BACHELOR THESIS – ME 184841

DATA-BASED MODELLING OF SHIP PROPULSION FOR A 2500 TEU FEEDER CONTAINER SHIP

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DOUBLE DEGREE PROGRAM
DEPARTMENT OF MARINE ENGINEERING
FACULTY OF MARINE TECHNOLOGY
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TUGAS AKHIR – ME 184841

PERMODELAN PROPULSI BERBASIS DATA UNTUK KAPAL FEEDER CONTAINER 2500 TEU

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SURABAYA
2020

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APPROVAL SHEET

DATA-BASED MODELLING OF SHIP PROPULSION FOR A 2500 TEU FEEDER CONTAINER SHIP

BACHELOR THESIS

Submitted to Comply One of The Requirement to Obtain a Bachelor Engineering Degree

On

Hochschule Wismar, Faculty of Engineering, Department of Maritime Studies
and
Institut Teknologi Sepuluh Nopember, Faculty of Marine Technology, Department of Marine Engineering

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BACHELOR THESIS

Asked To Meet One Of The Conditions

Obtained a Bachelor's Degree In Engineering

on

Major *Marine Operational and System* (MOM)

Department of Marine Engineering S-1 Double Degree Program

Faculty Marine Technology

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AGUSTUS, 2020

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Department	: Marine Engineering

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Jakarta, 29 August 2020

Jefferson Marcel Soadamara

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DATA-BASED MODELLING OF SHIP PROPULSION FOR A 2500 TEU FEEDER CONTAINER SHIP

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ABSTRACT

A sea-going vessel will always face the risk of rough weather along its voyages. The focus of this paper is on the creation of a data-based model to estimate the power increase or speed loss due to influence of weather, by using resistance estimation theories and added resistance approximation methods along with additional assisting tools. Furthermore, a theoretical simulation is done in order to benchmark and correct the model setup. The analysis of simulation results shows that at the available data range, the model proves reasonably precise within its capabilities, for academic applications. The general behaviour of the model complies with common ship theory, however, does not perfectly resemble the speed-power relation of the ship's recorded data averages. The analysis suggests that the model is most compatible at the ship load draft of 9,0 to 9,5 meters, and within the speed of 19 to 22 knots. The lack of data outside the typical operating range disables the ability to verify the model correspondingly. The theoretical simulation proves valuable in assessing ship data-based models.

Keywords: (Added Resistance, Data-based modelling, Ship Propulsion, Voyage Analysis, Weather Influence)

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PERMODELAN PROPULSI BERBASIS DATA UNTUK KAPAL FEEDER CONTAINER 2500 TEU

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ABSTRAK

Kapal yang beroperasi di laut akan selalu menghadapi risiko cuaca buruk selama berlayar. Fokus dari skripsi ini adalah pada pembuatan model berbasis data untuk memperkirakan peningkatan daya atau pengurangan kecepatan akibat pengaruh cuaca, dengan menggunakan teori estimasi hambatan, metode estimasi hambatan tambahan akibat cuaca, dan alat bantu tambahan lainnya. Selanjutnya dilakukan simulasi teoritis untuk melakukan komparasi lalu mengoreksi pemodelan. Analisis hasil simulasi menunjukkan bahwa pada rentang data yang tersedia, model tersebut terbukti cukup tepat dalam kemampuannya, untuk aplikasi akademis. Perilaku umum model sesuai dengan teori kapal, bagaimanapun, tidak secara sempurna menyerupai hubungan kecepatan-daya rata-rata data kapal yang direkam. Analisis menunjukkan bahwa model ini paling cocok pada draft muat kapal 9,0 hingga 9,5 meter, dan dalam kecepatan 19 hingga 22 knot. Kurangnya data di luar rentang operasi normal menghilangkan kemampuan untuk memverifikasi model secara lengkap. Simulasi teoritis terbukti penting dalam menilai model berbasis data kapal.

Kata Kunci: (Analisis Pelayaran, Hambatan Tambahan, Pemodelan Berbasis Data, Pengaruh Cuaca, Propulsi Kapal)

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NOMENCLATURE

A_T	Transom Surface Area
B	Ship Breadth
Bh	Fuel Consumption
BN, BN	Beaufort Number
c	Coefficient
C_A	Incremental Resistance Coefficient
C_{AA}	Air Resistance Coefficient
C_{AS}	Steering Resistance Coefficient
CB, C_B	Coefficient Block
C_β	Direction Reduction Coefficient
C_{Form}	Ship form coefficient
C_U	Speed Reduction Coefficient
C_F	Frictional Resistance Coefficient
C_{pv}	Power by Speed ratio coefficient
C_R	Residual Resistance Coefficient
C_T	Total Resistance Coefficient
Δ	Displacement
DWT	Deadweight Tonne
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
Fn, Fn	Froude Number
g	Gravitational Acceleration
H, H	Height

IMO	International Maritime Organization
L, L	Length
LCB, lcb	Longitudinal Centre of Buoyancy
LOA	Length Overall
LPP, L_{PP}	Length between Perpendiculars
LWL	Length on the Waterline
N	Engine Speed
P	Power
Pb, BHP	Brake Power
P_{Eff}	Effective Power
ρ	Density
R_A	Model-ship correlation resistance
R_{APP}	Appendages Resistance
R_{AWL}	Resistance in long crested irregular head waves
R_{AWM}	Resistance due to ship motion
R_{AWR}	Resistance due to wave reflection
R_B	Bulbous Bow Near-Surface Additional Pressure Resistance
R_n	Reynold's Number
R_{FS}	Frictional Resistance
R_{RS}	Residuary Resistance
R_{TR}	Immersed transom stern additional pressure resistance
R_{TS}, R_T	Total Resistance
R_{wave}	Added resistance in regular waves
S_{APP}	Wetted area of the appendages
T, T	Draft

TEU	Tonne-equivalent Unit
∇	Volume Displacement
V, V	Speed
Vs	Vessel Speed

1. INTRODUCTION

1.1 Background

The design and operation of ships worldwide, especially cargo ships, is increasing rapidly. One of the most focused aspect is the economical side. During the design phase, it is most desirable that a ship is built adequate to fulfil its purpose, while also being economically feasible. In other words, to get the most out of the least cost. Selection of the necessary machinery is crucial for a marine engineer when designing a vessel’s propulsion system.

One of the main concerns of the shipping industry is rough weather. Basically, the worse the weather gets, the higher the risk is, in terms of both safety and economically. The term “weather” is generally referring to the state of wind and waves at sea. Both of these elements have effect on the ship’s ability to travel.

Depending on the direction and magnitude, strong gusts of wind can affect the body of the ship above the waterline, causing higher air resistance. Theoretically, the stronger the wind gets, the larger the strength of the waves. These are called wind waves. Waves can affect a ship by causing rolling, pitching, accelerations, slamming, and propeller emergence. These occurrences cause increase in added resistance of the vessel. In larger magnitudes, these factors can cause a ship to run inefficiently due to the large power it requires in these conditions.

Ultimately, the effects of waves on the ship's hull directly affects the propulsion system. Pitching and rolling of the ship, and any imbalances of the ship's level may cause either addition of wake (Faltinsen, Minsaas, Liapis, & Skjordal, 1980), fluctuations in the propeller efficiency and occurrence of propeller emergence. Thus, it is logical for a vessel to avoid traveling in such conditions.

Since the release of the EEDI and EEOI requirements by IMO, there is an environmental goal in the maritime world to reduce the carbon emission emitted by the shipping industry. Thus, it is imperative for existing ships to travel as efficient as possible to reduce the carbon trail, and analysis of voyage operations is instinctively the initial step.

With the existing practice of weather routing, it is possible to minimize cost and uphold safety in terms of dealing with weather. Recording the voyage data and research enables the possibility to accurately predict the required power for a vessel, compared to just using a "weather margin" to compensate for rough weather. This shall help in meeting EEDI requirements for future shipbuilding. For the operation side, it assists in forming the voyage plan, to determine where the ship should sail and which direction it should move in order to minimize the impact of weather, consequently increasing the ship's efficiency and reduces the environmental waste.

1.2 Problem Statement

During an observation of ship voyage recorded data, it is often found that data is incomplete. Data from ship logs such as the noon report often only records the observed power and speed. To assist in evaluation of the voyages, it is necessary to create a theoretical estimation model to predict ship power-speed relation in various weather conditions.

1.3 Objectives

1. To create a data-based model that can predict power increase or speed loss due to wind and waves influences.
2. To apply the model into theoretical simulation, enabling assessment and benchmarking with actual recorded ship data within academically reasonable error tolerance.
3. To develop an understanding of ship operation data processing and to contribute towards its development.

1.4 Benefits

1. The creation of this thesis provides the writer an opportunity to have a deeper understanding of ship power-speed behaviour.
2. The result model provides an estimation of power and speed in various weather conditions for a typical 2500 TEU container vessel.

3. The result model may provide assistance in identifying causes of abnormalities such as hull and propeller failing during voyage analysis.
4. The result model may present the opportunity as a tool to assist voyage planning and optimization, e.g. bunker planning estimation.
5. The result model may provide assistance in voyage evaluation, e.g. to cross-check fuel consumption from the supposed power estimation.
6. The result model may possibly assist in voyage optimization to reach the IMO requirements of EEOI.

2. LITERATURE REVIEW

2.1 Base Theory

2.1.1 Ship Resistance and Propulsive Power

In the past, traditional vessels relied on wind power by using large sails and masts to direct the mechanical power into moving the ship. Most commercial ships today rely on machinery using an engine that is directly or indirectly coupled with a propulsor. There are several types of propulsion engines such as:

- Diesel Engines
- Steam Turbines
- Steam Engines
- Gas Turbines
- Diesel-electric and other electrical setup propulsion systems.

with several choices of propulsors, which are:

- Conventional Fixed Pitch Propellers
- Controllable Pitch Propellers
- Azimuth pods
- Waterjets
- Advanced technology propulsors

Depending on the design goal, each component listed above may be selected to achieve a desirable output. For example, large vessels opted to carry heavy load will usually have large diesel engines that run on low quality (economically feasible) fuels, along with large fixed pitch propellers which in combination results in provenly reduced operation costs.

This is closely related to the size and purpose of the ship. A larger magnitude of resistance that larger vessels experience is mostly due to its shape and size. Larger commercial ships require more power to travel, within the limits of its economic feasibility, where it is opted to carry as much cargo as it can, as opposed to ships designed for speed such as patrol ships.

In theory, the ship's resistance is related to the interaction between ship hull and the fluid flow. William Froude divided the total resistance (R_{TS}) into two parts: friction resistance (R_{FS}) and residuary resistance (R_{RS}), where friction resistance is caused by viscous and inertia forces, while residuary resistance is caused by gravity and inertia forces (Harvald, 1983).

$$R_{TS} = R_{FS} + R_{RS} \qquad \textit{Eq. 1}$$

This resistance force can be divided into three main contributors: frictional resistance, viscous pressure resistance, and wave resistance (Molland, Turnock, & Hudson, 2011). In generalized terms, frictional resistance is result of the shear force of the fluid flow acting on the hull, the viscous pressure resistance is the normal force acting on the hull by the surrounding flow, and the wave resistance is the measured energy associated with the ship's propagating wave field.

Guldhammer-Harvald Method

In obtaining the value of resistance of ships, there are several classical estimation methods in the past that are still used in presently. An example of this would be the Guldhammer and Harvald method. This method of resistance is derived from the analysis of results of towing tests (Harvald, 1983). This method determines the total resistance R_T as a function of speed, where the total resistance coefficient C_T affects how substantial the resistance changes as the speed varies. The total resistance coefficient is a sum of the frictional resistance coefficient C_F, residual resistance coefficient C_R, and the incremental resistance coefficient C_A which represents the model-ship surface roughness correction (Harvald, 1983).

$$C_T = C_F + C_R + C_A \qquad \textit{Eq. 2}$$

The frictional resistance coefficient C_F refers to the ITTC-1957 standard frictional model-ship correlation line, where a calculation based on Reynold's Number is provided (International Towing Tank Conference, 2002):

$$C_F = \frac{0.075}{(\log_{10} R_n - 2)^2} \qquad \textit{Eq. 3}$$

By definition, the residual resistance coefficient C_R is determined from the total resistance coefficient subtracted by the frictional resistance coefficient as described before. The value of the residual resistance coefficient is obtained from the standard ship form diagrams. It is plotted against the Froude Number, and categorized into curves depending on the vessel's longitudinal prismatic coefficient. An example can be seen in figure 2.1.

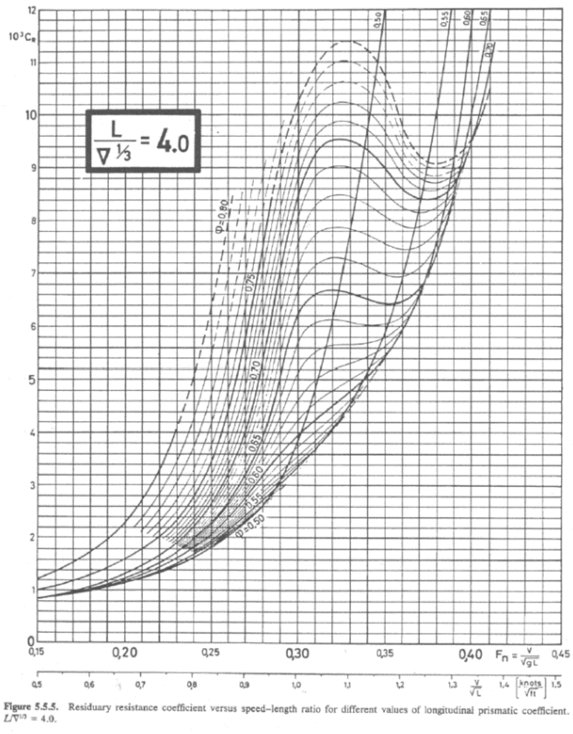

Figure 2. 1. Residuary resistance coefficient curves (Harvald, 1983)

Souce: Harvald (1983)

The Guldhammer-Harvald method suggests another correction for the difference in location of the longitudinal position of the center of buoyancy (LCB), where the increase in resistance of $10^3 C_R$ is found from the deviation value of the vessel's LCB to the standard. A residual resistance coefficient correction for LCB forward of standard is available. This is expressed by (Harvald, 1983):

$$\Delta LCB = LCB - LCB_{standard}(LCB\ in\ \%\ of\ L) \qquad Eq.\ 4$$

and,

$$10^3 C_R = 10^3 C_{R(standard)} + \frac{\partial 10^3 C_R}{\partial LCB}|\Delta LCB| \qquad Eq.\ 5$$

C_A, the incremental resistance coefficient represents the effect of the ship's surface roughness, to compensate the difference of skin smoothness between the model and the actual ship hull. This is expressed by (Harvald, 1983):

$$1000 \cdot C_A = 0{,}5 \cdot \log(\Delta) - 0.1 \cdot (\log(\Delta))^2 \qquad Eq.\ 6$$

In the Harvald method, there is also consideration of the air resistance and steering resistance. The air resistance coefficient C_{AA} from the ship's structure above the waterline is implemented as a correction of the residuary resistance coefficient C_R. The value of C_{AA} and C_{AS} is determined as:

$$10^3 C_{AA} = 0.07 \qquad Eq.\ 7$$

$$10^3 C_{AS} = 0.04 \qquad Eq.\ 8$$

The standard Harvald method does not consider the effect of the bulbous bow, as it is assumed the ship has a standard non bulbous bow (Kristensen

& Lützen, 2013). In a more recent study on the influence of bulbous bow, it is found that from the analysis of multiple model tests, the bulbous bow correction of residual resistance coefficient C_R is also a function of Froude Number (Kristensen & Lützen, 2013). The resulting value of the bulbous bow influence is a percentage of the initial value obtained from the Harvald method residuary resistance coefficient C_R:

$$\Delta C_{R,bulb} = (250 \cdot Fn - 90) \cdot \frac{C_{R\,Harvald\,NO\,bulbous\,bow}}{100} \qquad \textit{Eq. 9}$$

Holtrop-Mennen Method

Another classic method widely used to approximate a ship's initial total resistance is the Holtrop-Mennen Method. This method is a development from a regression analysis of various arbitrary model experiments and data, with slight modifications from additional experiments with means to be more applicable (Holtrop & Mennen, 1982).

