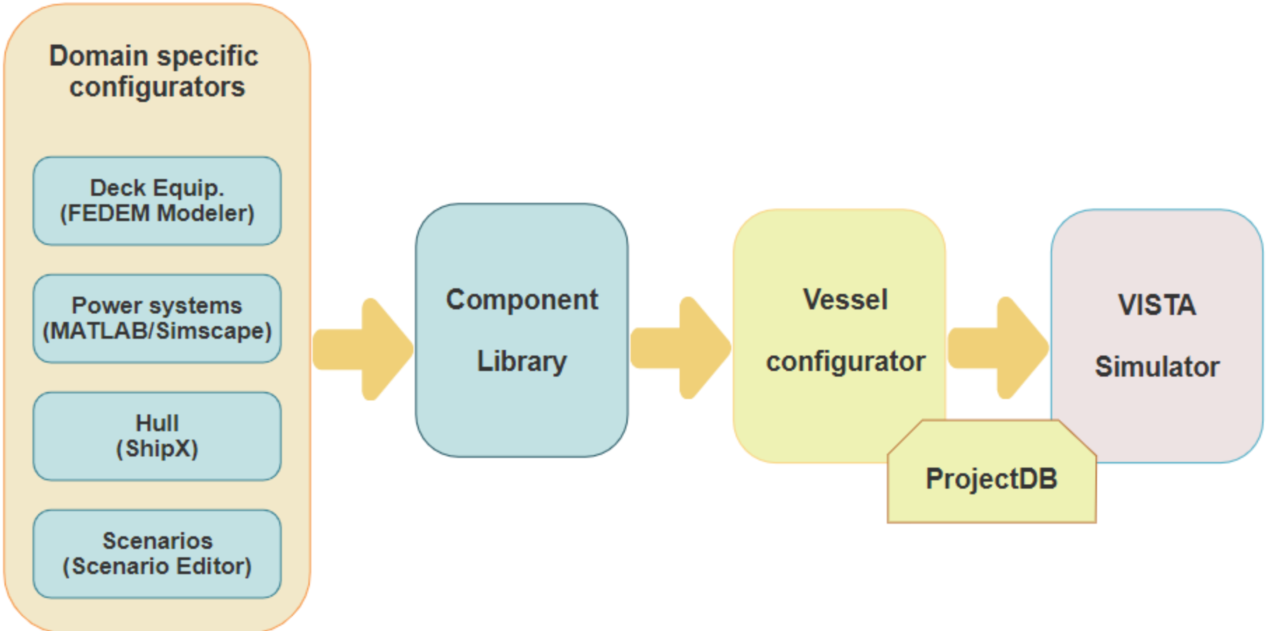

Figure 2.5: Architecture of Vista project [7]

The VISTA project was developed after the IDEAS project, and are being used as a proof - of - concept for some fundamental precondition, as example the logistic framework established for vessel operations, including routes, speed - and power policy and cargo operations. The methods developed here, are now core VISTA components. VISTA offers a virtual model of a new regime for verification and documentation of overall vessel performance and operation, and are mainly delivering prototypes. This was important for the Norwegian ship industry, wanting to be competitive in the shipping marked as well as meeting the newer emission restrictions.

The results from the paper of VISTA introduces important challenges of the simulation based approach. One of them was the challenge of looking into how one component separately are influencing the system. Vessels have complex system with many components that are interacting with each other.[7]

Chapter 3

Methodology

In this chapter, the methodology for calculating theoretical power consumption for vessels is presented. Calm water resistance is calculated by using the empirical formula Hollenbach [13]. The resistance curve is then used for finding the vessel's thrust T that will be evaluated against estimated thrust T_{est} for an iterative process of determining the propeller speed n. How this is modelled will be further described in chapter 4.4.1. This parameter will be input for finding open water efficiency η_0, that together with hull efficiency η_H and relative rotation efficiency η_R composes the propulsion efficiency η_D. The overall efficiency η_T will be the product of the the propulsion - and the mechanical efficiency η_M. The effective towing power P_E is defined as the product of calm water resistance R, found from Hollenbach and the vessels velocity, shown in equation 3.1. The overall power consumption is defined as the engines brake power P_B, and is calculated from the effective towing power P_E and the overall efficiency η_T. This is shown in equation 3.2.

$$P_E = R \cdot V \tag{3.1}$$

$$P_B = P_E \cdot \eta_T \tag{3.2}$$

Input for the calculations is the velocity for the general cargo vessel, that is found from the GPS-data. Propeller characteristics and hull perpendiculars are also used as input in several of the calculations. In addition is longitude and latitude coordinates input for STAWAVE-1 method, also found in the vessel's GPS-data. An overview of which characteristic that are used in the different methods are given in table 3.1. A further description of the parameters are given under respective method later in the chapter.

Table 3.1: Input parameters required for estimation of power consumption in each modelling approach

Method	Hull Description	Propulsion System	Constants	Weather
Hollenbach	L, L_{WL}, L_{OS}, B, S C_B, T_A, T_F	D_p, N_{Rud}, N_{Thr}, N_{Boss}	ρ, g, μ	-
STAWAVE-1	B, L_{BWL}	-	ρ, g	mwd, swh
Open water efficiency	C_P	$D, P, P/D, A_E/A_O, Z$	ρ	-
Estimated thrust	-	$D, P, P/D, A_E/A_O, Z$	ρ	-

Here, *mwd* is short for mean wave direction, and *swh* is short for significant wave height.
The first part of the chapter will present important flow condition around the propeller that are used for further calculation of the efficiencies. In the second part will a describtion of the theory of resistance methods that have been used for calculation and the third part will present a description of the methodology of finding propeller efficiency. A flowchart of how the overall estimated power consumption is calculated is shown in figure 3.1.

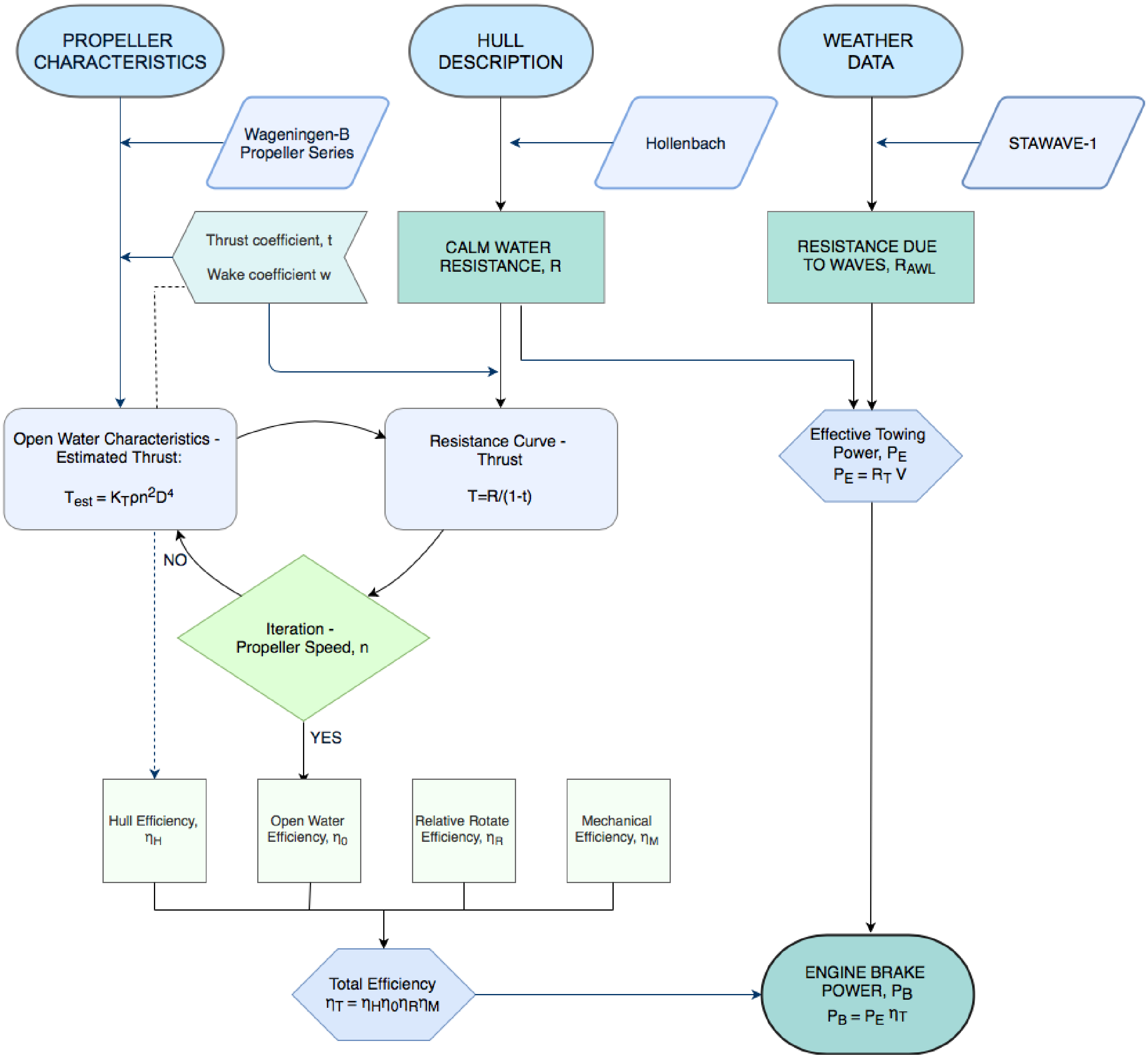

Figure 3.1: Flowchart of estimated power consumption

3.1 Flow Conditions Around the Propeller

In this section, the two coefficients wake fraction w and thrust deduction t will be described, and how they affects propeller performance will be presented. This section also provides an empirical method of how to calculate their values.

3.1.1 Wake Fraction Coefficient, w

The wake is usually defined of the following components: [25]

- Friction wake

  A boundary layer of water will develop around the hull of the vessel as it's moving due the friction, a so-called friction belt. The velocity of the water surface in the friction belt will be equal to the velocity of the vessel, but will be reduced with the distance from the hull. The friction belt will be thickest at the aft end of the hull. Since the thickness is proportional with the length of the vessel, a wake velocity will be generated due to friction on the sides of the hull. In addition will the vessel's displacement of the water develop wave wake fore and aft, which means that the propeller will be working in a wake field. [18]

- Potential wake

  The flow velocity at the stern in an ideal fluid, is similar to the flow velocity at the bow. The velocities will be lower at the stagnation points.

- Wave wake

  Due the orbital velocity under the waves will the steady wave system change locally the flow, and above the propeller will a wave crest increase the wake fraction.

Because of this, the velocity of the arriving water at the propeller, i. e. the velocity of advance V_A is lower than the observed velocity of the vessel, and the speed difference is the wake. The wake fraction coefficient is given dimensionless by the formula 3.3, defined by D. W. Taylor. [11]

$$w = \frac{V - V_A}{V} \tag{3.3}$$

The wake fraction coefficient are highly dependent on the shape of the hull, as well as the propellers size and placement behind the vessel.

The value used as input in the simulation for general cargo vessel is given by the empirical formula, established for single screw cargo ships by Hecksher [25]. Here, the wake is only depended by the prismatic coefficient C_P.

$$w = 0.7C_P - 0.18 \tag{3.4}$$

3.1.2 Thrust Deduction Coefficient, t

The thrust produces an acceleration of the water flowing through the propeller disc and reduces the pressure in the field ahead of it, compared to a ship being towed without the propeller. The effect of this will be an increase of the vessel resistance compared to the resistance that will be measured for a towed vessel. The thrust deduction can be expressed with the required propeller thrust T, and the resistance of the towed vessel without the propeller R_T, given in formula 3.5.

$$t = \frac{T - R_T}{T} \tag{3.5}$$

The value used as input in the simulation for general cargo vessel is given by the empirical formula, established for single screw cargo ships by Hecksher [25]. From the formula, the thrust deduction is only depended by the prismatic coefficient C_P.

$$t = 0.5C_P - 0.18 \tag{3.6}$$

3.2 Resistance

The resistance of a vessel is affected by its speed, displacement and hull form. It is composed of several components, that are usually divided into three bigger groups:

1. Viscosity resistance
2. Wave resistance

3. Air resistance

Viscosity resistance

The viscous resistance R_V is depended on wetted surface area of the hull, and are composed of the following components: [27]

$$C_V = (1+k)(C_F + \Delta C_F) + C_{BD} \tag{3.7}$$

where:

k is the form factor of the vessel.

$C_F = \frac{0.075}{[log(R_N)-2]^2}$ - ITTC'57 Friction coefficient line [15]
R_N is the Reynold's number

$\Delta C_F = \left[100 \cdot (H \cdot V)^{0.21} - 403\right] \cdot C_F^2$ - Roughness correction coefficient.
H is the roughness measured in μm, and V is the vessel's velocity in m/s

$C_{BD} = \frac{0.029 \cdot (S_B/S)^{3/2}}{(C_F^{1/2})}$ - Base drag coeficient
S is the wetted surface of the hull, and S_B is the area of the stern below waterline.

The viscous resistance is the main distributor to the total resistance. For low-speed vessel like bulk carriers and tankers, it contribute for 70 - 90 % of the total resistance [18].

The viscosity resistance can be expressed as:

$$R_V = C_V \frac{1}{2} \rho S V^2 \tag{3.8}$$

where:

R_V - Viscosity resistance in N

C_V - Viscosity resistance coefficient, which is dimensionless

S - Hull wetted surface, measured in square meters m^3

V - Vessel velocity in m/s

ρ - The water density measured in kg/m^3

Residual resistance

The residual resistance comprises wave resistance and eddy resistance. Wave resistance is the energy loss that are caused by waves created by the vessel during its propulsion through the water. Eddy resistance is the loss caused by flow separation which creates eddies, particularly at the aft end of the ship [18].

There exist three main methods for calculating wave resistance:

1. Empirical methods
2. Numerical methods
3. Experimental methods

One well-known empirical method that are widely used today is Hollenbach [13]. This method is used for added resistance in calm water in this thesis for the general cargo vessel, and will be explained further in section 3.2.1. Numerical methods are often divided into two main groups, namely potential theory-methods and CFD-methods. [25]. The residual resistance normally represents 8-25% of the total resistance for low-speed ships, and up to 40-60% for high-speed ships [18].

The residual resistance can be expressed as:

$$R_R = C_R \frac{1}{2} \rho S V^2 \tag{3.9}$$

where:

R_R - Residual resistance

C_R - Residual resistance coefficient

Air resistance

The air resistance will increase in line with how much of the hull is above waterline, and container vessels do typically have high air resistance. The air resistance typically range from 0.5-1.0. The air resistance R_{AA} is given i formula 3.10.

$$R_{AA} = \frac{1}{2}\rho_a V^2 C_D \cdot A_T \tag{3.10}$$

where:

R_{AA} - Air resistance

C_D - Drag coefficient

A_T - Cross section area of the ship above the water

ρ_a - Density of air

In calculation of ship resistance, the air resistance is expressed as a coefficient in terms of the hull's wetted surface: [27]

$$C_{AA} = \frac{\rho_a \cdot C_D \cdot A_T}{\rho \cdot S} \tag{3.11}$$

3.2.1 Hollenbach's Resistance Estimate

Hollenbach's model is an estimate of the power requirement of a ship, which focuses on the prediction of the resistance in calm water. The model is based on regression analysis of 433 ship models, and depends on the vessels main dimensions. The important details in the hull will therefore not have much of an effect in the resistance prediction [13]. Hollenbach is the most recent empirical method for commercial vessels, and more accurate than other methods like Holtrop and Guldhammer-Harvald, as it uses a wider set of data and more complex formulas [27]. The method separates the results in best and poor, with a difference of 5%. This gives the user the opportunity to decide whether the hull has good or poor hull lines.

