NATIONAL TECHNICAL UNIVERSITY OF ATHENS
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DIPLOMA THESIS:

"On the Energy Efficiency Design Index (EEDI) and Minimum Propulsion Power: A case study on the Interim Guidelines for determining minimum propulsion power to maintain the maneuverability of ships in adverse conditions"

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Abstract

The international maritime shipping accounts for approximately 2.7 percent of annual global greenhouse gas emissions[1]. The implementation of the Energy Efficiency Design Index (EEDI) regulation of MARPOL, was a major step forward for the environmental impact of the shipping industry, as a 30% decrease of the industry emissions in CO_2 is expected in 2025[2].

However, there are some serious concerns regarding the way in which ship owners/designers/builders will manage to achieve the EEDI requirements. Especially, when the choice is to lower the installed power and consequently the ships speed; this can lead to insufficient propulsion power to maintain maneuverability under adverse weather conditions[3].

As a result of the aforementioned was the development of the *Interim Guidelines for determining Minimum Propulsion Power to Maintain the Maneuverability of Ship in Adverse Weather conditions (MEPC 65/4/3, Annex I, 2013),* which is a three-level approach for verifying that the engine power and the corresponding vessel speed is sufficient to maintain maneuverability when operating in extreme weather conditions.

This diploma thesis is concerned, at first, with the calculation of the EEDI for three existing ships and one newly designed (for which the $EEDI_{weather}$ will also be determined). If the attained EEDI for each ship is greater than required one[5], then in order to comply, an optimization scenario is applied and the new corresponding vessel speed is calculated. Then for each ship the *Interim Guidelines* are applied, in order to check that their maneuverability in adverse weather conditions is still sufficient. In the same context, results in regard with operation in the short-wave domain are researched. Also, other methods (rather than limiting the engine power) for the reduction of the EEDI are considered for one of the studied vessels.

Introduction

This thesis is divided in seven chapters, which consist its main body and an appendix, where all results from used methods for our conclusions are presented; a brief description on the contents of each chapter is presented here.

In Chapter one, the Energy Efficiency Design Index is presented and explained, as well the different methods one can employ to achieve it. Also, the concern for minimum installed power is discussed.

In Chapter Two, the design, operational and environmental parameters which affected the current form of *Interim Guidelines* are investigated; background information on Minimum Power Lines and Simplified method is presented and discussed.

In Chapter Three, all the employed methods for getting the needed results in this thesis are presented and briefly explained.

In Chapter Four, speed trial curves and the general particulars of the studied ships are presented. Also, sources of uncertainty in calculations of this thesis are presented.

In Chapter Five, results regarding the resistance of the ships, the reference speed in EEDI conditions and finally the attained EEDI are presented. Also, results regarding the determination of the f_w coefficient and attained $EEDI_{weather}$ are presented.

In Chapter Six, the Interim Guidelines are applied on the four studied ships and the corresponding results are presented with the appropriate comments; also two optimization scenarios are theoretically investigated, for one of the vessels.

In Chapter Seven, a summary of the thesis and our findings is presented, along with concluding remarks and propositions for the future.

Chapter one:

Thesis framework

1.1 The Energy Efficiency Design Index (EEDI)

1.1.1 General information on EEDI

For the past few years, the International Maritime Organization (IMO) has been trying to give incentives to naval architects to design ships with reduced marine-based Greenhouse Gas emissions (GHG). These incentives include The Energy Efficient Design Index (EEDI), which aims at simplifying the machinery provisions in ships, and makes use of a reasonably simple equation to calculate the tones of CO2 emitted per ton of nautical miles travelled. This formula equation (MEPC 62) uses the capacity expressed in metric tons(usually the deadweight in summer load line condition), 75% of the Maximum Continuous Revolution (MCR) of the engines and the corresponding vessel speed V_{reff}, and some correction factors for fuels, as shown here:

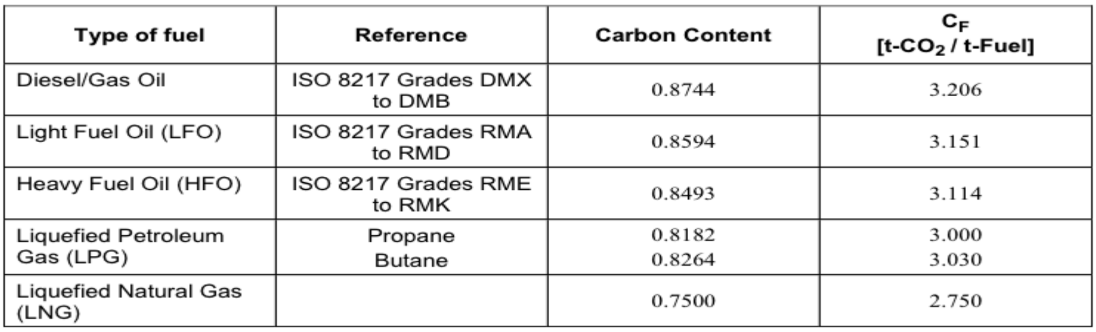
$$\mathrm{EEDI}_{attained} = \left\{ \overbrace{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{n_{ME}} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right)}^{\text{Main engine(s) } CO_2 \text{ emissions}} \right.$$

$$\left. + \overbrace{\left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}\right) + \left(\left(\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{n_{PTI}} P_{PTI(i)} - \sum f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right)}^{\text{Auxiliary engine(s) } CO_2 \text{ emissions}} \right.$$

$$\left. - \overbrace{\left(\sum_{i=1}^{n_{eff}} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}^{\substack{CO_2 \text{ emission reduction due to} \\ \text{Innovative technology(s)}}} \right\} \cdot \frac{1}{\underbrace{f_i \cdot f_l \cdot f_w \cdot f_c \cdot \text{Capacity} \cdot v_{ref}}_{\text{Transport work}}}$$

Picture 1: EEDI equation

The CO2 emissions factor signifies the total CO2 emission from the ignition and combustion of fuel, which also includes the propulsion and auxiliary engines and boilers. Commonly used marine fuels according to IGF-code are given in the table below:



Type of fuel	Reference	Carbon Content	C_F [t-CO_2 / t-Fuel]
Diesel/Gas Oil	ISO 8217 Grades DMX to DMB	0.8744	3.206
Light Fuel Oil (LFO)	ISO 8217 Grades RMA to RMD	0.8594	3.151
Heavy Fuel Oil (HFO)	ISO 8217 Grades RME to RMK	0.8493	3.114
Liquefied Petroleum Gas (LPG)	Propane Butane	0.8182 0.8264	3.000 3.030
Liquefied Natural Gas (LNG)		0.7500	2.750

Table 1 Carbon content index for most commonly used fuels

In addition, mechanical and electrical technologies installed on board a ship, such as the use of solar or wind energy, saved energy that is deducted from the overall CO2 emissions of the vessel, based on genuine effectiveness of the systems. The transport work is calculated by multiplying the ship's capacity (dwt), with the ship's design speed measured at the maximum design load condition and at 75 per cent of the rated installed shaft power (MCR) . Finally, naval architects and ship designers were free to select the technologies to fulfill the EEDI regulations of the given ship type, thus allowing diversity in the specific field.

The calculated as above EEDI index (Attained EEDI) must be less than a required price (Required EEDI) that comes from a baseline, created from different existing ships build from 1998 to 2007 (Reference Line). For its creation, data from the IHS-Fairplay data were utilized, This restriction on the EEDI index applies in new ships bigger than 400 gross tons (GT) and differs regarding the ships type, size and operation. The required EEDI index for Tankers is shown in Table2:

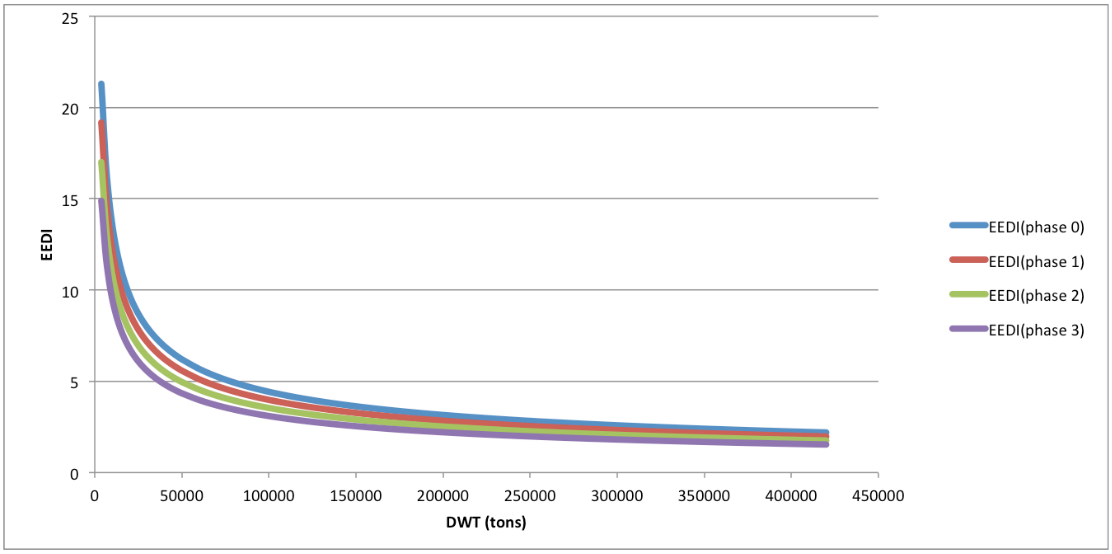


Table 2: Required EEDI value according to DWT for phase 0-phase 3 (tankers)

The Energy Efficient Design Index (EEDI) is a measure that makes ship owners reduce CO2 emissions, an imposition that got into effect in 2011. In order to achieve its objectives, the EEDI addresses operational measures by obliging owners of new vessels to consume a minimum energy efficiency level. This will be achieved through the stimulation of technical development of all the parts of the ship that affect its fuel efficiency and through the separation of operational and commercial measures from the design-based and the technical. The EEDI makes comparisons of the energy efficiency between similar individual ships, of the same size, that could carry the same cargo, are taking place.

As people increase their awareness and their concern on the effect of human activities to the environment and the emergence of the GHG emissions, there has been increasing pressure to reduce shipping's negative input to this occurrence. In order to achieve this, a new set of regulations has been introduced into the shipping market, in addition to the creation of Special Emission Control Areas (SECAs) and of Key Performance Indicators (KPIs). All these regulations are in the context of the efficiency performance of ships, that are the EEDI, the EEOI (Energy Efficient Operating Index) and the SEEMP (Ship Efficiency Management Plan.

Ever since these measures were introduced, naval architects must design ships that ensure that the baseline of the ship's type is met (seen for tankers in figure 1). When the actual sea trial takes place, the shipyard in which the ship was built must certify that the EEDI baseline is, in fact, met. The concept is to lower the baseline in each five years, in order for all the ships that will be designed and built in the future, to be getting more and more efficient. The reduction, as a percentage of the initial value(phase 0) of the required EEDI for tankers, is shown in the figure 1 above.

1.1.2 The EEDIweather

The calculation of the EEDI index includes the designation of a value for the speed V_{ref}, which is based in calm water resistance tests. But in everyday operation this is not the actual case; more often or not, weather conditions affect the normal operation of the vessel, leading in an increase in total resistance due to wind and the presence of waves in the seaway. So, we can conclude that for most ships (especially for ones that frequently encounter noticeable weather phenomena on their routes) the attained EEDI has an underestimated value, due to the fact that the reference speed is theorized higher than it actually is.

The formula of the index has a way of introducing the respective sea and wind conditions into its calculations; the coefficient f_w. The sea condition to determine the $EEDI_{weather}$ and the coefficient f_W is defined at Beaufort 6. If the calculations for v_{ref} are done in calm water, f_w has the value of 1, otherwise its equal with the ratio of the speed in sea condition (V_w) to the reference speed in calm water (V_{ref}). Both speeds are defined at PEEDI (75 % MCR) and EEDI draft (scantling).

The coefficient f_W can be calculated by two alternatives, which are mentioned here and both will be utilized in the test case of this thesis:

- Alternative 1: Calculation of f_W according to MEPC.1/Circ. 796 for decrease in ship speed in a representative sea condition
- Alternative 2: Calculating the coefficient f_W from the standard f_W curves

1.1.3 A preliminary analysis of factors influencing EEDI value

In order to do a preliminary analysis of how the different factors used in the calculation of the EEDI influence its attained value, a simplified formula of expressing it is used:

$$EEDI = \frac{0.75 \cdot Pme \cdot SFCme \cdot Cf}{DWT \cdot V}$$

For this simplified approach, the Admiralty coefficient is used to express the installed power as a function of speed and vice versa, in order to see how the reference speed or installed power affect the attained EEDI value. The Admiralty coefficient is constant for a given hull and gives the approximate relationships between the needed propulsion power P, ship speed V and displacement ∇; it is defined as follows:

$$CAD = \frac{\nabla^{\frac{2}{3}} \cdot V^3}{P}$$

One of the studied ships in this paper is used as a reference, namely "TEST_SHIP"; it's general particulars are listed in chapter 4.

For the results seen in table 2, the Admiralty coefficient formula was used to replace power P in the EEDI formula:

$$EEDI = \frac{0.75 \cdot \frac{\nabla^{\frac{2}{3}} \cdot V^3}{CAD} \cdot SFCme \cdot Cf}{DWT \cdot V}$$

The results for the attained EEDI are presented for three different fuels:

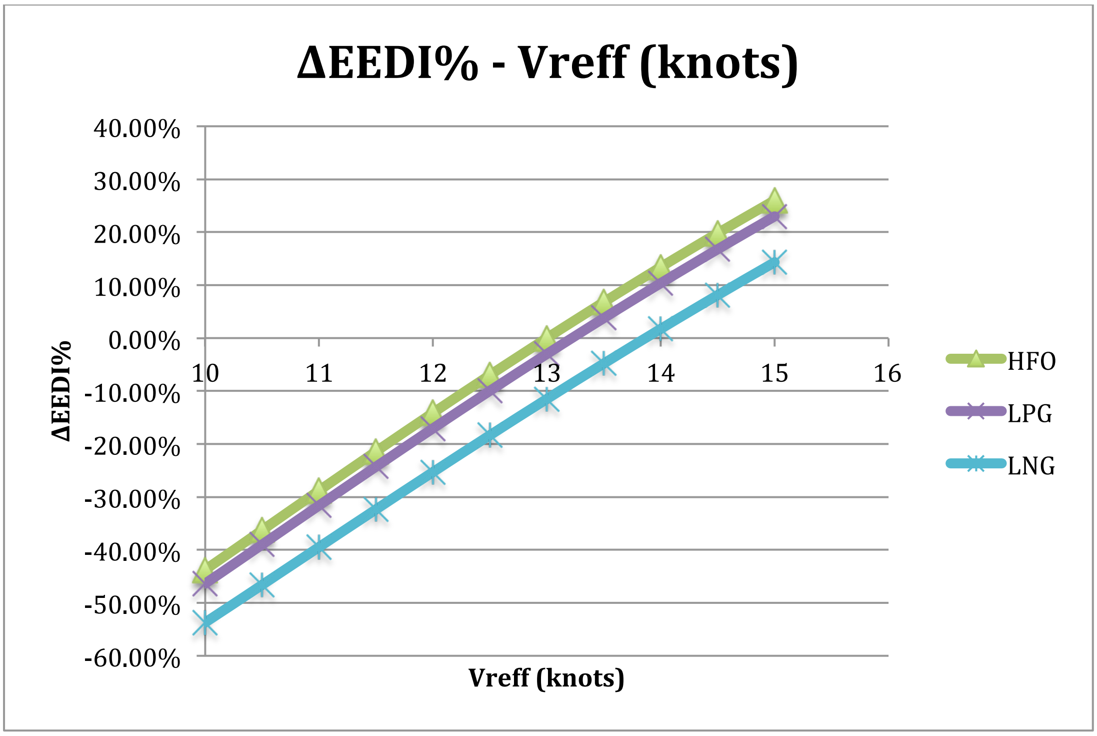


Table 2: How EEDI is affected by reference speed Vreff

For the results seen in table 3, the Admiralty coefficient formula was used to replace reference speed V_{reff} in the EEDI formula:

$$EEDI = \frac{0.75 \cdot Pme \cdot SFCme \cdot Cf}{DWT \cdot \left(\frac{\mathrm{Pme} \cdot CAD}{\nabla^{\frac{2}{3}}}\right)^{1/3}}$$

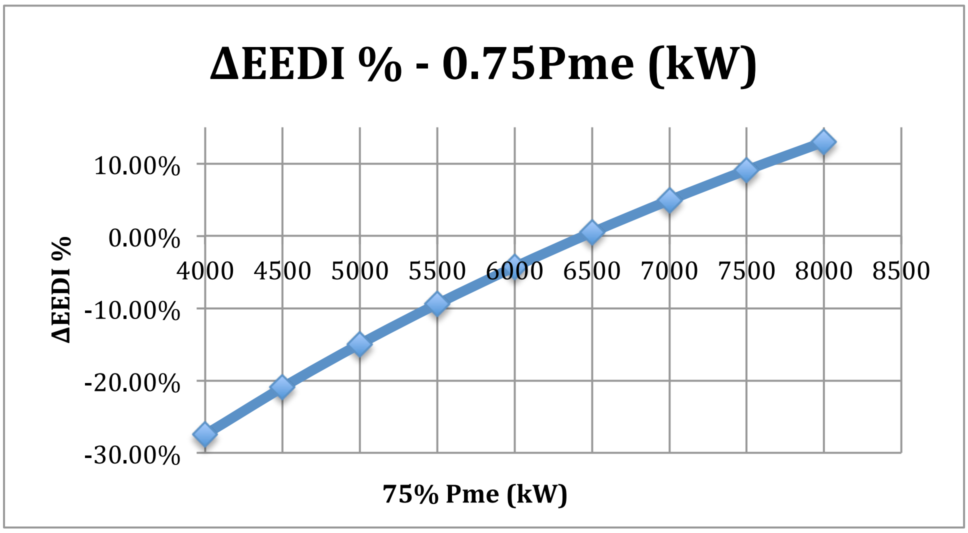


Table 3: How EEDI is affected by installed MCR

For the results seen in table 4, the effects of an involuntary loss of speed or a hydrodynamic optimization in the attained EEDI (without a change in propulsion power), expressed in a decrease and increase in speed respectfully

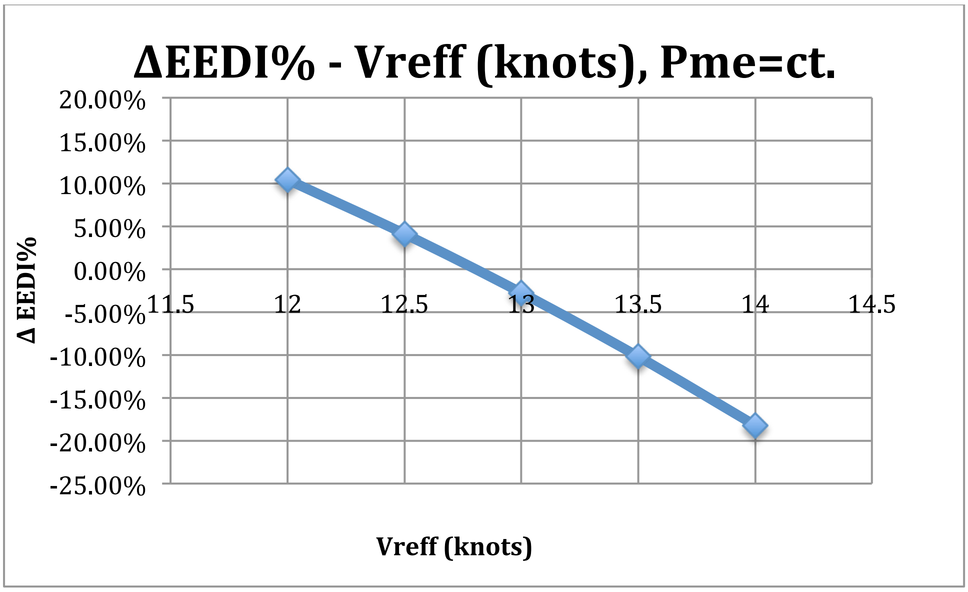


Table 4: How EEDI is affected by Vreff with propulsion power

For the results seen in tables 5 and 6, the effect of a change in deadweight and specific fuel consumption respectively, while other factors in the simplified EEDI formula remain constant, to the attained EEDI.

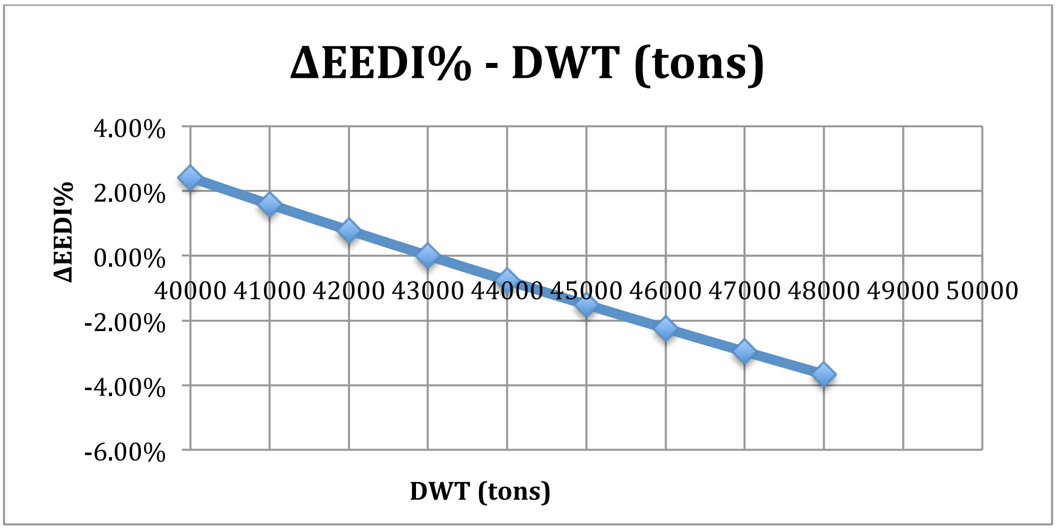


Table 5: How EEDI is affected by DWT

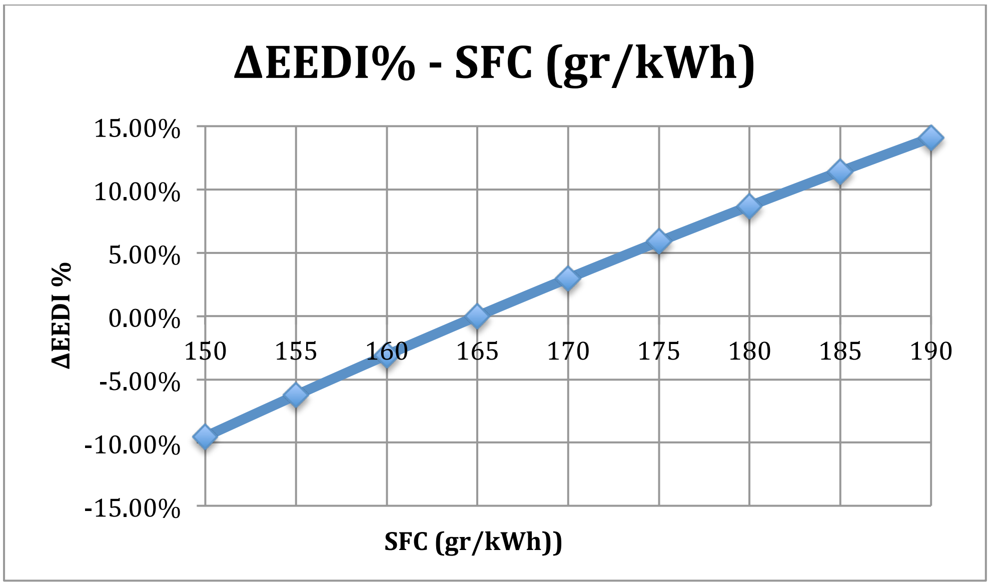


Table 6: How EEDI is affected by SFC

The EEDI is also influenced by other design factors, which are not evident of we just look at the formula. In 2012, Hans Otto Kristensen published a study which was focused on the changes of the main dimensions of tankers and bulk-carriers over the last 30-40 years. It was found that the design trend has moved in the wrong direction from an energy saving point of view; the block coefficient has increased during the last twenty years while the length displacement ratio has decreased over the same period. These two design changes have resulted in an increased EEDI.

In a study performed 2011 [6], it was stated that "*The analysis revealed that the EEDI for the analyzed ships in general increased over the last 30 years due to the higher power demand as a result of more unfavorable main dimensions. For most of the ship segments the ship speed increased, resulting in a higher Froude number (speed divided by the square root of the ship length), which also increases the propulsion power and the EEDI*". The study also communicated the message that no matter how the hull design is improved or modified, it will not be enough to have a vessel that will have the same present speed with 30% reduction of EEDI (Phase three of CO2 reduction). The present efficient hulls are good enough in most cases to comply the current phase zero and, with some modification of hull parameters and improved hull design, phase one requirements can be achieved without reducing the speed, but it is not possible for further phases.

1.2 Employed methods for achieving EEDI

A major issue for the ship owners is the way in which to achieve the required EEDI index, especially on already designed or built vessels, not only for phase 0 but most importantly for phases 1-3. For example, a vessel commissioned in 2008 will approximately be operational until 2030, which means that it must fulfill EEDI requirements for phase 3(active in 2025), which is a 30% reduction in the initial (phase 0) required EEDI value.

There are several methods one can employ as means of achieving the required EEDI index and almost absolute freedom of choice between. In this chapter we will cross-examine slow steaming, the most popular among the methods that one can employ, with other methods that do not require any loss in the vessels speed, and consequently compromise its sea-keeping and safety in adverse weather conditions. More analytically, these methods will be presented.

- slow-steaming, meaning the voluntary reduction of a ships MCR and consequently its fuel consumption and its carbon dioxide emissions
- increasing the product of speed in the denominator or decreasing the fuel consumption, by means of hydrodynamic optimization
- making realistic predictions for the power requirements of a vessel, based on its intended trading routes and expected weather conditions
- use of alternative fuels e.g. LNG, with reduced carbon content
- installation of innovative efficiency technologies

1.2.1 Slow-steaming

Slow steaming refers to the practice of operating transoceanic cargo ships, especially container ships, at significantly less than their maximum speed [6]. Slow steaming is a method well known to the shipping industry from 2007, when a dramatic increase in the price of crude oil occurred (July 2007 to July 2008: 350 to 700 USD/tons) [8], and it is evident why it was employed by most ship owners; marine engine manufacturer

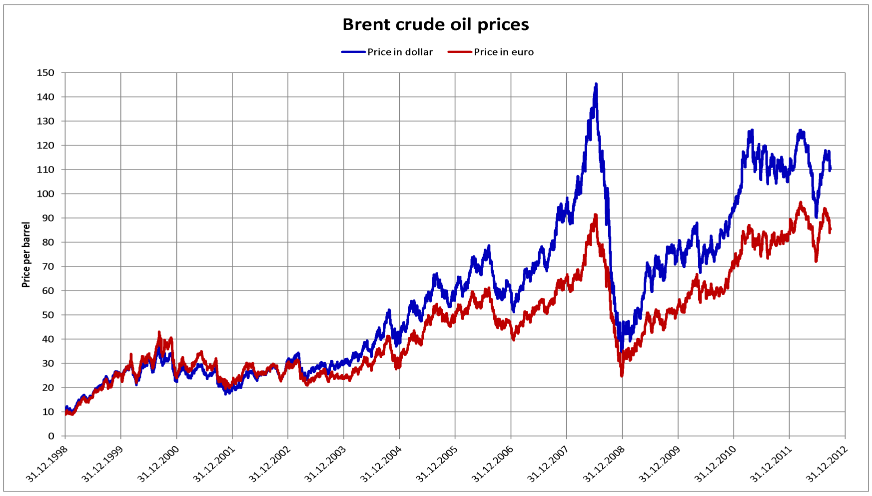


Table 7: Fuel oil cost 1998-2012

Wärtsilä calculated that fuel consumption may be lowered to 1/3 of its nominal value by reducing a vessels speed from 27 knots to 18 knots, at the cost of an additional week's sailing time on Asia-Europe routes, while adding a comparable 4-7 days to trans-Pacific voyages [9]. As we observe, with a relatively small increase in the duration of the trip, there are huge savings in fuel costs, which is the primary operational expense of a vessel.

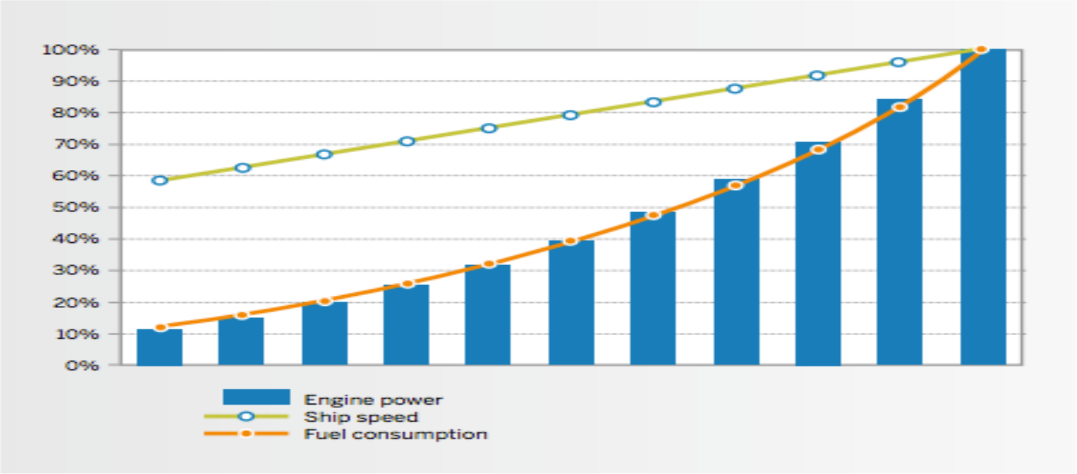


Table 8: Correlation between ship speed, engine power and fuel consumption

With the emergence of the EEDI, slow steaming proved to have another advantage; namely that for every ton of fuel saved, the industry reduces its carbon dioxide emissions (CO2) to the atmosphere by three tons, and the cylinder lubricating oil consumption of the main engine is reduced at almost the same percentages as the fuel, which also reduces solid particle emissions [9], which in turn reduces the nominator on the EEDI formula. Based on a recent market survey of over 200 liner and tramp companies, 75% apply slow steaming to various extents [10]. This widespread practice of slow steaming has given rise to a lot of questions; first of all, each ship is designed and built for operation in a specific load and speed range, something that is also valid for the selected engine, if fixed-pitch propellers are installed. This usually corresponds to the 70-85% of MCR for a two-stroke engine. The fuel efficiency of the engine, its operational parameters, the specification of the turbochargers, coolers, auxiliary systems, exhaust gas boilers, and so on, are chosen and optimized for that normal load range. It is natural, therefore, that when the engine is operated continuously in a load range below or even far below 60%, the overall system is no longer fully optimized, which may lead in problems in operation or well being of the systems. Various studies have been and are being carried out to test those concerns and the results have shown that an engine can function optimally in lower speeds with the installment of a slow steaming upgrade kit (provided by most manufacturers with a relatively small cost) or by means of permanently de-rating the engine.

So we have concluded that most of the already installed engines, with a small or no modification at all, can withstand permanent operation in a lower than the optimally designed operation point. But what about the behavior of the vessel itself? One of the main concerns that have been introduced with the practice of slow-steaming is the minimum installed power; a ship must have sufficient power to achieve a speed that enables it to navigate safely when adverse weather conditions are in play. We shall examine this concern in depth in a separate chapter of this thesis.

1.2.2 Increasing the product of speed in the denominator

Contrary to slow steaming, which decreases both speed and CO2 emissions (the latter more effectively), we will look into other ways of achieving the desired EEDI value by either increasing a ships speed (with the fuel consumption remaining constant) or reducing its fuel consumption (while the vessels speed remains the same), by means of improving the vessels hydrodynamic performance [11].

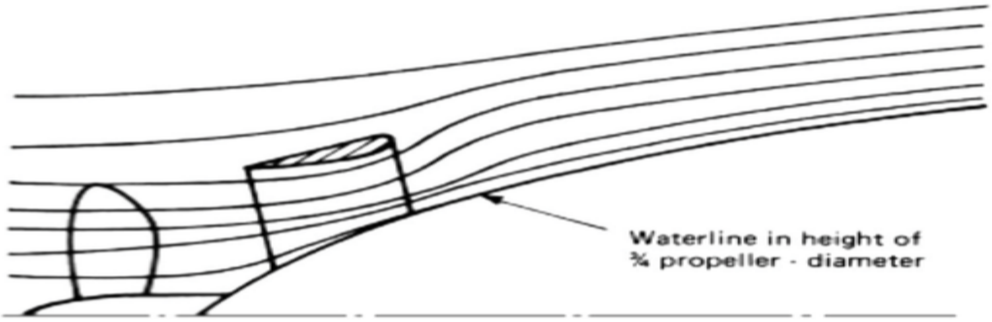
1.2.2.1 Installing a Wake Equalizing Duct (W.E.D)

A wake equalizer duct is a hydrofoil-section venturi bent to form two half shells, where the wider opening faces the bow and the camber of the hydrofoil the vessel's side, that are welded in front of the upper region where the propeller is installed(Picure 1).

Picture 2: A Wake Equalizing Duct

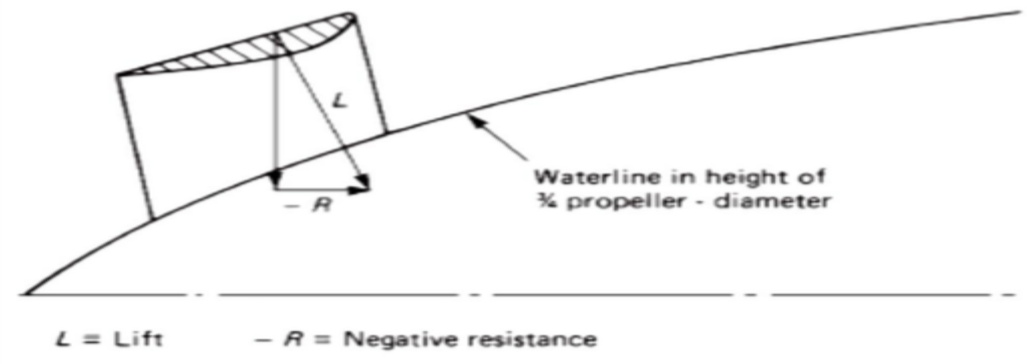
The primary principle governing this application is the acceleration of flow inside the duct, and a deceleration outside of them. Before installing a W.E.D duct, the flow that reaches the propeller is slower on its upper part, due to a fuller hull form and, usually, faster at its lower part. After the installation of a W.E.D duct, according to the basic principle that was explained earlier, we have an increased flow at the upper part and a decreased one at the lower one; what has been achieved is a more uniform wake flow towards the propeller, where its average speed Up (of the wake flow) practically stays the same. Up = U(1 − w); w is referred to as the wake fraction A typical wake fraction of 0.1, for example, indicates that the incoming velocity seen by the propeller is only 90% of the vessel's speed. The propeller is operating in a wake. In practical terms, the wake fraction comes about this way: Suppose the open water thrust of a propeller is known at a given ship speed U and n_p. Behind a vessel moving at speed U, and with the propeller spinning at the same n_p, the prop creates some extra thrust.

Another occurrence with the use of the ducts is the decrease in deviation of the streamlines in the aft section of the ships body. Normally, at this sections streamlines are not homogenous, due to the decrease of speed but carefully installed ducts can prevent streamlines from larger deviations following the hull form.



Picture 3: decrease of deviation of streamlines with use of W.E.D

Furthermore, due to the fact that the flow coincides to a hydrofoil section shaped as a duct, a Lift force, with its vector being perpendicular to that of the flow, and a Drag force are generated, as shown in the next image. By analyzing the Lift vector, we observe a negative Drag (-R) force along the longitudinal axis of the ship, which contributes positively to the achieved thrust of the propeller. Having in mind that the



Picture 4: Lift and Drag forces generated on a W.E.D

total resistance of a ship is the integral of all the perpendicular and tangent forces that the fluid wields on the hull, the correct installation of W.E.D is of major importance. The value of the resistance differs between a fully equipped ship without a propeller and a ship with one installed, as the operation of the propeller creates a pressure drop in the aft region of the ship, which means that the perpendicular and tangent forces are being modified, due to the change in the boundary layer. Therefore, there is an additional resistance due to the propeller motion, which is called augment of resistance or if expressed through thrust, thrust deduction t; it is obviously specific to both the hull and the propeller(s), and how they interact.

The ratio (1−t)/(1−w) is often called hull efficiency, and we see that a small thrust deduction t and a large wake fraction w are beneficial effects, but which are in competition. A high rotative efficiency and open water propeller efficiency (at Up) obviously contribute to an efficient overall system.

We can finally conclude that there are many advantages from installing a W.E.D, a vessel can benefit in vibration reduction up to 50%, remarkable decrease of material wear, decrease of tension damage, decrease of chances of cavitation corrosion(especially when compared with other duct types) and, especially, a decrease in fuel oil consumption up to 3-5% and, consequently CO2 emissions reduction. Coupling that with the low cost and simple installation, is a system ship owners should definitely consider for improving a vessels performance and attained EEDI.

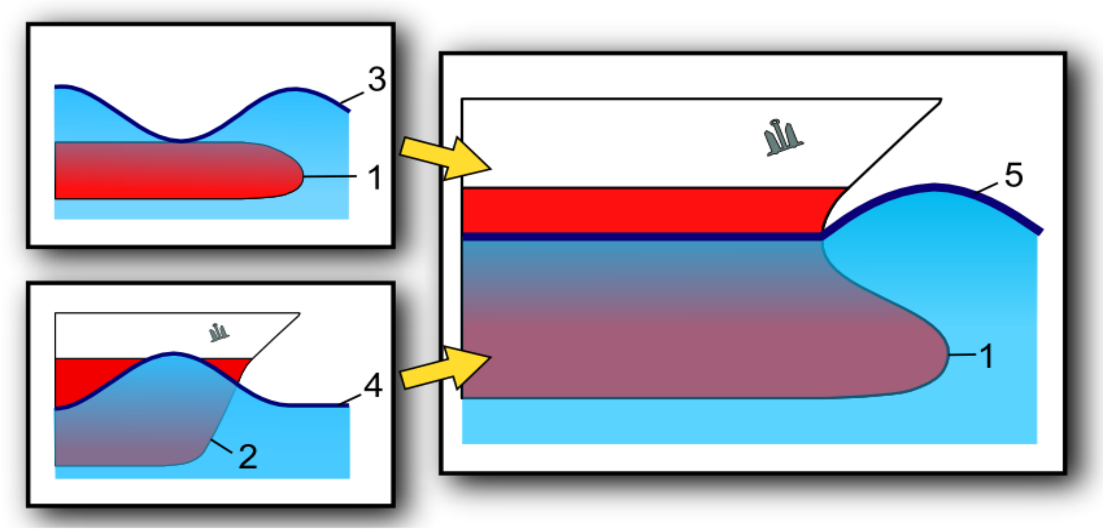
1.2.2.2 Optimizing the bulbous bow

A bulbous bow is a hydrodynamic appendage used to decrease resistance of a vessel at a set speed. It effectively increases waterline length, as well as the development a small wave, which will destructively interfere with the bow wave. In simpler terms, a bulbous bow changes the way in which water would flow in its absence, producing many benefits like reduced drag (and consequently larger speed) and better fuel efficiency. When a bulbous bow is being designed there main factors that affect its performance are:

- the cruising speed of the vessel (design speed)
- its depth below the waterline
- the length of the waterline (greater than 15 meters)

The positive effects of a bulbous bow become evident as the vessels speed increases, which means that an increasingly larger percentage of its total resistance consists of the wave making resistance. Studies have shown that the overall fuel efficiency with the installation of a bulbous bow may reach 12-15% [12], if designed properly, meaning that for the same fuel consumption we can increase the product of speed; in both scenarios we manage to achieve a lower value of the attained EEDI. On the contrary, when the ship sails in lower speeds, frictional resistance accounts for the larger portion of its total resistance, and the presence of a bulb means greater wetted surface area; the negative effects in fuel efficiency though are negligible.

Let’s examine how a bulbous bow works. Its proportions are derived from the features and dimensions of the vessel itself. The diameter (volume) is a direct result of the hull midship area. The length is determined by the stem profile, as the farther forward the bulb extends the more leverage it has but is generally kept shorter than the bow overhang. The section shape may be a modified ellipse to reduce pounding in head seas. The vertical placement is calculated so the bulb is just below the surface where it will create a wave in front of the ship interfering with the natural wave train of the vessel, creating a wave hollow where a crest should be. In this way the vessel will run flatter and the overall wave height will be reduced. Also, the induced wave, whilst energy consuming, due to its interference with the second wave stream, changes the pressure distribution along the hull (form effect) and thus reduces wave making resistance. In the next figure, it is graphically shown how the presence of a bulb modifies the water flow:

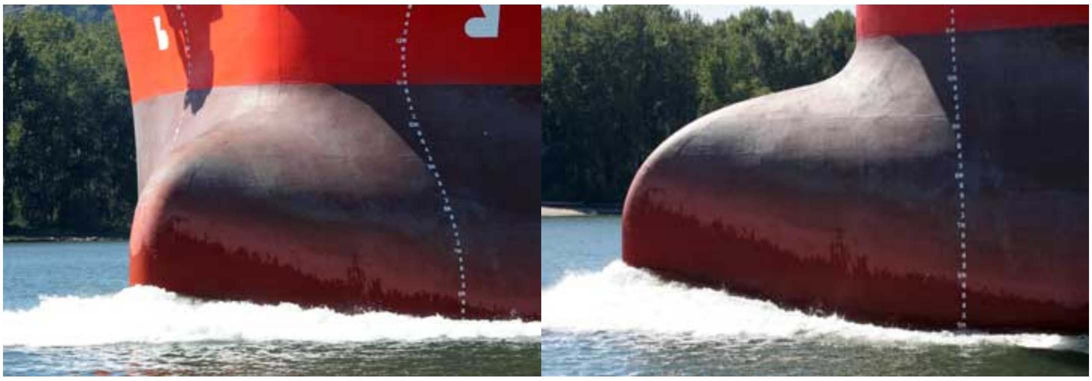


Picture 5: bulbous bow influence on water flow

As the water flows around the bulb, its speed is increased, significantly more over it than under it. This creates a pressure drop over the bulb, as well as an overall pressure difference, which tends to lift the bow, effectively improving its trim. Depending on the vessel type, different kinds of bulbous bows are used. Vessels that normally sail in increased speeds (such as containerships or warships) usually have bulbs that are longer and sharper (see Picture 5), so the waves produced around the bow are lower and thus, the resistance is smaller. The disadvantage of this kind of bulb becomes evident in quartering or side waves, where the larger surface area along its side means higher wave forces will act on it, which may cause pitching movements.

Picture 6: bulbous bow of a containership

Vessels that sail in lower speeds (such as tankers or bulk-carriers) tend to have a bulb that is wider and shorter (see Picture 6). For larger vessels with greater speeds the wave making resistance is the greater force impending their forward motion in a seaway; on lower speeds though frictional resistance is the main drag force in the ships motion, meaning that the damping of the bow wave generation is almost an insignificant factor, and the presence of a bulb may only have negative effects due to the larger wetted surface area.



Picture 7: bulbous bow of a bulk-carrier

A great example of whether or not to use a bulbous bow is a warship; they tend to cruise in two speeds, one significantly greater than the other, the patrol speed and the war speed. It is evident that when the ship sails with its patrol speed (low speed), which they usually do, a bulbous bow would have negative effects in its fuel efficiency and overall performance. On the other hand, it may prove more than beneficial when cruising in greater speeds.

1.2.2.3 Installation of a speed nozzle at the propeller and a Costa-bulb at the rudder of the vessel

To obtain the most thrust, a propeller must move as much water as possible in a given time, especially when a high thrust is needed at a low ship speed. Due to propeller immersion requirements at ballast drafts, the propeller diameter on a bulk carrier is normally restricted leading to a relatively high propeller loading. In connection with the low speed, typical of a bulk carrier, this leads to a relatively low propeller efficiency. Therefore a velocity increase of the flow, which would lead to a relatively higher level of kinetic energy in the propeller wash is necessary and would improve the relatively low propeller efficiency. The propeller nozzle creates a utilized circulation around the nozzle's wing section and the contraction of the flow forward of the propeller is increased diverting the flow aft of the propeller and creating a flow pattern equivalent to the flow generated by a larger propeller.
The following figure depicts a propeller with a speed nozzle

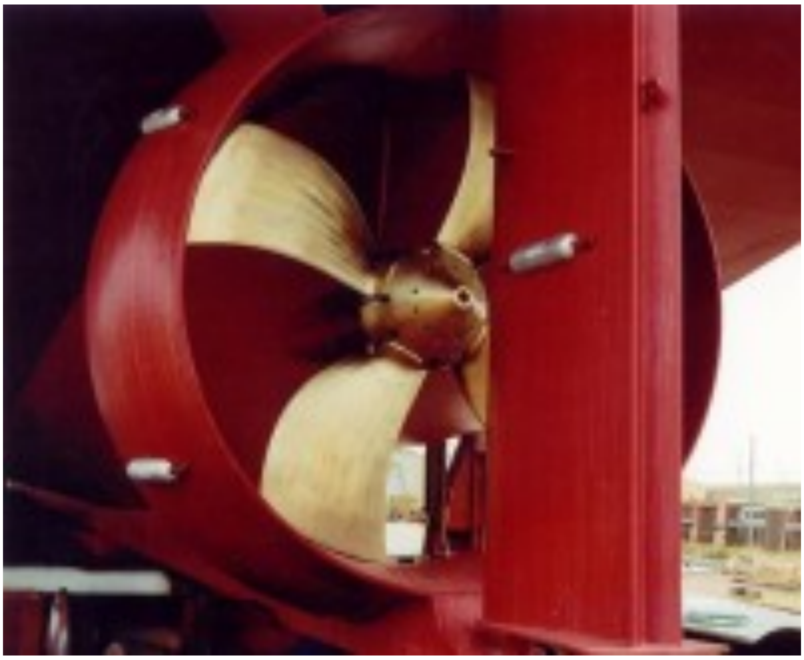


Figure 1: Propeller with speed nozzle

In order to have a more homogeneous flow distribution behind the hub area a Costa bulb can be installed. The Costa bulb is a streamlined body fitted on the rudder, behind the propeller hub, as we can see at the following figure. By creating a more homogeneous flow behind the hub area it minimizes the hub vortex and its related loss and therefore the energy of the propeller induced vortices can be partially converted into thrust.

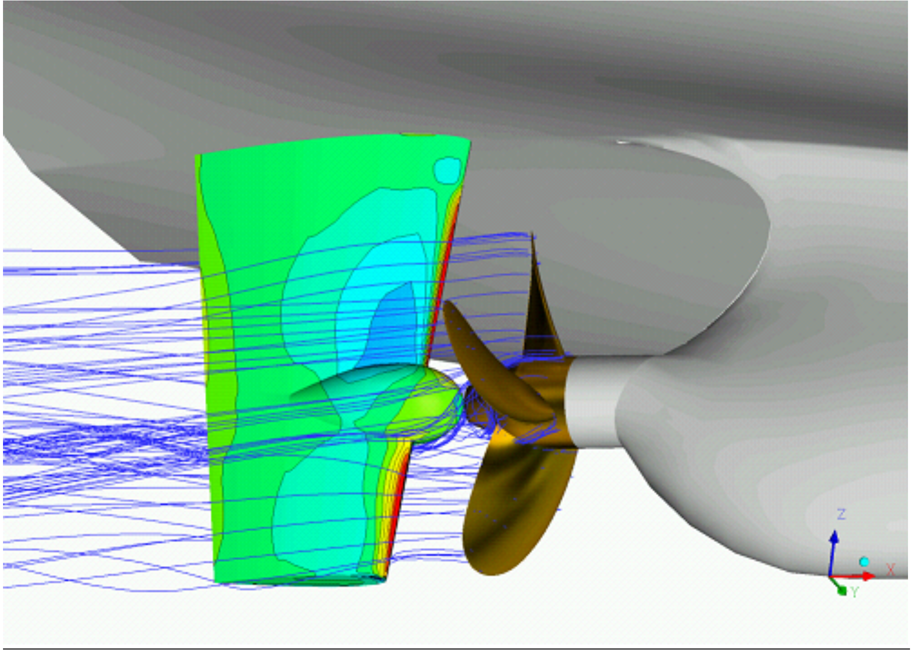


Figure 2: Costa bulb on rudder

The total reduction in propulsive power at service speed (85 % MCR) with an unchanged speed, from the application of the above-mentioned devices, has been estimated by FORCE Technology (the Danish ship model basin in Lyngby) to 4 %.