The total resistance R_T of the ship is expressed by (Holtrop & Mennen, 1982):

$$R_T = R_F(1 + k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A \qquad \textit{Eq. 10}$$

where:

R_F : frictional resistance as in the ITTC-1957 frictional standard

$(1 + k_1)$: form factor representing hull viscous resistance

R_{APP} : appendages resistance

R_W : wave-making and wave-breaking resistance

R_B : bulbous bow near-surface additional pressure resistance

R_{TR} : immersed transom stern additional pressure resistance

R_A : model-ship correlation resistance

The form factor prediction is expressed by (Holtrop & Mennen, 1982):

$$1 + k_1 = c_{13}\{0,93 + c_{12}(B/L_R)^{0,92497}(0,95 - C_P)^{-0,521448}(1 - C_P + 0,0225\ lcb)^{0,6906}\} \quad \textit{Eq. 11}$$

$$L_R = L\left(1 - C_P + 0,06C_P \frac{lcb}{4C_P - 1}\right) \quad \textit{Eq.12}$$

$$c_{12} = (T/L)^{0,2228446} \quad \text{when} \quad \frac{T}{L} > 0,05 \quad \textit{Eq.13}$$

$$c_{12} = 48,20\left(\frac{T}{L} - 0,02\right)^{2,078} + 0,479948 \quad \text{when} \quad 0,02 < \frac{T}{L} < 0,05 \quad \textit{Eq.14}$$

$$c_{12} = 0,479948 \quad \text{when} \ \frac{T}{L} < 0,02 \quad \textit{Eq. 15}$$

$$c_{13} = 1 + 0,003\ C_{stern} \quad \textit{Eq. 16}$$

The afterbody specific shape coefficient c_{13} is related to the C_{stern}, where the coefficient C_{stern} is given by the table 2.1. (Holtrop & Mennen, 1982):

Table 2. 1. Cstern Coefficient Values (Holtrop & Mennen, 1982)

Afterbody form	C_{stern}
V-shaped sections	-10

Normal section shape	0
U-shaped sections with Hogner stern	+10

Where:

lcb : longitudinal position of centre of buoyancy forward of 0,5 L as a percentage of L

C_P : prismatic coefficient based on waterline length L

B : ship breadth

T : average moulded draught

The frictional resistance R_F, is approximated according to the ITTC-1957 frictional standard, as discussed in previous sections in part 2.1.1 briefly.

The total resistance of the ship's appendages R_{APP}, (rudder, brackets, etc.) are expressed by (Holtrop & Mennen, 1982):

$$R_{APP} = 0{,}5\rho V^2 S_{APP}(1 + k_2)_{eq} C_F \qquad \textit{Eq. 17}$$

where:

S_{APP} : wetted area of the appendages

$(1 + k_2)_{eq}$: value which represents the combination of appendages

C_F : frictional resistance coefficient

In the Holtrop method, the wave resistance is determined from (Holtrop & Mennen, 1982):

$$R_W = c_1 c_2 c_5 \nabla \rho g \; exp\{m_1 F_n^d + m_2 \cos(\lambda F_n^{-2})\} \qquad \textit{Eq. 18}$$

with the coefficients expressed by:

$c_1 = 2223105 c_7^{3,78613} (T/B)^{1,07961} (90 - i_E)^{-1,37565}$ *Eq. 19*

$c_7 = 0{,}229577 \, (B/L)^{0,33333}$ when $B/L < 0{,}11$ *Eq. 20*

$c_7 = B/L$ when $0{,}11 < B/L < 0{,}25$ *Eq. 21*

$c_7 = 0{,}5 - 0{,}0625 \, L/B$ when $B/L > 0{,}25$ *Eq. 22*

$c_2 = exp\left(-1{,}89\sqrt{c_3}\right)$ *Eq. 23*

$c_5 = 1 - 0{,}8 A_T / (B \; T \; C_M)$ *Eq. 24*

$c_3 = 0{,}56 A_{BT}^{1,5} / \left\{BT\left(0{,}31\sqrt{A_{BT}} + T_F - h_B\right)\right\}$ *Eq. 25*

$\lambda = 1{,}446 C_P - 0{,}03 L/B$ when $L/B < 12$ *Eq. 26*

$\lambda = 1{,}446 C_P - 0{,}036$ when $L/B > 12$ *Eq. 27*

$m_1 = 0{,}0140407 \, L/T - 1{,}75254 \, {}^{\nabla^{1/3}}/_{L} + 4{,}79323 \, B/L - c_{16}$ *Eq. 28*

$c_{16} = 8{,}07981 C_P - 13{,}8673 C_P^2 + 6{,}984388 C_P^3$ when $C_P < 0{,}8$ *Eq. 29*

$c_{16} = 1{,}73014 - 0{,}7067 C_P$ when $C_P > 0{,}8$ *Eq. 30*

$m_2 = c_{15} C_P^2 exp(-0{,}1 F_n^{-2})$ *Eq. 31*

$c_{15} \quad = -1{,}69385 \quad \text{for } L^3/\nabla < 512$ *Eq. 32*

$c_{15} \quad = 0{,}0 \quad \text{for } L^3/\nabla > 1727$ *Eq. 33*

$c_{15} \quad = -1{,}69385 + \left(L/\nabla^{1/3} - 8{,}0\right)/2{,}36$ for $512 < L^3/\nabla < 1727$ *Eq. 34*

$$d = -0{,}9$$ *Eq. 35*

R_B is described as the additional resistance as effect of the proximity of a bulbous bow near the surface, and is determined by (Holtrop & Mennen, 1982):

$$R_B = 0{,}11\, exp(-3P_B^{-2}) F_{ni}^3 A_{BT}^{1,5} \rho g/(1 + F_{ni}^2)$$ *Eq. 36*

where:

P_B : a value representing the emergence of the bow

F_{ni} : Froude number based on the immersion

The equation components mentioned are found by:

$$P_B = 0{,}56\sqrt{A_{BT}}/(T_F - 1{,}5h_B)$$ *Eq. 37*

$$F_{ni} = V/\sqrt{g\left(T_F - h_B - 0{,}25\sqrt{A_{BT}}\right) + 0{,}15V^2}$$ *Eq. 38*

In this approximation method, R_{TR} is described as additional pressure resistance which is caused by transom immersion, where the transom surface area A_T affects, and is expressed by (Holtrop & Mennen, 1982):

$$R_{TR} = 0{,}5\rho V^2 A_T c_6 \qquad \textit{Eq. 39}$$

The coefficient c_6 is found from:

c_6	$= 0{,}2(1 - 0{,}2F_{nT})$	when $F_{nT} < 5$	*Eq. 40*
c_6	$= 0$	when $F_{nT} \geq 5$	

Eq. 41

$$F_{nT} = V/\sqrt{2gA_T/(B + BC_{WP})} \qquad \textit{Eq. 42}$$

A similarity found with the previously explained method is the existence of a model-ship correlation resistance R_A, which is equated by (Holtrop & Mennen, 1982):

$$R_A = {}^1/_2\, \rho\, V^2\, S\, C_A \qquad \textit{Eq. 43}$$

With C_A as correlation allowance expressed by (Holtrop & Mennen, 1982):

$$C_A = 0{,}006(L + 100)^{-0{,}16} - 0{,}00205 + 0{,}003\sqrt{L/7{,}5}\, C_B^4 c_2(0{,}04 - c_4)$$

Eq. 44

The coefficient c_4 is found according to:

c_4	$= T_F/L$	when $T_F/L \leq 0{,}04$	*Eq. 45*
c_4	$= 0{,}04$	when $T_F/L > 0{,}04$	*Eq. 46*

2.1.2 Wind and Waves

As seen in the classical resistance estimation methods, the value obtained is regarding the vessel being in the calm water environment, hence the addition of a “sea margin” to consider the added resistance effect of weather to the final power requirement value. However, this is a loose empirical approximation which only considers a general idea of how much resistance is added in different seas.

Ships (especially sea-going vessels) are unlikely to always operate in calm water. There will always be situations where wind and waves at sea are at a magnitude large enough to affect the ship’s propulsive capability. One important aspect to consider from the motion of a wave is that energy is transported through the material (in this case, water) itself. The frequent type of wave that occurs at the interface of the atmosphere and the ocean are called surface waves (The Open University, 1999).

The two types of water waves that occur are capillary waves and gravity waves. Self-explanatory, gravity waves are defined by its restoring force, the earth’s gravity. These types of waves exist in greater surface waves, which are of wavelength greater than 1,7 cm (The Open University, 1999), and are faced by a sea-going vessel more commonly. These gravity waves are caused by two main factors, wind and tides. The wind powered waves when occurring in a sufficiently long time period will form a “fully developed sea” where an equilibrium of dissipated energy and received energy of waves happens, and the wave characteristics are ideally unchanging (The Open University, 1999). Practically, the different strengths of winds consequently produce a variation in waves of the fully developed sea. This magnitude of wind energy also escalates the strength of the energy transfer at sea.

One of the commonly used characteristic to describe a state of the sea is the significant wave height, which is the mean height of the highest one-third of all waves occurring in a particular time (The Open University, 1999). In practical applications, the sea state is defined by the Beaufort Number, where the Beaufort Scale defines various sea states by certain parameters (Molland, Turnock, & Hudson, 2011). The significant wave height ($H_{1/3}$) is one of the parameters in the Beaufort Scale.

Table 2. 2 Beaufort Scale (The Open University, 1999)

Beaufort Number	**Name**	**Wind speed (mean)**		**State of the sea-surface**	**Significant wave height, $H_{1/3}$(m)**
		Knots	**m s^{-1}**		
0	Calm	<1	0.0-0.2	Sea like a mirror	0
1	Light air	1-3	0.3-1.5	Ripples with appearance of scales; no foam crests	0.1-0.2
2	Light breeze	4-6	1.6-3.3	Small wavelets; crests have glassy appearance but do not break	0.3-0.5

3	Gentle breeze	7-10	3.4-5.4	Large wavelets: crests begin to break; scattered white horses	0.6-1.0
4	Moderate breeze	11-16	5.5-7.9	Small waves, becoming longer; fairly frequent white horses	1.5
5	Fresh breeze	17-21	8.0-10.7	Moderate waves taking longer form; many white horses and chance of some spray	2.0
6	Strong breeze	22-27	10.8-13.8	Large waves forming; white foam crests extensive everywhere and spray probable	3.5
7	Near gale	28-33	13.9-17.1	Sea heaps up and white foam from breaking waves begins to be blown in streaks; spindrift begins to be seen	5.0
8	Gale	34-40	17.2-20.7	Moderately high waves of greater length; edges of crests break into spindrift; foam is blown in well-marked streaks	7.5
9	Strong gale	41-47	20.8-24.4	High waves; dense streaks of foam; sea begins to roll; spray	9.5

				may affect visibility	
10	Storm	48-55	24.5-28.4	Very high waves with overhanging crests; sea-surface takes on white appearance as foam in great patches is blown in very dense streaks; rolling of sea is heavy and visibility reduced	12.0
11	Violent storm	56-64	28.5-32.7	Exceptionally high waves; sea covered with long white patches of foam; small and medium-sized ships might be lost to view behind waves for long times; visibility further reduced	15.0
12	Hurricane	>64	>32.7	Air filled with foam and spray: sea completely white with driving spray; visibility greatly reduced	>15

The various weather conditions as seen in the table are part of the consideration on how long a vessel can reach its destination or how optimized its voyage can be. The practice of considering such weather factors into the planning of a ship's voyage is commonly known as "weather routing". With this action, it is possible to enable minimization of port service costs from precise arrival prediction, and reduction of fuel consumption from an optimal voyage plan.

In comparison of the effect of wind and waves, generally, the added resistance increases as the weather conditions grow stronger. Between added resistance from wind and added resistance from waves, waves have a larger effect. However, the dominant source of the added resistance from waves varies as the vessel speed increases. At lower speeds, the viscous resistance is larger, where at faster speeds, the wave-making resistance dominates. In seas with stronger weather conditions, the ship is also oscillating, caused by the ocean waves. This in turn, transfers energy to the waves, which also increases the total resistance, primarily transmitted with the ship's radiated waves. (Alexandersson, 2009).

2.2 Added Resistance in Wind & Waves

2.2.1 Semi-empirical approximation methods

In the past, there have been various studies on the influence of waves and wind on a ship.

As discussed in section 2.1, a variation of waves is naturally the true state in practical operating conditions. This is because normally, the waves at sea are unlikely to be constant. The result of these "regular" waves combining are known as "irregular waves". Most of the current advanced methods for predicting added resistance in waves use the approach of initially calculating the added resistance in regular waves with their respective methods, then applying the results to a wave energy spectrum to calculate the average added resistance in irregular waves. From results of studies in the past, the wave-induced added resistance is divided into resistance due to wave reflection R_{AWR}, and resistance due to ship motion R_{AWM}.

There have been several methods in approximating the value of this added resistance. One method is the practical STAwave-1 method, which approximates the resistance increase in long crested irregular head waves R_{AWL} (up to the angle of 45 degrees away from the bow) in speed trial conditions, where wave reflection added resistance is dominant (International Towing Tank Conference, 2014). The practicality of this method allows usage even with limited input. However, there are specific conditions that limit the validity of this method (International Towing Tank Conference, 2014):

1. Significant wave height, $H_{1/3} \leq 2.25\sqrt{L_{pp}/100}$
2. Small heave and pitch, vertical acceleration at bow <0.05g
3. Head waves

The STAwave-2 method is similar to the first version, however considers both resistance due to wave reflection R_{AWR}, and resistance due to ship motion R_{AWM}. There are also more input parameters, which are ship dimensions and speed (International Towing Tank Conference, 2014).

In the advanced method, which calculates added resistance in regular waves R_{wave}, the calculation for the components R_{AWR} and R_{AWM} are continually improved. One of the earliest basic methods is Maruo's theory which calculates R_{AWM}, based on wave propagation from ships to a far field.

2.2.2 Practical Approximation Methods

The Beaufort scale is a commonly used scale in rating the roughness of the weather at sea. This practical scale is also used as a parameter in empirical-based studies of the influence of wind and waves. One method is the Aertssen Formula, which estimates the speed loss for various sea conditions based on the Beaufort Number (Townsin & Kwon, 1983):

$$\frac{\Delta V}{V} \times 100\% = \frac{m}{L_{PP}} + n \qquad \textit{Eq. 47}$$

The values of m and n are defined by the encounter angle of waves and the Beaufort Number. However, this is a loose empirical approximation. The Aertssen Formula does not consider ship type, condition, nor fullness (Molland, Turnock, & Hudson, 2011). Therefore, the accuracy of the resultative added resistance is limited, but it is relatively easier to apply compared to the existing semi-empirical methods.

Kwon's method of predicting added resistance is also a general approach for a large variety of commercial displacement type ships. Even so, Kwon's approach considers the ship type, load condition, and the ship's general dimension (in the form of the coefficient block). The added resistance is expressed in the value of speed loss, which is the involuntary reduction of the calm water vessel speed to the vessel speed in wind and waves. The speed loss is formulated as (Kwon, 2008):

$$\frac{\Delta V}{V_1}100\% = C_\beta C_U C_{Form} \qquad \textit{Eq. 48}$$

In the approximation, the travel speed of the vessel, expressed in Froude Number F_n, is represented in the coefficient C_U. The value of F_n depends on the initial designated ship speed in calm water conditions. This also considers the block coefficient of the ship C_B and it's loading conditions. The value of the coefficient is seen in the following table:

Table 2. 3 Speed Reduction Coefficient table (Kwon, 2008)

Block Coefficient C_B	Ship loading condition	Speed Reduction Coefficient C_U
0.55	Normal	$1.7 - 1.4F_n - 7.4(F_n)^2$
0.60	Normal	$2.2 - 2.5F_n - 9.7(F_n)^2$
0.65	Normal	$2.6 - 3.7F_n - 11.6(F_n)^2$
0.70	Normal	$3.1 - 5.3F_n - 12.4(F_n)^2$
0.75	Loaded or normal	$2.4 - 10.6F_n - 9.5(F_n)^2$
0.80	Loaded or normal	$2.6 - 13.1F_n - 15.1(F_n)^2$
0.85	Loaded or normal	$3.1 - 18.7F_n + 28.0(F_n)^2$
0.75	Ballast	$2.6 - 12.5F_n - 13.5(F_n)^2$
0.80	Ballast	$3.0 - 16.3F_n - 21.6(F_n)^2$
0.85	Ballast	$3.4 - 20.9F_n - 31.8(F_n)^2$

The directional angle of the wind and waves is expressed by the coefficient C_β. The type of the vessel is expressed by the coefficient C_{Form}. Both of the values of these coefficients are determined by the corresponding Beaufort Number. The descriptive details of the coefficients can be seen in table:

Table 2. 4. Direction Reduction Coefficient table (Kwon, 2008)

Weather Direction	Angle (with respect to the ship bow)	Direction Reduction Coefficient C_β
Head sea	$0°$	$2C_\beta = 2$
Bow sea	$30°\ to\ 60°$	$2C_\beta = 1.7 - 0.03(BN - 4)^2$
Beam sea	$60°\ to\ 150°$	$2C_\beta = 0.9 - 0.06(BN - 6)^2$
Following sea	$150°\ to\ 180°$	$2C_\beta = 0.4 - 0.03(BN - 8)^2$

Table 2. 5. Ship Form Coefficient table (Kwon, 2008)

Type of (displacement) ship	Ship form coefficient C_{Form}
All ships (except container ships) in loaded condition	$0.5BN + BN^{6.5}/(2.7\nabla^{2/3})$
All ships (except container ships) in ballast condition	$0.7BN + BN^{6.5}/(2.7\nabla^{2/3})$
Container ships in normal loading conditions	$0.5BN + BN^{6.5}/(22.0\nabla^{2/3})$

2.2.3 Theoretical Modelling Simulation

In the current state of technology for industrial improvement, theoretical modelling is often applied, especially in financial planning, risk management and trend prediction. This can provide a presentation of “what ifs” and the respective series of consequential results. Typically, there will be several input variables that can be adjusted, along with some constants that then are put into the transfer function to acquire a set of results.