The analysis for generating the resistance curve for model, was done in the towing tank at MARINTEK. The Froudes number for the model was used to get the full scale resistance of the vessel, given in formula 3.12.

$$F_n = \frac{V}{\sqrt{g \cdot L_{fn}}} \tag{3.12}$$

Froudes length L_{fn} is varying for different values of the relation L_{OS}/L, where L_{OS} is length over surface, and L is the vessel's length between perpendiculars. L_{OS} is dependent on the loading condition, and is defined as follows [20]:

- for design draught, is it the length between aft end of design waterline and the most forward point at the vessel below the design waterline.
- for ballast draught is it the length between aft end of the design and the forward end of the hull at ballast waterline.

The values for L_{fn} is defined in table 3.2

Table 3.2: Definition of Froudes length L_{fn} [27]

	L_{fn}
$L_{OS}/L < 1.0$	L_{OS}
$1.0 < L_{OS}/L < 1.1$	$L + 2/3 \cdot (L_{OS} - L)$
$1.1 < L_{OS}/L$	$1.0667 \cdot L$

The residual resistance coefficient are defined in the formula 3.13, and the total resistance is expressed in formula 3.14

$$C_R = \frac{R_R}{\rho/2 \cdot V^2 \cdot B \cdot T} \tag{3.13}$$

$$R_{Tm} = \frac{\rho}{2} V^2 \cdot (C_{Fm} \cdot S + C_R \cdot B \cdot T) \tag{3.14}$$

The components that C_R consist of can be expressed as:

$$\begin{aligned} C_{RHollenbach} =& C_{R,Standard} \cdot C_{R,FnKrit} \cdot k_L \cdot \left(\frac{T}{B}\right)^{a1} \cdot \left(\frac{B}{L}\right)^{a2} \cdot \left(\frac{L_{OS}}{L_{wl}}\right)^{a3} \cdot \left(\frac{L_{wl}}{L}\right)^{a4} \cdot \left(\frac{D_p}{T_A}\right)^{a6} \\ & \cdot \left[1 - \frac{T_A - T_F}{L}\right]^{a5} \cdot (1 - N_{Rud})^{a7} \cdot (1 - N_{Brac})^{a8} \cdot (1 - N_{Boss})^{a9} \cdot (1 - N_{Thr})^{a10} \end{aligned} \tag{3.15}$$

where:

T_A - Draught at AP

T_F - Draught at FP

D_P - Propeller diameter

N_{Rud} - Number of rudders

N_{Brac} - Number of brackets

N_{Boss} - Number of bossings

N_{Thr} - Number of side thrusters

$C_{R,Standard}$ is defined as following:

$$C_{R,Standard} = b_{11} + b_{13} \cdot F_n + b_{13} \cdot F_n^2 + C_B \cdot \left(b_{21} + b_{22} \cdot F_n + b_{23} \cdot F_n^2\right) + C_B^2 \cdot \left(b_{31} + b_{32} \cdot F_n + b_{33} \cdot F_n^2\right) \tag{3.16}$$

where:

$$C_{R,FnKrit} = max\left[1.0, \left(\frac{F_n}{F_{n,krit}}\right)^{c1}\right] \tag{3.17}$$

$$F_{n,krit} = d_1 + d_2 \cdot C_B + d_3 \cdot F_n^2$$

$$k_L = e_1 \cdot L^{e2}$$

The formulas are valid for Froudes number in following intervals:

$$Fr_{min} = min(f_1, f_1 + f_2(f_3 - C_B))$$

$$Fr_{max} = g_1 + g_2 C_B + g_3 C_B^3$$

The maximum resistance is calculated as $R_{Tmax} = h_1 \cdot R_{Tmean}$. The minimum resistance case should K_L and $C_{R,FnKrit}$ be sat to 1.0 in equation 3.15. The coefficients in the equations for 'minimum' and 'mean' resistance are given in Appendix A, table A.1, for single and twin-screw vessels [20].

When accounting for the form factor, roughness and correlation coefficient, the total resistance coefficient is as in formula 3.18 [27]

$$C_{TS} = C_R + (1+k)(C_{FS} + \Delta C_F) + C_A \tag{3.18}$$

where:

C_{TS} - Total resistance coefficient

C_F - Friction resistance coefficient

k - Form factor

ΔC_F - Roughness resistance coefficient

C_R - Residual resistance coefficient

C_A - Correlation coefficient

For C_F is the ITTC'57 friction coefficient line[15] used for given Reynolds number, expressed in terms of the Reynolds number R_{NM} [27]

$$R_N = \frac{6 \cdot F_N \cdot \sqrt{6g}}{1.1395} \cdot 10^6 \tag{3.19}$$

$$C_F = \frac{0.075}{[l\o g(R_N) - 2]^2} \tag{3.20}$$

The total resistance is expressed as follows:

$$R_{TS} = \frac{1}{2}\rho V^2 S C_{TS} \tag{3.21}$$

The code that runs Hollenbach model is found in appendix C.2.3.The code is provided in lecture notes from the course *TMR7 Experimental Methods in Hydrodynamics* [28].

3.2.2 STAWAVE-1

For taken resistance due to waves into account, the method STAWAVE-1 can be applied. This is a correction method that can be used when a ship has limited pitch and heave. STAWAVE-1 is only limited to bow waves, or waves that are directed from ahead. In other words are waves outside a a limit of 0 to ±45° off the bow excluded from the wave correction [16]. The equation of added resistance are given in equation 3.22

$$R_{AWL} = \frac{1}{16}\rho_s g H_{1/3}^2 \sqrt{\frac{B}{L_{BWL}}} \tag{3.22}$$

where:

R_{AWL} represents the mean resistance in long crested irregular waves

ρ_s is the water density

$H_{1/3}$ is the significant wave height

B is the breadth of the vessel

L_{BWL} is defined as the distance from the bow to 95% of maximum breadth on the waterline in meters. The definition is of L_{BWL} is given in figure 3.2

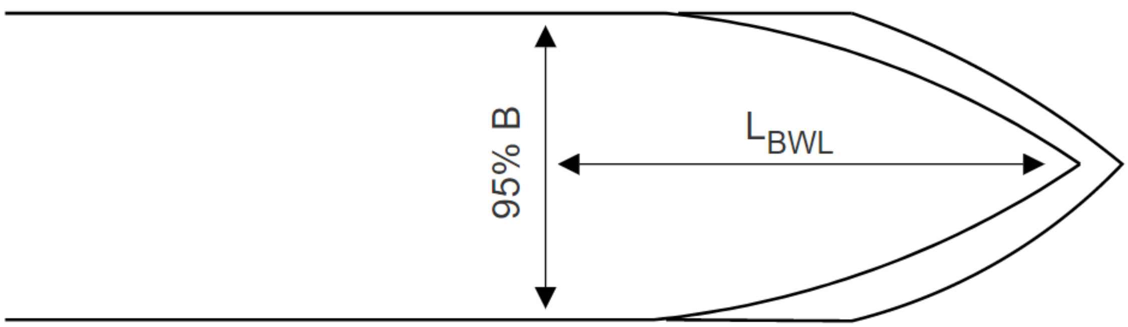

Figure 3.2: Definition of L_{BWL} [16]

3.3 Propulsion Efficiency

The overall efficiency for a vessel consist of the contribution of four components - open water efficiency, hull efficiency, relative rotate efficiency and mechanical efficiency. The propeller efficiency is used for theoretical calculation of the power output of the general cargo vessel, and will be used to predict the power output from the simulation, described later in the thesis. This chapter will give a description and definition of the contribution to the overall efficiency of the propeller. The overall propeller efficiency is given by the formula 3.23

$$\eta_T = \eta_0 \cdot \eta_H \cdot \eta_R \cdot \eta_M \tag{3.23}$$

η_T - The overall efficiency

η_0 - Open water efficiency

η_H - Hull efficiency

η_R - Relative rotate efficiency

η_M - Mechanical efficiency

The contribution to the overall efficiency is therefore the propulsion efficiency η_D and the mechanical efficiency η_M, where η_D includes the open water efficiency η_0, the hull efficiency η_H and relative rotate efficiency η_R. The structure of how the total efficiency is composed, is given in figure 3.3.

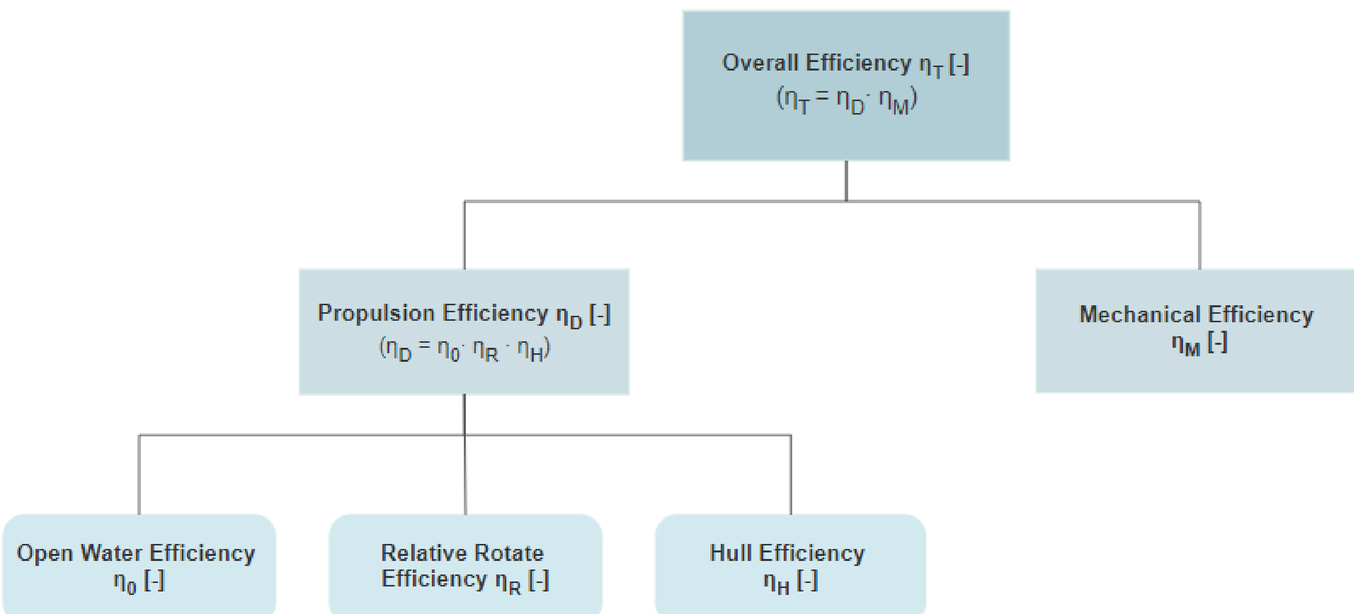

Figure 3.3: Structure of the overall efficiency of the propeller

3.3.1 Open Water Efficiency

The open water efficiency η_0 indicates the optimum efficiency the propeller is able to perform in an uniform and laminar flow, without the hull in front of it. The efficiency is found from an open water test, where the propeller is tested in a towing tank or cavitation tunnel without influence from the vessel. The efficiency is depended on propeller thrust and torque, and can expressed with dimensionless coefficients. In the open water diagram, the thrust- and torque coefficients K_T and K_Q are presented as the advance coefficient J. The open water efficiency can be calculated with formula 3.27.

$$K_T = \frac{T}{\rho n^2 D^4} \tag{3.24}$$

$$K_Q = \frac{Q}{\rho n^2 D^5} \tag{3.25}$$

$$J = \frac{V_A}{nD} \tag{3.26}$$

$$\eta_0 = \frac{J}{2\pi}\frac{K_T}{K_Q} \tag{3.27}$$

A typical example of open water diagram for a set of fixed pitch propellers working in a non-cavitating environment at forward, or positive, advance coefficient is given in figure 3.4. The diagram defines for the particular propeller, the complete set of operating conditions at positive advance and rotational speed. This is because the propeller can only operate along the characteristic line defined by its pitch ratio P/D, under steady conditions. The diagram is general in the way that, subject to scale effects, it's applicable to any propeller having the same geometric form as the one for which the characteristic curves were derived [5]. The propeller should operate at the combination of rate of revolution and advance velocity, since the efficiency is most optimal when the propeller operates at both. Because of boundary layer differences between model and full scale propellers, the open water diagrams are generally subject to scale.

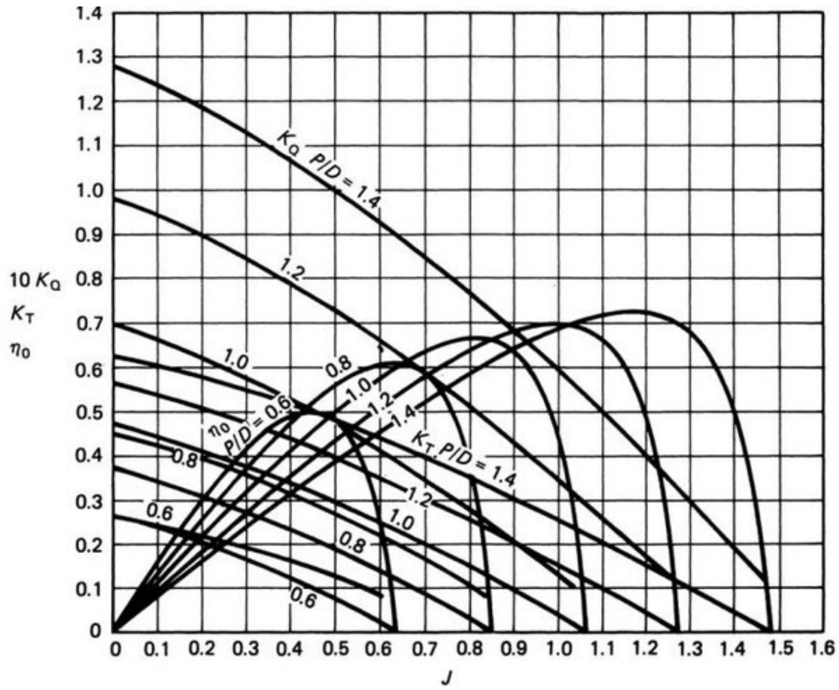

Figure 3.4: Open water diagram for Wageningen B5-75 screw series (In courtesy of [5])

Methodical Propeller Series: Wagneningen - B

Open water characteristics of a propeller can also be found using experimental methods, in addition to theoretical models. When using experimental propeller series tests result, the characteristics of a small number of the propellers belonging to a series is found. Since all the propellers in the series are related to one another, the characteristics of all the propellers in the series can be determined by calculation. Usually are the gross parameters, as the blade area ratio and pitch ratio, the varying variables and the detailed parameters are fixed variables [11]. There exist several experimental propeller series methods for finding characteristics, where Wageningen-B screw series will be used for this simulation.

Wageningen-B screw series is a widely used propeller series for an early estimate of the propeller design and performance. The characteristics was obtained by open water test result of over 120 propellers of screw model of series B, and analyzed with several polynomial regression analysis [21]. The thrust and torque coefficients K_T and K_Q is expressed as polynomials in terms of advance number J, number of blades Z, blade area ratio A_E/A_O, and the pitch ratio P/D. The thickness of the blade profile and the Reynolds number effect are also taken into account in the polynomials. The derived polynomials are given in formula 3.28.

$$
\begin{aligned}
K_T &= \sum_{s,t,u,v} C_T(s,t,u,v) \cdot (J)^s \cdot (P/D)^t \cdot (A_E/A_0)^u \cdot (Z)^v \\
K_Q &= \sum_{s,t,u,v} C_Q(s,t,u,v) \cdot (J)^s \cdot (P/D)^t \cdot (A_E/A_0)^u \cdot (Z)^v
\end{aligned}
\tag{3.28}
$$

The values of the polynomials provided are valid for a Reynolds number $R_e = 2 \cdot 10^6$. The values of C_T and C_Q are given in appendix B.1. The correction formula for other Reynolds numbers can be found in [21], but have not been used for the work in this thesis.

