Integrated and Multi-objective Optimization Approach to Ship Design applied to improvement of EEDI

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ABSTRACT: The purpose of this study is to investigate the effects of EEDI on parametric ship design according to the new regulations of the Annex VI from Marpol. Therefore, in this study a parametric modelling software was used to analyse and create geometry's in order to obtain better results regarding the hydrodynamic efficiency and ship cost always considering the EEDI parameter as a guiding constrain to the design process.
This work is based on the typical container vessel, which will be analysed to identify the relevant main curves and their geometric characteristics, then the hull optimised in order to minimise the hull resistance and therefore the EEDI, taking into consideration the constraints related with the cargo capacity.
The Friendship Framework software is used, to combine the 3D geometric modelling, naval architecture and optimization algorithms. For the optimization procedure, Sobol and the NSGA-II algorithms were combined to obtain the most suitable ship for the intended purposes. During this study, 2300 ships were created and analysed.
This work concludes with the reaching of an optimized container vessel obtained and with a clear view over the parameters that have a higher weight in energy efficiency, giving the designer a complete discretization and modification capability for further tests regarding other important naval architecture measures of merit that have impact on EEDI.

Keywords: MARPOL, EEDI, Friendship Framework, parametric modelling, container ship, multi-objective optimization

1. Introduction

The international shipping industry is responsible for the carriage of around 90% of world trade.
The United Nations Conference on Trade and Development (UNCTAD) estimates that the operation of merchant ships contributes about US$380 billion in freight rates. Regarding containerized cargo it grew 4.6% in 2013 taking a total volumes to 160 million TEU's up from 153 million TEUs in 2012, (UNCTAD, 2014).
This said, what if it would be possible to reduce 1% on its operational cost and environmental foot print?
Based on this desire The Energy Efficiency Design Index (EEDI) was conceived, and will be mandatory for new build vessels from January 1st, 2013 (contract date),(MARPOL, 2008).
According to the rules under discussion, the EEDI of a new ship is reduced to a certain factor compared to a reference value yet to be decided. Thus, ships built after 2025 are proposed to have a 30% lower EEDI than the reference line.
This results in more competitive commercial outputs, leading to the need of higher and more advanced methods to conduct ship design., Murphy, Sabat et al. (1963).
With the parallel CAD – CAE evolution along optimization concepts a new era of ship design is emerging creating a contrasting advance regarding the classical approach, (Evans, 1959), to design and thinking towards container vessels design synthesis, (Papanikolau, 2012).
The scope of this study was to analyse the hull form of a typical container vessel to identify the relevant main curves and their geometric characteristics. Then a set of shape parameters closely related to the hull propulsive resistance were identified and selected to be used as the design variables of an optimization process. In the following step, three dimensional hull forms were generated parametrically and selected the best suitable EEDI and cost value ship was chosen.

2. Vessel under analysis

The vessel chosen as the scope of this work was created with the friendship framework software adapted to reproduce real operational data. This model was validated and enriched with several new features and control parameters.
After choosing the ship, the main naval architecture lines were identified regarding their geometric conversion to code language on the software. The main curves such as flat of bottom, flat of side, bow contour were acquired regarding the actual geometric details of the container vessel in actual service.
From this database were also retrieved trend lines to validate the results of the 3D geometric production. During the design stage conformity had to be obtained from what was being designed to what actually exist.

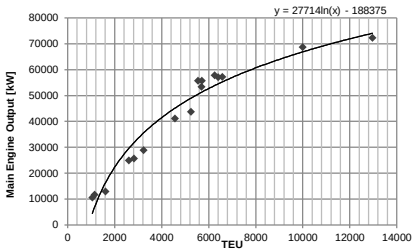

Figure 1 - Main Engine Output vs TEU capacity

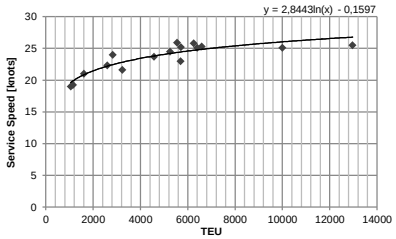

Figure 2 - Service Speed vs TEU capacity

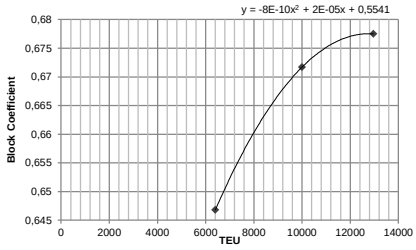

Figure 3 - Block Coefficient vs TEU capacity

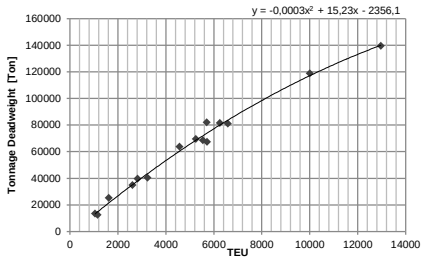

Figure 4 - Tonnage Deadweight vs TEU capacity

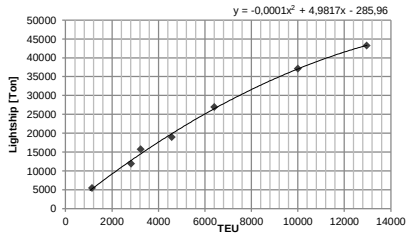

Figure 5 - Lightship vs TEU

The container vessel has the following starting characteristics, on Table 1:

Table 1 - Initial main particulars

GT	31129	Gross Tonnage
TDW	46527	Tonnage Deadweight
KW	24366	Power [kW]
V_S	20	Design speed [knots]
Lpp	270	Length between perpendiculars [m]
B	32	Maximum breadth moulded [m]
T	12	Design draft [m]
D	25	Depth [m]
TEU	5520	Container capacity
∇	69134	Displacement volume [ton]
C_B	0.65	Block coefficient

The major ships hydrodynamic design parameters such as speed, length breadth and depth depending on container quantity, draft, B/T ratio, prismatic coefficient are considered.

3. Design Parameter analysis

In order to carry on this study on the Energy Efficiency Design Index a parameter analysis was made with the purpose of measuring the effect that some critical parameters provoke on EEDI and validate all the code features developed during this study.

In the full variation charts there is an extra chart regarding the EEDI and power vs displacement curve plotted to observe and validate if this curve follows the attained EEDI or not. Since the EEDI attained is proportional to the power versus capacity when SFC and speed are constant the curves should have the same trend.

The fixed variable charts only have the EEDI and the respective variable active maintaining fixed all the other parameters of the random alteration created by the Sobol algorithm, (Sobol, 1979). These charts contain only a sample of the region in study with the aim of obtaining trend direction from the variable.

The objective of having both charts helps the reader to see clearly behind the fog of results created by the 500 variants of the Sobol distribution that in certain cases isn't conclusive regarding the direction of certain parameters.

Table 2 – Main Particulars

Parameters	Speed	Length	Beam	Depth	Draft	B/T	L/B	Block Coefficient
	(V)	(L)	(B)	(D)	(T)			(CB)

3.1 Variation in vessel speed

The results for the change in the EEDI with consideration to ship design and speed are shown on the Figure 6:

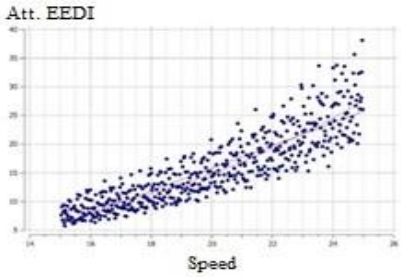

Figure 6 - EEDI and speed for each vessel of DOE

Some of the direct conclusions observed from the figure:

- Speed has a significant impact on the EEDI
- An increase in speed increases the attained EEDI drastically
- For the same speed different values are obtained for EEDI due to different DWT of the variants
- The higher the speed the higher the interval for minimum and maximum EEDI values.

3.2 Variation in length

The results for changing EEDI regarding the length of the variants are shown in Figure 7 and Figure 8:

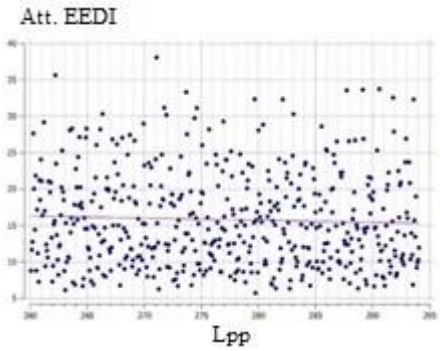

Figure 7 - EEDI and Length for each vessel of DOE

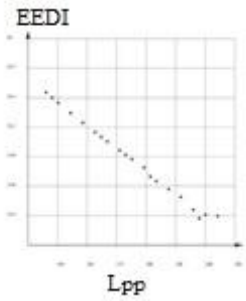

Figure 8 - EEDI and Length for each vessel of DOE fixed variation

On the previous figure is clearly observed a negative slope, showing that the attained EEDI decreases when the length parameter rises.
In the end the following characteristics are noted:

- Length affects the EEDI regarding the high impact on the ship resistance
- Logically an increase in length reduces the EEDI
- A substantial decrease in the attained EEDI is noticed from a certain increase of length
- The EEDI varies linearly with the length.

3.3 Variation in beam

The results for changing EEDI regarding the beam of the variants are shown in Figure 9 and Figure 10:

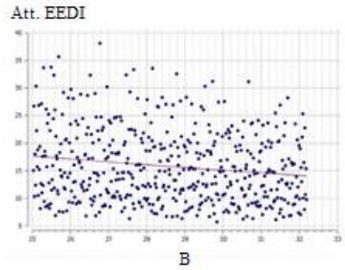

Figure 9 - EEDI and beam for each vessel of DOE

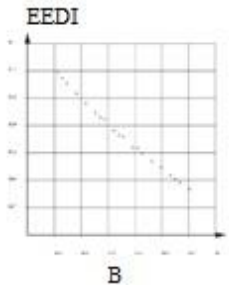

Figure 10 – EEDI and beam for each vessel of DOE fixed variation

- An increase in beam decreases the EEDI
- Beam has a significant impact on cargo so its increase reduces EEDI
- The EEDI linearly decreases with the increase of the beam dimensions.

