Energy Efficiency Design Index (EEDI) Impact on Superyacht Design.

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December 2012

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ABSTRACT

Global environmental agencies and maritime authorities have become increasingly concerned by the environmental impact of CO_2 emission. Increasing fleets of super yachts consume ever larger quantities of fossil fuel. Increasing social pressure and new legislative efforts to reduce environmental damage mean that the industry must respond accordingly.

Current yacht design legislation has a focus on occupational safety and the environment. However the legislation surrounding environmental protection has been increasing significantly. Environmental legislation addresses both the protection of the environment in the event of an accident and also on reducing the operational environmental impact.

EEDI or Energy Efficiency Design Index is a new standard, that was set by the IMO (the International Maritime Organization) for new ships greater than 400 GT with some exceptions that can be allowed by Administrative bodies until 2017 (regulation 19.4). The purpose behind the EEDI is to promote innovation from the initial ship design stage in order to reduce energy consumption at full load. It is applicable to many vessels: bulk carriers, tankers, container ships, general cargo ships, passenger ships, gas carriers, gen eral cargo and RO-RO vessels. Working class vessels such as offshore supply vessels, tugboats and dredgers are excluded for the present time.

There are no conformations until this point in time whether EEDI will be implemented on yachts. Azimut-Benetti is taking an early initiative to investigate any possibilities for improvement. In such event this could become a driver for sales. As the EEDI is measurable figure, this could become a way for comparing shipyards, hence increasing competition on this field. At the conclusion of this research, Azimut-Benetti Yachts will be presented with guidelines that will assist in calculating the EEDI and selecting the most efficient technologies that optimise both cost and efficiency. Azimut-Benetti has a keen interest in the cost and potential savings over time from implementing the EEDI compared to existing technologies and offer to owner’s efficient yachts.

Keywords: Energy Efficiency Design Index (EEDI), IMO, MEPC, Greenhouse Gas, MARPOL, Reference EEDI, Attained EEDI, United Nations Framework Convention on Climate Change, GHG.

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1.0 INTRODUCTION

Global shipping is considered one of the most efficient-low carbon modes of transportation. That being said, the amount of carbon dioxide emissions from shipping can be greater than 3% of the global green house gas (GHG) emission. Mid-range emissions scenarios show that by the year 2050, in the absence of policies, ship emissions could grow by more than 200% to 300% as a result of the growth in world trade[1]. This figure is based on shipping data showing that some 1118 million tonnes of carbon dioxide have been emitted since 1960 to the atmosphere[2]. This figure was presented by the IMO for various types of vessels as specified in the appendix of this thesis. It is noted that yachts occupy approximately 2.9 million tons of CO2 which is greater than "Other tanker group" by approximately 584 thousand tons of CO2 (IMO MEPC 60). This figure is distributed over a large range of yachts, half of which fall below the 400 GT[3].

The International Maritime organisation (IMO) has introduced the Energy Efficiency Design Index (EEDI) to limit the CO2 emission from shipping. The EEDI is primarily applicable to new ships from 2013 and after with certain requirements as described in the literature review section.

The EEDI is not fully enforced yet, so only time can tell whether or not it will be applicable to yachts. The author will investigate the possibilities of utilising the EEDI as a driving force to bring new technology, sustainability and innovation to the yachting industry. As part of this research supported by Azimut-Benetti yachts, they are taking an early initiative to investigate any possibilities of using the EEDI to add more improvements to their yachts for commercial and sustainability reasons. Since the EEDI is a measurable figure, shipyards and yachts can become more comparable in the future.

In this report the author focuses on statistical analysis of various yachts by calculating the Energy Efficiency Design Index (EEDI). This is followed by comparing different parameters that influences the EEDI value and may result in some energy saving.

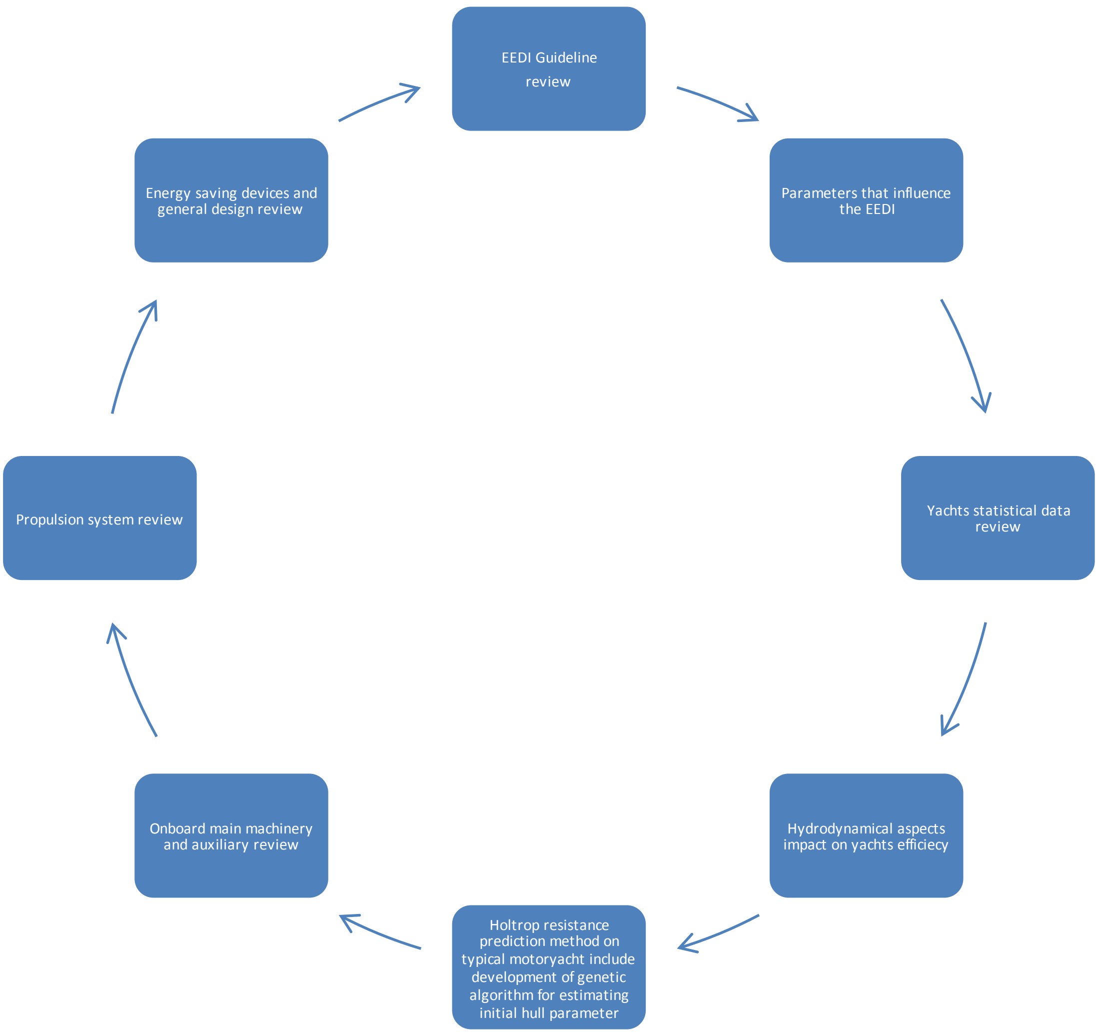
[1] IMO: Second Greenhouse Study published in 2009
[2] MEPC 60/WP 5
[3] IHSF DataBase

2.0 RESEARCH METHODOLOGY:

A short summary of the main investigated areas during this research can be presented as below:

1) An overview of the EEDI: Values of the EEDI were calculated for different yachts, this was followed by a comprehensive assessment of the different parameters that influenced the EEDI such as vessel's capacity (gross and net tonnage).
2) Resistance effect on the EEDI: various yachts were compared with respect to the Cb, Cp and L/B parameters. Statistical data were compared based on Azimut-Benetti's own yachts and various other yachts taken from various resources. The Holtrop and Mennen method was also utilized in conjunction with genetic algorithm to evaluate the best possible parameters to produce lower resistance values.
3) Propulsion arrangements: As part of searching for ways to improvement the efficiency, a small comparison was carried out for several propulsion arrangements. System such as Azimuthing pods, Mewis duct, CPP vs fixed pitch propeller and counter rotating propellers were compared.
4) Windows, Doors and Hatches (double vs laminated glazing) as well as various insulations effects on the EEDI.
5) Main Machinery: Comparing various main engines, main engine arrangements, and generators to see whether any efficiency can be improved.
    a. Main Engines: Traditional vs. Diesel-electric propulsion systems and hybrid propulsion.
    b. Auxiliary Machinery.
    c. Electrical power generators: Various electrical generators were briefly compared. Their overall performance was evaluated as well as their suitability to Benettti's yachts.
    d. Side propulsion system (thrusters):
    e. Stabilizers
        i. Fins (Active vs. passive)
        ii. Flume system
6) HVAC system

a. Accommodation air-conditioning and ventilation systems:
    i. Air conditioning System General Design review.
    ii. Electrical fan coils
    iii. Main Chillers unit
    iv. Heat-pump principal
    v. Diesel boiler principals
b. Cold Rooms and Refrigerated spaces
c. Engine room and Technical spaces ventilation system
    i. Engine room fans (in ventilation)
    ii. Engine room out (Out ventilation system)



3.0 EEDI GUIDELINES:

The Marine Environment Protection committee or MEPC resolution for controlling the CO_2 emission dates back to 1997. Historically the EEDI was proposed by DNV to the IMO at the MEPC57 in 2007[4], by using historical data from the existing world fleet as a benchmark system. The EEDI development timeline can be presented in the below diagram:

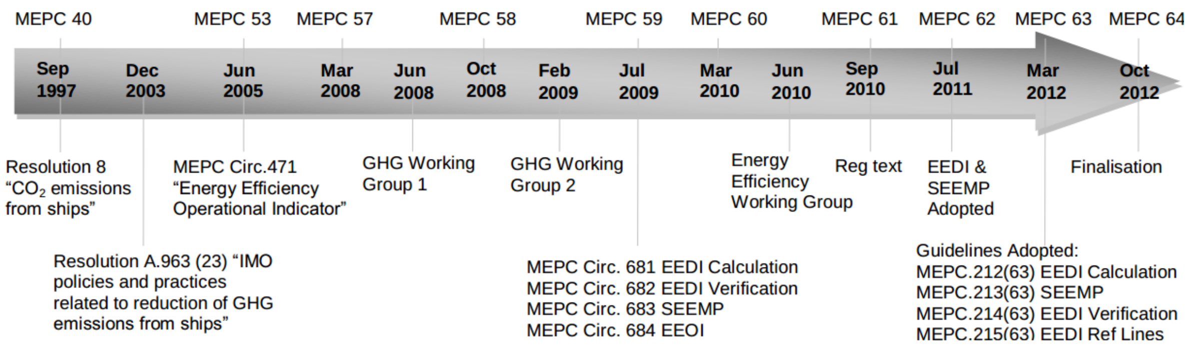


Figure 1: IMO timeline.

IMO timeline taken from the Lloyd's register publications: Implementing the Energy Efficiency Design Index 'EEDI'-Guide for ship owners, operators and shipyards.

Whether the yachting industry will suffer from EEDI implementation is a question which has to be investigated. Generally speaking yachts designers, builders, owners and operators are proactive in implementing improvements to have better and environmentally friendly yachts. The hope remains that implementing the EEDI will accelerate the environmental innovation in the industry without penalty.

So what are the practicalities behind the EEDI measures? The IMO regulation states that the EEDI is the ratio of the environmental impact of Shipping versus the benefit enjoyed by the community from Shipping as shown in the equation below:

[4] Calculating and Comparing CO2 Emissions from the Global Maritime Fleet by Rightship Pty Ltd.

$$EEDI = \frac{Environmental\ Impact}{Benefit\ to\ society\ (transportation\ work)}$$

(1)

The Environmental Impact was calculated using various statistical relations and coefficients where the final (or semi-final equation) of the EEDI is:

$$\begin{aligned} &Environmental\ impact\ of\ a\ vessel = \\ &CO_2\ emission\ in\ grams\ from\ propulsion \\ &+CO_2\ emission\ in\ grams\ from\ auxiliary \\ &-CO2\ emission\ reduction\ due\ to\ technologies. \end{aligned}$$

(2)

Since the EEDI is only a design index, the above expression can be rewriting more formally as:

$$\begin{aligned} &Environmental\ impact\ of\ a\ vessel = \\ &Installed\ Power \\ &\times Specific\ Fuel\ consumption\ (SFC) \\ &\times CO_2 Emmision\ conversion\ factor \end{aligned}$$

(3)

The lower denominator part of the EEDI equation is directly concerned with the benefits from this particular vessel to the society by means of transportation work. This part was again semi-presented mathematically with the following:

$$Benefits\ (of\ performed\ work) =$$

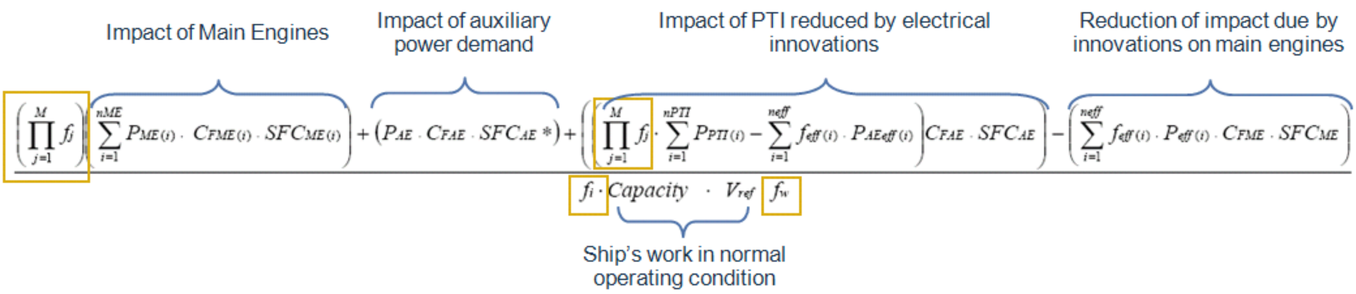
$$Capacity\ (GT\ or\ DWT\ or\ other\ form\ of\ benefits)$$

$$\times\ Ship\ speed$$

(4)

Yachts are intended for pleasure purpose, they carry very few passengers and their operational requirements have hardly any profile. Therefore, it is harder to pinpoint any direct benefit or performed work compared to ordinary merchant vessels. As results it is widely believed that any future enforcement the EEDI regulation may risks penalizing the yachting industry since their cargo and passenger's carrying capacity per nautical mile is very low. Nevertheless, using an index based measure can promote innovation and healthy market competition.

The final version of the EEDI equation is provided by the IMO MEPC 62/WP. 15, ANNEX 1, page 2.



$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}*\right) + \left(\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}{f_i \cdot Capacity \cdot V_{ref} \cdot f_w}$$

(5)

The above formula is used for the calculation of the attained EEDI (attained EEDI is the EEDI of a specific vessel). Results from this formula than later will be compared to the statistical baseline (required EEDI) as provided by the IMO and explained later in this section.

As can be seen above, there are various correction factors, constants and coefficients in the above EEDI equation. Some of these coefficients will directly impact and they are also applicable to yachts, they will be discussed with a short summary as shown below:

$$Main\ engine(s)CO_2\ emissions = \left(\sum_{j=1}^{M} fj\right)\left(\sum_{i=1}^{n_{ME}} P_{ME\,(i)}.\,C_{FME\,(i)}.SFC_{ME\,(i)}\right) \tag{6}$$

And

$$Auxiliar\ engine(s)CO_2\ emissions =$$

$$\left(P_{AE\,(i)}.\,C_{FAE\,(i)}.SFC_{AE\,(i)}\right)$$

$$+\left(\left(\prod_{j-1}^{M} f_j \times \sum_{i-1}^{n_{PTI}} P_{PTI\,(i)} - \sum f_{eff\,(i)} \times P_{AEeff\ \ (i)}\right)C_{FAE} \times SFC_{AE}\right) \tag{7}$$

f_j : Is the correction factor to account for ship specific design elements. In case of yachts, there were no direct specifications. Instead the IMO guideline advises to use 1. Normally this correction factor is very crucial as it takes account the ration of the L_{BP} and installed power (MCR). This of course will allow for correction (reduction) of the weighting average of the installed power, hence the value will be less than 1.

P_{ME} : Main engine power (kW) where the $P_{ME(i)}$ is 75% of the entire rated installed power (MCR) after deduction of any shaft generators of course. Explanation on the deduction factor can be found from the bellow figure which was taken from the IMO 681 circular page 3:

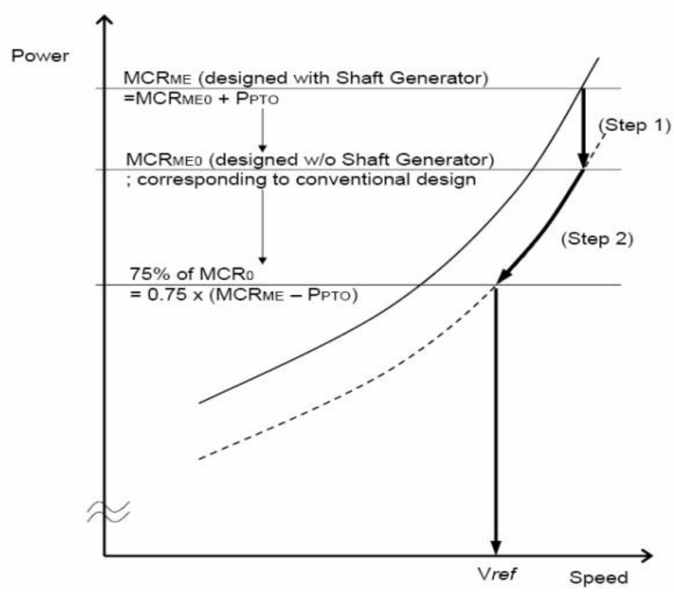


Figure 2: powers take on/off

The following relation is given by the IMO to determine the $P_{ME(i)}$

$$P_{ME\,(i)} = 0.75 \times (MCR_{MEi} - P_{PTOi}) \tag{8}$$

In the case of Azimut-Benetti yachts and many yachts on the database, there are no shaft generators or power take out/power take in. As results MCR for the main engine was accounted as 75% of the total installed power.