The range of variation in blade area ratio is depended on the number of blades. Table 3.3, shows the range of variation along with the other perpendiculars. The open water characteristics is given in diagrams giving K_T and K_Q as functions of J. The diagrams are available for each set of propeller blade Z between 2 and 7, area blade ratio A_E/A_0 varying between 0.3 and 1.05, in steps of 0.05 and pitch diameter ratio in the range of 0.5 to 1.2, in steps of 0.1.

Table 3.3: Range of variation with number of blades between 2 to 7

Z	P/D	A_E/A_O	t_0/D	d/D
2	0.5-1.4	0.3	0.055	0.180
3	0.5-1.4	0.35-0.80	0.050	0.180
4	0.5-1.4	0.40-1.00	0.045	0.167
5	0.5-1.4	0.45-1.05	0.040	0.167
6	0.5-1.4	0.45-1.05	0.035	0.167
7	0.5-1.4	0.55-0.85	0.030	0.167

3.3.2 Hull Efficiency

The hull efficiency η_H, is the effect from hull on a working propeller, and it's defined by the ratio between the effective towing power P_E and the thrust power the propeller delivers to the water P_T. The formula is given in equation 3.29.

$$
\eta_H = \frac{P_E}{P_T} = \frac{R_T \cdot V}{T \cdot V_A} = \frac{1-t}{1-w} \tag{3.29}
$$

Here are t representing the thrust deduction coefficient and w are the wake fraction coefficient, described in section 3.1. The values for hull efficiency is usually in the range of 1.1 to 1.4 for vessel with one propeller, and between 0.95 and 0.98 for vessels with two propellers. [18]

3.3.3 Relative Rotate Efficiency

The relative rotate efficiency η_R defines as the actual velocity of the water flowing into the propeller behind the hull. In open water condition will the propeller work in undisturbed water, whereas the propeller working behind the vessel are working in water with rotational flow, disturbed by the ship. These conditions are not equal, and the relative rotate efficiency will account for this. The relative rotate efficiency is the ratio of the efficiency of the propeller working in open water and the propeller working behind the vessel. Let T_0 and Q_0 be the thrust and torque of a propeller in open water, with speed of advance V_A and rate of revolution n, and let T and Q be the thrust and torque of a propeller working behind a vessel with same speed of advance and rate of rotation. The propeller efficiencies for open water and behind the vessel can then be expressed as:

$$\eta_0 = \frac{T_0 V_A}{2\pi n Q_0} \qquad \eta_B = \frac{T V_A}{2\pi n Q}$$

The ratio between η_0 and η_B is the relative rotate efficiency, which is given by formula 3.30.

$$\eta_R = \frac{T}{T_0}\frac{Q_0}{Q} \tag{3.30}$$

For single screw ships, the relative rotate efficiency range usually in the interval of 1.00 and 1.10, and between 0.95 and 1.00 for twin screw ships. [11].

3.3.4 Mechanical Efficiency

Mechanical effects consists of the two components shaftline efficiency, η_S, and reduction gear efficiency, η_G [2]. These efficiencies does not affect the vessel's hull-propeller, because they are not related to the waterflow around the vessel's propeller, hull and rudder [2]. The value is usually varying between 0.95 and 0.99 [17].

Chapter 4

Modelling

This section will give a description of how the method is implemented in MatLab. Measured operational data from the general cargo vessel, sailing in a time period from 01.05.2014 to 02.04.2017, is read in MatLab, using its velocity and position over time as input for the calculation. The methodology in this thesis will use weather data from Copernicus Climate Data Store [6], for predicting added resistance due to waves. For this will the vessel's position in longitude and latitude coordinates be input, as well as it will be used for evaluation whether the weather has an impact on resistance according to STAWAVE-1 method. This resistance will be added onto the resistance calculated for calm water with the empirical method Hollenbach. The calm water resistance will also be used for calculating thrust T, that will be used for iteration of finding a value for the propeller speed n. This will further be implemented in the calculation of the open water efficiency η_0. The hull efficiency η_H is found as a function of wake fraction coefficient w and thrust deduction coefficient t, according to Hecksher [25]. This was described in section 3.1.1 and 3.1.2.

4.1 Overview of the Modelling

The complete MatLab code is found in Appendix C. An overview and a short description of the different scripts are listed below:

- *make_power_histogram.m* - This is the main script that are used to estimate the total brake power output P_B. The script uses the resistance from Hollenbach, the resistance due to waves from STAWAVE-1, the iterated value for propeller speed n and the components that compose overall efficiency. By using the methodology from chapter 3, and the equations 3.1 and 3.2 will the estimated power consumption be determined.

- *Hollenbach.m* - This function calculates the vessel's resistance in calm water. The input is vessel velocity and dimensions of the hull, and the propeller diameter, and is calculated as described in section 3.2.1.

- *eta0.m* - The open water efficiency is calculated according to the method described in section 3.3.1. The input here is the velocity V, vessel - and propeller dimensions and the propeller speed n. The speed of advance V_A is also calculated here.

- *thrust.m* - This function find the estimated thrust using the Wageningen-B propeller screw series, and will be described in section 4.4.1, and shown in equation 4.1. Input for this function is propeller speed n, speed of advance V_A and propeller dimensions.

- *find_propeller_speed.m* - The function is iterating a value for propeller speed n, using the estimated thrust T_{est} and the thrust as a function of the calm water resistance from Hollenbach. This will be described further in section 4.4.1. The input is thrust T, velocity V and the prismatic coefficient Cp.

- *stawave.m* - The resistance due to waves is calculated in this function, using weather data from Copernicus Climate Data Store [6].

- *mergeweather.m* - This function compiles the stored data from *nc*-files containing weather data, into one big matrix.

- *bigfile.m* - This function compiles all of the *nc*-files containing weather data, into one file. The function uses the matrix stored data in *mergeweather.m* to arrange the files together.

- *datamodification.m* - This script will read modified measured data from the general cargo vessel. The modified data contain values for coordinates and time only at times when the vessel is at sea passage, enabling a more efficient calculation. The script will further on transfer the values from the GPS-data to make it comparable with how the values are presented in the weather data.

- *wavedimension.m* - The function will connect the indexing of coordinates from the modified GPS-data to the correct weather data, given its coordinates and time. Further on will it generate two arrays with values for the mean wave direction and the significant wave heights for the relevant GPS time, which is read from the weather data. The values for significant wave height and mean wave direction will be stored in the two respective arrays, WH_array and WD_array.

- *newtimearray.m* - This is a script that will index the added resistance due to waves from *stawave.m*, in the right places in the correct time, since the GPS-data that have been used in *stawave.m* calculation, has been modified to make the code more efficient. This script will create an array that only have time values at the indexes where the added resistance from waves should be computed for the overall power consumption of the vessel in *make_power_histogram.m*.

Input files that are needed to run the MatLab codes mentioned above, is:

- An *Excel* file with GPS-data of the general cargo vessel, including power consumption of the trip, velocity over time and the vessels position over time. Velocity is used for input calculating resistance in calm water R and open water efficiency η_0. The location coordinates is used for input in weather data, finding correct significant wave heights and mean wave direction.

- Several *nc*-files, compiled to one file in MatLab, containing weather data for the time period that are compared with GPS-data of the vessel.

- Vessel particulars and propeller characteristics that are required for the calculation. These are saved as arrays in each of the respective variables *Vdim* and *PropellerDim*, used as input in the functions.

The code is created to be able to calculate the estimated power consumption, using Hollenbach for calm water prediction, Wagneningen-B screw series for open water efficiency and for iteration of the propeller speed n. STAWAVE-1 will be used for adding resistance due to waves.

4.2 Input Parameters

The following section will give a detailed description of how the input data files are implemented in MatLab for predicting the power consumption.

4.2.1 GPS Data

Measured operational GPS-data is stored in an *Excel-* file, and read to MatLab as input in further calculations. Here is the GPS measured every fifteenth minute for a sailing period from 01.05.2014 to 02.04.2017. Velocity is stored as an array *Vsvec* in Matlab, used as input in the scripts *Hollenbach.m, eta0.m, find_propeller_speed.m* and *thrust.m.* The data also contains the vessels position in longitude- and latitude direction for each of the measured time step, which is input for STAWAVE-1 method for calculation of resistance due to waves. In addition does this file contains real-life operational power consumption of the vessel, that is used for comparison for the simulated estimated power consumption that includes the empirical methods.

4.2.2 Weather Data

Data from Copernicus Climate Data Store [6] was acquired in order to collect reliable weather data. The data was stored in *nc*-files. The data base contains hourly weather data across the globe, from the year 1979 up until today.

Weather data was defined for four hours of the day, respectively 0, 6, 12 and 18 o'clock for each day in the sailing period. The direction from the *nc*-files are defined in longitude and latitude direction. Longitude direction extends from 0 to 360 degrees from west to east, and latitude from 90 degrees in north to minus 90 degrees in south. The MatLab code transfers the configuration of the weather data in longitude direction to minus 180 to 180 degrees, in order to match the route of the measured operational data for the vessel. The grid in the *nc*-file was saved as a three dimensional matrix, were longitude direction defines the x-axis, latitude direction the y-axis and the time steps for every sixth hours is saved as steps in the depth of the grid. The time steps was defined as hours after 1.th of January in 1979, but was however transferred in MatLab for compliance with the timesteps for measured operational vessel data.

Two parameters were collected for analysis of resistance using STAWAVE-1 - significant wave height of combined wind waves and swell and mean wave direction. Significant wave height is defined in meters for a given coordinate in longitude and latitude direction, at a given time. Mean wave direction is defined in true degrees, from 0 to 360 degrees. The wave direction is defined as zero when moving from north to south, 90 degrees when the waves are moving from east to west, 180 degrees moving from south to north and 270 degrees when the waves are headed from west to east.

Large *nc*-files requires a big amount of computing power to process. The *nc*-files were therefore divided into quarters of three months at the time. This was done for a period of July 2014 to April 2017, resulting in eleven input files for the weather. The files was compiled into one matrix in the MatLab script named *bigfile.m*.

4.2.3 Vessel- and Propulsion Characteristics

The input parameters that describes the hull and propulsion system is defined in the scripts *VesselDim.m* and *PropDim.m*. The vessel info used in this thesis is provided by SINTEF. The following parameters is specific for particular vessel, and should be changed according to model test data.

Hull description

- $Vsvec$ - The ship's velocity in knots
- L - The ship's length between perpendiculars in meters
- L_WL - The ship's length in waterline in meters
- L_BWL - The distance from the bow to 95% of maximum breadth on the waterline in meters
- B - The ship's breadth in meters
- S - The ship's wetted surface area in square meters
- T - The ship's draught in meters
- TA - The ship's draught at after perpendicular in meters

- TF - The ship's draught at front perpendiculars in meters
- Cp - The ship's prismatic coefficient (dimensionless)
- CB - The ship's block coefficient (dimensionless)
- k - Form factor of ship
- $NRud$ - Number of rudders
- $NBrac$ - Number of brackets
- $NThr$ - Number of bossings
- $NBoss$ - Number of side thrusters
- $installedPower$ - Installed engine power for the general cargo vessel

Propulsion System

- D - Propeller diameter in meters
- P - Pitch of propeller in meters
- PD - Pitch to diameter ratio
- $AEAO$ - Blade area ratio
- Z - Number of blades
- n - Propeller speed measured in revolutions per second, $[rps]$

In addition will the following constants used as input for the code. These values are constant for all ships, and will be defined in the scripts.

- $gravk = 9.81$ - Gravitational constant $[m/s^2]$
- $\rho = 1025$ - Density of water $[kg/m^3]$
- $\mu = 1.1395 \cdot 10^{-6}$ - Viscosity of water $[m/s^2]$

4.3 Resistance Calculation

The following section provides a description of how the methods of calculating resistance will be implemented in MatLab.

4.3.1 Hollenbach

The added resistance in calm water is calculated in *Hollenbach.m* script. The code that runs the original Hollenbach is provided in part by [28]. The input is vessel velocity and dimensions of the hull and propeller diameter. The resistance is calculated as described in section 3.2.1.

4.3.2 Stawave-1

For taken resistance due to waves in advance, STAWAVE-1 was described in section 3.2.2. The method utilize the angle of attack ϕ, that are defined as the difference between the wave direction and the direction of the vessel, shown in figure 4.1.

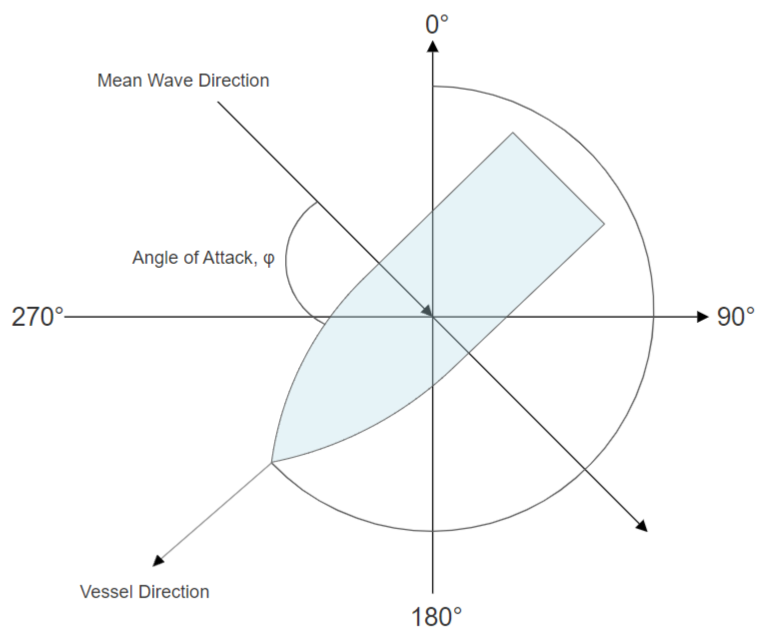

Figure 4.1: Definition of Angle of Attack ϕ

If the angle of attack is within an interval of ± 45 degrees of the bow, the STAWAVE-1 method is valid for computation of added resistance due to waves. For waves outside this interval will the waves be omitted and the resistance set equal to zero. For waves that's within this interval, the calculation of added resistance is straight forward using equation 3.22, from section 3.2.2.

$$R_{AWL} = \frac{1}{16}\rho_s g H_{1/3}^2 \sqrt{\frac{B}{L_{BWL}}}$$

The measured operational GPS-data of the vessel was modified for faster tracking of significant wave heights and directions in the weather data, and the Excel file that was read, only contained values where the vessel was in the state *Sea Passage*. The location in the GPS-data is defined as longitude coordinates ranging from minus 180 to 180 degrees, and latitude coordinates from 90 to minus 90 degrees. To calculate the direction of the vessel, an orientation of where the vessel was located according to its coordinates needed to be done. In the code does the variables *direction_x* and *direction_y* define whether the vessel is moving north or south, and east or west. Positive x-direction values indicates the vessel is moving towards east and positive y-direction values indicates moving up north, and negative values for west and south. The angle of the direction was transformed to azimuth angles, named *azimuth_angle* in the script, for straight-forward calculation the angle of attack ψ. The definition of azimuth angle θ is defined in figure 4.2