3.4 Variation in depth

The results for changing EEDI regarding the depth of the variants are shown in figure 11 and figure 12:

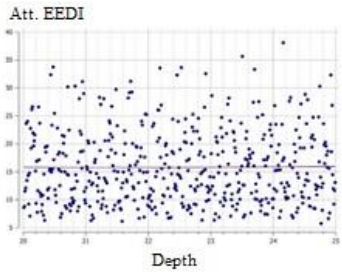

Figure 11 – EEDI and depth for each vessel of DOE

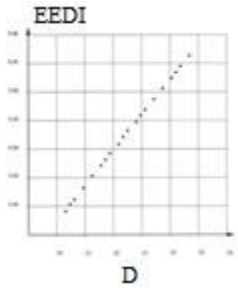

Figure 12 – EEDI and depth for each vessel of DOE fixed variation

- An increase in depth increases the EEDI
- The depth variation doesn't create any difference in EEDI ratio

3.5 Variation in draft

The results for the change on the draft are shown in the Figure 13 and Figure 14:

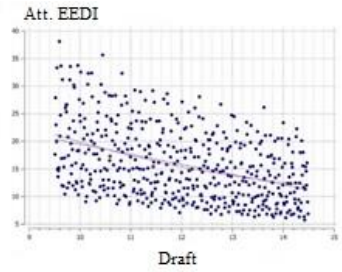

Figure 13 – EEDI and draft for each vessel of DOE

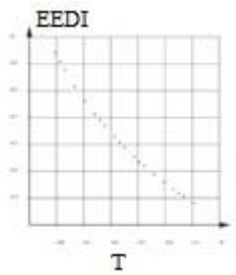

Figure 14 – EEDI regarding the draft of the DOE fixed variation

- Increasing draft decreases the EEDI
- Draft has a weighted impact on the EEDI
- The increase of draft means higher displacement that is directly connected to CGT creating a reduction on EEDI

3.6 Variation in CB

The results for changing EEDI regarding CB are shown on Figure 15 and Figure 16:

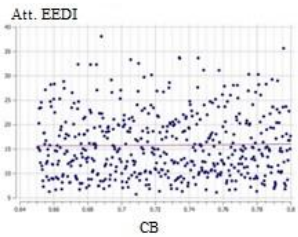

Figure 15 – EEDI regarding the block coefficient of the DOE

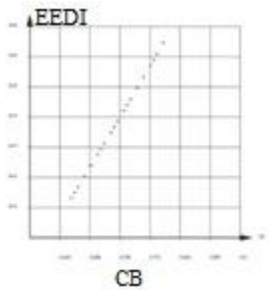

Figure 16 – EEDI regarding the block coefficient of the DOE fixed variation

- CB has a significant impact on EEDI
- The increase of CB increases the EEDI
- The EEDI shows linear evolution with the CB

3.7 Effective Power Displacement curve versus attained EEDI

The Effective Power Displacement curve is plotted against the attained EEDI to observe if the attained EEDI is proportional to the effective power (Kw)/ Capacity (Tonne), when SFOC is constant. In this condition the EEDI curve should have the same trend line has the Effective Power Displacement curve.

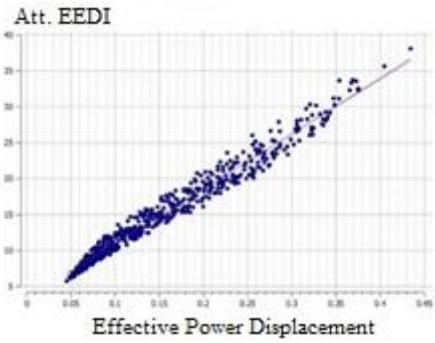

Figure 17 – EEDI regarding the Effective Power Displacement

- Power versus displacement curve follows the attained EEDI trend line
- The EEDI doesn't contradict the hydrodynamic rules of naval architecture
- Parametric

4. Parametric Model

The tool used in this project the Friendship Framework features a fully parametric shape descriptors and able to generate hull forms in a 3 step process: creation of b-splines, curve generation by curve engines and surface skinning, (Figure 18);

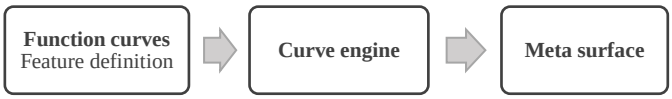

Figure 18 – FriendShip framework stage process

The first step consists on the production of a flexible set longitudinal curves from parametric input. The second step is the creation of a skeleton of transverse curves according to the parametric information contained in the basic curves. And finally the third step consists on the building of a fair set of surfaces interpolating the transverse curves parametric redesigning the existing curves.