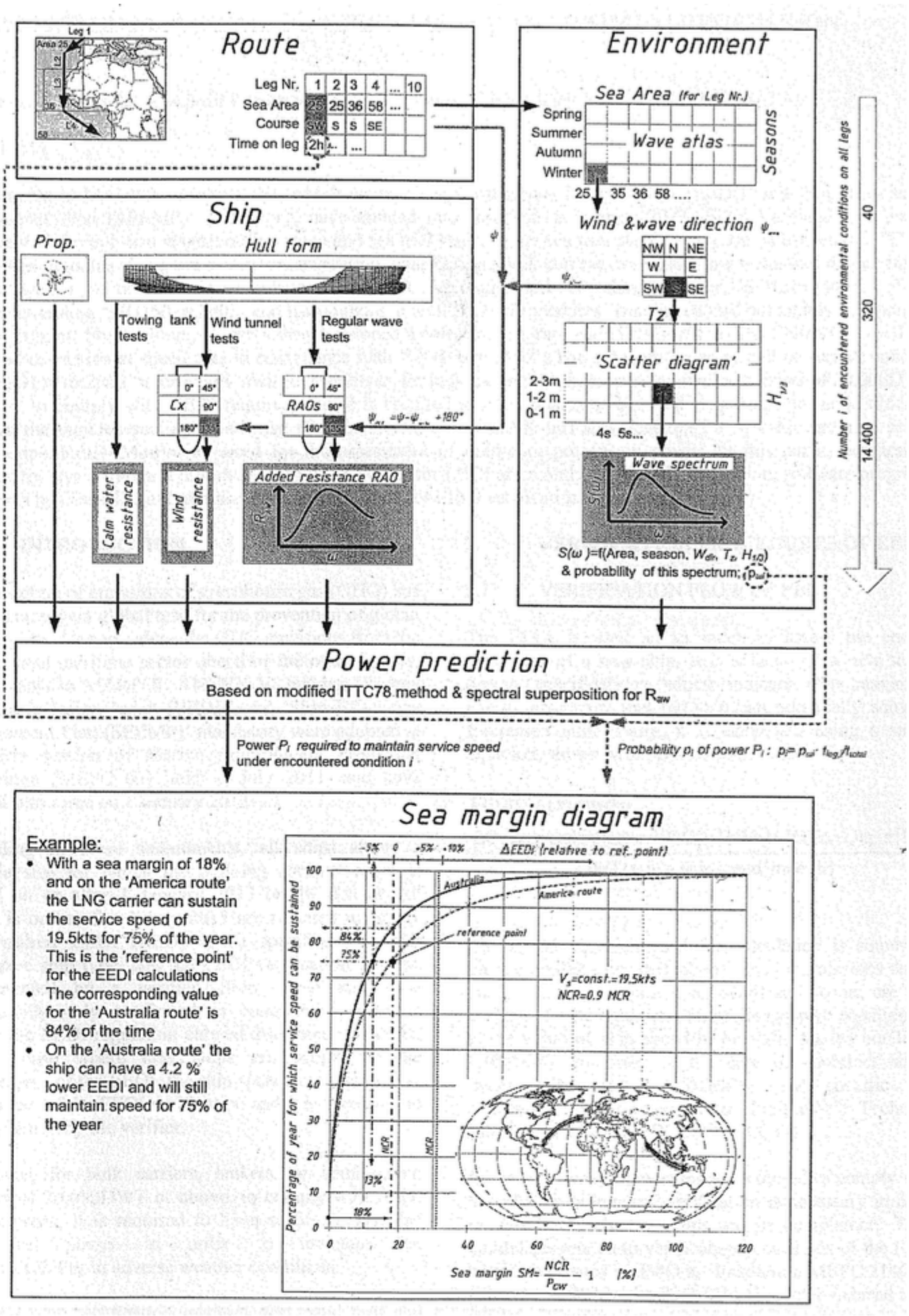
1.2.3 Making realistic predictions for the power requirements of a vessel

One major issue when selecting an engine for a vessel is the sea margin component; sea margin (or powering margin) as defined by the ITTC is: *The margin which should be added to the estimation of the speed power relationship of a newly built ship in ideal weather conditions to allow for the operation of the ship in realistic conditions. In practice this does not mean that the ship must meet full speed in all weather conditions, but that it can sustain its service speed(design speed) over a realistic percentage of conditions.*
So, we can deduce that by having sufficient information about the sea routes that the vessel is going to operate, its possible to make realistic predictions for the power demand of the ship, and not overestimated ones, which have a negative effect in the attained EEDI value. In a recently published paper [13] the authors achieved to create a theoretical model in which (as shown in figure):

- for the intended sea route, its respective weather conditions, as statistical data, were derived from a wave atlas: the probability of occurrence of certain wave directions W_{dir}, significant wave heights $H_{1/3}$ and periods T_z
- they were then combined to determine a wave spectrum S(ω) and its probability of occurrence as a function of area, season, W_{dir}, $H_{1/3}$ and T_z
- the hydrodynamic properties of the ship where modeled using data from towing and wind tunnel tests, and its sea keeping abilities where given in form of Response Amplitude Operators(RAOs)
- the wind and calm water resistance were calculated; also, using superposition theory, the added resistance in waves for the known wave spectra were calculated
- the propeller characteristics were modeled based on open water tests

The result was the creation of a matrix with j combinations of power P_j and probability p_j. Then a two parameter Weibull distribution was used to represent the power required to maintain service speed.

Their case study showed that the same LNG carrier when operating in two different sea routes, specifically in Indian and Atlantic ocean, can have a 4% greater EEDI when operating in the latter one; so it is evident that the prediction of a realistic sea margin, based on actual data and not theoretical safety standards, can have a noticeable impact in the attained EEDI value.



Example:

- With a sea margin of 18% and on the 'America route' the LNG carrier can sustain the service speed of 19.5kts for 75% of the year. This is the 'reference point' for the EEDI calculations
- The corresponding value for the 'Australia route' is 84% of the time
- On the 'Australia route' the ship can have a 4.2 % lower EEDI and will still maintain speed for 75% of the year

Picture 8: Sea margin study at fixed forward speed of 19.5 knots. Clean hull, no fouling

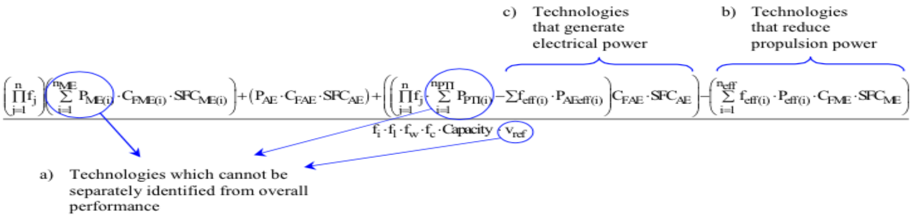
1.2.4 Use of alternative fuels

It is said that LNG fuel is the future of the Shipping industry. LNG fuel helps in reduction of air pollution from ships, and a combination of LNG fuel with diesel oil will lead to efficient engine performance, resulting in fuel saving.

Fuels with lower life-cycle CO2 emissions include biofuels and liquefied natural gas (LNG). The use of biofuels on board ships is technically possible; however, use of first-generation biofuels poses some technical challenges and could also increase the risk of losing power (e.g., due to plugging of filters). These challenges are, nevertheless, overshadowed by limited availability and unattractive prices that make this option appear unlikely to be implemented on a large scale in the near future. However, it is believed that LNG will become economically attractive, principally for ships in regional trades within ECAs where LNG is available.

1.2.5 Installation of innovative energy-efficiency technologies

There are many available technologies-which do not impact overall performance of the vessel-one can employ to improve a vessels attained EEDI as it is evident from the next figure:

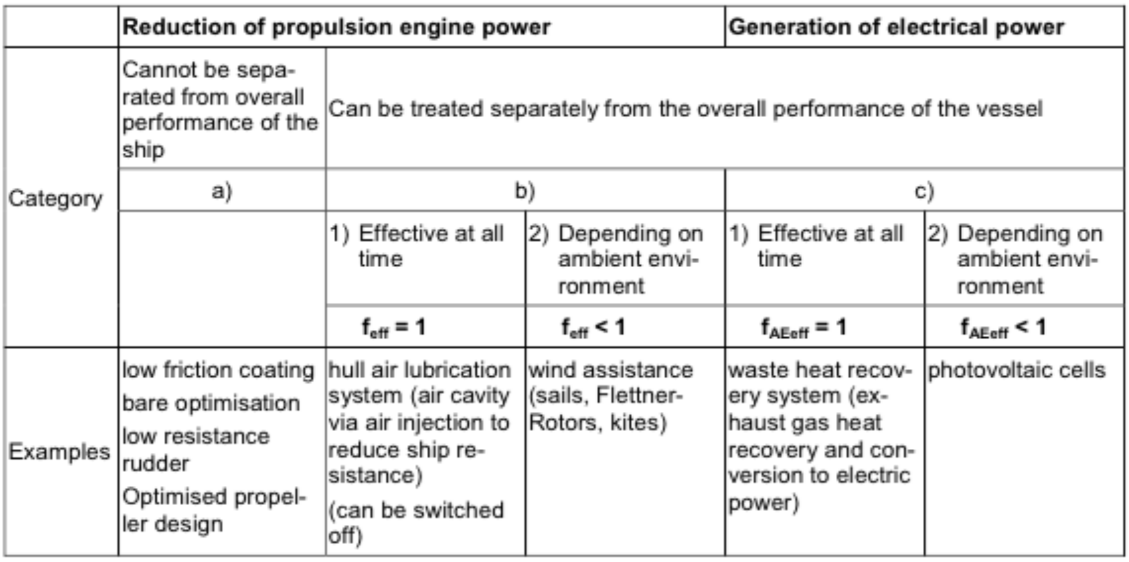


Picture 9: technologies that lower the attained EEDI value

For this purpose, GL has categorized innovative technologies into these categories:

a) Technologies with an impact on the speed-power curve of a vessel which cannot be separately identified from overall performance i.e. change the proportion of propulsion power and reference speed V_{ref}, due to ship design and applied materials.
b) Technologies that reduce the propulsion power (excluding generation of electricity). The saved propulsion power is P_{eff}. It is differentiated between technologies which may operate at any time and technologies operating under limited conditions.
c) Technologies that generate electrical power. The generated electrical power is P_{AEeff}. It is differentiated between technologies which may operate at any time and technologies operating under limited conditions.

Some examples of these innovative technologies can, as well as for the value of their respected f_{eff}, are are shown in the next table:



	Reduction of propulsion engine power			**Generation of electrical power**	
Category	Cannot be separated from overall performance of the ship	Can be treated separately from the overall performance of the vessel			
	a)	b)		c)	
		1) Effective at all time	2) Depending on ambient environment	1) Effective at all time	2) Depending on ambient environment
		$f_{eff} = 1$	**$f_{eff} < 1$**	**$f_{AEeff} = 1$**	**$f_{AEeff} < 1$**
Examples	low friction coating bare optimisation low resistance rudder Optimised propeller design	hull air lubrication system (air cavity via air injection to reduce ship resistance) (can be switched off)	wind assistance (sails, Flettner-Rotors, kites)	waste heat recovery system (exhaust gas heat recovery and conversion to electric power)	photovoltaic cells

Table 9: innovative energy efficiency technologies

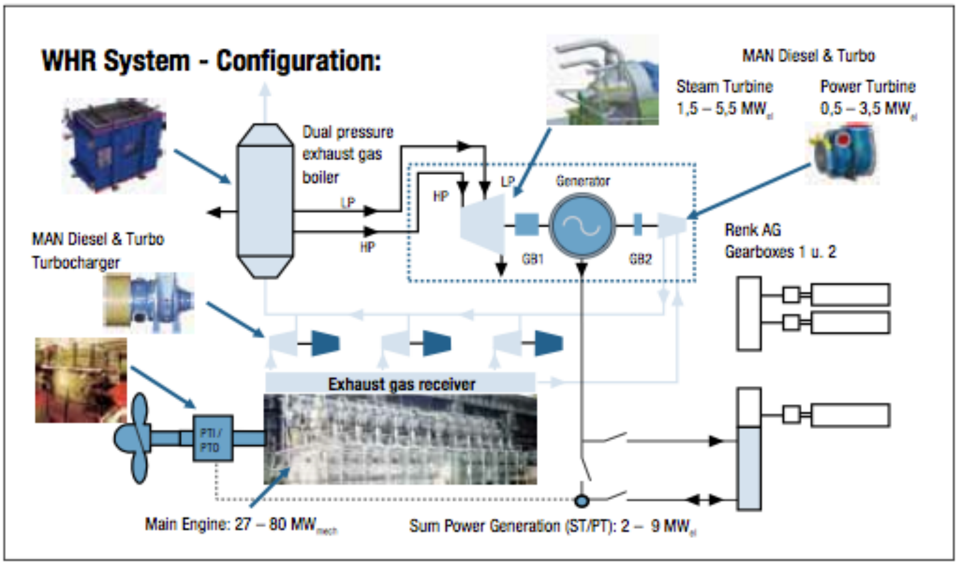
On the next pages, technologies that can be installed in already build vessels will be further examined, as well as some interesting technologies that will be employed from future new buildings.

1.2.5.1 Waste heat recovery system

Waste heat recovery systems is probably the most common method used in the reduction of the exhaust gas emissions and has been used on ships for decades. Based on existing installations WHRS gives by far the largest emission reduction and shows a potential for recovery of 10-15 % of the main engine power. In many cases, WHRS will be able to supply the total electricity need of the ship as a standalone power source.

The primary source of waste heat of a main engine is the exhaust gas heat dissipation, which accounts for about half of the total waste heat, i.e. about 25% of the total fuel energy. On the WHRS part of the exhaust gas flow is bypassed the main engine turbocharger(s) through an exhaust gas bypass resulting on a reduced amount of intake air and exhaust gas. The reduction of the intake air amount and the exhaust gas amount results in an increased exhaust gas temperature after the main engine turbocharger(s) and exhaust gas bypass, which increases the maximum obtainable steam production power for the exhaust gas fired boiler – steam and can be used in a steam turbine for electricity production. Moreover, the revised pressure drop in the exhaust gas bypass, part of the WHRS, by applying a power turbine can be utilized to produce electricity.

On the following figure we can see the principles of the Waste Heat Recovery system



Picture 10: Waste Heat Recovery System

1.2.5.2 Future technologies

These are technologies and resolutions that will mostly be employed in new buildings and coupled with optimized hull, propeller and rudder design, are expected to have a dramatic effect in lowering the industries emissions over the next years. Next, the most important ones are mentioned along with a brief description:

1. Air Lubrication System is a method to reduce the resistance between the ship's hull and seawater using air bubbles. The air bubble distribution across the hull surface reduces the resistance working on the ship's hull, creating energy-saving effects. With the right ship hull design, the air lubrication system is expected to achieve up to 10-15% reduction of CO2 emissions, along with significant savings of fuel.

2. Auxiliary engines on ships are main sources of power. Moreover they are one of those machines that are continuous running onboard vessels. LNG fuel for such engines can drastically reduce air pollution from ships.

3. The addition of water in fuel just before its injection into the combustion chamber can reduce the temperature inside the cylinder liner. An efficient system for this can result in NOx reduction of up to 30-35%.

4. An optimized cooling water system of pipes, coolers and pumps can result in decreased resistance to the flow. This will lead to savings of up to 20% of electric power of the ship and fuel consumption up to 1.5 %.

6. Sail and Kite propulsion system when used along with the conventional propulsion system can reduce the fuel as well as NOx, SOx and CO2 emissions by 35%.

7. The fuel cell propulsion utilizes power from a combination of fuel cells, solar cells and battery systems. This helps in reduction of GHG emission to a great extent.

1.3 Minimum propulsion power

As mentioned in the previous chapter, one of the most popular ways of reducing the CO2 emissions and, therefore, the value of the attained EEDI index, is reducing the installed power (slow-steaming), and as a result, the corresponding vessel's speed. At MEPC 61, some parties argued that a ship operating at a lower than the designed speed may cause unwanted effects, especially concerning its maneuverability (meaning its capacity to change and maintain a desirable route) which has a direct relation with the ship's speed among other factors. More importantly, when adverse weather condition are present, its of vital importance to know how the vessel's maneuverability will be affected.

The maneuverability of a ship, meaning its capacity to change and maintain a desirable route, is mainly affected by these parameters:

- the vessel's speed
- the vessel's ruder area
- drift forces due to weather conditions(wind and wave forces)

A new regulation was then adopted at MEPC62; addressing this matter, MARPOL, following a proposal from International Association of Classification Societies (IACS), added the following requirement to the Reg.21, Ch. 4 of Annex VI: *For each ship to which the regulation applies, the installed propulsion power shall not be less than the propulsion power needed to maintain the maneuverability of the ship in adverse weather conditions as defined in the guidelines to be developed by the organization*.

This led to the development of a three level assessment to evaluate the ships capacity to retain safe maneuverability under adverse weather conditions:

1. The minimum power lines assessment is based on the verification that a ship has larger installed power than the power defined as a function of the ship deadweight and type.

2. The simplified assessment is based on the verification that a ship has sufficient installed power to achieve the minimum required advance speed in head waves and wind conditions, defined to facilitate course-keeping in all wave and wind directions.

3. The comprehensive assessment is based on the verification that a ship has sufficient installed power to maintain advance speed and course-keeping in all wave and wind directions.

where adverse weather conditions is characterized by the following parameters, according the length of the ship:

Vessel's L_{bp} (meters)	Significant wave height, H_s (meters)	Peak wave period, T_p (seconds)	Mean wind speed, V_w (m/s)
<200	4.0	7.0 to 15.0	15.7
Intermediate lengths	Linear interpolated		Linear interpolated
>250	5.5		19.0

Table 10: Representative weather conditions

At MSC 91, the Interim Guidelines for determining minimum propulsion power to maintain the maneuverability of ships in adverse conditions were approved. However, the third of the methods to determine minimum power requirements was deleted in document MSC-MEPC.2/Circ.11, issued on 2 December 2012.

These methods are fairly simplified so there are to be used conservatively. Each ship that fulfills any of the three assessment levels is considered to have sufficient installed power to maintain its maneuverability in the weather condition described above. Also, it is natural to think that since the complexity of the methods increases as the level increases, should a vessel satisfy the first (and simpler) level of the assessment, it is assumed that it has sufficient installed power and there is no need to proceed to the next level assessment; hence rational thinking states that lower levels should be stricter than higher ones on a multi-level approach, something that has been contradicted by case studies already published [14].

The maneuverability of a ship, as already mentioned, is mainly dependent in the ships speed and rudder area. A rudder operates by redirecting the fluid past the hull, thus imparting a turning or yawing motion to the vessel; how effectively will this be accomplished is dependent on the speed (and equal generated forces on the rudder's surface) of the vessel. So in order for a ship to be sufficiently maneuverable it has to maintain a certain speed, which of course is dependent on the installed power, but not completely characterized by it, as other factors can have a negative affect like aging or fouling of the hull, and of course, extreme weather phenomena.

The study mentioned earlier [MSC93.21.5] also suggests, in line with the comments made in the previous paragraph, that the criterion should be changed to a minimum required advance speed, which more adequately describes a vessels performance under adverse weather conditions, as the delivered power to the propeller is lower than that installed and, even so, when adverse weather conditions are in play.

Chapter two:

Design and operational parameters that affect Interim Guidelines

2.1 Derivation of criteria for safe maneuvering in adverse weather conditions

The maneuverability of a ship is affected by its design parameters as much as by its operation; statistics have shown that most navigational accidents are of operational origin. It is next to impossible to regulate human error, so it is evident that the existence of some kind of minimum requirements for maneuverability is deemed necessary. Addressing this concern, IMO adopted the Interim Standards for Ship Maneuverability and after a revision based on collected data; IMO Standards for Ship Maneuverability was put in effect.

Norming the maneuverability capabilities of vessels is a complicated task and an open question for further research; no ship behaves the same under adverse weather conditions and not all of the safety concerns can be attributed solely to its maneuverability. It is argued that many of the safety concerns regarding the sea-keeping and maneuverability can be addressed by different design measures. An good example is a containership with a loading condition corresponding to a large metacentric height: roll excitation due to waves may lead to damage or loss of cargo; on the other hand, an increase in required roll damping or a stronger securing system can prevent such unwanted phenomena.

The way current IMO Standards for Ship Maneuverability examines the maneuverability characteristics of a vessel is through a series of turning maneuvers in calm water; it is evident that the impact of environmental forces present at adverse weather conditions is not accounted for, as well as the reduced speed of the vessel due to their manifestation.

Accident statistics [15] have shown that in presence of adverse weather conditions:

- the most frequently involved type of ships are general cargo, followed by bulk carriers and Ro-Ro ferries
- most accidents happen in port or restricted areas
- for tankers especially, but also bulk carriers and general cargo ships, there is a large percentage of accidents that happens en route
- the most frequent accident type is grounding, the most usual case of accident when in coastal areas

Requirements for maneuverability differ in respect with the following three scenarios:

- Maneuvering in coastal waters in increasing storms
- Maneuvering in open sea under adverse weather conditions
- Maneuvering in restricted areas with low speed

In the first scenario, when a ship is located at a coastal area in the presence of adverse advancing weather phenomena, two factors affect its safety; its ability to retain a minimum forward speed so as to distance itself from the occurring phenomena, as well as the ability to change and retain a wanted direction on the selected sea route. It is stated that if a ship can retain the direction which is most unfavorable in regard to its course keeping, it shall be able to perform any course change. Also, it must be assumed that the vessels in discussion will most probably be away from ports thus any assistance from a third party (e.g. from tugs) won't be available. To address the aforementioned issues, IMO adopted the following two regulations [MEPC 62/5/19, MEPC 62/INF.21]:

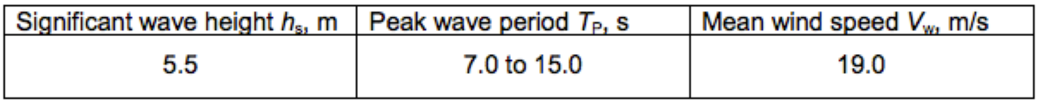
1. a ship must be able to retain its desired course whilst affected by winds and waves from any direction (course keeping in adverse weather conditions)
2. a ship, impacted by the same conditions, must be able to maintain a minimum advance speed of 4.0 knots

In the second scenario, the ship is sailing in open seas under adverse conditions; waves and winds are acting on the vessels body which may lead to an involuntary change of its heading as well as unwanted ship dynamics. In this case the ability to change direction to the most favorable seaway is most important; if a vessel is forced to drift (within a tolerable range) then its safety is ensured by the Weather Criterion.

In the third scenario low speed maneuverability is addressed, a situation most commonly encountered when entering a port; it is more an operational issue rather than a safety one. On the other hand, the high accident rate of ships in port under adverse weather conditions suggest that some minimum requirements should be employed; these will affect mainly its steering performance regardless the vessels installed power so there is no potential conflict with EEDI regulations. Especially, loading conditions that increase the lateral windage area or the submerged area of the hull, and thus affecting its course keeping abilities due to strong wing or large hydrodynamic forces respectively, should be examined.

2.2 Environmental conditions

What exactly constitutes adverse weather conditions? In the Interim Guidelines for determining minimum propulsion power to maintain the maneuverability of ships in adverse conditions adopted in MEPC.232(65), adverse weather conditions characterize a sea condition with the following parameters:

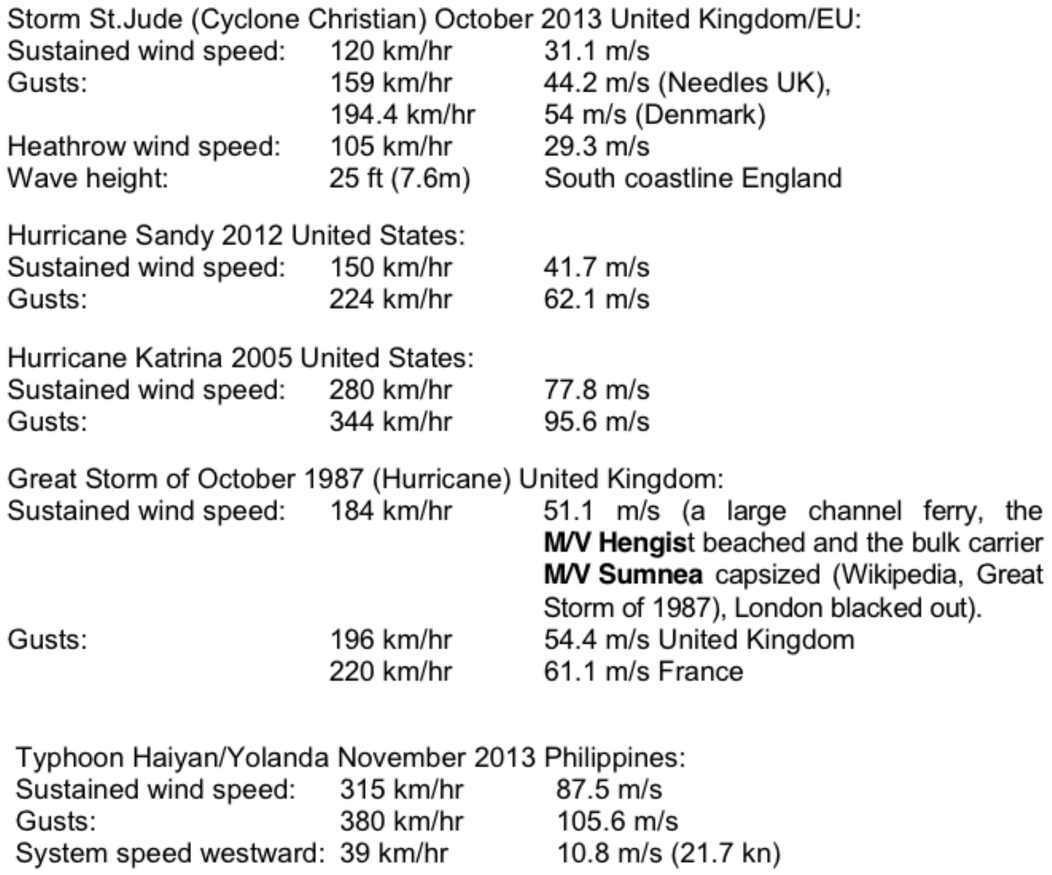


Significant wave height h_s, m	Peak wave period T_P, s	Mean wind speed V_w, m/s
5.5	7.0 to 15.0	19.0

Table 11: Adverse weather condition parameters (MEPC.232(65))

It is observed that these conditions are fairly similar with the conditions describing adverse weather in EEDI$_{weather}$ calculation. In the «Intact Stability Code 2008» for the purposes of applying the Weather Criterion, adverse weather conditions are equivalent to wind force of BF 10 or more (26.0 m/s plus gusts) and waves with significant wave height H_S = 8.0 m; an obviously much stricter regulation, but is based on the assumption that the ship might encounter such phenomena because it wont be able to avoid them (dead ship condition). In this chapter, we shall examine the dominant sea conditions of Atlantic's ocean main maritime transport routes based on statistical data and comment on the "adverse" weather condition that are used in the Interim Guidelines.

Having in mind that the Interim Guidelines apply on ocean going vessels, the worst case weather scenarios with a substantial possibility of occurrence should define these conditions. When traveling in open ocean, it is almost inevitable to not run in adverse or, in some cases, extreme weather phenomena such as sever storms or hurricanes. In the next table, data regarding extreme cases of weather phenomena from the last 30 years manifested in the Atlantic and Pacific ocean are presented:



Storm St.Jude (Cyclone Christian) October 2013 United Kingdom/EU:

Sustained wind speed:	120 km/hr	31.1 m/s
Gusts:	159 km/hr	44.2 m/s (Needles UK),
	194.4 km/hr	54 m/s (Denmark)
Heathrow wind speed:	105 km/hr	29.3 m/s
Wave height:	25 ft (7.6m)	South coastline England

Hurricane Sandy 2012 United States:

Sustained wind speed:	150 km/hr	41.7 m/s
Gusts:	224 km/hr	62.1 m/s

Hurricane Katrina 2005 United States:

Sustained wind speed:	280 km/hr	77.8 m/s
Gusts:	344 km/hr	95.6 m/s

Great Storm of October 1987 (Hurricane) United Kingdom:

Sustained wind speed:	184 km/hr	51.1 m/s (a large channel ferry, the **M/V Hengis**t beached and the bulk carrier **M/V Sumnea** capsized (Wikipedia, Great Storm of 1987), London blacked out).
Gusts:	196 km/hr	54.4 m/s United Kingdom
	220 km/hr	61.1 m/s France

Typhoon Haiyan/Yolanda November 2013 Philippines:

Sustained wind speed:	315 km/hr	87.5 m/s
Gusts:	380 km/hr	105.6 m/s
System speed westward:	39 km/hr	10.8 m/s (21.7 kn)

Table 12: Data regarding extreme weather conditions (various sources)

Data acquired from Asia-Pacific Data Research Center concerning the annual (average of periods when sea is not covered by ice) frequency of surface high winds stronger than 20 m/s, calculated from data ranging from September 1999 through August 2006 (in which the data contaminated from rain and sea ice have been eliminated), is shown in the next figure. The frequency is defined as the ratio (%; shown by color) of the number of high winds to the number of total valid wind observations. Two different scales are used (scale located at bottom) for the Northern and Southern Hemispheres.

Spatial variability of the high-wind frequency is associated with sea surface temperature (SST) and coastal orography. The figure shows the frequency (color) along with SST climatology (contour) and orography (shading over land).

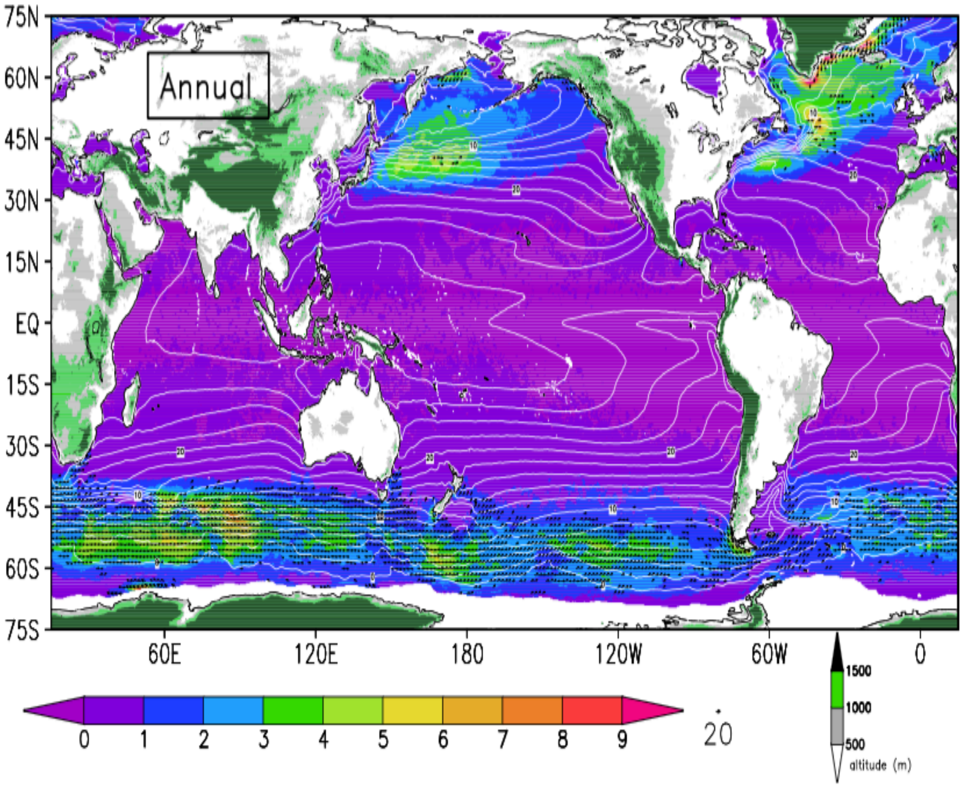
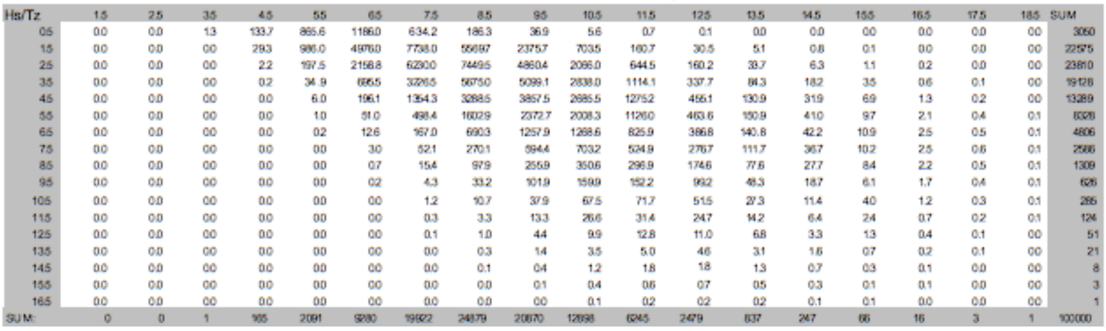


Figure 3: Frequency of winds stronger than 20m/s from data gathered over a 7 year period (IPRC-APRC)

When observed, it is evident that especially in north Pacific and Atlantic ocean seaways, there is a high probability of encountering strong winds greater than 20 m/s.

Also, data acquired from a Global Wave Atlas [16] illustrate the probability of sea-states characterized by the significant wave height Hs and peak wave period Tz, in the North Atlantic described as occurrence per 100000 observations.



Hs/Tz	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	SUM
0.5	0.0	0.0	1.3	133.7	865.6	1186.0	634.2	186.3	36.9	5.6	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	3050
1.5	0.0	0.0	0.0	29.3	986.0	4976.0	7738.0	5569.7	2375.7	703.5	160.7	30.5	5.1	0.8	0.1	0.0	0.0	0.0	22575
2.5	0.0	0.0	0.0	2.2	197.5	2158.8	6230.0	7449.5	4860.4	2066.0	644.5	160.2	33.7	6.3	1.1	0.2	0.0	0.0	23810
3.5	0.0	0.0	0.0	0.2	34.9	686.5	3226.5	5675.0	5099.1	2838.0	1114.1	337.7	84.3	18.2	3.5	0.6	0.1	0.0	19128
4.5	0.0	0.0	0.0	0.0	6.0	196.1	1354.3	3288.5	3857.5	2685.5	1275.2	456.1	130.9	31.9	6.9	1.3	0.2	0.0	13289
5.5	0.0	0.0	0.0	0.0	1.0	51.0	498.4	1602.9	2372.7	2008.3	1126.0	463.6	150.9	41.0	9.7	2.1	0.4	0.1	8328
6.5	0.0	0.0	0.0	0.0	0.2	12.6	167.0	690.3	1257.9	1268.6	825.9	386.8	140.8	42.2	10.9	2.5	0.5	0.1	4806
7.5	0.0	0.0	0.0	0.0	0.0	3.0	52.1	270.1	594.4	703.2	524.9	276.7	111.7	36.7	10.2	2.5	0.6	0.1	2586
8.5	0.0	0.0	0.0	0.0	0.0	0.7	15.4	97.9	255.9	350.6	296.9	174.6	77.6	27.7	8.4	2.2	0.5	0.1	1309
9.5	0.0	0.0	0.0	0.0	0.0	0.2	4.3	33.2	101.9	159.9	152.2	99.2	48.3	18.7	6.1	1.7	0.4	0.1	626
10.5	0.0	0.0	0.0	0.0	0.0	0.0	1.2	10.7	37.9	67.5	71.7	51.5	27.3	11.4	4.0	1.2	0.3	0.1	285
11.5	0.0	0.0	0.0	0.0	0.0	0.0	0.3	3.3	13.3	26.6	31.4	24.7	14.2	6.4	2.4	0.7	0.2	0.1	124
12.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.0	4.4	9.9	12.8	11.0	6.8	3.3	1.3	0.4	0.1	0.0	51
13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.4	3.5	5.0	4.6	3.1	1.6	0.7	0.2	0.1	0.0	21
14.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	1.2	1.8	1.8	1.3	0.7	0.3	0.1	0.0	0.0	8
15.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.6	0.7	0.5	0.3	0.1	0.1	0.0	0.0	3
16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2	0.1	0.1	0.0	0.0	0.0	1
SUM:	0	0	1	165	2091	9280	19922	24879	20870	12898	6245	2479	837	247	66	16	3	1	100000

Table 13: Probability of sea-states in the North Atlantic described as occurrence per 100000 observations.

A scatter plot diagram, shown in the next figure, was created to better understand these data; the plot presents the probability of occurrence of a sea state with significant wave heights corresponding to the values of the above table, for each different mean wave period included in the above range.

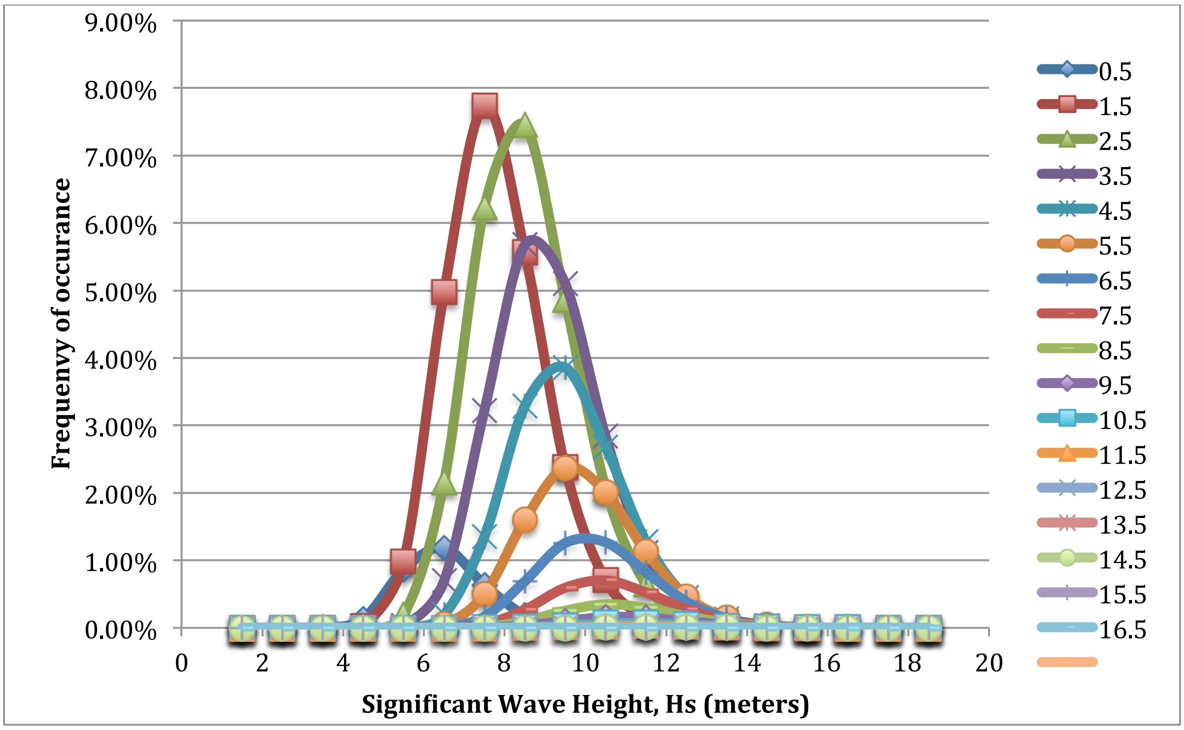


Figure 4: Probability of occurrence of selected sea states

As we observe, the probability of a vessel encountering waves with significant heights ranging from 8.0 to 10.0 meters with small wave periods (in the range of 1.5-3.5 s) is almost 7%; similar waves with larger peak periods (and length accordingly), in the range of 8.0-10.0 s, have a smaller frequency of occurrence, an average of almost 1%. According to data derived from a world wave atlas, waves in the Atlantic average a peak wave period of 8.0-12.0 seconds, meaning the chance of encountering waves of Hs greater than 8.0 meters is significantly small.

Another factor that can have negative effects in the maneuverability of a vessel, and hence the safety, under adverse weather conditions, is the presence of strong currents; though at this point in time, forces exerted on submerged hulls from them are not taken into account in the regulation studied. An example of current speeds vessels might encounter in the Golf stream is given in Figure 6.

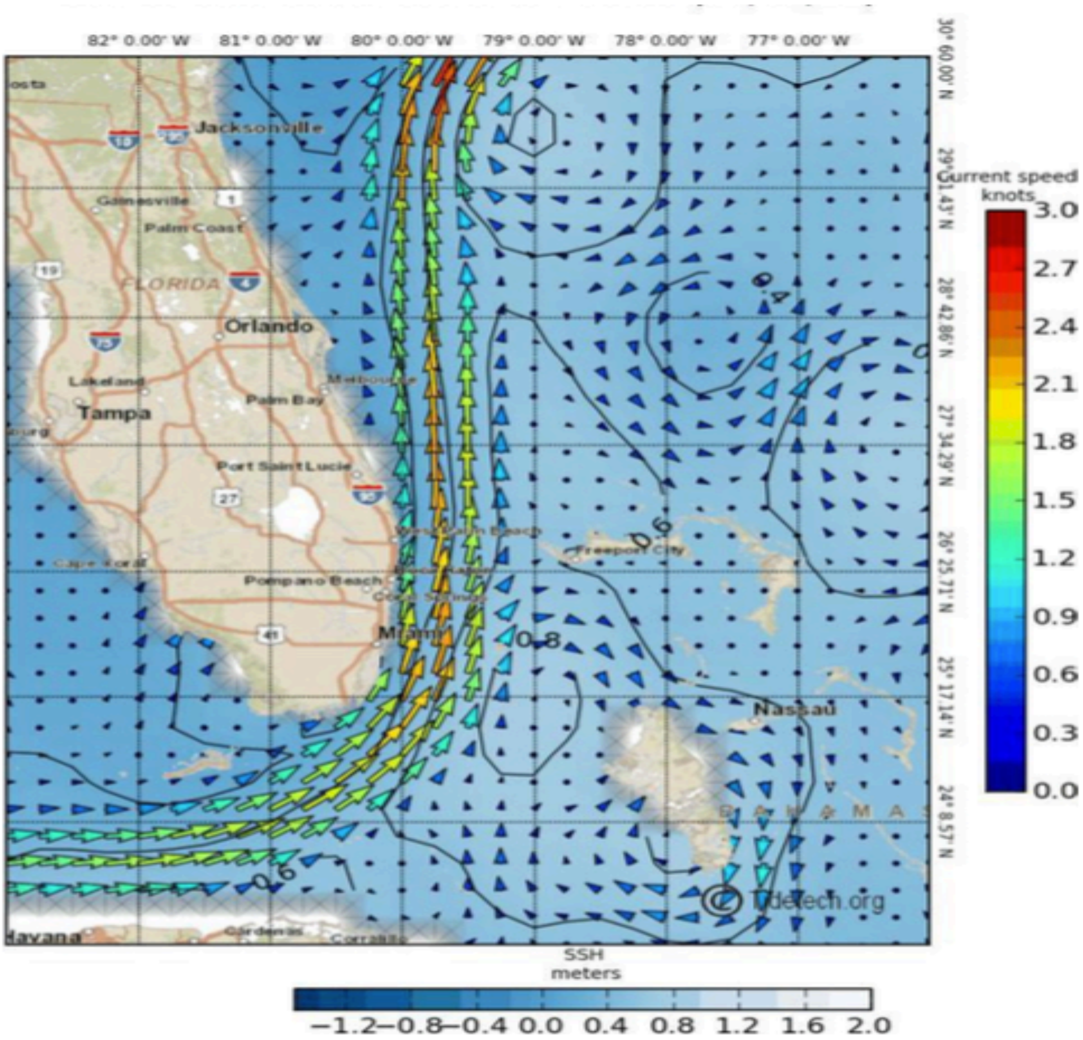


Figure 5: Gulf stream south current

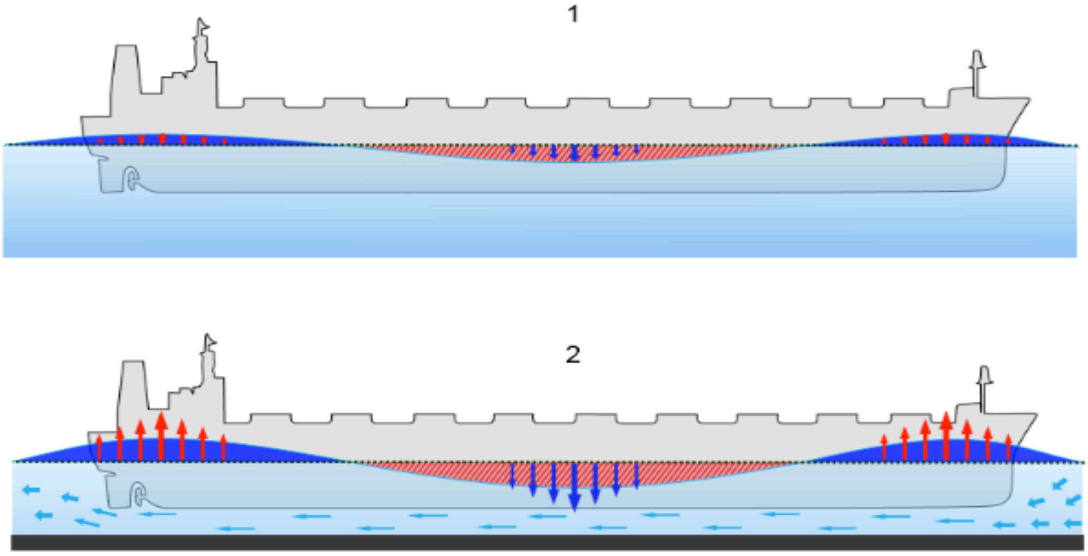
Though statistics of weather phenomena need to be validated and be further improved, comparing all of the above, it is clear that there is room for improvement of the current way adverse weather conditions are described in the Interim Guidelines to set a safer standard for calculations concerning minimum power; though harmonizing them with the conditions described in IMO's «Intact Stability Code 2008» [17], as has been proposed in *MSC 93.21.5,* seems excessive, as the probability of encountering phenomena of this magnitude without being able to avoid them is statistically improbable and msy also lead to unrealistic power needs.

2.3 Operational parameters

Maintaining the maneuverability of a vessel from an operational point of view means that a vessel can acquire and keep a wanted sea route from any given starting point, a point emphasized by a recent study performed on small size vessels (under 10k DWT); an analysis performed on the applicability of the guidelines while maintaining EEDI compliance, showed the ability to recover head seas is compromised by a significant power reduction [18]. There are a lot of parameters that affect a vessel's maneuverability capabilities, excluding the effects of waves, current or restricted areas; here few will be mentioned:

- Wind forces when a Loading Condition that maximizes the size of the windage area of a vessel, e.g. especially a ballast condition (small draft) or a vessel with large superstructures
- Even at zero forward speed, wave drift forces act on a vessel; a mean longitudinal and a mean transverse force which increase required ruder force and propeller thrust respectively
- Wave drift forces increase when a vessel is moving with forward speed but normally rudder response, hull and propeller efficiency improve as well; other safety issues might occur though, due to the increase of the ship vertical motions:
    - Rudder and/or propeller surfacing
    - Reduced propeller thrust, due to a reduction in propeller efficiency or the occurrence of propeller ventilation
    - Slamming, which leads to increased values in added wave resistance

- Shallow waters causing squatting; when a vessel is moving with increased speed in shallow waters, the velocity of water underneath its hull increases and thus creating an area of lowered pressure, increasing its draught



Picture 11: Squat effect

2.4 Minimum Power Lines

2.4.1 Minimum Power lines-a statistical approach

First of all, it is of major importance to emphasize that the Minimum Power Lines assessment in its current form is a statistical method; more accurately, the same fleet database that was used for the derivation of the EEDI reference lines was used to produce the minimum power lines assessment.