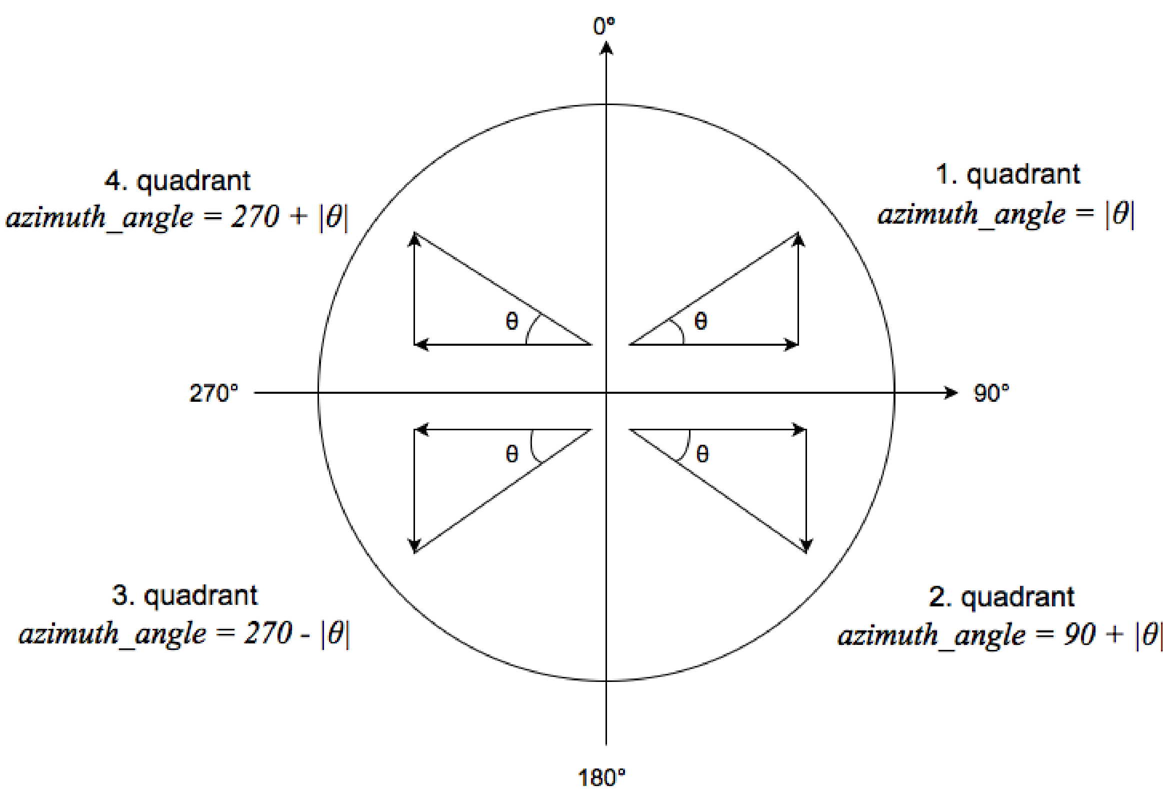

Figure 4.2: Definition of the azimuth angle, θ

If the absolute value of the difference between the mean wave direction and the value for the direction of the vessel is less than 45 degrees, an additional resistance due waves, labeled R_{AWL} will be added.

The *stawave.m* script calculates first whether added resistance due to waves according to STAWAVE-1 method should be added or not. The calculation is dependent on the vessel perpendiculars breadth B and length from the bow to 95% of maximum breadth, L_{BWL}. Variables that are used in this script are generated in *datamodification.m*, where longitude and latitude position for the vessel at respective GPS times are read from the modified measured data. The script also filters out only data at the hours of 0, 6, 12 and 18 o'clock of the day, so it can be compared to the weather data.

For transformation of the resistance calculated in the modified data, the script *newtimearray.m* generate an array with length equivalent to measured operational GPS-data of the vessel, but only with values at the points that are calculated with the STAWAVE-1 method. This is done so the added resistance due to waves can be implemented in *make_power_histogram.m*.

4.4 Propeller Power Prediction

This section will first describe the process of iterating a value for propeller speed n. Further on will the methods and assumptions for the components that compose the overall efficiency be presented.

4.4.1 Iteration of Propeller Speed n

The script *find_propeller_speed.m* uses an iteration method for finding the propeller speed n, since this parameter is unknown. The parameter occurs in the formula for estimated thrust, shown in equation 4.1.

$$T_{est} = K_T \rho n^2 D^4 \tag{4.1}$$

The estimated thrust is a function of the dimensionless thrust coefficient K_T that are further expressed as polynomials using Wageningen-B methodical propeller series, as described in section 3.3.1, and shown in equation 3.28. The estimated thrust is calculated in the MatLab script *thrust.m*.

Thrust can also be expressed as a function of resistance R and thrust deduction factor t, expressed in formula 4.2.

$$T = \frac{R}{1-t} \tag{4.2}$$

With these two equation determined, the MatLab script *find_propeller_speed.m*, will use iteration to find a value for propeller speed n. The value is obtained by using the MatLab function *fzero* for equation 4.2 and 4.1 with initial value 2. The value for n is implemented in the script *eta0.m* to determine the open water efficiency η_0.

4.4.2 Propeller efficiency

Open Water efficiency

Calculation of the open water efficiency η_0 will be done using the methodical propeller series Wageningen-B in the script *eta0.m*. The script uses global values from *init.m* where the coefficients for the polynomials of K_T and K_Q is stored. Other input here is propeller dimensions, the water density ρ and prismatic coefficient C_P for calculating wake.

Hull efficiency

The input for calculating the hull efficiency is the wake fraction coefficient w and thrust deduction factor t. These are dependent on the hull dimension prismatic coefficient C_P, and are calculated using the empirical method described in section 3.1.1. [25]

Relative Rotate efficiency

An assumption of $\eta_R = 0.98$ was implemented for calculation for the overall efficiency.

Mechanical efficiency

An assumption of $\eta_M = 0.97$ was implemented for calculation for the overall efficiency.

4.5 Prediction of Power Consumption

The script *make_power_histogram.m* will calculate the overall estimated power consumption of the vessel. It should be noted that for velocities that are below 0.1 knots, will the resistance R, the effective power P_E and the brake power P_B sat equal to zero. This is an assumption of that these values are mostly noise or error in measurements. The script reads in input from the earlier mentioned methods, which is listed below.

- Calm water resistance from *Hollenbach.m*
- An iterative value of propeller speed n from *find_propeller_speed.m*
- Resistance due to waves from *stawave.m*
- Open water efficiency from *eta0.m*

In addition does the script defines quantitative values for hull -, relative rotate - and mechanical efficiency for calculation of overall efficiency. The brake power is then calculated as described in the beginning of section 3, shown in equations 3.1 and 3.2.

In the script is the values for output are denoted as following:

- Pe - Effective power output, measured in Watt
- Pb - Brake power output, measured in Watt
- R - Prediction of calm water resistance, using Hollenbach method
- R_AWL - Prediction of resistance due to waves, using STAWAVE-1 method.

Chapter 5

Results and Discussion

5.1 Modelling Output

The constant output values from running the code are given in table 5.1. The parameters that were calculated, was the components of the overall efficiency, namely open water efficiency η_0, the hull efficiency η_H, the relative rotate efficiency η_R and the mechanical efficiency η_M. The last two were as described in section 4.4, given a possible value based on assumptions. The propeller speed n that were iterated in the simulation is also given in the table.

Table 5.1: Output values for estimated power consumption

n	η_0	η_H	η_R	η_M	η
1.0780 [rps]	0.5396 [-]	1.1601 [-]	0.9800 [-]	0.9700 [-]	0.5951 [-]

The results of the parameters effective power P_E, brake power P_B, resistance in calm water R, resistance due to waves R_{AWL}, and the total resistance R_{tot} is all presented as functions of time in the plots below.

Figure 5.1 and 5.2 shows respectively the effective power output P_E and the brake power output P_B, and 5.3 shows the analogy between these two. As shown in the plot, is the brake power output approximately the half as the effective power output. This correspond to the overall efficiency calculated in the simulation.

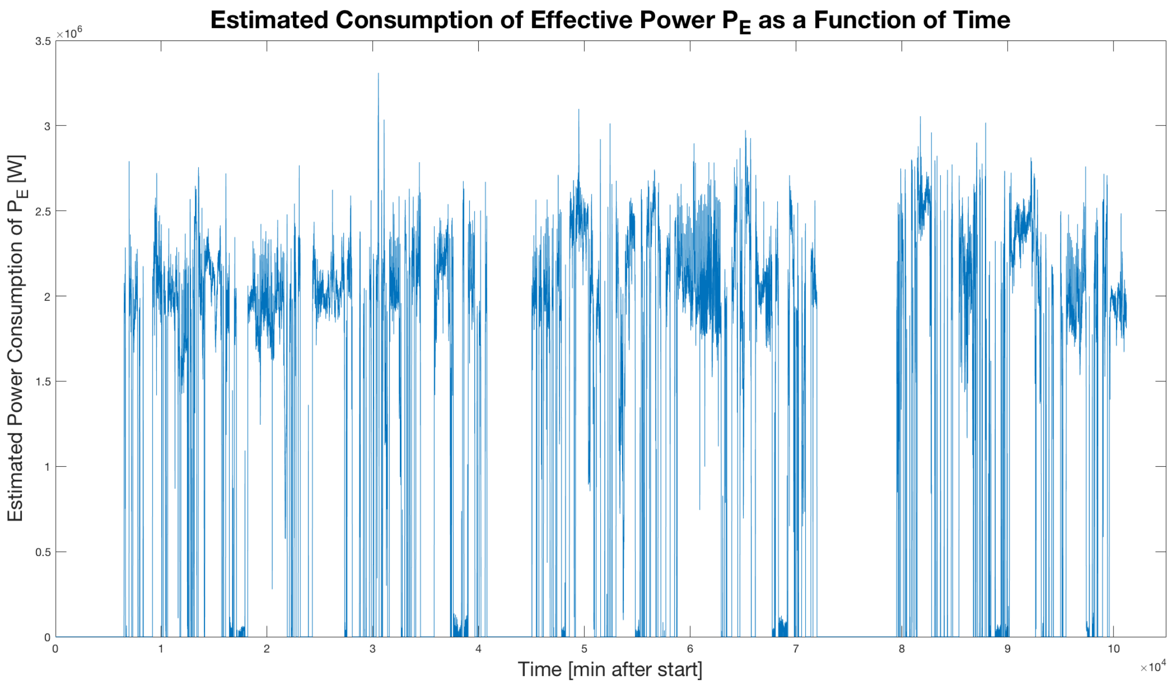

Figure 5.1: Estimated effective power P_E as a function of time.

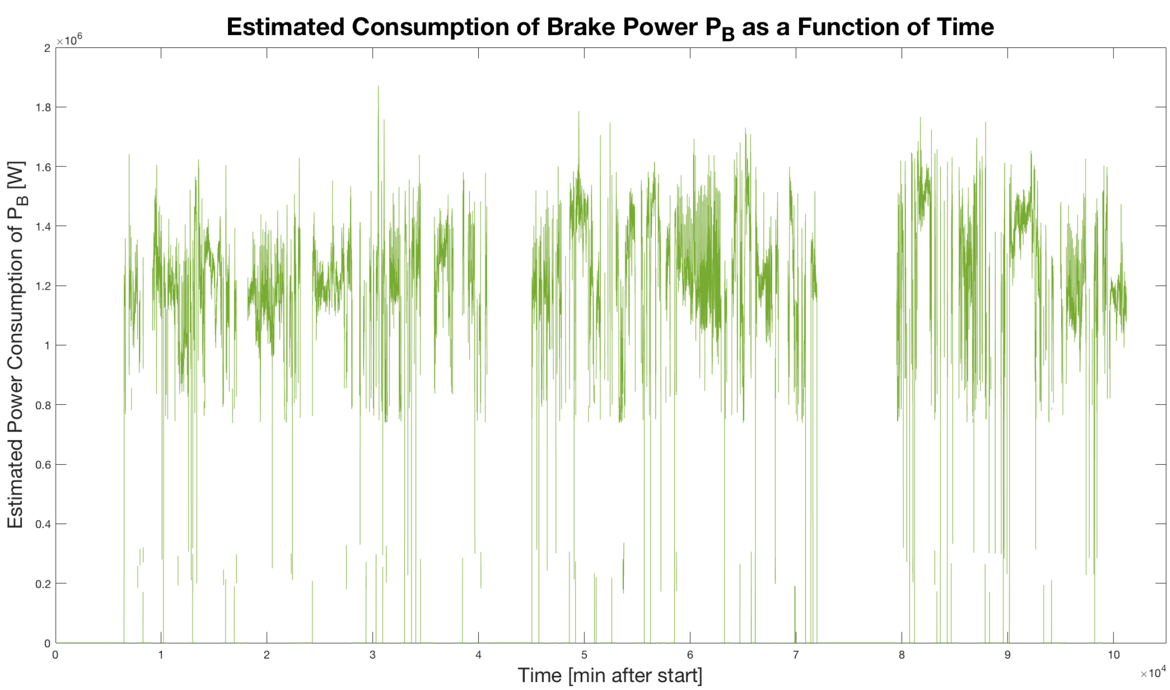

Figure 5.2: Estimated brake power P_B as a function of time.

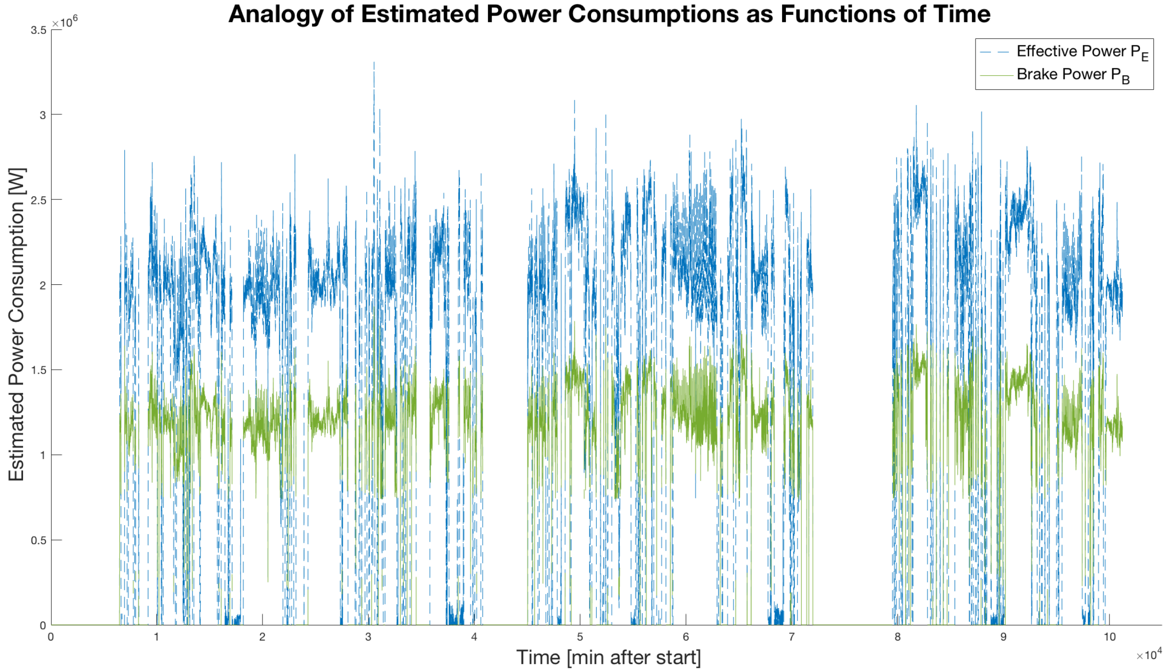

Figure 5.3: Analogy between estimated effective power P_E and brake power P_B as functions of time.

The results of the added resistance in calm water is shown in figure 5.4 and due to waves in figure 5.5. The total resistance is in figure 5.6. The added resistance will cause an increase in the overall power output of the vessel. By comparing the results for the resistance with the power consumption, the peaks for the consumption and resistance will therefore coincide at the same time.