P_{AE} : auxiliary engine power measured in (kW). This should corresponds and corrected according to the maximum hotel load + power needed to supply all machinery on board with exclusion of any power required for propulsion such as thrusters, pumps and fans for engine room at the reference speed V_{ref}(more details are available in the IMO EEDI guidelines).

There are simplified formulas provided by the IMO which can be used unless the installed power is significantly different from those as shown below:

$$If \quad \sum MCR_{ME\,(i)} > 10000\ kw, \ \ P_{AE} = 0.025 \times \ (MCR_{ME} + 250) \tag{9}$$

&

$$If \quad \sum MCR_{ME(i)} < 10000\ kw, \quad P_{AE} = 0.05 \times MCR_{ME} \tag{10}$$

SFC: Specific fuel consumption (g/kWh). This certification was provided by the engine manufacturers, further details also available on the IMO circular.

C_f: is a non-dimensional fuel conversion factor where for each unit mass of fuel there is a product of CO_2 associated. Example such as CO_2 factor (g Co_2/g Fuel) with factor of nearly 3, determined for approved NO_x technical file (at 75% MCR for main engine(s), 50% MCR for auxiliary engines), reference from BUREAU VERITAS EEDI circular. In the case of yachts, ordinarily marine diesel and gas oil are used, as results carbon content equal to 87.44% and Cf measure in t-CO_2/t-Fuel equals to 3.206 (according to IMO MEPC EEDI circular and ISO 8217).

Typical values of C_f are given in the bellow table which was taken as an example from the same IMO document:

Table 1:IMO fuel conversion guideline.

Type of fuel	**Reference**	**Carbon content**	C_F **(t-CO2/t-Fuel)**
Diesel/Gas Oil	ISO 8217 Grades DMX through DMC	0.875	3.206
Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.86	3.15104
Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.85	3.1144
Liquefied Petroleum Gas (LPG)	Propane Butane	0.819 0.827	3.0 3.03
Liquefied Natural Gas (LNG)		0.75	2.75

However, if different fuel will be used such as biodiesel the below formula can be used to calculate the C_F:

$$C_F = \frac{\sum_{i=1}^{n_{AE}} C_{FAE(i)} \cdot MCR_{AE(i)}}{\sum_{i=1}^{n_{AE}} MCR_{AE(i)}} \tag{11}$$

The last term in the numerator is the innovative technologies. The equation was also given in the IMO circular as shown below:

$$\overbrace{\left(\sum_{i=1}^{n_{eff}} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}^{\text{CO}_2\text{ emission reduction due to Innovative technology(s)}}$$

Equation (12)

This part is partially ignored for the moment (assumed equal to zero) as there are not many innovative technologies installed on the yachts the rotor ship, or Flettner ship.

Now for the bottom part of the equation where the capacity and speed are used to determine the transportation work as shown below:

$$\frac{1}{\underbrace{f_i \cdot Capacity \cdot v_{ref} \cdot f_w}_{\text{Transport work}}}$$

Equation (13)

Capacity: this can be summarised as below (reference IMO circular MEPC 62, ANNEX 1 page 3):

- For passenger ships, Ro-Ro ships with passengers, gross tonnage is used which is in accordance with the international tonnage convention.
- For dry cargo ships, tankers, LNG's, general cargo vessels and Ro-Ro vessels the deadweight is used.
- Containers are similar to the above with exception of capacity used as 65% of the total deadweight.
- For yachts capacity was taken as gross tonnage similar to passenger ships approach.

V_{ref} : According to the sea trial ISO the vessel's reference speed and it is measured in Nautical miles per hour (knot), this type of trials (speeds) are normally conducted in deep water with maximum design loading capacity (as discussed above) which in mariners term is read by the scantling draught with the corresponding trim, if the vessel already is built then the maximum design load must be taken from the approved stability booklet. Weather condition must be taken into account with no influence of wind and waves present at the time of the trails.
During the construction phase reference speed can be taken from the speed-power curve by means of towing tank experiment, equivalent means of CFD analysis or from a similar vessel.

f_i : correction factor for ship capacity. This coefficient was nicely explained in tables for other ships types; however there are no explanations for smaller capacity vessels such as yachts. As results and for the general purpose this was assumed to be 1 (MEPC 62 paragraph 2.11.3, page 9 of annex 1)

f_w : correction factor for performance in real weather. For the moment there are no clear guidelines for this non-dimensional coefficient and thus it was used as 1. When performing sea trials it is very important to note the reduction in speed due to the encountered waves. If simulations are to be performed for the added resistance due to waves and weather condition then this simulation must be verified by an authorised organisation such as classification society.

By summarising the units of the EEDI formula, it can be noted that efficiency does not mean vessel with low carbon emission but it is a ratio of the carbon emission per actual performed work:

$$EEDI = \frac{KW * \frac{g_{fuel}}{kwh} * \frac{g_{co_2}}{g_{fuel}}}{tonne * knotical \frac{miles}{hour}} = \frac{g_{CO_2}}{tonne * knotical\ miles} \tag{14}$$

From the above it is possible to draw some early observations based on the EEDI formulation that efficient ships are not only evaluated by having a lower resistance value, but are evaluated by complex process taking into account the functionality of the ship as a whole system, as well as specific fuel consumption and transport work.

The intention of this research was to use the above explanations and formulas to calculate the EEDI for as many yachts as possible, then to investigate each coefficient effect separately. However, such analysis was already provided by the IMO for other types of vessels such as tanker and container. It was formulated as a baseline where many ships EEDI was calculated by the IMO. In this research various yachts' EEDI will be calculated and line of best fit will be made accordingly, this will be used as benchmarking system similar to the IMO required EEDI baseline.

Required EEDI: is the maximum value of attained EEDI that is allowed by regulation 21 of Chapter 4 for the specific ship type and size."
Attained EEDI: is the EEDI value achieved by an individual ship in accordance with regulation 20 of Chapter 4.

They are interrelated as follow: Attained EEDI ≤Required EEDI=(1-X/100) x $EEDI_{reference\ line\ value}$. X is the percentage reduction factor as shown in table (3)

$$EEDI_{REFERENCE\ LINE} = a \times b^{-c} \tag{15}$$

Table 2: IMO Reference line guide (not yet available for yachts)

Ship type defined in regulation 2	a	b	c
2.25 Bulk carrier	961.79	DWT of the ship	0.477
2.26 Gas carrier	1120.00	DWT of the ship	0.456
2.27 Tanker	1218.80	DWT of the ship	0.488
2.28 Container ship	174.22	DWT of the ship	0.201
2.29 General cargo ship	107.48	DWT of the ship	0.216
2.30 Refrigerated cargo carrier	227.01	DWT of the ship	0.244
2.31 Combination carrier	1219.00	DWT of the ship	0.488

Percentage reduction factors (X) for $EEDI_{relative}$ to the $EEDI_{reference\ value}$.
The intention of the IMO to reduce this baseline by 10% every 3 years so world shipping will be forced to reduce its carbon emission. Such procedure can be shown as below:

Table 3: percentage reduction factor

Ship Type	Size	Phase 0 1 Jan 2013 – 31 Dec 2014	Phase 1 1 Jan 2015 – 31 Dec 2019	Phase 2 1 Jan 2020 – 31 Dec 2024	Phase 3 1 Jan 2025 and onwards
Bulk Carrier	20,000 DWT and above	0	10	20	30
	10,000 – 20,000 DWT	n/a	0-10*	0-20*	0-30*
Gas tanker	10,000 DWT and above	0	10	20	30
	2,000 – 10,000 DWT	n/a	0-10*	0-20*	0-30*
Tanker	20,000 DWT and above	0	10	20	30
	4,000 – 20,000 DWT	n/a	0-10*	0-20*	0-30*
Container ship	15,000 DWT and above	0	10	20	30
	10,000 – 15,000 DWT	n/a	0-10*	0-20*	0-30*
General Cargo ships	15,000 DWT and above	0	10	15	30
	3,000 – 15,000 DWT	n/a	0-10*	0-15*	0-30*
Refrigerated cargo carrier	5,000 DWT and above	0	10	15	30
	3,000 – 5,000 DWT	n/a	0-10*	0-15*	0-30*
Combination carrier	20,000 DWT and above	0	10	20	30
	4,000 – 20,000 DWT	n/a	0-10*	0-20*	0-30*

The effect of each phase on the EEDI reference is demonstrated in the bellow figure where IMO will have to review phase 2 and 3:

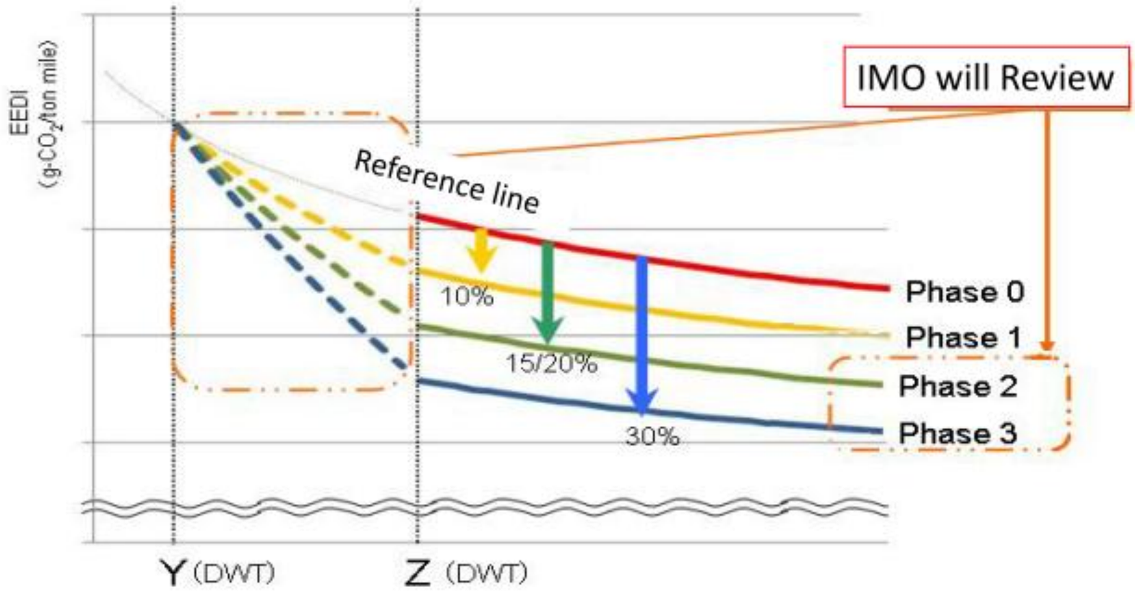


Figure 3: IMO reduction phase

$EEDI_{reference\ line}$ is an average value of EEDI which is obtained for global shipping, this value of the line is derived for each ship type from data in IHSF (Fairplay) which is a global shipping database. This line will be lowered gradually in the future with percentage so that ships have to lower their index.

4.0 VERIFICATION PROCEDURE:

Basically there are 2 ways in which a ship's EEDI can be evaluated, phase one is prior construction (pre-verification) with the vessel still in the design stage. For this stage Holtrop and Mennen methods or appropriate numerical methods can be utilised to calculate the resistance vs speed of a specific yacht. Alternatively towing tank results or various available data in Azimut-Benetti from similar ships can be used to evaluate the initial required power Vs speed.

The second phase is when the constructed ship already undergoes sea trail in accordance to IMO and ISO standards, during this method proposed software (or excel sheet) can be developed to calculate the EEDI. ISO 15016:2002 or similar standard must be used to evaluate the correct performance of the yacht. During the sea trials more than two points (range of which to include 75% MCR) in order to establish the reference EEDI speed for the calculation[5]. Extrapolation of data may be permitted to be used in an event where weather conditions do not allow for complete sea trials.

Verification guideline documents are taken from the Lloyds register (Lloyd's register: Implementation of the energy efficiency design index (EEDI)) - guidelines for owners, operators and shipyards. (Jun 2012 version 2.1)) which are based on the IMO MEPC standards for EEDI calculation:

Quoted"

Verification documents:

I. Pre-verification: Pre-verification will involve submission of the following:
   1) EEDI-TF that will include details of the calculated EEDI;
   2) Supporting documents including (but not limited to):
      - Report on the method and results of the tank test for an individual ship including predicted speed vs power curves at both EEDI condition and speed trial condition;
      - Estimation process and methodology of the power curves at design stage;

[5] Lloyd's register: Implementation of the energy efficiency design index (EEDI)) - guidelines for owners, operators and shipyards. (Jun 2012 version 2.1)

- Detailed calculation process of the ship speed, including the estimation basis of parameters such as roughness coefficient, wake coefficient;
- Reasons for exempting a tank test, if applicable; including lines and tank test results for ship of the same type, and the comparison of the principal particulars of such ships and the ship in question.
- Lines of a model ship and an actual ship for the verification of the appropriateness of the tank test;
- Lightweight of the ship and displacement table for the verification of the deadweight;
- Principal particulars and the overview of propulsion system and electricity supply system on board;
- Description of energy saving equipment;
- Main and auxiliary engine NOx technical files and shop test data.

3) EEDI Speed Trial plan for measuring EEDI reference speed at 75% MCR.

II. Final verification: this will involve submission of the following:

1) Final EEDI-TF updated with regard to;
   - Verified EEDI reference speed at 75% MCR (obtained from measured results of the speed trial)
   - Final technical parameters supporting the calculation of the EEDI value.
2) Supporting documents including (but not limited to):
   - Speed trial data and detailed report of corrections and extrapolation methods used as well as technical parameters required to perform verification to ISO 15016:2002 or equivalent;
   - Final displacement table and the measured lightweight, or a copy of the survey report of deadweight;
   - Approved NOx technical file (if not already supplied as part of pre-verification).

Simplified methods are illustrated in the diagram bellow:

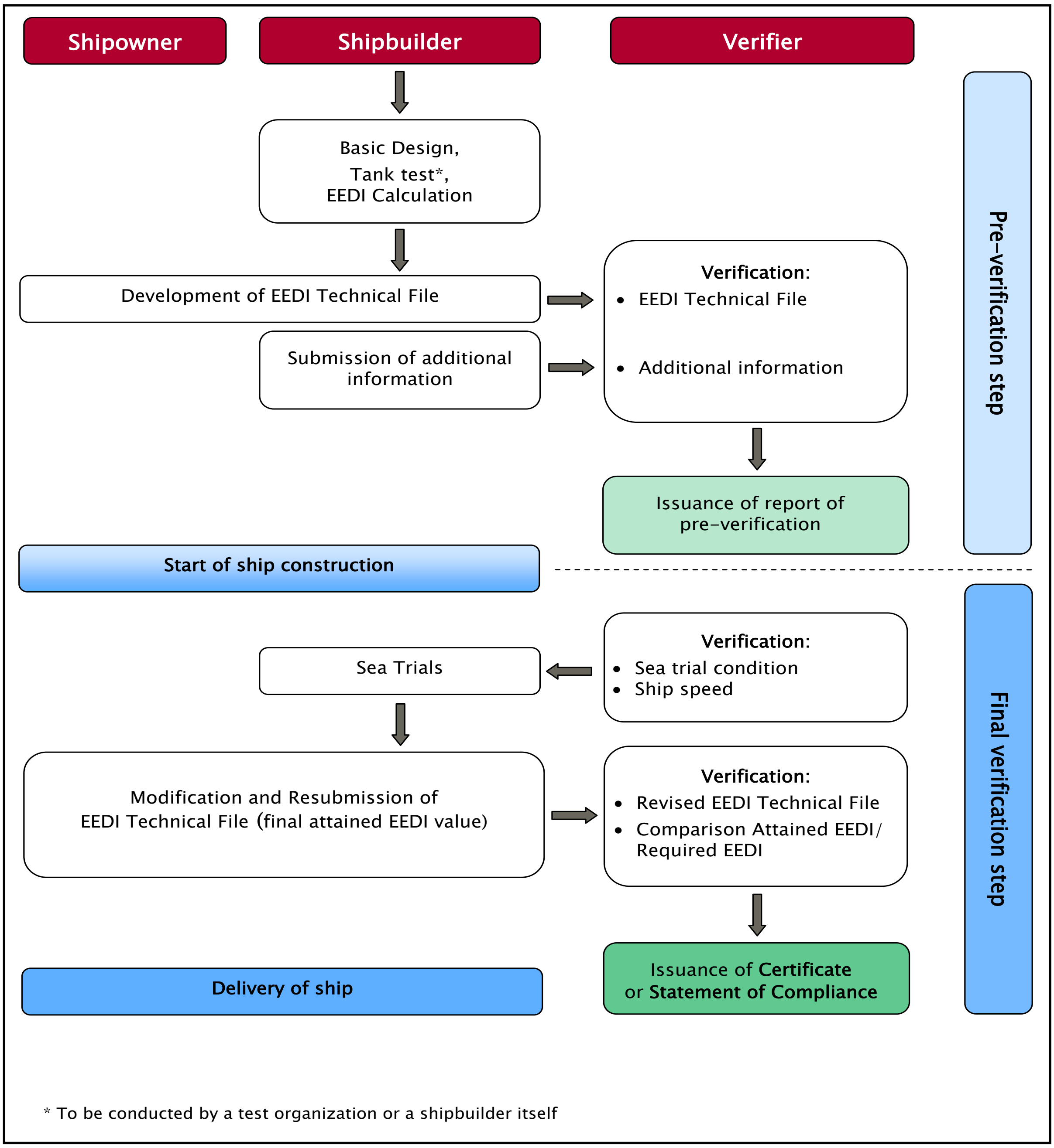


Figure 4: EEDI verification stages that must be followed by the shipyard.