The methodology followed was, that, for each ship type (whose deadweight is larger than that specified in regulation 21 for phase 0), a plot was made that specified the installed power-deadweight relationship. In the next figure the correlation between deadweight and installed power for tankers and combination carriers above 20000 tons is depicted; each point represents a different vessel.

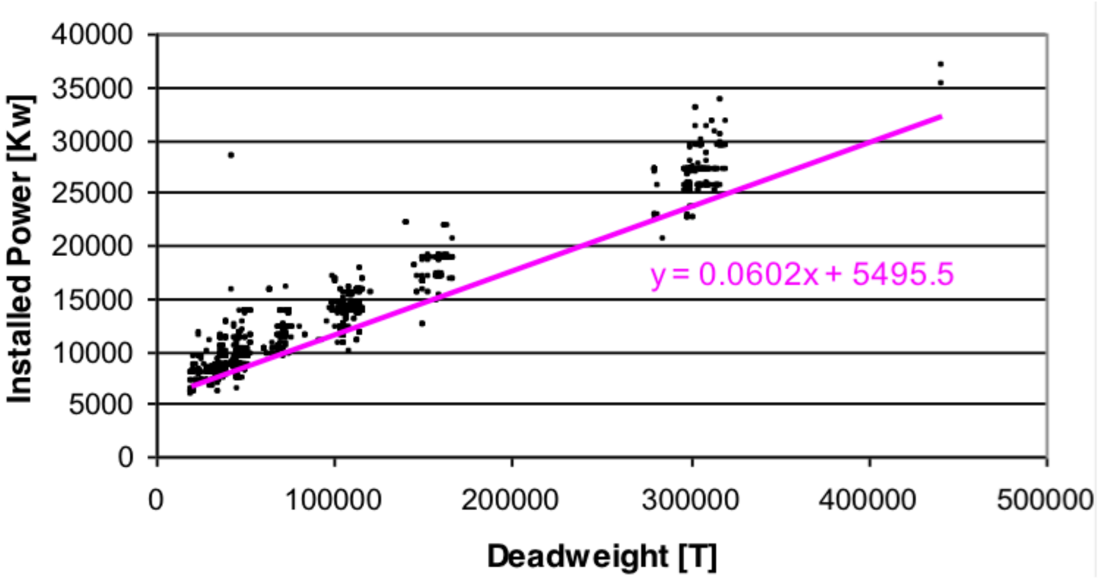


Figure 6: Tankers and combination carriers above 20k DWT

For each plotted sample, a trend line for the installed power as a function of their deadweight was produced. The trend line depicted in the previous figure was obtained so that 90% of the vessels considered were placed above it. As the plotted sample suggests, the larger number of ships that are placed below the trend line, have deadweight lower than 50000 tons; this amplifies the concern that a large number of relatively small vessels of the global fleet are underpowered.

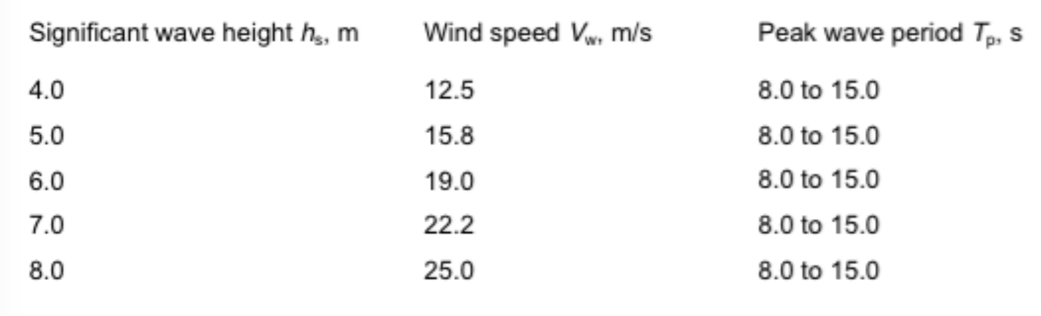
It is evident that such a simplified approach is practically a free pass for almost every ship that this method will apply; only seriously underpowered vessels won't be able to make the benchmark. A study conducted by Greece [3] proved exactly that for the four vessels studied; all of them managed to pass from the first level assessment, where the installed MCR easily exceeded the minimum power lines with a margin ranging from 8% (corresponding to the smallest vessel) up to 20% (for the largest vessels) while almost every ship failed the second stage assessment. This is indicative of the margin available for a stricter safety standard.

2.4.2 Minimum power lines based on comprehensive assessment

There is no doubt that these are important issues that need to be addressed and IMO has already taken steps in the right direction [19]; this is the estimation of new minimum power lines based on the comprehensive assessment meaning that factors that are important for the maneuverability of a ship will be also considered. These include the effect of:

- the lateral windage area, defining corresponding wind forces and moments
- the lateral submerged area, defining second order drift forces due to waves
- the rudder area

Also, in order to define the minimum required installed power, the right criteria for safe maneuvering in adverse weather conditions needed to be employed. The assessment used potential code GL-Rankine and RANSE-CFD simulations, to define second order drift forces due to waves and calm water drift and wind forces, for three ship types: bulk carriers, tankers and containerships in their maximum draught loading condition. The environmental conditions applied are shown in the table below, with wave directions varying from 0 to 360 degrees.



Significant wave height h_s, m	Wind speed V_w, m/s	Peak wave period T_p, s
4.0	12.5	8.0 to 15.0
5.0	15.8	8.0 to 15.0
6.0	19.0	8.0 to 15.0
7.0	22.2	8.0 to 15.0
8.0	25.0	8.0 to 15.0

Figure 7: Environment used for derivation of minimum power lines

Then, the most unfavorable combination of peak wave period and angle of attack for each significant wave height were found for both criteria:

- Minimum installed power to ensure advance speed of at least 4.0 knots in waves and wind from any direction
- Minimum installed power to ensure course-keeping in waves and wind from any direction

Following a statistical approach taking into account weather and travel patterns of the selected seaway and ship respectively, peak wave height of 6 m was selected. For tankers, the results showed that the dimensioning criterion for the minimum installed power was in direct correlation with the rudder area:

- for a rudder area greater than 1.1 percent of the lateral submerged area, minimum advance speed of 4.0 knots was found to be the case;
- for a rudder area less than 1.1 percent of the lateral submerged area, course keeping in adverse coditions was the dimensioning criterion

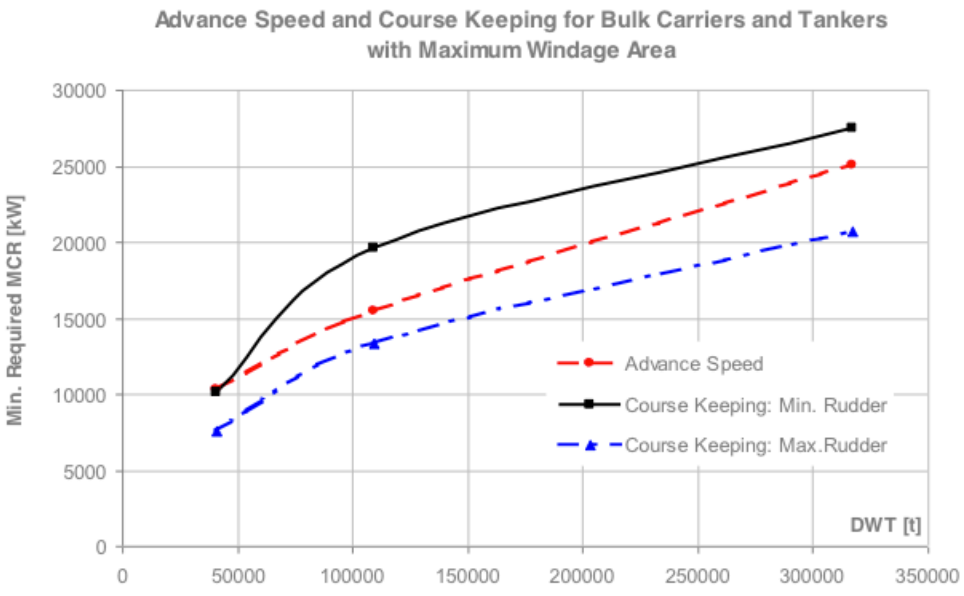


Figure 8: minimum required MCR vs. DWT to ensure (a) minimum advance speed of for knots and (b) course-keeping

Finally, for the formulation of minimum power line was based on the minimum advance speed of 4.0 knots along with a correction factor for ships equipped with small area rudders. In the next figure, the resulting power line for peak wave heights of 5.0, 6.0 and 7.0 meters is compared with the statistics-based one.

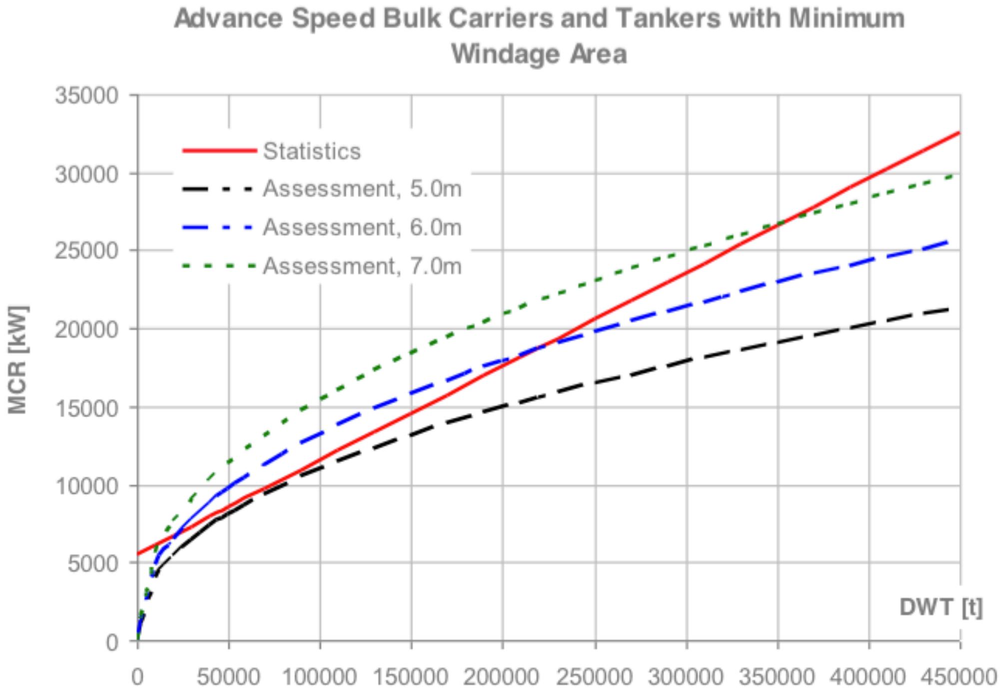


Figure 9: minimum required MCR vs. DWT for tankers in comparison with statistics-base MPL

These results show the available margin for a stricter approach regarding the currently employed minimum power lines; especially for ships with deadweight less than 200000 tons, the installed power predictions based on statistics fall short in both cases of peak wave heights of 6.0 and 7.0 meters while the case for larger vessels is the opposite. Its clear that the statistics-based generation of the trend line suffers from the already underpowered vessels (which constitute the bottom samples of the scatter area in Figure 4) used and it seems, at least, unconservative for all ships not being in the bottom 10% to be provided with an IMO accepted safety standard.

2.5 Simplified assessment

The aim of the Simplified Assessment was, by using the same criteria as the Minimum Power Lines approach, to introduce a simplification to the method itself; this was based on the assumption that if a vessel has sufficient installed power to move with a certain advance speed in head waves and wind (considered the most unfavorable condition), then it will also be able to keep course with waves and wind coming from any direction.
For the development of the method the required minimum installed power, which corresponds to a minimum advance speed, was selected so that the fulfillment of the advance speed also ensured the fulfillment of the course keeping criterion; so the simplification is than only the longitudinal direction is of concern.
As described in the previous chapter, the methods included in comprehensive assessment were employed to investigate the dependency of the required advance speed with the lateral windage and rudder area; second order wave forces were computed with the 3D potential code GL-Rankine, forces from wind and calm water drift forces were found from RANSE-CFD computations and rudder forces were computed with the help of an empirical model (BRIX-1993). Computations were performed for a variation of significant wave heights and peak wave periods (as seen in figure 8 of the previous chapter) and advance speed, so as to enable the course keeping requirement; regarding the loading conditions especially in tankers, it was found that the most unfavorable was the fully loaded condition (see next figure).

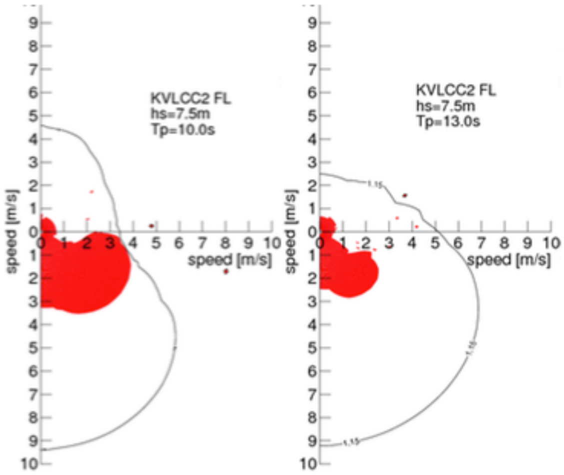


Figure 10: Course-keeping criterion

Also, the same computations were performed with variations of the original rudder area, so as to find the required advance speed in head waves and wind. The results of the dependency between the required advance speed depending on the ratio of the submerged rudder area to the submerged lateral area of the hull, are shown in the next figure.

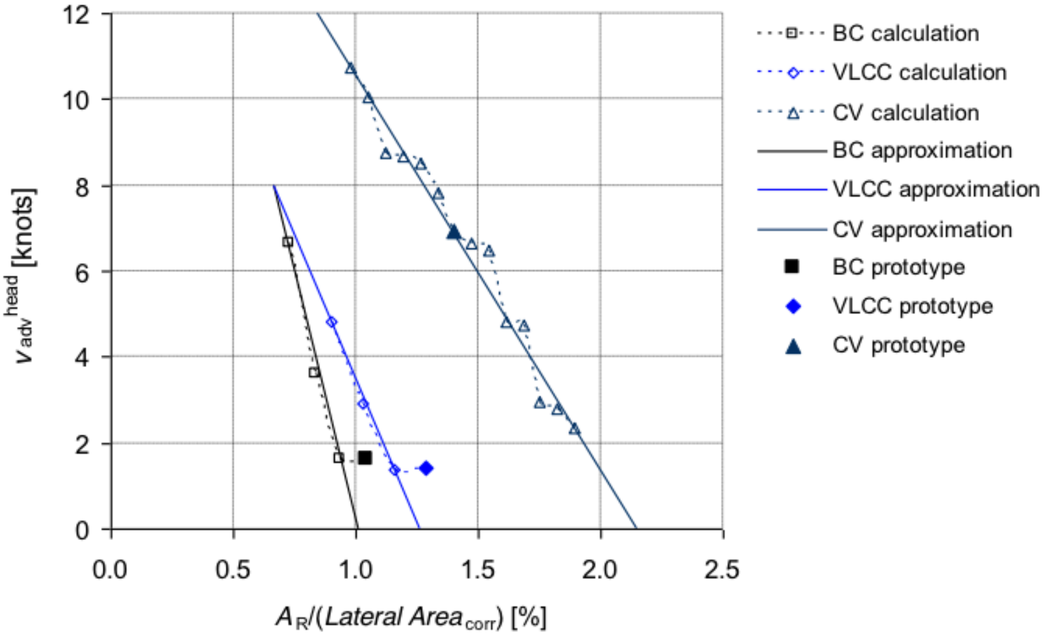


Figure 11: Required advance speed in head waves in relation with submerged ruder area

Further studies on more vessel showed that the dependency of the required advance speed with the rudder area have an almost linear relationship, as shown in the next figure.

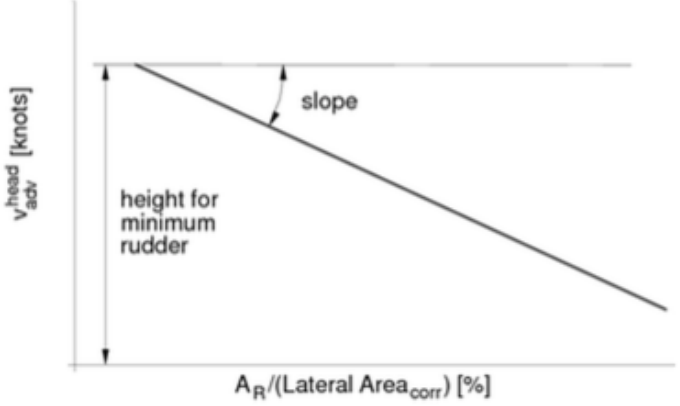


Figure 12: Required advance speed in relation with ruder area

So it seems that the results produced for the development of the simplified assessment, although based on a small number of vessels and specific loading conditions, are quite conservative and, if applied, are able to ensure the course keeping abilities of a vessel; on the other hand, a study showed [3] that the heavy ballast condition seemed to be more critical due to the excessive vertical sea-keeping responses in adverse weather, meaning an increase in added wave resistance, as well as a smaller submerged rudder area.

Chapter three:

Employed methods for estimation of resistance, reference speed V_{ref} and coefficient f_w and sea-keeping

3.1 Scope of work

In order to evaluate the EEDI for the studied ships, the corresponding reference speed had to be calculated, as the only data that were available regarding the ships speed was either from the speed trial tests, which were conducted in Full Load Departure condition or their cruising speed, which corresponded to the same loading condition; reference speed is to be taken at maximum loading condition (scantling draught). This led to the employment of a graphical method that uses the powering curves, proposed by IACCS [20] for adjusting the trial tests speed to the correspondent EEDI loading condition speed.

For the use of the aforementioned method, the powering curves and hence the total resistance of the studied vessels in both loading conditions had to be calculated; for this purpose the Holtrop [21] method was used. It should be noted that Holtrop method is a statistical method and as such it cannot make accurate predictions of the hull form's exact shape and therefore is unable to detect problems or irregularities that occur due to the vessel's particular shape, which especially affect problems at the viscous pressure resistance and the induced wave field.

We selected the newly designed ship TEST_SHIP for the purposes of this study, being the only one that a 3D lines plan was available. The full geometry of the hull was constructed using the program AVEVA based on a 3D hull of a similar vessel. The original hull form was distorted accordingly to match the general particulars of the designed vessel; repetitive smoothing sessions and retrofitting of sections and waterlines led to a hull form with the wanted hydrostatic and general characteristics.

In order to calculate the value of $EEDI_{weather}$ for the newly designed ship TEST_SHIP , the coefficient f_w (as it appears in EEDI formula) needed to be evaluated. For its calculation added resistance due to waves and wind must be calculated:

- for the added resistance due to wind, normally a model wind tunnel test is required to assess the value of a wind resistance coefficient; due to the lack of a physical model, empirical data from similar vessels shall be employed,
- for the added resistance due to waves, for the short wave region ($\lambda<L/2$), a new formula [22] is used; for longer waves, two different 3D-Panel codes were used, capable of calculations of wave induced loads for a moving vessel. For the generation of the panelized surface of the hull, the C.F.D program Shipflow was utilized.

Particularly, for the estimation of added wave resistance concerning the weather conditions defined in the estimation of $EEDI_{weather}$ the formula developed by Liu and Papanikolaou is used, as the defined wavelength is in the shortwave region; the adverse weather conditions defined in Interim Guidelines correspond to greater wave lengths, so the two 3D-panel codes will be used for the calculation of the added wave resistance and to produce the sea-keeping results in the form of RAO diagrams.

3.2 Estimation procedure of the EEDI reference speed V_{Ref}

Due to the fact that the available speed trial test data for all three ships were conducted on speed and loading condition that differed from those specified by EEDI guidelines, an adjustment procedure specified by IACCS that is applicable in cases as such was employed.

The adjustment procedure uses the graphical construction of the powering curves depicted in Figure 4 that can be described by the following general procedure, applied only to EEDI functioning point (75% of MCR):

For each corrected power value measured during sea trial the ratio $P_{measured}$ / $P_{Holtroppredicted}$ was computed. These ratios were put on the curve obtained from the Holtrop method in EEDI condition, in order to obtain the curve of the trial results for EEDI condition.

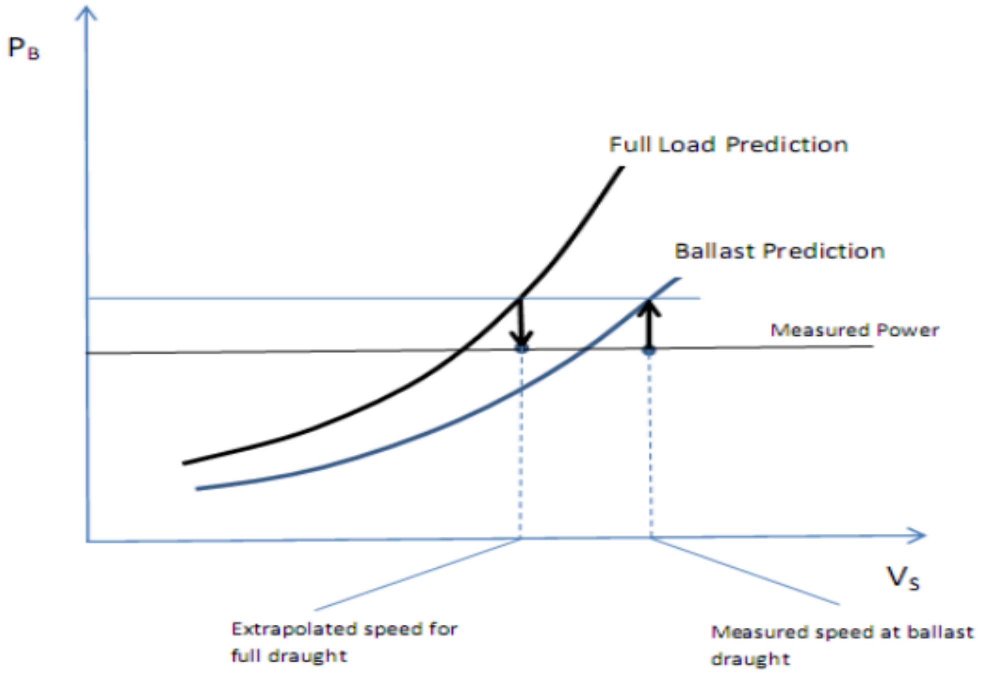


Figure 13: graphical representation of assessment procedure for Vreff

It should be noted that the results given by this graphical method should be used conservatively; although it is expected that the speed in the corresponding EEDI condition should not deviate much from her value in Full Load Departure condition.

3.2 Estimation of resistance - HOLTROP Statistical method

In order to generate the powering curves for each vessel for both Loading Conditions, their corresponding total resistance in calm water for a range of different speeds needed to be calculated; for this reason the semi-empirical Holtrop method was used.

The Holtrop method is a semi-empirical statistical method created (and later revised) by J. Holtrop provided for the calculation of the total resistance of o vessel with forward speed in it's design stage and hence a prediction for the required propulsive power needed. The original power prediction method was based on a regression analysis of random model and full scale test data so it's prediction abilities are limited and for several types of vessels, that their combinations of main dimensions and block coefficients deviate much from those of the original database. Also predictions for larger Froude numbers (above 0.5) were proven to be often incorrect [21]. To address these issues, a revised method was developed with the addition of data from a new sample of 64 vessels, extended in such ways in order to cover a broader range of parameters that are of interest. This revised method was used for the generation of the powering curves needed for the purposes of this thesis as Froude numbers of the studied vessels are lower than 0.4 and greater accuracy is expected; a more detailed description follows.

The total resistance of a vessel in calm water is given by the following formula which is subdivided in the components shown at the right section of the equation and analyzed further below.

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

Equation 1: total resistance and its components

where:

- R_F is the frictional resistance computed according to the ITTC-1957 formula. Frictional resistance accounts for a major percentage of total resistance for slow moving vessels with large wetted surface areas, e.g. large bulk carriers with low Froude numbers.
- (1+k1) is a hull form factor which correlates the viscous resistance of the hull to its frictional resistance
- R_{app} is the appendages resistance and it is affected by the presence of appendages on the submerged surface of the hull e.g. rudder(s), anodes, anti-rolling fins, shafts or spoilers
- R_W is the wave resistance, meaning the loss of energy due to the induced wave field caused by the motion of a semi-submerged slender body, is calculated using a formula derived from the aforementioned statistical analysis, which considers the vessel's main dimensions, the design of the bulbous bow, the corresponding Froude number, the entrance angle of the design waterline and its prismatic coefficient. Because the ships studied in this thesis have low Froude numbers, it is expected that the

added wave resistance will account for a small part of their total resistance.

- R_B is the additional pressure resistance due to the presence of a bulbous bow and is mainly affected by the distance of its' transverse area center in relation to the water surface
- R_{TR} is the additional pressure resistance due to immersed transom stern. It depends largely on the shape (and size) of the transom area and accounts for the flow separation that occurs there, as well as the increased pressure and induced wave
- R_A is the model-ship correlation resistance and describes the effects of still air resistance and hull roughness

As mentioned before the Holtrop method has proven to be most accurate when a vessel's resistance is mainly comprised of its frictional resistance ie has a large block coefficient and a low Froude number. The ITTC-1957 formula, when applied to fairly simple hull forms, like the ones examined in this paper (single rudder, single propeller, no anti-rolling fins) yields a good approximation of the vessel's frictional resistance. Also, due to the low values of Froude numbers for the vessels examined as well as the presence of a bulbous bow, the wave making resistance is expected to constitute a small fraction of their total resistance.

For the use of Holtrop method for the studied ships, most of the data that was needed for the calculations was provided. For those that couldn't be provided, either we were able to measure them from the General Arrangement plans or calculate them in other ways. A table describing the data, their respective source and their unit of measurement, used for Holtrop method is presented in the table below.

Input data	Unit of measurement	Source
Length between perpendiculars, L_{bp}	meters	GIVEN
Breadth molded, B	meters	GIVEN
Draft at midship, T	meters	GIVEN
Draft at A.E, T_{aft}	meters	GIVEN
Draft at F.E, T_{fore}	meters	GIVEN
Displacement, D	tons	GIVEN
Volume, V	m_3	GIVEN
Block coefficient, C_b	-	GIVEN
Midship coefficient, C_m	-	GIVEN
Prismatic coefficient, C_p	-	GIVEN
Warplane coefficient, C_{wl}	-	GIVEN
Transverse area of bulb, A_{bt}	m^2	ASSUMED
Center of A_{bt} from keel, h_b	meters	MEASURED FROM G.A
LCB, as percentage of L from 0.5L	-	GIVEN
Sea water density, ρ	Kg/m^3	KNOWN
Gravity's acceleration, g	m/s^2	KNOWN
Rudder area	m^2	MEASURED FROM G.A
Submerged transom area	m^2	ASSUMED

Propeller diameter, Dp	m	MEASURED FROM G.A

Table 14: Data used in Holtrop statistical method

The revisited method also includes formulae for the prediction of wake and thrust deduction of single screw ships, that, when coupled with the open water characteristics of the propeller and with the help of the GRID program, produces an fairly accurate estimate of the propulsion power needed by a ship.

3.3 Computational methods for numerical calculations of ship sea-keeping

The evaluation of motions and loads of freely oscillating bodies with forward speed at a seaway is of primary importance for a ship's design and operational planning. Contrary to moored offshore structures, ships are characterized by their slender bodies (mono-hull or multi-hull) and the fact that they move with substantial forward speed.

If the effect of the wave amplitude on the ship seak-eeping is significantly nonlinear, there is little sense in investigating the ship in elementary waves, since these waves do not appear in nature and the non-linear reaction of the ship in natural seaways cannot be deduced from the reaction in elementary waves. In these non-linear cases, simulation in the time domain is the appropriate tool for numerical predictions.

However, if the non-linearity is weak or moderate the sea-keeping properties of a ship in natural seaways can be approximated by superposition of the reactions in elementary waves of different frequency and direction. In these cases, the accuracy can be enhanced by introducing some relatively simple corrections of the purely linear computations to account for force contributions depending quadratic-ally on the water velocity or considering the time dependent change of position and wetted surface of the ship, for example. Even if iterative corrections are applied the basic computations of the ship sea-keeping is still based on its reaction in elementary waves, expressed by complex amplitudes of the ship reactions. The time dependency is then always assumed to be harmonic, i.e. sinusoidal.

The Navier-Stokes equation (conservation of momentum) and the continuity equation (conservation of mass) suffice in principle to describe all phenomena of ship sea-keeping flows. However, we neither can nor want to resolve all little turbulent fluctuations in the ship's boundary layer and wake.

Therefore we average over time intervals which are long, compared to the turbulent fluctuations and short, compared to the wave periods. This then yields the Reynolds-averaged Navier-Stokes equations (RANSE). By the late 1990s RANSE computations for ship sea-keeping were subject to research, but were still limited to selected simplified problems.

If viscosity is neglected the RANSE turn into the Euler equations. Euler solvers do not have to resolve the boundary layers (no viscosity - no boundary layer) and allow thus coarser grids and considerably shorter computational times. By the late 1990s, Euler solvers were also still limited to simplified problems in research applications, typically highly non-linear free surface problems such as slamming of two-dimensional sections.

In practice, potential flow solvers are used almost exclusively in sea-keeping predictions. The most frequent application is the computation of the linear sea-keeping properties of a ship in elementary waves. In addition to the assumption for Euler solvers potential flow assumes that the flow is irrotational. This is no major loss in the physical model, because rotation is created by the water adhering to the hull and this information is already lost in the Euler flow model.

Relevant for practical applications is that potential flow solvers are much faster than Euler and RANSE solvers, because potential flows have to solve only one linear differential equation instead of four non-linear coupled differential equations. Also potential flow solvers are usually based on boundary element methods and need only to discretize the boundaries of the domain, not the whole fluid space. This reduces the effort in grid generation (the main cost item in most analyses) considerably. On the other hand, potential flow methods require a simple, continuous free surface. Flows involving breaking waves and splashes can hardly be analyzed properly by potential flow methods.

In reality, viscosity is significant in sea-keeping, especially if the boundary layer separates periodically from the hull. This is definitely the case for roll and yaw motions. In practice, empirical corrections are introduced. Also, for flow separation at sharp edges in the aft-body (e.g. vertical stems, rudder, or transoms) a Kutta condition is usually employed to enforce a smooth detachment of the flow from the relevant edge.

The ship flow in elementary waves is described in a coordinate system moving with ship speed in the x direction, but not following its periodic motions. The derivatives of the potential give the velocity of water relative to such a coordinate system. The total velocity potential is decomposed:

$$\varphi' = (-V_x+\varphi^S)+(\varphi^W+\varphi^I)$$

with:

φ' : potential of total flow
$-V_x$: potential of (downstream) uniform flow with ship speed V
φ^S: potential of the steady flow disturbance
φ^W: potential of the undisturbed wave
φ^I: remaining unsteady potential

The first parenthesis describes only the steady (time-independent) flow, the second parenthesis the periodic flow due to sea waves. The potentials can be simply superimposed, since the fundamental field equation (Laplace equation, describing continuity of mass) is linear with respect to φ':

$$\Delta\phi' = \left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)\phi' = 0$$

Various approximations can be used for potential of the steady flow disturbance and remaining unsteady potential which affect computational effort and accuracy of results. The most important are mentioned here and those utilized from programs used in this thesis, are analyzed further:

- Strip method
- Unified theory
- High speed strip theory (HSST)
- Green function method (GFM)

  ISSC (1994) gives a literature review of these methods. GFM distribute panels on the average wetted surface (usually for calm-water floating position neglecting dynamical trim and sinkage and the steady wave profile) or on a slightly submerged surface inside the hull. The velocity potential of each panel (Green function) fulfills automatically the Laplace equation, the radiation condition (waves propagate in the right direction) and a simplified free-surface condition (omitting the boundary surface completely). The unknown (either source strength or potential) is determined for each element by solving a linear system of equations such that for each panel at one point the no-penetration condition on the hull (zero normal velocity) is fulfilled.
  The various methods, e.g. Ba a.nd Guilbaud (1995), lwashita (1997), differ primarily in the way the Green function is computed. This involves the numerical evaluation of complicated integrals from 0 to co with highly oscillating integrands. Some GFM approaches formulate the boundary conditions on the ship under consideration of the forward speed, but evaluate the Green function only at zero speed.
  As an alternative to the solution in the frequency domain (for excitation by elementary waves), GFM may also be formulated in the time domain (for impulsive excitation). This avoids the evaluation of highly oscillating integrands, but introduces other difficulties related to the proper treatment of time history of the flow in so-called convolution integrals. Both frequency and time domain solutions can be superimposed to give the response to arbitrary excitation, e.g. by natural seaway, assuming that the problem is linear.

- Rankine Singularity Method (RSM)

  Bertram and Yasukawa (1996) give an extensive overview of these methods covering both frequency and time domains. RSM, in principle, capture φ^S completely and also more complicated boundary conditions on the free surface and the hull. In summary, they offer the option for the best approximation of the sea-keeping problem within potential theory. This comes at a price. Both ship hull and the free surface in the near field around the ship have to be discretized by panels. Capturing all waves while avoiding unphysical reflections of the waves at the outer (artificial) boundary of the computational domain poses the main problem for RSM. Since the early 1990s, various RSM for ship sea-keeping have been developed. By the end of the 1990s, the time-domain SWAN code (SWAN = Ship Wave ANalysis) of MIT was the first such code to be used commercially.

- Combined RSM-GFM approach

  GFM are fundamentally limited in the capturing the physics when the steady flow differs considerably from uniform flow, i.e. in the near field. RSM have fundamental problems in capturing the radiation condition for low τ values. Both methods can be combined to overcome the individual shortcomings and to combine their strengths. This is the idea behind combined approaches. These are described as 'Combined Boundary Integral Equation Methods' either as 'hybrid methods'. Initially only hybrid methods were used which matched near-field RSM solutions directly to far field GFM solutions by introducing vertical control surfaces at the outer boundary of the near field. The solutions are matched by requiring that the potential and its normal derivative are continuous at the control surface Ship sea-keeping between near field and far field. In principle methods with overlapping regions also appear possible.

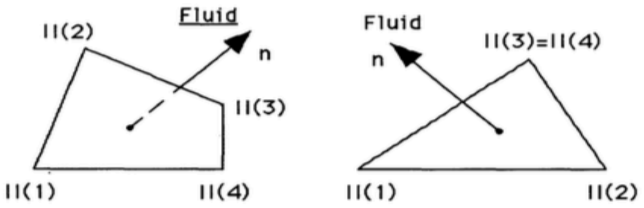
3.4.1 Computational codes NewDrift v.7 and LIU

As already mentioned, a significant part of environmental loads acting on a vessel's body is due to the action of waves. Except the presence of first order wave effects that oscillate with the frequency of the incident wave and are assumed sinusoidal and of small amplitude, second order wave effects exist as well with double the wave frequency; the resulting second order wave forces exhibit non zero averages over one period (steady components) known as drift forces.

The added wave resistance is a steady force of second order with respect to the incident's wave amplitude acting in the opposite direction of the vessel's longitudinal speed. When the ship is at zero forward speed the longitudinal drift force is identical with the added wave resistance [23]. To calculate the second order, steady drift forces based on results of first order velocity potentials, there are two methods known, which are respectively employed by the two programs used, namely LIU and NewDrift:

- the far-field method [introduced by Maruo, 1957], which are based on considerations of the diffracted and radiated wave energy and momentum flux at infinity, leading to the steady added wave resistance force by the total rate of momentum change
- the near-field method, which computes the added wave resistance as the steady second order force obtained by direct integration of the hydrodynamic, steady second order pressure acting on the hull's wetted surface, which can be calculated exactly from first order potential functions and their derivatives

For the application of both methods, a panelized surface of sufficient accuracy of the hull needed to be produced; the procedure followed is analytically described in the next chapter (3.4.2). The surface can be described by triangular or quadrilateral elements, which are formed based on four points; when using the right hand rule, the accrued vector should be facing the fluid.



points 1,2,3,4 on the same plane
quadrilateral element
(ICK = 1)

triangular element
(ICK = 0)

Figure 14: panels form and relevant vector direction

NEWDRIFT is a 6 degrees of freedom, 3D frequency domain panel code for the seakeeping and wave induced loads analysis of ships and arbitrarily shaped floating structures, including multi-body arrangements. The code enables the evaluation of 6DOF first- and quasi second-order motions and wave-induced loads, including drift deviations, forces and moments and is applicable to arbitrarily shaped 3D floating or submerged bodies (like ships, floating structures or underwater vehicles), operating at zero or nonzero forward speed, finite or infinite water depth and being excited by sinusoidal linear waves of arbitrary frequency and heading. The solution of the fundamental boundary value problem for the velocity potential is performed on the basis of Zero-speed Green function so as to avoid complexities of speed dependence on the free surface boundary condition. Hydrodynamic forces and sectional loads are derived from the surface integration of hydrodynamic pressure over the wetted hull. A variant of Stoke's theorem is used to transform the resulting surface integrals that contain the derivatives of the velocity potential in the integrand, into two-part integrals which now contain the velocity potential in the integrand; these comprise a surface integral over the ship's wetted surface and a line integral along the ship's design waterline. The importance of including these line integral terms has been demonstrated [24] and their exclusion may lead to significant errors.

3.4.2 Approach of added wave resistance in short waves

Nowadays, semi-empirical formulas for the prediction of added wave resistance in short waves and low speeds is of high practical interest, as IMO regulations [MEPC.232(65)] regarding the EEDI and Minimum Installed Power, require simplified methods for its estimation in absence of tank test models. In the present paper two older methods and a new one are employed for the estimation od added wave resistance in short waves; Faltinsen's formula(1980), Tsujimoto method, and a new formula developed by Liu and Papanikolaou (2015).

Fatinsen’s formula(1980) was developed for the prediction of added resistance in short waves, as a derivative of the near-field method by using an approximate velocity potential in the bow region for integrating the pressure over the hull surface; this formula proved to work well for full hull forms but not for finer ones:

$$F_1 = \int_C \vec{F}_n \sin\theta \, d\ell$$

$$\vec{F}_n = \frac{1}{2}\rho g \zeta_a^2 \left\{ \sin^2(\theta + a) + \frac{2\omega_0 U}{g}\left[1 - \cos\theta\cos(\theta + a)\right] \right\}$$

Equation 2: Fatinsen's formula (1980)

where C is the waterline curve, ζα the incident wave amplitude, α the wave propagation direction, θ the inclination angle of a line segment and U is the vessel’s speed.

Besides assuming vertical walls (full hull forms, Fatinsen’s formula also neglected diffraction and viscous effects produced by sharp geometry of the hull; the above formula was improved [Papanikolaou and Zaraphonitis], by including the effect of flare at the bow region, as diffraction effects become of major importance when calculating added resistance due to incoming waves. Also, another correction factor was introduced for finer hull forms by using the block coefficient powered by 1+n*sqrt(Fn), where n is a constant to be determined by model tests, as it was revealed that coefficient of the speed’s correction is related to the ship’s hull form. The formula for the head waves case is presented below:

$$\vec{F}_n = \frac{1}{2}\rho g \zeta_a^2 \sin^2\theta \sec\alpha_{WL}\alpha_d \left(1 + \frac{2\omega_0 U}{g}\right)\left(\frac{0.87}{C_B}\right)^{1+n\sqrt{Fn}}$$

Equation 3: Liu and Papanikolaou formula (2015)

For a numerical application, the waterline of interest is discretized to a series of nodes, each of which is assigned with a different flare angle, which corresponds to the part of the hull surface immediately above and below the examined waterline.

The environmental conditions for determining the EEDIweather coefficient fw dictate a peak wave period of T=6.7s which corresponds to a wave length of λ=70.1 m. For the ship studied, this means that the wavelength is lower than half its length, λ<(L_{bp}/2); this is a region that the already employed 3D-panel codes, do not necessary yield satisfactory results. For this reason, the newly developed simplified method [22] for calculating the added resistance in short waves will be used, and compared with already mentioned methods regarding short waves, as well as with the far-field and near-field methods. In the next figure, added resistance due to waves for various heading by using the far-field method (Liu) and the aforementioned formula are presented.

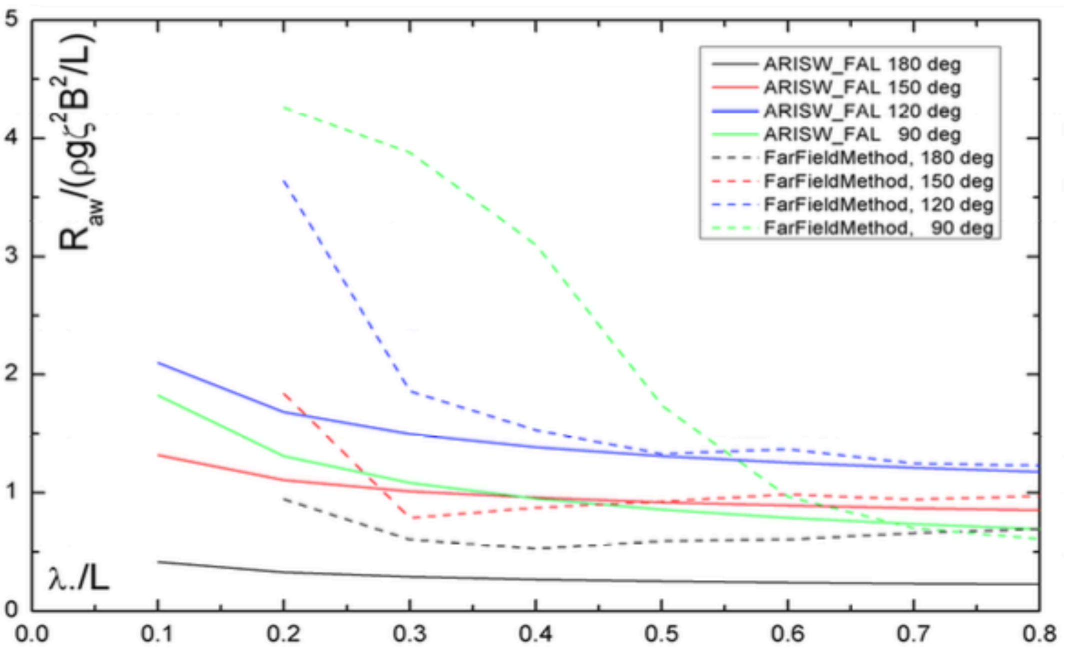


Figure 15: added resistance in short waves for various headings, Fn=0.15

For the head waves case, a simplified (level 1) formula was developed, based on simplification of some factors of the previously reviewed formula:

$$F_1 = \int_L \vec{F}_n \sin\theta\, d\vec{l}$$

$$\vec{F}_n = \frac{1}{2}\rho g \zeta_a^2 \alpha_d \sin^2\theta \left(1+5\sqrt{\frac{L}{\lambda}}Fn\right)\left(\frac{0.87}{C_B}\right)^{\cos\alpha\left(1+4\sqrt{Fn}\right)}$$

For the shortwave domain (λ/L<0.5), a_d can be considered equal with 1, and $F_1 = \int_L \sin^2\theta \sin\theta\, d\vec{l}$ can be approximated by the curve shown in the following figure, according to the vessel's block coefficient:

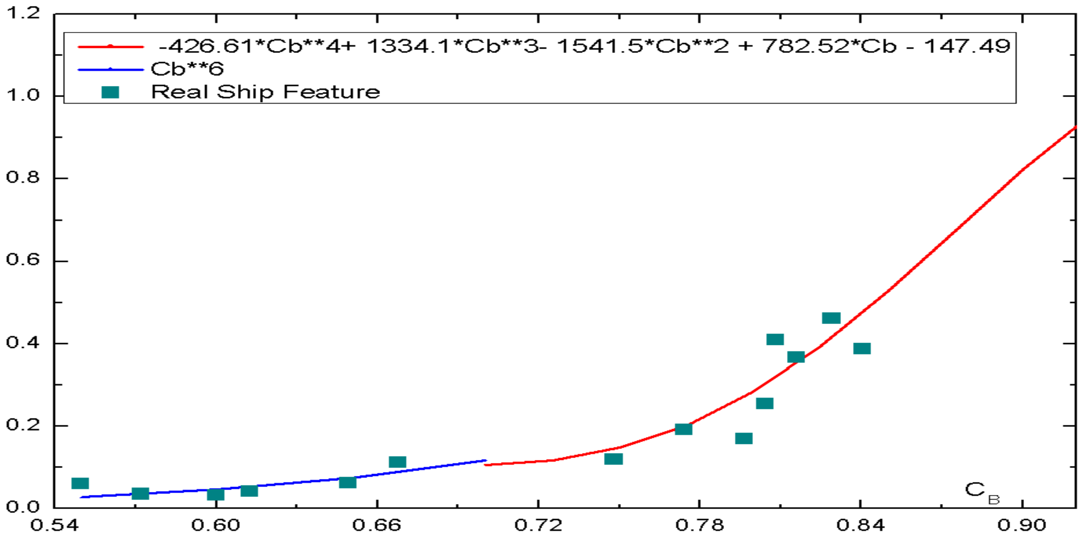


Figure 16: The developed curve

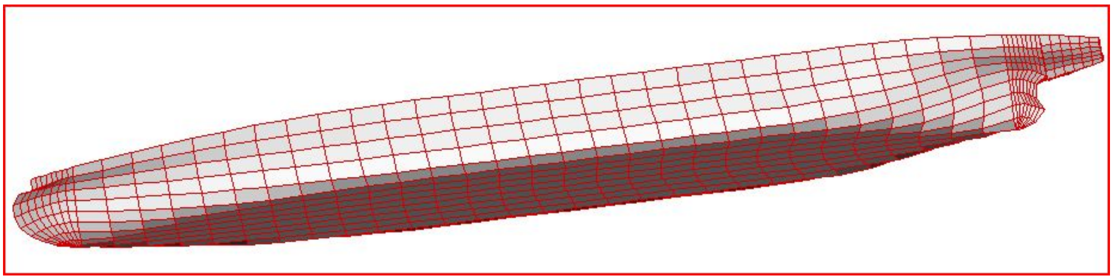
3.4.3 Program Shipflow

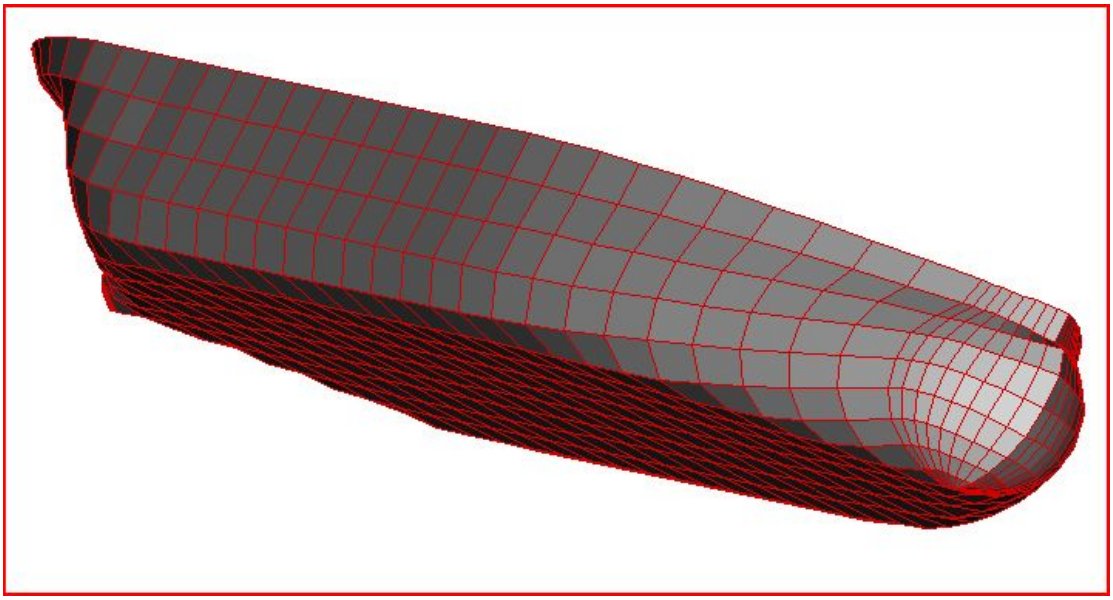
In order to produce the panelized surface needed for the program input of the program NewDrift v.7 we used Shipflow-CFD computational package. The hull form obtained from the program AVEVA was extracted as a .xyz text file to serve as the input. Because program Shipflow creates the hull form by only using section lines, the sections of the hull form needed to be divided in groups of different density in order to describe more accurately areas of the hull of increased geometric complexity; more accurately, the hull form was divided in four groups: stern, boss, and bulb (of increased density) and the main hull (of decreased density).