Observing figure 5.4 and 5.5, it is shown that the resistance due to waves is considerable lower than the resistance in calm water. Resistance due to waves will therefore contribute minimal to the total resistance, and have a significant smaller impact on the output power consumption.

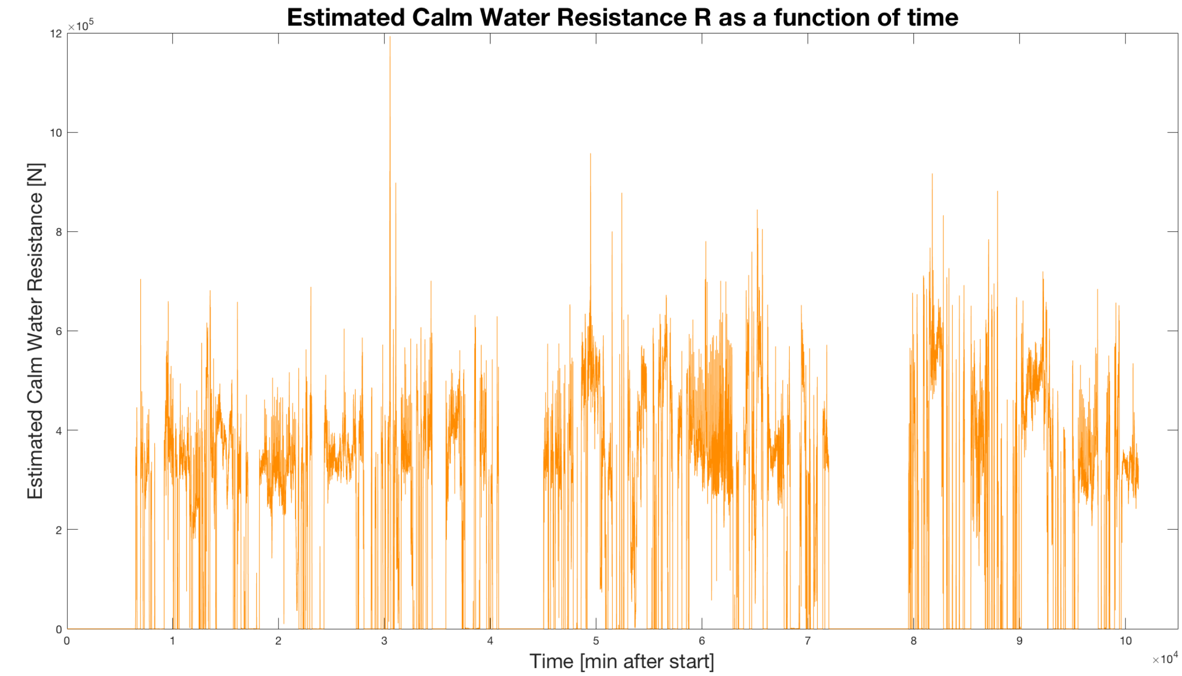

Figure 5.4: Calculated calm water resistance as a function of time.

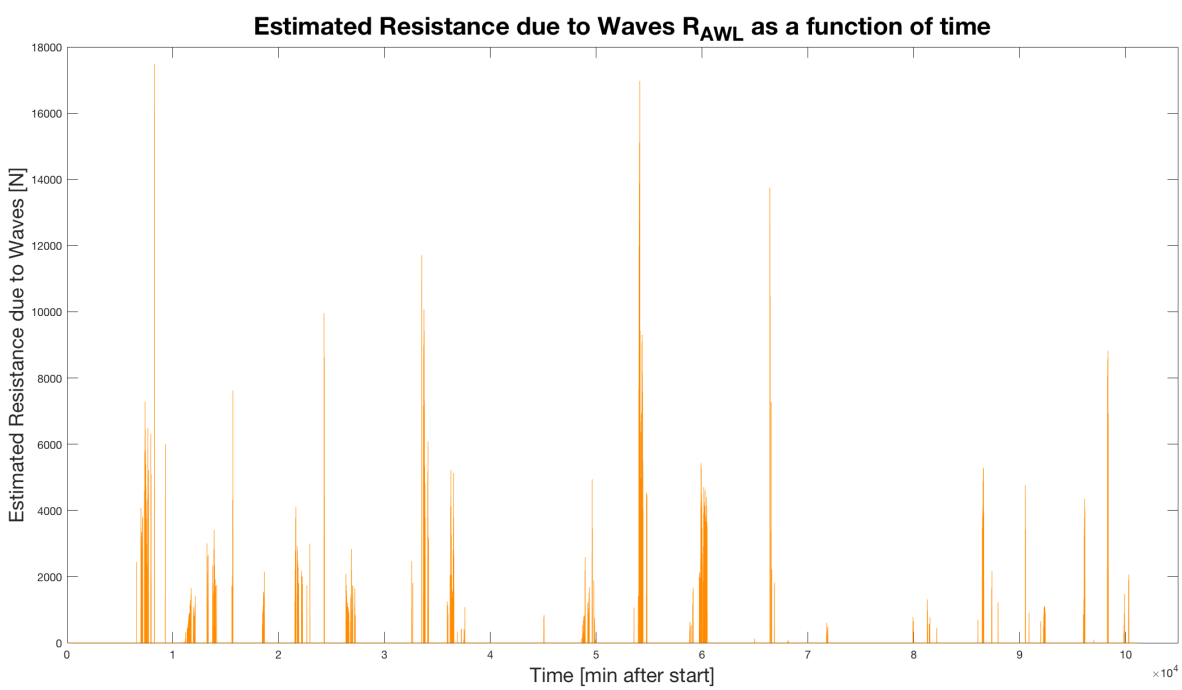

Figure 5.5: Calculated resistance due to waves as a function of time.

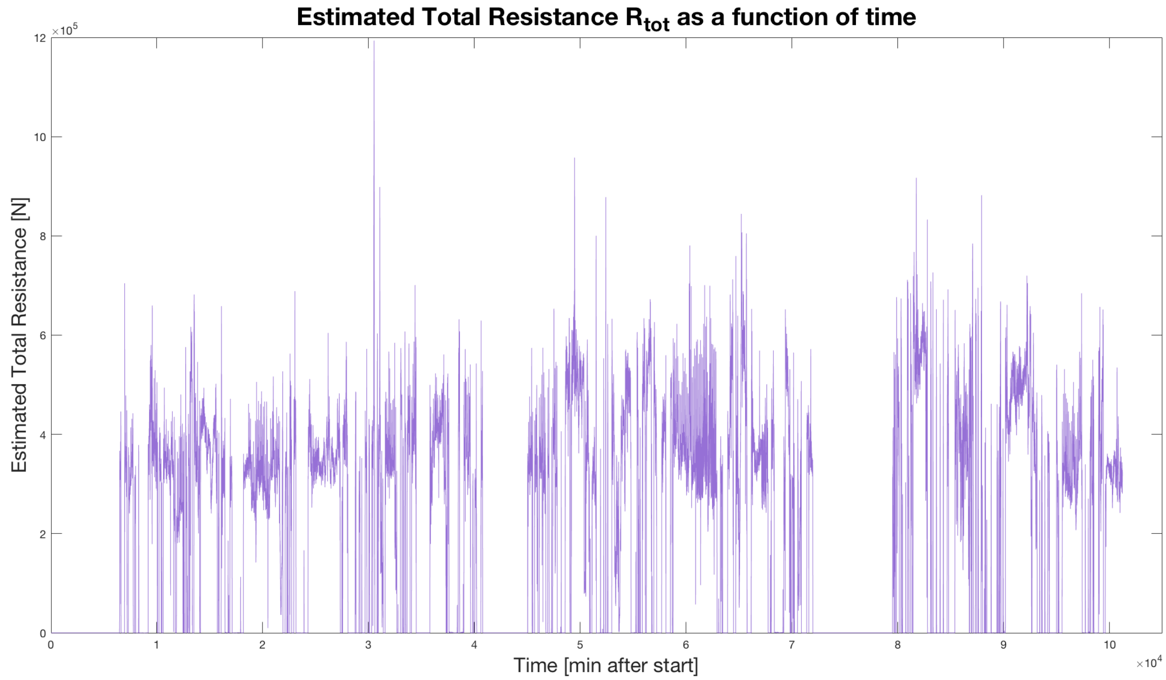

Figure 5.6: Calculated total resistance as a function of time.

5.2 Results of Power Consumption and Efficiency

For evaluation of the methodology of the simulation based approach, the shape of estimated power consumption will be compared to the shape of the measured operational data. The estimated power consumption is plotted as percentage time spent at different consumption levels, and is displayed in absolute values. Looking into the histogram for estimated power, it is shown that most of the consumption is to be found at zero, where the vessel is operating almost 47% of the time. When excluding zero consumption, most of the consumption is in the interval between 1100 kW and 1600 kW, peaking at approximately 1200 kW. This is shown in figure 5.7 and is scaled in figure 5.8, excluding the zero consumption. The measured operational data is displayed as normalized values, i.e. the power consumption in percentage of installed power of the propulsion system. This is shown in figure 5.9 and scaled in figure 5.10, excluding the zero consumption. Since these figures are displayed in different measurements, an evaluation of similarities and differences between the shapes will be discussed. The scaled histogram in figure 5.8 and figure 5.10 is included in the results for a better comparability of the shapes of the two histograms.

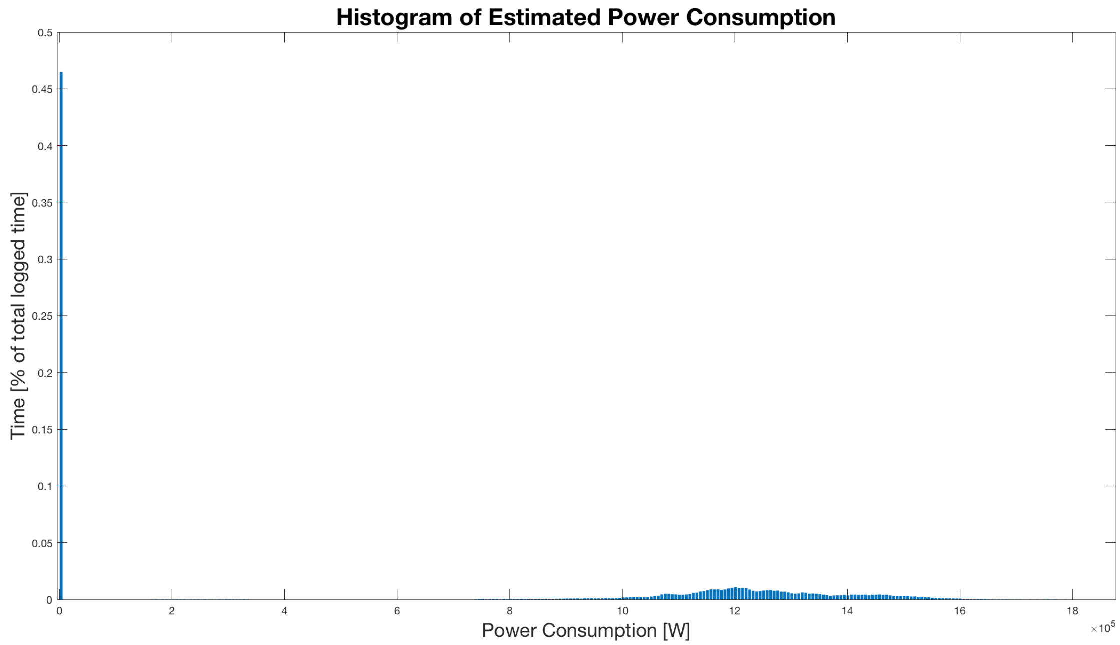

Figure 5.7: Estimated power consumption in [W], shown as percentage time spent for each consumption, including zero consumption.

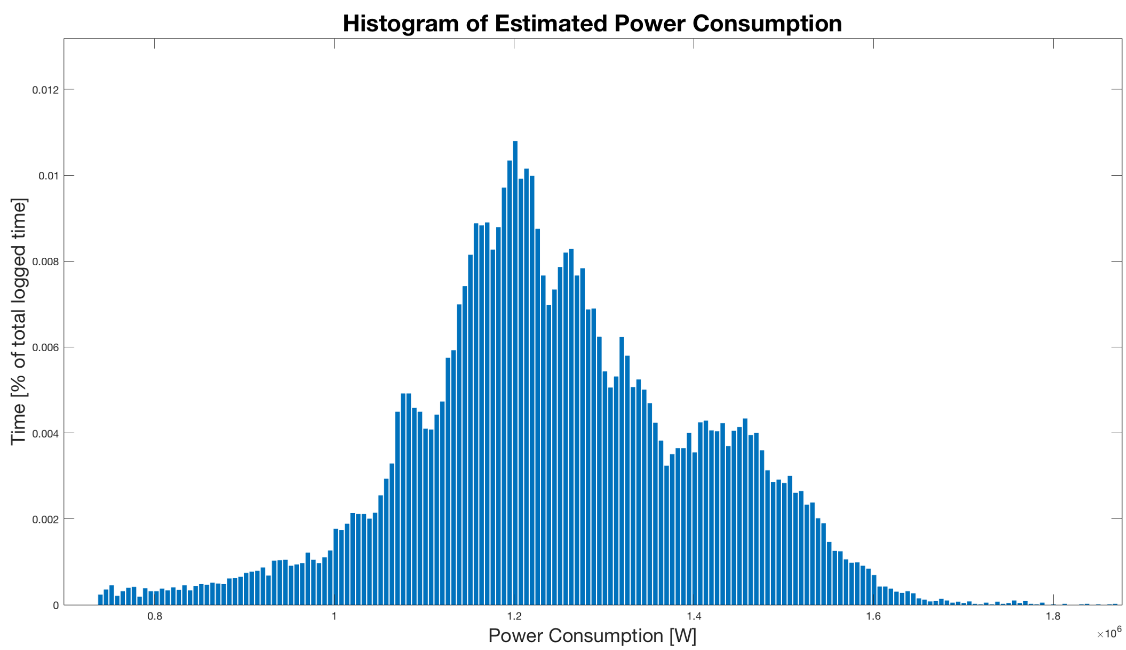

Figure 5.8: Scaled estimated power consumption in [W], shown as percentage time spent for each consumption, excluding zero consumption. Zero consumption contributes to 47% of total.

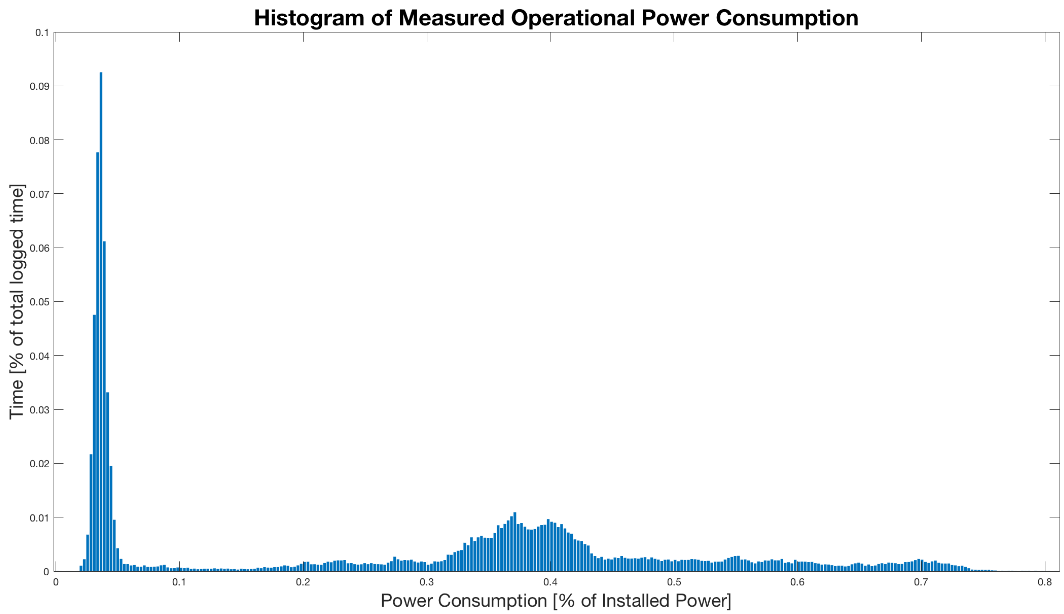

Figure 5.9: Measured operational power consumption shown as percentage of installed power. The consumption is displayed as percentage time spent for each consumption, including zero consumption.