5.0 EEDI STATISTICAL OVERVIEW:

Since the EEDI reference line for yachts are not given by the IMO, it was obligated to estimate the characteristics of the yachting EEDI reference line. This was performed by searching the web as well as various yachting databases, then calculating the EEDI for each yacht. This might assist in giving some prediction of the yachting EEDI of various reasonably new built yachts and conclude to the EEDI reference line.

During this research an EEDI modelling system was constructed to assist in creating a research and decision making. By gathering enormous amount of data and calculating the EEDI this may lead to some logical consistency by tighten the data and the EEDI equation to some physical outputs.

Data were collected (most of which were collected manually) from various places such as superyachttimes.com, SuperYachtIntelligence.com and HIS Fairplay database. EEDI was calculated for over 400 yachts, most of which were built between the years of 2000 and 2010. The smallest yacht on the performed EEDI record was a yacht with 400 GT, 40 m LOA and the largest with 13000 GT and 160 m LBP. Results were calculated using the following parameters:

- Specific fuel consumption of both engine and gen set = 215 g/kWh. This value was selected based on the average specific fuel consumption of yachts on the Data set. Engines varied from 230 g/kWh to 201 g/kWh.
- Cf for main engine and generators as 3.206 t-CO_2/t-Fuel
- Maximum continuous rating (MCR) of 75% of the reported installed power (as per IMO guideline), it is worth to note that many ships do normally operate at the nominal continuous rating which is 85% of the 90% MCR. This of course relates to the propeller design and as results, it could mean higher MCR as large as 77%.
- Generators power was calculated using the following:
  - If the installed power greater than 10000 kW, PAE = 0.025 * MCR + 250 (as per IMO guidelines)
  - If the installed power less than 10000 kW, PAE = 0.05 * MCR (as per IMO guidelines)
- V_{ref} was used as reported from various sources

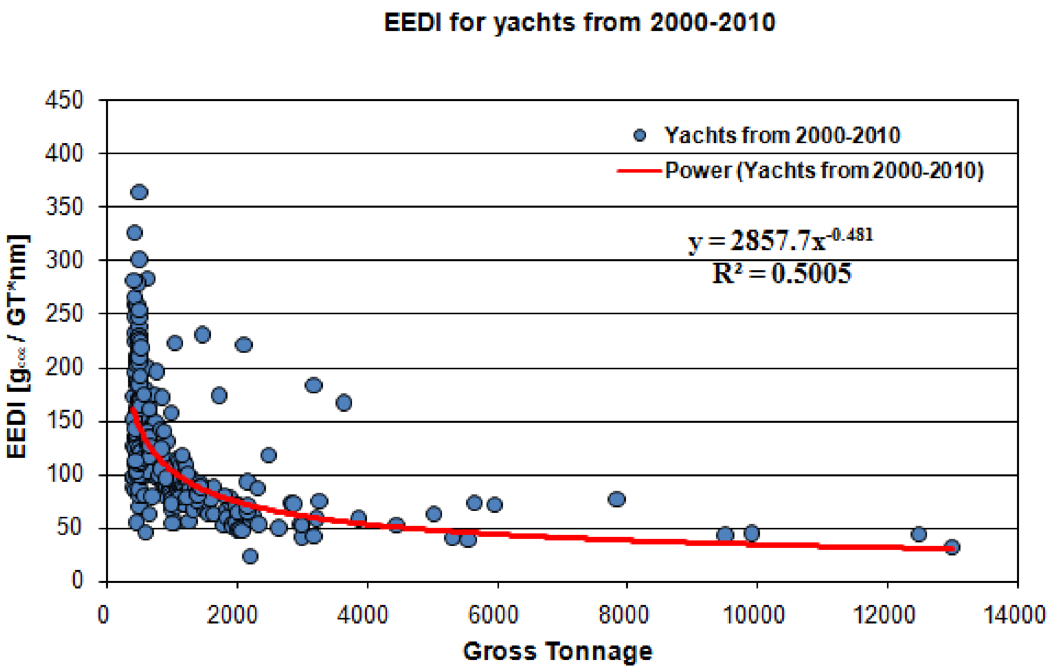


Figure 5: The x-axis is represents the gross tonnage as the EEDI distributed over the gross tonnage. The y-axis is the typical EEDI measured in grams of CO2 per transport work (GT*knts)

A new scenario was developed by using lower specific fuel consumption for main engine and generators from 215 g/kWh to 190 g/kWh, this is very feasible for larger ships as there are many engines with such low specific fuel consumption (low speed marine diesel engines) results are shown below:

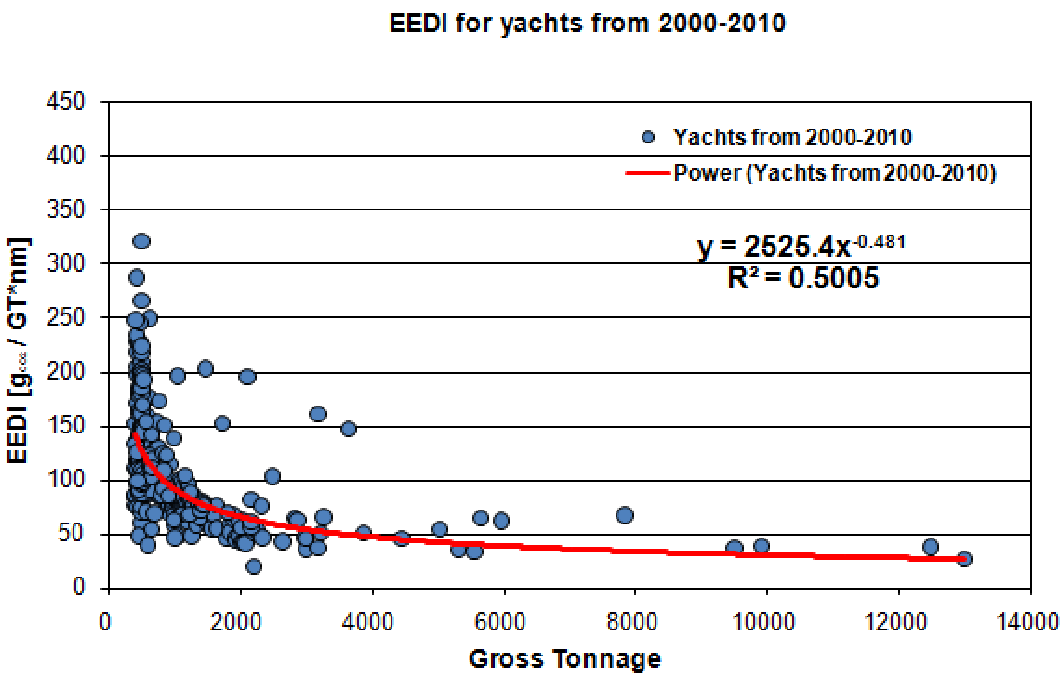


Figure 6 The x-axis is represents the gross tonnage. The y-axis is the typical EEDI measured in grams of CO2 per transport work (GT*knts).

By choosing more efficient engines as shown in the above 2 figures it is worth noting that the overall value of the EEDI has been reduced by a factor of approximately 12 %. This is rather possible to achieved, there are various engines manufactures they can offer much lower values of SFC even as low as 185 g/kWh. Further discussion on engine selection, suggestions of increase the efficiency of yachts are included in section 9.

Since Azimut-Benetti produces yachts below the 3000 gross tonnage range, and since there are various category of yachts (400GT-1200GT and 1200GT-3000GT). Therefore, calculating the EEDI for various range of GT then compare whether such calculations can actually give different results than the entire yachting data set. Results are presented below:

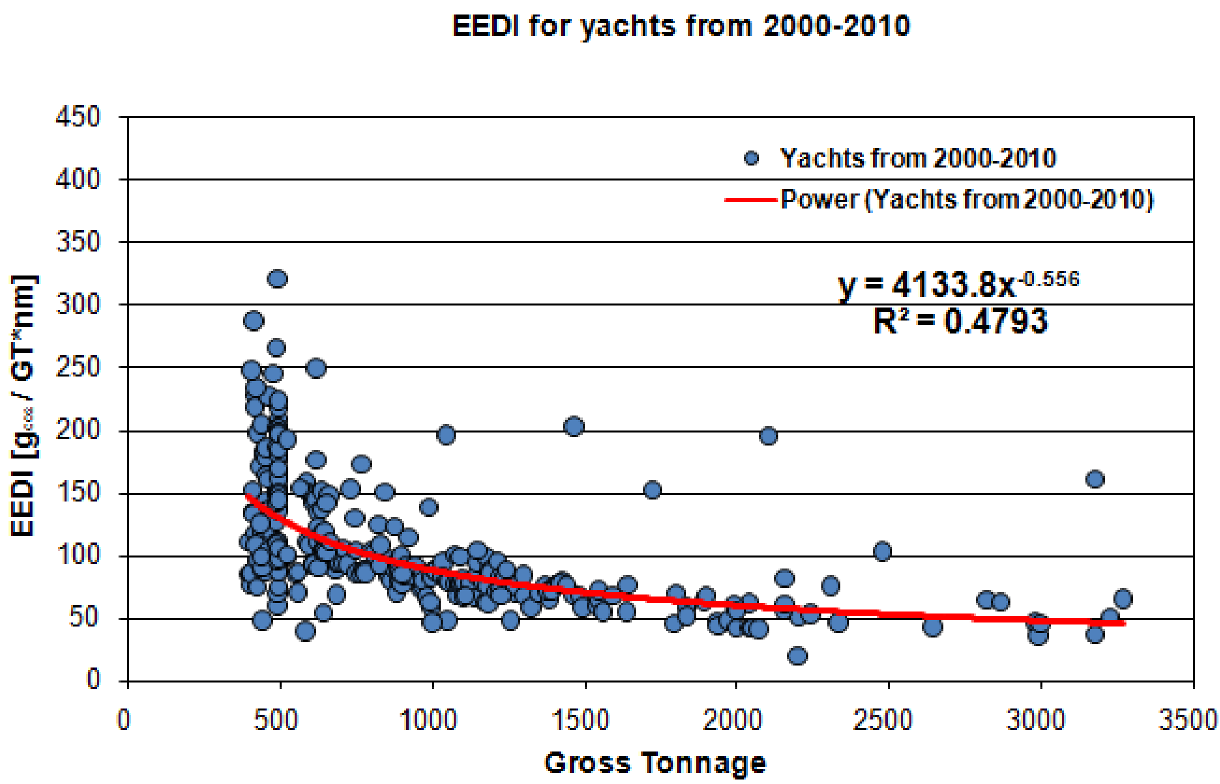


Figure 7: EEDI vs GT for yachts from 400 to 3300 GT.

From the above figure we can note that the EEDI values for individual yachts remains constant as well as the method of calculation. However the trend line of those yachts is significantly lower than the original EEDI line, this is mainly because the data set is extensive between 400-500 GT. This may give some misleading weighting average.

By carrying out an individual inspection was noted that several of the smaller yachts are preplanning or fully planning yachts with variation in various aspects such as gensets and

HVAC, comparing this to larger yachts which are in general displacement yachts. This may explain the reason for having such huge scattered data just below the 500 GT.

For the purpose of having more accurate benchmarking by using the EEDI, it will be advisable to group yachts based on their GT (related to hotel load as well as yacht main dimensions) or based on other design parameter such as the Froude number similarity or a combination of both since these two parameters seem to effect fuel consummation significantly. Now by calculating the probability distribution function of the EEDI we can see that the majority of the yachts have an EEDI between the values of 50 and 200 [g_{CO2}/ton*nm]. This is really large gap and what was proposed is to subgroup yachts according to their design parameters such as the Froude approach or GT smaller groups then treating each group separately.

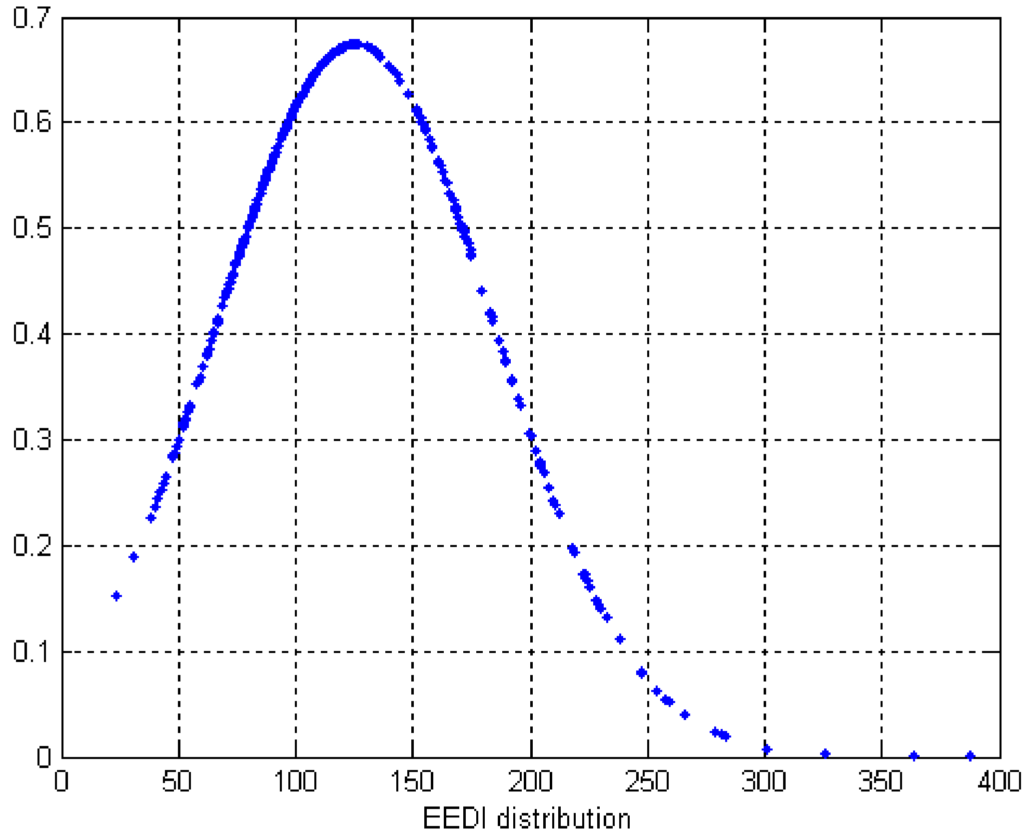


Figure 8: the probability distribution of the EEDI calculated from various yachting data. This shows great concentration of the population between the values of 50 and 200. Numbers are clipped around the 40 EEDI marker as there is no yacht can produce lower EEDI value.

By using the same approach for calculating the energy efficiency design index (EEDI) but instead we plot the ratio of the installed power converted to grams of CO_2 (following the IMO EEDI guidelines) then divided by the gross tonnage, this will be plotted against the Froude number this time. Therefore, equation would look as shown below, units are gCO2/GT. Efficient of the propulsion system was also compared using the EPDI (Efficient Propulsion Design Index) which is derived from the EEDI Equation without consideration of other coefficients from the generators. The EPDI will be plotted against the Froude number.

$$\frac{\overbrace{\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right)}^{\text{Impact of Main Engines}} - \overbrace{\left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}^{\text{Reduction of impact due by innovations on main engines}}}{Capacity}$$

Equation (15): EEPDI equation for estimating the performance of the main engines

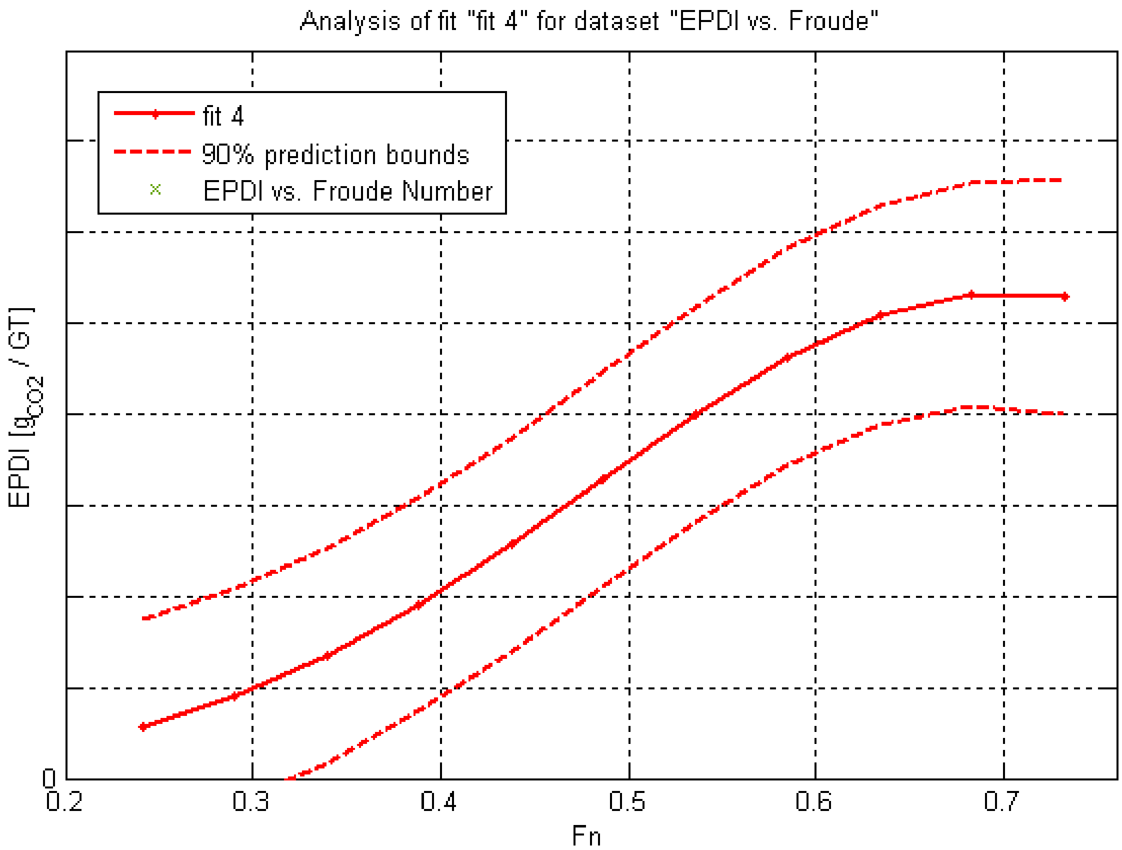


Figure 9: EPDI values plotted against the Froude number.