The parameterization is implemented on the basis of a user readable, marine design-oriented model file which features DIR visualization organized by tree diagram of the parameters functions and features that in a hole constitute the model.

In this case study the fully parametric hull model was developed for typical containership forms. The model is divided into forebody and aftbody.

The aftbody is constituted of one single parametric surface while the forebody is a sum of several parametric surfaces, (Figure 19 & 20).

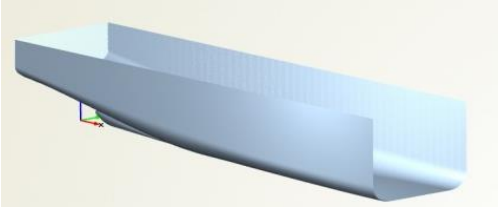

Figure 19 – Aft part of the hull

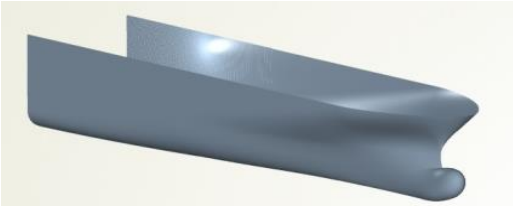

Figure 20 – Forward part of the hull

The basic curves depend on global variables and local variables that influence only small regions. The shapes of the basic curves are controlled by specifying the tangents at their start and end positions, respectively, as well as specific areas between the curve and an axis of reference.

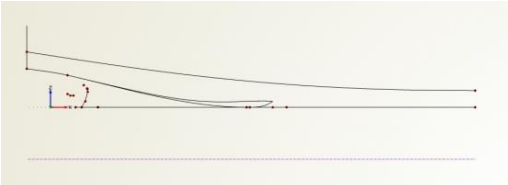

Figure 21 – Aft part generation function curves

Figure 22 - Forward part generation function curves

It´s important to refer that the software also integrates an environment for optimization that offers strategies for the deterministic and stochastic search of the design space. This part of the work will be explained in the next chapters along with its structure and sequence of the procedure adopted.

5. Geometric generation

Using the internal design oriented language of the software all the computational geometry had to be converted into the feature definitions of the program.

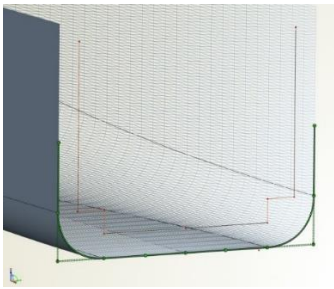

Figure 23 – Main Section and main cargo section

5.1 Created features

In order to assess the characteristics of the generated ship hull the environment features had to be created (Figure 24).

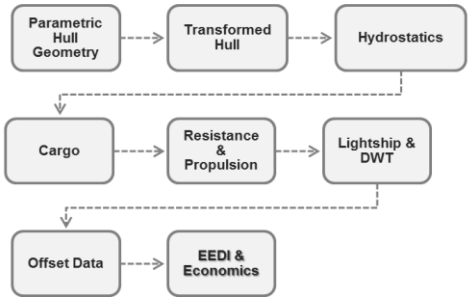

Figure 24 –Codes and design process

A brief description of the previously mentioned codes will follow.

5.1.1 Hydrostatics

The sections used for this module are obtained from the CAD feature for the offset command but have to be after transformed on an offset assembly.

On the scope of this study the designer had two principal features: first called ‘Displacement’ second ‘SW’ and they both use has input the transverse section till the draft waterline. As output the designer has for every variants instantly for parallel analyses and optimization purposes if necessary the values of: maximum draft waterline area, displacement and correspondent volume, waterplane longitudinal inertia, waterplane transverse inertia, transverse metacentric height above molded base, vertical position of the center of buoyance, longitudinal position of the center of buoyance.

These features will provide the necessary hydrostatic data to be used in the other stages of the design.

On the same scope another feature called offsetdata analyses the offset data from the hull geometric form it generates the base i.e. characteristic curves for a given offset group, (Figure 25):

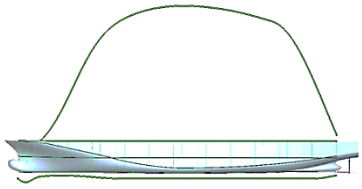

Figure 25 – Sectional area curve

The following curves are getting generated: Flat of side (fos), flat of bottom (fob), design waterline (dwl - depending on a given draft), center plane curve (cpc), deck curve (deck) and sectional area curve (sac - depending on a given LPP) as well as flare (tangent angle at draft). The offset group as required input data should be designed on baseline.

5.1.2 Resistance and Propulsion

In order to have an approximation to the hull resistance and the required propulsion the method of Holtrop & Mennen was applied. For this purpose this code had to be computed into the software language by the creation of a feature.
In order to proceed had to be accepted lack of precision regarding this area but it was required a way of calculus to be able of estimating the Energy Efficiency Design Index (Holtrop and Mennen 1982).