The practice of using theoretical modelling especially in mathematical calculations are done vastly, from monthly planning of a simple direct sales business model to complex engineering problems. An example of theoretical modelling for simple business scenarios is calculating the profit of a company in 5 years from sales, with consideration of initial and operational costs, and commonly along with inflation and interest. In engineering, it is often used for reliability evaluation of a system.

One of the common methods of study of a system is through simulation techniques. Simulations estimate results of different scenarios of a system by simulating the actual process and the behaviour of the system accordingly (Billinton & Allan, 1992). In the simulation technique, theoretically the input data of the model should be random to experiment with all possible scenarios, so it is common sense to use a random number generator. A large number of random input data is generated then applied to the model to obtain a vast series of results (Billinton & Allan, 1992). However, the randomness of the results may not directly provide the users with a needed solution, so it is common to provide time-based intervals or other constraints. At the end of the process, it is still a requirement to execute analysis on the results, for example, by analyzing graphs binned into specific characteristics.

An example of the simulation methods described in the previous text is the Monte Carlo Simulation. An important factor that defines Monte Carlo simulation is that it is stochastic, which is shown in the input of the simulation, which is randomly generated from probability distributions. So, for a deterministic model, the Monte Carlo simulation evaluates the model stochastically, resulting in a large random output. The result of a Monte Carlo simulation is a visual representation (e.g., Histograms) used to determine how random variation, lack of knowledge, and other factors affect the performance and reliability of the model system (Wittwer J. , 2004).

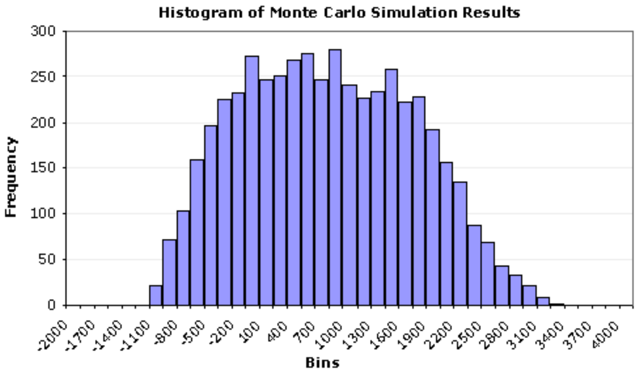

Figure 2. 2. Histogram of profit frequency as result of a Monte Carlo Simulation (Wittwer J. W., 2004)
Source: Vertex42.com (2004)

From the figure, it can be seen in the example that plotting the results of a Monte Carlo Simulation into a visual representation may help derive conclusions. In the example, out of the many randomly generated financial setups, within the set constraints, the resulting profits are mostly positive, however the uncertainty is rather large starting from values of -1000 to 3400.

3. METHODOLOGY

3.1Flowchart

The research done in this thesis is conducted according to the proposed steps as seen in figure 3.1.

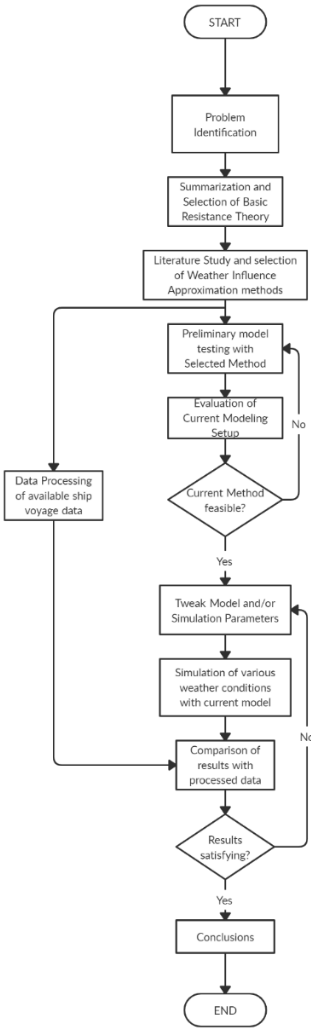

Figure 3. 1. Research Flowchart

3.2 Description of Flowchart

3.2.1 Problem Identification

The first step in the procedure to start the thesis is problem identification. This part of the study defines what questions are the focus for research. The main problems that are identified become a case to solve. In this stage, specific identification for existing problems are done to further determine objectives of the overall thesis. With completion of this step, the purpose of the research can be recognized.

3.2.2 Summarization and Selection of Basic Resistance Theory

The second step in the procedure is to collect and summarize the basic theory that the writer has already obtained from previous studies. The study resources that are collected should be necessary and related to the topic of the thesis. A selection of the existing theories that will be used, especially of ship resistance, should also be done to narrow down the scope for further study. Examples of this are the classic ship resistance estimation theories, and basic knowledge of the nature of ship resistance.

3.2.3 Literature Study

After problem identification is executed, and current knowledge has been summarized, research on existing related literature should be done to catch up with the current knowledge on the topic, and have the necessary information to assist analysis. In the case of this thesis, primarily a literature study on current methods for approximating weather influence on a ship. This is done by extensively reading books, published scientific articles, journals, literature from the International Maritime Organization, and other existing sources.

3.2.4 Data Processing of Available Ship Voyage Data

One of the important steps to do early in the thesis is to process the available voyage data. This is done to identify possible points of reference and analysis. The results of data processing in the modelling thesis are especially important for model correction, as a benchmark for the model.

3.2.5 Preliminary Model testing with Selected Method

This step is indicated with the formulation of a framework from gathered materials. A preliminary model should be created to be able to start theoretical experimenting. This process allows further critical assessments and provides insight on what to work towards.

3.2.6 Evaluation of Current Modelling Setup

An evaluation of the current model is necessary to check whether the current work is worth for testing. The most important thing to look out for is whether the output is reachable, and whether the available data is sufficient for the application of the current model setup. The feasibility of the model is assessed during this step.

3.2.7 Tweaking of the Model and/or Simulation Parameters

This step is when the model is corrected or adjusted to fit with the desired goal. This is the step that defines the experimenting of the model and the simulation. As the simulation is parametric, it is important to iterate various constraints of the simulation to achieve a necessary output. The fine tuning of the model is done intended to best represent the actual nature of the ship.

3.2.8 Comparison of Results with Processed Data

As explained in point 3.2.4, the results of processed data are used as a benchmark to form the model, and to create decisions in improving the model. Points of references from the processed data is used as the “real” results which the model should aim to provide. In this step, it is decided whether the current simulation results with the model’s framework provides satisfying results. The criteria for results may be the error margin, how accurate the trends are, or how explicable the results are.

3.2.9 Conclusions

The final step in the thesis research begins with the summarization of the research results. The results of the model are given the best explanation of its nature, its limitations and the overall interesting occurrences of the simulation. Conclusions are made and a fairly logical explanation shall be provided for each drawn conclusion.

4. ANALYSIS

4.1 Data Processing

4.1.1 Ship Data

As explained in Chapter 3, one of the focuses of this thesis is to benchmark the model created with the actual data processed. The actual ships which will be discussed in this thesis are two sister ships which at the time of the recorded data were under the names MV IMPALA and MV LIBERTA.

These two vessels are products of the CV 2500 container ship model. As the name of the model is self-explanatory the vessel is designed to carry container up to a load of approximately 2500 TEUs. The container capacity starts from 2468 TEUS, up to 2524 TEUS (Wikipedia, 2019). It is equipped with a 19.810 kW two-stroke diesel engine (DMR - 7L70 MC-C), and fitted with a five-blade propeller (Wikipedia, 2019).

The dimensions and other general details of the vessels may be seen in table 4.1. Some assumptions for the values are done within reasonable logic to provide necessary values to complete analysis.

Table 4. 1. General Details of CV 2500

Container Vessel Type WARNOW CV 2500		
LOA	m	208,11
LPP	m	197,19
LWL	m	199,2
Tmax	m	11,4

H	m	16,4
B	m	29,8
CB	-	0,65
DWT at Tmax	t	34000
Weight / Light Displacement	t	11078
Loaded Displacement	t	45078
Loaded Displacement	m^3	43978,54
C_D-T		2099,47
Wake fraction	-	0,26
Hull efficiency	-	1,08
Thrust deduction factor		0,2

When diving into the subject of ship efficiency, one of the most discussed topics are the problem of fuel efficiency. Looking from the perspective of ship operations, higher fuel consumption is directly related to a higher usage of engine power. This however is also compensated by how much load it carries, and how fast the ship is traveling. The best plot for an efficient ship operation is indicated by an efficient voyage plan, where typically rough weather is avoided, hence higher engine power settings are unnecessary. This is also the reason why most ship operators will have in either conventionally or advanced technologically record its voyages.

In this thesis, the voyage data (apparently, results of noon reports) which will be discussed are of voyages of MV Liberta from 06/10/1997 to 25/12/2000, and MV Impala from 02/02/2000 to 29/06/2000. The data can be seen in tables, 4.1 and 4.2.

Table 4. 2. Ship Voyage data of MV Liberta

No	***Date***	***Time***	***N***	***Pb***	***Bh***	***Vs***

			[rpm]	*[kW]*	*[kg/h]*	*[kn]*
1	06/10/1997	14:56:01	103,149	13848	2776	20,742
2	08/10/1997	15:02:44	76,159	5455	876	16,284
3	08/10/1997	16:45:43	89,533	8723	1414	19,230
4	08/10/1997	17:16:15	94,035	9838	1595	19,790
5	08/10/1997	18:29:59	108,138	15230	2377	22,719
6	08/10/1997	20:16:00	108,189	15650	2435	21,357
7	08/10/1997	22:48:23	108,110	15333	2454	22,490
8	09/10/1997	16:44:03	108,186	15496	2813	21,188
9	09/10/1997	17:50:42	90,104	8688	1684	19,208
10	09/10/1997	18:34:22	65,461	3691	754	12,790
11	09/10/1997	20:22:11	76,426	6115	1143	15,073
12	31/10/1997	03:11:20	102,148	13344	2813	21,399
13	06/11/1997	00:42:57	103,303	15877	3181	19,025
14	06/11/1997	08:08:29	104,140	16186	3226	20,171
15	06/11/1997	12:42:21	104,113	15813	3168	20,513
16	06/11/1997	15:10:00	104,142	15768	3162	19,468
17	06/11/1997	17:17:47	106,267	16856	3357	19,900
18	07/11/1997	01:43:50	107,192	15858	3303	21,507
19	07/11/1997	02:45:19	107,223	15915	3318	21,433
20	07/11/1997	03:38:26	107,193	15842	3302	21,690
21	07/11/1997	05:51:16	107,191	15951	3257	21,593
22	07/11/1997	07:31:59	107,208	16066	3286	21,507
23	07/11/1997	09:59:24	107,153	16047	3283	21,136
24	07/11/1997	13:58:10	107,168	15949	3260	21,308
25	07/11/1997	17:49:57	108,209	16495	3366	21,205
26	07/11/1997	21:25:21	108,197	16335	3312	21,442
27	28/02/1998	17:35:53	106,118	15565	2958	20,718
28	01/03/1998	08:46:22	107,106	15043	2868	21,460
29	02/03/1998	00:52:11	106,986	14947	2860	21,598
30	02/03/1998	23:09:31	107,232	14915	2857	21,741
31	03/03/1998	07:27:53	98,772	11716	2304	19,852
32	04/03/1998	16:23:12	93,082	14213	2741	13,795
33	05/03/1998	20:01:56	98,758	11848	2355	18,981
34	06/03/1998	23:29:11	95,190	10358	2088	19,242
35	12/03/1998	11:58:58	104,247	13789	2677	20,993
36	16/03/1998	02:42:31	104,230	13685	2688	21,476
37	16/03/1998	22:04:13	104,159	13998	2745	21,426
38	17/03/1998	16:16:11	104,160	14194	2778	19,804
39	20/03/1998	01:18:00	104,253	13906	2738	20,931
40	21/03/1998	14:43:29	104,146	13583	2689	21,109
41	22/03/1998	18:23:30	106,697	14890	2935	21,166
42	23/03/1998	11:30:34	107,823	16319	3217	20,763
43	24/03/1998	05:12:07	108,175	15643	3089	21,579
44	26/03/1998	09:27:32	102,120	13283	2627	20,456
45	27/03/1998	14:30:00	102,544	13084	2600	20,804
46	30/04/1999	05:07:46	105,963	15115	2960	21,042
47	01/05/1999	14:32:15	102,110	12881	2604	21,256
48	09/05/1999	08:52:25	106,003	14621	2935	21,711
49	12/05/1999	10:37:54	106,003	14855	2978	21,300
50	13/05/1999	00:33:04	105,993	14357	2904	21,679
51	15/05/1999	08:42:06	100,138	12236	2559	20,030
52	15/05/1999	14:48:29	100,112	13315	2721	19,042
53	15/05/1999	20:43:57	100,018	14922	2988	17,086
54	16/05/1999	00:48:57	97,854	14820	2960	17,045
55	16/05/1999	17:37:16	98,199	12860	2613	18,899
56	24/05/1999	21:15:10	106,106	14067	2650	21,774
57	25/05/1999	02:04:29	106,063	15128	2826	20,423
58	28/05/1999	04:57:50	105,056	14407	2710	20,360
59	30/05/1999	02:12:53	105,112	13993	2647	20,901
60	31/05/1999	09:05:18	105,053	14057	2660	21,157
61	01/06/1999	08:27:12	105,928	14661	2748	21,021
62	01/06/1999	15:10:25	106,017	14300	2695	21,900
63	02/06/1999	02:29:06	106,007	15411	2874	20,604
64	02/06/1999	13:40:15	106,054	14799	2775	21,194