Later on, in order to have more accurate results, the paneling procedure was manually configured using the XMESH program. The panelization was done separately, continuing the same logic employed before, on the following groups:

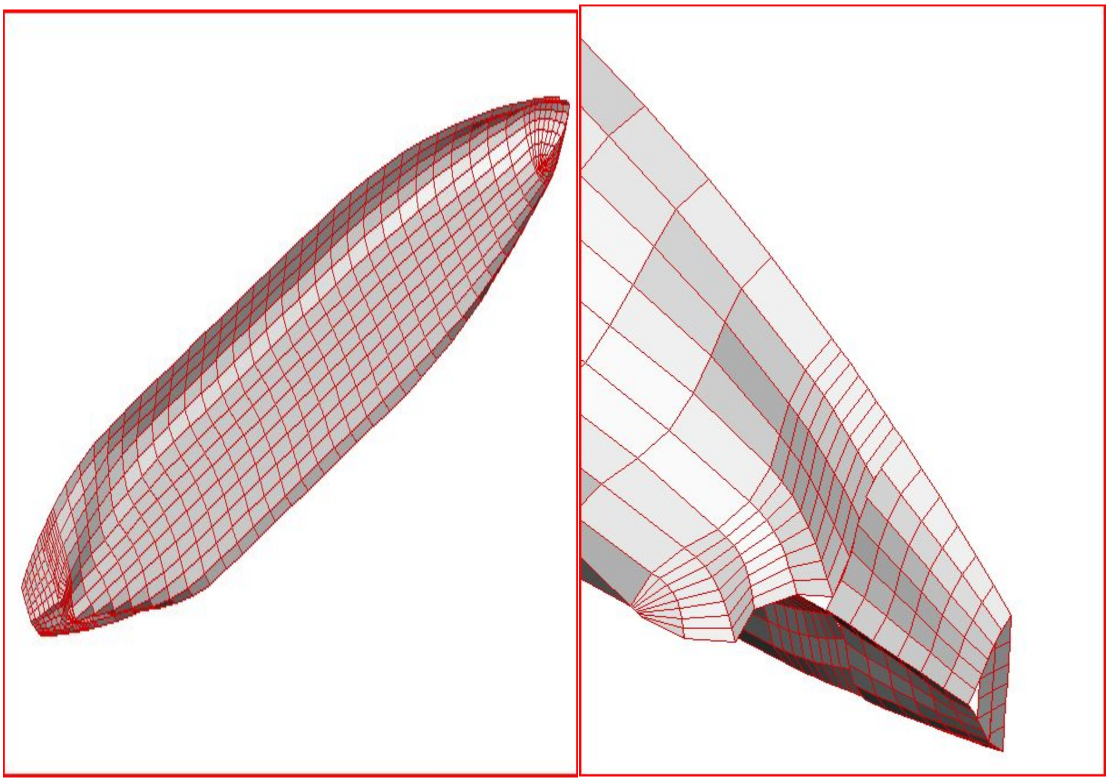
- for the hull: Bulb – Hull – Stern – Boss
- for the free surface: Free surface – Transom

The created adjoining panels should be of similar size and their number sufficient enough in order for the calculations to describe accurately the induced wave system and include all potential wave energy; however, there is a max limit on the number of panels that NewDrift can use to make calculations, but is considered sufficient. The final panelization achieved, after several configurations, in order to match the hydrostatic characteristics as close as possible, is depicted in the figures below, which were prodused using the program Techplot:

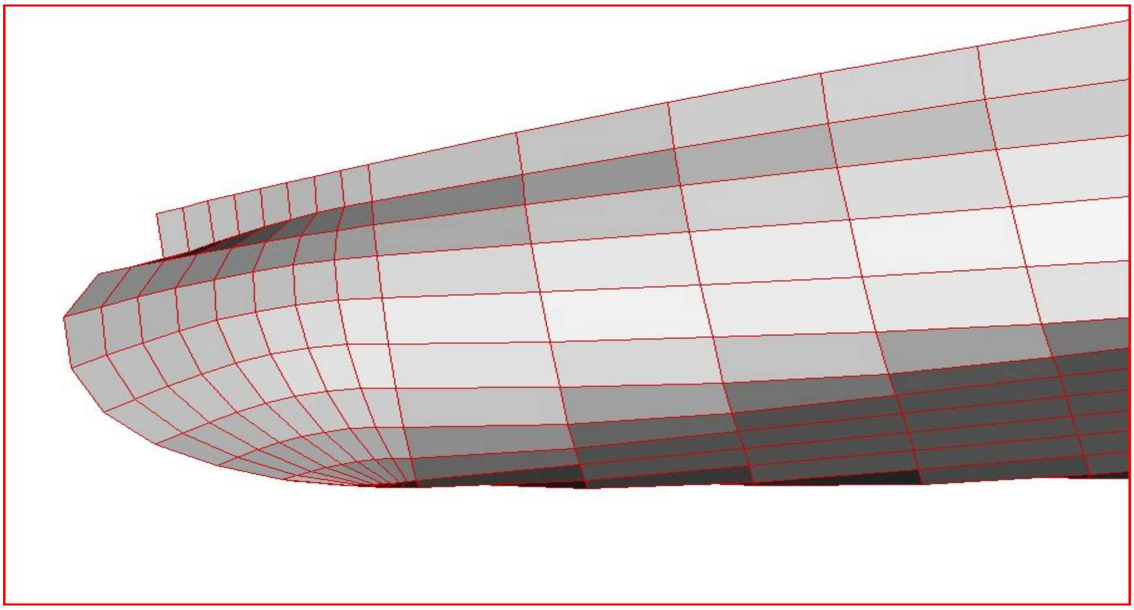




Picture 12: Achieved panelisation of hull for ship “TEST_SHIP”



Picture 13: Achieve panelization n FOB and detail from transom area


Picture 14: Detail of achieved panelization in bulbous bow area

The total number of panels used to discretize the hull form was 1080, which is expected to yield results of sufficient accuracy.

Chapter four:

General information and particulars for the studied ships

4.1 General information

Due to the diversity of vessels used for the generation of the Interim Guidelines, as well as the benchmark values for the EEDI, the four vessels selected satisfy a diverse range of particulars.

The four ships in question are three tankers and a newly designed chemical carrier, of various sizes, so as to examine a broad range of particulars for the applicability of the interim guidelines. Today, tankers (crude oil carriers) make up almost 62% of the world's merchant fleet, while chemical carriers account for only 0.6% . In the following figure we can see the composition of different types of the world fleet.

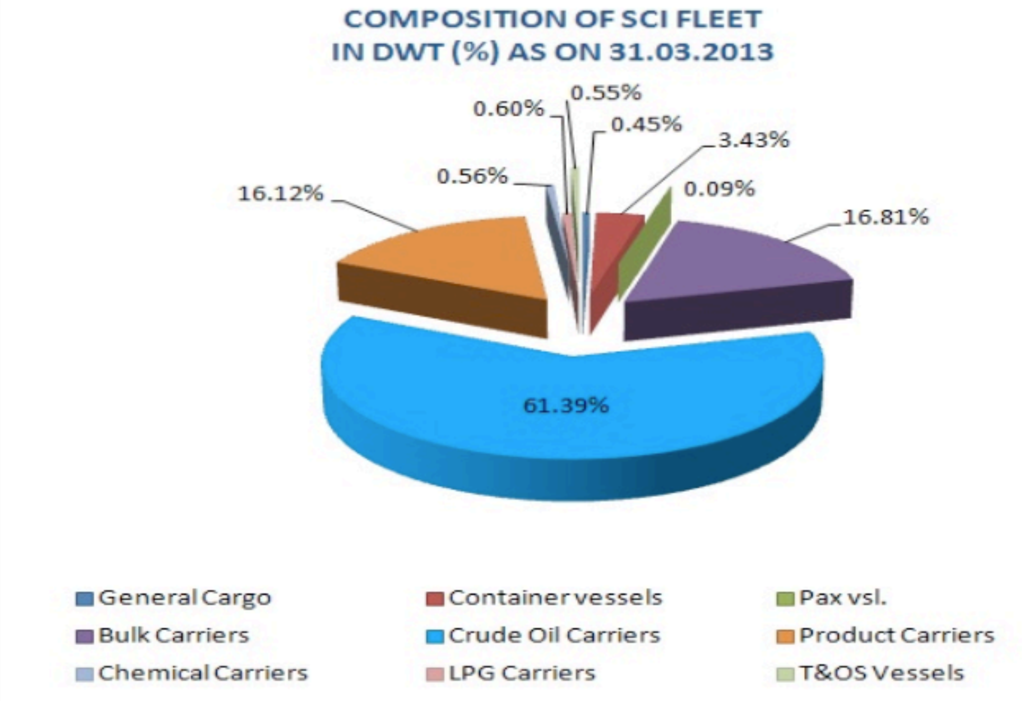


Figure 17: composition of world shipping fleet

At the following table we can see the major crude oil carrier sizes , their percentages of each in the market as well as the prices for a new or used one.

Major crude oil carrier size categories

Name	Size in DWT	Ships	Traffic	New price	Used price
Handysize	10,000 to 50,000	34%	18%	$25M	$20M
Panamax	50,000 to 80,000	37%			

Aframax	80,000 to 120,000	19%	20%	$35M	$25M
Suezmax	120,000 to 200,000	10%	58%	$58M	$54M
ULCCS and VLCCS	200,000 and over	10%	4%	$100-120M	-

Table 15: crude oil carrier sizes

4.2 General particulars and other data of the studied ships

The general particulars and other data of the studied ships are given in the table below. For the newly designed ship TEST_SHIP, the needed data was available from the preliminary study performed, for both loading conditions investigated. Data for the other three studied ships were provided from AVIN shipping, as presented in the next table, and regard the loading condition that corresponds to the scantling draught.

PARAMETER	UNIT	SHIP_1	SHIP_2	SHIP_3	TEST_SHIP
Built	-	2008, Korea	1994, Croatia	1994, Ireland	-
LOA	m	183.09	244.30	274.00	178.70
LBP	m	174.00	236.00	268.22	171.00
B	m	32.20	39.40	44.40	32.20
D	m	19.10	21.34	24.10	16.60
Ts	m	13.02	14.67	16.97	12.34
CB	-	0.811	0.844	0.922	0.788
DWTs	tons	50,349	101,605	169,568	47,029.75
Δs	tons	60,644	117,932	192,088	56224.03
LS	tons	10,295	16,327	22,520	9,154
Cargo Vol. at 98%	m3	53,527	113,109	163,279	48,315
Vs	knots	14.000	13.0	13.50	13.80
Propeller	-	One, 4-bladed	One, 4-bladed	One, 4-bladed	One, 4-bladed
M/E Maker	-	MAN B&W	MAN B&W	MAN B&W	MAN B&W
M/E Type	-	6S50 MC-C	6L60 MC	6S70 MC	G50ME-B9
M/E MCR	kW	9,620	10440	12,945	8,600
M/E Speed	rpm	127	117	74	100
M/E SFOC at NCR	gr/kwh	172.90	176	164.60	164.0
M/E Fuel Type	-	HFO 380cSt	HFO 380cSt	HFO 380cSt	HFO 380cSt
M/E Gearbox Ratio	-	N/A	N/A	N/A	N/A

D/G Maker	-	MAN B&W	MAN B&W		MAN B&W	MAN B&W
D/G Type	-	6L23/30H	5L23/30H	6L23/30H	7L23/30	6L23/30H
D/Gs Fitted	sets	3	2	1	3	3
D/G MCR (Engine)	kW	960	650	985	910	812
D/G Speed	rpm	900	720	900	720	
D/G SFOC	gr/kwh	198.5	199.0		197.0	185.0
D/G Fuel Type	-	HFO 380cSt	HFO 380cSt		HFO 380cSt	HFO 380cSt
D/G Efficiency	%	94%	94%		94%	95%
Shaft Generator	kW	N/A	N/A		N/A	N/A

Table 16: data for the studied ships provided by AVIN shipping

AVIN shipping also provided us with the General Arrangement plans of the studied ships which proved to be most helpful for obtaining values af particulars that we had no other information about, as shown in the next table.

PARAMETER	UNIT	SHIP_1	SHIP_2	SHIP_3
measured from General Arrangement Plans				
lateral windage area, Al	m2	1751.410	2,558.400	2418.870
frontal windage area, Af	m2	460.650	765.540	789.740
ruder area, Au	m2	30.600	50.950	58.700
Submerged lateral area, Als				
propeller diameter, Dp	m	5.200	6.400	8.800
Waterplane area, Awl	m2	4677.000	8,773.780	10962.320
Waterline length, Lwl	m	176.400	243.190	270.160
Midship section area, Am	m2	584.980	839.550	1044.350
Hb	m	5.67	6.880	8.04
derived from measurements and empirical formulae				
midship coefficient, Cm	-	0.951	0.998	0.976
prismatic coefficient, Cp	-	0.853	0.845	0.950
waterplane coefficient, Cw	-	0.823	0.916	0.914
wetted surface area, S	m2	8651.851	15,021.332	19368.325
transverse bulb area(as % of Am), Abt	m2	40	75.560	104.435
A_e/A_0	-	0.6	0.300	0.8

Table 17: data obtained from measurements and empirical formulae

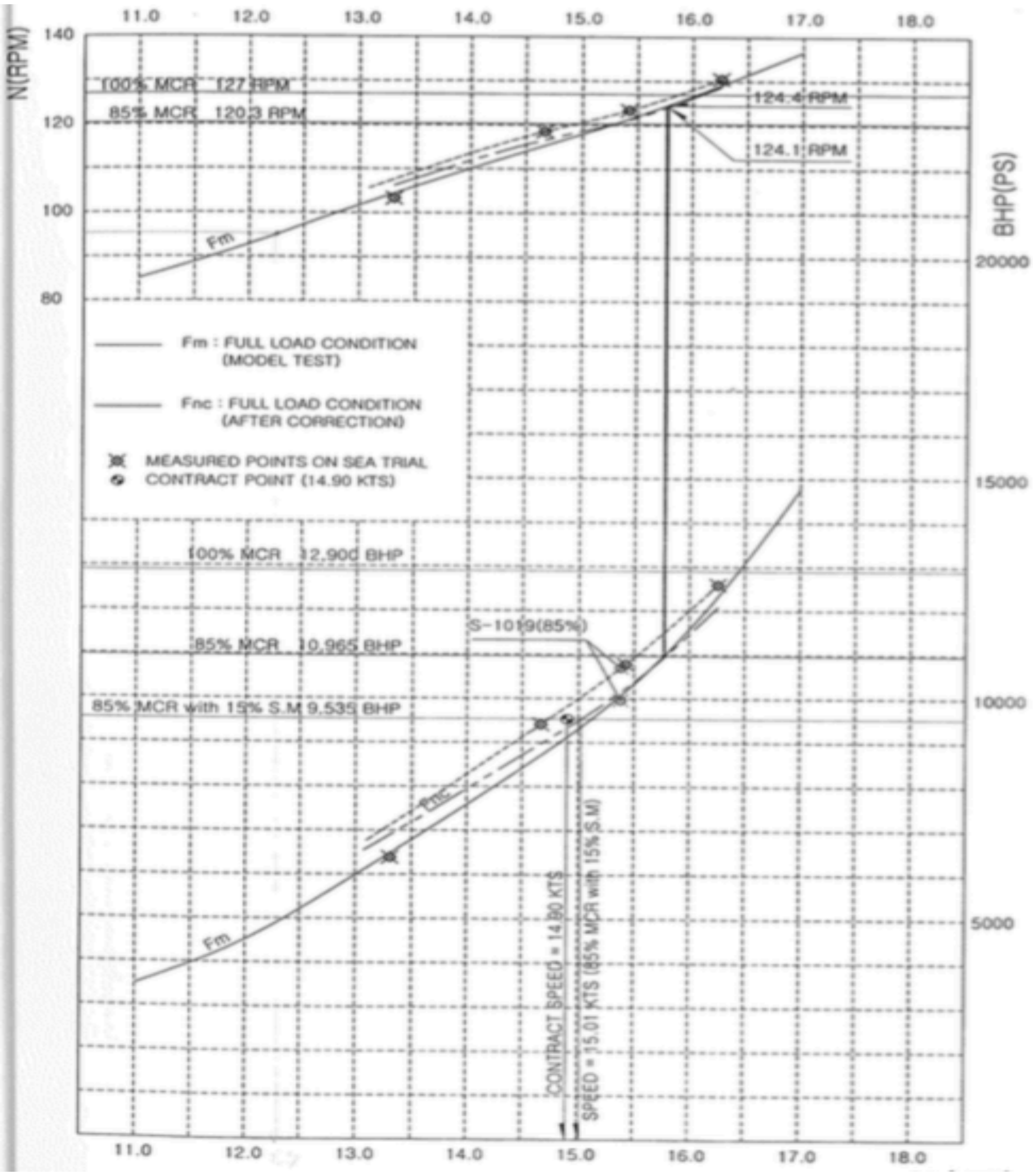
The formulas used for the above calculations are:

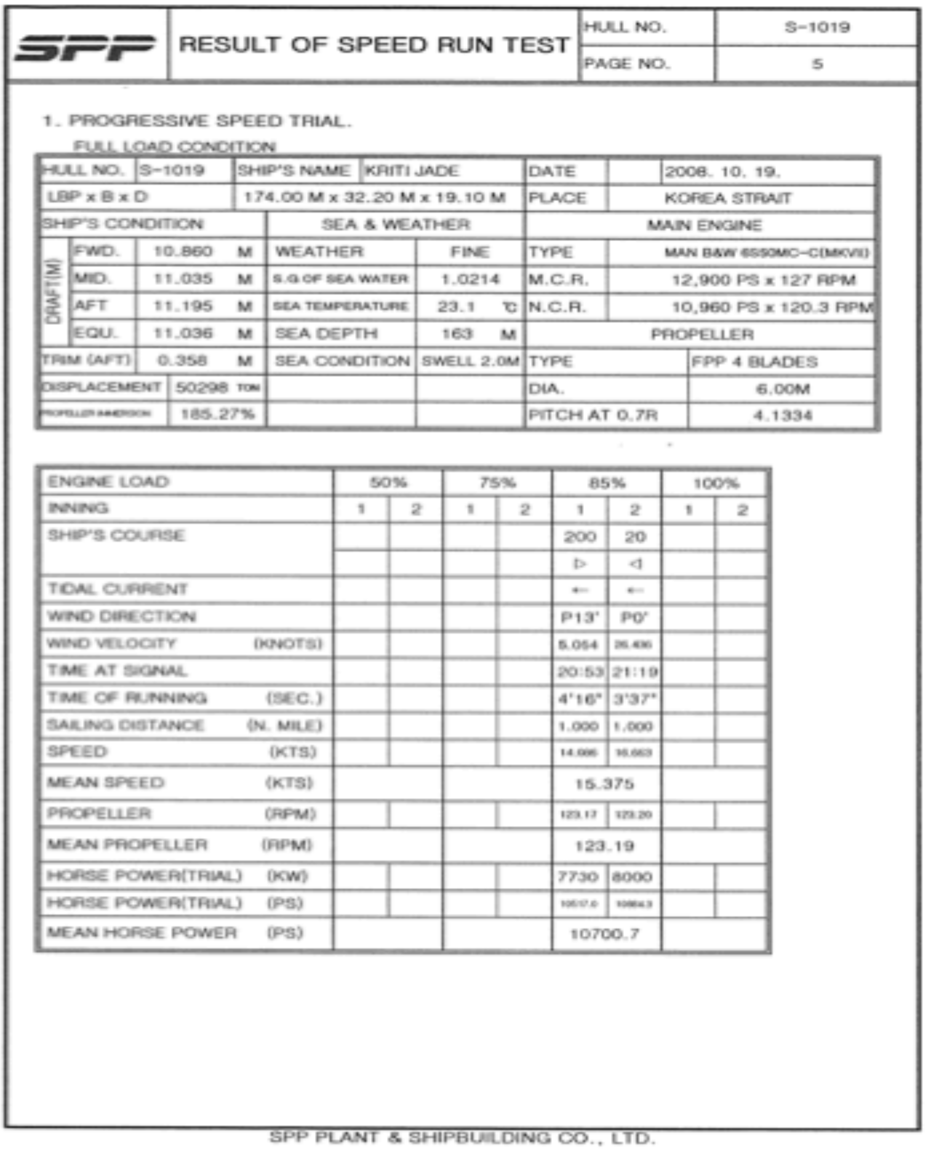
- Wetted surface area:
  $$S = L(2T + B)\sqrt{C_M}\left(0.453 + 0.4425C_B - 0.2862C_M - 0.003467\frac{B}{T} + 0.3696C_{WP}\right) + 2.38A_{BT}/C_B$$

- expanded surface area of the propeller

Also, AVIN shipping was able to provide us with the speed trial curves, which were conducted on Full Load Departure condition for the three studied ships, as shown below.

Picture 15: speed trial results for SHIP_1





SPP	RESULT OF SPEED RUN TEST	HULL NO.	S-1019
		PAGE NO.	5

1. PROGRESSIVE SPEED TRIAL.

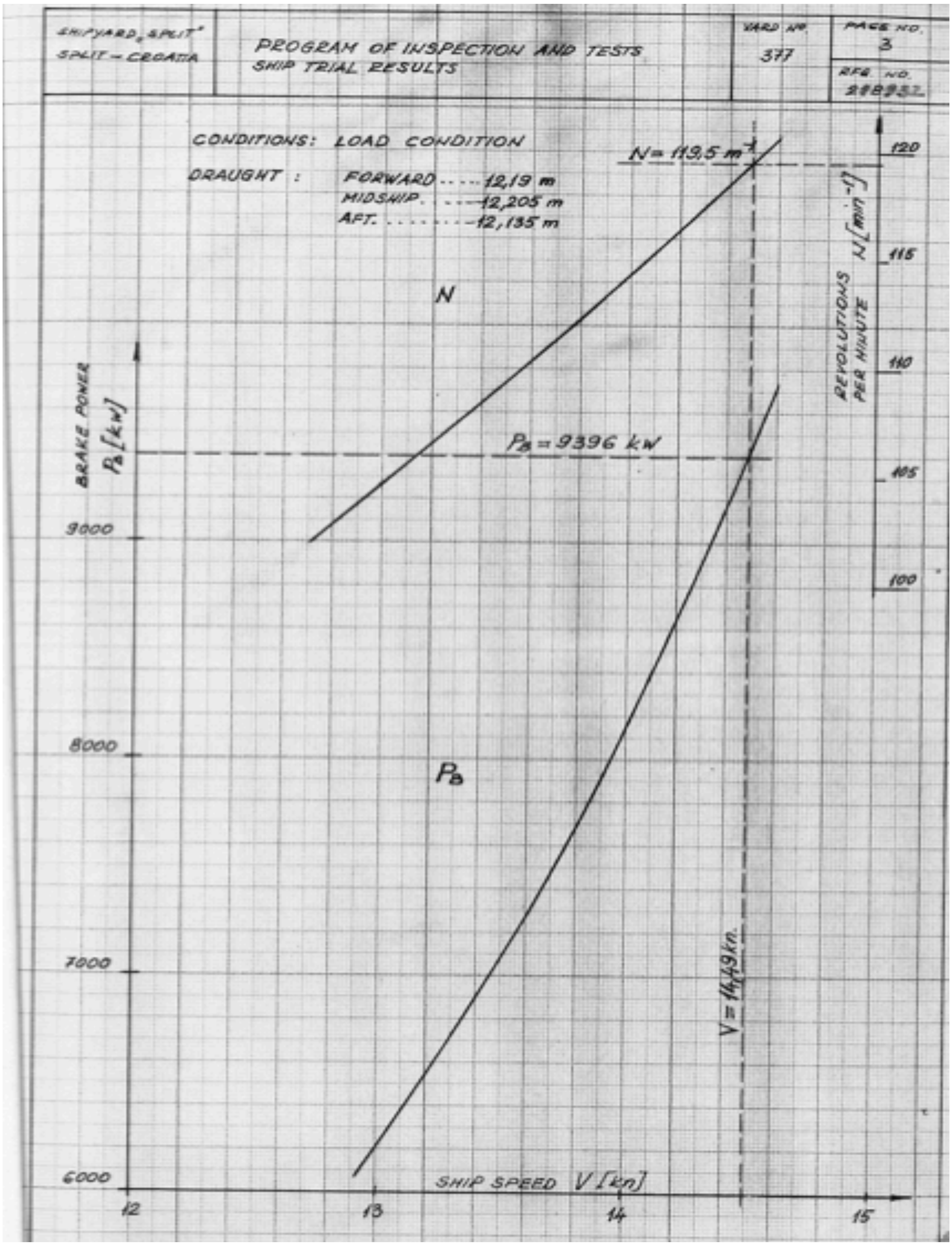
FULL LOAD CONDITION

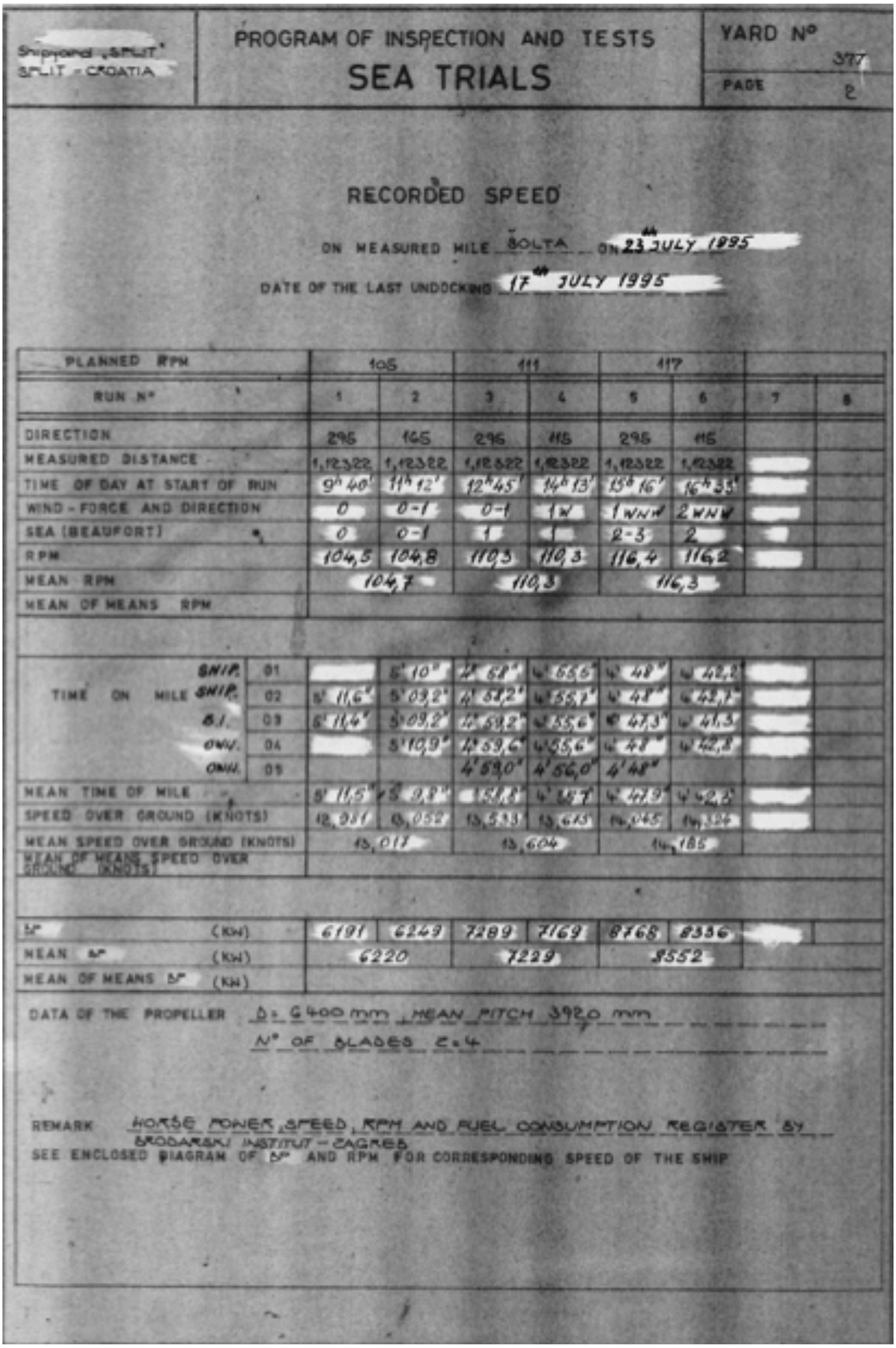
HULL NO.		S-1019		SHIP'S NAME	KRITI JADE		DATE	2008. 10. 19.
LBP x B x D		174.00 M x 32.20 M x 19.10 M					PLACE	KOREA STRAIT
SHIP'S CONDITION				SEA & WEATHER			MAIN ENGINE	
DRAFT(M)	FWD.	10.860	M	WEATHER	FINE		TYPE	MAN B&W 6S50MC-C(MKVII)
	MID.	11.035	M	S.G OF SEA WATER	1.0214		M.C.R.	12,900 PS x 127 RPM
	AFT	11.195	M	SEA TEMPERATURE	23.1	℃	N.C.R.	10,960 PS x 120.3 RPM
	EQU.	11.036	M	SEA DEPTH	163	M	PROPELLER	
TRIM (AFT)		0.358	M	SEA CONDITION	SWELL 2.0M		TYPE	FPP 4 BLADES
DISPLACEMENT		50298	TON				DIA.	6.00M
PROPELLER IMMERSION		185.27%					PITCH AT 0.7R	4.1334

ENGINE LOAD		50%		75%		85%		100%	
INNING		1	2	1	2	1	2	1	2
SHIP'S COURSE						200	20		
						▷	◁		
TIDAL CURRENT						←	←		
WIND DIRECTION						P13'	P0'		
WIND VELOCITY	(KNOTS)					5.054	26.406		
TIME AT SIGNAL						20:53	21:19		
TIME OF RUNNING	(SEC.)					4'16"	3'37"		
SAILING DISTANCE	(N. MILE)					1.000	1.000		
SPEED	(KTS)					14.086	16.663		
MEAN SPEED	(KTS)					15.375			
PROPELLER	(RPM)					123.17	123.20		
MEAN PROPELLER	(RPM)					123.19			
HORSE POWER(TRIAL)	(KW)					7730	8000		
HORSE POWER(TRIAL)	(PS)					10517.0	10884.3		
MEAN HORSE POWER	(PS)					10700.7			

SPP PLANT & SHIPBUILDING CO., LTD.

Picture 16: speed trial results for SHIP_2





Shipyard „SPLIT"
SPLIT - CROATIA

PROGRAM OF INSPECTION AND TESTS

SEA TRIALS

YARD Nº 377

PAGE 2

RECORDED SPEED

ON MEASURED MILE ŠOLTA ON 23th JULY 1995

DATE OF THE LAST UNDOCKING 17th JULY 1995

PLANNED RPM		105		111		117			
RUN Nº		1	2	3	4	5	6	7	8
DIRECTION		295	165	296	115	295	115		
MEASURED DISTANCE		1,12322	1,12322	1,12322	1,12322	1,12322	1,12322		
TIME OF DAY AT START OF RUN		9h 40'	11h 12'	12h 45'	14h 13'	15h 16'	16h 35'		
WIND - FORCE AND DIRECTION		0	0-1	0-1	1 W	1 WNW	2 WNW		
SEA (BEAUFORT)		0	0-1	1	1	2-3	2		
RPM		104,5	104,8	110,3	110,3	116,4	116,2		
MEAN RPM		104,7		110,3		116,3			
MEAN OF MEANS RPM									
TIME ON MILE	SHIP. 01		5'10"	4'58"	4'55,6"	4'48"	4'42,2"		
	SHIP. 02	5'11,6"	5'09,2"	4'58,2"	4'55,7"	4'48"	4'42,1"		
	B.I. 03	5'11,4"	5'09,2"	4'59,2"	4'55,6"	4'47,3"	4'41,3"		
	OWN. 04		5'10,9"	4'59,6"	4'55,6"	4'48"	4'42,8"		
	OWN. 05			4'59,0"	4'56,0"	4'48"			
MEAN TIME OF MILE		5'11,5"	5'9,9"	4'58,8"	4'55,7"	4'47,9"	4'42,2"		
SPEED OVER GROUND (KNOTS)		12,981	13,052	13,533	13,675	14,045	14,324		
MEAN SPEED OVER GROUND (KNOTS)		13,017		13,604		14,185			
MEAN OF MEANS SPEED OVER GROUND (KNOTS)									
BP (KW)		6191	6249	7289	7169	8768	8336		
MEAN BP (KW)		6220		7229		8552			
MEAN OF MEANS BP (KW)									

DATA OF THE PROPELLER D = 6400 mm , MEAN PITCH 3920 mm
Nº OF BLADES Z = 4

REMARK HORSE POWER, SPEED, RPM AND FUEL CONSUMPTION REGISTER BY BRODARSKI INSTITUT - ZAGREB
SEE ENCLOSED DIAGRAM OF BP AND RPM FOR CORRESPONDING SPEED OF THE SHIP

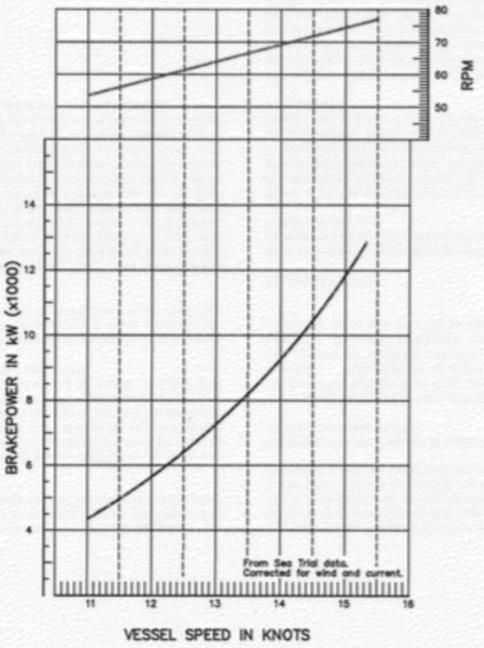
Picture 17: speed trial test results for SHIP_3

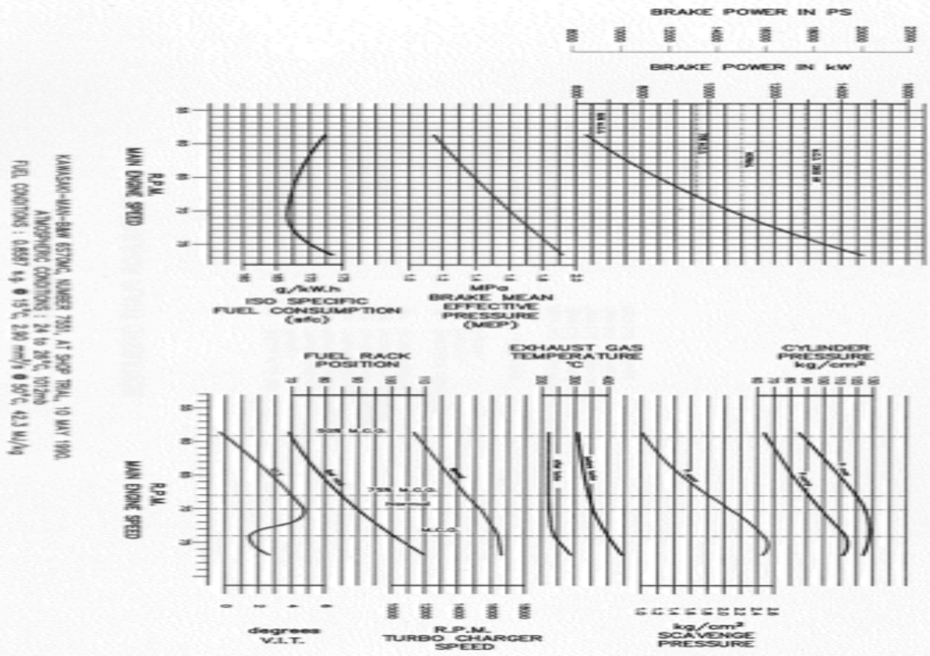
TRIAL CONDITIONS

Sea: Sheltered waters, no swell, 150m deep.

Ship:	Knock Allan
Length	274.0m
Breadth (mid)	44.4m
Depth (mid)	24.1m
Engine	6S70MC
Power (MCO)	12 936kW at 74 RPM
Clean bottom.	

Ship at Full Load Trial:	
Displacement	154 827tonne
Draft(mean)	15.625m
Trim	0.09m by stern





4.3 Sources of uncertainty

Firstly, we have to emphasize that data gathered from measurements of the General Arrangement plans, may lack of accuracy due to an inexact measuring tool or human error; all measurement though were conducted as exact as possible using computer measuring tools on the digitized versions of the plans.

Secondly, results from empirical formulae used for the calculation of the ratio A_e/A_0 as well as for the wetted surface area of the hull, should be taken into account with a level of conservativeness.

It should also be mentioned that in the preliminary study for the ship "TEST_SHIP", due to the employed empirical methods for the estimation of resistance and propulsion needs (Lap-Keller, BSRA), an overestimation of the required power is observed when comparing it to similar vessel's installed MCRs; this has a negative effect on the attained EEDI index, while at the same time ensures that the vessel is not underpowered regarding its course keeping abilities in adverse weather conditions. The principal matter though, is that the compliance for future EEDI phases while satisfying the Interim Guidelines assessment shall be challenging.

Finally, we must point out that while researching data for the studied vessels, the HS-Fairplay data was utilized; but, to our surprise, there seemed to be inaccuracies regarding the installed power of the vessels. Specifically, for the vessel SHIP_2, the value of the installed engine's MCR was 8% greater in HS-Fairplay than the one provided to us by AVIN shipping. Also, AVIN shipping had informed us that these vessels were obtained second-handed and had their engines may have been modified or replaced, while HS-Fairplay database contained the original values.

This shows that a percentage of the data regarding vessels' MCR used for the generation of the EEDI reference curves as well as for the Minimum Power Lines assessment in the Interim Guidelines, do not necessarily correspond with the actual values of installed engines MCRs of the current fleet. This shows the need for validation of current methods as well as for an update in most commonly used databases.

Chapter five:

Calculation of ship resistance, powering curves, reference speed V_{reff} and EEDI for the studied ships

5.1 HOLTROP results

In an effort to determine the reference speed V_{reff}, HOLTROP method was used to estimate the resistance of the examined ships at both EEDI and sea trial (FLD) conditions. In the following figures, the results concerning total resistance for the maximum load line condition (EEDI condition-scantling draught) are presented for the studied ships, along results for the newly designed ship "TEST_SHIP" .

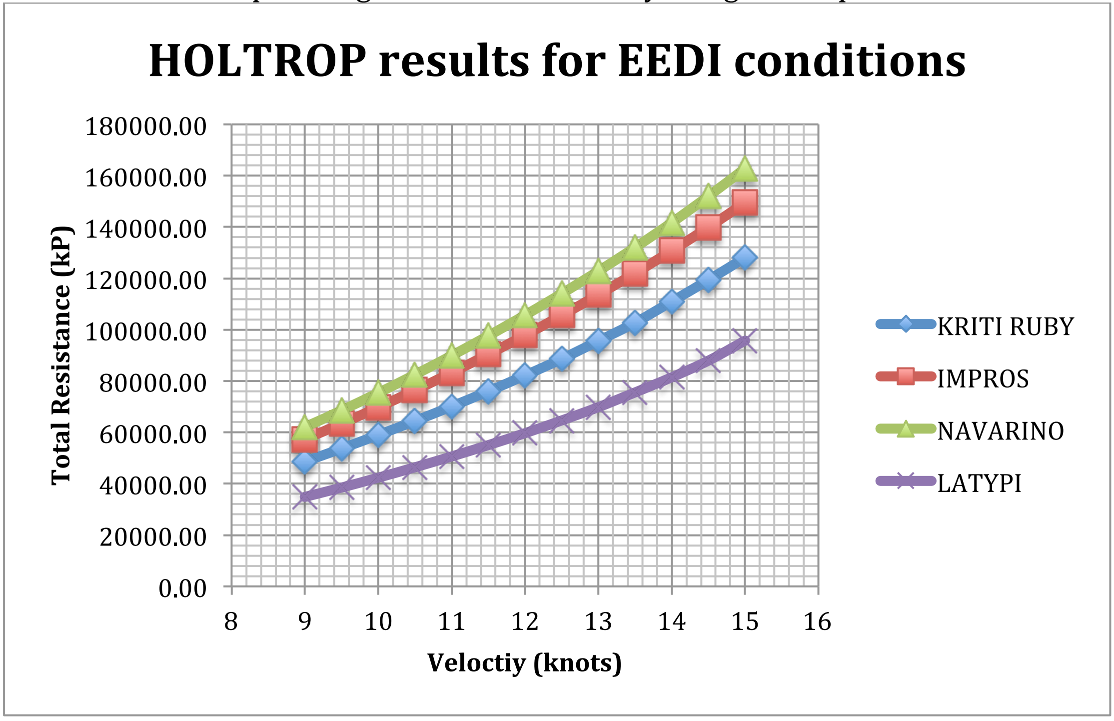


Figure 18: HOLTROP results for the three studied ships (EEDI condition)

In the following figures, the results of HOTROP method for total resistance for the maximum sea trial condition (for all three cases that was full load departure) are presented for the studied ships.

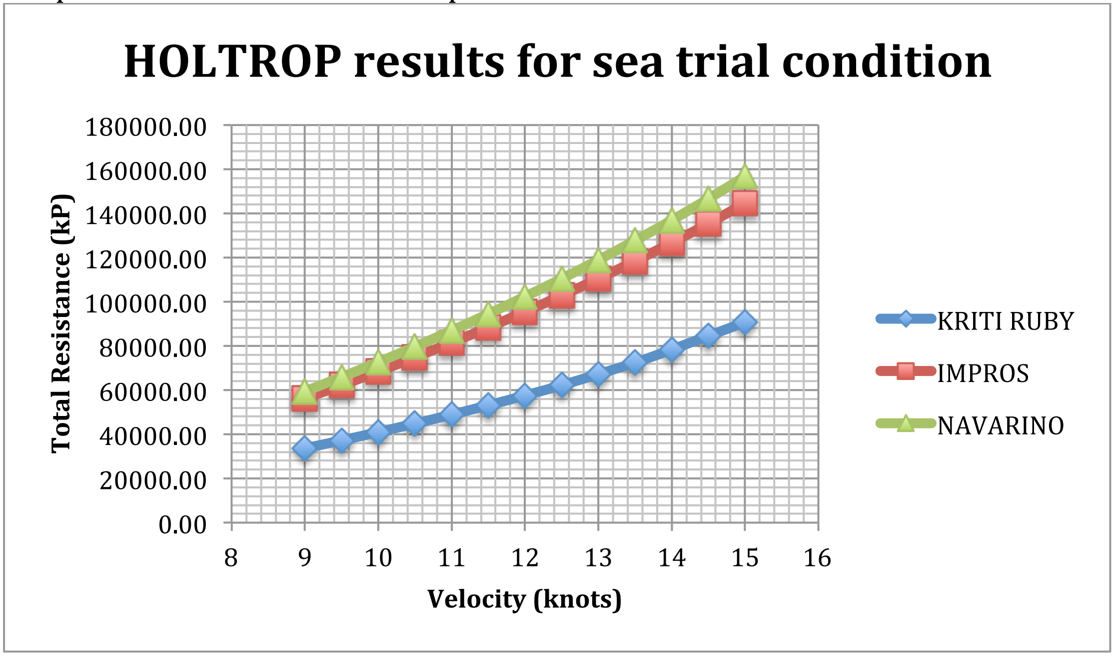


Figure 17: HOLTROP results for the three studied ships (sea trial condition)

For the same conditions, their respective powering curves are presented, as calculated from the HOLTROP method-estimation of propulsion in conjunction with program GRID, used to calculate the propeller efficiency.

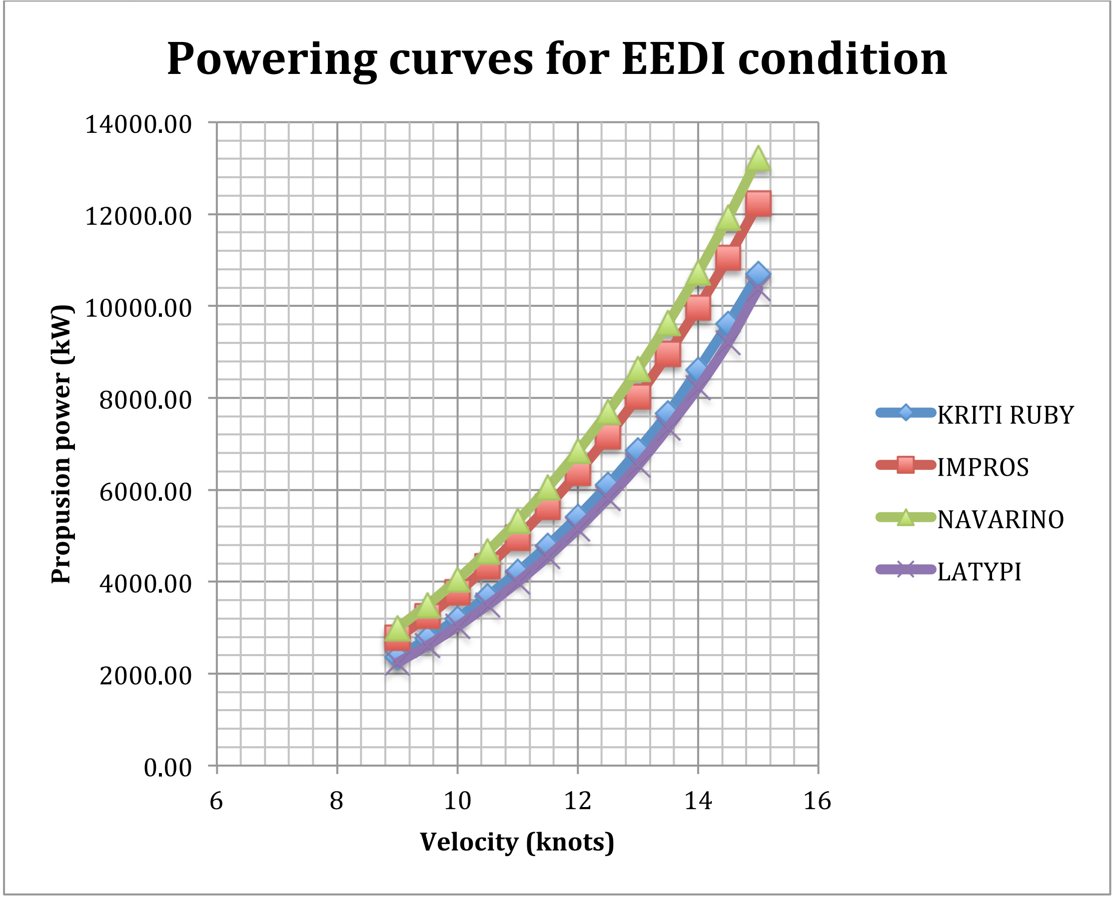


Figure 19: Powering curves for the four studies ships at EEDI conditions

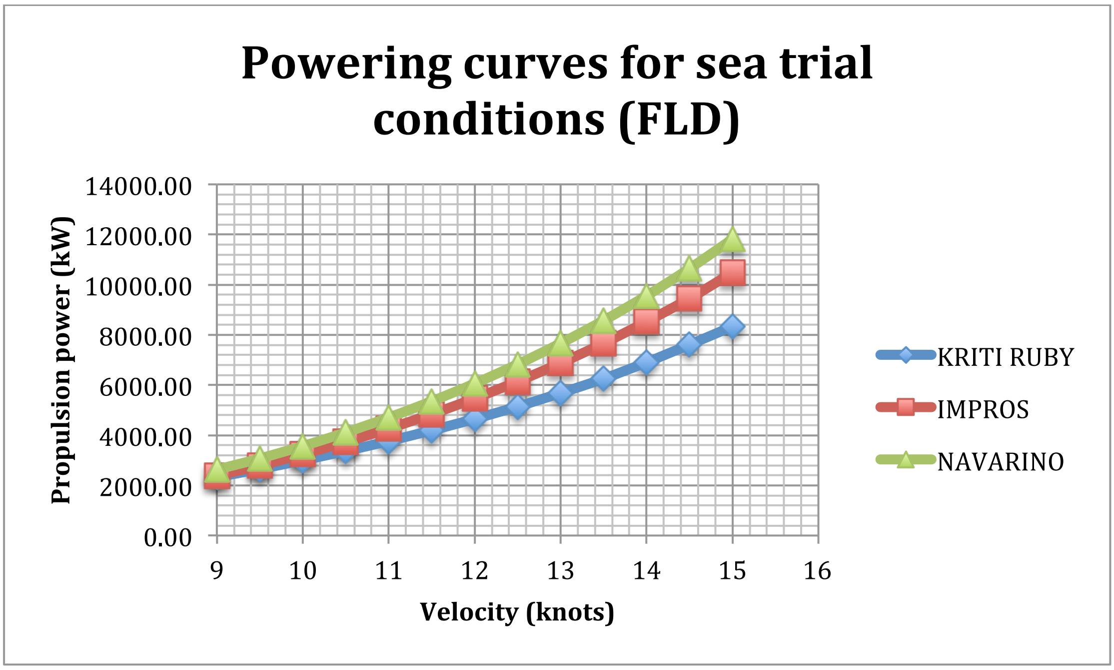


Figure 20: Powering curves for the three studied ships at sea trial conditions

5.2 Estimation of reference speed V_{reff}

In the next figures, HOLTROP propulsion results for the sea trial condition for the three ships are presented (for the speed range that is of interest), along with the actual speed test curve and the corrected curve for EEDI condition, for the calculation of V_{reff}, as dictated from the graphical method proposed by IACCS, already presented in chapter *3.2 Estimation procedure of the EEDI reference speed V_{reff}*. We can observe that that the HOLTROP powering curve follows the same trend as the speed test curve, giving though higher predictions. This can be attributed to the inaccuracy of Holtrop method when describing the morphology of hulls, which differ than those used for the derivation of the method.