5.1.3 EEDI & Economics

The Energy Efficiency Design Index was also computed into a feature so for every new variant the designer can immediately compare the values. The method for calculating the EEDI (1) is obtained from the guidelines on the method of calculation of the attained Energy Efficiency Design Index, resolution MEPC.212 (63), Annex-11, pp. 1-4, 2012.

$$EEDI_{attained} = \frac{CO_2 Emission}{Transport\ work}$$

$$= \frac{Power * Specific\ Fuel\ Consumption * \ CO_2 Conversion\ Factor}{Capacity * Speed}$$

$$= \frac{Emission\ from\ Main\ Engine + Emission\ from\ Auxilliary\ Engine + Emission\ for\ running\ shaft\ motor - Efficient\ Tech.Reduction}{Capacity * Reference\ Speed}$$

$$= \left[\left(\prod_{j=1}^{n} f_j\right) * \left(\prod_{i=1}^{nME} P_{ME(i)} * C_{FME(i)} * SFC_{ME(i)}\right) + (P_{AE} * C_{FAE} * SFC_{AE}) + \left(\left(\prod_{j=1}^{n} f_j * \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} P_{AEeff(i)}\right) * C_{FAE} * SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} * C_{FME} * SFC_{ME}\right) \right]$$

$$* \frac{1}{f_i * f_c * Capacity * V_{ref} * f_w}$$

$$= \frac{kw * \frac{g_{fuel}}{kwh} * \frac{g_{CO2}}{g_{fuel}}}{Tonne * knotical \frac{mile}{h}} = \frac{g_{CO2}}{Tonne * knotical\ mile}, (1)$$

This attained EEDI must be less than the reference EEDI or reference line (2). This reference becomes different at different phases.

$$Reference\ line\ value = a \times b^{-c}, (2)$$

Where a, b and c are the parameters given in table 3 The reference line is based on the vessel database of Lloyd's Register Fair play, (Table 4).

Table 3 - Reference requirement for EEDI

Ship type defined in regulation	a	b	c
Container	174.22	DWT	0.201

Table 4 Phases for EEDI requirement

Ship Type	Size (DWT)	*Phase 0* 01.01.2013 to 31.12.2014	*Phase 1* 01.01.2015 to 31.12.2019	*Phase 2* 01.01.2020 31.12.2024	*Phase 3* 1.01.2025 to and onwards
Container Ship	≥ 15000	0	10	20	30
	10,000 - 15,000	n/a	0 - 10*	0- 20 *	0- 30*

5.1.4 TEU and Container Feature

During the progress of this study and the development of hull form it was clear that although the main theme of this thesis was to improve the EEDI, it was also in fact crucial to understand the feasibility of each design regarding operation and cargo. Having the main particulars of the ship dependent of the tiers, rows and bays of cargo from the ship the sequence of project was always considering if in fact the ship was feasible regarding stowage and if it could be allocate in a class of container vessels.
To have a reference regarding cargo the parametric model was connected with a new feature to design inner cargo spaces and then a second geometry was implemented on deck to have an approximation on the number of container present either in cargo hold space and on deck.
The main particulars of the design were assigned as a condition of the number of tiers, rows and bays of the ship and then the IMO visibility normative was applied to control assess the possible number of container on deck (Figure 26).

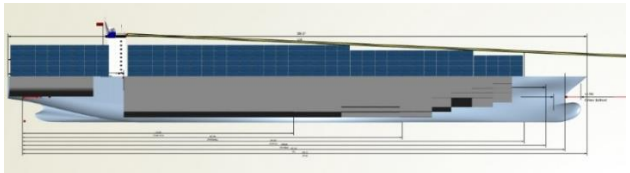

Figure 26 – Visibility cargo line

5.1.5 Lightship Approximation Feature and DeadWeight assumption

The Lightship weight approximation is a key part of the preliminary design. The LW is obtained from a feature based on estimation of weights regarding the fact that in order to have a complete description of material

quantity, outfitting, machinery and superstructure an entire project had to be developed.
Deadweight Analysis is connected to the LW mentioned before. Because the theme of hull optimization is already a large field, contemplating a route and calculating with precision consumables and all the main components of deadweight would deviate from the main theme of Energy Efficiency. So on this work the deadweight is obtained by simply subtracting the displacement from the parametric model that has perfect precision from the empirically obtained lightweight, (Figure 27 & 28).

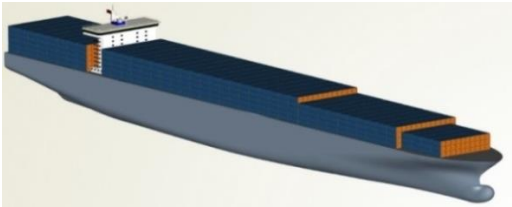

Figure 27 – Container vessel cargo distribution on deck

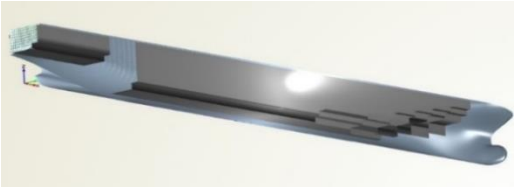

Figure 28 – Modeled cargo holds

6. Optimization Sequence

The optimization sequence is a structured stage process which travels on the field of solutions gradually zooming close to the main objective or group of aimed parameters.
In order to attain the minimum EEDI for the parametric ship the first step of the optimization sequence requires a previous space of reliable solutions, where a domain of combinations of global and local variables produce an approximate solution regarding the desired one. This initial part of the optimization structure is powered by a quasi-random Sobol design engine.
The algorithm outputs the design variables in a random way creating an evenly distribution over the design space to create all the possible combinations of design vectors and variants.
On the figure 29 all the 500 variants are displayed regarding the attained EEDI and the speed and run number.