65	03/06/1999	02:28:41	107,013	14927	2789	21,753
66	17/06/1999	06:39:09	107,060	15085	2882	21,787
67	19/06/1999	06:43:04	107,102	14803	2836	21,913
68	20/06/1999	01:12:25	106,986	14914	2865	22,208
69	20/06/1999	21:30:38	107,050	14913	2864	22,895
70	21/06/1999	04:16:31	107,122	15092	2890	22,917
71	23/06/1999	19:24:20	106,061	14755	2840	21,566
72	27/06/1999	18:31:44	101,122	12343	2455	20,634
73	01/07/1999	02:04:45	106,050	15660	2970	19,505
74	09/07/1999	08:33:37	106,046	14415	2657	21,744
75	10/07/1999	15:06:30	103,072	13514	2523	20,930
76	11/07/1999	03:12:23	103,083	13648	2563	20,130
77	14/07/1999	7:05:59	103,068	14403	2703	19,415
78	15/07/1999	7:27:50	104,188	13544	2568	20,892
79	15/07/1999	11:40:26	97,285	11246	2216	18,392
80	31/07/1999	23:55:43	107,127	15183	2887	20,553
81	01/08/1999	7:54:03	107,078	15362	2922	21,988
82	02/08/1999	3:51:59	107,023	14852	2851	21,945
83	05/08/1999	13:25:06	107,068	14745	2835	22,121
84	06/08/1999	5:56:30	107,090	14888	2862	21,697
85	07/08/1999	12:13:59	100,133	12069	2406	20,854
86	08/08/1999	4:24:02	100,099	12010	2391	20,005
87	08/08/1999	12:48:05	103,049	13300	2590	21,448
88	11/08/1999	20:02:52	102,121	13374	2592	19,845
89	16/08/1999	9:15:54	107,029	15229	2899	21,046
90	16/08/1999	21:25:50	107,012	14673	2812	22,024
91	17/08/1999	10:43:27	107,023	15449	2939	20,650
92	18/08/1999	2:23:05	107,066	15125	2882	20,324
93	20/08/1999	11:58:32	107,056	14840	2849	22,900
94	21/08/1999	6:04:54	107,013	15134	2903	19,951
95	21/08/1999	19:32:19	107,070	14897	2876	21,460
96	23/08/1999	2:08:57	106,092	15589	2998	20,289
97	24/08/1999	6:12:56	107,118	16207	3107	19,861
98	26/08/1999	9:02:55	106,048	14509	2813	21,465
99	29/08/1999	12:53:42	106,048	14721	2842	21,603
100	05/09/1999	21:28:18	106,038	15149	2890	20,879
101	08/09/1999	11:48:38	105,993	15363	2935	20,790
102	09/09/1999	12:35:57	106,075	15819	3014	20,407
103	10/09/1999	12:44:50	107,094	15157	2924	21,523
104	11/09/1999	9:02:48	107,107	15207	2945	22,148
105	11/09/1999	20:54:31	106,065	14531	2839	21,556
106	12/09/1999	1:17:27	106,155	14881	2885	23,080
107	12/09/1999	12:26:37	106,077	14512	2831	20,821
108	12/09/1999	22:04:12	106,078	14446	2819	21,894
109	15/09/1999	19:48:04	107,084	15084	2938	22,004
110	16/09/1999	15:01:04	106,007	14382	2823	21,956
111	19/09/1999	23:13:36	104,083	14374	2798	20,843
112	20/09/1999	11:28:16	105,057	14748	2865	21,016
113	20/09/1999	18:29:23	105,078	14609	2844	21,009
114	24/09/1999	4:35:57	101,060	12546	2524	20,303
115	24/09/1999	18:14:57	101,147	12699	2575	19,871
116	30/09/1999	19:10:21	106,046	14615	2883	21,731
117	01/10/1999	3:32:39	106,127	15137	2959	20,518
118	04/10/1999	5:33:41	102,040	13309	2657	19,840
119	08/10/1999	10:06:35	106,031	14485	2902	21,502
120	11/10/1999	15:22:42	101,131	12614	2588	20,975
121	12/10/1999	22:28:12	107,102	15274	3003	20,531
122	15/10/1999	8:45:13	100,085	12626	2617	19,474
123	15/10/1999	17:45:34	100,188	12709	2613	20,360
124	15/10/1999	23:58:18	100,119	12747	2624	19,723
125	16/10/1999	7:30:57	101,182	13406	2720	18,716
126	17/10/1999	20:13:32	104,060	14559	2898	20,438
127	18/10/1999	8:25:59	104,044	14772	2942	20,490
128	19/10/1999	6:53:04	103,977	14755	2947	20,558
129	19/10/1999	13:21:26	104,082	15051	3004	20,219

130	22/10/1999	20:02:13	105,609	15003	3004	21,053
131	24/10/1999	1:30:17	104,939	14039	2878	21,778
132	26/10/1999	5:20:46	104,992	13928	2864	20,888
133	29/10/1999	9:35:37	101,148	12177	2623	21,342
134	29/03/2000	16:49:48	105,959	14873	2746	21,554
135	30/03/2000	0:23:48	107,048	15619	2873	20,567
136	30/03/2000	4:33:37	107,044	15958	2933	19,959
137	01/04/2000	9:25:29	106,079	14846	2744	21,263
138	02/04/2000	6:10:02	106,050	15140	2773	21,028
139	06/04/2000	20:31:24	106,964	14881	2750	21,732
140	09/04/2000	1:14:39	103,052	13434	2504	19,982
141	09/04/2000	9:10:24	103,101	13263	2491	20,574
142	22/04/2000	23:13:24	101,997	13487	2523	18,554
143	02/05/2000	13:44:47	107,015	15211	2869	21,248
144	02/05/2000	17:40:41	107,062	15336	2891	21,045
145	03/05/2000	1:49:04	105,064	14221	2704	21,126
146	04/05/2000	2:21:29	102,135	13211	2460	20,866
147	04/05/2000	6:25:19	102,066	13214	2450	20,861
148	10/05/2000	8:39:15	106,051	15200	2815	20,629
149	10/05/2000	21:35:19	103,037	13892	2592	19,998
150	10/05/2000	23:29:20	100,115	12965	2436	18,259
151	11/05/2000	6:11:11	102,120	13470	2518	20,021
152	12/05/2000	9:14:09	106,069	15086	2784	20,708
153	14/05/2000	7:45:04	106,085	14913	2769	21,314
154	14/05/2000	18:49:28	107,036	15125	2806	21,493
155	15/05/2000	1:35:41	106,013	14993	2787	21,183
156	15/05/2000	20:57:08	106,042	15246	2812	21,200
157	15/05/2000	22:59:36	67,003	4309	903	11,542
158	18/05/2000	7:19:26	105,884	14703	2733	21,770
159	25/05/2000	5:13:56	100,181	11973	2325	21,296
160	30/05/2000	23:50:02	102,101	13874	2633	20,425
161	08/06/2000	21:14:46	100,220	12296	2385	20,347
162	12/06/2000	13:18:38	106,976	16210	3087	20,340
163	17/06/2000	7:36:13	106,057	14729	2861	21,322
164	20/06/2000	18:12:04	101,137	13652	2673	19,230
165	21/06/2000	15:08:53	104,084	14433	2814	20,410
166	23/06/2000	22:06:25	99,115	11886	2390	20,128
167	24/06/2000	9:06:32	100,183	12898	2545	19,721
168	29/06/2000	4:07:57	105,754	14953	2896	21,197
169	30/06/2000	5:46:15	106,707	15244	2940	21,670
170	04/07/2000	3:07:39	100,194	12041	2452	19,916
171	11/07/2000	21:43:34	102,109	14388	2850	19,932
172	12/07/2000	4:09:23	102,203	14039	2790	20,237
173	12/07/2000	10:44:02	102,125	13150	2650	20,448
174	14/07/2000	17:35:27	100,147	12480	2552	19,571
175	14/07/2000	20:26:49	101,115	13050	2641	20,222
176	15/07/2000	5:00:00	100,164	12342	2526	20,410
177	24/07/2000	5:24:04	105,021	14504	2885	20,728
178	25/07/2000	16:55:33	107,968	15866	3120	20,685
179	02/08/2000	22:01:57	104,077	14307	2853	20,320
180	06/08/2000	8:52:47	103,113	13841	2760	20,655
181	07/08/2000	0:02:20	103,167	14253	2838	20,117
182	07/08/2000	6:15:47	103,091	15067	2980	19,242
183	11/08/2000	19:07:06	105,982	14578	2933	21,823
184	12/08/2000	1:01:06	102,044	12954	2639	21,221
185	14/08/2000	0:54:32	106,015	14581	2918	21,115
186	23/08/2000	9:23:24	106,004	15078	3047	21,463
187	04/09/2000	0:46:34	104,084	14109	2907	20,645
188	04/09/2000	10:21:12	104,059	13740	2837	21,209
189	05/09/2000	3:38:17	106,069	14643	2999	21,414
190	06/09/2000	19:42:41	104,046	13564	2819	21,679
191	09/09/2000	13:16:42	108,099	16438	3313	20,987
192	11/09/2000	2:54:01	108,074	16006	3218	21,309
193	12/09/2000	15:59:08	104,035	14609	2973	19,997
194	14/09/2000	13:24:59	104,100	14381	2924	19,846

195	14/09/2000	14:28:13	102,074	13496	2786	19,463
196	14/09/2000	16:35:24	101,269	13402	2763	18,692
197	14/09/2000	19:30:56	98,185	12519	2602	18,695
198	15/09/2000	7:40:16	98,152	12342	2579	19,074
199	15/09/2000	10:28:21	98,102	11994	2523	19,684
200	20/09/2000	8:30:48	103,122	14911	3024	19,804
201	21/09/2000	1:39:46	104,988	14267	2931	21,874
202	22/09/2000	4:23:59	104,911	14437	2958	21,464
203	24/09/2000	4:51:41	103,063	13335	2788	21,247
204	24/09/2000	15:56:14	103,222	13332	2795	21,664
205	30/09/2000	8:19:54	103,020	13267	2808	20,362
206	02/10/2000	13:28:30	104,084	14145	2972	20,868
207	04/10/2000	1:22:06	106,086	15224	3165	21,348
208	05/10/2000	13:18:09	106,034	14707	3093	21,768
209	15/10/2000	22:58:40	103,124	13276	2453	20,893
210	17/10/2000	4:59:59	103,110	13481	2498	20,603
211	21/10/2000	9:18:06	107,075	15277	2802	21,413
212	25/10/2000	17:48:05	107,083	15986	2933	20,433
213	02/11/2000	4:41:20	105,089	14205	2617	21,742
214	03/11/2000	11:29:59	105,050	14242	2633	21,495
215	09/11/2000	11:19:36	106,052	14491	2744	21,969
216	11/11/2000	18:19:33	106,033	14953	2835	20,883
217	14/11/2000	12:14:21	103,024	14540	2754	20,744
218	14/11/2000	19:26:00	107,062	15970	3011	21,631
219	17/11/2000	4:22:21	106,040	14777	2796	21,529
220	24/11/2000	16:46:15	104,095	14654	2722	17,998
221	25/11/2000	20:37:02	107,050	15312	2870	21,509
222	27/11/2000	0:30:15	107,134	15359	2894	21,186
223	07/12/2000	12:37:31	105,057	14729	2785	20,321
224	08/12/2000	7:21:37	105,072	14730	2803	20,869
225	09/12/2000	2:03:16	105,058	15388	2914	20,113
226	09/12/2000	12:51:24	105,014	15162	2879	20,985
227	10/12/2000	22:44:41	102,109	14160	2675	19,667
228	16/12/2000	22:26:40	104,884	14113	2706	21,084
229	22/12/2000	14:06:01	102,093	13507	2669	20,728
230	24/12/2000	10:00:42	105,136	14729	2880	20,810
231	25/12/2000	13:29:06	102,021	15167	2946	19,005

Table 4. 3. Ship Voyage Data of MV Impala

No	***Date***	***Time***	***N [rpm]***	***Pb [kW]***	***Bh [kg/h]***	***Vs [kn]***
1	02/02/2000	05:31:15	103,138	13413	2671	21,438
2	03/02/2000	10:23:26	100,117	12455	2522	20,573
3	06/02/2000	17:33:01	102,111	13494	2732	21,324
4	13/02/2000	22:37:23	100,106	13453	2699	19,526
5	15/02/2000	06:47:58	104,117	13846	2765	20,788
6	16/02/2000	10:33:59	102,059	13429	2696	20,652
7	16/02/2000	23:17:43	100,119	12525	2544	20,556
8	18/02/2000	12:26:19	100,100	12138	2497	21,066
9	20/02/2000	04:03:13	100,146	12371	2523	20,285
10	20/02/2000	13:29:47	97,318	11403	2382	20,182
11	20/02/2000	21:33:46	97,358	11663	2416	21,214
12	21/02/2000	02:05:05	100,078	12534	2551	21,716
13	21/02/2000	18:33:46	100,110	12525	2551	21,016
14	22/02/2000	07:59:40	100,026	12373	2529	21,342
15	23/02/2000	01:47:27	105,148	14175	2836	21,944
16	24/02/2000	17:30:14	102,113	13510	2724	21,255

17	25/02/2000	16:44:35	100,100	13151	2669	20,443
18	26/02/2000	09:13:09	100,136	13594	2743	19,995
19	28/02/2000	01:51:13	100,061	12709	2594	20,953
20	02/03/2000	14:43:20	104,166	14251	2792	21,247
21	07/03/2000	09:41:37	106,128	14677	2824	22,006
22	07/03/2000	23:25:11	106,061	15054	2890	21,375
23	11/03/2000	07:19:19	106,094	15247	2949	20,764
24	12/03/2000	06:03:38	107,890	16461	3164	20,999
25	14/03/2000	07:42:33	108,002	16042	3101	21,615
26	15/03/2000	06:39:56	107,014	15663	3040	21,836
27	17/03/2000	12:29:44	106,151	14723	2886	22,000
28	18/03/2000	20:18:49	106,069	14331	2814	22,419
29	25/03/2000	22:48:42	107,991	16172	3190	21,742
30	31/03/2000	00:25:05	106,063	15254	3027	21,304
31	01/04/2000	08:12:59	104,139	14297	2871	21,034
32	03/04/2000	06:30:09	106,066	15050	3007	21,214
33	04/04/2000	09:09:22	106,082	15325	3058	20,855
34	04/04/2000	16:38:38	102,121	13421	2728	20,738
35	05/04/2000	21:44:44	102,041	13456	2745	20,873
36	09/04/2000	00:08:39	106,134	15629	3111	21,391
37	10/04/2000	05:28:34	106,110	16054	3183	20,853
38	11/04/2000	03:29:19	106,097	15086	3008	21,462
39	14/04/2000	05:45:01	106,132	16632	3281	21,312
40	15/04/2000	09:16:42	104,119	16074	3204	20,295
41	15/04/2000	21:38:38	103,664	16204	3240	18,977
42	19/04/2000	07:22:04	106,049	16480	3287	22,445
43	20/04/2000	23:08:29	105,993	17087	3436	21,038
44	23/04/2000	13:57:37	106,107	17381	3547	20,827
45	24/04/2000	09:51:44	106,205	17314	3534	19,225
46	25/04/2000	02:33:05	106,125	17064	3496	21,160
47	27/04/2000	02:10:41	105,633	16896	3484	21,262
48	29/04/2000	06:23:28	106,617	16894	3497	21,703
49	29/04/2000	23:46:13	101,221	14243	2997	20,790
50	05/05/2000	04:35:08	105,898	16599	3408	21,031
51	09/05/2000	07:22:30	104,096	15230	3168	22,271
52	09/05/2000	15:04:32	104,130	15233	3172	22,235
53	10/05/2000	00:26:44	102,123	14364	3022	21,635
54	12/05/2000	11:32:10	104,120	16428	3431	20,436
55	13/05/2000	11:39:32	105,145	16386	3400	21,461
56	14/05/2000	02:11:00	105,047	16305	3406	21,463
57	15/05/2000	08:08:46	105,199	16014	3327	22,121
58	17/05/2000	01:40:07	104,805	16640	3469	23,536
59	17/05/2000	19:49:00	105,974	16729	3473	22,027
60	20/05/2000	22:15:36	105,923	16952	3533	21,367
61	22/05/2000	02:32:05	106,078	16358	3404	21,932
62	25/05/2000	15:05:03	104,095	16167	3356	20,347
63	31/05/2000	02:04:53	105,976	16929	3580	21,658
64	01/06/2000	07:58:22	103,713	16750	3535	19,749
65	04/06/2000	20:13:09	105,588	16808	3577	19,510
66	06/06/2000	18:49:15	105,572	16655	3581	20,936
67	07/06/2000	13:19:34	105,454	16711	3600	20,941

68	09/06/2000	22:50:29	105,878	16328	3527	21,582
69	15/06/2000	05:18:38	106,085	16115	3500	22,492
70	19/06/2000	19:41:41	98,108	12884	3008	20,712
71	21/06/2000	20:35:54	104,481	16539	3710	20,556
72	23/06/2000	10:48:09	105,191	16608	3749	21,292
73	25/06/2000	00:38:04	106,064	16675	3790	21,622
74	26/06/2000	00:24:11	104,083	15748	3592	21,732
75	27/06/2000	13:32:33	104,032	15895	3620	21,538
76	29/06/2000	18:43:52	105,678	16984	3810	21,638

From the ship voyage data, it is seen that data for engine power, engine speed, and vessel travel speed is available. From the general principle of power and speed correlation,

$$P = c \cdot V^n \qquad \textit{Eq. 49}$$

it is possible to sort the voyage recorded data into bins based on the Power by Speed ratio coefficient, C_{pv}. With the assumption that the engine and other machinery are in prime condition, a lower C_{pv} may indicate a higher efficiency, which is bound to happen when a vessel travels in relatively calm sea conditions. With a value of $n = 3$, having the C_{pv} divided into bins per its value will give a general sense of direction for analysis. Note that data No. 26 is disregarded during analysis for its extreme value. Data No. 123 and Data No. 126 is also considered extra attention because the recording shows a very low setting of power and speed compared to the average.