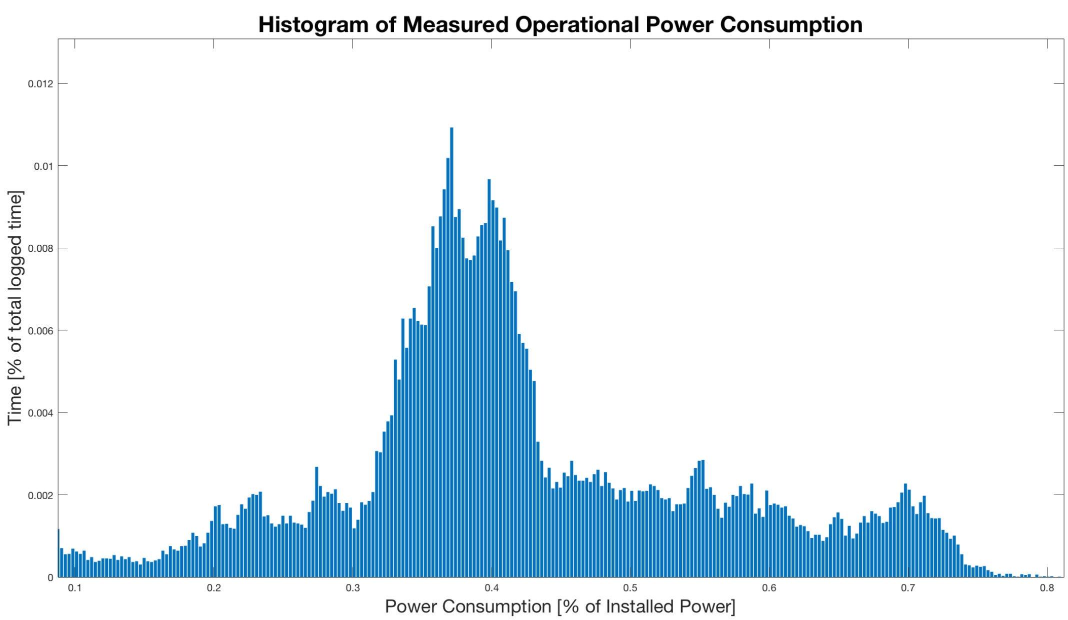

Figure 5.10: Scaled measured operational power consumption shown as percentage of installed power. The consumption is displayed as percentage time spent for each consumption, excluding zero consumption.

Shown in the figures above, the shape of estimated power consumption is similar in several ways with the shape of the measured data from real life operation. Both of the plots contains a noticeable peak, where the vessel is operating more frequent. From this peak follows a slope to each of the sides. In both of the plots can it be shown that there are a bigger amount of a higher consumption i. e. to the right of the peak than to the left.

Differences that can be pointed out for the plots, is that the plot of measured operational data does have a second peak that almost reach the size as the highest, which does not appear in the plot for estimated power consumption. It's also to be noted that there exist more consumption levels in the plot for measured data with considerable frequency. This does not appear in the same degree for the estimated consumption, where the slope is moving faster to zero power consumption at both sides of the peak. The overall zero consumption appears significantly higher in the histogram of the estimated power consumption than for the measured operational data, and the bars are more concentrated around the highest peak. In the histogram of measured data is the consumption more partitioned out.

The histogram for estimated consumption has as mentioned, a consumption at zero that is significant more frequent than for the measured data, but should be noted that the values at the other low consumption is neglectable. The reason that the consumption at zero is so frequent for the measured data, can be explained with the assumption of calculating the brake power P_B to zero when the velocity is below 0.1 knots. This assumption excludes all the states the vessel is operating at low loading, e.g. when maneuvering to port or the engine running at idle. Compared to frequency at lower consumption for the measured operational data, the zero consumption is significant less frequent. However, the consumption is more frequent at the other low power consumption that stands out from the estimated consumption. This can also be explained with the same assumption of setting the power output equal to zero at velocities below 0.1 knots. The consumption at states the engine are running at low load, at low speed or the engine speed running at idle will therefore be included in measured data, but have possibly been sat equal to zero using the simulation based approach.

5.3 Limitations of the Modelling

This section presents the limitations that have been observed with the methodology given in this thesis. The limitations is divided into three parts - one part describing the limitation with the GPS-data, another part with the method used for predication of overall power consumption and in the end, the disadvantages with the empirical methods for the prediction.

5.3.1 GPS-data

The methodology is based on the measured operational data from only one vessel, more specific a general cargo vessel. The hull description and propulsion system is based on one set of input, and the consumption measured from one GPS-data at the vessel.
The weaknesses using this simulation based methodology for only one set of GPS-data for one vessel, is pointed out in the list below:

1. First of all, it can not be specified what input parameters that will have a significant variance depending on the size of the parameter, according to the simulation based approach described. The approach is therefore indefinite whether or not it can be functional for other types of ships, or other vessels with other dimensions at all. It is a possibility this methodology suit better for some ranges of input parameters than others. This can be covered by looking a several measured operational data, with a great range of values for input parameters. By comparing these results, it can be determined whether the simulation based approach is a better fit for an interval of parameters than others, or is a better model for some types of vessels than others.

2. Using only one set of GPS-data, it can not be pointed out the precision with the GPS measurement that have been utilized. Error sources, e.g. noise at the engine that have been measured as power consumption etc. can not be captured using only one set of GPS-data. It is recommended for further research to have more than one set, to cover the errors from the GPS.

5.3.2 Choice of methodology

The drawbacks with the methodology that have been utilized, will be presented in the list below.

1. Weather data have only been used at the hours 0, 6, 12 and 18 o'clock, in order to limit the data size. Because of this, only one sixth of the day been compared to historical weather data for further calculations. This can possibly have resulted in a lower resistance estimate due to waves, compared to the real life operation. Improvement of the method would be to capture weather data for several hours of the day.

2. For taken resistance into account, Hollenbach was used for resistance in calm water and STAWAVE-1 for resistance due to waves. As mentioned in section 3.2 about resistance, does the resistance consist of several components that contributes to the overall performance of the vessel, e.g. resistance due to wind, friction, hull roughness and air resistance. This components will contribute to the overall resistance, and result in a overall higher power consumption. Including more of these components will results in a more accurate prediction. Resistance is divided into dimensionless coefficients uses empirical methods based on Froude scaling, and can easily be implemented into simulation based approach.

5.3.3 Choice of Empirical Methods

There is some drawbacks with the choice of empirical methodologies that have been chosen for the simulation based approach, that will bring on errors in the results. This is mentioned below.

Hollenbach

Hollenbachs method is originally limited to merchant vessels, and it's hard to tell which type of hull lines that apply for other types of vessels. Using Hollenbachs method for predicating resistance in calm water uses a simplified description of the hull dimensions, that does not cover all the details of the hull. Another disadvantage with this method, is that Hollenbach does not take propulsion system into account when calculating the resistance.

STAWAVE-1

STAWAVE-1 has a restriction of only being applied to waves with significant wave heights $H_{1/3} = 2.25\sqrt{L_{PP}/100}$. This was not taken into account using this simulation based approach, which uses STAWAVE-1 for all significant wave heights. Wave heights above this limit should be calculated using STAWAVE-2. STAWAVE-2 approximate the transfer function of the mean resistance increase in regular waves, which makes this method limited to waves within an angle of 45 degrees as well. Formula 5.1 shows the main equation for this method. [16]

$$R_{AWL} = 2\int_0^\infty \frac{R_{wave}(\omega, V_S)}{\zeta_A^2} S_\eta(\omega) d\omega \tag{5.1}$$

where:

R_{AWL} - mean increase of resistance in short crested irregular waves, measured in Newton.
ζ_A - the wave amplitude in meters
ω - is the circular frequency of regular waves measured in rad/s
S_η - is the frequency spectrum in square meter seconds

Here, R_{wave} is noted as the empirical transfer function. This parameter includes the mean resistance increase due wave reflection, noted as R_{AWRL} and the motion included resistance R_{AWML}, shown in figure 5.2

$$R_{wave} = R_{AWML} + R_{AWRL} \tag{5.2}$$

The frequency spectrum is found by assuming a Pierson-Moskowitz type, which is an empirical relationship that defines the distribution of energy with frequency within the ocean. The calculation is shown in equation 5.3

$$S_\eta = \frac{A_{fw}}{\omega^5} exp\left(-\frac{B_{fw}}{\omega^4}\right) \tag{5.3}$$

where

$$A_{fw} = 173\frac{H_{1/3}^2}{T_{01}^4}$$

and

$$B_{fw} = \frac{691}{T_{01}^4}$$

Here is ω the circular frequency of regular waves in rad/s, $H_{1/3}$ the significant wave height in meters, and T_{01} is the mean wave period in seconds.

It should be noted that the STAWAVE-2 method has a restricted interval of vessel dimensions for modelling, which makes it not applicable for all types of vessels. The restrictions are as follows:

- 75 m < L_{PP}
- 4.0 < $\frac{L_{PP}}{B}$ < 9.0
- 2.2 $\frac{B}{T_M}$ < 9.0
- 0.10 < Fr < 0.30
- 0.50 < C_B < 0.90

An improvement of the simulation could be to implement STAWAVE-2 for other significant wave heights, whereas STAWAVE-1 is restricted from. It should be recalled that STAWAVE-2 has a limited application for modelling on type of vessels because if its restrictions mentioned above.

In addition does STAWAVE-1 and STAWAVE-2 neglect waves that is outside a interval of 45 degrees from ahead of the bow, as head waves having the largest impact on the resistance. This excludes the impact waves incoming at other angles has on the resistance, that will increase the overall resistance. This causes an error in the estimating a lower resistance due to waves than for real life operation.

Wageningen-B Screw Series

Implementing Wageningen-B screw series in the simulation based approach, has the disadvantage that it's only limited to the propeller series tested. The field of validity of Wageningen-B screw series is given in table 5.2.

Table 5.2: Field of validity for Wageningen-B screw series

Z	A_E/A_O	P/D
2-7	0.3-1.05	0.6-1.4

However, this is the most extensive and widely used propeller series, and the series numbers a range of 20 different area-blade configurations. The series covers most of general propellers and will therefore not necessary provide a considerable error in the calculation when using this assumption.

Chapter 6

Conclusion and Further Work

6.1 Conclusion

The methodology uses a simulation based approach to estimate the power consumption of a general cargo vessel. The approach involves the empirical methods i.e. Hollenbach for estimating the resistance in calm water and Wageningen-B screw series for open water efficiency. In addition is these methods utilized to find an iterative value for the propeller speed, using the estimated thrust from the equation of thrust coefficient in Wageningen-B, and the thrust as a function of calm water resistance and the thrust deduction factor. Weather data was implemented for estimating the resistance due to waves, using STAWAVE-1.

The results from the simulation was compared to measured operational power consumption of the general cargo vessel. The purpose with the modelling was to evaluate whether a simulation based approach provides approximately the same results as the real life operational. The intention with the modelling is to find a substitution for the traditional methods used in ship design, which is usually based on historical data and iterative methodology. The simulation based approach allows the user to implement changes in vessel design and investigate the vessel performance in an early stage of the design process.

The results shows that there are several similarities between the estimated- and measured power consumption. The general shape and the peaks in the histograms are roughly at the same location in both of the graphs, and both of the histograms shows slopes to each of the sides from the peak. The consumption is greater on the right side in both of the histograms, revealing a higher amount of consumption appears more frequently. The results are also presenting how resistance affects the overall power consumption. For the two resistance components that were included in this methodology, did resistance in calm water have a significant higher impact on the total resistance, and the resistance due to waves were negligible in comparison.

This work has shown there is great potential of using simulation that includes empirical methods for predication of resistance and propulsion efficiency. The simulation based methodology allows the user to implement new information in the preliminary design stage, and to investigate the vessel performance without an iterative "try-and-error" approach. However, the differences in the shapes between the histograms of estimated and measured power consumption is noteworthy. This shows that there is still a need for a deeper understanding of what assumption and empirical methods will be the best fit for the simulation methodology. As mentioned in the discussion in chapter 5, is much of the estimated consumption especially at the lower loading's being neglecting. This is because the methodology uses simplified assumptions and a simplistic hull description that will cause error in the estimated results compared to measured consumption in real-life operation. Involving more resistance components and improve the resistance due to waves is suggestions that will reduce these errors. It should also be noted that using the methodology for only one vessel does limit the certainty of the range of validation for the method, as it is undetermined whether the approach will function for all vessel types. It is therefore recommended to expand the methodology involving other dimensions for further research. With some improvements of the methodology for more accurate prediction, will the methodology be a useful tool for investigating the predictive performance of innovative configurations whereas historical data doesn't exist.

6.2 Further Work

The errors can be reduced by adding more aspects and less simplifications in the method. One of the advantages of using simulation, is that it's easy to implement methodology that will improve the overall result, which was introduced in this thesis. Suggestion for further work that can be implemented in the method for improvement is listed below.

1. **Extension of range valid types of vessels**

   The simulation could be applied for other vessel types than a general cargo vessel. It should also simulate including the extreme alternatives from smaller fishing vessels to the biggest supertankers. This is to cover the field of validity of the different input parameters that will be the best fit for this approach.

2. **Resistance due to waves**

   This methodology uses only STAWAVE-1 for adding resistance due to waves. This is originally only limited to significant wave heights of $H_{1/3} = 2.25\sqrt{L_{PP}/100}$ whereas is not taken into account here. For more significant wave heights should another methodology be utilized, e. g. STAWAVE-2 as discussed in chapter 5. Wave heights has a great impact on the overall resistance, and should be implemented for reducing error and improving this methodology. However, it should be noted that for the STAWAVE-2 method follows a set of restrictions to the hull dimensions, mentioned in section 5.3.3. Waves that comes from other angles than towards the bow within 45 degrees should also be taken into consideration for improving the methodology.

3. **Include more resistance components**

   In this method is only two resistance components taken into account - resistance in calm water and resistance due to waves. Resistance is complex and is a contribution of several components. Including empirical methods for other components will increase the overall resistance, and make it more accurate to the measured data from the real-life operation. Several of these methods are empirical from earlier model tests, and can easily be implemented in the methodology described in this thesis.

4. **Weather data**

   A proposal of using weather data for more frequent hours of the day than only every sixth hours could be considered. This will give a more accurate picture of the real-life operation and reduce the error of resistance due to waves. Weather data can also be used for estimating other resistance components, e.g. resistance due to wind.

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Appendix A

Coefficients of Hollenbach Resistance Regression

The coefficients that are implemented in Hollenbach resistance method for calm water are given in table A.1.