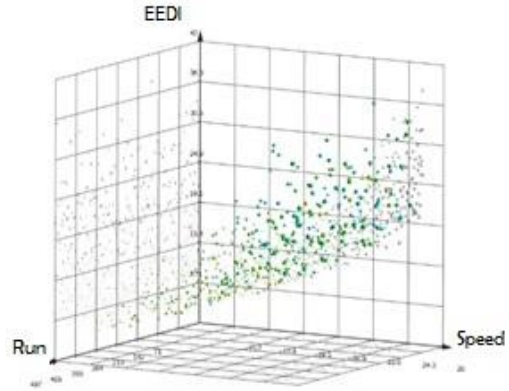

Figure 29 – Field of variants DOE

On this runs there is an even percentage of variants that do not comply with the constrains,(Table 6), showing the range of applicability of the parametric model for the study target.
After the conclusion of the DOE the designer has the application limits and may choose to wide or restrict the range of the design variables viewed on the Table 5.

Table 5 - Design variables

Parameter	dependent on
Length	bays
Beam	rows
Depth	tiers on hold
Draft	-
C_B	-
Speed	-

Table 6 - Design constraints

Constraints	dependent on
Att EEDI lower than	Req EEDI
Free Board higher than	Free Board min
DW between	max DW min DW

From the results it's possible to visualize the validity and domain in an independent way of each variant having at disposal a clear view of their behaviour pattern.
It is important to notice that in modern optimization the designer has to have a clear view of the problem ahead and of the tool used to solve it. Regarding the tool and of course the dependencies between the different parts of the parameter field many combinations of output may be obtained, the question is how to control it and how to understand the different effects of the several modifiable components on the input vector seen on Table 7.

Table 7 – Objective functions

Merit Measures
MIN Energy Efficiency Design Index
MIN Ship Total Cost

After DOE stage to create a design of experiments baseline a multi objective genetic algorithm NSGA II is used for multi objective optimization, see Deb, Pratap et al. (2002). The algorithm focuses in minimizing the defined objectives simultaneously. During this simulation the genetic algorithm is employed in three different stages after the use of Sobol. Each time the

NSGA II runs, a population of 50 variations from the previous run is used on a six generations cycle.
During this search of solution field the priority target was always the EEDI although the ship cost is also and parameter under evaluation. Stage after stage the variables where adjusted with the previous understanding of their behaviour in order to minimize the EEDI. The Figure 30 discretises the process.

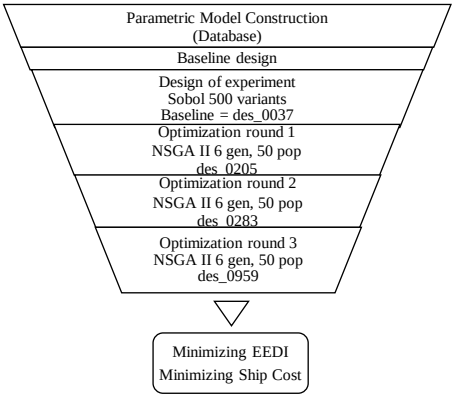

Figure 30 – Hierarchy stage optimization model

7. Results Analysis

The behaviour of the different variables on this last stage gave an insight in to the design process and showed how intuitive it can be after the input vector and output solutions are analysed. The designs will converge not to a single solution but to a region where several possible variants are accepted has optimum. At this point the designer has to choose the one that brings conformity and satisfies in a better sense the proposed target.
The variation of the design variables are strongly constrained because of the model constrains. The following scatter diagrams show a common trend between the main particulars of the optimized model.
The Figures 31 to 38 represent the last optimization run and show the region and values for the different variants extracted from the parametric model.
It is possible to observe where the highest condensation of results is located and if the designer would have to repeat the process of viewing where is located the best result for the desired variable and where, according to this particular model, it has more chance of acquiring the best value to a certain parameter.