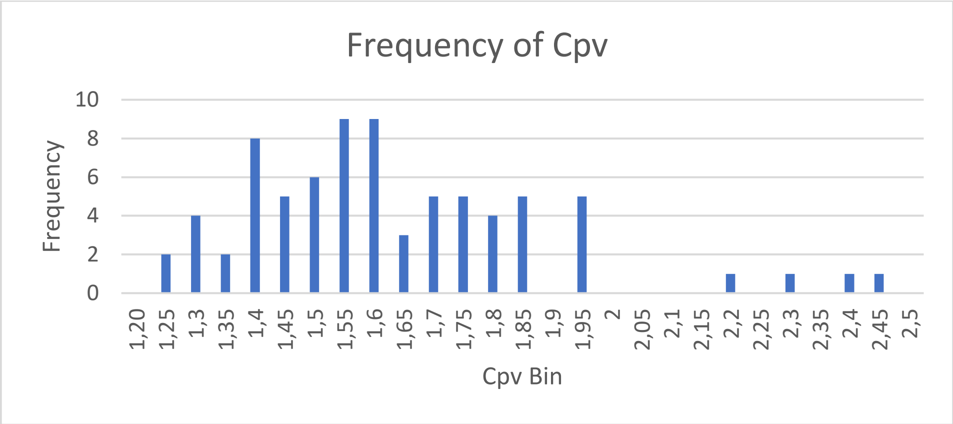

Figure 4. 1. MV Impala C_{pv} count

As seen in figure 4.1., for MV Impala, the voyage recordings show that during most of its operations the C_{pv} is between 1,40 to 1,65. This information can be used to narrow down the analysis, by constraining the are for simulation to this range of resultant C_{pv}.

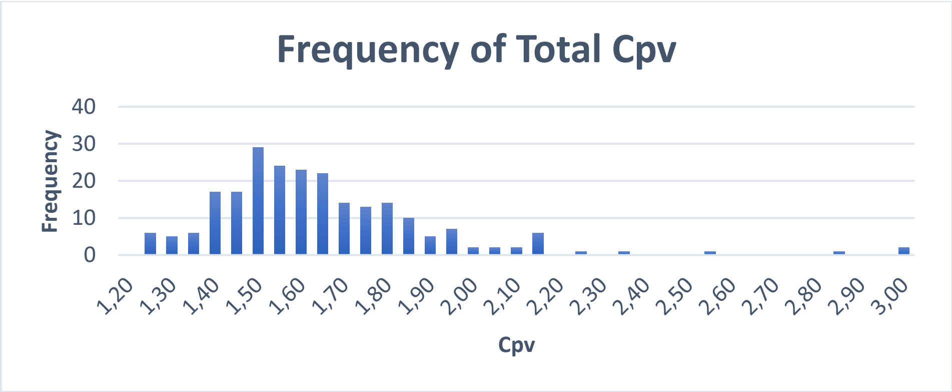

Figure 4. 2. MV Liberta C_{pv}count

Figure 4.2. shows that the data count for MV Liberta has most frequent recordings in the C_{pv} range of 1,50 to 1,65. However, it must also be

considered that MV Liberta has a significantly larger amount of recorded data points available.

4.1.2 Ship Hull Form

In the estimation of ship resistance, the form of the hull is very detrimental to the result total resistance. To assist in the calculations, a representative hull form is necessary to have. In the analysis of this thesis, a typical bulbous-bow container vessel form is generated using Maxsurf software. The model is adjusted to be within the dimensions of the ship data, and is converted to a CAD model, providing sufficient hull information for further steps.

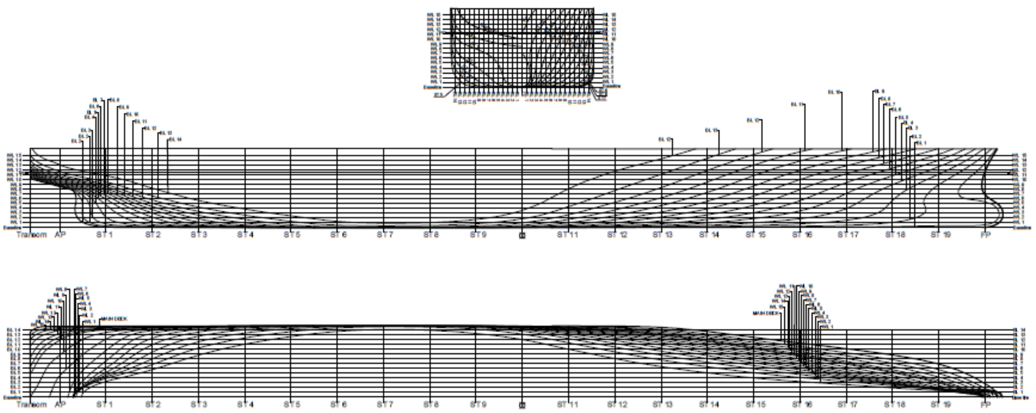

Figure 4. 3. CAD Model of Hull Form

4.2 Estimation for Ship Resistance

4.2.1 Estimation for Calm Water Ship Resistance – Method A

Guldhammer Method

When considering the influence of weather on a vessel, it is intuitive to first obtain the ship resistance in calm water. The methods applied in this thesis are the Guldhammer-Harvald and Holtrop resistance estimation methods, along with some modifications from recent studies on those classic methods. The analysis is done within the vessel's service speed and operating range.

Essentially, the Guldhammer method results in a total resistance coefficient, C_T which will be used to find the total resistance R_T :

$$R_T = C_T(0{,}5 \times \rho \times V^2 \times S) \qquad \textit{Eq. 50}$$

In this thesis, the method is begun with the estimation of frictional resistance.

$$C_F = \frac{0.075}{(\log_{10} R_n - 2)^2}$$

The Reynolds Number R_n, is obtained from:

$$R_n = \frac{VL}{\upsilon} \qquad \textit{Eq. 51}$$

Table 4. 4. Reynold's Number at various speeds

For sea temp at 17 deg		For sea temp at 6 deg	
V (knots)	**Reynold's No**	**V (knots)**	**Reynold's No**
23	2,085E+09	23	1,541E+09
22	1,994E+09	22	1,474E+09
21	1,903E+09	21	1,407E+09
20	1,813E+09	20	1,340E+09
19	1,722E+09	19	1,273E+09
18	1,631E+09	18	1,206E+09
17	1,541E+09	17	1,139E+09
16	1,450E+09	16	1,072E+09
13	1,178E+09	13	8,712E+08
10	9,064E+08	10	6,702E+08
7	6,345E+08	7	4,691E+08
4	3,626E+08	4	2,681E+08
1	9,064E+07	1	6,702E+07
0	0,000E+00	0	0,000E+00

Table 4. 5. Frictional Resistance Coefficient at various speeds

For sea temp at 17 deg		For sea temp at 6 deg	
V (knots)	**Frict Resist (Cf)**	**V (knots)**	**Frict Resist (Cf)**
23	1,400E-03	23	1,452E-03
22	1,407E-03	22	1,459E-03
21	1,415E-03	21	1,468E-03
20	1,424E-03	20	1,476E-03
19	1,432E-03	19	1,486E-03
18	1,442E-03	18	1,496E-03
17	1,452E-03	17	1,506E-03
16	1,462E-03	16	1,517E-03
13	1,500E-03	13	1,557E-03
10	1,549E-03	10	1,610E-03
7	1,621E-03	7	1,685E-03
4	1,743E-03	4	1,815E-03
1	2,113E-03	1	2,209E-03
0	0,000E+00	0	0,000E+00

C_R, the residual resistance, is obtained by from $10^3 C_R$ diagrams in the Guldhammer-Harvald method. These diagrams vary, depending on the value of $\frac{L}{\nabla^{1/3}}$, where L in this calculation is taken as the length on the waterline, L_{WL}, and ∇ is the ship's displacement volume. In this example, the vessel is at it's design loaded draft 11,4 meters.

$$\frac{L}{\nabla^{1/3}} = \frac{199{,}16}{43978{,}53^{1/3}}$$

$$\frac{L}{\nabla^{1/3}} = 5{,}64$$

The C_R graphs does not present one for a specific number such as the result shown, so an interpolation between graphs $\frac{L}{\nabla^{1/3}} = 5{,}5$, such as seen in figure 4.3., and $\frac{L}{\nabla^{1/3}} = 6{,}0$ is applied for precision of results. The results can be seen in table 4.6. Since the Ship dimensional B/T is not equal to the diagram's standards dimension:

$$B/T = 2{,}5$$

Thus the $10^3 C_R$ result values are modified according to the correcting formula:

$$10^3 C_R = 10^3 C_{R(B/T=2{,}5)} + 0{,}16(B/T - 2{,}5)$$

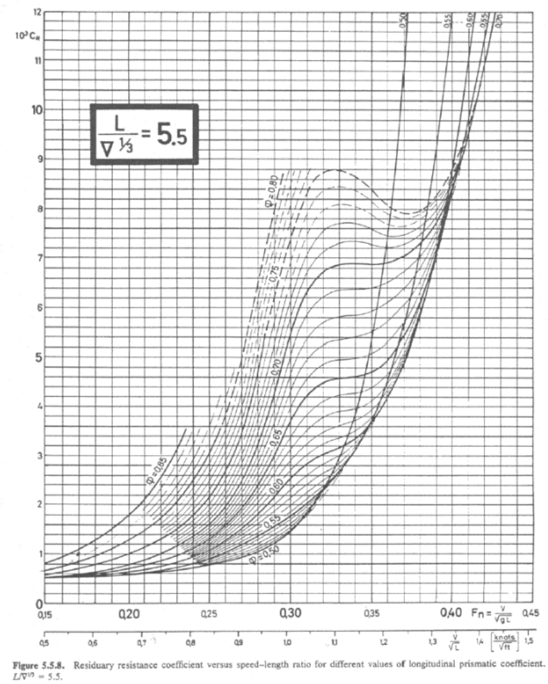

Figure 4. 4. Residual Resistance Coefficient Graph (Harvald, 1983)
Source: Harvald (1983)

Table 4. 6. Calculation of Residual Resistance

V (knots)	Cr*10^3 (5,5)	Cr*10^3 (6,0)	Cr*10^3 (Final)	Cr*10^3 (B/T Correction)
23	2,35	1,96	2,239	2,257
22	1,78	1,59	1,726	1,744
21	1,5	1,36	1,460	1,478
20	1,2	1,07	1,163	1,181
19	1	0,9	0,972	0,990
18	0,83	0,77	0,813	0,831
17	0,78	0,69	0,754	0,773
16	0,68	0,6	0,657	0,675
13	0,5	0,5	0,500	0,518
10	0,5	0,5	0,500	0,518
7	0,5	0,5	0,500	0,518
4	0,5	0,5	0,500	0,518

1	0,5	0,5	0,500	0,518
0	0	0	0,000	0,000

A residual resistance coefficient correction for LCB forward of standard is available. However, in the present reference ship model, the LCB is aft of the standard LCB, which in this case the neglection of the correction shall be of minimal error (Harvald, 1983).

The coefficient which represents the effect of difference between model and actual ship roughness, Incremental Resistance Coefficient C_A, can be estimated using the following expression (Harvald, 1983):

$$1000 \cdot C_A = 0{,}5 \cdot \log(\Delta) - 0.1 \cdot (\log(\Delta))^2$$

$$1000 \cdot C_A = 0{,}5 \cdot \log(45077) - 0.1 \cdot (\log(45077))^2$$

$$1000 \cdot C_A = 0{,}00016$$

The steering resistance and air resistance are expressed, respectively by (Harvald, 1983):

$$10^3 C_{AA} = 0.07$$

$$10^3 C_{AS} = 0.04$$

From the results of calculations obtained above, the coefficients above are processed to acquire table 4.7.:

Table 4. 7. Total Resistance Coefficient at various speeds

For sea temp at 17 deg		**For sea temp at 6 deg**	
V (knots)	**Ct**	**V (knots)**	**Ct**
23	3,963E-03	23	4,014E-03
22	3,457E-03	22	3,509E-03
21	3,199E-03	21	3,252E-03
20	2,910E-03	20	2,963E-03
19	2,728E-03	19	2,781E-03
18	2,578E-03	18	2,632E-03
17	2,530E-03	17	2,584E-03
16	2,443E-03	16	2,498E-03
13	2,324E-03	13	2,381E-03
10	2,373E-03	10	2,433E-03
7	2,444E-03	7	2,509E-03
4	2,567E-03	4	2,639E-03
1	2,937E-03	1	3,033E-03
0	3,054E-04	0	3,054E-04

The effect of bulbous bow on decrease of resistance is expressed by (Kristensen & Lützen, 2013):

$$\Delta C_{R,bulb} = (250 \cdot Fn - 90) \cdot \frac{C_{R\ Harvald\ NO\ bulbous\ bow}}{100}$$

The expression above is applied to the initial C_T values in table 4.7.:

Table 4. 8. Total Resistance Coefficients after bulbous bow correction at various speeds

For sea temp at 17 deg		**For sea temp at 6 deg**	
V (knots)	**Ct**	**V (knots)**	**Ct**
23	3,443E-03	23	3,494E-03
22	3,004E-03	22	3,056E-03
21	2,772E-03	21	2,825E-03
20	2,535E-03	20	2,588E-03
19	2,384E-03	19	2,438E-03
18	2,266E-03	18	2,320E-03
17	2,217E-03	17	2,271E-03

16	2,150E-03	16	2,205E-03
13	2,053E-03	13	2,110E-03
10	2,058E-03	10	2,118E-03
7	2,084E-03	7	2,148E-03
4	2,161E-03	4	2,233E-03
1	2,486E-03	1	2,582E-03
0	3,054E-04	0	3,054E-04

Table 4. 9. Results of Total Resistance with rough estimation of effective Power

		For sea temp at 17 deg		**For sea temp at 6 deg**	
V (knots)	**V (m/s)**	**Rt (kN)**	**P eff. (kW)**	**Rt (kN)**	**P eff. (kW)**
21	10,803	1298,784	14031,183	1327,204	14338,212
20	10,289	1077,121	11082,369	1102,801284	11346,590
19	9,774	914,327	8937,031	937,5244234	9163,772
18	9,260	779,847	7221,375	800,7294457	7414,748
17	8,746	680,547	5951,752	699,3033908	6115,791
16	8,231	584,680	4812,563	601,4079521	4950,251
13	6,688	368,623	2465,269	380,0033438	2541,376
10	5,144	218,574	1124,441	225,6165596	1160,671
7	3,601	108,460	390,578	112,1366603	403,816
4	2,058	36,726	75,573	38,05773747	78,314
1	0,514	2,640	1,358	2,750686657	1,415
0	0,000	0,000	0,000	0	0,000

The effective power P_{Eff} values in kilowatts in table 4.9. are obtained from the commonly used rough empirical estimation expressed by:

$$P_{Eff} = R_T \cdot V_S \qquad \textit{Eq. 52}$$

4.2.2 Estimation for Calm Water Ship Resistance – Method B Holtrop Method

As briefly explained in chapter 2, the Holtrop Method of finding total resistance of a vessel is expressed by (Holtrop & Mennen, 1982):

$$R_T = R_F(1 + k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A$$

The components of calculation in the total resistance approximation are calculated according to the ship dimensional information and additional information obtained from the generated hull model.

$$1 + k_1 \qquad = c_{13}\{0{,}93 + c_{12}(B/L_R)^{0{,}92497}(0{,}95 - C_P)^{-0{,}521448}(1 - C_P + 0{,}0225\ lcb)^{0{,}6906}\}$$

$$L_R = 199{,}162\left(1 - 0{,}69 + 0{,}06 \cdot 0{,}69 \frac{-8{,}35\%*}{4 \cdot 0{,}6967 - 1}\right)$$

*negative sign indicates aft of ship

$$L_R = 60{,}027$$

$$c_{12} = (T/L)^{0{,}2228446} \text{ when } \frac{T}{L} > 0{,}05$$

$$c_{12} = (11{,}4/199{,}1619)^{0{,}2228446}$$

$$c_{12} = 0{,}529$$

$$c_{13} = 1 + 0{,}003\ C_{stern}$$

$$c_{13} = 1 + 0{,}003 \cdot 0$$

$$c_{13} = 1$$

Then, applying the components found for the hull form $1 + k_1$:

$$1 + k_1 \qquad = 1{,}179$$

The appendages resistance is expressed by:

$$R_{APP} = 0{,}5\rho V^2 S_{APP}(1 + k_2)_{eq} C_F$$

The approximated surface area of the appendages is obtained from the hull model obtained, while the frictional coefficient is obtained as of the standard approximation recommended by ITTC-1957.