Appendix A.1: Hollenbach: Resistance regression coefficients [20]

Hollenbach: Resistance regression coefficients

	Mean			Minimum	
	Single-screw			Single-screw	
	Design draught	Ballast draught	Twin-screw	Design draught	Twin-screw
$a1$	−0.3382	−0.7139	−0.2748	−0.3382	−0.2748
$a2$	0.8086	0.2558	0.5747	0.8086	0.5747
$a3$	−6.0258	1.1606	−6.7610	−6.0258	−6.7610
$a4$	−3.5632	0.4534	−4.3834	−3.5632	−4.3834
$a5$	9.4405	11.222	8.8158	0	0
$a6$	0.0146	0.4524	−0.1418	0	0
$a7$	0	0	−0.1258	0	0
$a8$	0	0	0.0481	0	0
$a9$	0	0	0.1699	0	0
$a10$	0	0	0.0728	0	0
b_{11}	−0.57424	−1.50162	−5.34750	−0.91424	3.27279
b_{12}	13.3893	12.9678	55.6532	13.38930	−44.1138
b_{13}	90.5960	−36.7985	−114.905	90.59600	171.692
b_{21}	4.6614	5.55536	19.2714	4.6614	−11.5012
b_{22}	−39.721	−45.8815	−192.388	−39.7210	166.559
b_{23}	−351.483	121.820	388.333	−351.483	−644.456
b_{31}	−1.14215	−4.33571	−14.35710	−1.14215	12.4626
b_{32}	−12.3296	36.0782	142.73800	−12.3296	−179.505
b_{33}	459.254	−85.3741	−254.76200	459.25400	680.921
c_1	$Fr/Fr{\cdot}krit$	$10C_B(Fr/Fr{\cdot}krit-1)$	$Fr/Fr{\cdot}krit$	–	–
d_1	0.854	0.032	0.8970	–	–
d_2	−1.228	0.803	−1.4570	–	–
d_3	0.497	−0.739	0.7670	–	–
e_1	2.1701	1.9994	1.8319	–	–
e_2	−0.1602	−0.1446	−0.1237	–	–
f_1	0.17	0.15	0.16	0.17	0.14
f_2	0.20	0.10	0.24	0.20	0
f_3	0.60	0.50	0.60	0.60	0
g_1	0.642	0.42	0.50	0.614	0.952
g_2	−0.635	−0.20	0.66	−0.717	−1.406
g_3	0.150	0	0.50	0.261	0.643
h_1	1.204	1.194	1.206	–	–
Ship length $L(m)$	42.0–205.0	50.2–224.8	30.6–206.8	42.0–205.0	30.6–206.8
$L/\nabla^{1/3}$	4.49–6.01	5.45–7.05	4.41–7.27	4.49–6.01	4.41–7.27
C_B	0.60–0.83	0.56–0.79	0.51–0.78	0.60–0.83	0.51–0.78
L/B	4.71–7.11	4.95–6.62	3.96–7.13	4.71–7.11	3.96–7.13
B/T	1.99–4.00	2.97–6.12	2.31–6.11	1.99–4.00	2.31–6.11
L_{OS}/L_{WL}	1.00–1.05	1.00–1.05	1.00–1.05	1.00–1.05	1.00–1.05
L_{WL}/L	1.00–1.06	0.95–1.00	1.0–1.07	1.00–1.06	1.00–1.07
D_P/T	0.43–0.84	0.66–1.05	0.50–0.86	0.43–0.84	0.50–0.86

Appendix B

Coefficients of K_T and K_Q

The coefficients that have been implemented to determine the open water efficiency η_0 is given in table B.1

Table B.1: Coefficients for K_Q and K_T of the Wageningen B screw series, valid for $R_e = 2 \cdot 10^6$, [21]

Thrust K_T						Torque K_Q					
n	$C_{s,t,u,v}$	$s(J)$	$t(P/D)$	$u(A_E/A_0)$	$v(Z)$	n	$C_{s,t,u,v}$	$s(J)$	$t(P/D)$	$u(A_E/A_0)$	$v(Z)$
1	0.00880496	0	0	0	0	1	0.00379368	0	0	0	0
2	-0.204554	1	0	0	0	2	0.00886523	2	0	0	0
3	0.166351	0	1	0	0	3	-0.032241	1	1	0	0
4	0.158114	0	2	0	0	4	0.00344778	0	2	0	0
5	-0.147581	2	0	1	0	5	-0.0408811	0	1	1	0
6	-0.481497	1	1	1	0	6	-0.108009	1	1	1	0
7	0.415437	0	2	1	0	7	-0.0885381	2	1	1	0
8	0.0144043	0	0	0	1	8	0.188561	0	2	1	0
9	-0.0530054	2	0	0	1	9	-0.00370871	1	0	0	1
10	0.0143481	0	1	0	1	10	0.00513696	0	1	0	1
11	0.0606826	1	1	0	1	11	0.0209449	1	1	0	1
12	-0.0125894	0	0	1	1	12	0.00474319	2	1	0	1
13	0.0109689	1	0	1	1	13	-0.00723408	2	0	1	1
14	-0.133698	0	3	0	0	14	0.00438388	1	1	1	1
15	0.00638407	0	6	0	0	15	-0.0269403	0	2	1	1
16	-0.00132718	2	6	0	0	16	0.0558082	3	0	1	0
17	0.168496	3	0	1	0	17	0.0161886	0	3	1	0
18	-0.0507214	0	0	2	0	18	0.00318086	1	3	1	0
19	0.0854559	2	0	2	0	19	0.015896	0	0	2	0
20	-0.0504475	3	0	2	0	20	0.0471729	1	0	2	0
21	0.010465	1	6	2	0	21	0.0196283	3	0	2	0
22	-0.00648272	2	6	2	0	22	-0.0502782	0	1	2	0
23	-0.008417228	0	3	0	1	23	-0.030055	3	1	2	0
24	0.0168424	1	3	0	1	24	0.0417122	2	2	2	0
25	-0.00102296	3	3	0	1	25	-0.0397722	0	3	2	0
26	-0.0317791	0	3	1	1	26	-0.00350024	0	6	2	0
27	0.018604	1	0	2	1	27	-0.0106854	3	0	0	1
28	-0.00410798	0	2	2	1	28	0.00110903	3	3	0	1
29	-0.000606848	0	0	0	2	29	-0.000313912	0	6	0	1
30	-0.0049819	1	0	0	2	30	0.0035985	3	0	1	1
31	0.0025983	2	0	0	2	31	-0.00142121	0	6	1	1
32	-0.000560528	3	0	0	2	32	-0.00383637	1	0	2	1
33	-0.00163652	1	2	0	2	33	0.0126803	0	2	2	1
34	-0.000328787	1	6	0	2	34	-0.00318278	2	3	2	1
35	0.000116502	2	6	0	2	35	0.00334268	0	6	2	1
36	0.000690904	0	0	1	2	36	-0.00183491	1	1	0	2
37	0.00421749	0	3	1	2	37	0.000112451	3	2	0	2
38	0.0000565229	3	6	1	2	38	-0.0000297228	3	6	0	2
39	-0.00146564	0	3	2	2	39	0.000269551	1	0	1	2
						40	0.00083265	2	0	1	2
						41	0.00155334	0	2	1	2
						42	0.000302683	0	6	1	2
						43	-0.0001843	0	0	2	2
						44	-0.000425399	0	3	2	2
						45	0.0000869243	0	3	2	2
						46	-0.0004659	0	6	2	2
						47	0.0000554194	1	6	2	2

Appendix C

MatLab Code

C.1 Main Script For Estimating Power Consumption

C.1.1 make_power_histogram.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%             make_power_histogram.m
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Reading vessel data
init;

[numData, numText, alldata] = xlsread('OpDataCargoVessel.xlsx');
gpsSpeed = numData(:,16);
logSpeed = numData(:,17);

% Ship velocities in m/s
Vsvec = gpsSpeed*0.5144;
N = length(Vsvec);
Pe = zeros(N,1);
Pb = zeros(N,1);

%Total resistance
```

```
R_tot=R+R_AWL_array;

%Prismatic coefficient
Cp = Vdim(16);

%Thrust - and wake coefficient
w = 0.7 * Cp - 0.18;
t = 0.5 * Cp - 0.12;

%Efficiency
eta_H = (1-t)/(1-w);          % Hull Efficiency
eta_M = 0.97;                 % Mechanical Efficiency
eta_R = 0.98;                 % Relative Rotate Efficiency


%Installed power from vessel info
%For normalisation of measured operatinal data
installedPower = Vdim(18);            %[kW]

% Measured operational power consumption
enginePower = numData(:,9);           %[kW]
auxPower    = numData(:,8);           %[kW]
logPower = (enginePower + auxPower); %[kW]
normPb = logPower./installedPower;

% Calculate Power Consumption
for i = 1:N                   % Iterates through every row in logged data
    v = Vsvec(i);
    if v < 0.1                % Pe and Pb equals 0 when v less than 0.1 knots
        R = 0;
        Pe(i) = 0;
        Pb(i) = 0;

    else
        R = Hollenbach(v);            % Calm Water Resistance from Hollenbach
        T = R/(1-t);                          % Thrust
```

```
        n = find_propeller_speed(T, v);      % Propeller Speed
        eta_free = eta0(n,v);                % Open Water efficiency
        Pe(i)=(R_tot(i))*v;                  % Effective Power Consumption
        eta = eta_free*eta_H*eta_M*eta_R;    % Propeller efficiency
        Pb(i)=Pe(i)*eta;                     % Brake power consumption
    end
end

%   Plots

% Histogram: Measured Operational Consumption displayed as
% Normalised Power as % of Installed Power,
figure(1)
[Number3, EDGES3] = histcounts(normPb, 300, 'Normalization','Probability');
xt3 = EDGES3(1:end-1)+mean(diff(EDGES3))/2;
bar(xt3,Number3);
title('Histogram of Measured Operational Power Consumption');
xlabel('Power Consumption [% of Installed Power]');
ylabel('Time [% of total logged time]');

% Histogram: Estimated Power Consumption [W]
figure(2)
[Number2, EDGES2] = histcounts(Pb, 300, 'Normalization','Probability');
xt2 = EDGES2(1:end-1)+mean(diff(EDGES2))/2;
bar(xt2,Number2);
title('Histogram of Estimated Power Consumption');
xlabel('Power Consumption [W]');
ylabel('Time [% of total logged time]');

% Plot: effective power Pe as a function of time
figure(3)
plot(Pe,'Color', [0, 0.4470, 0.7410]);
title('Estimated Consumption of Effective Power P_{E} as a Function of Time');
xlabel('Time [min after start]');
ylabel('Estimated Power Consumption of P_{E} [W]');
axis([0 10.5*10^4 0 3.5*10^6])
```

```
% Plot: brake power Pb as a function of time
figure(4)
plot(Pb,'Color', [0.4660, 0.6740, 0.1880]);
title('Estimated Consumption of Brake Power P_{B} as a Function of Time');
xlabel('Time [min after start]');
ylabel('Estimated Power Consumption of P_{B} [W]');
axis([0 10.5*10^4 0 2*10^6])

% Plot: figure(3) and figure(4) for comparison
figure(5)
y=[1:length(Pb)];
hold on;
plot(y, Pe, 'Color', [0, 0.4470, 0.7410], 'Linestyle', '--')
plot(y, Pb, 'Color', [0.4660, 0.6740, 0.1880]);
title('Analogy of Estimated Power Consumptions as Functions of Time');
xlabel('Time [min after start]');
ylabel('Estimated Power Consumption [W]');
axis([0 10.5*10^4 0 3.5*10^6]);
legend('Effective Power P_{E}','Brake Power P_{B}')
hold off;

% Plot: Resistance due to Waves
figure(10)
plot(R_AWL_array, 'Color', [1.000000 0.550000 0.000000]);
title('Estimated Resistance due to Waves R_{AWL} as a function of time');
xlabel('Time [min after start]');
ylabel('Estimated Resistance due to Waves [N]');
axis([0 10.5*10^4 0 18000]);

%Plot: Calm Water Resistance
figure(11)
plot(R, 'Color', [1.000000 0.550000 0.000000]);
title('Estimated Calm Water Resistance R as a function of time');
xlabel('Time [min after start]');
ylabel('Estimated Calm Water Resistance [N]');
```

```
axis([0 10.5*10^4 0 12*10^5]);

%Plot: Total Resistance
figure(12)
plot(R_tot, 'Color',[0.590000 0.440000 0.840000])
title('Estimated Total Resistance R_{tot} as a function of time');
xlabel('Time [min after start]');
ylabel('Estimated Total Resistance [N]');
axis([0 10.5*10^4 0 12*10^5]);
```

C.2 Propulsion prediction

C.2.1 thrust.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%            thrust.m
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function T_est = thrust(n, Va, PropellerDim)

%Wagening reynolds number
Re_wag = 2*10^6;

%KT coeffisients
global KQ_Data KT_Data
CT_stuv = KT_Data(:,1).';
s_kt = KT_Data(:,2).';
t_kt = KT_Data(:,3).';
u_kt = KT_Data(:,4).';
v_kt = KT_Data(:,5).';

%KQ coeffisients
CQ_stuv = KQ_Data(:,1).';
s_kq = KQ_Data(:,2).';
t_kq = KQ_Data(:,3).';
```

```
u_kq = KQ_Data(:,4).';
v_kq = KQ_Data(:,5).';

%Propeller Characteristics from vessel info

D = PropellerDim(1);     %Propeller diameter [m]
P = PropellerDim(2);     %Pitch of propeller [mm]
PD = PropellerDim(3);    %Pitch to diameter ratio
AEAO = PropellerDim(4); %Blade area ratio
Z = PropellerDim(5);     %Number of propeller blades

%Constants
rho = 1025;              %Density of water, [kg/m^3]

%Advance coeffisient
J = Va./(n*D);

%Calculating
KT1 = (CT_stuv.*J.^s_kt).*(PD.^t_kt).*(AEAO.^u_kt).*(Z.^v_kt);
KQ1 = (CQ_stuv.*J.^s_kq).*(PD.^t_kq).*(AEAO.^u_kq).*(Z.^v_kq);

KT = sum(KT1);
KQ = sum(KQ1);

% Negative KT and KQ are outside the range of Wageningen B
% experimental results. Setting KT = NaN for KT < 0 for
% correction

for p = 1:length(KT)
    if KT(p) < 0
        KT(p) = NaN;
    else
        KT(p) = KT(p);
    end

    if KQ(p) < 0
```

```
        KQ(p) = NaN;
    else
        KQ(p) = KQ(p);
    end
end

%Estimated thrust
T_est = KT.*rho*n^2*D^4;

end
```

C.2.2 find_propeller_speed.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%             find_propeller_speed.m
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Iteration process of rate of revolution n

function n = find_propeller_speed(T, V, Vdim)

%Prismatic coefficient from vessel info
Cp = Vdim(16);

%Wake coefficient
w = 0.7 * Cp - 0.18;