Kindly note: Most of the data for calculating the EPDI were confidential, therefore values of the y-axis were masked out, and just schematic of the figure is presented to give a general indication.

From the above figure (**Figure 9: EPDI values plotted against the Froude number.**) we can see that 90% of the data fits within the data fitting range. Yacht with higher Froude number experience higher g_{CO2} per gross tonnage than those of a lower Froude number, hence follows the usual physical trend as higher speed semi-displacement hulls normally will have greater installed power to lower gross tonnage or weight ratio.

The trend of the above graph looks somewhat similar to those of the resistance to displacement ratio against the Froude number as shown in the below figure 10:

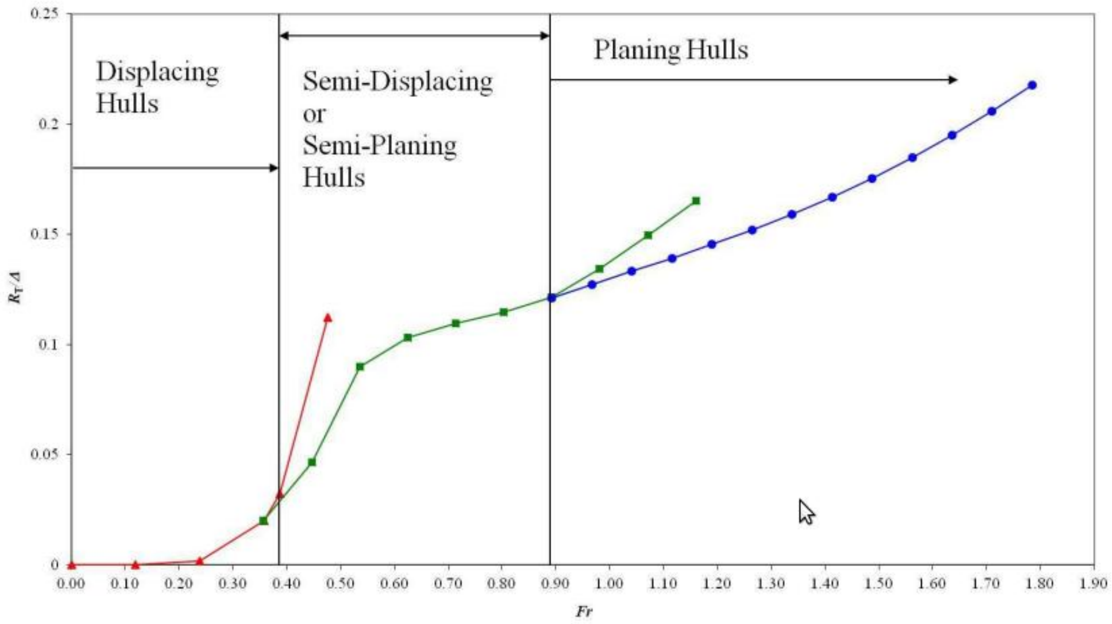


Figure 10: Typical resistance to Froude number graph.

As shown in Figure 10 that when displacement hulls operate above the hull speed will require significantly greater power to propel. Now days it is a trend to see that many yachts (as shown in the analysis in Figure **17** yet to follow) operate beyond their hull speed. Certain displacement hulls with bulbous bow as well as some Fast Displacement Hull Form (FDHF)[6] can be characterised with similar While having small displacement yachts can be designed as semi planning but when greater displacement exist hulls must be rethought through.

[6] MOTOR YACHT HULL FORM DESIGN FOR THE DISPLACEMENT TO SEMI-DISPLACEMENT SPEED RANGE, 10th international conference on Fast Sea Transport. FAST 2009, Athens, Greece, Oct 2009.

There are some published research papers concerning other vessels where the EPDI values were plotted against the Froude number. An example below was taken from Deltamarin published study to the EMSA (page 29)[7].

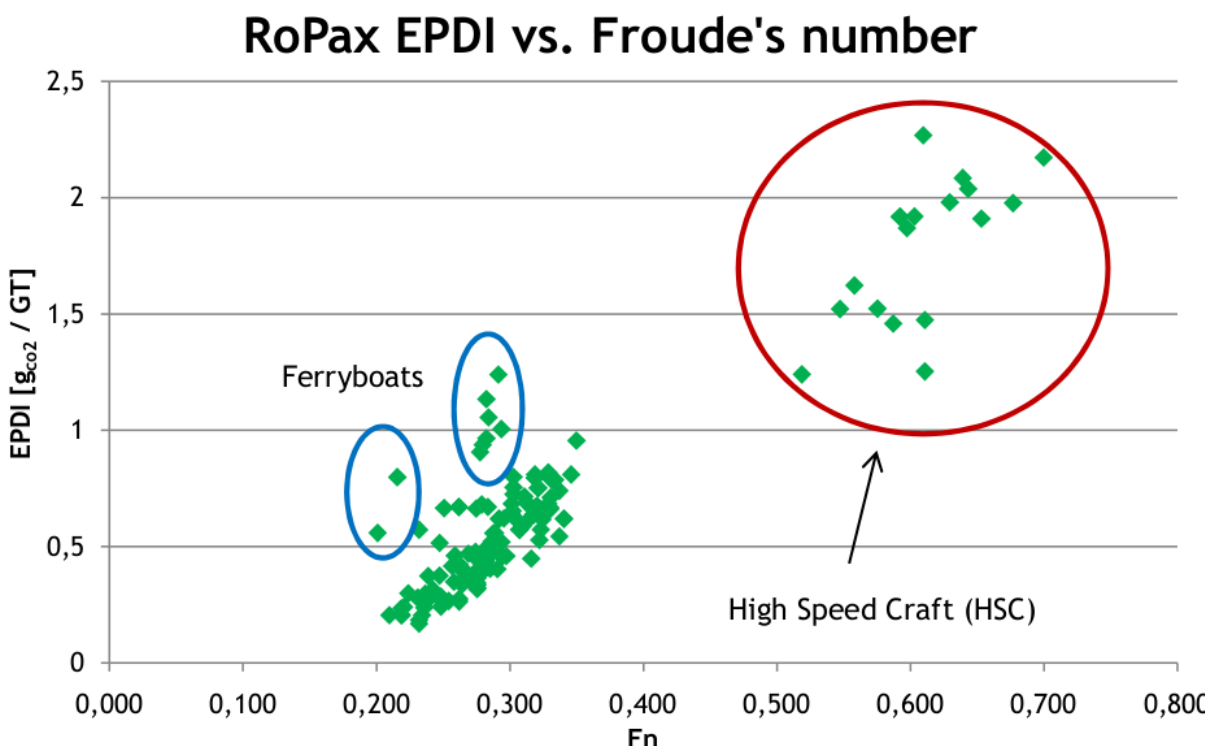


Figure 11: Applicability and Refinement of the EEDI for RoRo vessels and special ships dated o the 24.05.2011

From the above Figure, we can observe that higher Froude number will most certainly be associated with greater carbon emission "per gross tonnage ratio". In addition, ferryboat they usually shares many common parameters with yachts (especially super and mega yachts), hence there results is mostly scattered due to hotel load and variation in luxury items/performance characteristics. It is also worth to note that other type of ships are more standardized when compared to yachts as yachts are highly customizable according to the owners request and the size (market value and what not).

[7] Deltamarine: Applicability and Refinement of the EEDI for RoRo vessels and special ships dated o the 24.05.2011

The ratios of GT to installed power (kW) is an interesting aspect for shipbuilders as this can provide them with a quick and easy method of predicting whether a yacht is likely to be efficient on the EEDI scale. In order to make such ratio more useful and more relatable to the EEDI scale, this ratio plotted against the Froude number. By taking the ratios of the gross tonnage divided by the installed power of over 423 yachts, we can observe that for the same Froude number, EEDI can be lowered by having greater gross tonnage to power ratio (Example by utilizing and constructing for greater internal volume especially above the waterline). Results shown in the below figures (Figure 12):

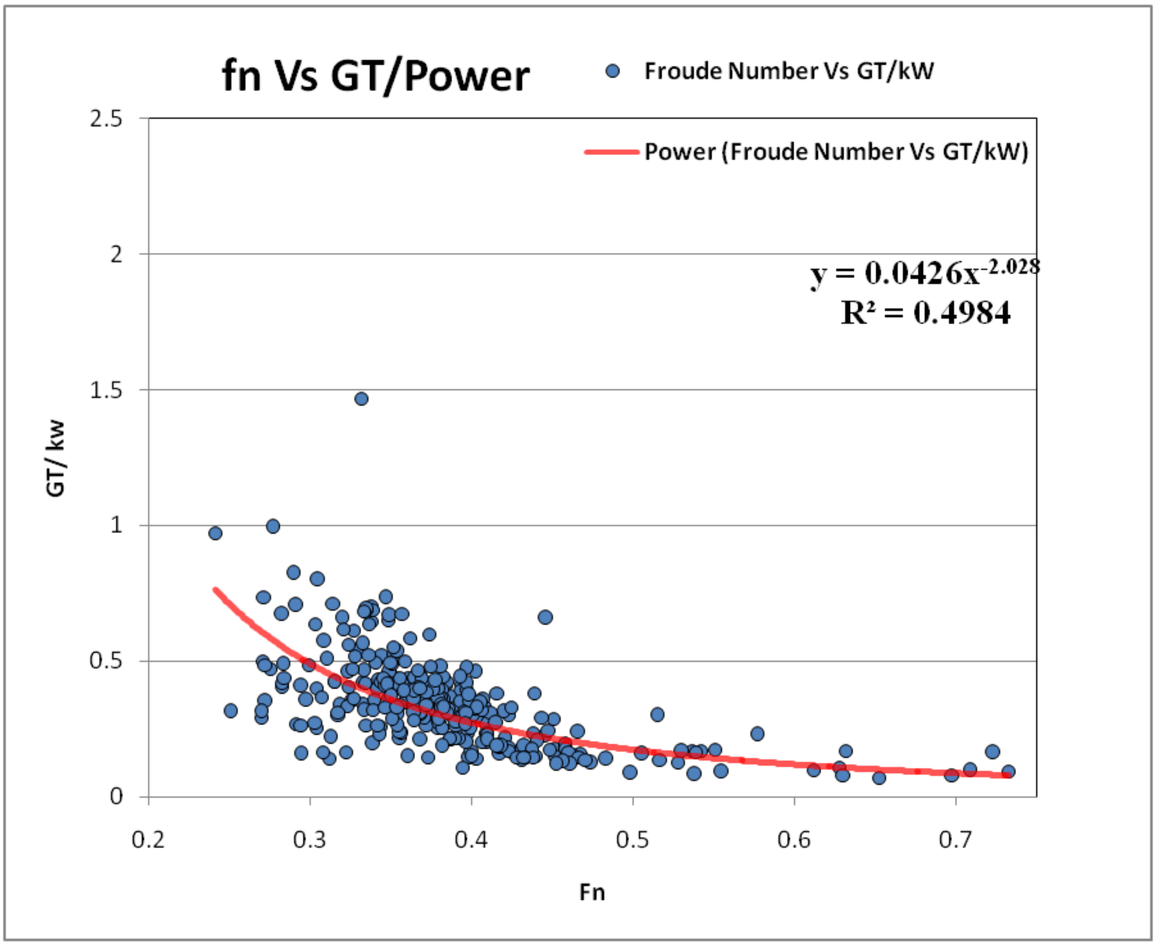


Figure 12: GT/kW Vs fn.

From the above Figure, we noted that some yachts have ultra high ratio of gross tonnage to installed power. After careful inspection, those yachts were found to be relatively on the larger side with low speed (hence, more merchant ship like characteristics). It is also noted that when inspecting individual yachts with Fn =0.5 or greater, gross tonnage was limited (lower GT yachts) and parameters of those ships are more towards the semi-planning/high speed displacement hulls.

Since the resistance to speed ratio is in the higher order (cubic relation or so), it is thought that the EEDI may have large influence with respect to the speed of the yacht. Therefore, two graphs were made to compare various yachts EEDI values against the Froude number and against the speed in knots as shown in the below Figure **13**:

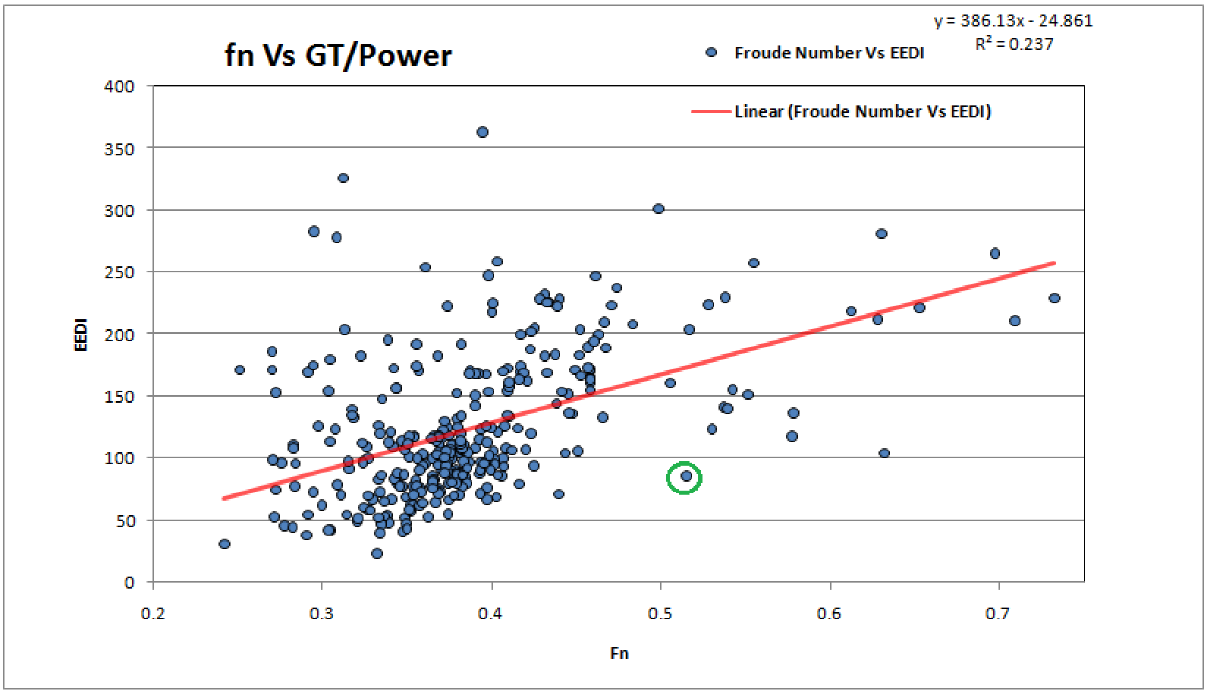


Figure 13

Surprisingly the above figure provides no significant results, however this does suggest that some yachts do have the right design parameters to meet the required EEDI even when traveling at reasonably higher Froude number crossing into the semi-displacement region. A selected example from the data shows a super yacht with the following details (Figure **14**):

Figure 14: photo was taken from superyachttimes.com, accessed on December 19 2012.

LBP = 45 m, LOA = 46 m, Draft = 2.1 m, Beam = 9.45 m, small displacement of 230 tons, GT=498, Speed = 21 knots, Power 1648 kW (as published on superyachttimes.com and accessed on January 08 2013).

Since understanding the EEDI and how it response to certain parameter is the main objective of this section. Therefore, by plotting the L/Breadth ratios Vs EEDI would be interesting as the L/B ratios always on the mind of the naval statisticians.

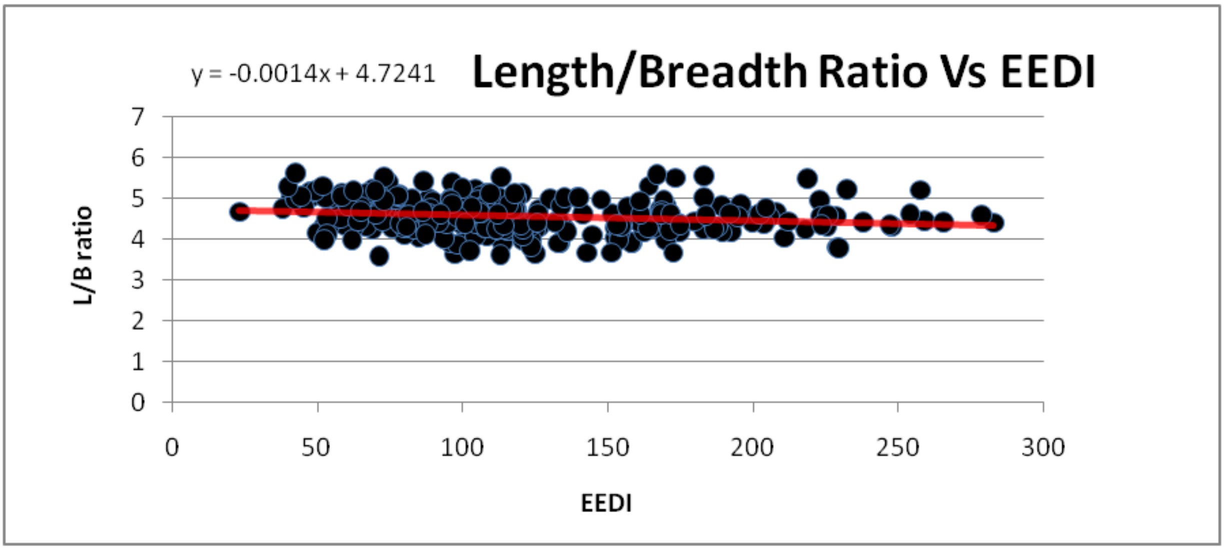


Figure 15

From the above figure, 361 yachts L/B ratio against EEDI value were compared. We can note that L/B ratios for yachts can vary from 3.4-5.8 with small negative slope towards the higher EEDI values, hence more slender hulls may have better resistance characteristics but on the contrary they may have lower gross tonnage. We can also observe that the EEDI value is almost independent from this coefficient as long as the yacht remains in between the previously mentioned ratios.