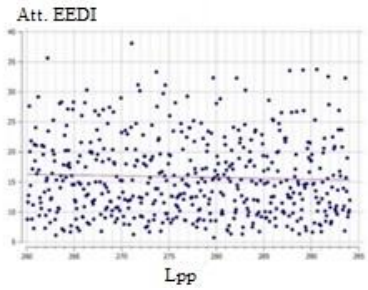

Figure 31 – Optimization of EEDI regarding Length

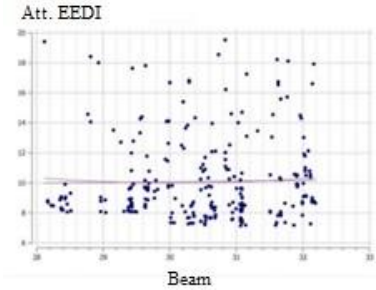

Figure 32 - Optimization of EEDI regarding beam

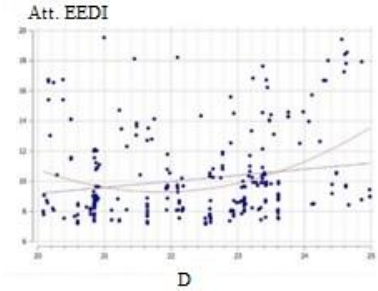

Figure 33 – Optimization of EEDI regarding depth

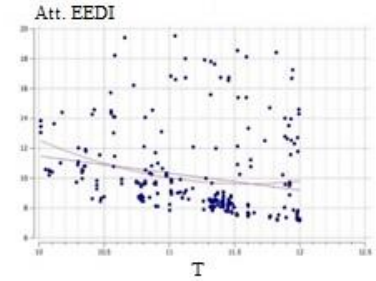

Figure 34 – Optimization EEDI versus draft

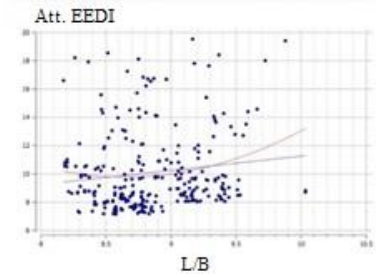

Figure 35 – Optimization of EEDI regarding L/B

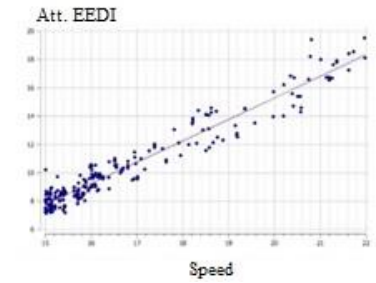

Figure 36 – Optimization of EEDI regarding speed

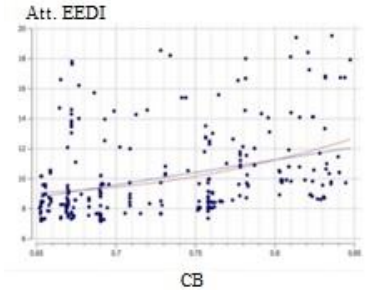

Figure 37 – Optimization of EEDI regarding CB

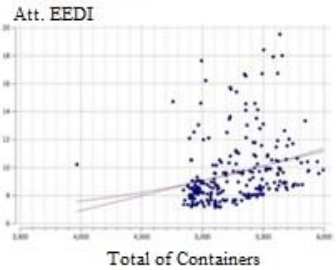

Figure 38 – Optimization of EEDI regarding total container

From observation is possible to continue studying and closing the boundaries of the field of solution forcing the engine of optimization to focuses on certain regions for a certain variable. This process becomes exhaustive if repeated many times and if the problem has higher levels of complexity may create incoherence's also if the form of the hull simply is unable to arrive at a certain set of variables configuration.

During this study the EEDI result was always coherent, being minimized after each step and after all the intervals of adjustments, (Table 8).

When the Pareto curve and the single design is chosen from the priority two main merit functions a brief analogy is executed regarding the starting point of design.

The scatter diagram shows the several combinations and the domain of the solutions. By minimizing the both objectives, the designer gets to the stage where the further improvement of one objective will degrade the performance from the other.

On the Figure 39 a line is drawn to represent the Pareto frontier and the chosen model is marked.

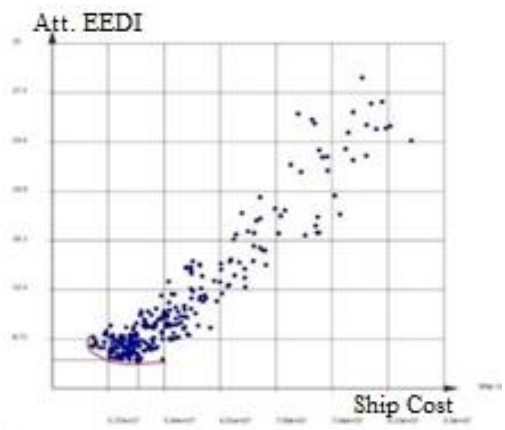

Figure 39 – Pareto front for EEDI and Ship Cost

This numeric model has 82 local shape parameters for the mathematical model this file contains, 6 design parameters and 2 merit parameters.

There are in total 21 parameters used for this work. From these 21 parameters 18 were created and are only viewable on the model file.