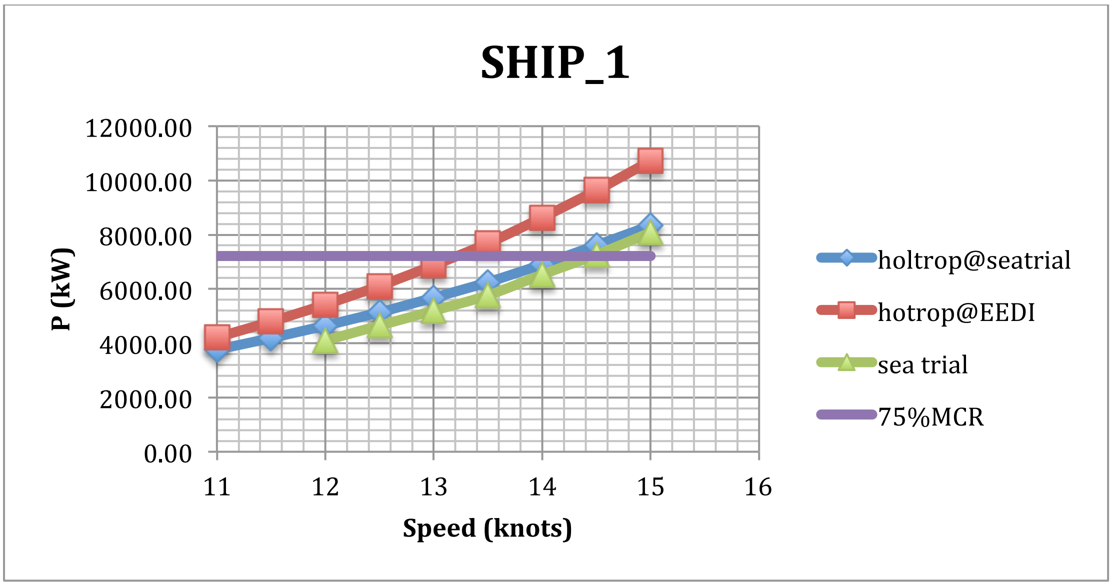


Figure 21: Powering curves for determination of EEDI speed V_{reff} for SHIP_1

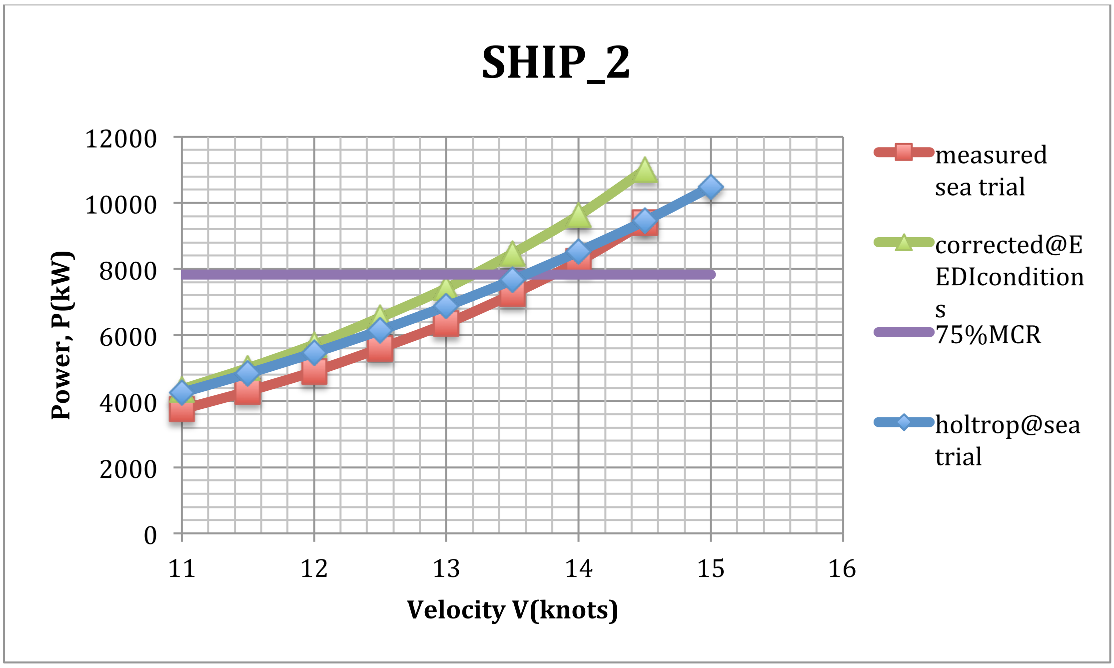


Figure 22: Powering curves for determination of EEDI speed V_{reff} for SHIP_2

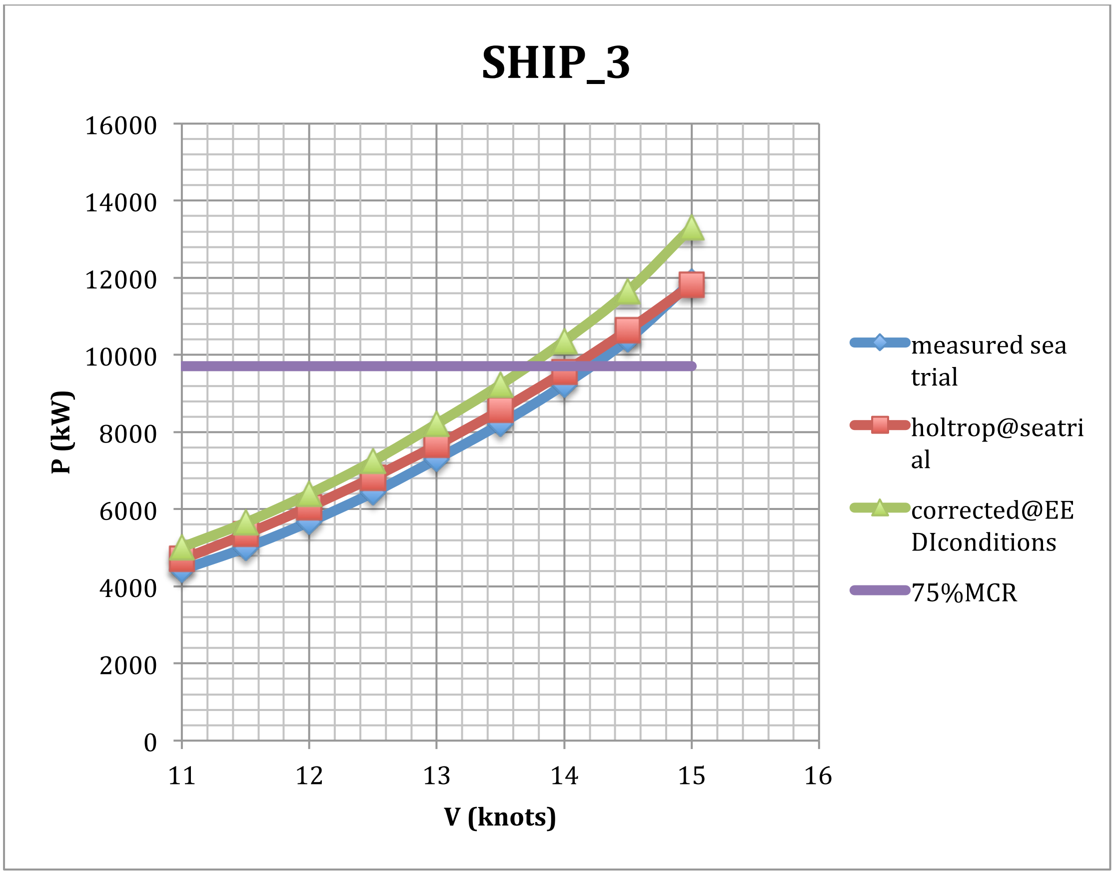


Figure 23: Powering curves for determination of EEDI speed V_{reff} for SHIP_3

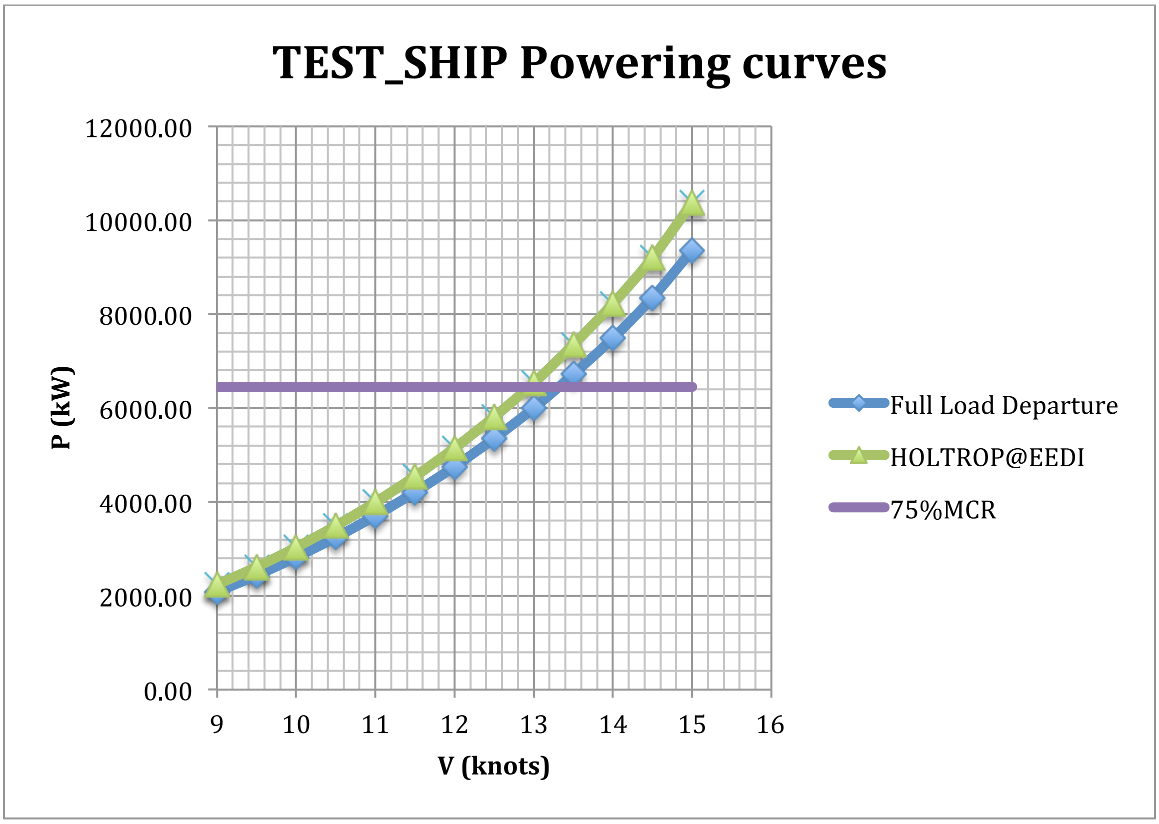


Figure 24: Powering curves for determination of EEDI speed V_{reff} for TEST_SHIP

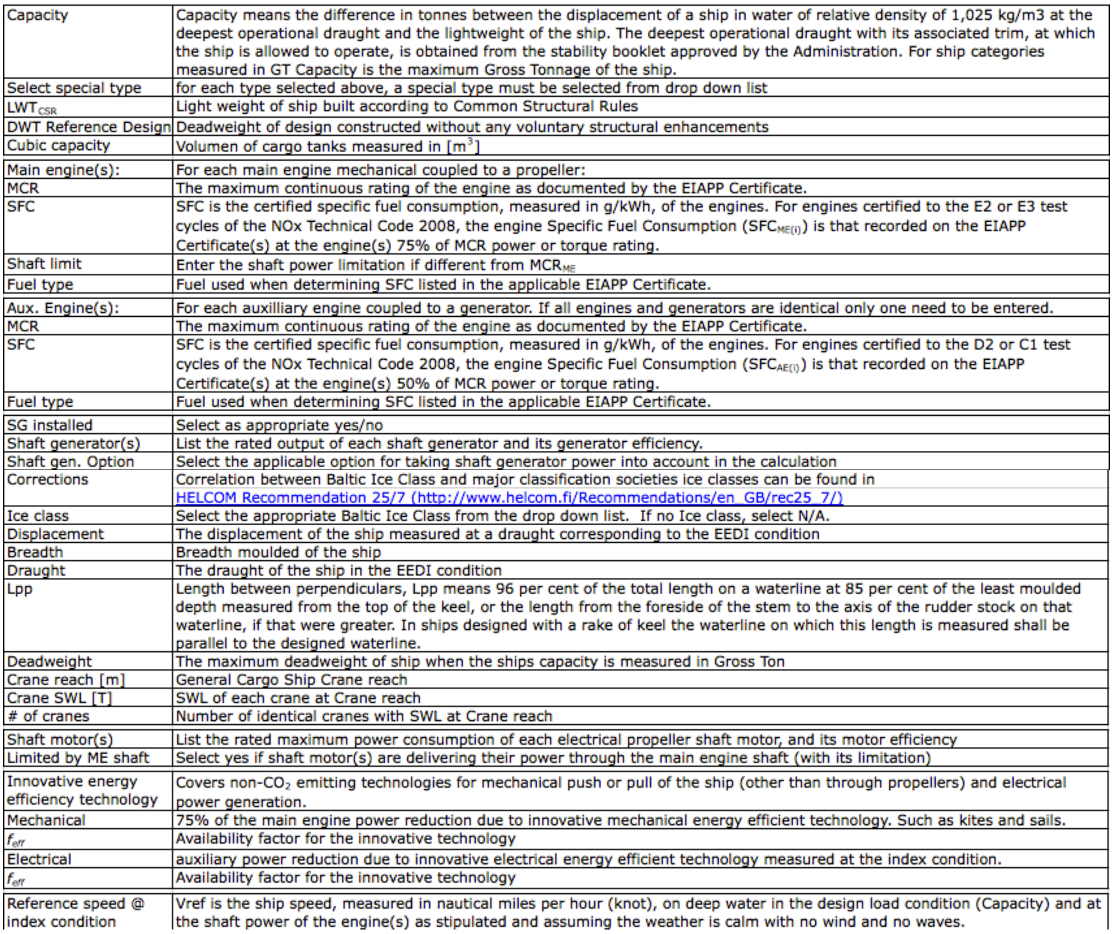
Using the diagrams above we were able to determine graphically the reference speed V_{reff} corresponding to EEDI conditions. In the next table, the reference speed determined for each vessel is presented along with the 75%MCR power.

Vessel Name	75% MCR (kW)	Reference Speed, V_{reff} (knots)
TEST_SHIP	6450	13.0
SHIP_1	7215	13.48
SHIP_2	7830	12.89
SHIP_3	9708.75	13.34

Table 18: Calculated Vreff @EEDI conditions

5.3 Calculation of attained EEDI

For each studied ship, the attained EEDI is calculated according to IACCS guidelines; the input quantities needed for its calculation are explained briefly in the next table. The arithmetic values for individual parameters are analytically presented in the Appendix of this study.



Capacity	Capacity means the difference in tonnes between the displacement of a ship in water of relative density of 1,025 kg/m3 at the deepest operational draught and the lightweight of the ship. The deepest operational draught with its associated trim, at which the ship is allowed to operate, is obtained from the stability booklet approved by the Administration. For ship categories measured in GT Capacity is the maximum Gross Tonnage of the ship.
Select special type	for each type selected above, a special type must be selected from drop down list
LWT_{CSR}	Light weight of ship built according to Common Structural Rules
DWT Reference Design	Deadweight of design constructed without any voluntary structural enhancements
Cubic capacity	Volumen of cargo tanks measured in $[m^3]$
Main engine(s):	For each main engine mechanical coupled to a propeller:
MCR	The maximum continuous rating of the engine as documented by the EIAPP Certificate.
SFC	SFC is the certified specific fuel consumption, measured in g/kWh, of the engines. For engines certified to the E2 or E3 test cycles of the NOx Technical Code 2008, the engine Specific Fuel Consumption ($SFC_{ME(i)}$) is that recorded on the EIAPP Certificate(s) at the engine(s) 75% of MCR power or torque rating.
Shaft limit	Enter the shaft power limitation if different from MCR_{ME}
Fuel type	Fuel used when determining SFC listed in the applicable EIAPP Certificate.
Aux. Engine(s):	For each auxilliary engine coupled to a generator. If all engines and generators are identical only one need to be entered.
MCR	The maximum continuous rating of the engine as documented by the EIAPP Certificate.
SFC	SFC is the certified specific fuel consumption, measured in g/kWh, of the engines. For engines certified to the D2 or C1 test cycles of the NOx Technical Code 2008, the engine Specific Fuel Consumption ($SFC_{AE(i)}$) is that recorded on the EIAPP Certificate(s) at the engine(s) 50% of MCR power or torque rating.
Fuel type	Fuel used when determining SFC listed in the applicable EIAPP Certificate.
SG installed	Select as appropriate yes/no
Shaft generator(s)	List the rated output of each shaft generator and its generator efficiency.
Shaft gen. Option	Select the applicable option for taking shaft generator power into account in the calculation
Corrections	Correlation between Baltic Ice Class and major classification societies ice classes can be found in HELCOM Recommendation 25/7 (http://www.helcom.fi/Recommendations/en_GB/rec25_7/)
Ice class	Select the appropriate Baltic Ice Class from the drop down list. If no Ice class, select N/A.
Displacement	The displacement of the ship measured at a draught corresponding to the EEDI condition
Breadth	Breadth moulded of the ship
Draught	The draught of the ship in the EEDI condition
Lpp	Length between perpendiculars, Lpp means 96 per cent of the total length on a waterline at 85 per cent of the least moulded depth measured from the top of the keel, or the length from the foreside of the stem to the axis of the rudder stock on that waterline, if that were greater. In ships designed with a rake of keel the waterline on which this length is measured shall be parallel to the designed waterline.
Deadweight	The maximum deadweight of ship when the ships capacity is measured in Gross Ton
Crane reach [m]	General Cargo Ship Crane reach
Crane SWL [T]	SWL of each crane at Crane reach
# of cranes	Number of identical cranes with SWL at Crane reach
Shaft motor(s)	List the rated maximum power consumption of each electrical propeller shaft motor, and its motor efficiency
Limited by ME shaft	Select yes if shaft motor(s) are delivering their power through the main engine shaft (with its limitation)
Innovative energy efficiency technology	Covers non-CO_2 emitting technologies for mechanical push or pull of the ship (other than through propellers) and electrical power generation.
Mechanical	75% of the main engine power reduction due to innovative mechanical energy efficient technology. Such as kites and sails.
f_{eff}	Availability factor for the innovative technology
Electrical	auxiliary power reduction due to innovative electrical energy efficient technology measured at the index condition.
f_{eff}	Availability factor for the innovative technology
Reference speed @ index condition	Vref is the ship speed, measured in nautical miles per hour (knot), on deep water in the design load condition (Capacity) and at the shaft power of the engine(s) as stipulated and assuming the weather is calm with no wind and no waves.

Table 19: EEDI input

Also, the required EEDI, as well as margin of compliance for the attained EEDI for all phases and a graphical representation that includes the curves of phases 1,2 and 3 are presented.

EEDI							
		Vessel	Attained EEDI	DWT	75% MCR		
		TEST_SHIP	5.73	47029.75	6450		
		SHIP_1	6.10	50349.00	7215		
		SHIP_2	3.57	101605.00	7830		
		SHIP_3	2.43	169568.00	9708.75		
Required EEDI/Margin of compliance(%)							
Phase 0		Phase 1		Phase 2		Phase 3	
6.39	10.41%	5.75	0.45%	5.11	-11.99%	4.48	-21.87%
6.18	1.36%	5.57	-9.60%	4.95	-23.30%	4.33	-29.03%
4.39	18.78%	3.95	9.76%	3.51	-1.52%	3.07	-13.81%
3.42	28.88%	3.08	20.97%	2.74	11.10%	2.39	-1.58%

Table 20: EEDI calculations

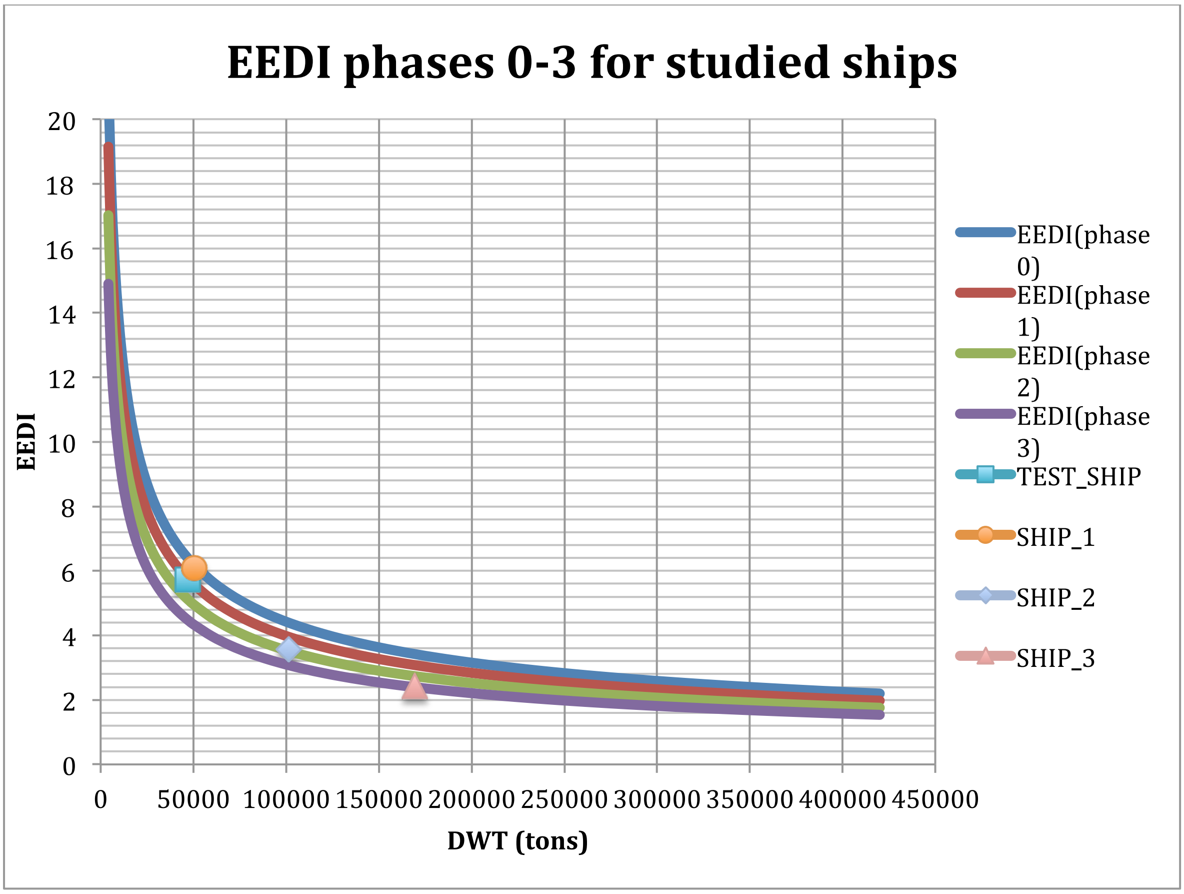


Figure 25: EEDI curves

5.4 Calculation of attained $EEDI_{weather}$ for the ship “TEST_SHIP” - The significance of Added Resistance in Waves in Total Resistance

The representative weather conditions for the calculation of $EEDI_{weather}$ and therefore, the f_w coefficient is BF 6; the exact values of significant wave height, wave heading and mean wind speed are presented in the next table.

Wind force (Beaufort)	Mean wind speed U_{wind} [m/s]	Mean wind direction γ [deg]	Significant wave height H [m]	Mean wave period T [s]	Mean wave direction θ [deg]
6	12.6	0 (head wind)	3.0	6.7	0 (head sea)

Figure 26: representative sea and wind conditions

The added resistance in waves was calculated from $0.6V_{reff}$ to V_{reff} (with intervals of $0.1V_{reff}$) using the new simplified method (formula) for added resistance in shortwaves, as mentioned in *chapter 3.4*; in the next figure results for added wave resistance for shortwaves from three different simplified methods, as well as the far-field and near-field methods are presented for V_{reff} in head waves. Results for all velocities of interest are presented in the Appendix.

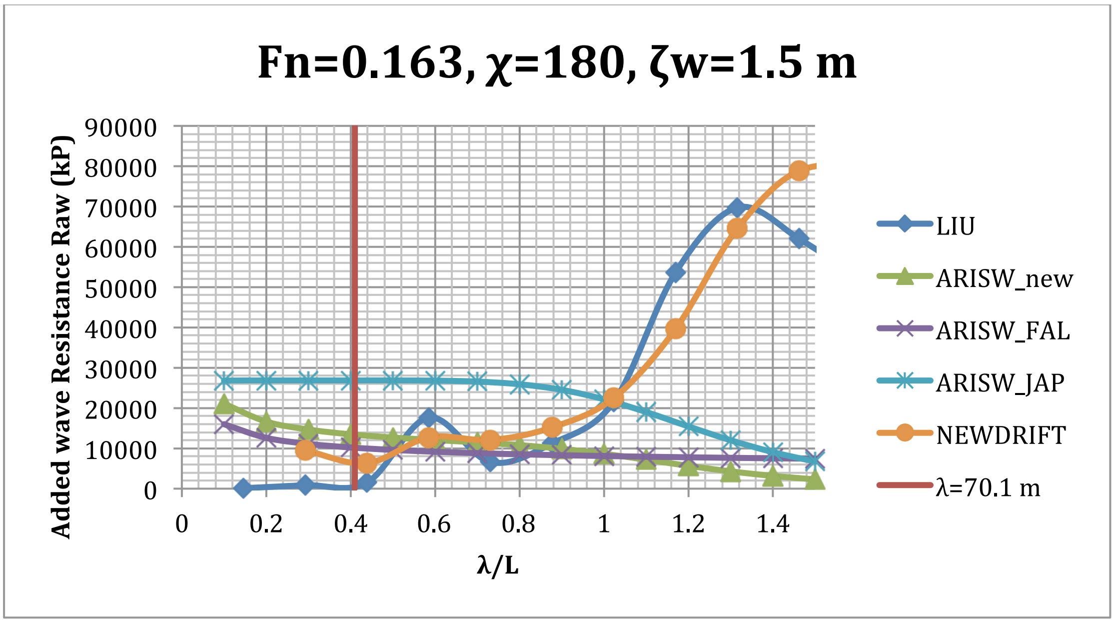


Table 21: Added wave resistance in Vreff (Fn=0.163), in head waves

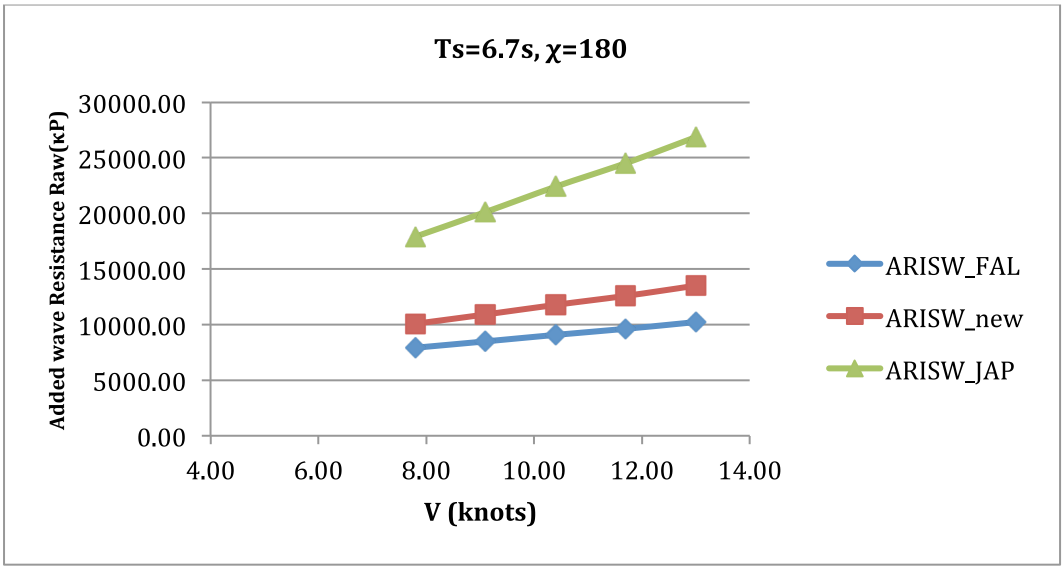


Figure 27: Added wave resistance in head waves in the range of 0.6Vreff-Vreff

At this point, we should comment on the relation between added resistance in waves and the total resistance of a vessel for a range of speed's. In *Figure 28* the results regarding the resistance (and its components) of the vessel from HOLTROP method with the addition of the added resistance in waves are presented.

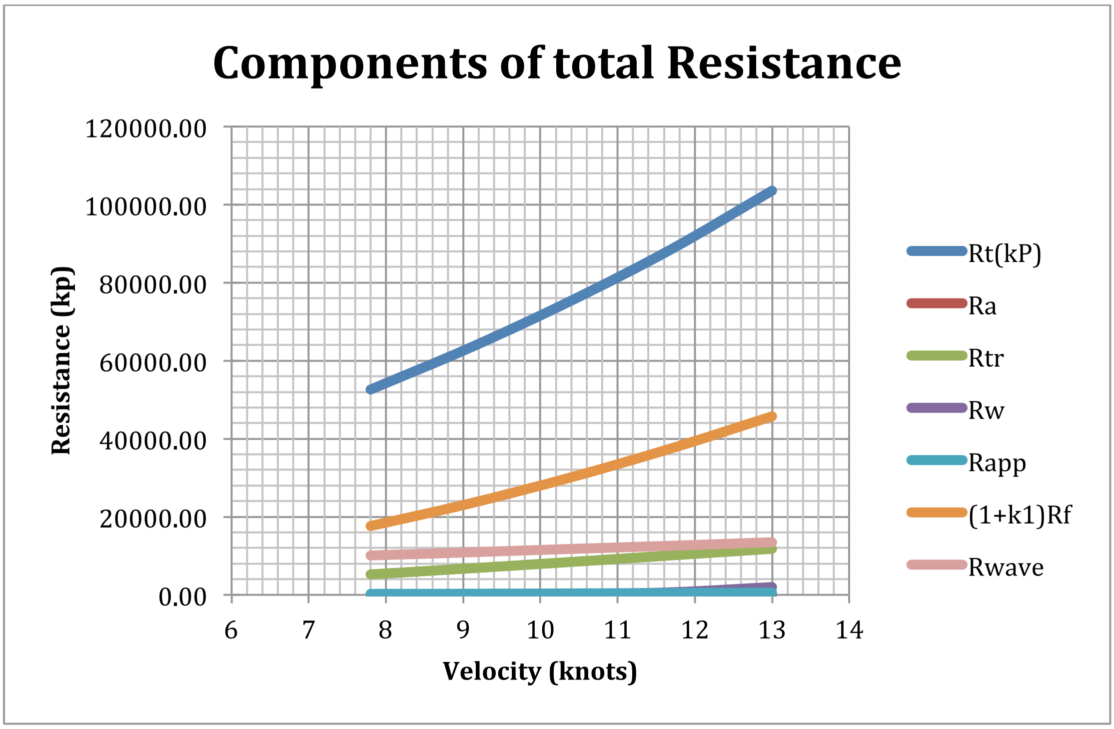
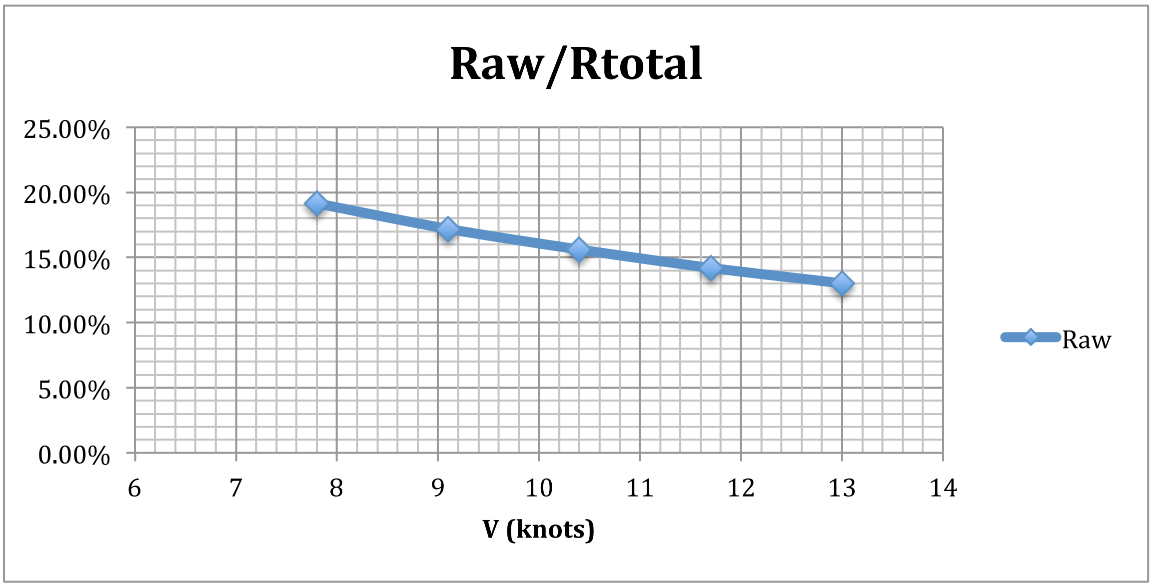


Figure 28: Components of total resistance for SHIP_1

It is obvious from the previous figure that, the main component of the total resistance consists of its friction part; second to that comes the added resistance in waves, with the other components following. This shows the importance of calculating R_{aw} , when predicting the propulsion power needs of a vessel, as these are conditions (environmental) that are met frequently in the sea domain.

The next figure shows their relation between added resistance in waves and the vessel's total resistance, as a percentage:



It is known that both R_{aw} and R_f increase as the vessel's speed increases ; we can observe from the previous figure that as the speed increases the ratio between added resistance in waves and total resistance reduces, meaning that R_{aw} is increasing with a lower rate than some other components of the resistance, especially the friction resistance component. This shows that in increasingly smaller (relatively low) speeds, R_{aw} is a major contributor to the total resistance of the vessel, as it accounts for 1/5 of it's total resistance; as the speed increases, it becomes less important to the total resistance.

For the added resistance due to wind the following empirical formula was employed [GL, Guidelines for Determination of the Energy Efficiency Design Index, 2014]

$$\Delta R_{wind} = 0.5\rho_a C_{Dwind} A_T \left(\left(U_{wind} + V_w \right)^2 - V_{ref}^{\ 2} \right)$$

Equation 4: Added resistance due to wind

For this new condition, a portion of the powering curve was created that includes the added resistance from winds and waves forces, which are shown in the next figure, along with the powering curve in calm water. By having a straight line at 75%MCR in the same diagram, the V_{wind} can be determined from the intersection with the powering curve, and the corresponding f_w calculated.

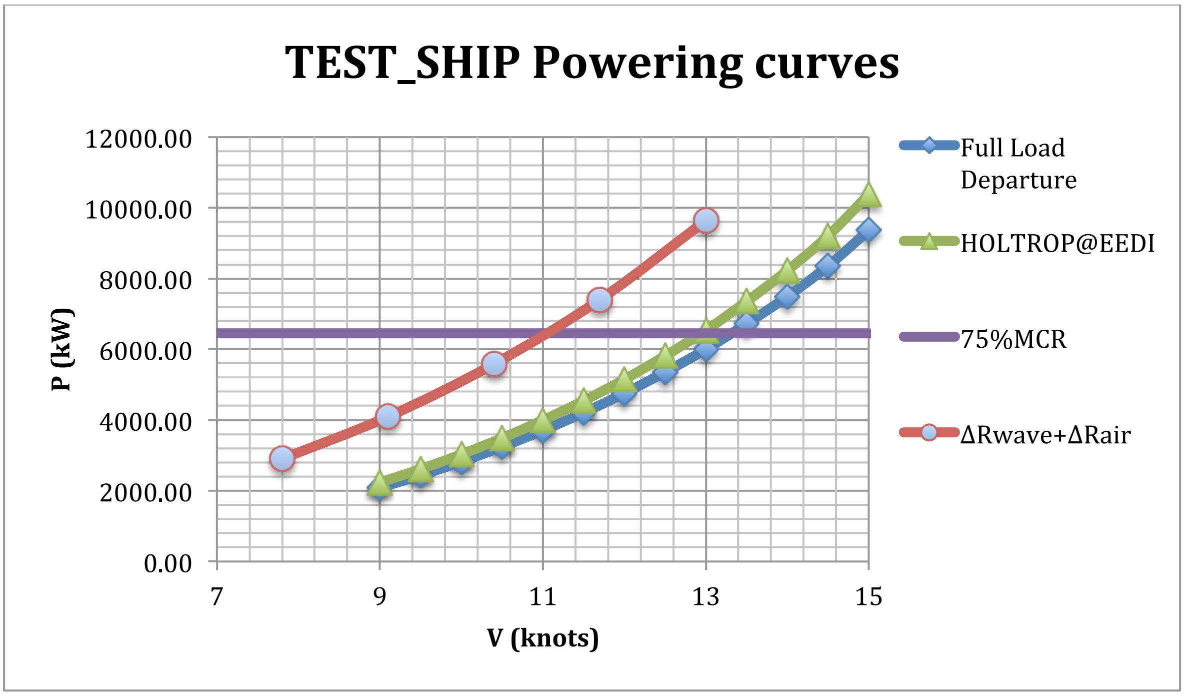


Figure 29: Powering curves in representative weather conditions

Also, coefficient f_w and the respective $EEDI_{weather}$ will be calculated using the standard f_w curves, so as to compare the results of two methods proposed by IACCS. The cumulative results of the vessel speed in the respective conditions (V_w), coefficient f_w and attained $EEDI_{weather}$, are presented in the next table.

TEST_SHIP					
	V_{wind} (knots)	**Speed reduction(%)**	**f_w**	**$EEDI_{weather}$**	***Attained EEDI***
LIU	11.04	15.00	0.85	6.74	5.73
Standard Curves	10.14	22.00	0.78	7.32	

Table 22: Results concerning $EEDI_{weather}$

We can observe that the value from the standard curves overestimates the prediction for speed loss, according to the value obtained by the applied simplified method [LIU], for approximately 7% or 0.9 knots. So if standard curves are used when designing a new ship, they can lead in an overestimation of the power needs of the vessel leading to an increased attained EEDI value and making compliance more difficult.

Chapter six:

Application of Interim Guidelines *for determining Minimum Propulsion Power to Maintain the Maneuverability of Ship in Adverse Weather conditions on the studied ships*

6.1 Reference environment and summary of methods

The environmental conditions for applying the *Interim Guidelines* as dictated by IACCS are presented in the next table:

Vessel's L_{bp} (meters)	**Significant wave height, H_s (meters)**	**Peak wave period, T_p (seconds)**	**Mean wind speed, V_w (m/s)**
<200	4.0	7.0 to 15.0	15.7
Intermediate lengths	Linear interpolated		Linear interpolated
>250	5.5		19.0

Table 23: Reference environment for applying Interim Guidelines

In the context of this thesis, we shall also investigate the compliance for the ship “TEST_SHIP”, for reference environments based on the analysis done in chapter *2.2 Environmental conditions,* which are analytically described in the next table:

Regulation	**Significant wave height, H_s (meters)**	**Peak wave period, T_p (seconds)**	**Mean wind speed, V_w (m/s)**
Lower value based on Interim Guidelines	4.0	7.0 to 15.0	15.7
Highest value based on Interim Guidelines	5.5		19.0
Intact stability Code 2008	8.0		26.0

Table 24: Investigated environments for ship "TEST_SHIP"

We have included the environmental conditions described in ISC 2008, knowing that these are extreme weather conditions that a ship would most likely avoid, to validate or not the proposal of MSC 93.21.5 of harmonizing the environmental conditions in Interim Guidelines with that of ISC 2008.

A summarized description of the two level assessment proposed by Interim Guidelines is given in the next table:

<table>
<tr><td colspan="2" align="center">Assessment level 1: Minimum power lines</td></tr>
<tr><td colspan="2" align="center">Installed power must be greater than Minimum installed power= ax(DWT)-b [kW]</td></tr>
<tr><td colspan="2" align="center">a, b defined per ship type</td></tr>
<tr><td colspan="2" align="center">Assessment level 2: Simplified assessment</td></tr>
<tr><td>Assumption:</td><td>A certain advance speed in head-on condition ascertains also course keeping ability in all wave and wind directions</td></tr>
<tr><td>Requirement:</td><td>Minimum advance speed (V_{ref}) is between 4.0-9.0 knots
Lower value for the referenced vessels</td></tr>
</table>

	check on lateral/frontal windage area Higher values following check on high windage and low rudder area
Calculation:	Preliminary calm water resistance calculation Added resistance normally require model tests - in this thesis derives from numerical calculation methods (needs to be validated)
Check:	1. Ratio frontal/lateral (A_{FW}/A_{LW}) windage areas <0.4 down to 0.1 then advance speed to 9.0 knots (linearly interpolated in between) 2. Ratio rudder area/lateral wetted area $A_{R\%}<0.9\%$ then advance speed adjusted according to $V_{coursekeeping}=V_{ref}-10x(A_{R\%}-0.9)$

Table 25: Summarized description of Interim Guidelines

The assessment for the installed is to be performed in maximum draught condition at the required advance speed defined above. The principle of the assessment is that the required propeller thrust, T, defined from the sum of bare hull resistance in calm water R_{cw}, resistance due to appendages R_{app}, aerodynamic resistance R_{air}, and added resistance in waves R_{aw}, can be provided by the ship's propulsion system, taking into account the thrust deduction factor t:

$$T = (R_{cw} + R_{air} + R_{aw} + R_{app})/(1-t)$$

Then, in order to check whether the required thrust can be provided by the engine, the required advance ratio of the propeller J and coefficients K_T, K_Q are found from the equation:

$$T = u_a^2 D_p^2 K_T(J)/J^2$$

where $K_T(J)$ is the thrust coefficient curve, and $u_a = V_s(1-w)$, by matching the $K_T(J)/J^2$ curve with the propeller open water characteristics.

6.2 Application of method on studied ships

6.2.1 Assessment level 1: Minimum power lines

The results from the application of the minimum power lines assessment for the studied ships are presented in the next table.

Vessel	Installed MCR (kW)	Minimum Installed Power (kW)	Compliant	Margin of (or no) compliance (percentage)
SHIP_1	**9620.00**	*8531.44*	YES	11.32 %
SHIP_2	**10440.00**	*11622.00*	NO	11.32 %
SHIP_3	**12495.00**	*15720.45*	NO	25.81 %
TEST_SHIP	**8600.00**	*8331.39*	YES	3.1 %

Table 26: results from application of Minimum Power Lines assessment

We observe that the two smaller ships (according to their DWT) satisfy the first assessment level, especially “SHIP_1”, which has a satisfactory margin; the vessel “TEST_SHIP” does also so, but with a significantly smaller margin.
On the other hand, the two larger vessels, contrary to what we expected according to the analysis of the previous chapters, fail to meet the minimum requirement for the installed power.

6.2.2 Assessment level 2: Simplified assessment

According to the Simplified Assessment, for each vessel the required advance speed was set as the maximum of the minimum navigational speed V_{ns}=4.00 knots and a course keeping speed, defined in relation with V_{reff} and ruder area (as a percentage of the lateral submerged area).
The reference speed V_{reff} is defined in regard with the block coefficient and the ratio of frontal to lateral windage area.
For the assessment of the installed power meaning if a vessel has enough power to retain the course keeping speed in the respective conditions, the required thrust is defined as the sum of bare hull resistance in calm water R_{cw}, resistance due to appendages R_{app}, aerodynamic resistance R_{air}, and added resistance in waves R_{aw}, can be provided by the ship's propulsion system, taking into account the thrust deduction factor t:

$$T= (R_{CW}+R_{air}+R_{aw}+R_{app})/(1-t)$$

The different components of total resistance are calculated using formulas proposed in the Simplified Assessment. The required power to maintain the V_{ck} is calculated from the next formula and for a successful assessment needs to be smaller than the installed propulsion power.

$$P_D=2\pi\rho n^3D^3K_Q(J)$$

The application of the Simplified method required, among others, the calculation of the added wave resistance in weather condition defined in Table 24, for wave headings ranging from 0.00 to 180.00 (head waves) degrees, for every 30.00 degrees; in the shortwaves case, only the head waves scenario was considered. For the each vessel the worst combination of peak wave period and wave heading i.e. the combination that yields the greater added wave resistance was used. The vessel's speed is the course-keeping speed, as defined in the Simplified Assessment.

6.2.2.1 Results from Newdrift, LIU and shortwave methods

For the ship "TEST_SHIP", the head-waves case gave the greater results concerning the peak added wave resistance value; in the next figures, results from all methods mentioned are presented for the head wave case, for the three different wave amplitudes. More results are presented in the Appendix.