Since comparing length to breadth against the EEDI did not results in no much significant finding, it is worthwhile to look at the length to breadth ratios alone to see whether yachting industry follows a certain design tendency.

The graph below (**Figure 16**) shows the length to breadth ratios, it is noted that the majority of the yachts in the database follows a nice trend with few exceptions. After inspecting those exception it was found that the beamier hulls (LOA less than 40 m and breadth greater than 10 m) have significantly low EEDI values on the contrary to those circled in red as they suffer significantly higher EEDI value.

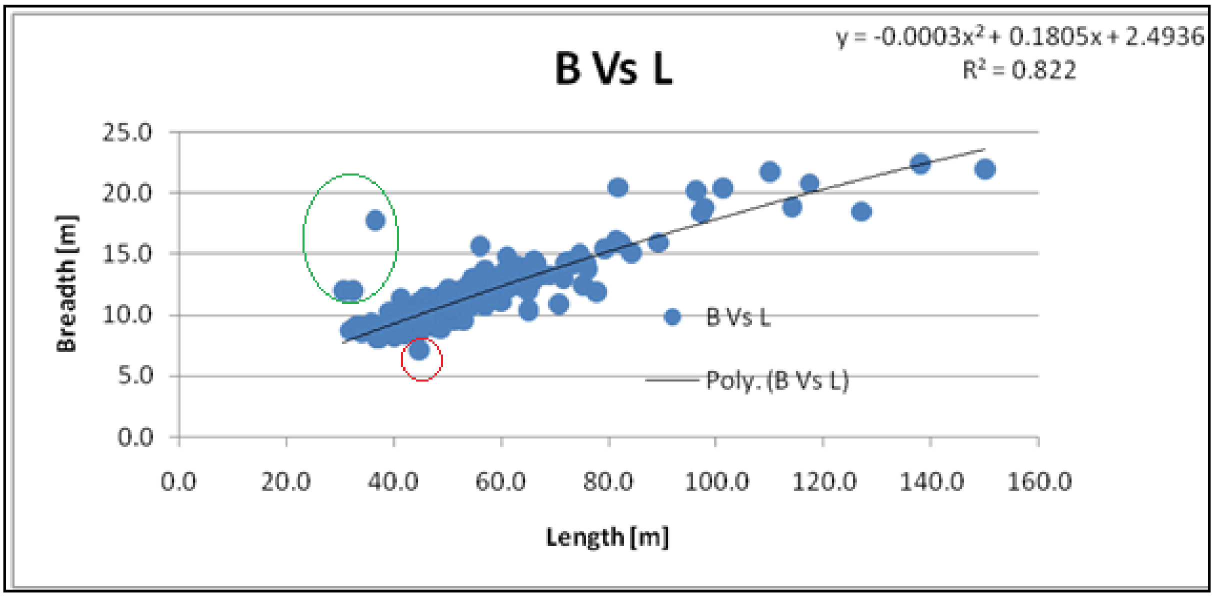


Figure 16

In any statistical data analysis the quality of the analysis is directly related to the quality of the data. Yachting data is extremely scattered, reported numbers of yachts are very low and not easily available.

It is also necessary to know under which base some of the EEDI assumptions are made, an example to that is when looking at the yachts available data there are significantly higher number of yachts between 400 and 500 GT when compared to other groups based on the GT. Correction factors for design parameters and dimensions must be provided by the IMO similar to those of other ship groups.

5.1 Section Summary:

Recapping on the previous discussion:

1. EEDI values were successfully computed for over 450 yachts between 400GT and 12000GT using the IMO guideline.

2. Lines of fit suggest that scattered EEDI data for smaller yachts. Smaller yachts have greater ratio of being semi-displacement or customizable.

3. Lowering the engines Specific fuel consumption was tested against the EEDI, it was found that lowering the SFC from 215 g/kW will reduce the EEDI value by 12% on average. Findings were significant reduction in the total EEDI values (across the rage of yachts). In addition, there are possibilities of using larger single marine diesel engine with low SFC but this will require complete new design philosophy.

4. Sub grouping yachts into smaller groups based on their GT by removing very large yachts as their philosophy is different from those of smaller yachts (more similar to those of cruise ships). Alternatively, if correction factor to the design parameter were used so not all yachts will suffer from having an odd out yachts in the data.

5. EEDI yachting data is densely distributed around the figures of 50-200 [g_{CO2}/GT*nm]. This means that any yachts between 400GT to 12000 GT fall within this EEDI range is most likely to be part of the population.

6. Calculating an alternative index to the EEDI named EPDI. Some of Azimut-Benetti's data were used as well as others resources. Results indicate similar trend to those of resistance against Froude number.

7. Published EPDI for merchant ships was compared to calculated EPDI, in conclusion merchant ships followed more systematic approach in the design and construction and therefore having greater consistency (unlike yachts).

8. A plot of GT to installed power [kW] ratio against the Froude number was developed. This graph was specifically for use as a quick design tool to estimate how much kW required for a GT with respect to the Froude number. Efficient regions were identified the yachts can comply with EEDI values. A separately graphs will be provided in different report to Azimut-Benetti.

9. Fn plotted against the EEDI as shown in (figure 13). Findings were that at higher Froude number (greater than 0.5), yachts can still have low EEDI value by selecting the right design parameter from hull type, displacement, length to breadth and arrangement of the accommodation. An example was provided from the data as a reference.

10. L to B ratio against the EEDI was plotted, it showed hulls on the beamier side with the right Froude number and gross tonnage can still have a low EEDI value. On the contrary, it was noted that having narrow hull with shallower drafts would likely contribute to having higher EEDI value due to their GT.

6.0 HYDRODYNAMICS ASPECTS:

In order to increase efficiency of any vessel resistance must be considered as first since fuel consumption is significantly linked to hull characteristics. The resistance of yachts is complex matter and requires some careful analysis. By looking through the super and mega yachts statistics we can observe that the majority of yachts operate at a higher end of the displacement region which is approximately 0.4 as shown in the below figure:

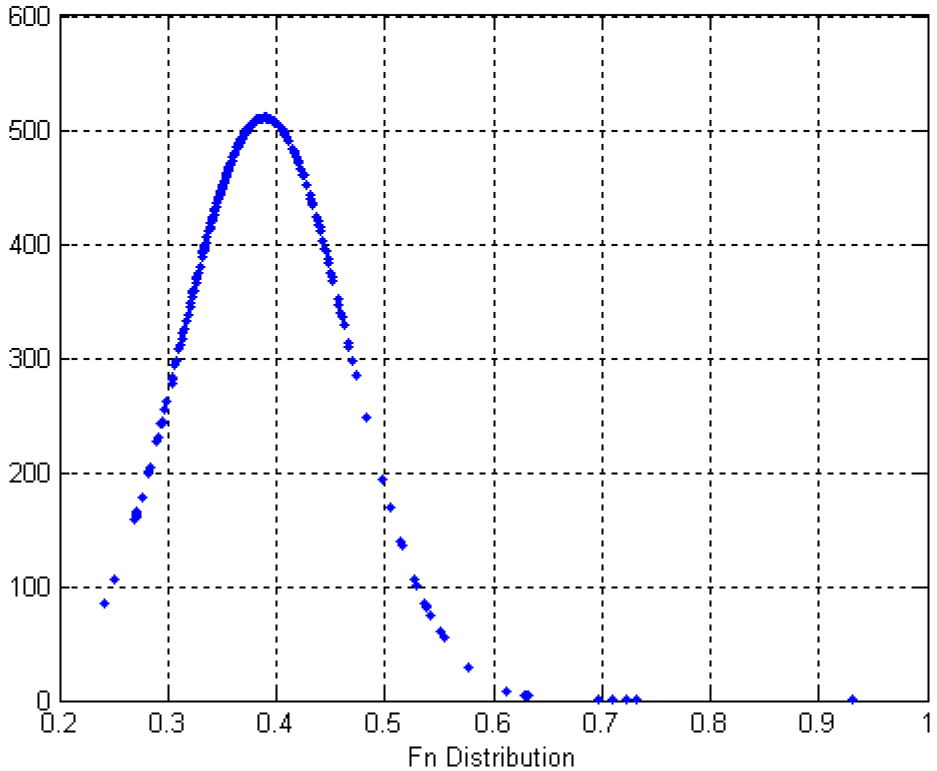


Figure 17:Froude number distribution from over 400 yachts.

The hulls model which were provided by Azimut-Benetti for the purpose of this study were operating at approximately 0.4 Froude which follows many high speed displacement crafts as shown above in the probability distribution plot, this distribution was made for approximately 400 motor yachts.

The main task of this part of the analysis to see whether similarities in the analysis of the resistance data does exist, in addition whether it is possible to find some hydrodynamic and resistance improvements using first principal and empirical methods without resulting into any numerical analysis (at least for the scope of this project).

6.1 Telfer coefficient, © coefficient and R/ Displacement for hulls comparison:

Azimut-Benetti shipyard is famous of their ground luxurious yachts and especially their hulls for various reasons such as the seakeeping characteristics, the sleek designed hulls and super structure, so the first place was to set up a benchmarking model which will be based on non-dimensional coefficients such as the Telfer coefficient (Telfer 1963) and the presentation agreed upon by the BSRA as published by the ITTC (Subject 7 presentation of resistance and propulsion data). The following coefficients were taken from the presentation:

$$F_n = \frac{V}{\sqrt{gL_{WL}}} \qquad (16)$$

$$© = \frac{R}{\rho \nabla^{\frac{2}{3}}} \times \frac{1000}{4\pi} \qquad (17)$$

$$C_T = \frac{2}{\frac{L}{\nabla^{\frac{1}{3}}} \times \frac{S}{\nabla^{\frac{2}{3}}}} \times \frac{\frac{R}{\Delta}}{fn^2} \qquad (18)$$

V: Velocity m/s

g: Gravitational acceleration m/s^2

fn: is the Froude number

©: Is non-dimensional coefficient

R: resistance in N

Δ: Displacement in Tonne

∇: Displaced Volume in m^3

C_T: is the total resistance coefficient,

Three different hulls were presented in this analysis, towing tank reports were also provided by Azimut-Benetti. The first hull contains two sets of results for 2 different drafts, this hull is characterised by means of having lower gross tonnage and breadth to length ratio, hence more slender hull but also with shallower draft than the 2nd and 3rd hulls. The remaining two hulls (2nd and 3rd) are similar in dimensions and being beamier and deeper draft than the first hull. Also all 3 hulls share similar Froude range in their operation and all fitted with bulbous bows.

Before going further into the coefficient it was decided to compare the resistance per unit displacement against the Froude number (this is the same old Froude method). Results are shown in the below figure:

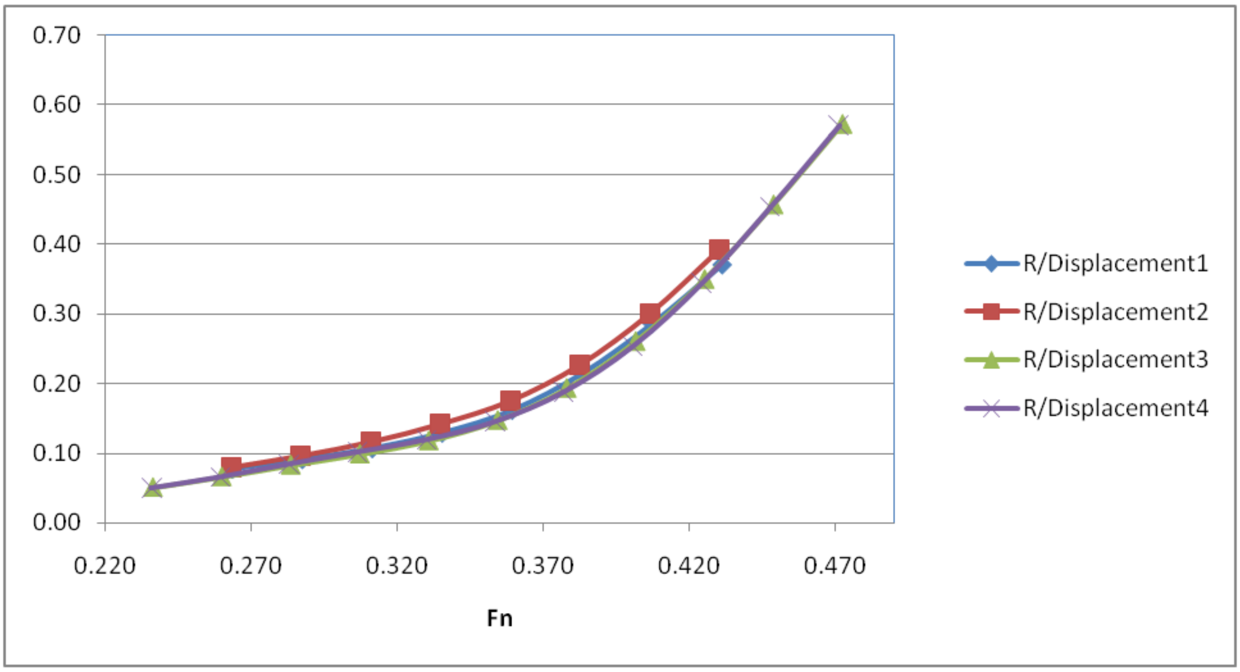


Figure 18

From the above **Figure 18** the Y-axis represents the ratio of the resistance per unit displacement; this is very typical values when compared to many hulls from the available statistical dataset. It is very hard to distinguish whether there is much difference in the resistance per unit displacement apart from the 2nd hull (brown colour) which corresponds to higher resistance per unit displacement values.

Since the previous analysis did not results into much luck, it was decided to go with plotting the © against the Froude number as shown below. The below figure it is possible to see that differences are becoming more apparent. 2nd hull is having much greater resistance coefficient and as results higher resistance values along the entire operational Froude. Also now it is possible to measure some difference between hulls number four and three. Hull number three is offering some superb resistance coefficient from the low Froude until 0.4 Fr.

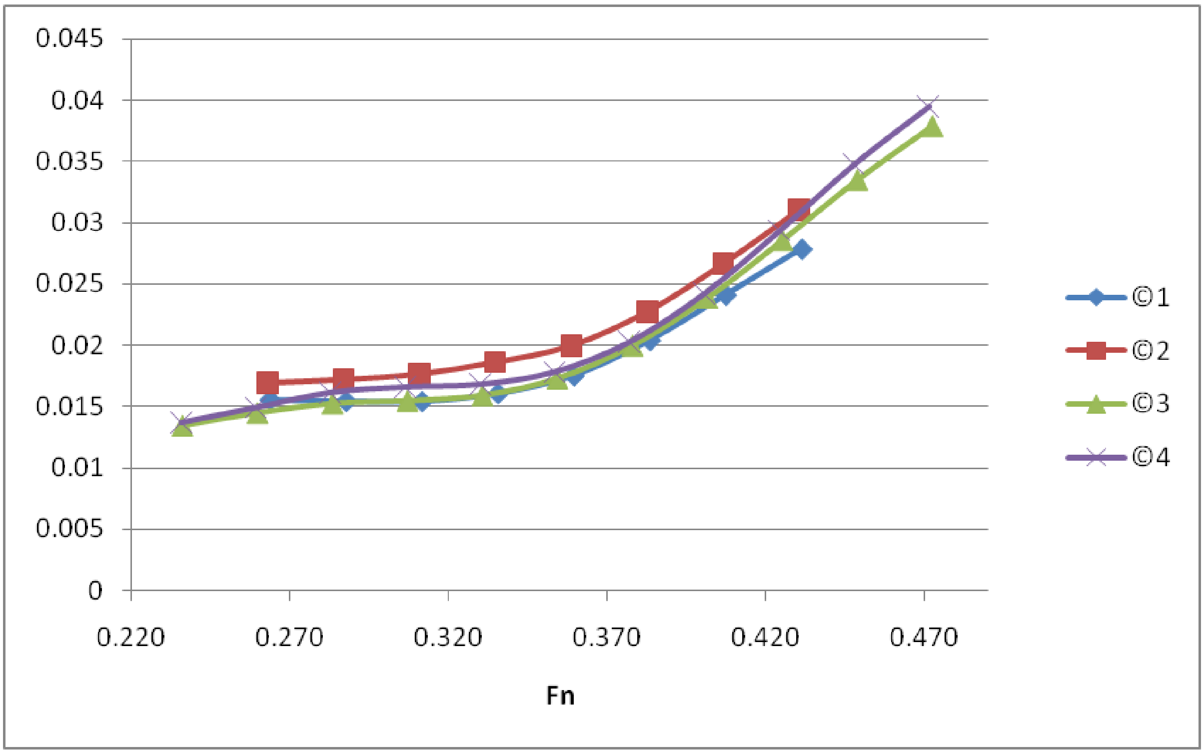


Figure 19:

The Telfer coefficient was normalized by the displacement plotted against the Froude number to see whether it can offer any conformation to the above results or any extra advantage.