% Ship velocities in m/s
Va = V.*(1-w);
f = @(n) thrust(n, Va)-T;

n = fzero(f, 2);

end
```

C.2.3 Hollenbach.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%             Hollenbach.m
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function R = Hollenbach(Vsvec, Vdim)

% Ship particulars from vessel info:
L = Vdim(1);          %Length between perpendiculars
Lwl = Vdim(2);        %Length Waterline
Los = Vdim(3);        %Length over Surface
T = Vdim(4);          %Draught
B = Vdim(5);          %Bredth
S = Vdim(6);          %Wetted surface area
CB = Vdim(7);         %Block coefficient

TA = Vdim(8);         %Draught at AP
TF = Vdim(9);         %Draught at FP
Dp = Vdim(10);        %Propeller diameter
NRud = Vdim(11);      %Number of rudders
NBrac = Vdim(12);     %Number of brackets
NThr = Vdim(13);      %Number of bossings
NBoss = Vdim(14);     %Number of side thrusters
k = Vdim(15);         %Form factor of the vessel

%Constants
rho = 1025;      %Density of water, [kg/m^3]
gravk = 9.81;    %Gravity, [m/s^2]
nu = 1.1395E-6; %Viscosity, [m^2/s]

%Calculation of 'Froude length', Lfn:
if Los/L < 1
   Lfn = Los;
elseif (Los/L >= 1) && (Los/L < 1.1)
```

```
   Lfn = L+2/3*(Los-L);
elseif Los/L >= 1.1
   Lfn = 1.0667*L;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Constants from Hollenbachs paper:
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% 'Mean' resistance coefficients
   a = [-0.3382 0.8086 -6.0258 -3.5632 9.4405 0.0146 0 0 0 0];
%a1 means a(1) and so on
   b = [-0.57424     13.3893    90.5960;    %b12 means b(1,2)
       4.6614   -39.721 -351.483;
      -   1.14215   -12.3296    459.254];
   d = [0.854 -1.228 0.497];
   e = [2.1701 -0.1602];
   f = [0.17 0.20 0.60];
   g = [0.642 -0.635 0.150];

   % 'Minimum' resistance coefficients
   a_min = [-0.3382 0.8086 -6.0258 -3.5632 0 0 0 0 0 0];
   b_min = [-0.91424 13.3893 90.5960;...
         4.6614 -39.721 -351.483;...
         -1.14215 -12.3296 459.254];
   d_min = [0 0 0];
   e_min = [1 0];
   f_min = [0.17 0.2 0.6];
   g_min = [0.614 -0.717 0.261];

R = zeros(1,length(Vsvec)); %Preallocate resistance values

% Loop over velocities
for i = 1:length(Vsvec)

    % Froude's number
```

```
    Fn = Vsvec(i)/sqrt(gravk*Lfn);
    Fnkrit = d*[1 CB CB^2]';

    c1 = Fn/Fnkrit;
    c1_min = Fn/Fnkrit;

    Rns = Vsvec(i)*L/nu;                    % Reynold's number for ship
    CFs = 0.075/(log10(Rns)-2)^2;           % ITTC friction line for ship

    % Calculation of C_R for given ship
    % Mean value

    CRFnkrit = max(1.0,(Fn/Fnkrit)^c1);

    kL = e(1)*L^(e(2));

    % There is an error in the hollenbach paper and in Minsaas' 2003
    % textbook, which is corrected in this formula by dividing by 10

    CRstandard = [1 CB CB^2]*(b*[1 Fn Fn^2]')/10;

    CR_hollenbach = CRstandard*CRFnkrit*kL*prod([T/B B/L Los/Lwl Lwl/L ...
            (1+(TA-TF)/L) Dp/TA (1+NRud) (1+NBrac) (1+NBoss) (1+NThr)].^a);


    CR = CR_hollenbach*B*T/S;               % Resistance coefficient,
                                            % scaled for wetted surface
    C_Ts = CFs + CR;                        % Total resistance coeff. ship
    R_T_mean = C_Ts*rho/2*Vsvec(i)^2*S;     % Total resistance to the ship

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % When accounting for form factor, roughness and correlation coef.,
    % as given by Minsaas

    Rnm = 6*sqrt(6/L)*10^6/1.1395*Vsvec(i); % Reynold's number for model
    CFm = 0.075/(log10(Rnm)-2)^2;           % ITTC friction line for model
```

```
    dCF = (110.31*(150*Vsvec(i)/0.514)^0.21 ...
        - 403.33)*CFs^2;            % Increase in friction due to roughness
    CA = -0.228*10^(-3);                    % Correlation coefficient
    CR_2 = CR_hollenbach*B*T/S - k*CFm;     % Resistance coefficient
    C_Ts_2 = (1+k)*(CFs + dCF) + CR_2 + CA; % Total resistance coeff. ship
    R_T_mean_2 = C_Ts_2*rho/2*Vsvec(i)^2*S; % Total resistance to the ship

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % Minimum values

    % There is an error in the hollenbach paper and in Minsaas' 2003
    % textbook, which is corrected in this formula by dividing by 10
    CRstandard_min = [1 CB CB^2]*(b_min*[1 Fn Fn^2]')/10;

    CR_hollenbach_min = CRstandard_min*prod([T/B B/L Los/Lwl Lwl/L ...
            (1+(TA-TF)/L) Dp/TA (1+NRud) (1+NBrac) (1+NBoss) ...
            (1+NThr)].^a_min);

    CR_min = CR_hollenbach_min*B*T/S;

    % Total resistance coefficient of the ship
    C_Ts_min = CFs + CR_min;
    % Total resistance
    R_T_min = C_Ts_min*rho/2*Vsvec(i)^2*S;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % When accounting for form factor, roughness and correlation coef.,
    % as given by Minsaas

    CR_min_2 = CR_hollenbach_min*B*T/S - k*CFm; % Resistance coeff.
    C_Ts_min_2 = (1+k)*(CFs + dCF) + CR_min_2 + CA; % Total resistance
                                                    % coeff. ship
    R_T_min_2 = C_Ts_min_2*rho/2*Vsvec(i)^2*S;  % Total resistance to
                                                    % the ship

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
    % Store results
    CFsvec(i) = CFs;
    CRvec(i) = CR;
    C_Tsvec(i) = C_Ts;
    C_Ts_2vec(i) = C_Ts_2;
    R_T_meanvec(i) = R_T_mean;
    R_T_mean_2vec(i) = R_T_mean_2;
    CR_minvec(i) = CR_min;
    C_Ts_minvec(i) = C_Ts_min;
    C_Ts_min_2vec(i) = C_Ts_min_2;
    R_T_minvec(i) = R_T_min;
    R_T_min_2vec(i) = R_T_min_2;

    % Resistance calm water
    R(i) = max(R_T_meanvec(i),R_T_mean_2vec(i));

end

end
```

C.2.4 eta0.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%             eta0.m
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Calculating Open Water Efficiency

function eta = eta0(n, V, Vdim, PropellerDim)

%Prismatic Coefficient from vessel info
Cp = Vdim(16);

%Wake - and thrust coefficient
w = 0.7 * Cp - 0.18;
```

```
% Speed of advance
Va = V.*(1-w);

% Propeller characteristics from vesselinfo
D = PropellerDim(1);    %Propeller diameter [m]
P = PropellerDim(2);    %Pitch of propeller [mm]
PD = PropellerDim(3);   %Pitch to diameter ratio
AEAO = PropellerDim(4); %Blade area ratio
Z = PropellerDim(5);    %Number of propeller blades

%Constants
rho = 1025;             %Water densisty, kg/m^3

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Using Wageningen-B Propeller Series

%Wagening reynolds number
Re_wag = 2*10^6;

%KT coeffisients
global KT_Data KQ_Data
CT_stuv = KT_Data(:,1).';
s_kt = KT_Data(:,2).';
t_kt = KT_Data(:,3).';
u_kt = KT_Data(:,4).';
v_kt = KT_Data(:,5).';

%KQ coeffisients
KQ_Data = xlsread('KQ.xlsx');
CQ_stuv = KQ_Data(:,1).';
s_kq = KQ_Data(:,2).';
t_kq = KQ_Data(:,3).';
u_kq = KQ_Data(:,4).';
v_kq = KQ_Data(:,5).';
```

```
%Advance coeffisient
J = Va./(n*D);

%Calculating
KT1 = (CT_stuv.*J.^s_kt).*(PD.^t_kt).*(AEAO.^u_kt).*(Z.^v_kt);
KQ1 = (CQ_stuv.*J.^s_kq).*(PD.^t_kq).*(AEAO.^u_kq).*(Z.^v_kq);

KT = sum(KT1);
KQ = sum(KQ1);

%Open water efficiency
eta = (KT.*J)./(2*pi*KQ);

end
```

C.3 Weather Data

C.3.1 mergeweather.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%              mergeweather.m
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function waveheight_vec = mergeweather(filename, waveheight_vec, dataname)
temporary=ncread(filename,dataname);
lengde=length(temporary(1,1,:));
waveheight_vec(:,:,(end+1):(end+lengde)) = temporary;
end
```

C.3.2 bigfile.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%              bigfile.m
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
function waveheight_vec = bigfile(dataname)
waveheight_vec = ncread('2014_Q3.nc',dataname);
waveheight_vec = mergeweather('2014_Q4.nc',waveheight_vec, dataname);
waveheight_vec = mergeweather('2015_Q1.nc',waveheight_vec, dataname);
waveheight_vec = mergeweather('2015_Q2.nc',waveheight_vec, dataname);
waveheight_vec = mergeweather('2015_Q3.nc',waveheight_vec, dataname);
waveheight_vec = mergeweather('2015_Q4.nc',waveheight_vec, dataname);
waveheight_vec = mergeweather('2016_Q1.nc',waveheight_vec, dataname);
waveheight_vec = mergeweather('2016_Q2.nc',waveheight_vec, dataname);
waveheight_vec = mergeweather('2016_Q3.nc',waveheight_vec, dataname);
waveheight_vec = mergeweather('2016_Q4.nc',waveheight_vec, dataname);
waveheight_vec = mergeweather('2017_Q1.nc',waveheight_vec, dataname);
```

C.3.3 datamodification.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%             datamodification.m
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Read modified data
[numData2, numText2, alldata2] = xlsread('OpDataCargoVesselModified.xlsx');
data_time = numData2(:,2);  %Time
data_lat = numData2(:,3);   %Latitude coordinates
data_lon = numData2(:,4);   %Longitide coordinates

% Array that containts only 6.th every hour,
% Data at 00.00, 06.00, 12.00, 18.00
integer = data_time./360;
idx = find(floor(integer)==integer);

logged_time = integer(idx).*6; %for hours
logged_lat = data_lat(idx);
logged_lon = data_lon(idx);
```

```
%Round to nearest 0.5, for comparison with weather data
rounded_lon = (round(logged_lon*2)/2);
rounded_lat = round(logged_lat*2)/2;
rounded_time = logged_time;
```

C.3.4 wavedimension.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%             wavedimension.m
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [WD_array, WH_array]=wavedimension(filename,dataname)

waveheight_vec = bigfile('swh');
wavedirection_vec = bigfile('mwd');

weather_lat2 = bigfile('latitude');
weather_lon2 = bigfile('longitude')-180;

pos_lon=zeros(1,length(rounded_lon));
pos_lat=zeros(1,length(rounded_lat));
pos_time=zeros(1,length(rounded_time));

%Wave heights and directions for logged data coordinates.
WH_array=zeros(length(rounded_lon),1);
WD_array=zeros(length(rounded_lon),1);

for i=1:length(rounded_lat)

    %Locating position in weather matrix
    pos_lon(i)=((180+rounded_lon(i))/0.5)+1;
    pos_lat(i)=((90-rounded_lat(i))/0.5)+1;
    pos_time(i)=((rounded_time(i)-1626)/6)+28;

    %Array with waveheight and direction for given latitude, longitude and
```

```
    %time
    WH_array(i) = waveheight_vec(pos_lon(i),pos_lat(i),pos_time(i));
    WD_array(i) = wavedirection_vec(pos_lon(i),pos_lat(i),pos_time(i));

end
```

C.3.5 stawave.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%            stawave.m
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function R_AWL=stawave(Vdim)

% Ship particulars from vessel info
B = Vdim(5);          % Breadth
L_BWL = Vdim(17);     % The distance from the bow to 95% of maximum breadth
                      % on the waterline in meters

% Constants
rho = 1025;           % Water densisty, kg/m^3
gravk = 9.81;         % Gravity

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Read data
% Using weatherdata from timeperiod of sailing
waveheight_vec = bigfile('swh');
wavedirection_vec = bigfile('mwd');

weather_lat = bigfile('latitude');
weather_lon = bigfile('longitude')-180;
weather_time = bigfile('time');

% Preallocating space for position in weather matrix, for lat, lon, time
pos_lon=zeros(1,length(rounded_lon));
```

```
pos_lat=zeros(1,length(rounded_lat));
pos_time=zeros(1,length(rounded_time));

% Wave heights and directions for measured operational data coordinates
WH_array=zeros(length(rounded_lon),1);
WD_array=zeros(length(rounded_lon),1);

for i=1:length(rounded_lat)

    % Locating position in weather matrix
    pos_lon(i)=((180+rounded_lon(i))/0.5)+1;
    pos_lat(i)=((90-rounded_lat(i))/0.5)+1;
    pos_time(i)=((rounded_time(i)-1626)/6)+28;

    % Array with waveheight and direction for given latitude, longitude,
    % time
    WH_array(i) = waveheight_vec(pos_lon(i),pos_lat(i),pos_time(i));
    WD_array(i) = wavedirection_vec(pos_lon(i),pos_lat(i),pos_time(i));
end

% Preallocating space for vectors
direction_x = zeros(2020,1);
direction_y = zeros(2020,1);
theta_rad = zeros(2020,1);
theta_deg = zeros(2020,1);

azimuth_angle = zeros(2021,1);      %Last value is zero, has no direction
R_AWL = zeros(1,length(WD_array));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Direction in longitutde and latitude direction

for j=1:length(rounded_lat)-1 %2020
    %Creating array for direction vessel
    direction_y(j)=rounded_lat(j+1)-rounded_lat(j);     %Longitude dir
    direction_x(j)=rounded_lon(j+1)-rounded_lon(j);     %Latitude dir
```

```
    theta_rad(j)=atan(direction_y(j)/direction_x(j));
end

theta_deg=rad2deg(theta_rad);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Azimuthangle: Adding right angle depending on quadrant

for k=1:length(direction_x)
    %1. quadrant, between 0 and 90 degrees
    if direction_y(k)>0 && direction_x(k)>0
        azimuth_angle(k)=theta_deg(k);
    %2. quadrant, between 90 and 180
    elseif direction_y(k)<0 && direction_x(k)>0
        azimuth_angle(k)=90+abs(theta_deg(k));
    %3. quadrant, between 180 and 270 degrees
    elseif direction_y(k)<0 && direction_x(k)<0
        azimuth_angle(k)=270-abs(theta_deg(k));
    %4. quadrant, between 270 and 360 degrees
    elseif direction_y(k)>0 && direction_x(k)<0
        azimuth_angle(k)=270+abs(theta_deg(k));
    %If azimuthangle is 90 degrees
    elseif direction_y(k)==0 && direction_x(k)>0
        azimuth_angle(k)=90;
    %If azimuthangle is 270 degrees
    elseif direction_y(k)==0 && direction_x(k)<0
        azimuth_angle(k)=270;
    %If azimuthangle is 0 degrees
    elseif direction_y(k)>0 && direction_x(k)==0
        azimuth_angle(k)=0;
    %If azimuthangle is 180 degrees, straight south
    elseif direction_y(k)<0 && direction_x(k)==0;
        azimuth_angle(k)=180;
    %Last value in array is 0
    else
```

```
        azimuth_angle(end)=0;
    end

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Direction of wave, check condition for stawave-1
for l=1:length(WD_array)
    if abs(azimuth_angle(l)-WD_array(l)) <= 45
        R_AWL(l)=(1/16)*rho*gravk*WH_array(l)^2*(sqrt(B/L_BWL));
    else
        R_AWL(l) = 0;
    end
end

% Array with index mathing index in array of measured operational time
R_AWL_array=zeros(length(new_time_array),1);
index=find(new_time_array ~= 0);

R_AWL_array(index)=R_AWL;

end
```

C.3.6 newtimearray.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%             newtimearray.m
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Indexing only the hours that will modeled with STAWAVE-1

[numData3, numText3, alldata3] = xlsread('OpDataCargoVessel(Starts15).xlsx');
dataTimeNotmod=numData3(:,2);

%Converting measured operational data from minutes to hours
```

```
data_time_hours=dataTimeNotmod/60;


new_time_array=zeros(length(data_time_hours),1);
for i=1:length(data_time_hours)
    for j=1:length(rounded_time)

        if data_time_hours(i)==rounded_time(j)
            new_time_array(i)=rounded_time(j);
        else
            new_time_array(i)=new_time_array(i);
        end
    end
end
```

Siri Helene Ludviksen Thorsen

Simulation Based Estimation of Power Consumption

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