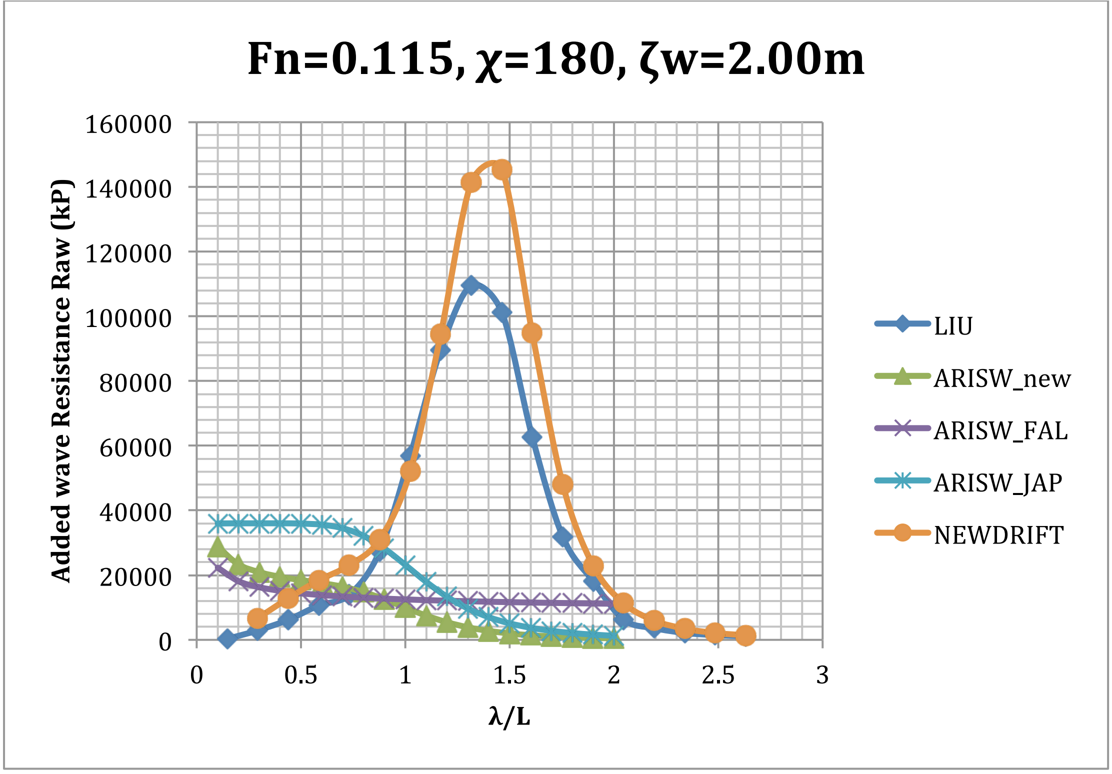


Figure 30: Result regarding added wave resistance for ζw=2.00m for "TEST_SHIP"

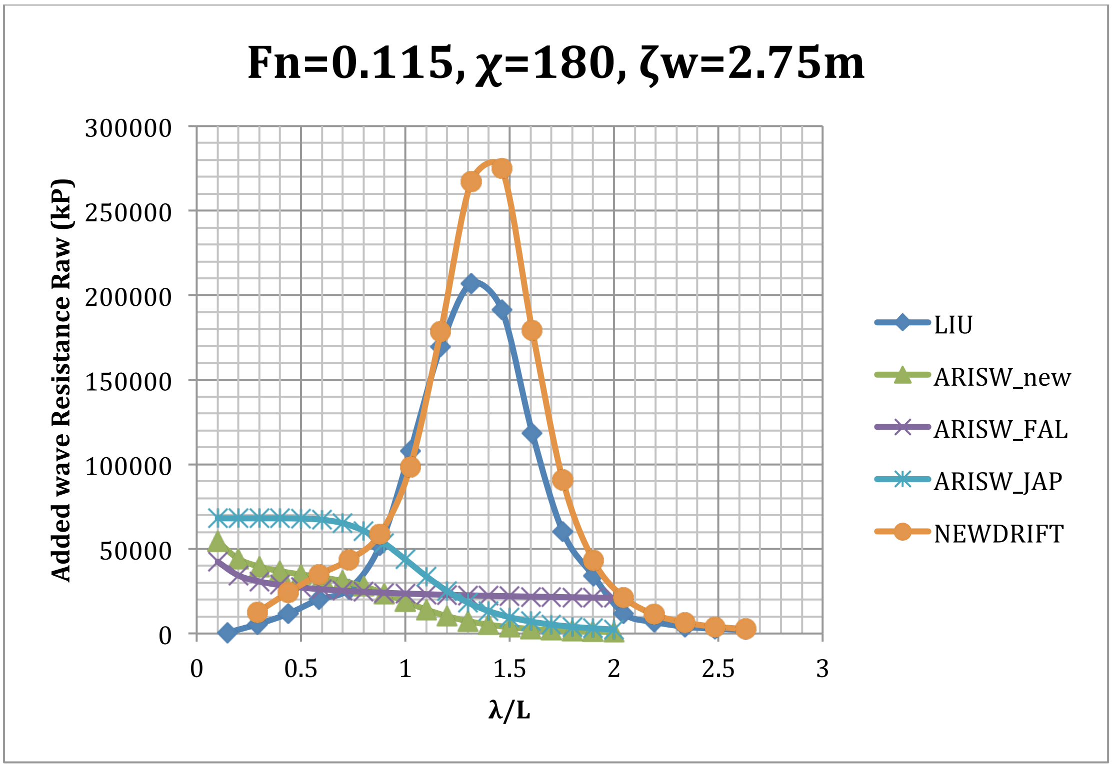


Figure 31: Result regarding added wave resistance for ζw=2.75m for "TEST_SHIP"

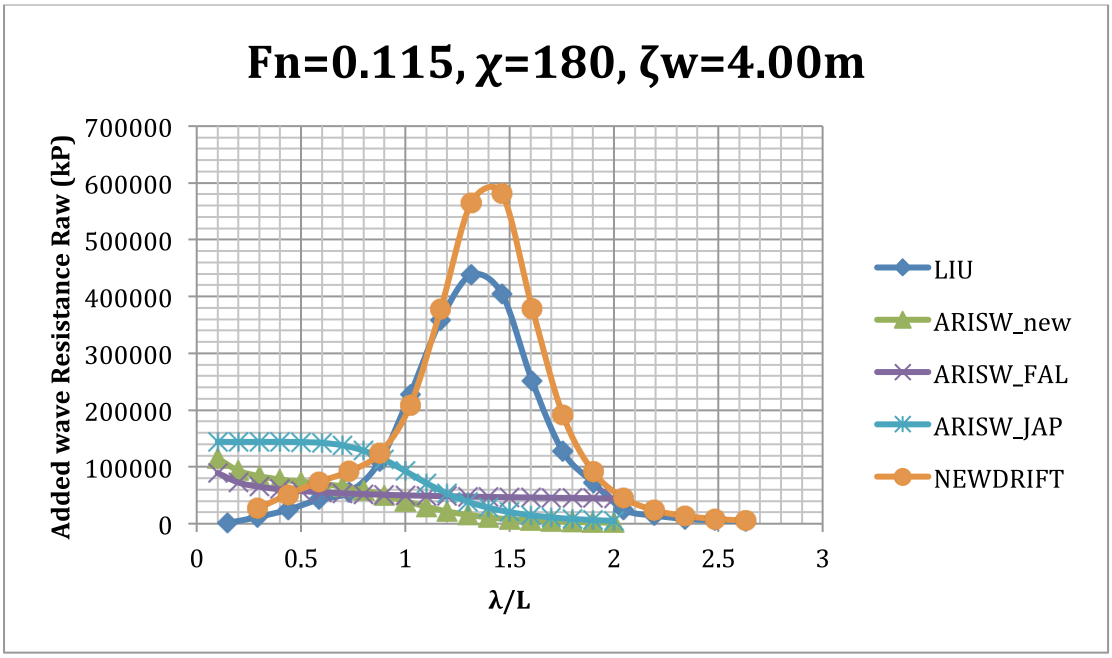


Figure 32: Result regarding added wave resistance for ζw=4.00m for "TEST_SHIP"

It is observed that the added wave resistance is maximized when λ/L=1.315, i.e. when the length of the incident wave is λ= 224.87m. For each case investigated, the added wave resistance for the aforementioned wave length, is presented in the next table.

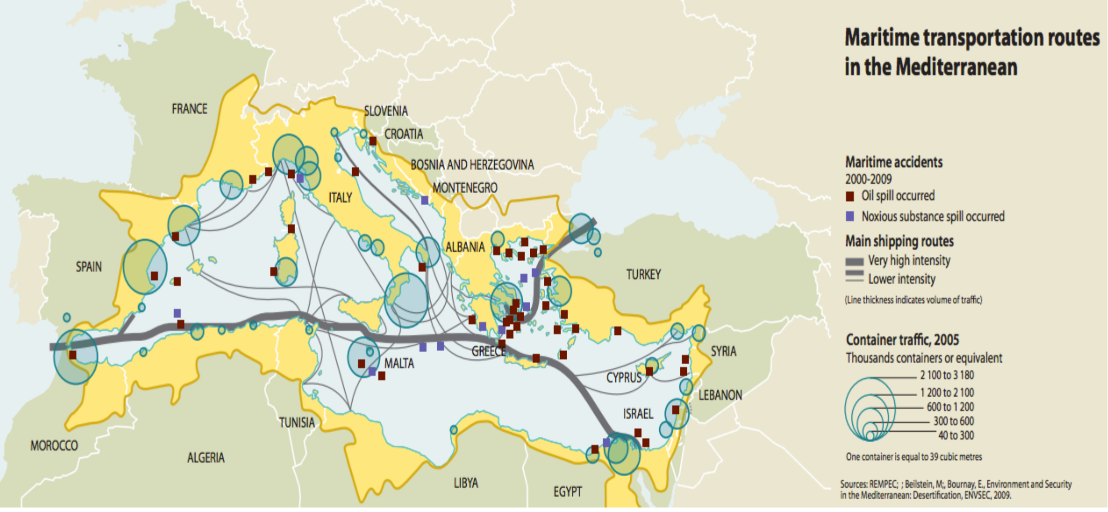
Vessel	***Case***	**Rrequired Advance Speed (knots)**	***Raw (kP)***
TEST_SHIP	*Interim Guidelines*	9.16	109517.03
	Interim Guidelines (peak value)		207055.64
	ISC 2008		473022.93

Figure 33: Added wave resistance for ship "TEST_SHIP"

6.2.2.2 Results from level 1 Raw curve

Concerning the other three vessels, an assumption was made that they all operate in the Mediterranean sea; in an effort to investigate the issues most commonly presented to ships that operate under the specific environmental conditions of this important seaway.

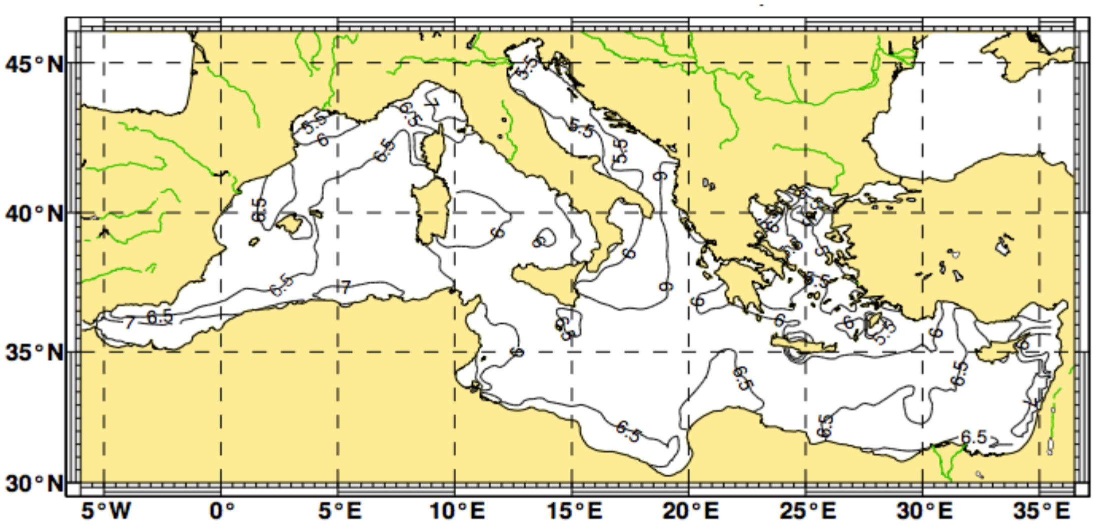
The next picture presents the most important maritime transportation routes used in the Mediterranean sea:



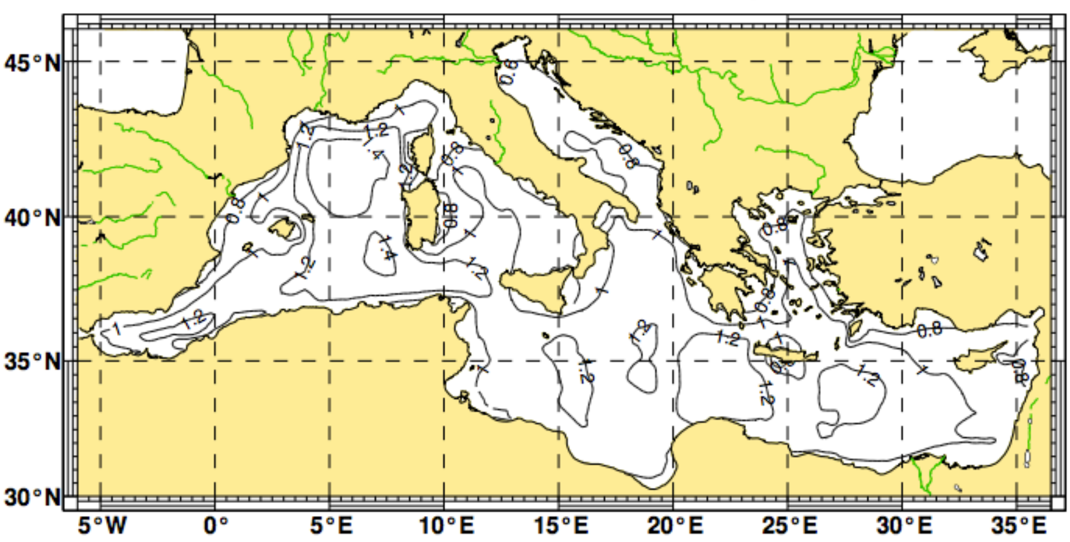
Sources: REMPEC; ; Beilstein, M;, Bournay, E., Environment and Security in the Mediterranean: Desertification, ENVSEC, 2009.

Figure 34: Maritime transportation routes in the Mediterranean

In an effort to understand the specific environmental conditions, especially concerning peak wave period T_p (which is in direct correlation with the wavelength) and significant wave height H_s , that are consistent in the Mediterranean region, the wave atlas MedAtlas [25] was used; our object was to determine a specific value of peak wave period T_p, which would best represent the conditions more likely for a ship travelling in this region to encounter. The following pictures show the annual spatial distribution of T_p and H_s:



Picture 18: Annual spatial distribution of peak wave period T_p



Picture 19: Annual spatial distribution of specific wave height H_s

So, for the application of the Simplified Assessment, we will select the most prominent value for peak wave period, that falls within the range proposed by the method. We presume that the specific wave height H_s remains the same as proposed by the method, as we want to investigate the least unfavorable combination of T_p and H_s in the shortwave region. For the easier application of the method, the following table was constructed:

Vessel	L_{bp} (meters)	Significant wave height, H_s (meters)	Peak wave period, T_p (seconds)	Mean wind speed, V_w (m/s)
SHIP_1	174.00	4.00	7.0	15.70
SHIP_2	236.00	5.08		18.08
SHIP_3	268.22	5.50		19.00

Table 27: Environmental condition for applying Simplified Assessment

For each ship, the added wave resistance is computed using the level 1 formula ,as described in *Chapter 3.4.2* . The level 1 formula is:

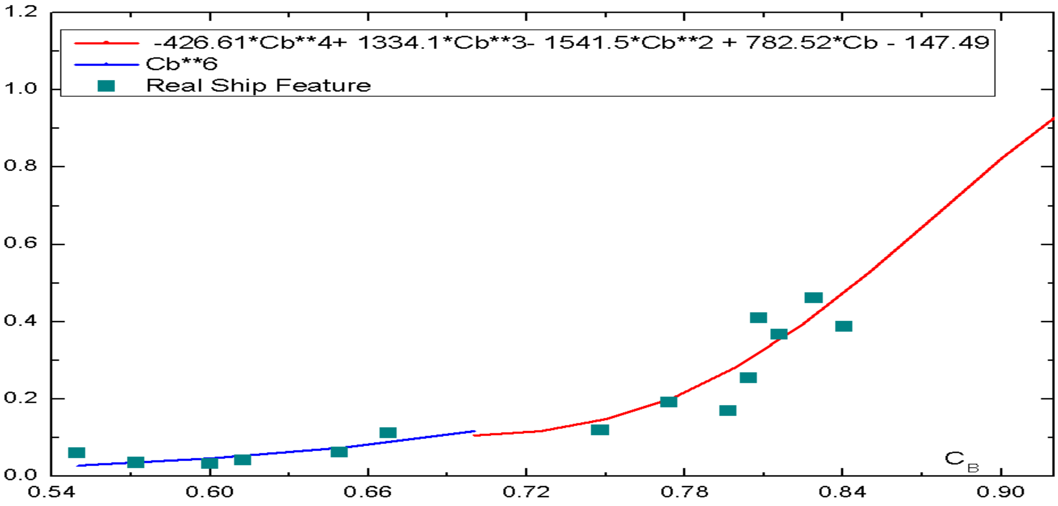
$$F_1 = \frac{1}{2}\rho g \zeta_a^2 \left(1+5\sqrt{\frac{L}{\lambda}}Fn\right)\left(\frac{0.87}{C_B}\right)^{1+4\sqrt{Fn}} f(C_B)$$

Equation 5: Level 1 formula for added wave resistance in shortwaves, χ=180

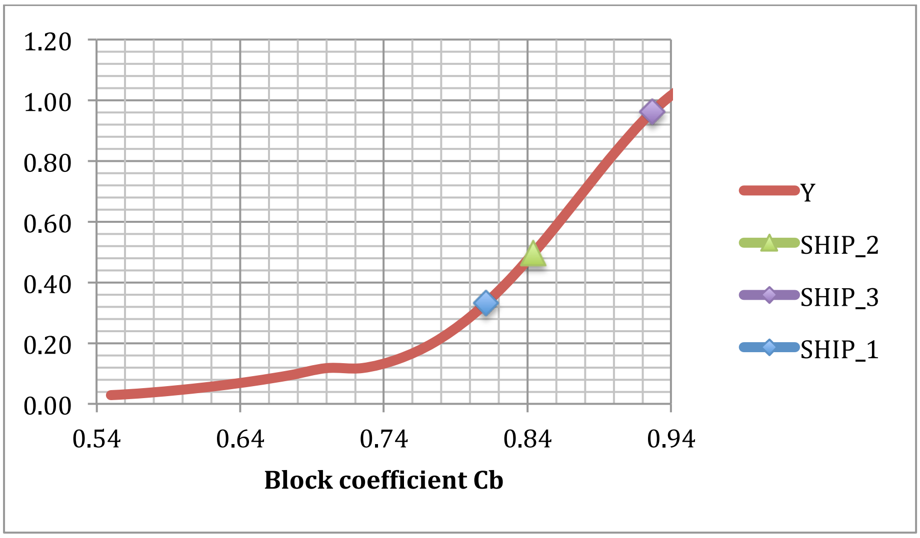
where:

- ρ: water density
- g: gravity's accelerations
- ζa: wave amplitude
- λ: wave length
- Fn: Froude number
- C_B: block coefficient

and $f(C_B)$ is determined from the following curve:



Picture 20: Level 1 Curve



The application of the level 1 method provided the results shown in the next tables and figures:

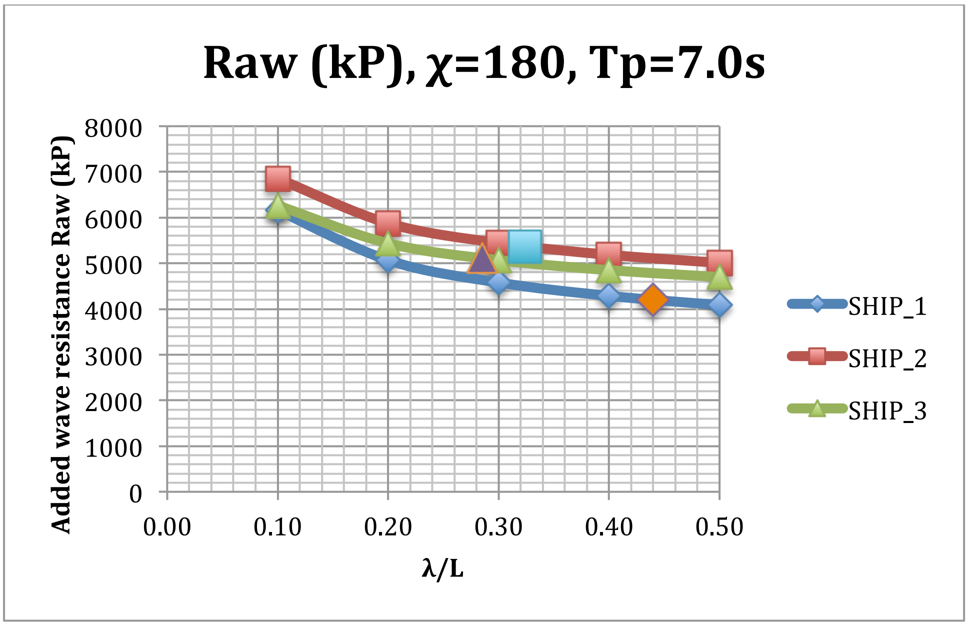


Figure 35: Added wave resistance in shortwaves, χ=180, various ζw

Vessel	*λ/L*	**Rrequired Advance Speed (knots)**	*Raw (kP)*
SHIP_1	*0.440*	7.95	16388.42154
SHIP_2	*0.324*	5.62	21787.21766
SHIP_3	*0.285*	5.19	20446.78955

Table 28: Results for Raw from level 1 formula

The same calculations were also applied in accordance with the environmental conditions for wind and waves described in the ISC 2008 regulation. Results for all three vessels are presented below:

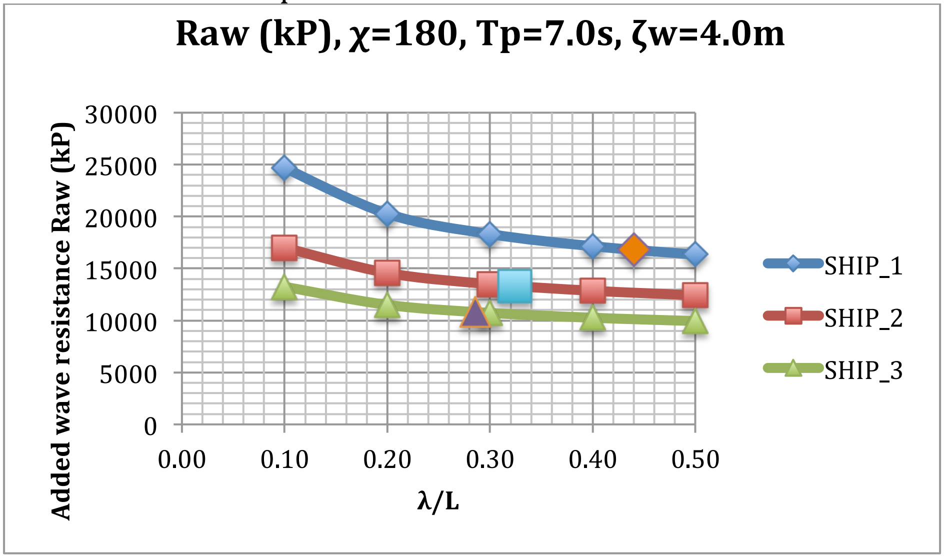


Figure 36: Added wave resistance in shortwaves, χ=180

Vessel	λ/L	Rrequired Advance Speed (knots)	Raw (kP)
SHIP_1	0.440	7.95	16388.42154
SHIP_2	0.324	5.62	21787.21766
SHIP_3	0.285	5.19	20446.78955

Table 29: Results for Raw from level 1 formula (ISC2008)

6.2.2.3 Results from application of Simplified Assessment for all studied ships

For each vessel the simplified method was applied, in order to check that the available thrust produced by the engine is sufficient, the advance coefficient J needed to be calculated. Using the following equation, proposed in Interim Guidelines, the $K_T(J) = C \cdot J^2$ curve was produced which was then matched with the propeller open water characteristics (figures can be found in the Appendix):

$$T = \frac{u_a^2 \cdot D_p^2 \cdot \rho \cdot K_T(J)}{J^2}$$

$$\frac{K_T(J)}{J^2} = \frac{T}{u_a^2 \cdot D_p^2 \cdot \rho} = ct.$$

After finding the cross section point between the $K_T(J) = C \cdot J^2$ and the $K_T(J)$ - J curve of the propeller, we were able to graphically determine the respective torque and advance coefficients, namely K_Q and J. In the next table, the arithmetic values for the components of the resistance, the needed thrust, the advance coefficent J and the respective available propulsion power for each vessel are given:

Vessel	Case		Required Advance Speed (knots)	Rcw (kP)
SHIP_1	Interim Guidelines	Tp=7.0s	7.95	16101.94
	ISC 2008			
SHIP_2	Interim Guidelines		5.62	18535.41
	ISC 2008			
SHIP_3	Interim Guidelines		5.19	8073.93
	ISC 2008			
TEST_SHIP	Interim Guidelines	9.16		19912.91
	Interim Guidelines (peak value)			
	ISC 2008			

Rair (kP)	Raw (kP)	T (kP)	J (m)	Pd(kW)	Compliant	Margin
3877.37	4200.51	49067.31	0.37	1747.09	YES	75.78%
16101.94	16802.04	62317.84	0.24	7087.47	YES	1.76%
12038.95	5370.39	59861.29	0.27	2085.01	YES	73.37%
25531.23	13318.58	78239.92	0.18	8202.53	NO	-4.76%
17806.43	5111.70	52968.79	0.32	1582.93	YES	83.70%
33343.89	10814.83	75396.81	0.25	4069.24	YES	58.09%
8182.81	207055.64	171822.40	0.22	18653.68	NO	-189.20%
11984.24	233744.03	307201.22	0.17	41022.76	NO	-536.01%
22441.41	438068.15	621678.76	0.12	109962.22	NO	-1604.84%

Table 30: Arithmetic values of important factors computed for applying the Simplified Assesment

We can observe that the TEST_SHIP, where the worst combination of Tp and incident wave heading was selected, fails to comply in all three scenarios investigated. The other ships manage to successfully pass the level 2 assessment with a great margin; but for the peak values of Hs, as described in the level 2 assessment, SHIP_1 complies marginally, SHIP_2 fails to comply and SHIP_3 complies with a sufficiently large margin.

6.3 Comments on the results of applied methods

Based on our results for the application of the Minimum Power Lines and Simplified Assessment, we make the following observations:

- the two smaller (according their DWT) vessels manage to successfully comply with the first level assessment; the other two vessels fail to meet the Minimum Power Lines Assessment

- for all vessels that the Simplified method was applied, the formula proposed for the lateral submerged area corrected for breadth effect, gave results up to 80-100% of the actual value, measured from their respective General Arrangement Plans; this can lead to a wrong estimation of the course-keeping speed, as it's calculation heavily relies on the lateral submerged area value

- all three vessels that were tested for intended operation in the Mediterranean (T_p=7.0s), successfully, and by a great margin, meet the requirements for available propulsion power for the case of significant wave height as proposed in Simplified Assessment; for the case of wind and waves characteristics according to ISC2008 regulation, "SHIP_2" fails to meet the requirements, "SHIP_1" complies marginally, and "SHIP_3" complies with a sufficient margin

- the vessel "TEST_SHIP", given that the worst possible combination of wave heading and length (the one that maximized added wave resistance) was chosen for the calculations, the assessment was negative for all three cases investigated; the added wave resistance was almost equal 10 times greater than the value of the combined friction and air resistance. This may be due to the large course-keeping speed that the vessel had to maintain which value is directly affected by the lateral submerged area.

- especially, for the environmental conditions proposed in *ISC 2008, TEST_SHIP* fails to comply with a far greater margin, as the prediction for added resistance in waves is too large; this shows that the proposition for harmonizing the proposed conditions with that described in ISC 2008 is an excessive measure, as a ship should be able to avoid such extreme case phenomena

- the same vessel, considering the same operational scenario as the other three (Mediterranean ocean), and using the powering curve attained for the $EEDI_{weather}$ calculation, manages to meet the assessment's requirements for installed propulsion power

- for all vessels that the Simplified method was applied, there is no account of a power margin due to aging or fouling; a ships age and the condition of the hull's surface should be accounted for in the resistance computations of the method, so that predictions can be more accurate

- the relation between a ships length and the environmental conditions that it will come across (if considered ocean-going) is non-existent; a vessel, regardless it's size, that travels the same region with another, will come across the same environmental conditions. It would be more practical to have a distinction amongst environmental conditions a ship might encounter based on it's intended operational routes. I believe that the current way of describing environmental conditions a vessel might encounter should be changed - at least be harmonized with the peak values proposed in the level 2 assessment (meaning those for ships with L>250.0m), if not become even stricter, as long as it considers all vessels ocean going

- Interim Guidelines based on a three-level assessment approach, in which ships were considered to have sufficient power to maintain their maneuverability in adverse conditions if they fulfilled any of the three assessment levels. Since the complexity of the methods is increasing as the level increases, the concept of satisfying the first and simpler of the proposed levels was assumed sufficient. Only in the case of non-compliance with the first level was it considered necessary to proceed to the second level.

- the TEST_SHIP, as mentioned, marginally complies with the level 1 assessment but doesn't comply with the level 2 assessment. This contradicts the purposes of a multi-level assessment; higher levels should be stricter than lower ones meaning that if a vessel complies with level 1 assessment, it should comply with level 2, as it's available propulsion power is already considered sufficient.

6.4 Optimization attempt

In an effort to improve the attained EEDI rating for the vessel "SHIP_1", two optimization scenarios will be attempted:

- an optimized trim that reduces the added wave resistance
- the effect of a W.E.D being installed

In order to approach the first scenario, HOLTROP method was used to calculate the added wave resistance for different loading and trim conditions, as a part of total resistance.
For the second scenario, the effects that a vessel would theoretically have from installing a W.E.D are examined.
It is important to note that based on the preliminary analysis done in *Chapter 1.3,* we know that a small increase in speed, as a result of a hydrodynamic optimization, won't make a significant difference in the attained EEDI; but it will shift the powering curve, so with less power (and less fuel consumption), the same speed can be achieved. So, we could argue that by de-rating the main engine in order for the 75%MCR to correspond this new point of operation for EEDi conditions, a significant reduction in the attained EEDi could be achieved.

6.4.1 The significance of added wave resistance (wave making) in the total resistance-effect of trim

In this scenario the effect of added wave resistance, as a component of the total resistance, on the needed propulsion power will be investigated; the scope of this research is finding a suitable trim in which the added wave resistance is minimized. HOLTROP method was used to calculate the added wave resistance for different loading and trim conditions; we have to mention that the wave resistance in the range of speeds that V_{reff} falls into, is only a small portion of the total resistance, so it is not expected to have great impact on the total resistance. Also, due to the nature of HOLTROP method, the results should be used conservatively but are indicative of the deviations one should expect. The results for all conditions are presented in the following figures, with the curve representing the percentage of added wave resistance to the total resistance for different speeds:

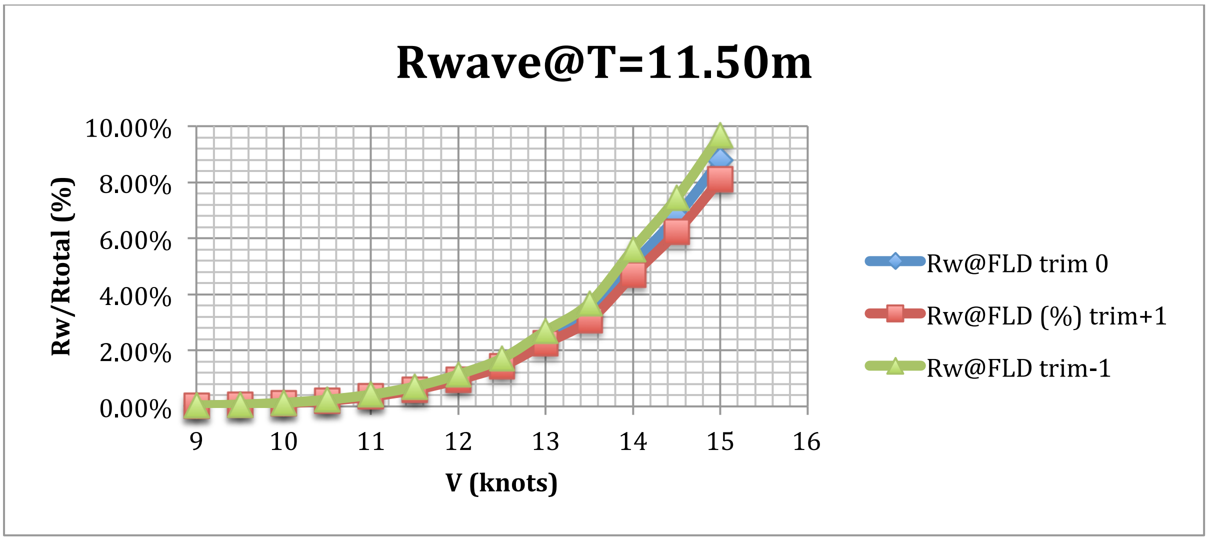


Figure 37

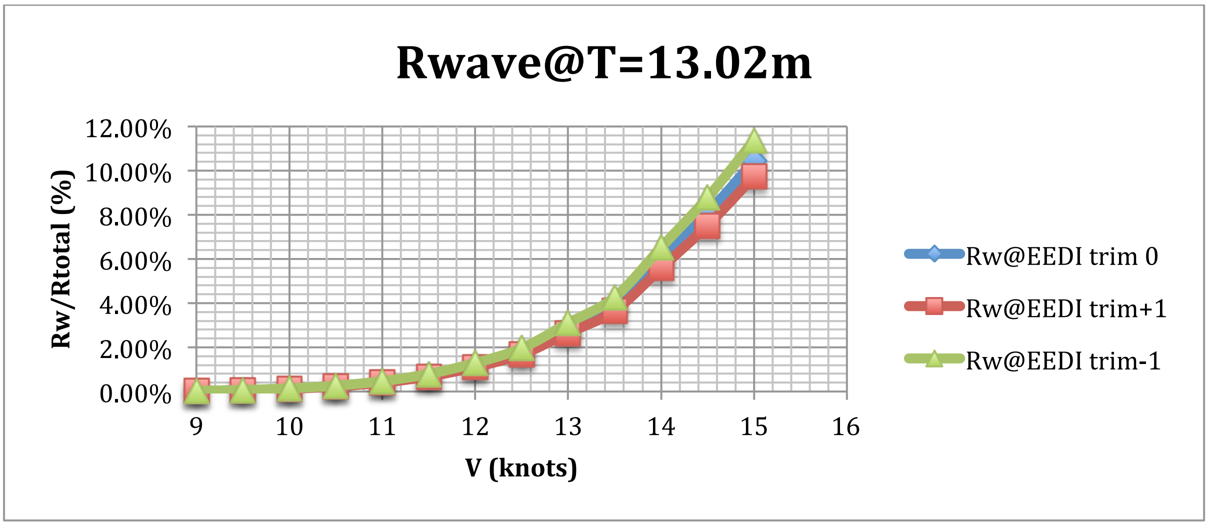
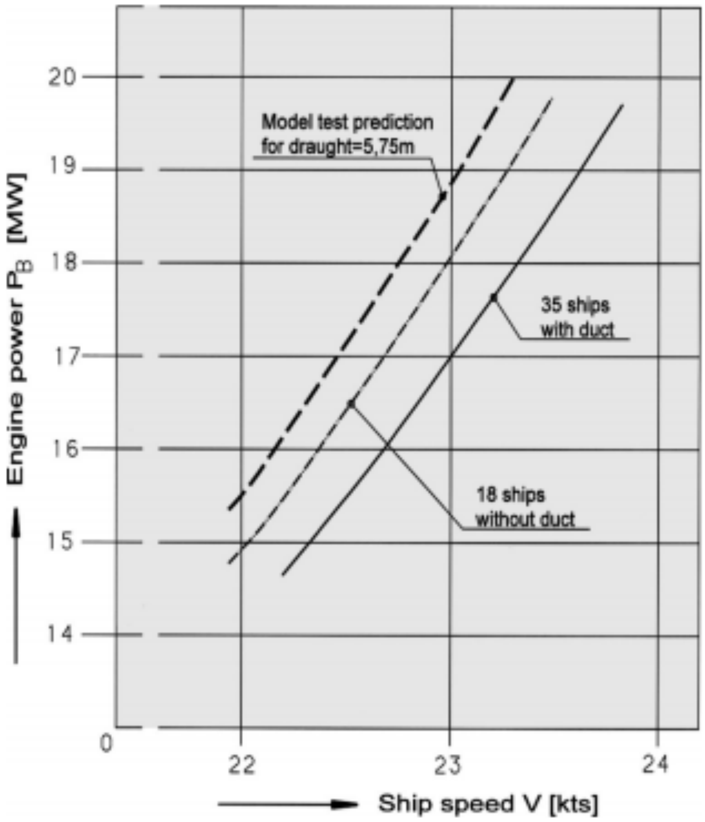


Figure 38

It can be observe that the added wave resistance R_w begins to play a significant role in the total resistance R_T in speeds greater than 15.0knots; for the EEDI operation point, and the corresponding V_{reff} , R_w is only a small percentage that had almost no impact in the R_T (as the effect of other components "compensates" for the gains, in such a low speed). These minor changes observed could not lead to any useful conclusions regarding an optimal trimming condition

6.4.2 Installation of a W.E.D

The effects of installing a W.E.D (provided the installation is done correctly) can result in an increase in speed of 0.3 knots or a 5% increase in the propeller efficiency [11]. This statement results from the averaging of a multitude of values at widely differing power stages. The merit of this type of evaluation is that it refers to values measured on ships of one and the same series with and without duct (see Picture 13) and not to model test.



Picture 21: effect of a W.E.D

This gain in efficiency from conversion of the engine power into propeller thrust is achieved by several influencing factors; the course of flow upstream of the propeller is characterized by areas with more or less pronounced flow separations which arise from the ship's form which gets finer towards the rear and the thrust deduction of the hull in general. It is at this very point that the WED is placed, accelerating the water flow by its special configuration and directing it towards the area of maximum non-uniformity in the propeller disk, i.e. 12 o'clock position. As a result the wake current is rendered more homogenous overall. Consequently, the setting angle of the propeller blade profile better matches the effective admission flow across a major portion of the circumference, and the propeller efficiency is improved. Reduction of the flow separation area by the Schneekluth duct acts in the same way as the reduction of the thrust deduction fraction and as such as in increase in the propulsive efficiency.

Finally, the WED itself also provides a propulsion component by its favorable profile configuration and the resulting circulating flow around the duct. The increase in the admission flow velocity resulting from the duct installation causes the propeller to rotate more easily by 1.5 – 2 rpm as compared to a vessel without duct. An improvement of this magnitude neither requires an adaptation of the propeller when retrofitting a vessel with a duct, nor any consideration when designing the propeller for a new ship with duct. Enlargement of the range of light running is of advantage for the operating conditions of the diesel engine and usually is within the limits of tolerance of the propeller design point.

In an effort to improve the attained EEDI for the vessel “SHIP_1” the effects that an installation of a W.E.D duct would have, in reference with speed or fuel consumption, two quantities that are significant in the EEDI calculation. The effects of a W.E.D installation on the ship “SHIP_1”, are presented in the next table:

Installing a W.E.D	
Quantity	**Effect**
Propeller efficiency	+5%
Speed	+0.3 knots
(new) Reference speed V_{reff}	13.78 knots
(new) Attained EEDI	5.96
Percentage of reduction	2.29%
Target EEDI (phase 1)	<5.562

Table 31: Effects of installing a W.E.D on ship “SHIP_1”

So, the installation of the duct and the corresponding improved efficiency of the propeller, led to a decrease of almost 2.30% in the attained EEDI value. This result shows that for already built ships, the available optimization methods will fall short in making a vessel meet the future required EEDI values, except if a vessel is marginally exceeding them.

Chapter seven:

Summary - Conclusions and Way Ahead: Summary of Work, Main Findings and Future Perspectives

Since 2009, when the International Maritime Organization (IMO) published the outcome of the 2nd Green House Gas Study (GHG), the reduction of gaseous emissions attributed to the shipping industry has seen its way into becoming a matter of principal importance for regulators, shipbuilders, owners and operators. To address this matter IMO, in July 2011, introduced the Energy Efficiency Design Index (EEDI), which is a performance-based indicator that expresses ship's carbon dioxide emissions (in grams) per ship's transportation work, given as capacity-mile. EEDI takes into account the involuntary loss of speed due to adverse weather conditions, which is expressed by the f_w correction coefficient and may be referred to as $EEDI_{weather}$.

Newbuildings (ship's building contract as from 1st of January 2013 and the delivery of which is on or after 1 July 2015) will have to meet an EEDI marginal value criterion (or not surpass the relevant EEDI reference line), which depends on ship type and size. Following the two-year phase zero period (between January 2013 and January 2015), the reference level will be tightened incrementally every five years, in 2015, 2020 and 2025 (via 10% EEDI value reduction each time) to keep pace with technological developments related to new efficiency and powering reduction measures.

Ships whose attained EEDI happens to be greater than the required need to take measures in order to comply; designers and operators have various options regarding the way they will choose to decrease ship's attained EEDI value. The most popular, albeit less costly, method to achieve this amongst ship owners/operators proved to be slow-steaming; a practice already widespread in the shipping industry since 2007, when a dramatic increase in the price of crude oil occurred. This enabled the shipping industry to both reduce operational costs and comply with the new regulations. However, operating ships at a lower speed, than originally planned, is not optimal in many respects. If lower speed becomes a design specification, this will inevitably lead to less installed power and smaller engines.

In practice and after the introduction of the EEDI reference lines for the various types and sizes of ships, it proved that set levels were unrealistically low for some modern newbuldings (tankers and bulk-carriers, at least for the phase 2 and 3 compliance) and industry complaints found their way to IMO. In parallel, concerns were expressed that with the introduction of slow steaming and of underpowered ships, ships' maneuverability will be affected, especially when ships operate in extreme weather phenomena. This raised a question regarding ship's safety in the form of a requirement for *minimum installed power*; a ship must have sufficient power to achieve a speed that enables it to navigate safely when adverse weather conditions are present.

In order to address this issue, IMO developed on the basis of a study IACS (Int. Assoc. of Classification Societies) the *Interim Guidelines for determining minimum propulsion power to maintain the maneuverability of ships in adverse conditions,* which includes a three-level assessment (the third level has been removed for now) aimed to determine if a ship has the available propulsion power to maintain her maneuverability in adverse weather conditions. If a vessel complies with any one of the assessment levels, it means that its installed propulsion power is deemed sufficient. The Level 1 (Minimum Power Lines) method consists of a comparison of the installed MCR, that needs to be greater than a calculated value (Minimum Power), which takes into account the vessel's capacity (expressed in DWT at load line draft for most ship types) and some given constant values for each ship type. Level 2 (Simplified Method) assessment consists of Excel-level arithmetic calculations, but also requires the calculation of added resistance in waves in respective environmental conditions, which are chosen according to the ship's length and need to be determined through tank-tests or computer codes.

Following that, in Maritime Safety Committee (MSC) 93/21/5 a document was submitted by Greece entitled *Safety evaluation of the interim guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships under adverse weather conditions,* which aimed to bring to the committee's attention safety issues regarding the minimum propulsion power and the associated minimum speed. In this document, serious concerns regarding the adequacy of the proposed weather criteria (which were considered not sufficiently severe) were expressed; also, a proposal that a more proper adverse weather criterion for safe maneuverability is minimum speed, and not minimum installed power. It should be noted, however, that the minimum powering and speed requirements are not sufficient to express a ship's maneuverability in adverse conditions, if not accompanied by a requirement for sufficient steering, thus enhanced maneuvering criteria for ship's operation in adverse conditions.

The scope of this thesis was to investigate the viability of sample ships in regard with compliance of both the EEDI and the *Interim Guidelines for determining minimum propulsion power to maintain the maneuverability of ships in adverse conditions,* as well as, the further investigation of the proposals made by Greece; for this reason four ships (two chemical-oil and two crude-oil carriers) of incrementally larger sizes were selected to be tested; one of the above ships is still in the design stage and three already operational. Also, for one of the selected ships (TEST_SHIP), the $EEDI_{weather}$ is calculated and the relation between added resistance in waves to total resistance is being explored.

The calculation of a vessel's acquired EEDI corresponds to a specific loading condition (namely the load line condition), available power (which equals with the 75% MCR), and the associated speed, called reference speed (V_{reff}). Sea trial data available for the ships tested were corresponding to different loading conditions (in most cases, full load departure); for this reason, a graphical method proposed by IACS was used to determine V_{reff}. The application of the method required the construction of the ships' speed-powering curves for both conditions, load line and sea trial; HOLTROP's method, which is a statistical based, semi-empirical method was used for the estimation of resistance with quite satisfactory results for ships with low Froude numbers (like those tested), in conjunction with code GRID to achieve that.

After determining the V_{ref} value for each ship, their respective EEDI was calculated; all ships tested complied with the required phase 0 EEDI value. In order to calculate the $EEDI_{weather}$ for TEST_SHIP the coefficient f_w (which expresses the loss of speed due to adverse weather phenomena) needed to be specified; a new powering curve needed to be constructed that would take into account the added resistance due to waves and wind in the respective weather conditions. For this purpose, a new level 1 method (in the form of a computer code) developed by the Ship Design Laboratory of NTUA [REF...LIU-PAP] that takes into account, among others, ship's block coefficient and flare angle of the respective waterline, was used in order to determine the added resistance in waves for a specified speed range; then the decreased speed corresponding to the 75%MCR was specified graphically. The coefficient f_w was also determined using the standard f_w curves.

Results showed that the loss of speed (from original reference speed V_{ref}) calculated using the standard curves was 7% greater than the one derived from the level 1 computer code, which led to an increased attained $EEDI_{weather}$ value; specifically of 14.6% and 8.6% greater than the required EEDI value for phase 0, and 31.6% and 24.8% for phase 1. In comparison with the attained EEDI value, the calculated $EEDI_{weather}$ was greater by 27.7% and 17.6% for the respective methods. The consideration of $EEDI_{weather}$ is not mandatory yet, but if it comes into effect, and the respective currently required EEDI value must be met, it will be very difficult for already operating vessels to comply; design optimization combined with smaller engines, high efficiency rudders and other efficiency technologies will be needed in future vessel designs.

Also, regarding the relation of Added Resistance in Waves, R_{AW}, to the Total Resistance, R_T, for different speeds, results from the computer code showed that in increasingly larger Froude numbers the R_{AW} also increases, but with a decreasingly gradient rate, accounting for 20.0% to 8.0% of the respective R_T in the speed range examined. This shows how significant the effect of R_{AW} is in low speeds ($F_n<0.4$), as it accounts for almost a quarter of a vessel's R_T; correctly predicting the minimum installed power required to sustain low (minimum course-keeping) speeds in adverse conditions is one of the important issues for regulators, designers, yards and the shipping industry.

The next step was the application of *Interim Guidelines for determining minimum propulsion power to maintain the maneuverability of ships in adverse conditions* to the four studied ships. The two smaller ships (TEST_SHIP and SHIP_1) passed successfully, especially SHIP_1, the level 1 (Minimum Power Lines) assessment; on the other hand, the two larger crude oil carriers (SHIP_2 and SHIP_3) were found seriously underpowered, contrary to what was expected.

In order to apply the level 2 assessment, the added resistance in waves (and wind) needed to be determined; for this, the computer 3D-panel codes of NTUA-SDL namely NEWDRIFT and LIU where utilized [40], as well as a new simple method (level 1) in the form of a function for use in the short-wave domain, developed also by NTUA-SDL[42]. The absence of any offset data for all but one ship, did not allow a detailed sea-keeping investigation; however, the practical interest is in vessels' behavior when encountering *short waves*, which are waves of *length less than 0.5 the ship length*; it is noted that the short wave assumption is not violating realistic ship conditions, as most encountered waves are of short wave size; this led us to regard the two following operational scenarios concerning the applied weather conditions:

- the ship TEST_SHIP, which was considered operating in the open ocean (North Atlantic scenario), was tested for the conditions according to *Simplified Method's* respective values , as well as, the values described in the *International Stability Code (ISC) 2008; this is a very extreme scenario condition, noting that the ISC-2008 code considers the ship in 'survival, dead-ship' condition*
- the other three ships, were considered to operate in the Mediterranean region; with the help of a Wave Atlas the most frequent values of wave characteristics were determined and those in accordance with part of the level 2 assessment's method were selected

In all cases, the worst possible combination of the incident wave's angle and peak wave period was selected (as dictated by the *Interim Guidelines*), meaning the one that maximizes the added resistance in waves and consequently the propulsion power needs, to achieve the minimum course-keeping speed; for all cases this proved to be the head-waves case.

Results for TEST_SHIP showed that the available propulsion power to retain maneuverability (course-keeping speed) in the conditions proposed by the regulation was by far insufficient, as Raw resulted to over 80.0% of the calm water R_T; naturally, the vessel did not comply for either of the other two (stricter) conditions it was tested in. This can be attributed to the large course-keeping speed derived by the method which is directly affected by the lateral submerged area; as previously stated, the proposed formula for its computation yields results higher than the actual value, leading to greater demands for the needed speed to retain maneuverability and adequate directional stability. It should be however reminded that the results based on the *ISC 2008* criteria are very extreme and the use of the ISC-2008 conditions for this purpose is not part of the adopted guidelines (*but proposed by Greece to IMO*). Harmonizing the Interim Guidelines criteria with the ISC-2008 weather criteria would effectively render the majority of present vessels unfit for operation.