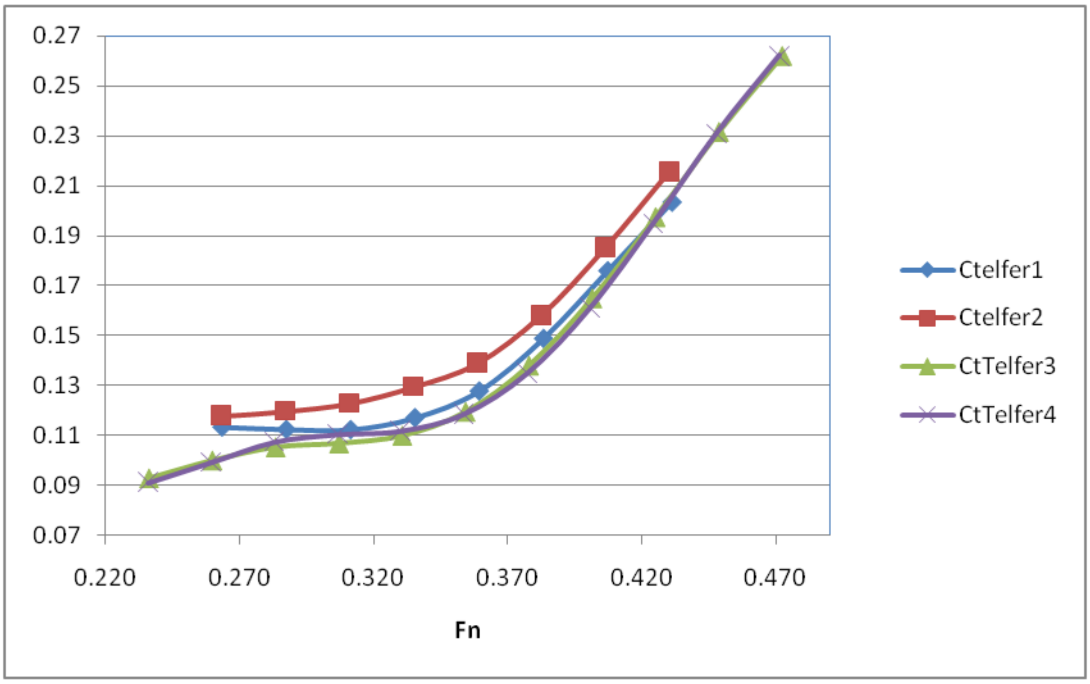


Figure 20

From the final figure (Figure **20**) an observation can be made that hull number 3 appeared to have lower resistance coefficient throughout the entire analysis. Now since those yachts were already built (historic per se), it is worth to obtain some good results from sea trials to validate the calculation/model test.

Also since both hulls come with very large amount of appendages and an immersed transom stern similar to the figure below, it adds more uncertainty to the estimation of the real resistance based on model scale only. This is due to the fact that drag induced by appendages is affected by the boundary layer of the hull. From towing tank photos and videos a note was taken of the large amount of spray around the bow area, this need to be verified on the real hull whether it is due to wave breaking or simple low spray that was magnified due to water surface tension.

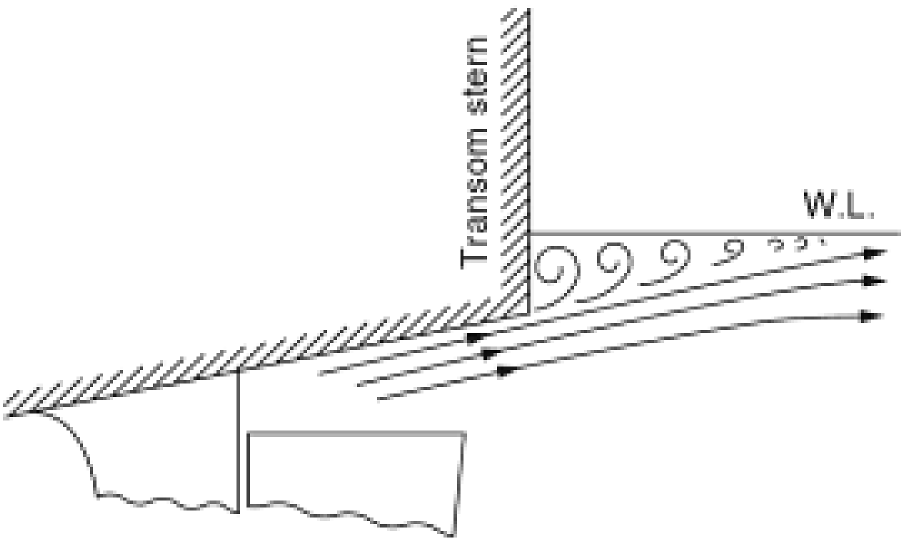


Figure 21

Above items combined together will result in some uncertainties due to scaling effect. Therefore it is very advisable to have a complete CFD viscous flow analysis to estimate the total resistance, the direction of the flow and to perform some alignments of the appendages. Similar tasks can be include but not limited to:

- The positioning of the propeller strut and appendages.
- Feasibility study of the Mewis duct to check the water inward and outward flows from the propeller.
- Propeller boss cap fins might also increase the efficiency; this can be studied during the same time of performing the CFD model optimization.
- Hydroplanes/stabilizers system and underwater exhaust gas flow,

- The position of the tunnel thrusters with respect to the bow wave.
- Bow bulbous performance review in waves. It is widely thought that bulbous bow do not perform their task as well when waves exist. Added resistance must be taken into account even when sea trials are made.

6.1.1 Added Resistance between docking:

Reducing fuel consumption and improving efficiencies at the design stage is always important, however data are emerging from many places with regard the operational cost amplified by the increase in resistance. A typical diagram which was published in Copenhagen during the Motorship Propulsion Conference on the 26th of January 2006 suggest that added resistance increase due to marine biofouling increases something similar to the below figure. Also such resistance can be reduced by regular docking or using specific marina coating to reduce time between docking. By understanding such factors it will allow engineers to decide on the safety margin that allowed by the installed power.

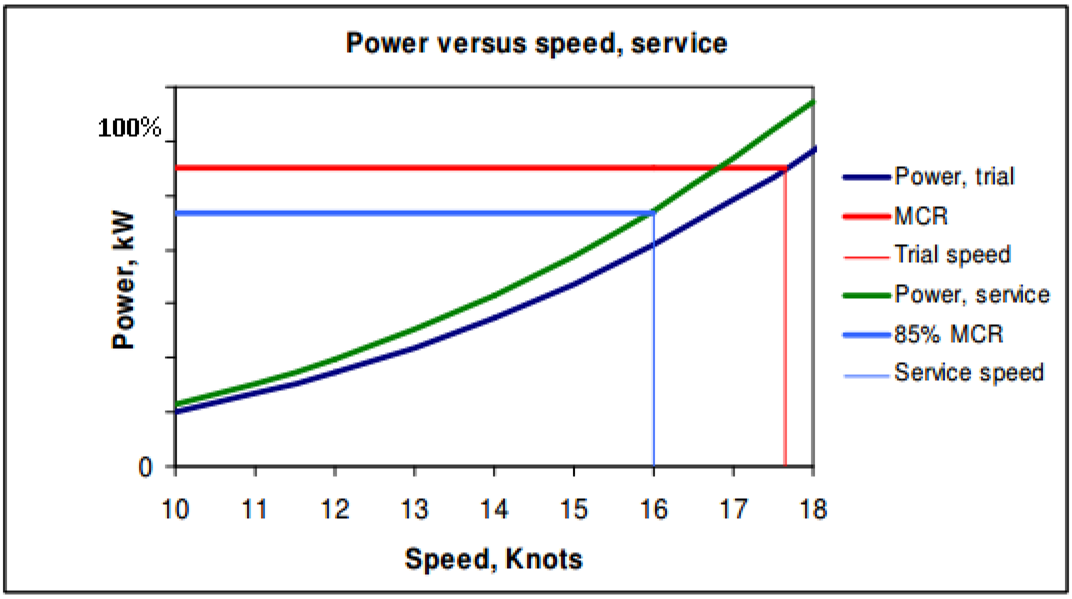


Figure 22

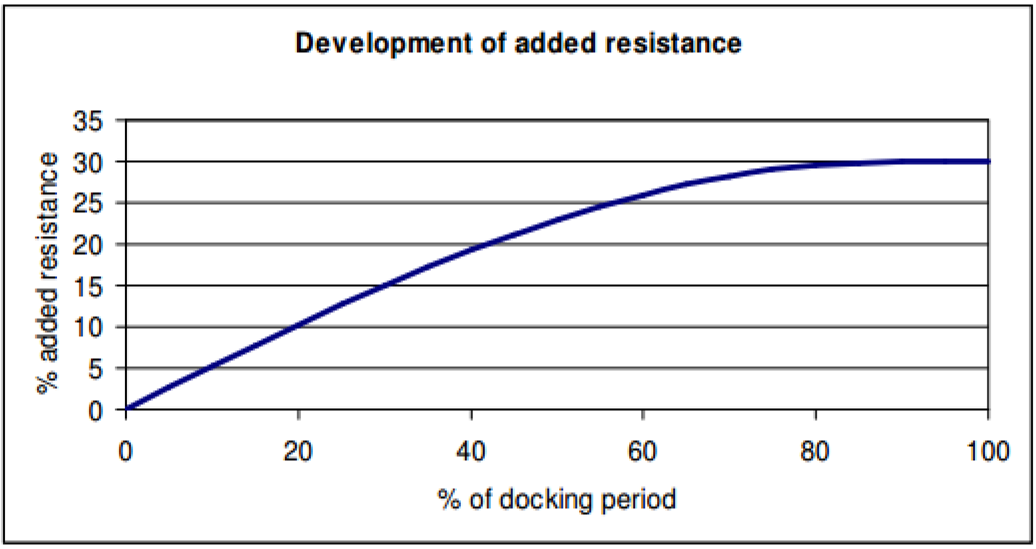


Figure 23

6.2 Holtrop and Mennon resistance prediction method with multi objective Genetics algorithm:

To evaluate the resistance during the early design stage a program is under development using an open source free programming language which utilises the Holtrop and Mennen resistance prediction as well as the MOGA (multi objective genetic algorithms). The program as well as a separate report to guide the user shall be provided to Azimut-Benetti once evaluation is completed.

Holtrop and Mennen method is widely known and quick analysis method for resistance prediction during the early design stages. Resistance prediction can be performed to obtain an approximate resistance to speed curve for yachts (displacement hulls). During the development of this software a great deal of attention was paid to have more validation with some of Azimut-Benetti's hulls. This method is very widely used in the maritime industry, it comes integrated inside many commercial software such as Hullspeed. It is considered as a suitable method for displacement hulls (below Froude number of 0.4). (**Figure 24: Holtrop and Mennen explained published by as Holtrop.**) As published by Holtrop and Mennen explains the fractional resistance (resistance breakdown) over various speed and its contributions. Such diagrams assist in explain parts of the hull's resistance combined with the propulsion system, this shall assist designers to concentrate on various parts of the resistance separately.

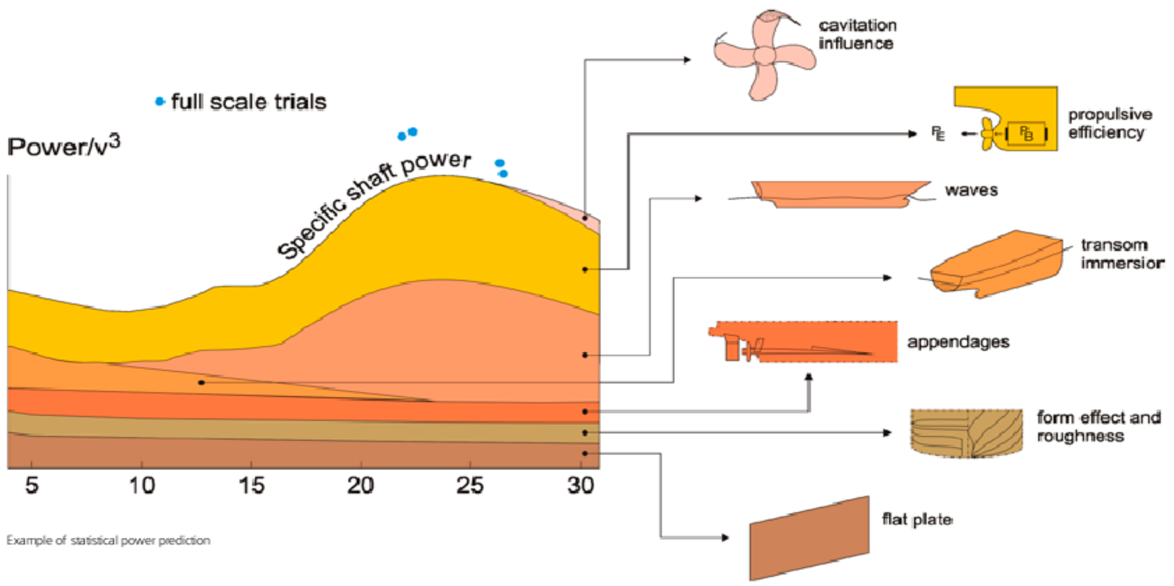


Figure 24: Holtrop and Mennen explained published by as Holtrop.

In this section of the report a short analysis was made to see whether variation of certain values such as the prismatic coefficient. L_{WL} to Breadth, Draft, C_P and C_B, can be analysed with the developed software. A typical hull from a mid 50 m range displacement motor yacht was used with Holtrop method; parameters were extracted and varied in order performing some sensitivity analysis on the total resistance. This will assist in evaluating which parameter has direct effect on the EEDI. Minor modifications were made as shown in Table 4

Table 4

Trial #	Lwl (m)	Beam (m)	T (m)	Cp	Cb
R1 (kW)	48.355	9.8	2.84	0.582	0.523
R2 (kW)	48.855	9.6	2.64	0.576	0.568
R3 (kW)	47.855	10	3	0.588	0.490

Only marginal modifications were performed to the above parameters while keeping the displacement value unchanged. Results of the analysis are shown below:

Table 5

V (knt)	R1(kW)	R2(kW)	R3(kW)
13	57	55.99	59
14	75	69.5	77.7
15	101.5	90	105
16	142.6	123	148
17	208.2	173.4	216
18	295.7	224.1	306.6

Variation R2 gives the best results in terms of the resistance. Small modification to the length has contributed significantly to the reduction in the wave making resistance especially at higher speeds. While small modification (reduction) to the breadth might be compensated by having larger block coefficient and therefore no significant loss from the tonnage side.

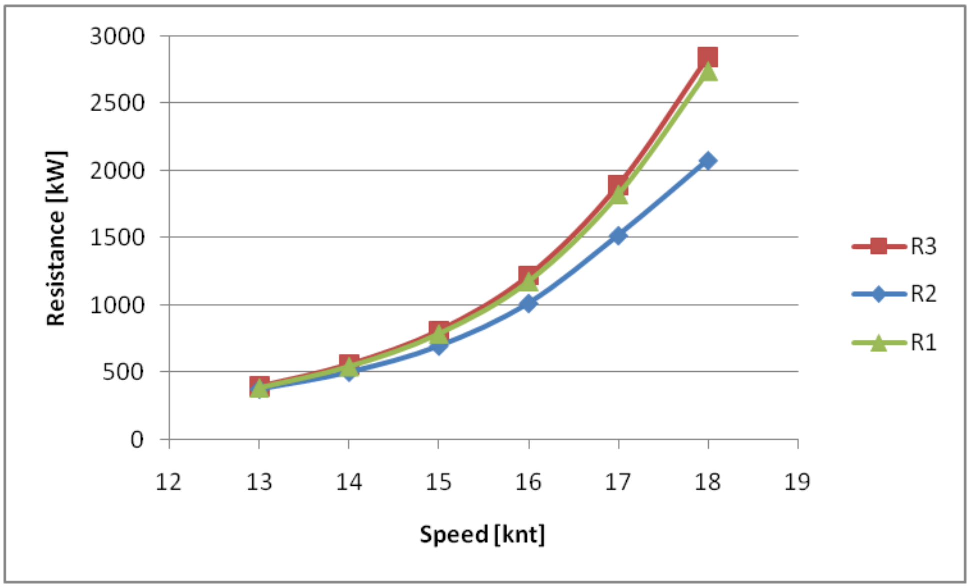


Figure 25

By inspecting several yachts resistance data with respect to the Froude number, it was evident how resistance will increase dramatically for every extra knot (and in consequence engine size). Therefore it is more advisable from efficiency standpoint to design yachts with sufficient margin below the hull speed (0.4 Froude number). Also since there are no correction factors for design element in the current EEDI equation with respect to yacht's main dimension, yachts travelling at higher speed will not have the same weighting average as those travelling at lower speed (hence more panellized).

Some hydrodynamics and shipping design companies are suggesting narrowing the beam, also to streamline (fairing) of the hull form (at the bow "shoulders" and stern) to create fine entry into the water and smoother long exit transition stern to reduce pressure drag (if possible due to the need of internal volume). Volume can be maintained by increasing depth and draft of the yacht. There are also other claims of removing the bow bulbous bow all together, the hull will have a sharp straight vertical tapered shape at the bow instead of the classical form (knife edge like finer bow entry), this will reduce impact from waves at the bow during long ocean voyage such as the Atlantic crossings (reduces added resistance from the encountering waves). Also other claims that bulbous bows are very sensitive to variation in depth since they work by creating a low pressure region above the bow which interacts with the bow pressure wave so it can reduce the bow wave's effect. Hence, by varying the dept (due to waves) the pressure distribution above the bulbous bow will vary and it might alter their functionality for the moment. An evaluation must be made at the early design stage by means of numerical analysis the balance between the bow pressure wave reduction effect (by the bulbous bow) and increase in the frictional resistance caused by having more area due to the bow.[8]

Figure 26 A typical new yacht was built with straight bow is the

[8] TEEKAY Corp, ONE SPIRIT: THE GREEN PROJECT, from: www. Teekay.com, accessed on January the 7th 2013.