Table 8 – Performance comparison

		Base line	Sobol	NSGAII			Variation
		(Database)	*des_0037*	*run 1* *des_0205*	*run 2* *des_0283*	*run 3* *des_0959*	*Baseline* *Final Design*
Design variables	**L_{pp} [m]**	270	279,73	274,81	268.92	272,42	-1,34%
	B [m]	32	29,83	31,08	32.05	31,77	-3,03%
	D [m]	25	24,76	20,22	20,91	21,03	-11,11%
	T [m]	12	14,42	11,95	11,98	11,93	0,00%
	V_S [knot]	18	15,156	15,07	15,11	15,02	-19,84%
	C_B	0,65	0,7	0,75	0,7	0,66	5,80%
Objective Functions	**Att EDDI**		**8,74558**	**7,234**	**7,0978**	**7,013**	**19,67%**
	Ship Cost [$]		**69408459**	**58403900**	**57463500**	**57052500**	**-8,10%**
Evaluation	**Nr TEUs**		4753	4587	4549	4237	6,86%

Although the chosen design for maximum reduction on the EEDI was (des_0959), another run was done to obtain the design closest to the tier three EEDI boundary line. This allowed understanding how the design would evolve when approaching the required EEDI limit. The particulars of the design are presented here for reader understanding even though this exercise was purely for test and no conclusion is opt to be obtain beside the fact that for this individual model and restrictions when moving towards the EEDI requirement the vessel will primarily modify the speed and the block coefficient.

Table 9 – Tier 3 optimized main particulars

Particulars	Value
Length [m]	264,10
Beam [m]	30,20
Depth [m]	21,33
Draft [m]	11,95
C_B	0,75
Speed [knot]	18,75
Cost [$]	6,25E+07
EEDI	12,27

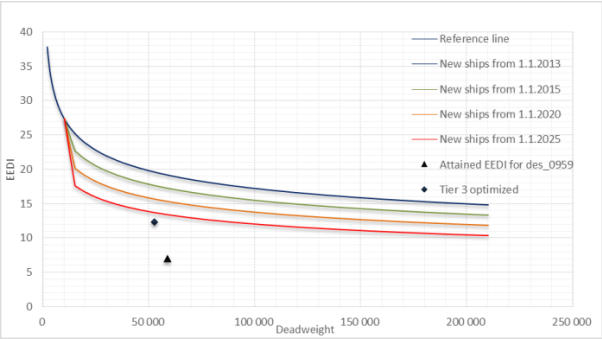

Figure 40 - Energy Efficiency Design Index reference lines and designs

The final ship obtained from the run number 3 of the NSGA II algorithm is shown in the Figure 41.

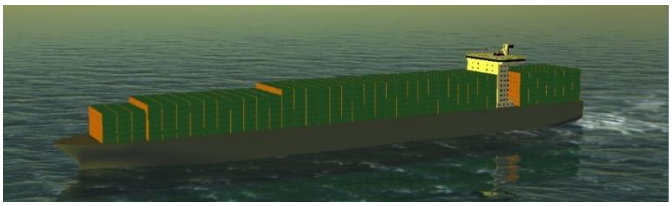
Figure 41 - Operating final version

8. Conclusions and Further Improvements

The Energy Efficiency Design Index will be viewed for the next years as a reference for the industry and designers.
It will drive the need for more efficient ships with the aim of reducing the CO2 emissions and by doing so redefining a new economic marine trade age. It is in its core a new naval architecture requirement for transport efficiency and ship improvement.
It makes no sense to compare EEDI values from ships with fair differences in sizes, doing so would be a mistake although it can be understood that scale economy is applied when looking at EEDI as a design parameter.
According to the reference line it may seem that smaller ships are allowed to have lower EEDI requirements. This would mean that small ships could operate in higher speeds but in fact it actually means that the reference line allows higher EEDI for smaller vessels because they usually have lower levels of efficiency.
From this study was also noticeable that no matter how extremely improved the hull would be its initial form would dictate from the beginning the outcome of the optimization.
Most hulls analysed from the database easily complied with the phase 0 of the EEDI with few modifications or none. Mostly of the first phase requirements could also be achieved without reducing speed. Even if the design keeps evolving in order to comply with requirements of the last stage of the EEDI, there will be no other alternative than reducing speed.
Although the EEDI is not an accurate way to measure emissions it is indeed useful for the designer to have it has an indicator to avoid pre design stage miss considerations that lead to unfeasible ship regarding energy efficiency.
After the three stages of optimization it was conclude that although it is a highly constrained process there is still margin to meet extra requirements to change the direction of the project without any exponential loss of time.
The parametric model has proven to produce effective ship shapes and follow a dense process of optimization that run over 2300 ships in a 4 stage hierarchy multi objective engine reaching the desired goal that was set to achieve, Integrated and Multi-objective Optimization Approach to Ship design applied to improvement of Energy Efficiency Design Index.
There are several improvements that could be made to this study like integration with a CFD software, a detailed way of calculating weights and a fully parametric cargo calculation would largely increase the value of the work done.
Loading conditions could be studied and simulated to have a clear view of the operational coefficient that must be considered when designing the best ship possible for a set of main particulars.
In a further work it could also be studied hull design according to sea and route.

9. REFERENCES

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