In either case, this result is of course contradictory for TEST_SHIP, as she had complied with the Minimum Power Lines assessment which means that her installed power for retaining her maneuverability was deemed sufficient, when following the Interim Guidelines; higher levels on a multi-level assessment should be stricter than lower ones. Level 1 assessment should act as a "filter" for seriously underpowered vessels; then Level 2 assessment should be used in order to check whether or not the individual design and performance characteristics of a vessel enable it to retain a minimum course-keeping speed, so as to successfully pass the assessment. It is evident that Minimum Power Lines (level 1) assessment should become stricter (if the proposal of Greece is adopted), with the simultaneous refinement of Simplified Assessment's proposed methods and validation of numerical tools for correctly predicting R_{AW}.

Results regarding the other three ships, which where considered to operate in the Mediterranean region, where tested only for the head waves case and for peak wave period of T_S=7.0s (which adequately describes the most frequent wave characteristics of this region). All three ships where found to have sufficient installed power to retain the respective minimum course-keeping speed for the significant wave height and air speed proposed in the Level 2 method; when tested against the *ISC 2008* environmental conditions (which are highly unlikely to come across in Mediterranean shipping routes), only SHIP_2, and this one marginally, was found to have insufficient installed power. So, although SHIP_2 and SHIP_3 were not successful in level 1 assessment, they were found to have sufficient installed power to retain their maneuverability from level 2 assessment; this kind of results show how this multi-level method is supposed to function. Of course, conservativeness is advised over the aforementioned results, as it's unclear if the same ships would successfully pass the assessment if the proposed by *Simplified Method* range of peak wave periods to be tested in were investigated.

A theoretical approach to optimize the performance characteristics of SHIP_1, in order to reduce the attained EEDI while still retaining a positive assessment from the *Interim Guidelines*, was attempted. For this reason, the effect of trim in wave making resistance and the installation of a Wake Equalizing Duct (W.E.D) were explored: the first in order to find a suitable trim than minimizes the total resistance of the ship and, the second in order to enhance the propeller performance, aimed at reducing the powering needs and increasing the speed respectively, and consequently reducing the attained EEDI value without compromising the already established performance characteristics of the vessel. Both methods are considered to be economically viable, as their application cost is quite small.

In order to study the effect of trim in the wave making resistance, and consequently its total resistance, HOLTROP method was used for different trims; unfortunately the results were inconclusive (partly due to the insensitivity of HOLTROP's method in this respect), as the vessel's reference speed was quite low and wave resistance is only a small portion of its R_T in low Froude numbers. The change of trim had effectively no impact on the vessel's powering needs, and hence no considerable effect on the attained EEDI value.

For the effect an installation of a W.E.D would have, results concerning the improvement of the propeller efficiency, based on the manufacturer's website and third party studies where employed; an increase of 5.0% in the propeller's efficiency was selected, which translates into an increase in speed of 0.3 knots. This led to a decrease in the attained EEDI value by almost 2.3% which can be considered significant, but a reduction of almost five times greater is needed to achieve the required EEDI value for phase 1. This may be achieved by other means like hydrodynamic optimization of the hull by e.g. changing its main dimensions (if at design stage), an optimized bulbous bow or the use of other energy efficient technologies which can reduce the attained EEDI value; the economic viability of these methods on already constructed ships is a subject not explored in this thesis. As a recent study [6] showed, no matter how the hull design is improved or modified, it will not be enough to have a vessel that will have the same present speed with 30% reduction of EEDI (phase 3).

In conclusion, it is apparent for vessels, especially smaller ones, that were designed prior to the introduction of the EEDI, that they will struggle to comply with the required EEDI values of future phases without a significant decrease in speed; over the last 30 to 40 years, the design trend of bulk carriers and tankers has moved in a wrong direction seen from an energy saving point of view. The block coefficient has increased during the last twenty years while the length displacement ratio (L/displ.volume1/3) has decreased over the same period, which have resulted in an increased EEDI.

The introduction of *Interim Guidelines for determining minimum propulsion power to maintain the maneuverability of ships in adverse conditions* is a positive first step towards the guarantee of safety for ships sailing in lower than indented speeds in adverse weather conditions. This case study showed that there is room for stricter limits regarding the *Minimum Power Lines* assessment, as well as the proposed weather criteria used in *Simplified Method* and the way they are applied (dependent on length); the proper definition of the severeness of the weather conditions (wave height and wind speed) is crucial for the rationale of the guidelines; this should be based on accident analysis and related weather statistics (see, project SHOPERA, www.shopera.org); in my opinion, the application of different environmental criteria should be based on indented operating routes of individual vessels, if not become uniform for all. Also, ageing and fouling of the vessels' hulls is not accounted for in the method, something that I think should be revisited.

From the way level 2 assessment is constructed, it is evident that speed is the ultimate measure for describing the maneuverability capabilities of a vessel, and not installed power. A Minimum Achievable Speed is a more adequate safety measure, as ships with required minimum propulsion power that are badly designed can turn out to be adverse weather inadequate; as level 2 assessment method only takes certain basic design parameters as inputs, it is highly unlikely to make accurate predictions for a vessel's performance and sufficiency of the installed power. The evolution of the accuracy of numerical calculations and constant upgrade of computer programs, make possible the employment of larger amounts of data and will definitely improve current methods accuracy. Of course, maneuverability performance without proper criteria is another issue not properly touched yet in the guidelines.

It is evident that there is a need to rethink certain design constants of the past; future vessels will need to be radically changed in terms of design, something that has already began in the shipping industry with an example being Maersk Triple E's containerships. Slower speeds will be almost unavoidable; the objective of achieving the required EEDI values for future phases and still be deemed safe on account of ship's maneuverability is becoming a subject of increasing importance to the shipping industry. A wide range of energy efficiency technologies, the continuous research and optimization of the prediction methods is certainly the way to go towards achieving this goal.

APPENDIX

A. Calculation of attained EEDI

For each studied ship, the attained EEDI is presented along with the values of its components, used for its computation as per IACS guidelines. Also, the margin of compliance for the required EEDI for phase 0 as well as a graphical representation that includes the curves of phases 1,2 and 3 are presented.

EEDI quantity	**Value**	**Units**
C_{FME}	3.114	
P_{ME}	7215	kW
SFC_{ME}	172.9	gr/kWh
CF_{AE}	3.114	
P_{PTI}	0	kW
P_{AE}	481	kW
SFC_{AE}	198.5	
P_{eff}	0	kW
P_{AEeff}	0	kW
f_{eff}		-
f_j	1	-
f_i	1	-
f_w	1.00	-
f_c	1.00	-
Capacity	50349	tons
V_{ref}	13.84	knots
EEDI	**6.10**	-
required EEDI	6.18	-
margin of compliance	2.96%	-

Table 32: EEDI quantities for SHIP_1

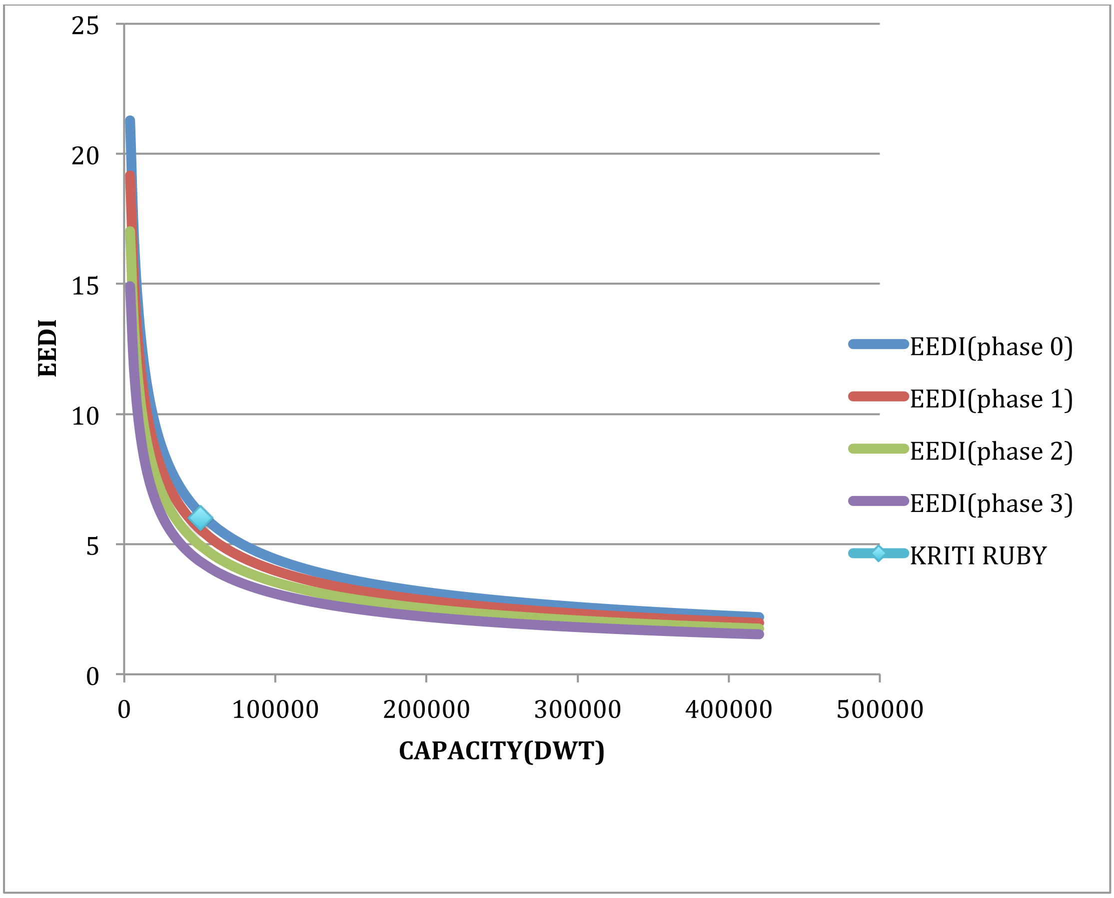


Figure 39: EEDI curves SHIP_1

EEDI quantity	**Value**	**Units**
C_{FME}	3.114	
P_{ME}	7830	kW
SFC_{ME}	176	gr/kWh
CF_{AE}	3.114	
P_{PTI}	0	kW
P_{AE}	611	kW
SFC_{AE}	199	
P_{eff}	0	kW
P_{AEeff}	0	kW
f_{eff}		-
f_j	1	-
f_i	1	-
f_w	1.00	-
f_c	1.00	-
Capacity	101605	tons
V_{ref}	12.3	knots
EEDI	**3.74**	-
required EEDI	4.39	-

margin of compliance	14.88%	-

Table 33: EEDI quantities for SHIP_2

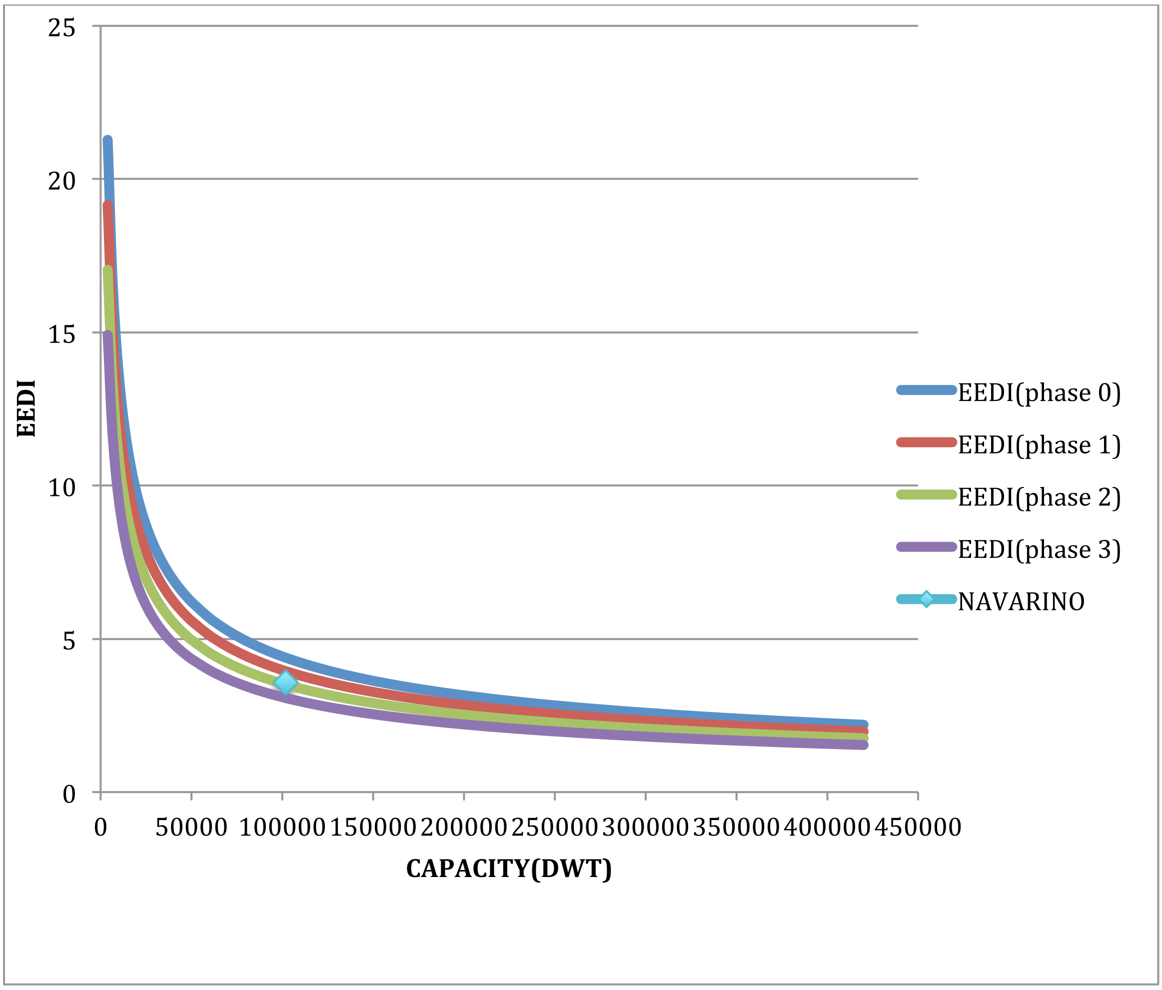


Figure 40: EEDI curves SHIP_2

EEDI quantity	**Value**	**Units**
C_{FME}	3.114	
P_{ME}	9708.75	kW
SFC_{ME}	164.6	gr/kWh
CF_{AE}	3.114	
P_{PTI}	0	kW
P_{AE}	855.4	kW
SFC_{AE}	197	
P_{eff}	0	kW
P_{AEeff}	0	kW
f_{eff}	1	-
f_j	1	-
f_i	1	-
f_w	1.00	-

f_c	1.00	-
Capacity	169568	tons
V_{ref}	12.92	knots
EEDI	**2.51**	-
required EEDI	3.42	-
margin of compliance	26.45%	-

Table 34: EEDI quantities for SHIP_3

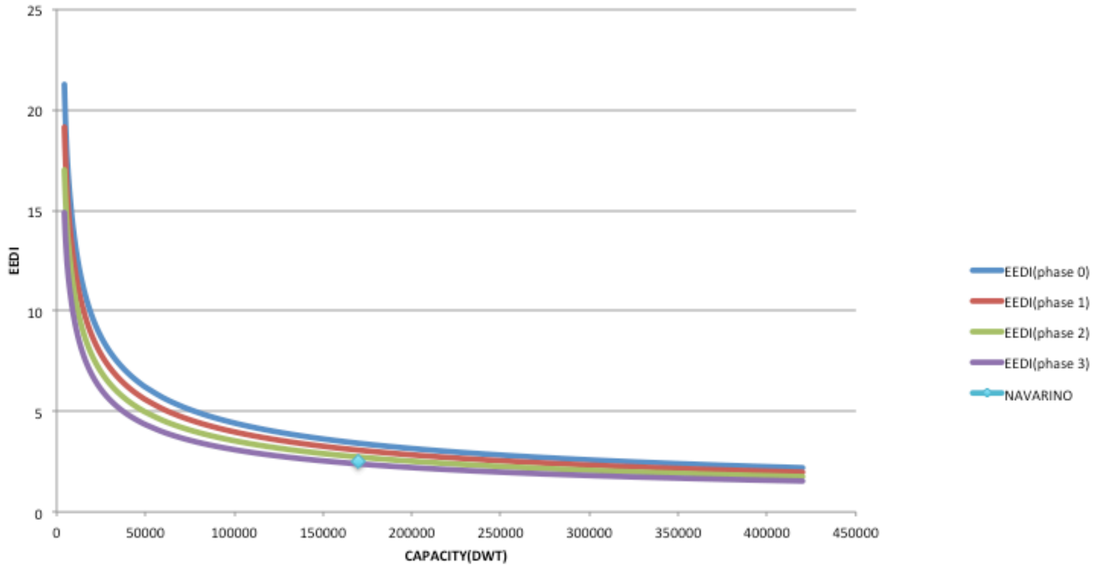


Figure 41: EEDI curves SHIP_3

EEDI quantity	**Value**	**Units**
C_{FME}	3.114	
P_{ME}	6450	kW
SFC_{ME}	165.5	gr/kWh
CF_{AE}	3.114	
P_{PTI}	0	kW
P_{AE}	430	kW
SFC_{AE}	185	
P_{eff}	0	kW
P_{AEeff}	0	kW
f_{eff}		-
f_j	1	-
f_i	1	-
f_w	1.00	-
f_c	1.02	-
Capacity	47029.75	tons

V_{ref}	13.00	knots
EEDI	**5.73**	-
required EEDI	6.39	-
margin of compliance	10.41%	-

Table 35: EEDI quantities for

TEST_SHIP

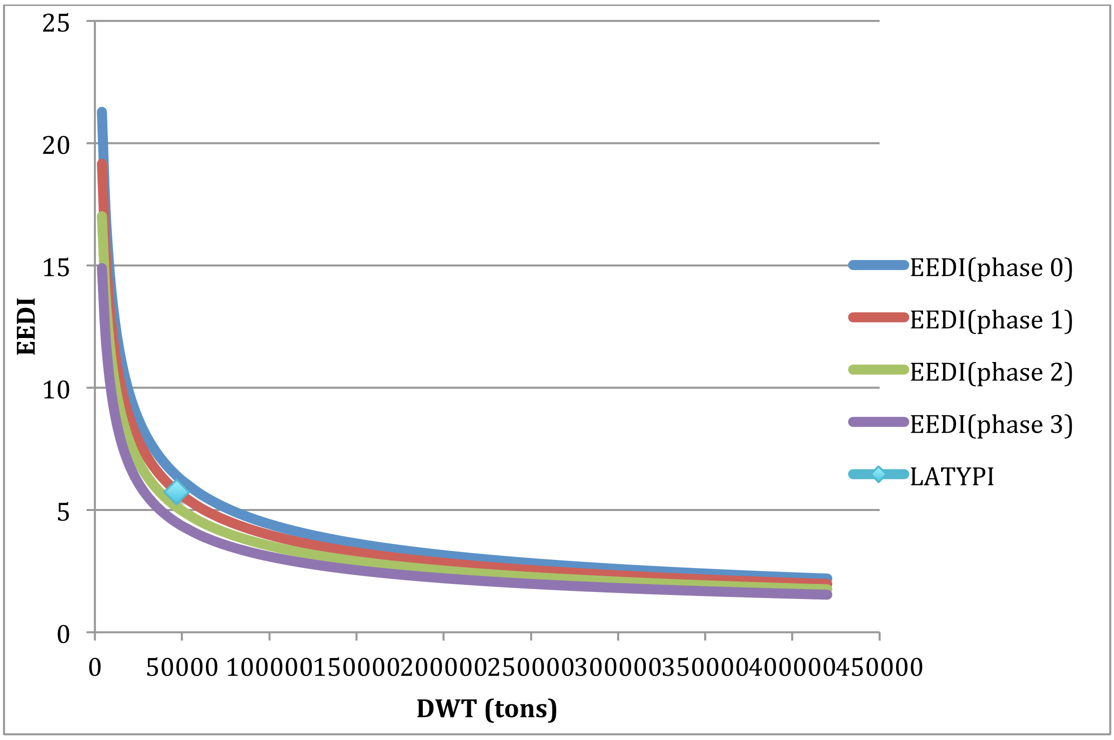


Figure 42: EEDI curves TEST_SHIP

B. Results from Newdrift, Liu and simplified methods for shortwaves

B.1 Zero-speed drift forces

The next figures show results from 3D Panel code Newdrift for the zero speed case concerning the horizontal drift forces due to incident waves from various angles, for the infinite depth and finite depth cases.

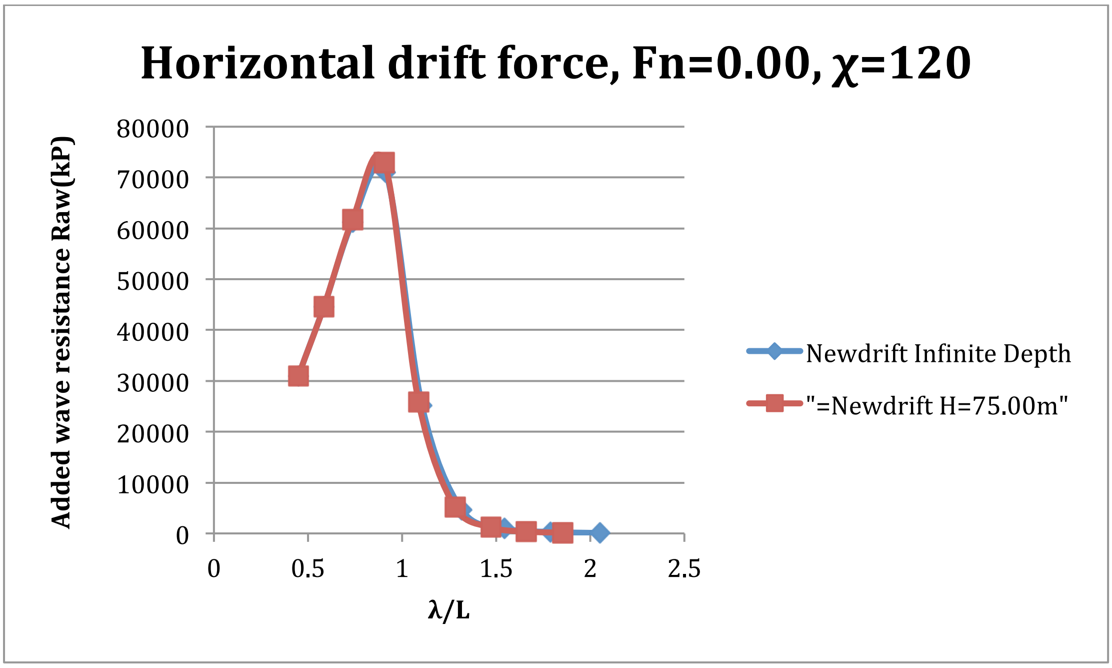


Figure 43: Zero speed drift force, χ=120

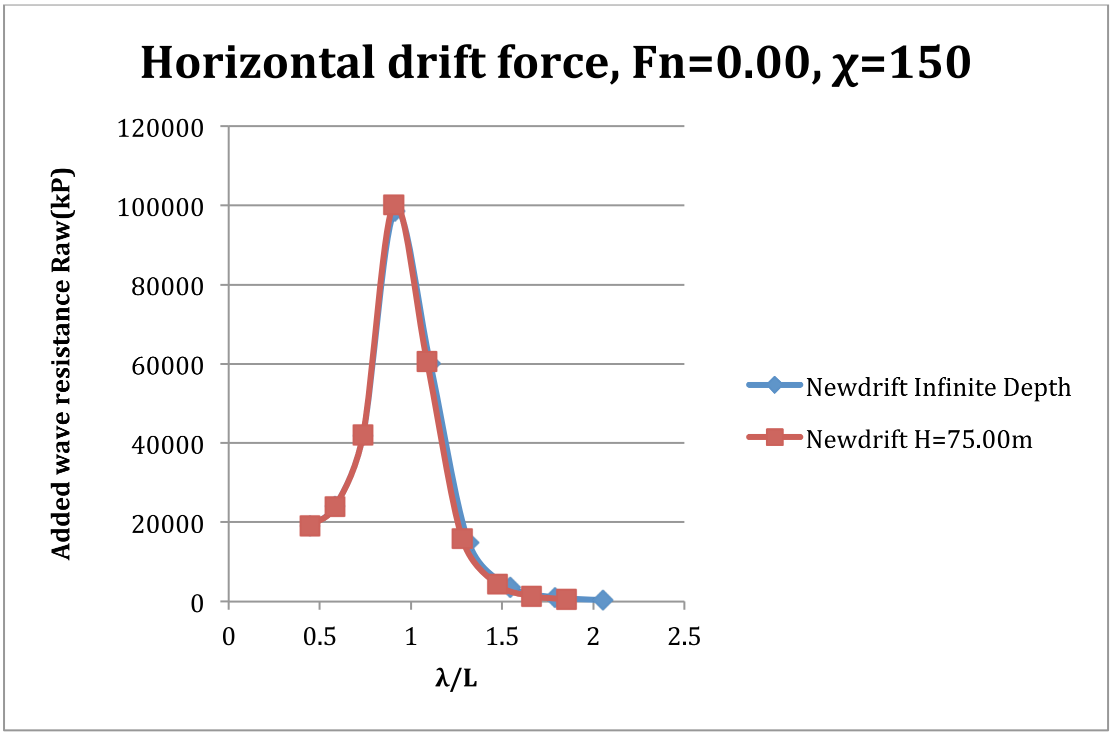


Figure 44: Zero speed drift force, χ=150

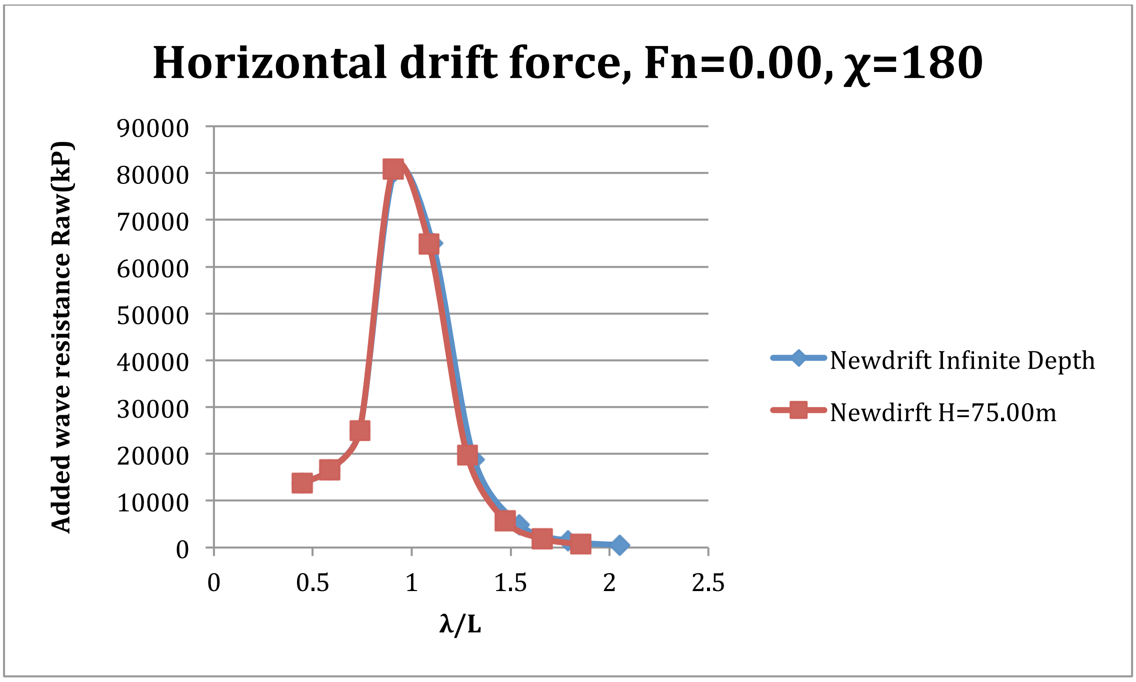


Figure 45: Zero speed drift force, χ=180 (head-waves)

B.2 Added resistance in waves for F_n=0.115

The next figures show results from 3D Panel codes Newdrift and LIU for the course-keeping speed case (Interim Guidelines-Simplified assessment) concerning the added wave resistance due to incident waves of significant wave heights of 4.00m, 5.50m and 8.00m from various angles, for the infinite depth case.

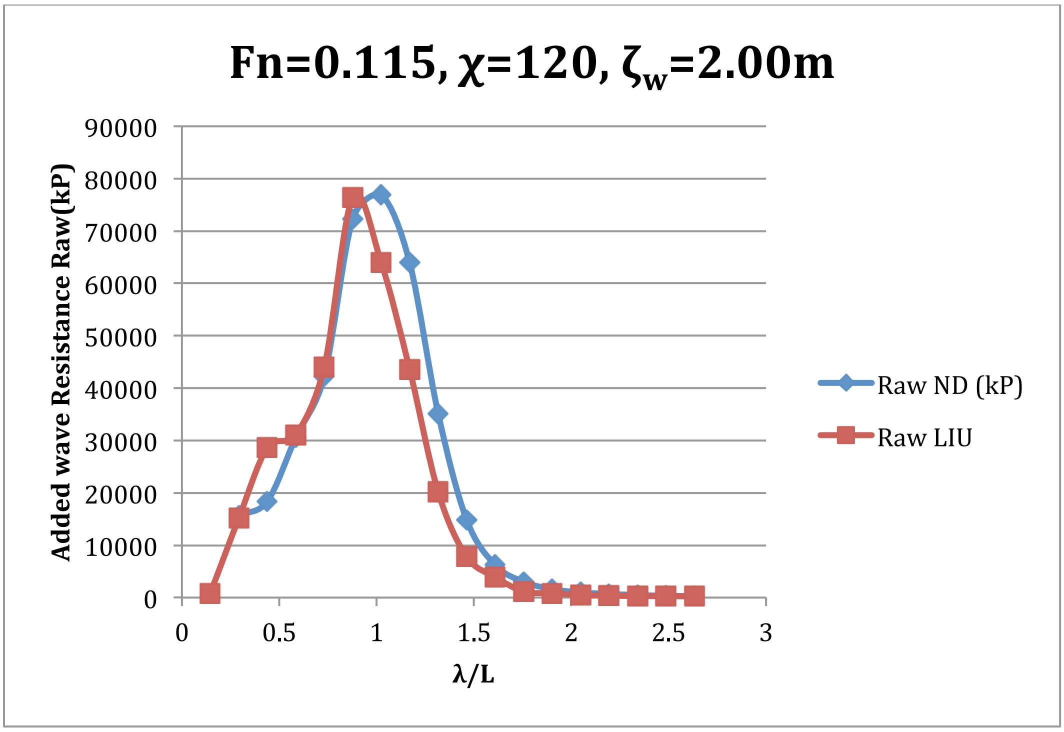


Figure 46: Added Resistance in Waves, χ=120, ζ=2.00

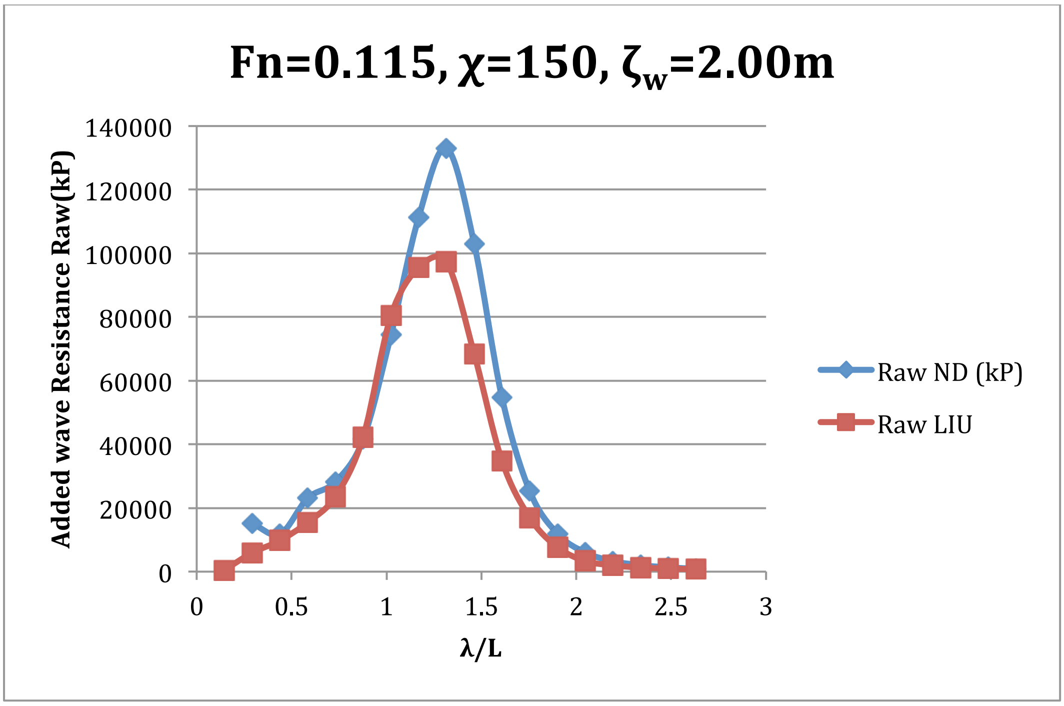


Figure 47: Added Resistance in Waves, χ=150, ζ=2.00

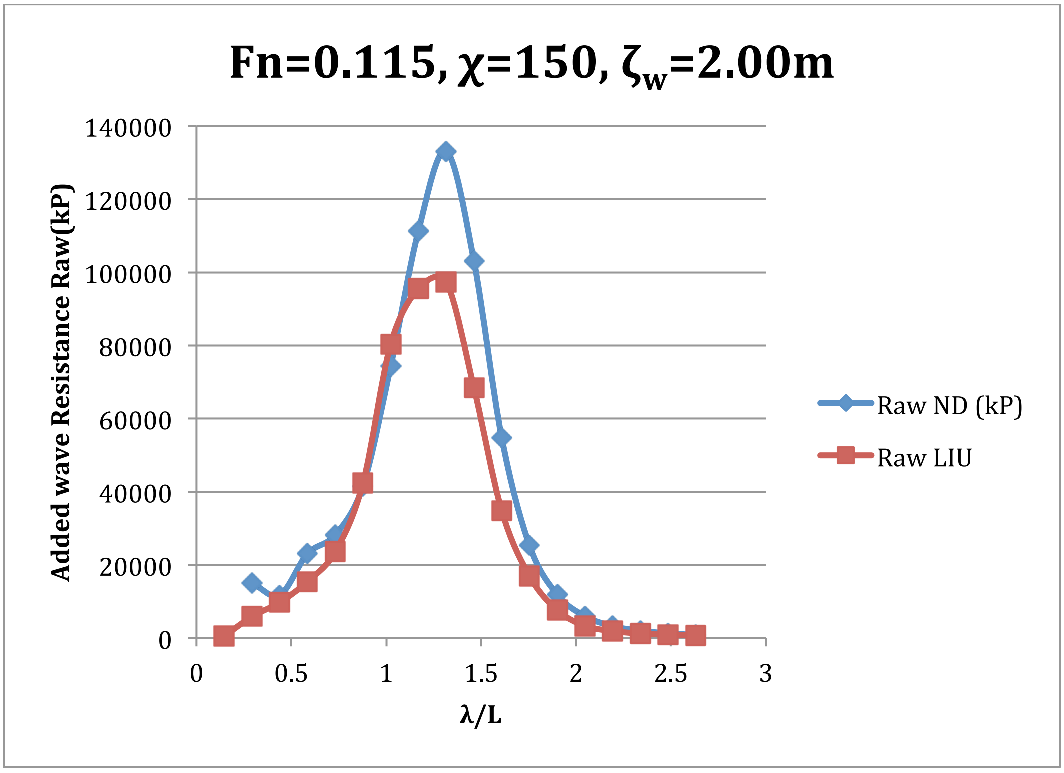


Figure 48: Added Resistance in Waves, χ=180, ζ=2.00

For the head-wave case, we also present the results from the three methods for calculating added resistance in shortwaves:

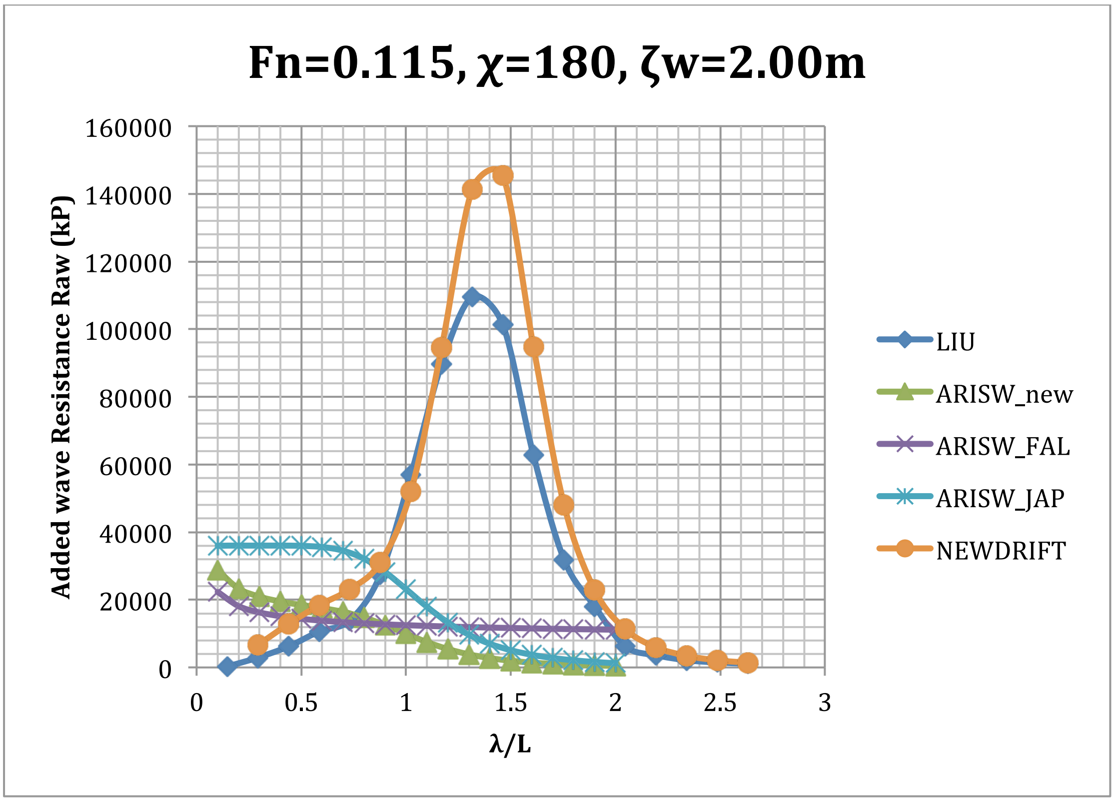


Figure 49: Added Resistance in Waves, χ=180, ζ=2.00 (all methods)

The respective results are presented for significant wave heights Hs=8.00m:

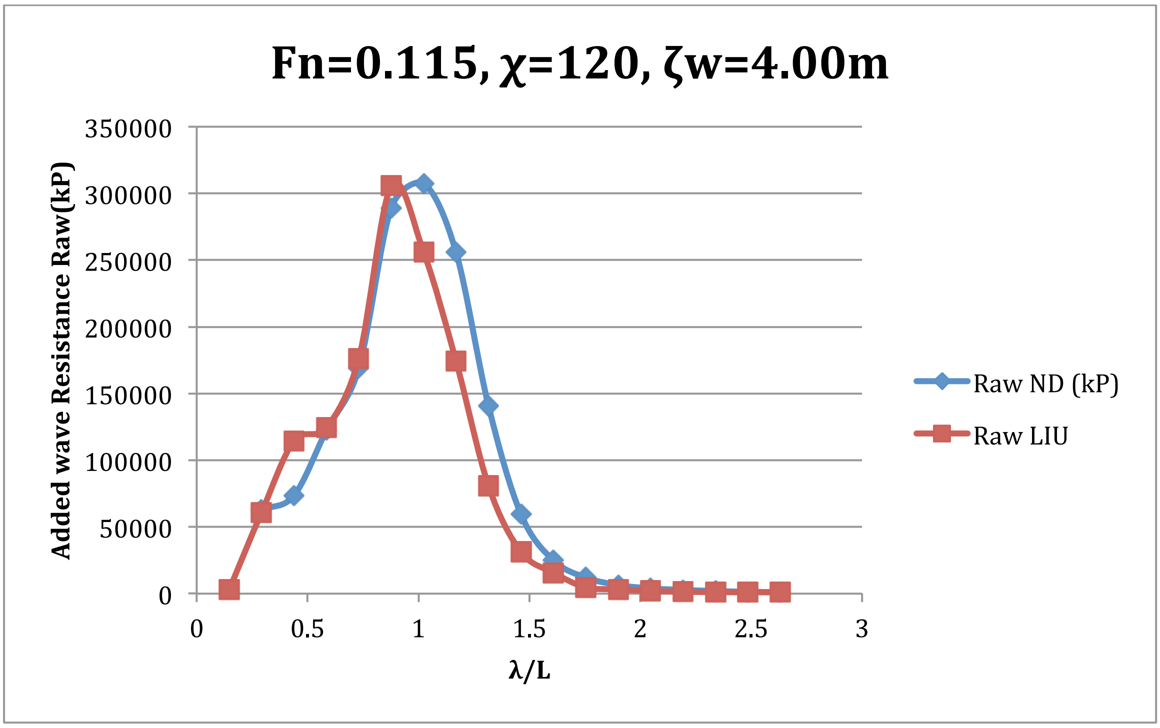


Figure 50: Added Resistance in Waves, χ=120, ζ=4.00

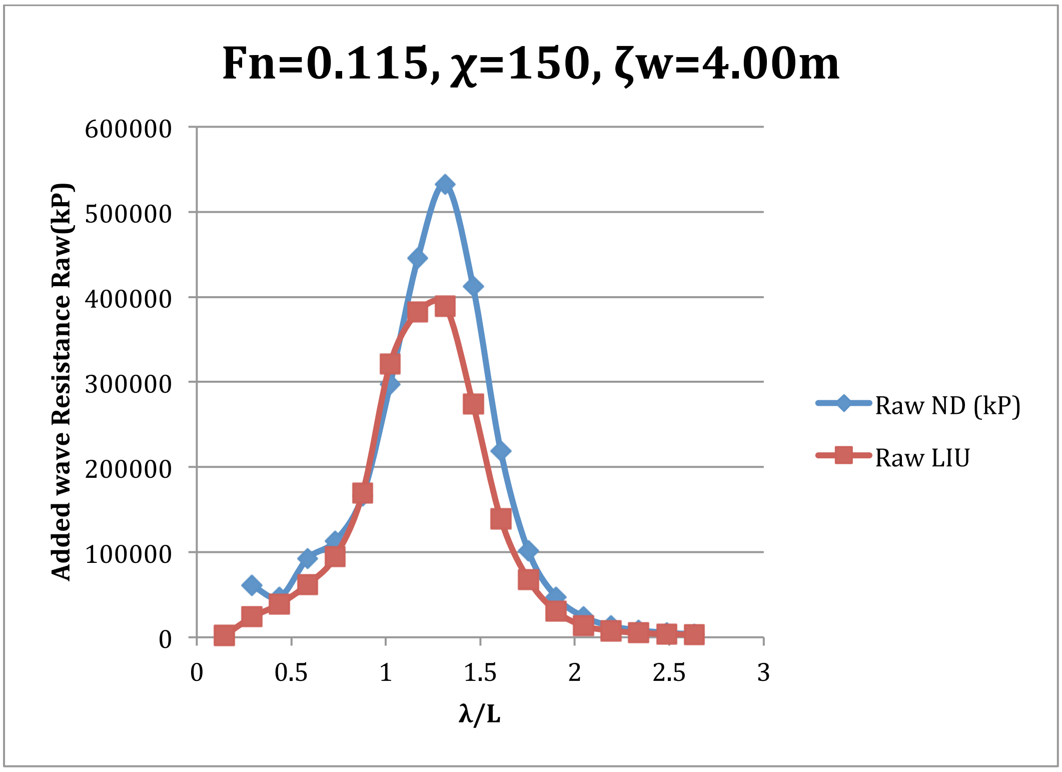


Figure 51: Added Resistance in Waves, χ=150, ζ=4.00

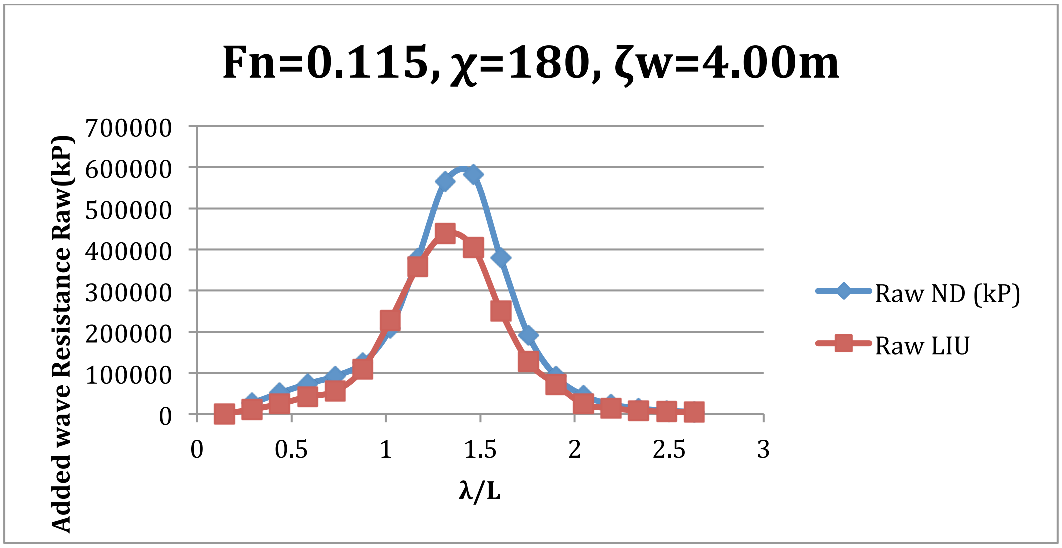


Figure 52: Added Resistance in Waves, χ=180, ζ=4.00

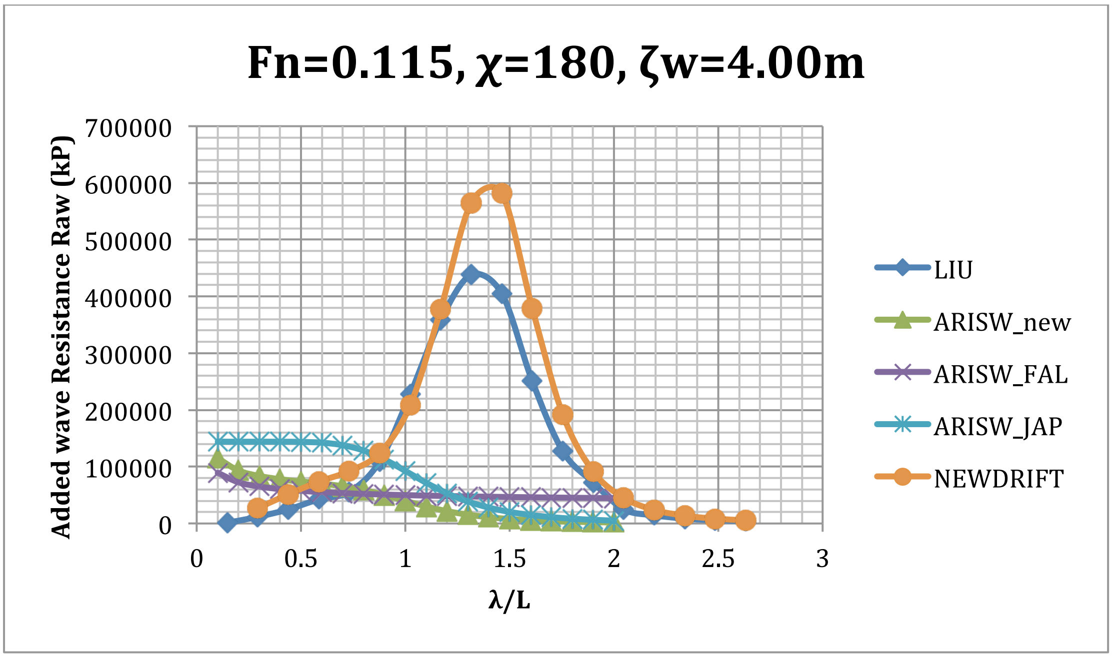


Figure 53: Added Resistance in Waves, χ=180, ζ=4.00 (all methods)