Typical results from the early stage design analysis with Holtrop method and MOGA are presented below:

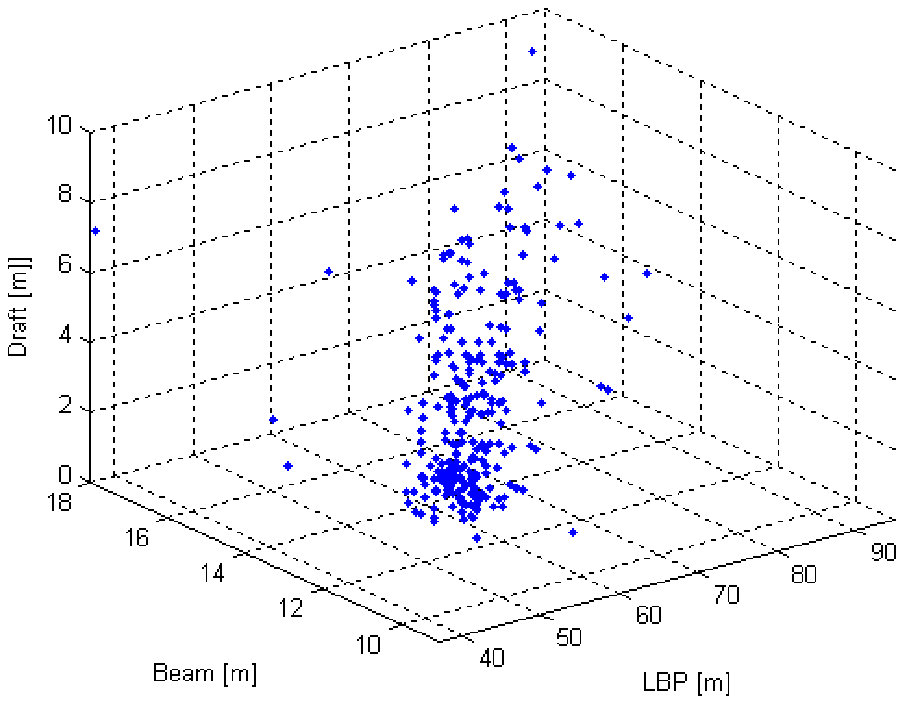


Figure 27: Breadth, Draft and length parameters were varied around set range using the genetic algorithm function.

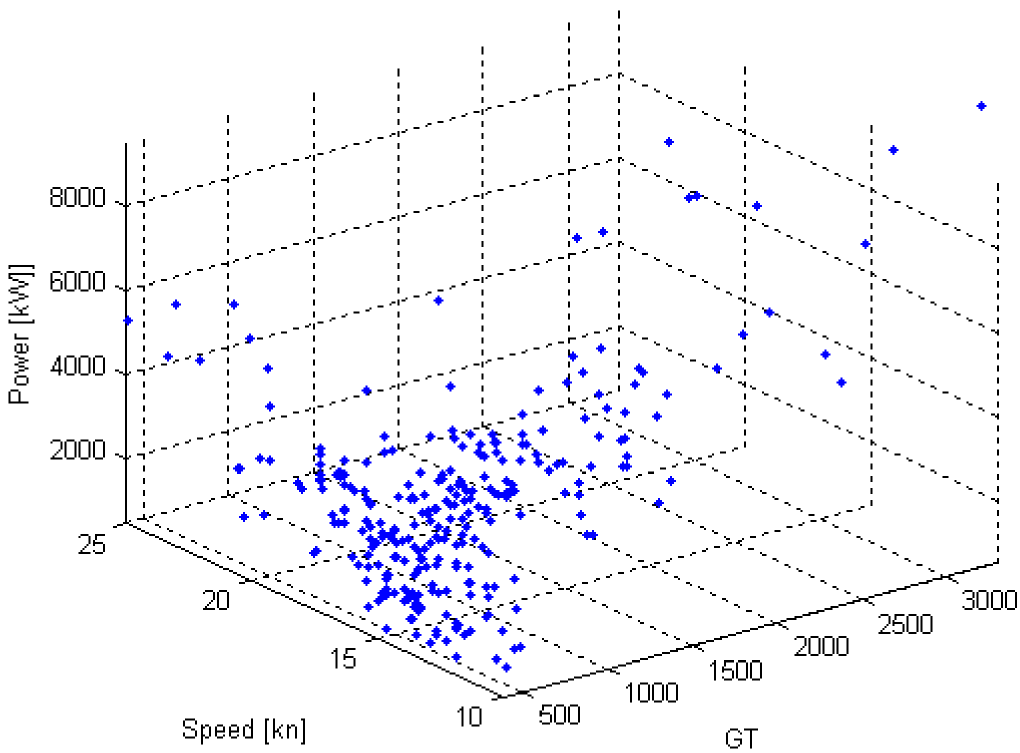


Figure 28: Power and speed predictions were made with Holtrop method, also estimation of the gross tonnage based on internal volume.

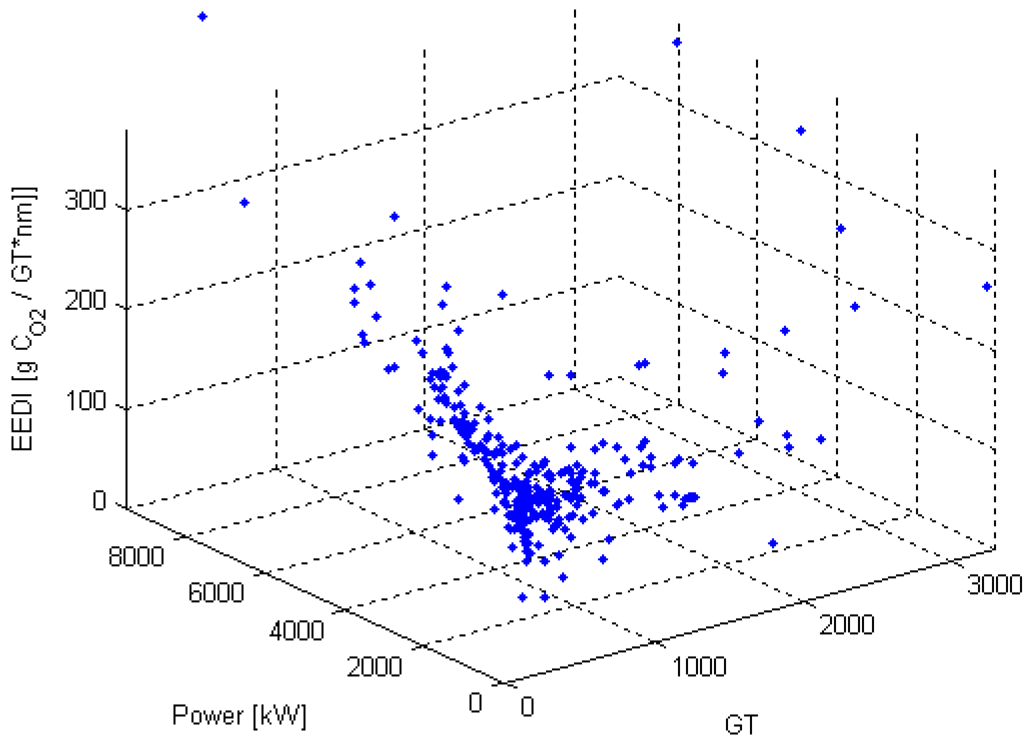


Figure 29: using power, speed and tonnage prediction EEDI values can be estimated as shown above.

From this we can see that initial design parameters can be optimised for the EEDI value instead of the resistance alone.

Since multiple decisions on which will affect the EEDI value is hard to make during the initial design stage, designers can evaluate fixed set of parameters such as fixed displacement, fixed value for cruising speed and range of other hull parameters then find the best possible hull and design combinations that will give the lowest possible EEDI value.

7.0 ENERGY SAVING ONBOARD:

During this section of the research, the feasibility of various concepts on motor yachts was to be investigated. Current motor yachts are fitted with significant amount of insulation that complies with statuary requirements. Insulation materials are taking into account fire, thermal and noise insulation requirements which are normally supplied with a diagram. Typical materials such can be found on yachts are Rockwool and fibreglass panels with typical non-combustible. In the construction process it is very difficult to estimate whether all insulations layouts are sufficient and installed soundly. An early suggestion was made for that every yacht must carry out a thermal survey prior to delivery or during the construction. This will assist the engineers in evaluating the real world insulation coefficients.

Doors, hatches and windows are greater source of thermal losses from radial heat to convection transmission as they certainly contribute more significantly than bulkheads in comparison. Typical marine glass windows U coefficient (W/m^2K) can be as high as 6 (W/m^2K) for laminated glass where double glassing can be on an average of 1.8 (W/m^2K). This may seem like a significant energy investment to check at first but when comparing the weight and energy saving of the double glazing that meets the statuary requirements to those of a single glazing it was rather minimal. For super and mega yachts an average area can vary significantly but let's take an example from a yacht with $90m^2$ total windows area:

If the temperature difference between the inside and the outside was 25°C: That is $25°C*90m^2$

$$1.8 = \frac{W}{25°\mathrm{C} * 90\mathrm{m}^2} = 4.050\ kW\ Net\ Loss$$

$$6 = \frac{W}{25°\mathrm{C} * 90\mathrm{m}^2} = 13500\ W\ or\ 13.5kW\ net\ loss$$

The difference between the two values is only 9.45 kW of thermal saving. On yacht this figure might be an expensive but the issue with double glassing that an increase of 40-60% in weight. On a typical 50 – 60 meters motor yacht this means an addition of 2.5 to 3.5 tonnes to the yacht. After deducting the small offset on the resistance due to weight increase the gain might be small but the improvement on energy losses from the glass in the figure of 60%.

Another factor that contributes to significant amount of lost energy onboard is the HVAC system. Various different principals were investigated theoretically or along the suppliers of the products. As a short review of this topic it was found that Heat pumps principal for winter time may not serve as effectively as those on commercial or domestic uses. The reason for that electricity onboard of yachts is very fuel intensive due to the efficiency low of almost all type of generators found in today's market without exception (Details on generators efficiency will come further in the next section). Another two principals were investigated theoretically, the first of which was based on recovering heat from the main engine or the generators exhaust. It was found that both diesel engine and generators do lose a lot of heat through radiation, exhaust and the cooling system. Exhaust heat data and flow rates were obtainable and therefore short investigation was made. Conclusion to the heat recovery system from exhaust can be summarised below:

A) Diesel engines do not operate continuously due to the fact that yachts have no mission profile with extensive high and low load operation, therefore building a scrapper system for energy recovery will not be economically viable. Furthermore scrapper system was found to increase exhaust back pressure. Since luxury super and mega yachts have underwater exhaust system this may result in some complications.

B) There is a lot of wasted heat by the exhaust from generators but also it is not economically viable to recover through means of scrapper. This is mainly due to the fact that extra cost, complexity and space will be incurred by such system.

The best economical, practical and environmentally feasible solution for heating found is to use direct marine classed diesel boiler system or to build similar boiler system custom made. By comparing efficiency of the diesel boiler principal against using electrical source for heating onboard, it was found that the diesel boiler can provide up to 60% improvements over the electrical heading when made by an electrical resister principal. The diesel boiler can also stand to be more efficient than having heat pump onboard by over 20%.

8.0 MAIN AND AUXILIARY MACHINERY:

In this part of the research, energy was evaluated directly from the main source (the fuel). This was made according to ISO 8217:2010 (Petroleum product-Fuel Class F, Specification for Marine Fuels). By using the available energy content in the fuel (calorific value) and the engine specification from manufacturers and sea trials, it was possible to compute the provided energy and efficiency by the engine and the generators set.

It is also known that marine engines now days come with various form of certification for air pollution and specific fuel consumption (SFC). Choosing an engine or a generator with low specific fuel consumption is a good choice in terms of the EEDI value. However this is not always the case since choices for machineries onboard motor yachts is highly involved with owner's preferences, space requirement, noise level, levels of maintenance, insulations level of complexity and various other commercial reasons.

A good concept for the engineering architects to follow similar diagram to the one below (**Figure 30: ABB Generations Energy Efficiency 2012.**). This diagram might be complex to follow at times however it can offer a very good picture of the energy flow throughout the entire system.

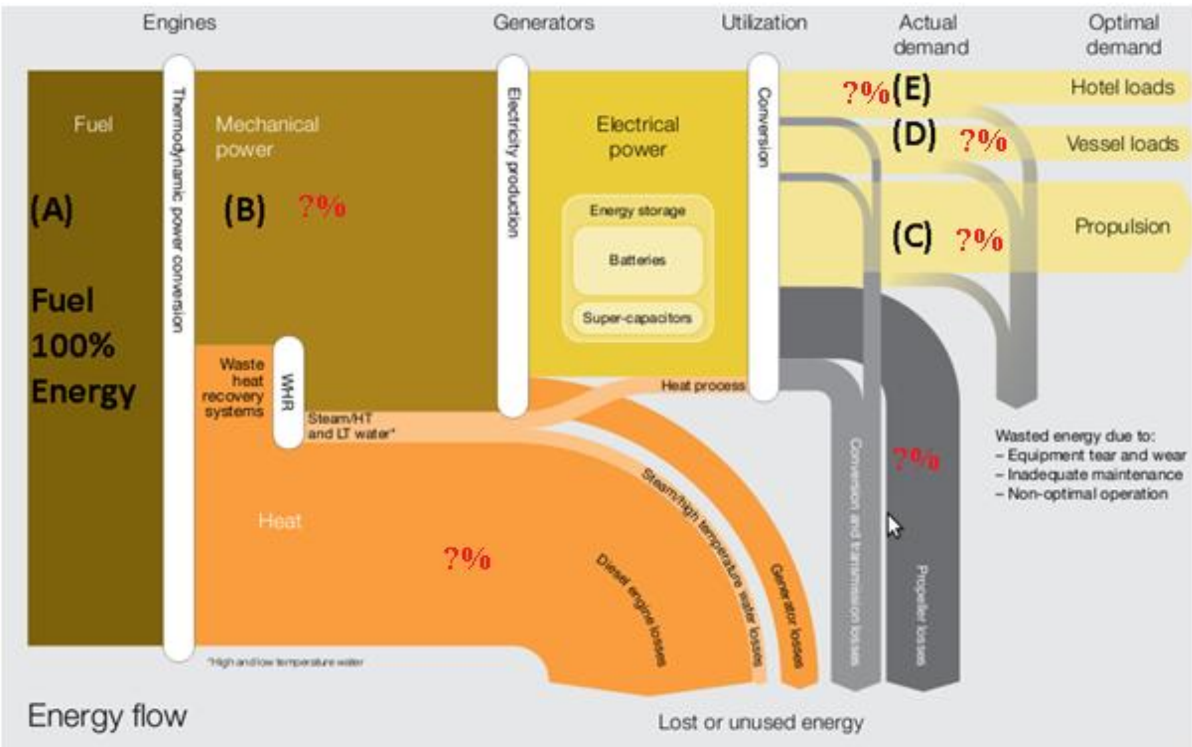


Figure 30: ABB Generations Energy Efficiency 2012.

After evaluating approximately 60 different set (sizes and manufacturers) of marine diesel engines and generators, it was noted that yachts normally designed not with the most efficient engines. Values of specific fuel consumption can be as high as 230 g/kWh or even worse when taking into account wear and tear factors. When comparing these figures with engines from the offshore industry (SFC = 177 g/kWh), we can see there is approximately 23% reduction in consumption for the proximity of the same power. However such engines are larger in size. Since space onboard of motor yachts is a luxury item, designers and owners cannot afford to waste. Another matter is the engine revolution and power matching with the yacht requirement and the propeller, normally those engines come in larger blocks with over 3000 kW.

Fuel quality can affect engines performance and efficiency significantly. Offshore engines and larger slower engines are less prone to fuel defaces. From the below diagrams we can see that fuel quality is an important factor in the combustion timing. Whether ship-owners or shipyards will intend to use various catalysts to accelerate the ignition timing is a question engine manufacturers have to answer. However, it is widely spoken that accelerating engine combustion time beyond design parameters may cause engine knocking and wear in the engine (especially in the engine valves).