Table 4. 10. Frictional Coefficient and Appendages Resistance results

For sea temp at 17 deg			For sea temp at 6 deg		
V (knots)	**Cf**	**Rapp**	**V (knots)**	**Cf**	**Rapp**
10,803324	0,00142	16,12885908	21	0,00147	16,72597
10,28888	0,00142	14,71489032	20	0,00148	15,26129
9,774436	0,00143	13,36208111	19	0,00149	13,85981
9,259992	0,00144	12,07077274	18	0,00150	12,52191
8,745548	0,00145	10,84132812	17	0,00151	11,24795

8,231104	0,00146	9,674134355	16	0,00152	10,03835
6,687772	0,00150	6,550365831	13	0,00156	6,800213
5,14444	0,00155	4,003952642	10	0,00161	4,159247
3,601108	0,00162	2,052307143	7	0,00169	2,133773
2,057776	0,00174	0,720721289	4	0,00181	0,750423
0,514444	0,00211	0,054609877	1	0,00221	0,057096
0	0,00000	0	0	0,00000	0

The wave resistance as described in chapter 2 is expressed by:

$$R_W = c_1 c_2 c_5 \nabla \rho g \; exp\{m_1 F_n^d + m_2 \cos(\lambda F_n^{-2})\}$$

with the coefficients expressed by (along with calculation results):

$c_1 \quad = 2223105 c_7^{3,78613} (T/B)^{1,07961} (90 - i_E)^{-1,37565}$

$c_7 \quad = B/L$ when $0,11 < B/L <$
$0,25$

$c_7 \quad = 29,8/199,1619$

$c_7 \quad = 0,15$

$c_3 \quad = 0,56 A_{BT}^{1,5} / \{BT(0,31\sqrt{A_{BT}} + T_F - h_B)\}$

$c_3 \quad = 0,56 \cdot 16/\{29,8 \cdot 11,4(0,31\sqrt{16} + 11,4 - 2,85)\}$

$c_3 \quad = 0,010776$

$c_2 \quad = exp(-1,89\sqrt{c_3})$

$c_2 \quad = exp(-1,89\sqrt{0,010776})$

$c_2 \quad = 0,822$

$c_5 \quad = 1 - 0{,}8 A_T/(B\ T\ C_M)$

$c_5 \quad = 1 - 0{,}8 \cdot 9{,}592/(29{,}8 \cdot 11{,}4 \cdot 0{,}93)$

$c_5 \quad = 0{,}976$

$\lambda \quad = 1{,}446 C_P - 0{,}03 L/B$ when $L/B < 12$

$\lambda \quad = 1{,}446 \cdot 0{,}69 - 0{,}03 \cdot 199{,}1619/29{,}8$

$\lambda \quad = 0{,}807$

$c_{16} \quad = 8{,}07981 C_P - 13{,}8673 C_P^2 + 6{,}984388 C_P^3$ when $C_P < 0{,}8$

$c_{16} \quad = 8{,}07981 \cdot 0{,}69 - 13{,}8673 \cdot 0{,}69^2 + 6{,}984388 \cdot 0{,}69^3$

$c_{16} \quad = 1{,}26$

$m_1 \quad = 0{,}0140407\, L/T - 1{,}75254\, {\nabla^{1/3}}/{L} + 4{,}79323\, B/L - c_{16}$

$m_1 \quad = 0{,}0140407\, 199{,}1619/11{,}4 - 1{,}75254\, {43978^{1/3}}/{199{,}1619} + 4{,}79323\, 29{,}8/199{,}1619 - 1{,}26$

$m_1 \quad = -2{,}043$

$c_{15} \quad = -1{,}69385$ for $L^3/\nabla < 512$

$c_{15} \quad = -1{,}69385$

$m_2 \quad = -1{,}69385 \cdot 0{,}69^2\ exp(-0{,}1 F_n^{-2})$

m_2 = [refer to table]

$d \quad = -0{,}9$

The results of the values of m_2 vary along with different speeds, and can be seen in table 4.11.

Table 4. 11. Wave Resistance results along with m² values

V	Velocity(m/s)	Fn	m_2	Rw
1+	10,803	0,24454	-0,154392371	392,782
SS	10,289	0,23289	-0,130071612	339,631
1-	9,774	0,22125	-0,106580607	234,668
2-	9,260	0,20960	-0,084403297	135,835
3-	8,746	0,19796	-0,064067785	95,291
4-	8,231	0,18631	-0,046108157	58,465
7-	6,688	0,15138	-0,010464244	8,654
10-	5,144	0,11645	-0,000515257	0,438
13-	3,601	0,08151	-2,3901E-07	0,002
16-	2,058	0,04658	-7,88702E-21	0,000
19-	0,514	0,01164	0	0,000
10-	0,000	0,00000	0	-

The near-surface bulbous bow additional resistance is expressed by:

$$R_B = 0,11\, exp(-3P_B^{-2})F_{ni}^3 A_{BT}^{1,5}\rho g/(1+F_{ni}^2)$$

To fulfil the equation, a requirement to calculate some values are necessary:

$$P_B = 0,56\sqrt{A_{BT}}/(T_F - 1,5h_B)$$

$$P_B = 0,56\sqrt{16}/(11,4 - 1,5 \cdot 2,85)$$

$$P_B = 0,314$$

$$F_{ni} = V/\sqrt{g\left(T_F - h_B - 0,25\sqrt{A_{BT}}\right) + 0,15V^2}$$

The value of the immersed Froude Number F_{ni} varies along the speed, and the values can be seen in table 4.12.

Table 4. 12. Immersed Froude Number values per speed

For sea temp at 17 deg		For sea temp at 6 deg	
V (knots)	**Fni**	**V (knots)**	**Fni**
21	2,150	21	2,149
20	2,117	20	2,116
19	2,081	19	2,080
18	2,040	18	2,039
17	1,995	17	1,994
16	1,945	16	1,944
13	1,759	13	1,758
10	1,503	10	1,502
7	1,157	7	1,156
4	0,711	4	0,710
1	0,184	1	0,184
0	0,000	0	0,000

With the calculation obtained in table 4.12, it is possible to obtain R_B:

Table 4. 13. Bulbous bow surface proximity Additional Resistance calculation results

For sea temp at 17 deg		For sea temp at 6 deg	
V (knots)	**Rb**	**V (knots)**	**Rb**
21	8,2226E-12	21	8,24161E-12
20	8,0514E-12	20	8,06964E-12
19	7,8618E-12	19	7,87921E-12
18	7,6514E-12	18	7,66798E-12
17	7,4177E-12	17	7,43331E-12
16	7,1577E-12	16	7,17224E-12
13	6,1858E-12	13	6,19672E-12
10	4,8482E-12	10	4,85483E-12
7	3,0815E-12	7	3,08382E-12
4	1,1109E-12	4	1,1106E-12
1	2,8231E-14	1	2,81933E-14
0	0	0	0

The transom immersion resistance as explained in chapter 2 is expressed by (Holtrop & Mennen, 1982):

$$R_{TR} = 0{,}5\rho V^2 A_T c_6$$

The coefficient c_6 is found from:

$c_6 \quad = 0{,}2(1 - 0{,}2F_{nT}) \quad$ when $F_{nT} < 5$

$c_6 \quad = 0 \quad$ when $F_{nT} \geq 5$

$F_{nT} \quad = V/\sqrt{2gA_T/(B + BC_{WP})}$

Table 4. 14. Calculation of Transom Immersion Resistance

For sea temp at 17 deg				For sea temp at 6 deg			
V (knots)	**Fnt**	**c6**	**R TR**	**V (knots)**	**Fnt**	**c6**	**R TR**
21	17,89628	0	0	21	17,87015	0	0
20	17,04408	0	0	20	17,01919	0	0
19	16,19187	0	0	19	16,16823	0	0
18	15,33967	0	0	18	15,31727	0	0
17	14,48747	0	0	17	14,46631	0	0
16	13,63526	0	0	16	13,61535	0	0
13	11,07865	0	0	13	11,06247	0	0
10	8,522039	0	0	10	8,509595	0	0
7	5,965428	0	0	7	5,956717	0	0
4	3,408816	0,063647369	1,32489	4	3,403838	0,063846472	1,329034147
1	0,852204	0,165911842	0,215852	1	0,85096	0,165961618	0,215917037
0	0	0,2	0	0	0	0,2	0

The model-ship correlation resistance R_A as briefed in chapter 2 is expressed by:

$$R_A = {}^{1}/_{2}\,\rho\, V^2\, S\, C_A$$

$C_A \quad = 0{,}006(L + 100)^{-0{,}16} - 0{,}00205 + 0{,}003\sqrt{L/7{,}5}\, C_B^4 c_2 (0{,}04 - c_4)$

$c_4 \quad = 0{,}04$ when $T_F/L > 0{,}04$

$T_F/L \quad = 0{,}057$, so

$c_4 \quad = 0{,}04$

$C_A \quad = 0{,}006(+100)^{-0{,}16} - 0{,}00205 +$
$0{,}003\sqrt{199{,}16/7{,}5}\,0{,}65^4\;0{,}822(0{,}04 - 0{,}04)$

$C_A \quad = 0{,}00036$

Table 4. 15. Calculation of Model-Ship correlation resistance

For sea temp at 17 deg		**For sea temp at 6 deg**	
V (knots)	**R A**	**V (knots)**	**R A**
21	167,746447	21	167,7464471
20	152,150972	20	152,1509725
19	137,316253	19	137,3162526
18	123,242288	18	123,2422877
17	109,929078	17	109,9290776
16	97,3766224	16	97,37662237
13	64,2837859	13	64,28378586
10	38,0377431	10	38,03774311
7	18,6384941	7	18,63849413
4	6,0860389	4	6,086038898
1	0,38037743	1	0,380377431
0	0	0	0

With the available information of each resistance components from the tables previously calculated, the total resistance can be found, which is the sum of the components:

$$R_T = R_F(1 + k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A$$

The results of the summation is found in table 4.15.

Table 4. 16. Results of total resistance calculation

For sea temp at 17 deg		For sea temp at 6 deg	
V (knots)	**Rt**	**V (knots)**	**Rt**
21	1354,56974	21	1383,966001
20	1216,212	20	1243,111639
19	1029,814	19	1054,317915
18	853,334249	18	875,5441869
17	738,95059	17	758,969196
16	632,109381	16	650,0402711
13	395,419353	13	407,7196065
10	235,594717	10	243,2400204
7	119,677835	7	123,6884663
4	42,8928071	4	44,3591774
1	3,28473225	1	3,4071682
0	0	0	0

Table 4. 17. Comparison of results of classic resistance estimation methods

From the approximation of the total resistance, both classic estimation methods have a similar result. A comparison between the Holtrop method and the Guldhammer-Harvald method results can be seen in table 4.16. Table 4.17. shows data from the sea trial recording. A direct comparison between the calm water resistance estimation and the sea trial would not be

		For sea temp at 17 deg		For sea temp at 6 deg	
V (knots)	**V (m/s)**	**Rt [Harvald] (kN)**	**Rt [Holtrop] (kN)**	**Rt [Harvald] (kN)**	**Rt [Holtrop] (kN)**
21	10,803	1298,784	1354,56974	1327,204	1383,966001
20	10,289	1077,121	1216,212	1102,801284	1243,111639
19	9,774	914,327	1029,814	937,5244234	1054,317915
18	9,260	779,847	853,334249	800,7294457	875,5441869
17	8,746	680,547	738,95059	699,3033908	758,969196
16	8,231	584,680	632,109381	601,4079521	650,0402711
13	6,688	368,623	395,419353	380,0033438	407,7196065
10	5,144	218,574	235,594717	225,6165596	243,2400204
7	3,601	108,460	119,677835	112,1366603	123,6884663
4	2,058	36,726	42,8928071	38,05773747	44,3591774
1	0,514	2,640	3,28473225	2,750686657	3,4071682
0	0,000	0,000	0	0	0

precise, considering that the sea trial conditions (also stated) do not qualify as the ideal calm water sea state. However, even if a far-fetched comparison, it could provide clarity for further corrections and for finding conclusions.

Table 4. 18. Sea Trial test records

Test No	kW indic. kW	kW eff. kW	Log knots knots	Obs knots knots	RPM	Wind m/s	AngleWind deg	Wave height m	AngleWave deg	Draft fore m	Draft aft m	Draft Mean m
5	17282	16259	22,2	21	108	8	135	1	180	9,9	10,3	10,1
6	14781	13796	22	21,5	104	2	350	0,5	340	9,8	10,4	10,1
9	13634	12676	20,9	20,2	101,1	7	75	1	75	8,7	9,5	9,1
16	16072	14840	20,2	20,5	103,4	3	80	0	0	10,3	11,5	10,9
20	16483	15850	22	22	108	5	300	0,5	300	9,7	10,7	10,2
22	15414	14710	21,5	20,3	104,1	6	310	0,2	10	10,4	11,1	10,75
-	14902	14720	20	20,3	104,1	6	280	1	280	11,5	11,6	11,55
-	16963	16440	21	20,9	107,9	8	10	1,5	35	11	11	11

When calculated with a propulsive coefficient, the brake power BHP of the engine can be estimated from an EHP approximation.

$$BHP = \frac{EHP}{\eta_G \cdot \eta_S \cdot \eta_{RR} \cdot \eta_O \cdot \eta_H} \qquad \textit{Eq. 53}$$

For this comparison example, a total of the propulsive efficiency multiplication is assumed 0,723. The example from classic resistance theory will be taken at Vs of 21 knots with a resistance of 1298,784 kN (from the first method).

$$BHP_{est.} = \frac{1298{,}784 * 10{,}803}{0{,}723}$$

$$BHP_{est.} = 19407 \text{ kW}$$

A sample from the sea trial, “Test No. 16” at 16072 $kW_{indic.}$ / 14840 kW_{eff} is selected (refer to Table 4.18). Note here that the effective power refers to the measured power at the engine. This sample is necessary for the comparison because the general direction of weather is bow waves, with relatively small wind and waves strength.

$$BHP_{est.} > BHP_{actual}$$

When compared with the resultative brake horsepower estimation, the results suggest that the actual required power is of the ship is lower than the results of using the current setup with the classical resistance estimation theories. The quite large difference in magnitude does not satisfy accuracy of the model. However, the results of the classical estimation methods may provide clarity for further analysis when tweaking the model.

4.3 Computer-Based Numerical Simulation

4.3.1 Simulation Overview

In chapter subsection 2.2.3, it was concisely explained about the concept of theoretical model simulation, which one of the methods mentioned is the Monte Carlo Simulation. However, in the Monte Carlo Simulation, the simulation is done by stochastic means, where the inputs are totally random resulting in widely various outputs.

To narrow down the scope of research when testing the model, it is necessary to put up certain parameters based on current knowledge that will result in an output more relatable with the actual ship recorded data. These parameters are in a certain range that are likely to occur for the target range of operating speed and power.

The simulation is can be easily understood when divided into three main sections, the Input, the Transfer Function (Model processing), and the resultative Output. The variation of values under parameters are done for the input section. The members of each section can be seen in Figure 4.5.

The input section consists of:

i. Initial Forward Speed $V_{s\ init.}$

   The initial forward speed refers to the desired travel speed of the vessel that isn't affected by the change in weather conditions. The model assumes the hull and machinery are in optimal conditions, therefore influence towards speed from such factors are ignored.

ii. Beaufort Number

   The weather conditions are represented in the Beaufort Number, which mainly determines the magnitude of the speed loss or power increase.

iii. Angle of Attack

   The overall angle of the wind and waves which also determine the severity and nature of the weather influence.

iv. Draft

Conditions of a loaded container ship are unlikely always the same, however the change in draft load influence the displacement of the ship, affecting the total resistance and consequently increasing or decreasing propulsive power requirement.

v. Propulsive Efficiencies

Propulsive efficiencies refer to the efficiencies of the propulsive coefficient, the gearbox and shaft efficiency which are determinants of the transition between Effective Horsepower EHP, and Brake Horsepower BHP. In this case, the propulsive efficiencies are held as constant values (not generated variously during simulation).

The transfer function consists of:

i. Displacement Volume (∇)

The displacement volume is the ship's displacement in volume m^3 and is essential to the determination of the ship form coefficient.

ii. Corresponding Resistance

The corresponding resistance refers to the initial resistance which is the approximation of the calm water resistance required under certain conditions and a specific travel speed.

iii. Speed Reduction Coefficient (C_U)

The speed reduction coefficient relates to the speed of the vessel which is expressed in the value of the Froude Number (F_n). The value is also determined by the ship's coefficient block.

iv. Direction Reduction Coefficient (C_β)

The direction reduction coefficient, self-explanatory, relates to the overall angle of the weather, in respect to the ship's bow, which is determinant towards the value of the coefficient itself.

v. Ship Form Coefficient (C_{form})

The ship form coefficient is dependent on the ship type, the load conditions, the displacement volume (∇), and the weather magnitude on the Beaufort Scale.

vi. Percentage Speed Loss

The results of the approximation of weather influence is represented in the form of a percentage of speed loss according to Kwon's method.

vii. Initial Power Requirement

This is the estimated engine brake power when the ship is subjected to the initial speed input in calm water with optimal conditions.