B.3 Added resistance in waves for F_n=0.163 and ζ_w= 1.50m

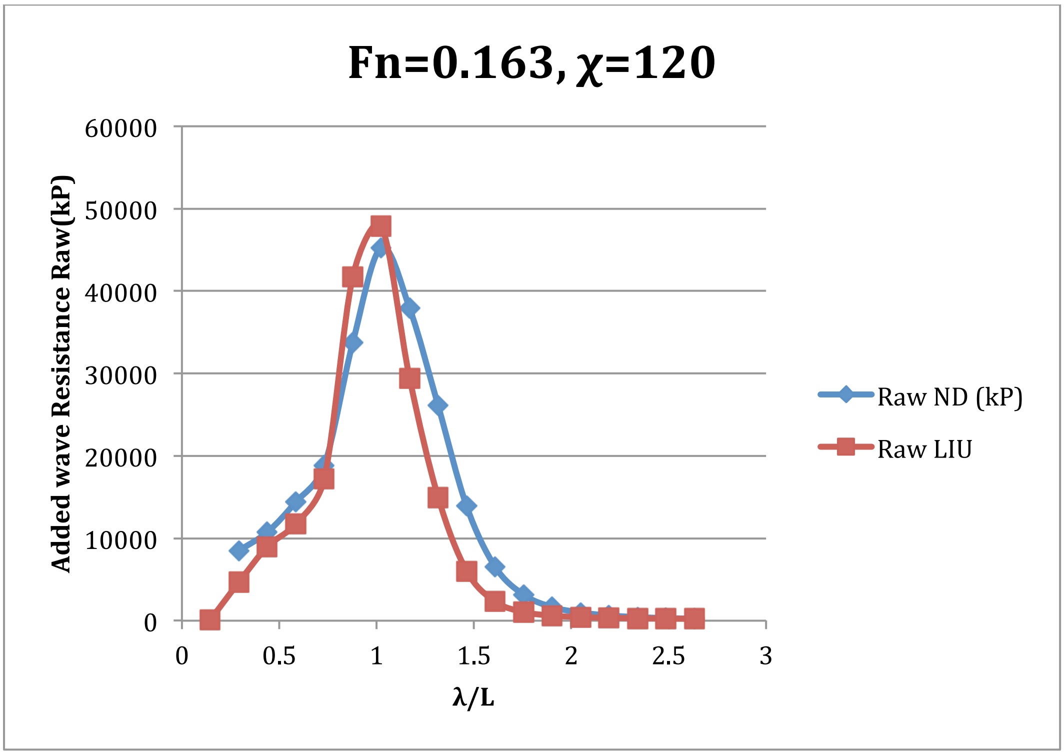


Figure 54: Added Resistance in Waves, Fn=0.163, χ=120, ζ=1.50

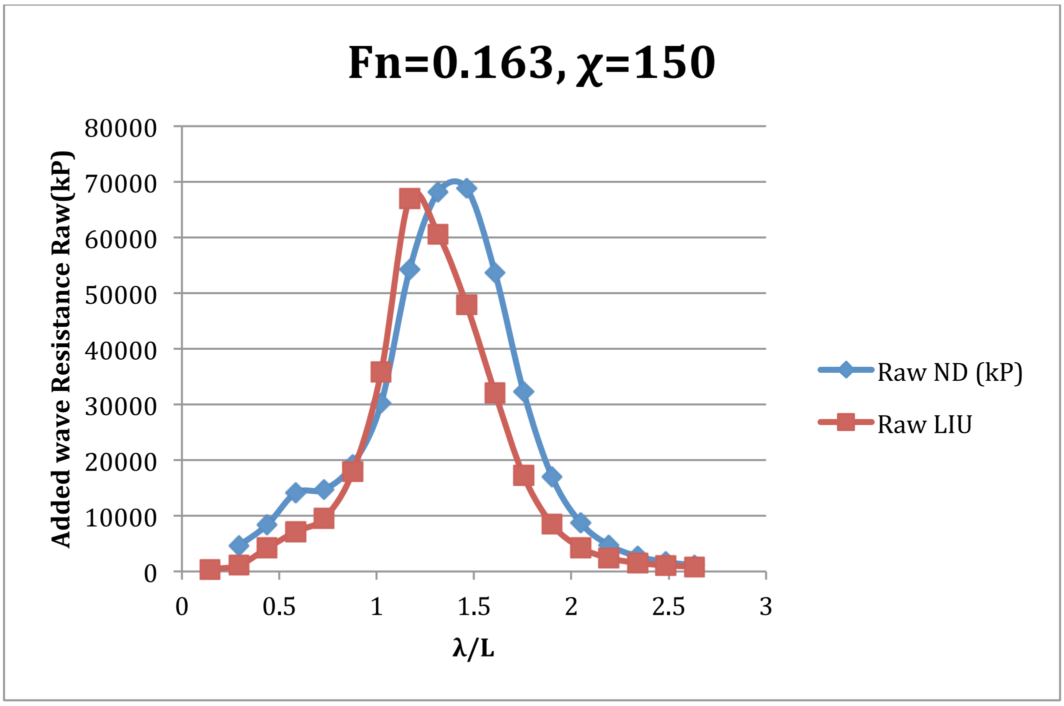


Figure 55: Added Resistance in Waves, Fn=0.163, χ=150, ζ=1.50

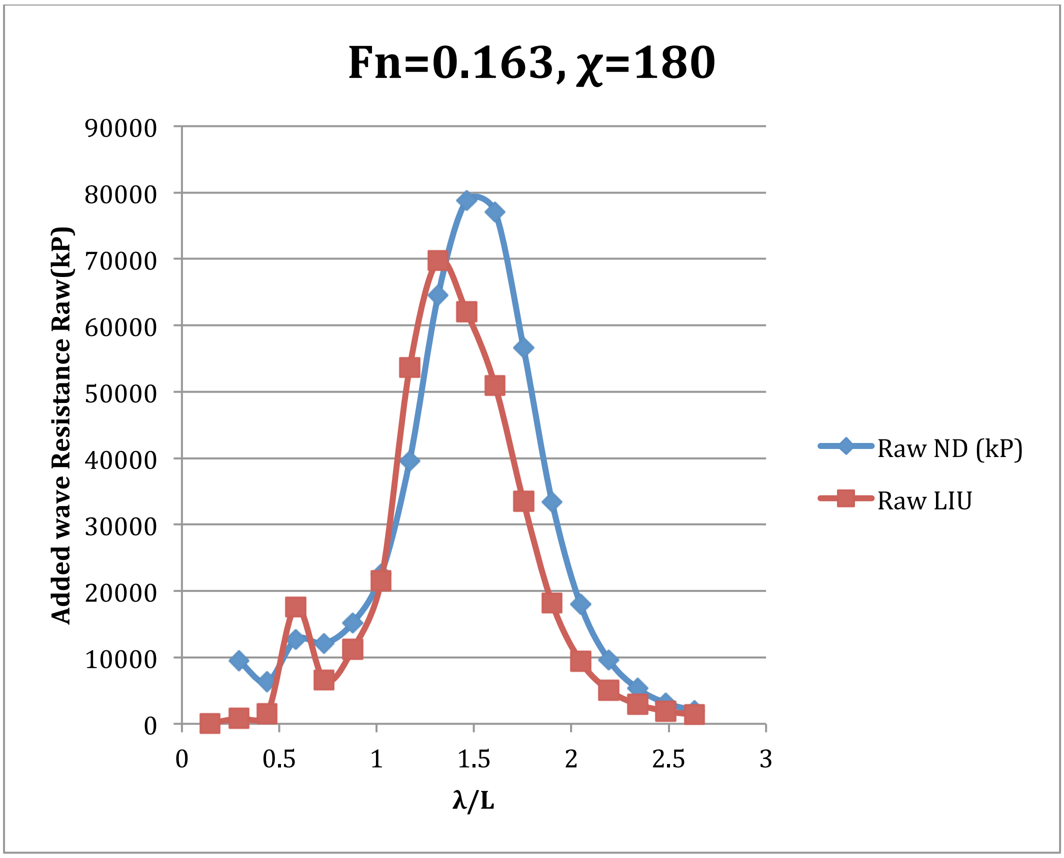


Figure 56: Added Resistance in Waves, Fn=0.163, χ=180, ζ=1.50

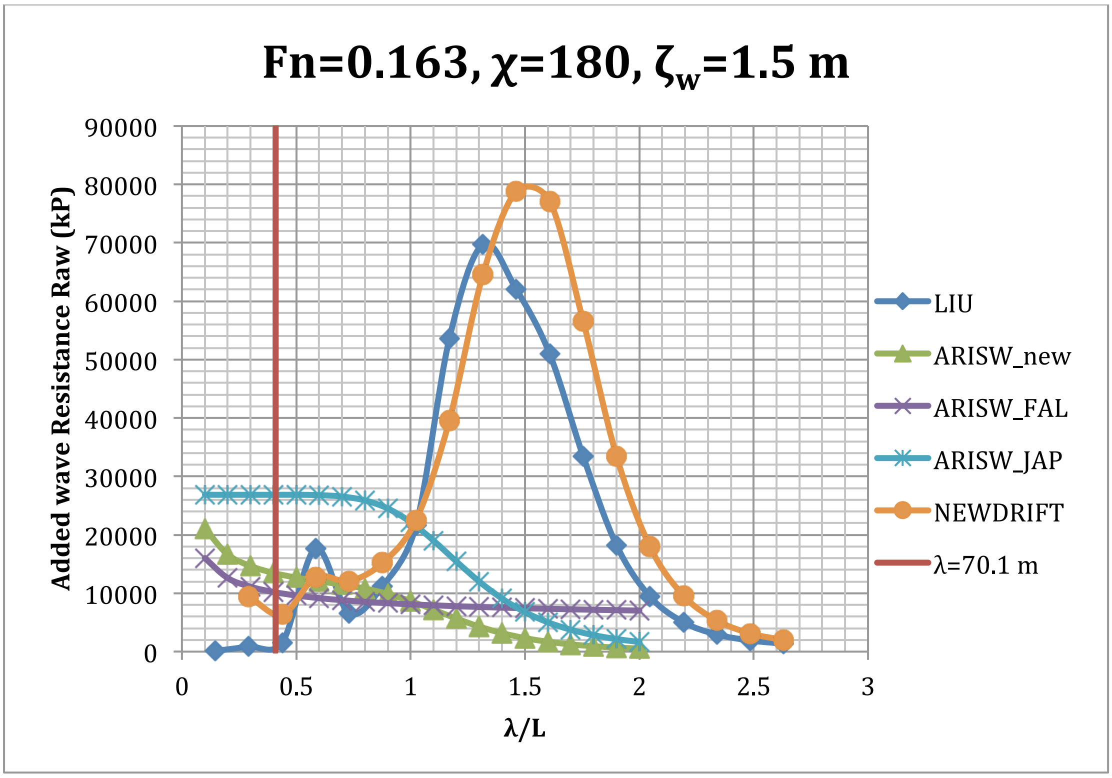


Figure 57: Added Resistance in Waves, Fn=0.163, χ=180, ζ=1.50 (all methods)

B.4 Added resistance in short-waves for ζ_w= 1.50m in range of $0.6V_{reff}$-V_{reff}

Here are presented the results for added resistance in shortwaves from three methods, which were used to determine the value of coefficient f_w for a specific range of speeds, as dictated by IACCS guidelines.

The results are given in non-dimensionlized form from the code in the form of:

$$Cx = Raw \Big/ \frac{\rho \cdot g \cdot \zeta_w^2 \cdot B^2}{L_{bp}}$$

The results of added resistance in the desired speed range are presented in the next figures:

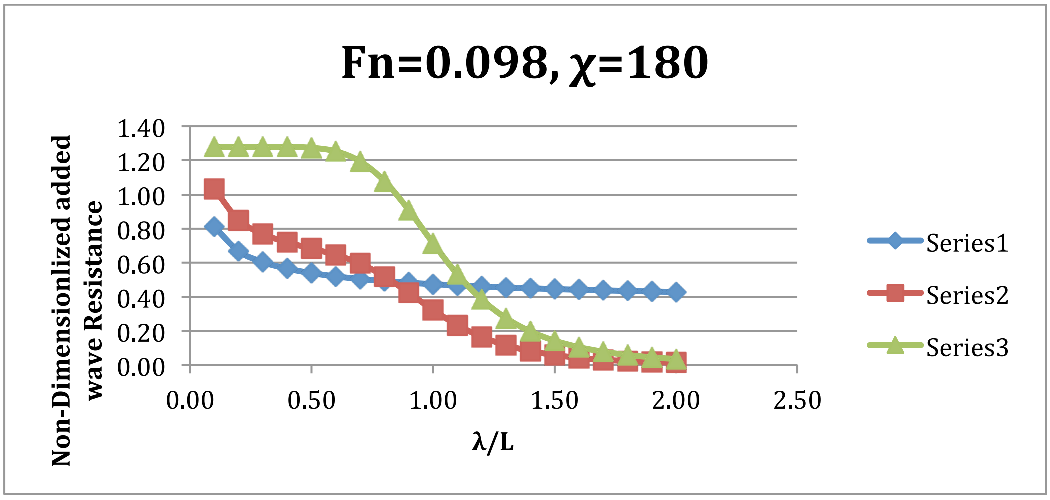


Figure 58: Added Resistance in short-Waves, $V=0.6V_{reff}$, χ=180, ζ=1.50

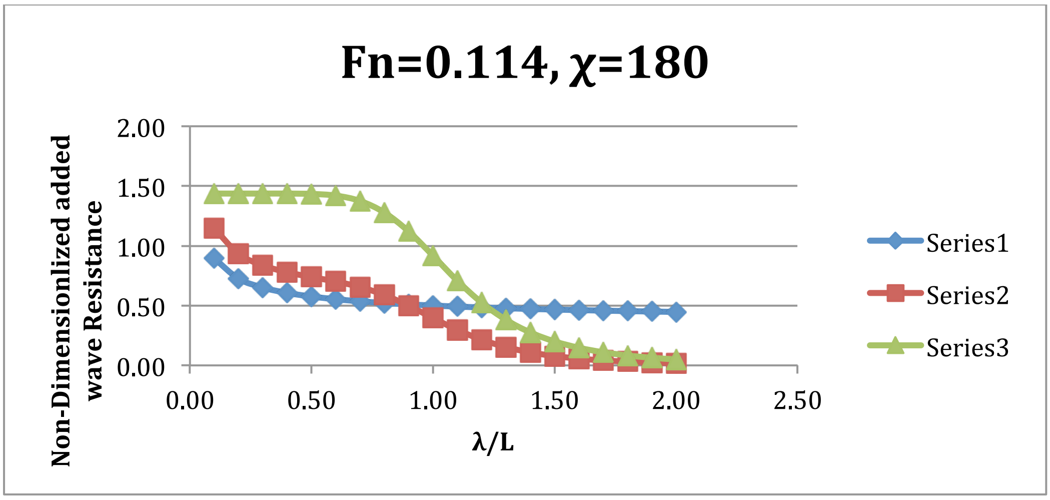


Figure 59: Added Resistance in short-Waves, $V=0.7V_{reff}$, χ=180, ζ=1.50

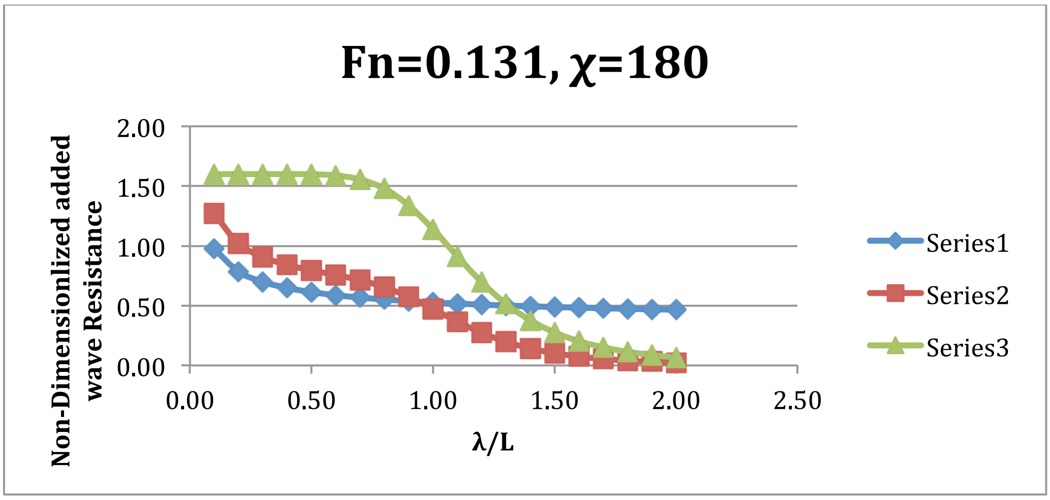


Figure 60: Added Resistance in short-Waves, V=0.8V$_{reff}$, χ=180, ζ=1.50

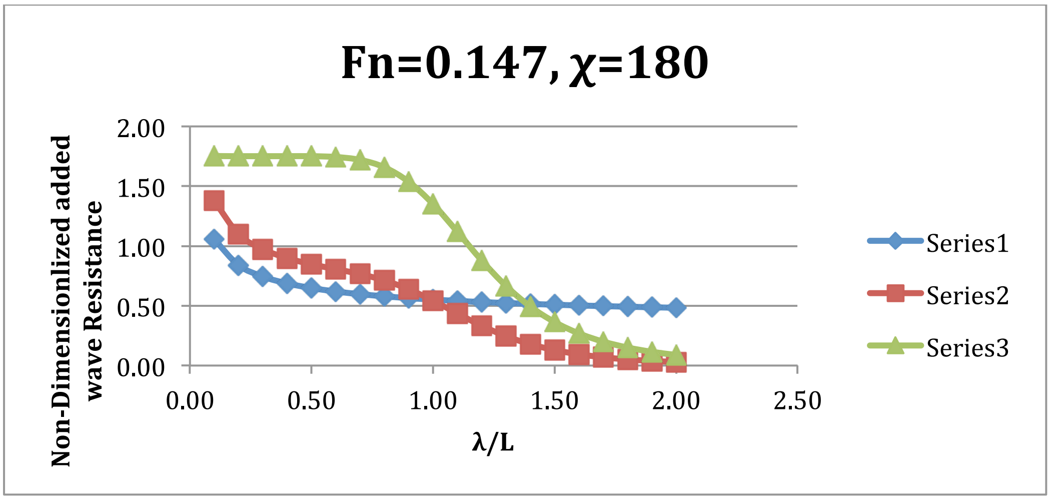


Figure 61: Added Resistance in short-Waves, V=0.9V$_{reff}$, χ=180, ζ=1.50

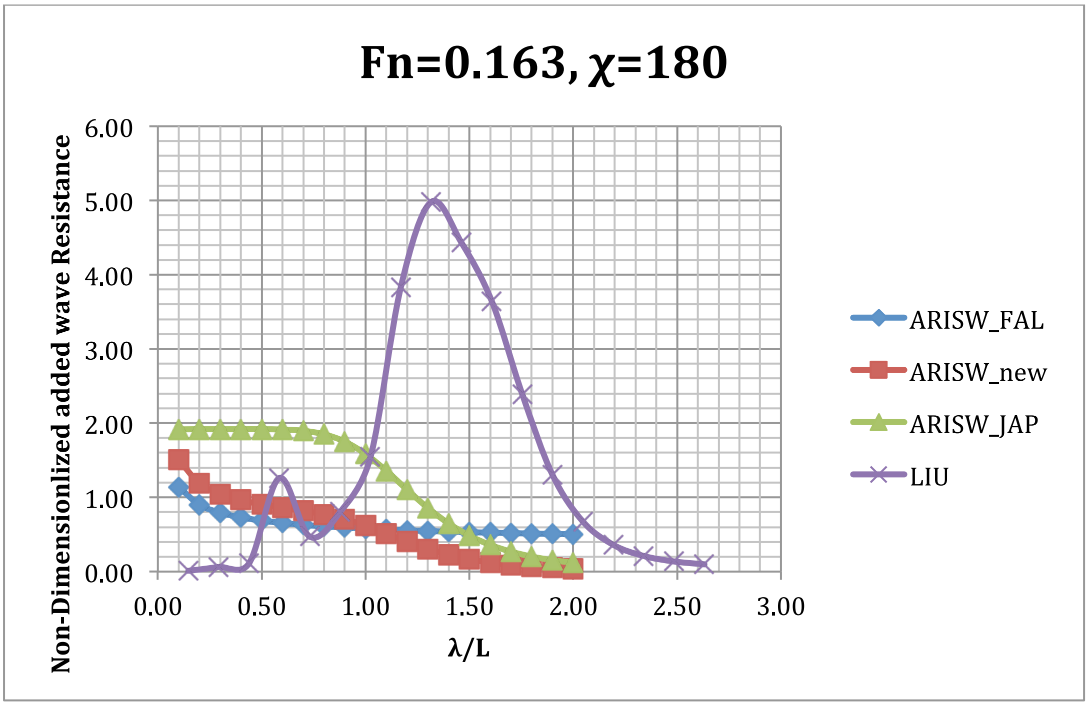


Figure 62: Added Resistance in short-Waves, V=V$_{reff}$, χ=180, ζ=1.50

For incident head waves with wave amplitude ζw=1.50m, peak wave period Ts=6.7s in the range of $0.6V_{reff}$-V_{reff} , the results are presented in the next table.

V (knots)	ARISW_FAL(kP)	ARISW_new(kP)	ARISW_JAP(kP)	Fn
13.00	10217.75	13481.33	26853.45	0.163
11.70	9617.12	12581.08	24515.33	0.147
10.40	9072.49	11771.84	22401.21	0.131
9.10	8485.86	10906.59	20119.09	0.114
7.80	7917.43	10073.54	17906.97	0.098

Table 36: Result for added resistance in waves from short-wave methods

Next, a graphical representation of these values is presented as a function of the ship's speed in their non-dimensionlized form:

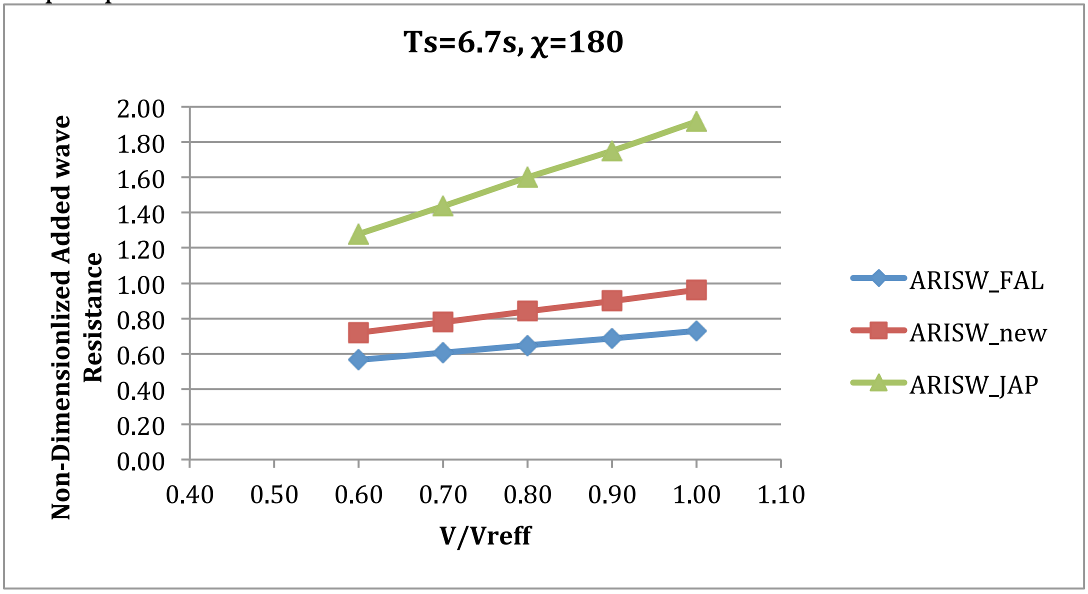


Figure 63: Added Resistance in short-waves in speed range $0.6V_{reff}$-V_{reff}

C. Propeller open water characteristics

For each vessel the simplified method was applied, in order to check that the available thrust produced by the engine is sufficient, the advance coefficient J needed to be calculated. Using the following equation, proposed in Interim Guidelines, the $K_T(J) = C \cdot J^2$ curve was produced which was then matched with the propeller open water characteristics.

$$T = \frac{u_a^2 \cdot D_p^2 \cdot \rho \cdot K_T(J)}{J^2}$$

$$\frac{K_T(J)}{J^2} = \frac{T}{u_a^2 \cdot D_p^2 \cdot \rho} = ct.$$

After finding the cross section point between the $K_T(J) = C \cdot J^2$ and the $K_T(J)$ - J curve of the propeller, as shown in the next figures, we were able to graphically determine the respective torque and advance coefficients, namely K_Q and J.

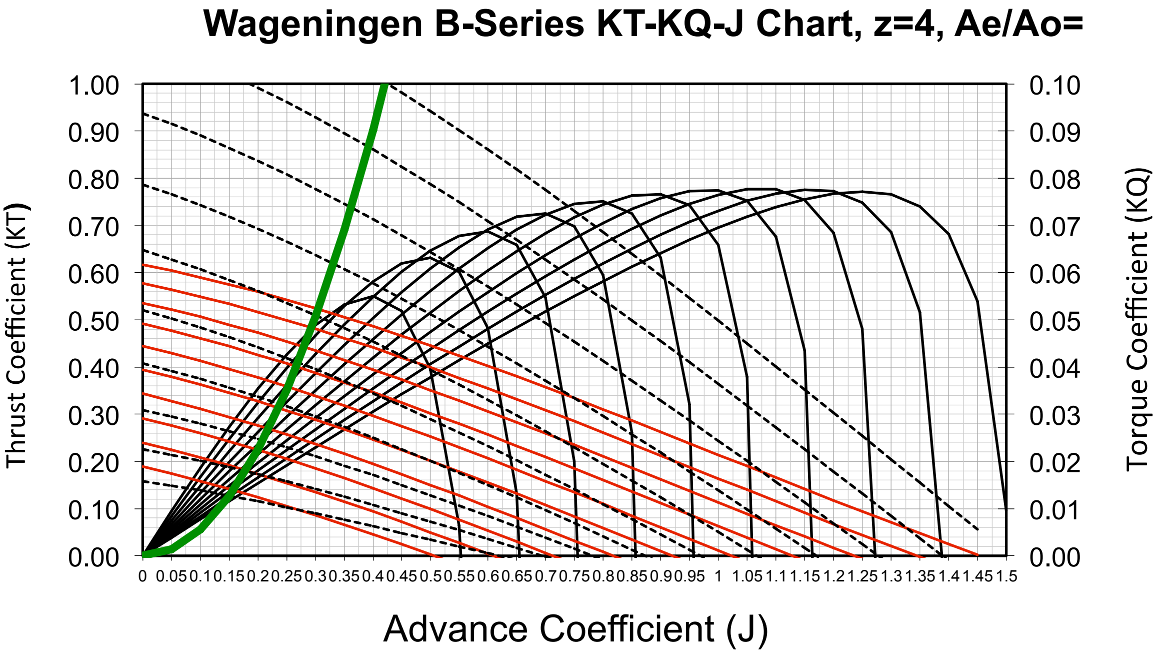


Figure 64: K_T-J curve for TEST_SHIP, ζw=2.00 m

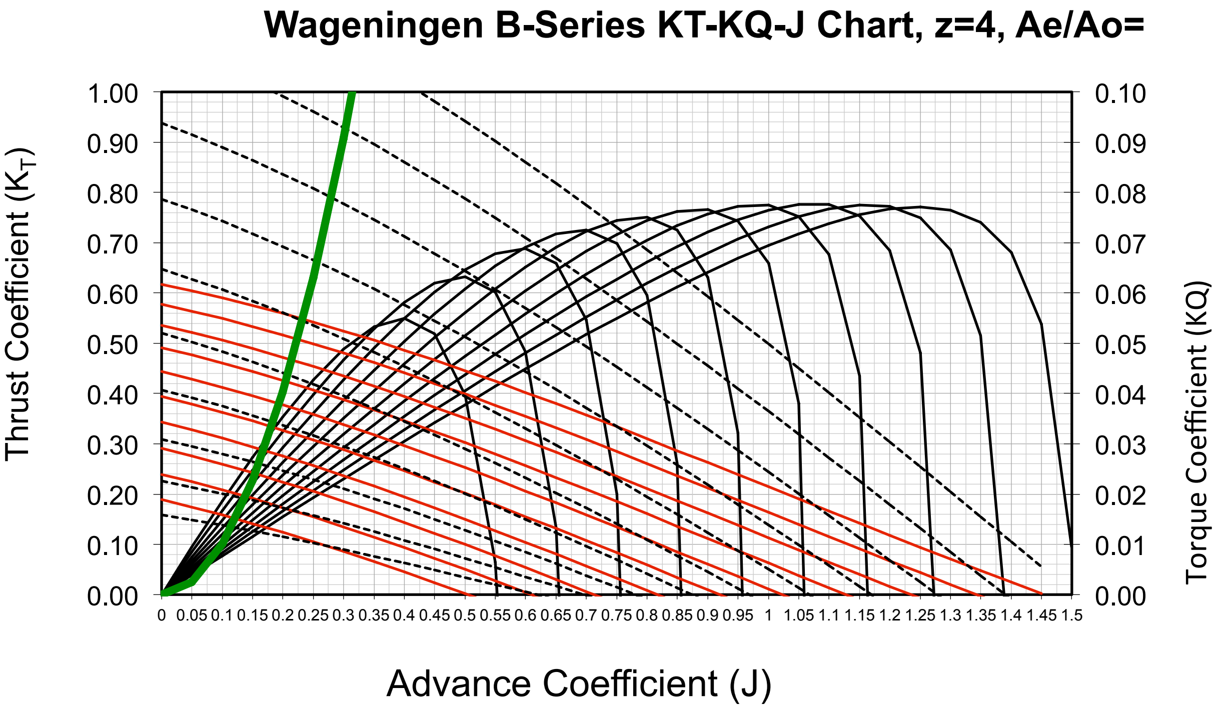


Figure 65: K_T-J curve for TEST_SHIP, ζw=2.75 m

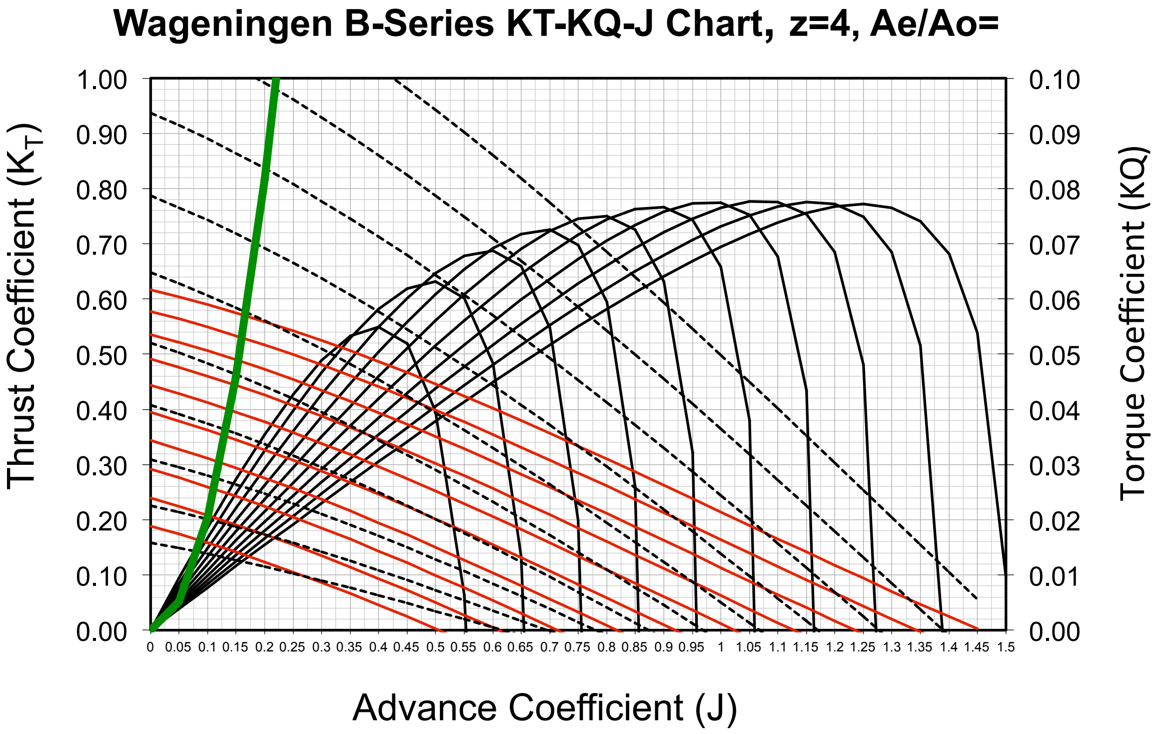


Figure 66: K_T-J curve for TEST_SHIP, ζw=4.00 m

For each case examined, the data gathered and used in the application of the Simplified Assessment is presented in the next table.

Vessel	Case	J	K_T	K_Q
TEST_SHIP	ζ_w=2.00m	0.224	0.279	0.036

	ζ_w=2.75m	0.169	0.29	0.034
	ζ_w=4.00m	0.124	0.31	0.036

The results concerning the other three ships are presented next:

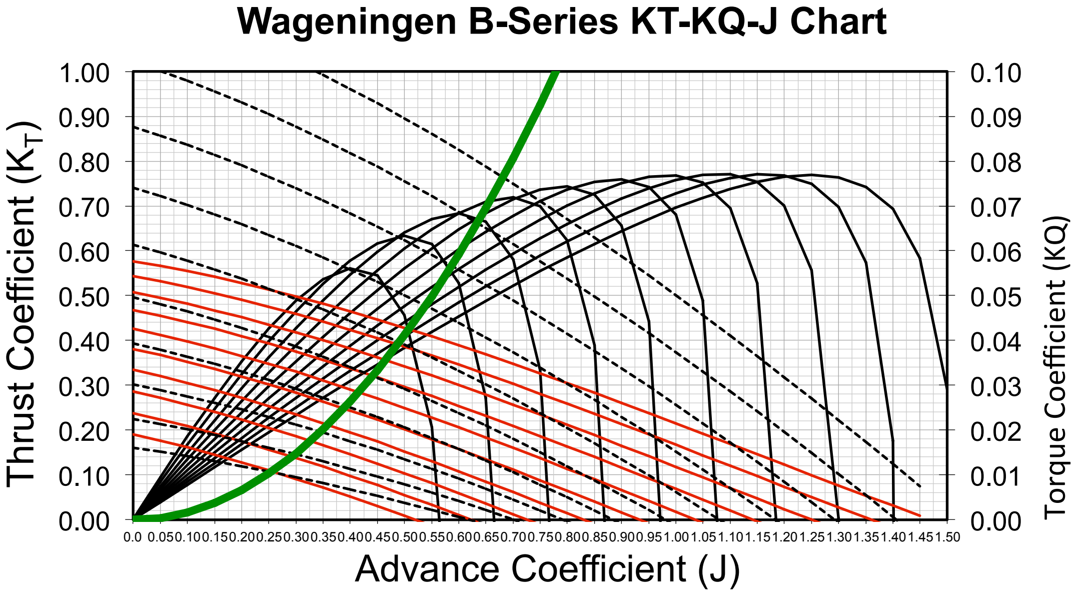


Figure 67: K_T-J curve for SHIP_1, ζw=2.00 m

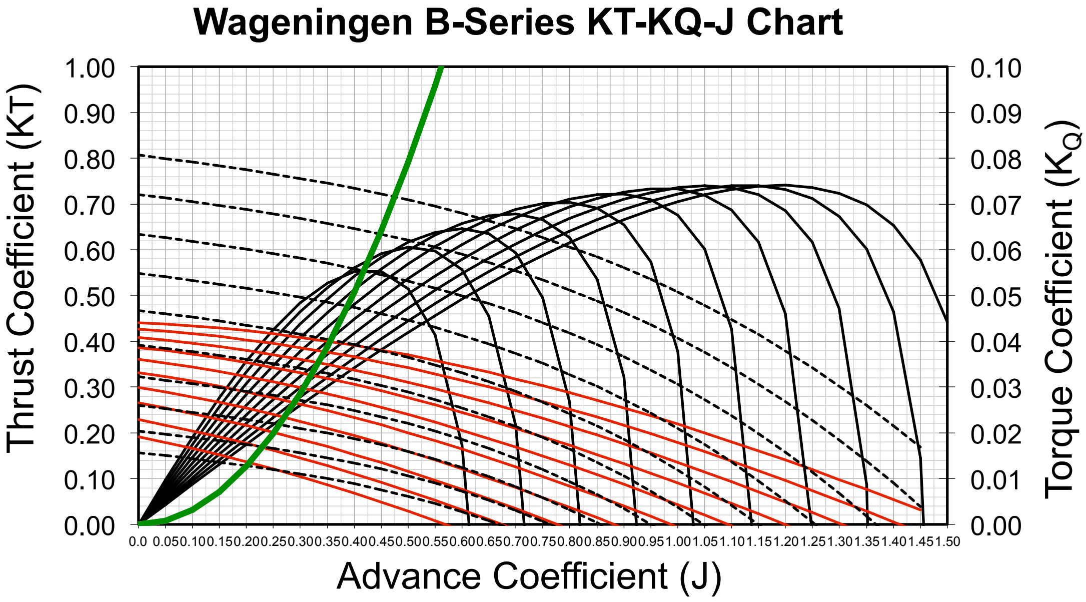


Figure 68: K_T-J curve for SHIP_2, ζw=2.54 m

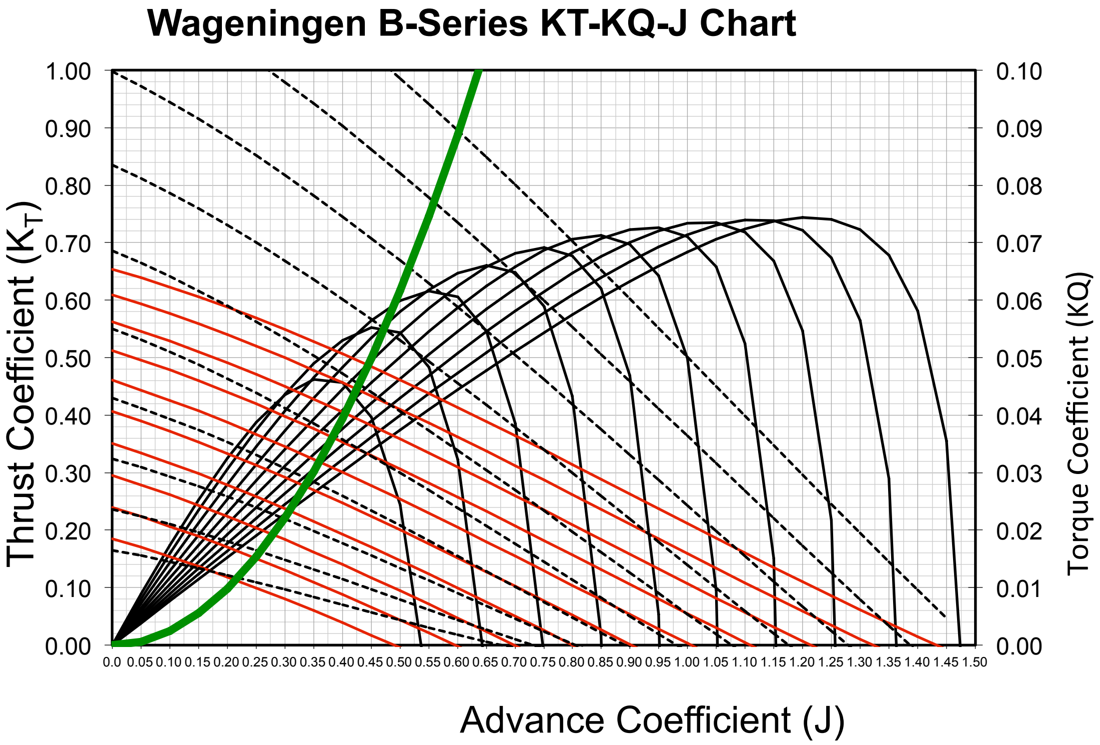


Figure 69: K_T-J curve for SHIP_3, ζw=2.75 m

Vessel	Case	J	K_T	K_Q
SHIP_1	ζ_w=2.00m	0.370	0.220	0.028
SHIP_2	ζ_w=2.75m	0.270	0.240	0.024
SHIP_3	ζ_w=4.00m	0.320	0.031	0.240

Table 37: Propeller open water characteristics for Simplified method

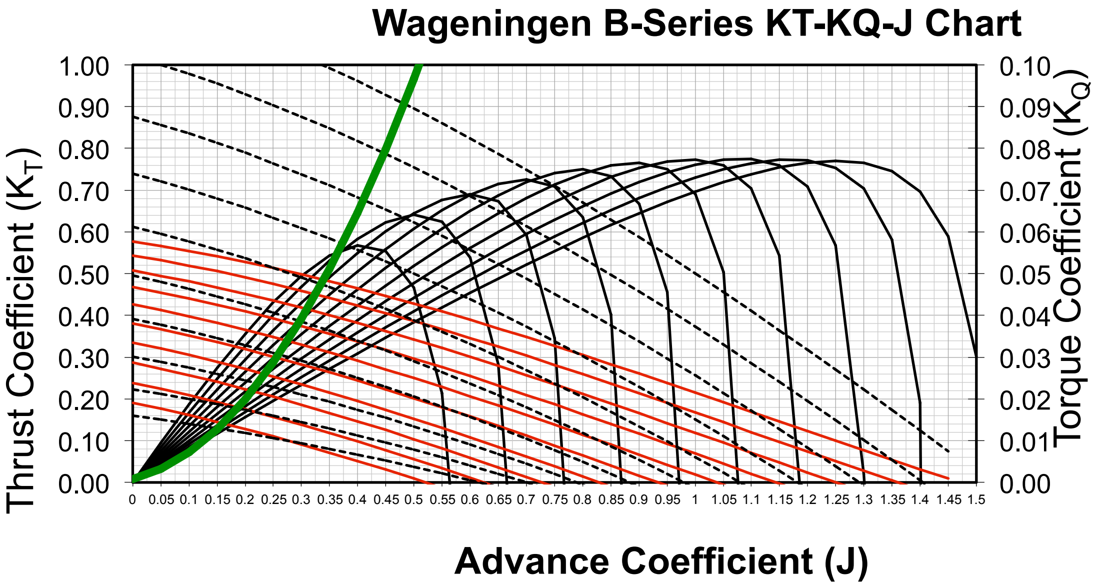


Figure 70: K_T-J curve for SHIP_1, ζw=24.00 m

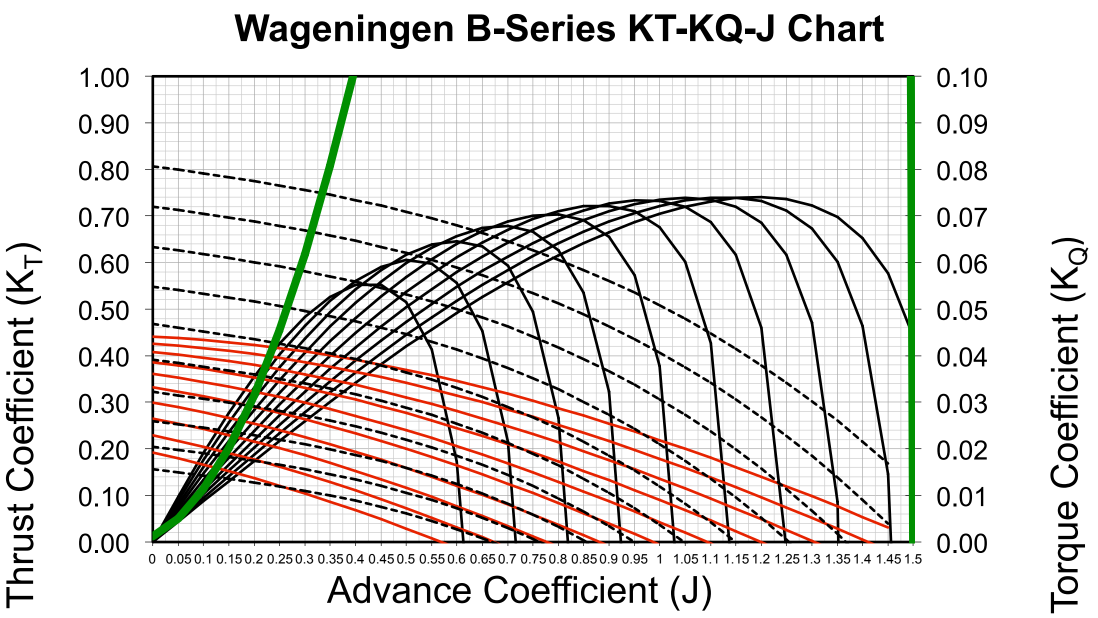


Figure 71: K_T-J curve for SHIP_2, ζw=4.00 m

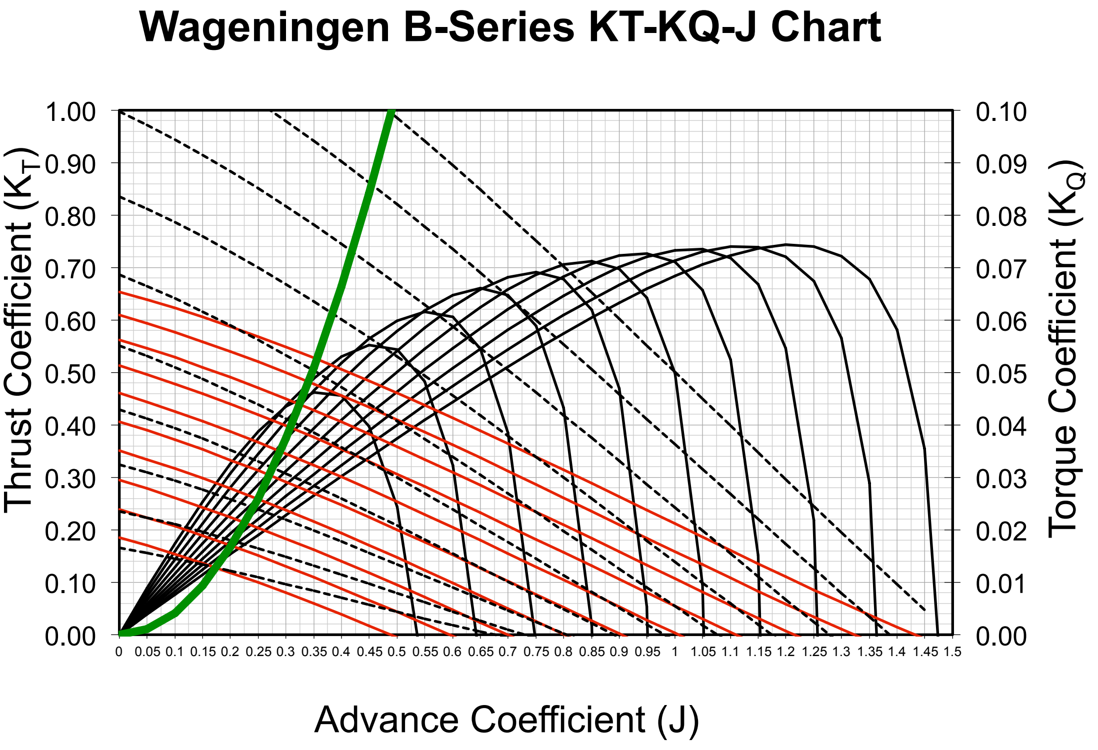


Figure 72: K_T-J curve for SHIP_3, ζw=4.00 m

Vessel	Case	J	K_T	K_Q
SHIP_1	ζ_w=4.00m	0.24	0.23	0.031
SHIP_2		0.18	0.26	0.028
SHIP_3		0.26	0.038	0.26

Table 38: Propeller open water characteristics for ISC 2008 case

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