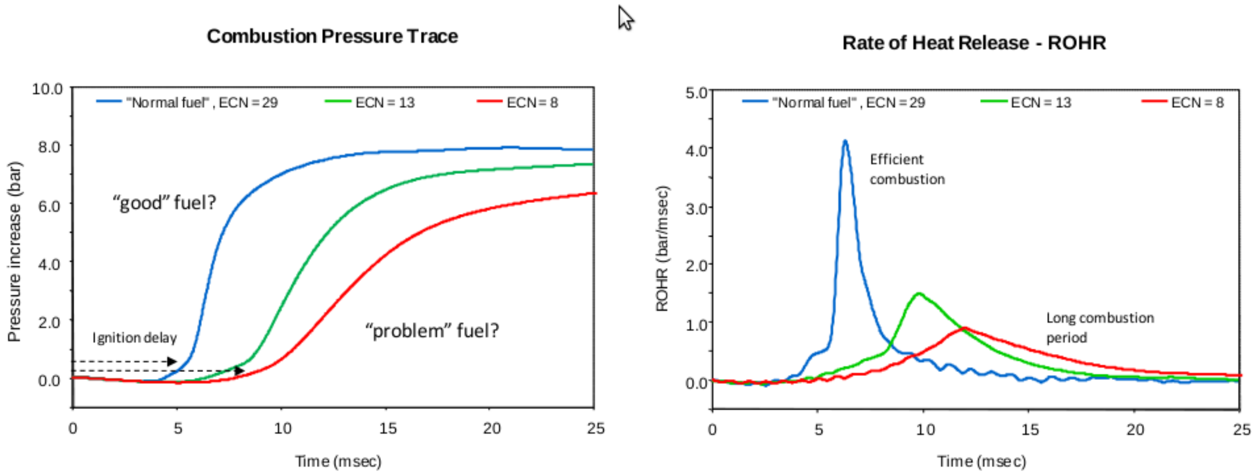


Figure 31 (a & b)

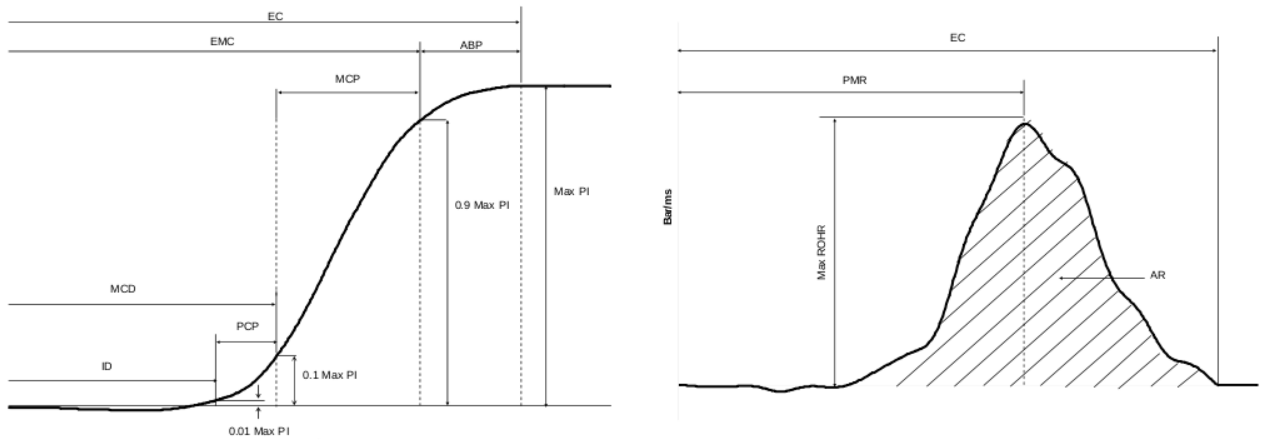


Figure 32 (a & b)

During the selection process engines, propellers and the vessels resistance vs speed must match drastically. Any mismatch will results in the yacht being under powered which will incur financial penalties or a dispute, alternatively the engine will be over powered as will increase the environmental impact and the running cost.

Typical engine rpm against power with respect to the ship resistance for semi-displacement motor yacht or motor yacht fitted with bulb is shown below (from MTU-Technical project guide for marine application, part 1 general).

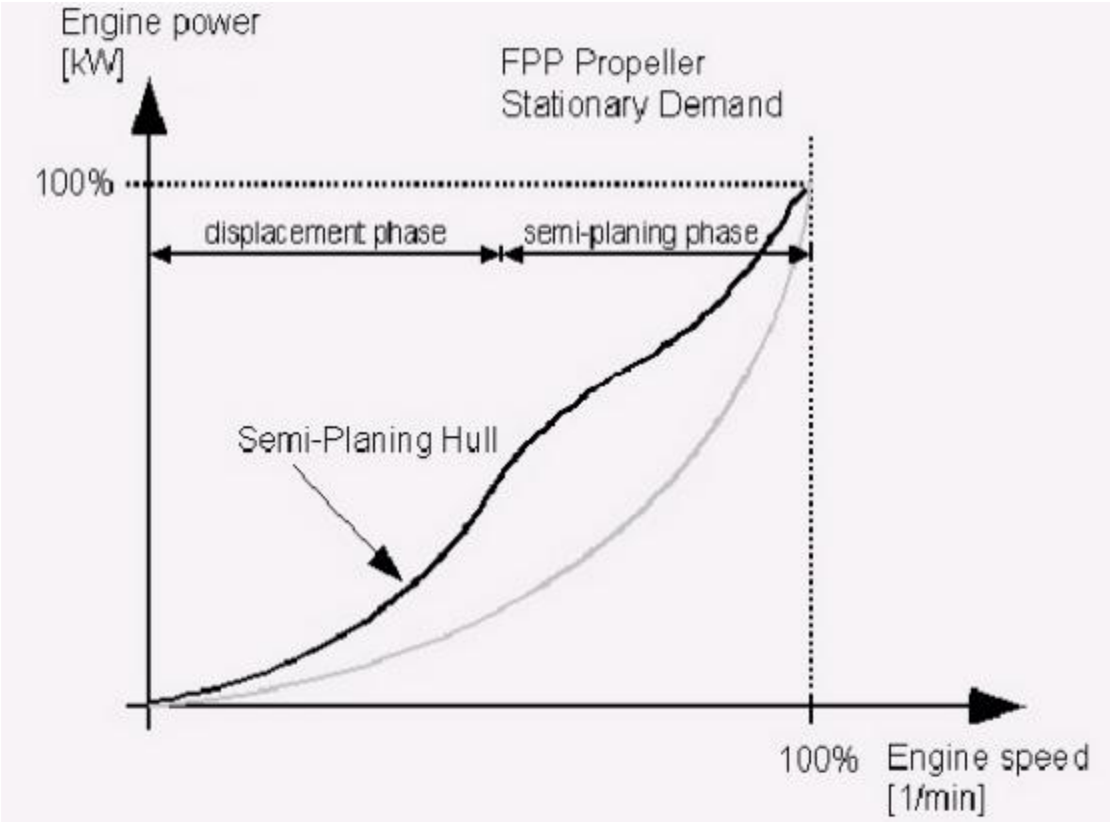


Figure 33

Since the most efficient operation of the engines is at MCR 75-80%. Choosing controllable pitch propeller with varying speed may offer some advantages in terms of efficiency if the delivered power curve by the engine passes the design point of the propeller but does not go through the lower region of SFC. Pitch can be adjusted to partial load. Also in an event where the engine cannot reach the required power, the propeller pitch can be corrected so the engine is allowed to reach the required power at the required speed; this can also be true when service life and fouling effect the resistance of the hull. Also since yachts do not have specific operational profile, therefore efficiency can be increased at low speed by adjusting the propeller pitch.

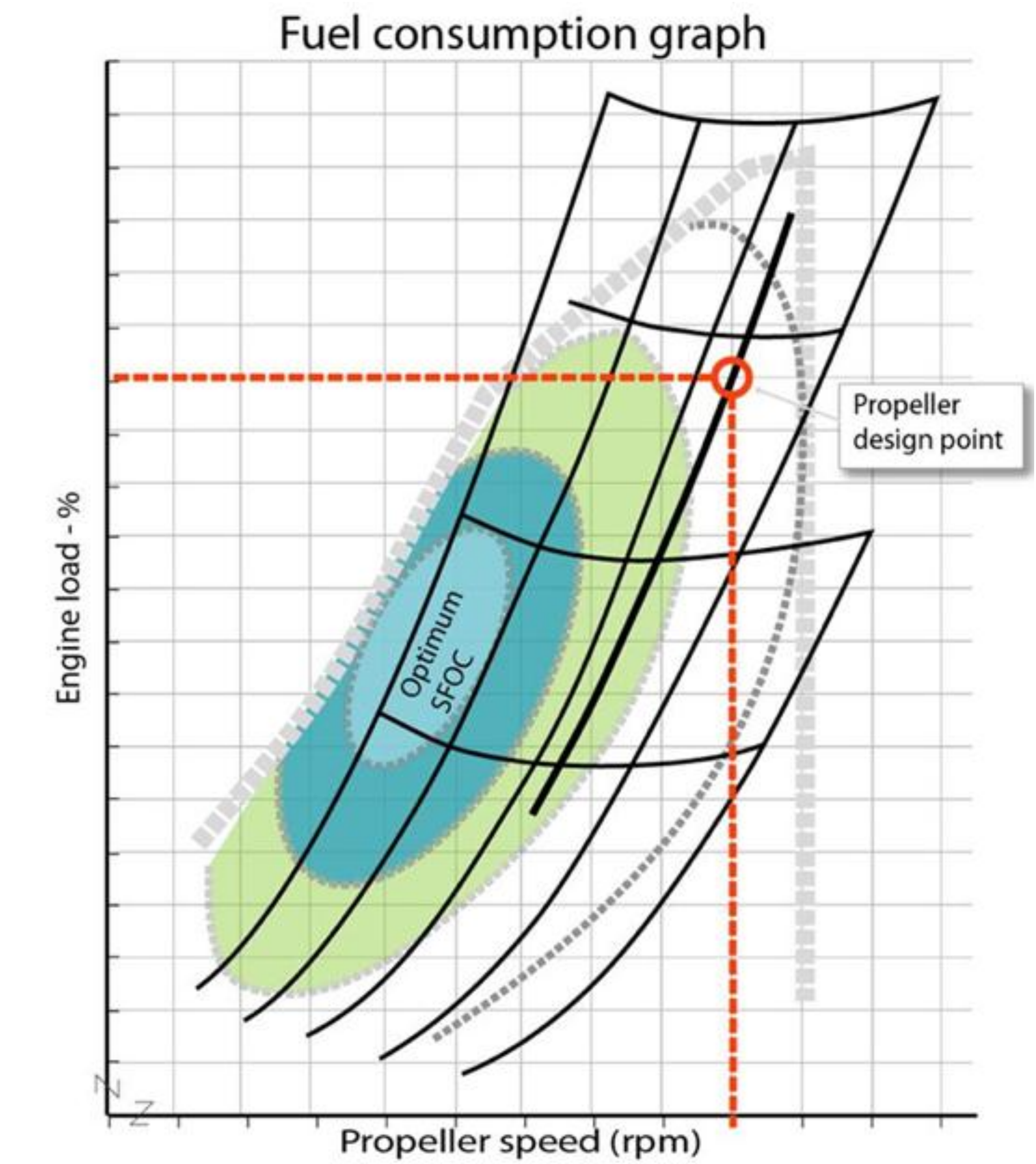


Figure 34 (Source: Wärtsilä)

In the above figure we can see that the engine is not running at the optimum SFC, this can result from having the wrong matching propeller and as results significant increase in the fuel consumption as shown above.

9.0 CONCLUSION:

At the start of this research there were several questions to be answered, tasks were to calculate the EEDI for several yachts built by Azimut-Benetti and to find some energy saving in the machinery side. After becoming more involved, more questions were raised from investigating various areas. After a preliminary analysis it has been decided to give priority to tasks where has been seen significant results while other minor tasks will be possible future work because the efficiency onboard a yacht is the sum of different aspects with small percentage of contribution.

The EEDI as a benchmarking index is superb idea to promote innovation and to create more sustainable environmentally friendly industry. However for the yachting industry until this point of time the research finding indicates that the EEDI still lack a lot of correction factors for speed, for design element and for some solid statistics to backup such index. This is clearly proven by the scattered EEDI results especially around the lower tonnage which will certainly result in an unfair benchmarking system. However, in practice the EEDI is most likely to push yachts to the larger or smaller sides of the tonnage, as for the moments majority of yachts produced after the year 2000 are clustered around the 400GT - 498GT. Smaller displacement vessels in that tonnage range cannot have sufficient speed without having to increase their power per GT ratio. If the EEDI enforced such vessels will have to find another optimum design point by reducing the speed and decrease the size of the installed power, or alternatively to shift into larger range where they can travel fast enough without having to increase their power to GT ratio.

As for finding an alternative method for emission reduction in the yachting industry, it was suggested by many online articles (Deltamarin: EEDI for RoRo vessels and special ships) that controlling the bunker price for yachts by means of taxation system. Thus will become financially feasible to invest in greener technologies while at the design stage or in operation.

There were some interesting findings with regard energy savings investigation. There were some significant findings in terms of heating with improvements can reach up to 50% reduction for the heating energy cost, for engines without having to go to extreme design changes there is about 3-4% savings in terms of different engine. Propulsion system was not discussed significantly in this report however there are many new developments where yachts seem to lag behind in terms of efficiency by concentrating more on comfort (such as noise level) and installation space than efficiency comparative to commercial merchant ships.

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11.0 APPENDICES:

ANNEX 1

BASIC EMISSION POTENTIALS

1-A: Estimated CO_2 emission potentials based on EEDI coverage per ship type main group (total tonnes of CO_2 emissions)

Ship Types	Total CO_2 emissions	% to total emissions	Cumulative sum
Crude oil tanker	112,769,764	10.1%	10.1%
Products tanker	43,378,360	3.9%	14.0%
Chemical tanker	64,139,731	5.7%	19.7%
LPG tanker	14,334,344	1.3%	21.0%
LNG tanker	33,250,235	3.0%	24.0%
Other tanker	2,377,084	0.2%	24.2%
Bulk	178,176,226	15.9%	40.1%
General cargo	95,915,792	8.6%	48.7%
Other dry-Reefer	19,220,666	1.7%	50.4%
Other dry-Special	1,050,811	0.1%	50.5%
Container	263,976,591	23.6%	74.1%
Vehicle	27,416,137	2.5%	76.6%
Roro	18,250,134	1.6%	78.2%
Ferry-Pax only	17,648,095	1.6%	79.8%
Ferry-RoPax	64,188,634	5.7%	85.5%
Cruise	21,307,727	1.9%	87.4%
Total EEDI coverage	**977,400,330**	**87.4%**	
Yacht	2,961,512	0.3%	87.7%
Offshore-Anchor handling T/S	343,305	0.0%	87.7%
Offshore-Crew/supply vessel	2,016,424	0.2%	87.9%
Offshore-Pipe(various)	1,694,125	0.2%	88.0%
Offshore-Platform supply	7,847,436	0.7%	88.7%
Offshore-Support/safety	1,287,720	0.1%	88.9%
Offshore-Tug supply	4,867,580	0.4%	89.3%
Service-Dredging	5,454,387	0.5%	89.8%
Service-Other	9,084,457	0.8%	90.6%
Service-Research	4,559,833	0.4%	91.0%
Service-SAR & patrol	2,399,215	0.2%	91.2%
Service-Tug	36,548,686	3.3%	94.5%
Service-Workboats	839,629	0.1%	94.6%
Miscellaneous-Fishing	22,606,670	2.0%	96.6%
Miscellaneous-Other	718,334	0.1%	96.6%
Miscellaneous-Trawlers	37,513,822	3.4%	100.0%
Total Non-EEDI coverage	**140,743,136**	**12.6%**	
Total for 2009	**1,118,143,466**	**100.0%**	
Total million tonnes for 2009	**1,118**		

Note: Ship types are classified as per IMO GHG Study 2009

Annex A

EEDI Technical File

Glossary

Abbreviations

DWT	Deadweight
PTI	Power take in
PTO	Power take off
MCR	Maximum continuous rating
MDO	Marine Diesel Oil
SFC	Specific fuel oil consumption

Subscripts

AE	Auxiliary engine
ME	Main engine
SG	Shaft generator

Symbols

NO_x	Nitrogen oxide
η_{SG}	Efficiency factor

A. Tables

Table A.1 General information

IMO no.	
GL Reg. no.	
Ship name	
Ship type	
Ship builder	
Year of delivery	
Ice class	

Table A.2 Principal particulars

Parameter	Value	Unit	Remark
L_{pp}		m	
B moulded		m	
Depth moulded		m	
Draft summer load line		m	to be taken from stability booklet
Lightship weight		t	from the lightship weight survey
DWT_{design}		t	to be taken from stability booklet
$DWT_{summer\ load\ draft}$		t	
$DWT_{70\ \%\ summer\ load\ draft}$		t	only for container ships
$Displacement_{ballast}$		t	from the sea trial report
$Displacement_{70\ \%\ DWT\ summer\ load\ draft}$		t	only for container ships
$Displacement_{design}$		t	to be taken from stability booklet
$Displacement_{summer\ load\ draft}$		t	from the summer load draft stability booklet

Table A.3 Main engine(s) particulars

No. of engines		General arrangement
Manufacturer		to be taken from the NO_x Technical File
Type		
MCR		
SFC (corrected) at 75 % MCR		
Fuel type used for NO_x certification		

Table A.4 Auxiliary engine(s) particulars

No. of engines		General arrangement
Manufacturer		to be taken from the NO_x Technical File
Type		
MCR		
SFC (uncorrected) at 50 % MCR		to be taken from the NO_x Technical File
SFC (ISO corrected) at 50 % MCR		ISO 8178
Fuel type used for NO_x certification		to be taken from the NO_x Technical File

Table A.5 Particulars of shaft generator

No. of shaft generators		
Manufacturer		from the manufacturer's documentation
Power (PTO(i))		
Power (PTO(i))		
η_{SG}		

Table A.6 Particulars of shaft motors (PTO)

No. of PTO		
Manufacturer		from the manufacturer's documentation
Power (PTO(i))		
Power (PTO(i))		
Generator manufacture		
Generator type		
Generator electrical output		
Efficiency of the generators		

Table A.7 Particulars innovative electrical auxiliary systems

No. of systems		
Manufacturer		from the manufacturer's documentation
Output capacity		
Availability factor		

Table A.8 Particulars of innovative technologies reducing main engine power for propulsion

No. of systems		
Manufacturer		from the manufacturer's documentation
Mechanical output		
Availability factor		

Table A.9 Model test information

Model facility		Model test report
Model scale		
Measured drafts		

Table A.10 Reference speed

Speed at EEDI conditions	

B. EEDI Calculation

The EEDI calculation shall be submitted. The calculation shall be complete and comprehensible as described in Section 2.