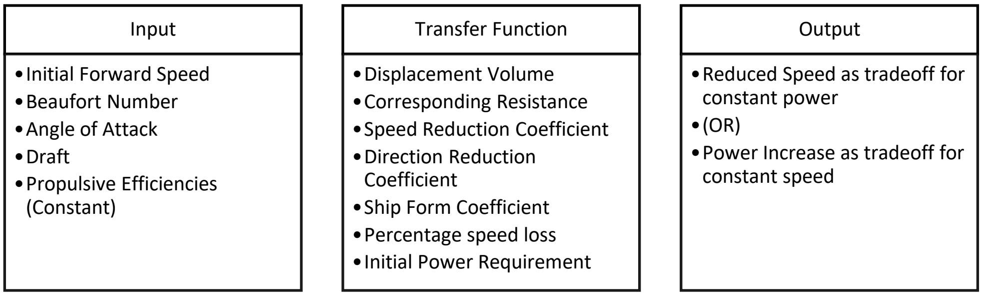

Figure 4. 5. Simulation Overview

The output section consists of:

i. The reduction of speed from the desired travel speed if a decision to remain at the same initial power is made.
ii. The increase of required engine power from the initial power setting if a decision to remain at the same initial speed is made.

4.3.2 Creation of the Model-Simulation

The model is created based on the Kwon method of approximating speed loss caused by weather influence, with a basis on the classical estimation methods to supply the required calm water resistance. As mentioned in section 4.2, the classic resistance theory methods' results do not well reflect the sea trial test results. The simulation done in the analysis of this thesis is created to correct the values by iterating experiments with the model.

The creation of the model-simulation is done using the Microsoft Excel spreadsheet software, which enables a simple creation of a stochastic simulation with a relatively large number of generated inputs.

η_G	1
η_S	0,98

Input Side							
BN	Angle	Draft	Vs init.	Vs init. m/s	η_H	η_{RR}	η_O
5	3	11,82722	20,38213	10,48463	1,081	1,05	0,65
4	3	11,88967	21,97342	11,3032	1,081	1,05	0,65
4	2	11,36595	21,51044	11,06504	1,081	1,05	0,65
9	2	11,07355	21,02747	10,8166	1,081	1,05	0,65
3	3	9,305214	20,8388	10,71954	1,081	1,05	0,65

Figure 4. 6. Input side of the model-simulation

Figure 4.6 shows the input section of the model-simulation. As seen, the numbers in the content of the table are arbitrary, this is because of the intended function used. An example of the generation of input which will be showcased is the Beaufort Number generation. It can be seen in figure 4.7, that the function “RANDBETWEEN” is used to generate a random value between the lower limit and upper limit parameters, respectively in order; cell “H5” and “I5”. It is then added with the lower limit value to enter the intended range. The result is a rounded value, which is the correct form to use the Beaufort Scale. The same steps are done to find the “Angle” input generation.

Figure 4. 7. Function formula for Beaufort Number generation

Another type of input variable uses a slightly different function, which for example is the generation of a draft value. The "Draft" function uses the "RAND" function, which generates a random number including the decimals, which is more ideal for the draft number form. The generated random value is added with the lower limit value to enter the intended range. The same steps are applied to the generation of the initial vessel speed.

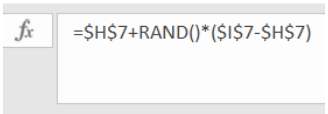

Figure 4. 8. Function formula for random Draft generation

The parameters used in the showcase simulation is listed in table 4.18. The range of parameter values shown are selected after several iterations and shown to near the ship recorded data when analysed in graphs and is satisfactory in some areas. This is one of the principles when attempting the model simulation.

Table 4. 19. Showcased simulation parameters

Parameter	**Min**	**Max**
BN	0	9
Angle	1	4
Draft	9,0	12,0
Vs Init.	19	23,5

The transfer side of the model-sim reflects the series of processes of conversion from the generated input to an output based on the theories and approximations mentioned in chapter 2.

Transfer Side								
R Init. (kN)	Draft (Rd)	V Disp (m^3)	Froude	C_B	C_U	C_{Form}	$\frac{\Delta V}{V_1}100\%$	Power Init.
890,8547	9,6	35464,2	0,23061	0,835	1,129846	3,971258	3,746569	12494,9
1169,17	10,9	41553,55	0,245669	0,33	0,990931	32,09249	10,49448	17469,31
1181,016	11,1	42517,87	0,245914	0,79	0,988624	7,264284	5,6735	17663,92
963,8108	11,1	42517,87	0,229256	0,61	1,142077	31,6661	22,06072	13438,81

Figure 4. 9. Transfer side of the model-simulation

The function for the initial resistance (R Init.), is determined by the generated initial speed value and draft value, and then refers to the value of resistance plotted in the resistance per draft table as seen in Figure 4.11. The values of resistance are found from iterations of each 0,1 change in draft value using the Guldhammer-Harvald method of approximating resistance. The range of the information is obtained and listed from the draft of 9 meters to 12 meters, and from the speed range of 19 knots to 23 knots.

```
fx  =IF(AND(E19>=18,5;E19<19,5);VLOOKUP(L19;'Displacement Table'!$C$3:
    $J$33;4;FALSE);IF(AND(E19>=19,5;E19<20,5);VLOOKUP(L19;
    'Displacement Table'!$C$3:$J$33;5;FALSE);IF(AND(E19>=20,5;E19<21,5);
```

Figure 4. 10. Initial Resistance function formula

The formula for the initial resistance function can be seen in Figure 4.10, where the function “IFAND” is used to determine the speed value (cell

“E19”) available, and the “VLOOKUP” is used to gather the correct information from the displacement/resistance per draft table seen in Figure 4.11.

No.	T (m)	Displacement (ton)	Displacement (m^3)	R at V=19	R at V=20	R at V=21	R at V=22	R at V=23
1	9	33590	32770,392	719,577	851,424	1048,195	1265,167	1556,499
2	9,1	34045	33214,268	723,9541111	857,99578	1055,05589	1273,5246	1567,833
3	9,2	34502	33660,256	728,3312222	864,56756	1061,91678	1281,8821	1579,166
4	9,3	34961	34108,147	732,7083333	871,13933	1068,77767	1290,2397	1590,5
5	Plot Area	35422	34558,063	737,0854444	877,71111	1075,63856	1298,5972	1601,833
6	9,5	35885	35010,128	741,4625556	884,28289	1082,49944	1306,9548	1613,167
7	9,6	36351	35464,203	745,8396667	890,85467	1089,36033	1315,3123	1624,5

Figure 4. 11. Screen capture of Displacement-Resistance per draft series

The Draft information in the transfer side is only the rounded values of the draft value in the previous input table. This is done in order to enable the function in the “R init.” and “Draft” to gather information required according to the corresponding rounded draft value.

The “V Disp” column function behaves with the same principle as the initial resistance function has. The “V Disp” and “R Init” both make use of the spreadsheet function “VLOOKUP”, where both are determined by gathering information from the resistance-displacement per draft table (refer to Figure 4.11). The “V Disp” value is crucial to represent the differences caused by various draft levels, such as the ship form coefficient as explained in previous points.

The Froude function is simply the spreadsheet operation which represents the normal Froude Number conversion from speed traveling in a fluid:

$$Fn = \frac{V}{\sqrt{gL}}$$

This equation in the excel function form can be seen in figure 4.12.

```
fx  =(E19/1,944)/SQRT(9,80665*197,19)
```

Figure 4. 12. Froude Number function

The direction reduction coefficient C_β function makes use of the spreadsheet function “IF” to determine which direction (Angle which is referred to as cell “B19” in figure 4.13) the Beaufort Number (referred as cell “C19”) value in the input side is grouped in, and then applying the matching formula described in Kwon’s approximation method. Figure 4.13 shows the spreadsheet function applied to attempt this.

```
fx  =IF(C19=1;1;IF(C19=2;(1,7-0,03*POWER((B19-4);2))/2;IF(C19=3;(0,9-
    0,06*POWER((B19-6);2))/2;IF(C19=4;(0,4-0,03*POWER((B19-8);2))/2))))
```

Figure 4. 13. Direction Reduction Coefficient function

The speed reduction coefficient C_U function is simply the mathematical spreadsheet function of the corresponding formula expressed by Kwon, according to the ship loading condition and coefficient block and Froude Number.

$$2.6 - 3.7F_n - 11.6(F_n)^2$$

Refer to figure 4.14 to see the spreadsheet function form of the expression mentioned.

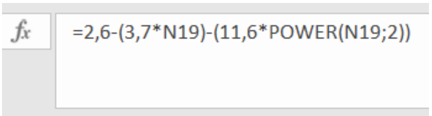

Figure 4. 14. Speed Reduction Coefficient function

The speed loss percentage is simply the multiplication of the three coefficients required by Kwon's method. However, the initial brake power (Power Init.) is the function of the loose approximation of effective horsepower divided by the propulsive efficiencies mentioned in the beginning of subchapter 4.3.1.

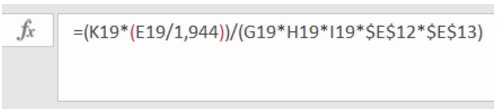

Figure 4. 15.Initial Brake Power function

The output side of the spreadsheet model-simulation is straightforward the result of the percentage speed loss and the conversion to power. The Power Increase function follows the expression of speed loss to power conversion which is (Molland, Turnock, & Hudson, 2011):

$$\frac{\Delta P}{P} = \frac{1}{\left(1 - \frac{\Delta V}{V_S}\right)^3} - 1 \qquad \textit{Eq. 54}$$

Figure 4.16 shows the spreadsheet operational function formula which portrays the expression, with cell "Z19" as the reduced speed and cell "F19" as the initial speed (in calm water), both in units of meters per second. The "Vs constant" is just a reinsertion of the initial speed "V Init".

The "Vs red. m/s" column is the reduced speed in units of meters per second. The spreadsheet function formula is shown in figure 4.17 with cell "F19" as the initial speed and cell "R19" as the percentage speed loss.

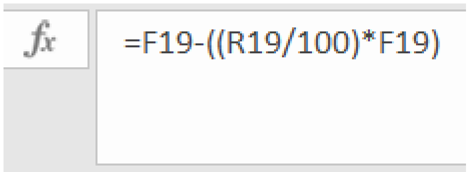

Figure 4. 16. Reduced Speed function formula

The last column is the "Cpv" function is the spreadsheet function of the coefficient of the increased power (the brake power after conversion from speed loss) divided by the initial speed to the power of 3. This follows the principle of power-speed relation expressed by:

$$P \sim c \cdot V^n$$

with the assumed value of n as 3. The use of this information is crucial towards the evaluation and benchmarking of the model-simulation. It will be explained in subchapter 4.3.3.

The last step in the creation of the model-simulation is the setup of the "Cpv Bin". The term "bin" is understood in the means of collection of the nearly similar values. The bins vary per a 0,5 difference starting from a C_{pv} value of 1,25 to 2,15. The value of "-1" is the indicator if the C_{pv} results in a value outside of that range, and could be understood as "others". Figure 4.17 shows the spreadsheet function "IF" which can determine which bin the C_{pv} value

```
fx  =IF(AND(AA19>=1,25;AA19<1,275);1,25;IF(AND(AA19>=1,275;AA19<
    1,325);1,3;IF(AND(AA19>=1,325;AA19<1,375);1,35;IF(AND(AA19>=1,375;
    AA19<1,425);1,4;IF(AND(AA19>=1,425;AA19<1,475);1,45;IF(AND(AA19>=
```

Figure 4. 17. C_{pv} Bin function formula

4.3.3 Evaluation of Simulation Results

One of the most important aspects of the modelling scheme is to benchmark the model results with the actual recorded data, to ensure the level of accuracy and to draw conclusions of the behaviour of the model. Using the bin system explained in 4.3.2, a comparison between the model results and the ship recorded data can be done. Figure 4.18 shows an example of the results of a couple of samples from one attempt of random number generation.

Accumulation
Cpv Bin
-1
1,7
1,7
2,15
-1
-1

Figure 4. 18. C_{pv} bin result example from a random attempt

The results of the C_{pv} bins are very detrimental to the results that will be analysed and compared to the ship recorded voyage data. It can be seen from figure 4.20 that the tendency from random number generation with the current parameters results mostly in a "-1" value (out of range). It is inferred from subchapter 4.1.1 that the ship recorded data shows that in the recorded lifetime most C_{pv} values are in the range of 1,40 to 1,65. One step that will support the analysis to be more credible is if the generation of samples are closer to the recorded data range of bins. After a few regenerations of the simulation using the spreadsheet refresh "F8" function, a more optimal set of samples is obtained.

The next step that is done to narrow down the scope of analysis is by removing extreme values which are the values outside the average range of the ship data. The model-simulation results first must be frozen to avoid another regeneration of generated data. This is done by copying the input values with a "RAND" function and pasting the values to stop it from generating new results.

Figure 4. 19. Two sheets: Sheet with active sample regeneration, and a sheet with frozen sample results

After the sample results are frozen, it is possible to use the spreadsheet "Sort & Filter" tool to sort and let the values with "-1" indicators to appear in one section. The values with "-1" are deleted, which results in removing clutter and simplifying the analysis process.

Bin Count	Amount	Probability Count
1,25	0	0%
1,3	0	0%
1,35	6	0%
1,4	28	1%
1,45	51	1%
1,5	73	1%
1,55	122	2%
1,6	153	3%
1,65	162	3%
1,7	179	4%
1,75	172	3%
1,8	186	4%
1,85	233	5%
1,9	226	5%
2,15	178	4%
-1	3232	65%

Figure 4. 20. Bin Count of one random generation attempt

Figure 4.21 shows the showcased generated set of samples. The results seen are an even narrower filtering of the C_{pv} bins, where most results out of the recorded ship data range are omitted. It is seen from this set of results, a larger number of samples are available in the 1,60 – 1,70 range, which is quite close to the desired range of samples. The resulting samples are deemed worthy for an analysis attempt.

Bin Count	Amount	Probability Count
1,25	0	0%
1,3	0	0%
1,35	0	0%
1,4	0	0%
1,45	15	2%
1,5	56	6%
1,55	100	11%
1,6	126	14%
1,65	191	22%
1,7	244	28%
1,75	142	16%
1,8	0	0%
1,85	0	0%
1,9	0	0%
2,15	0	0%
-1	0	0%

Figure 4. 21. Filtered set of frozen showcase sample results

After the application of the steps above, it is possible to analyse and compare the simulation results with the processed ship recorded data. One of the most common analysis methods in the Monte Carlo Simulation and other similar concepts are through the plotting of data on a histogram. To observe the comparison at a larger scale, the immediate action is to plot the set of results to a graph in comparison with each vessel.

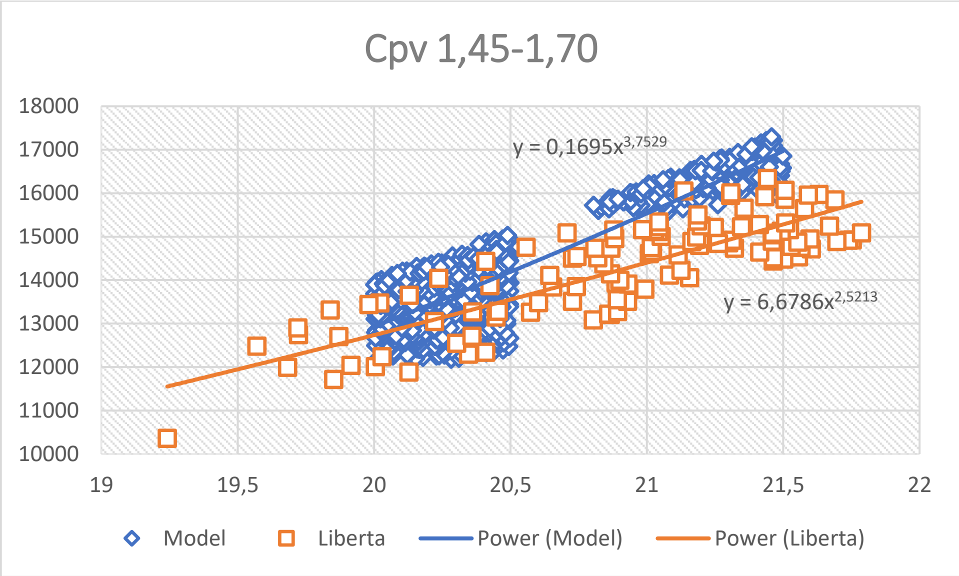

Figure 4. 22. Comparison of Liberta recorded data with model results (Overall)

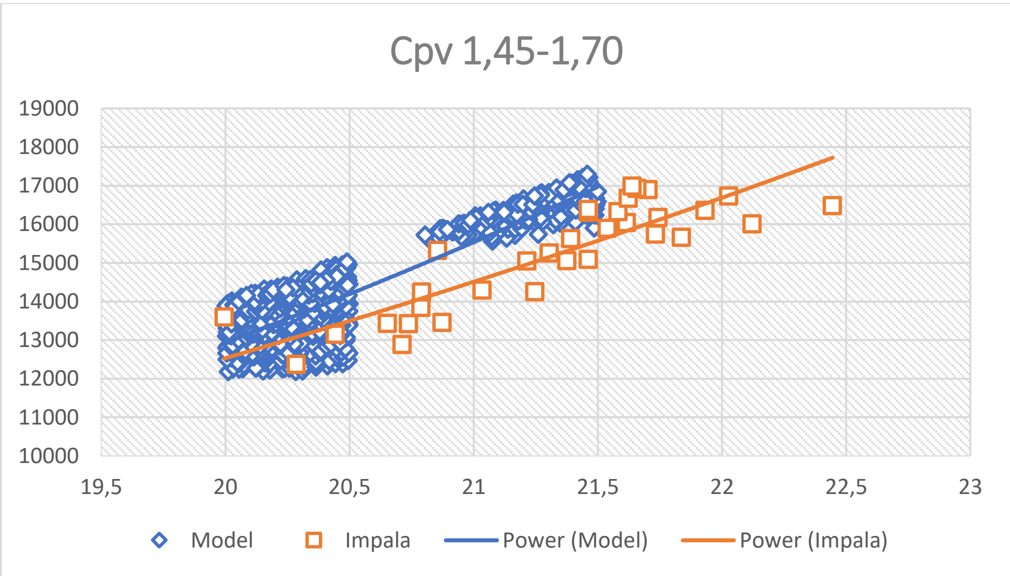

Figure 4. 23. Comparison of Impala recorded data with model results (Overall)

It can be inferred from Figure 4.22 and figure 4.23 that the average line of the simulation results is situated quite close to the average line of the model results. However, the data samples for Impala are significantly fewer compared to its counterpart, so its relevancy is more questionable. One trait that both comparisons show is the increase in the model average line's deviation from the ships' recorded data average lines. To see the percentage error, the following expression can be used:

$$\delta = \left|\frac{\upsilon_A - \upsilon_E}{\upsilon_E}\right| \cdot 100\% \qquad \textit{Eq. 55}$$

δ : percentage of error

υ_A : actual observed value

υ_E : expected value

From the application of the error percentage formula, the diagram in Figure 4.24 is obtained. The error count of the average line comparison suggests that at the speed of approximately 19,7 knots, the average model-simulation results is close to the actual recorded observation. One conclusion of the model that can be inferred from this phenomenon is that the power-speed behaviour from the current setup does not perfectly reflect the actual ship power-speed relation.

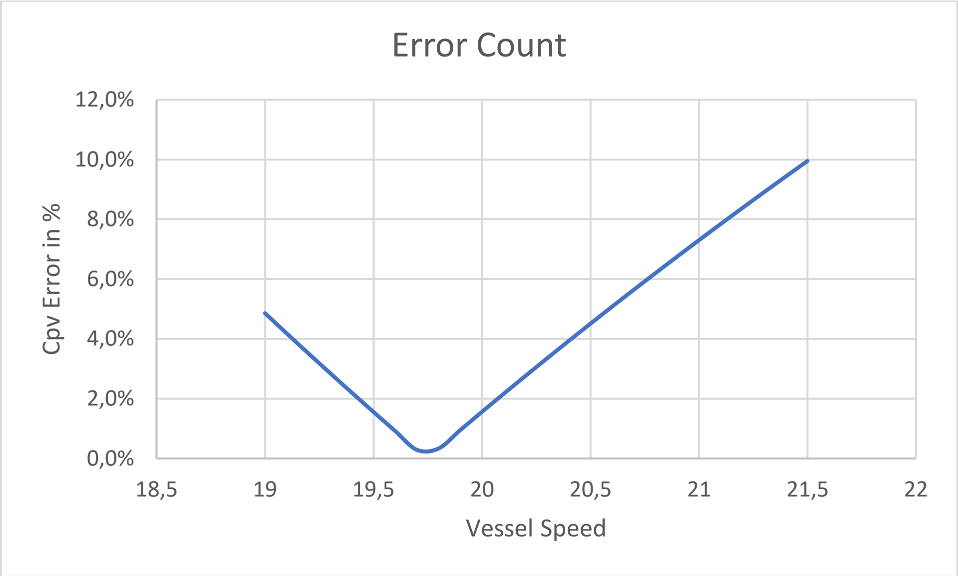

Figure 4. 24. Error Count of comparison between simulation results and Liberta data

This conclusion is strengthened by the results in figure 4.25, where plotting the function of power of both average lines results in two lines that intersect at approximately 19,7 knots, however stray away when at higher and lower speeds.

Figure 4. 25. Comparison between the Model average and Liberta average equations at average operation speed

By using the function of power from the average line of the filtered model simulation results and the ship recorded observation data, a plot to see a rough comparison of the average value of the current model setup and actual data can be done.

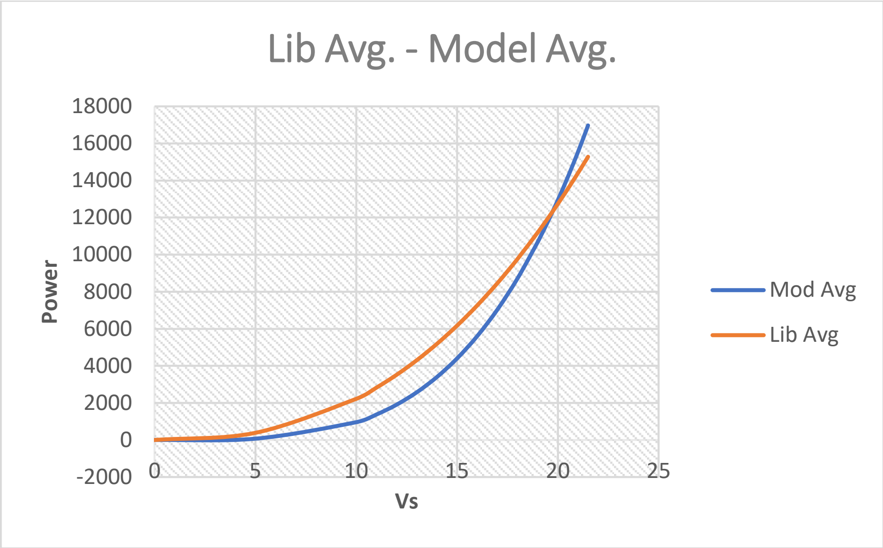

Figure 4. 26. Comparison of Model analysis average line with the ship average line at a larger scale

Figure 4.26 shows that both of the average lines behave relatively similar, however at the middle range of the plot, the error is larger. This is naturally the effect of the model being based on the available operational data, where most of the samples of data fall in the 19 knots – 22 knots. Operational data samples outside that range are too few to be considerable.

A deeper analysis towards this occurrence is done by narrowing the scope of research even more. One opportunity is to narrow down the set of results to a smaller draft range.

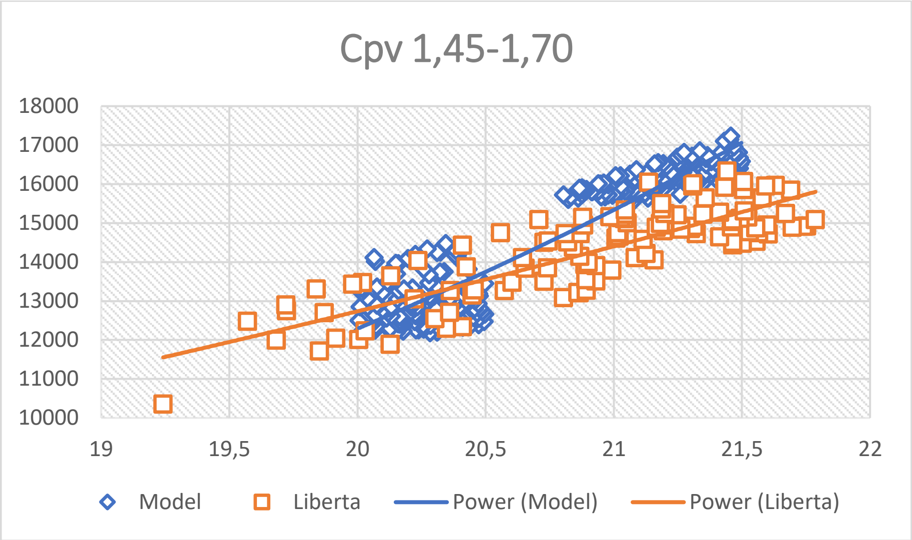

Figure 4. 27. Comparison of the average lines under a smaller scope (Draft 9,0 m-9,5 m)

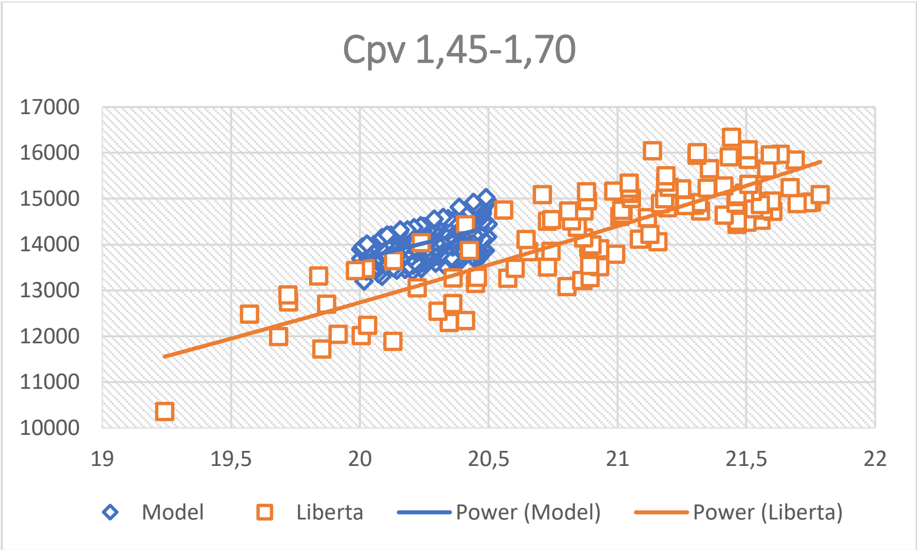

Figure 4. 28. Comparison of the average lines under a smaller scope (Draft 10 m - 10,5 m)

From Figure 4.27, the intersection which was not seen in the overall graph (refer to Figure 4.22) is present in this scope of analysis. This suggests that the current model-simulation setup is well adjusted to this range of draft. A far-fetched conclusion may also be inferred that the average load draft of the ship has operated in is in this range. Figure 4.28 shows that at a higher draft range the estimated ship power deviates more, and the lack of compatible samples at higher speeds suggests that with the current model setup this range of draft is less accurate.

In an operational data-based research by Lakshmynarayanana and Hudson to acquire added power estimation from derivation of the total operational power, the classic semi-empirical calm water resistance estimation (Holtrop method) also shows an increasingly larger deviation at higher drafts. In the research it is seen that between the Holtrop method (converted to shaft power) and data fit line of the operational data, a very similar situation occurs. The estimation and operational data line are closer to each other at the draft of 9,0 m – 9,5 m.

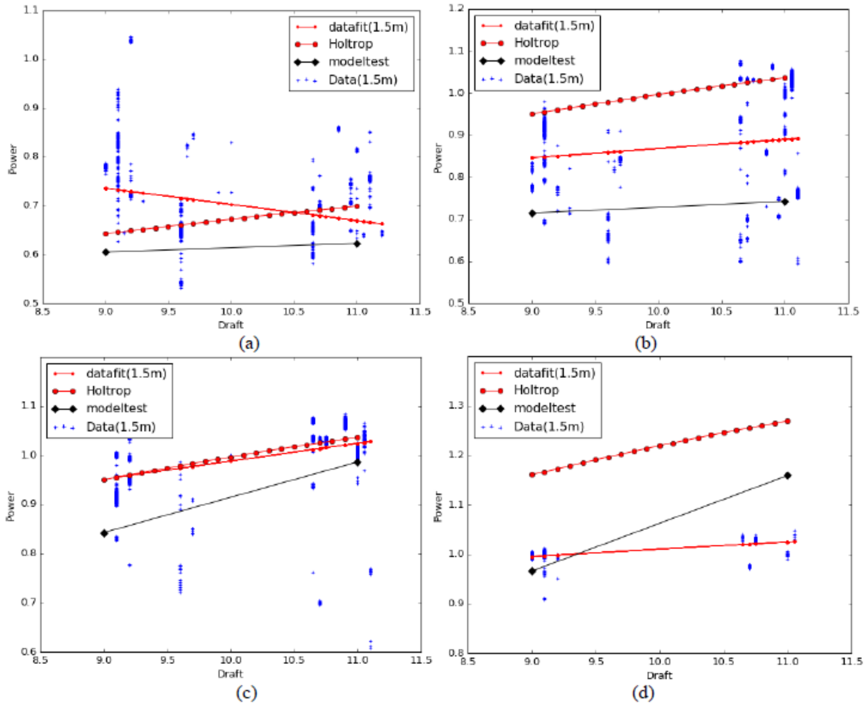

Figure 4. 29. Calm water power-draft comparison of operational data to a Holtrop estimation and model test result during a research of acquiring added power from operational data (Lakshmynarayanana & Hudson, 2017). (a) 16-17 knots (b) 17-18 knots (c) 18-19 knots (d) 19-20 knots.

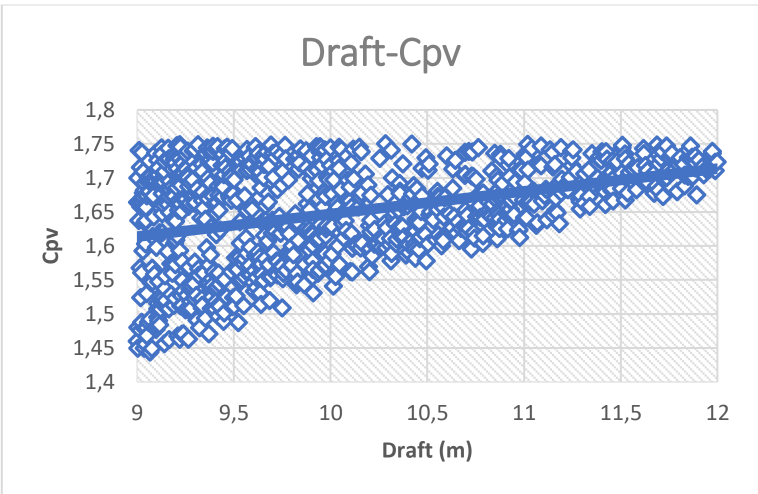

Figure 4. 30. Overall Draft-Cpv sample plot and average line

Principally, the increase of draft shall raise the immediate total resistance of the ship according to theory. This is proven true in the model-simulation as seen in figure 4.30, where albeit the samples generated vary in C_{pv} range, the average line follows a trend of increase.

When considering the application of this model, observing figure 4.24 the maximum error in the model's limited range reaches a maximum of 10%. The applicability of this model for a professional setting in evaluating voyage operations may not be recommended. However, the behaviour and proximity of the results deem it reasonable to be considered as reference, and especially for study or further research on the same topic.

5. CONCLUSIONS

5.1 Conclusions

1. A model to predict estimation of the power increase in rough weather at various Beaufort Numbers, wind & wave directions, speed settings, and various load drafts is possible to be created using the classic calm water resistance estimation theory along with the Kwon method of approximating added resistance due to wind and waves, with a tolerable applicability for reference, study and further academic research on the topic of ship operations data-based modelling.

2. A theoretical stochastic simulation for ship data-based modelling proves to provide value in testing and benchmarking, when applied with sufficient analysis and iterations at different parametrical setups. It can be used to assess the behaviour of the model.

3. The lack of data samples from recorded operational data at speeds outside the average operational range limit the model to a certain speed range, from 19 knots to 23 knots. There is no means of verification of lower speeds if applying the current model setup. It can be concluded that not only the quantity of data is required, but also the quality (especially considering the variety of data) of the data should be considered.

4. The variety of draft load is determinant in benchmarking the model with actual operational records, this is initially seen when comparing the results of the classic calm water resistance estimation at maximum draft. At such conditions, the available ship data does not comply. At the latter parts of the analysis, the overall recorded data is compatible within the model’s limited range, especially in the range of 9,0 to 9,5 meters, where the average ship operation line and the model simulation results average line even intersect at a point.

5.2 Suggestions

1. To further enhance ship data-based modelling it is desirable to collect more operational variety in data samples, so that all ranges of speed can be tested and verified. Data from modern monitoring technology in present day shipping may present advantage.

2. To reduce the randomness of the simulation generated results analysis, it may be preferable to narrow down the scope of research to a certain range of weather conditions and operational conditions.

3. The model setup in this research may be further developed by addition of unconsidered factors, such as the change in efficiency of varying propeller speeds and the propulsion plant behaviour itself.

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