Parametric design and multi-objective optimisation of containerships

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ABSTRACT: The introduction of new regulations by the International Maritime Organisation (IMO), the fluctuation of fuel price levels, along with the continuous endeavour of the shipping industry for economic growth and profits has led the shipbuilding industry to explore new and cost-efficient designs for various types of merchant ships. In this respect, proper use of modern computer-aided design/computer-aided engineering systems (CAD/CAE) extends the design space, while generating competitive designs in short lead time. The present paper deals with the parametric design and optimisation of containerships. The developed methodology, which is based on the CAESES/Friendship-Framework software system, is demonstrated by the conceptual design and multi-objective optimisation of a midsized, 6,500 TEU containership. The methodology includes a complete parametric model of the ship's external and internal geometry and the development and coding of all models necessary for the determination of the design constraints and the design efficiency indicators, which are used for the evaluation of parametrically generated designs. Such indicators defining the objective functions of a multi-objective optimisation problem are herein the energy efficiency design index (EEDI), the required freight rate (RFR), the ship's zero ballast (Z.B.) container box capacity and the ratio of the above to below deck number of containers. The set-up multi-objective optimisation problem is solved by use of the genetic algorithms and clear Pareto fronts are generated.

KEYWORDS: parametric; design; multi-objective; optimisation

1 INTRODUCTION

1.1 *Container shipping industry*

Global containerised trade has been facing constant growth since 1996. It is worth mentioning that in 2013, there was a 4.6% growth, which can be translated to a total movement of 160 million TEUs in one year (Clarkson Research Services, 2014).

The fluctuation of fuel price has caused changes in the operation of ships. Since 2008, the fuel price has dropped and nowadays heavy fuel oil (HFO) costs as low as 250 $/t. Marine diesel oil (MDO) has been following similar course and can be found at prices of around 450 $/t (Ship & Bunker, 2016). However, this does not always result in lower shipping rates. The introduction of emission control areas (ECAs) has affected the fuel type ships use. Use of low sulphur fuel is now required in certain parts of the world. The price difference between fuel types can be significant. Hence, it is imperative that cost-efficient designs are created to overcome this encumbrance (Koutroukis et al., 2013).

Lately, the shipping industry has adopted several practices to reduce fuel consumption. One of them is slow steaming. Traveling at lower speeds, vessels can achieve major fuel savings, as well as lower EEDI levels (Tozer, 2008, White, 2010).

Port efficiency has become one of the most important factors in containership design. The less time containerships spend in port, the more time is available for cruising at sea. That can be translated to lower cruising speeds and reduced fuel consumption (Soultanias, 2014). As a result, port efficiency is included in the optimisation criteria of this study.

1.2 *State of international regulations*

Recently, there have been developments in the international maritime regulations that greatly affect future ship designs and herein particularly containerships.

One major development is the introduction of the EEDI (IMO, 2012a, b). The EEDI relates the toxic gas emissions of a ship to her transportation work and is in fact an indicator of a vessel's energy efficiency. The requirement for new ships started with

some baseline values in 2013, which will be being lowered successively in three steps until 2025. It is evident that EEDI is a ship efficiency performance indicator that should be minimised in the frame of a ship design optimisation.

New rules have been recently developed regarding the control and management of ships' ballast water and sediments and are applied to all ships as of today. Although various systems and technologies dealing with ballast water treatment are currently available, their installation increases the overall building and operational costs. Therefore, research has been focusing lately at solutions to reduce the amount of required ballast water. This issue is magnified for containerships, which inherently carry more ballast water, even at the design load condition.

Finally, new stability criteria are currently being developed by the IMO. The introduction of ships with newly developed characteristic and operation modes has challenged the assumption that the current criteria are sufficient to prove their stability. Hence, the new criteria, which will complement the existing regulations, will be performance-based and will address four modes of stability failure; parametric roll, pure loss of stability, stability under dead ship condition and surf-riding/broaching (Peters et al., 2011). As far as containerships are concerned, parametric roll is considered to be one of the most important modes of stability failure (Spyrou, 2005). Hence, the draft criteria of level 1 and 2 for parametric roll failure mode according to SDC 2/WP.4 are applied as part of the optimisation process in this study.

2 PARAMETRIC CAD MODELLING

In recent years, several authors have presented significant CAD methodologies dealing with ship design process and inherently its optimisation (Brown, 2003, Campana et al., 2009, Mizine, 2010). A common characteristic of most of the earlier presented works is that they are dealing with specific aspects of ship design or with new system approaches to the design process. On the other hand, the present study deals with a fast, holistic optimisation of a 6,500 TEU containership, focusing on optimisation of the ship's arrangements, while considering all side effects on ship design, operation and economy (Fig. 1) (Priftis et al., 2016). Holism is interpreted as a multi-objective optimisation of ship design and is based on the main idea that a system, along with its properties, should be viewed and optimised as a whole and not as a collection of parts (Papanikolaou, 2010).

2.1 Geometric model

The model is produced within CAESES/Friendship-Framework and consists of four main parts; the aft body, the fore body, the main frame and the main deck (Fig. 2). Several parameters are defined at this stage in order to control certain parts of the hull.
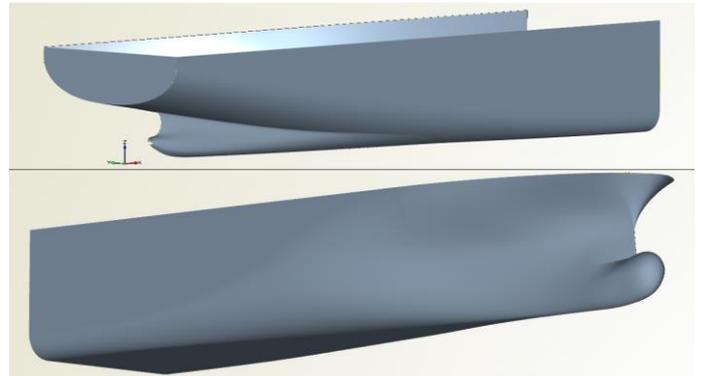

Figure 2: Modelled aft and fore body

In order to create an adequately faired and smooth hull surface, a Lackenby transformation takes place. By adjusting the prismatic coefficient (c_P) and the longitudinal centre of buoyancy (LCB), the final hull of the model is produced (Abt, 2007).
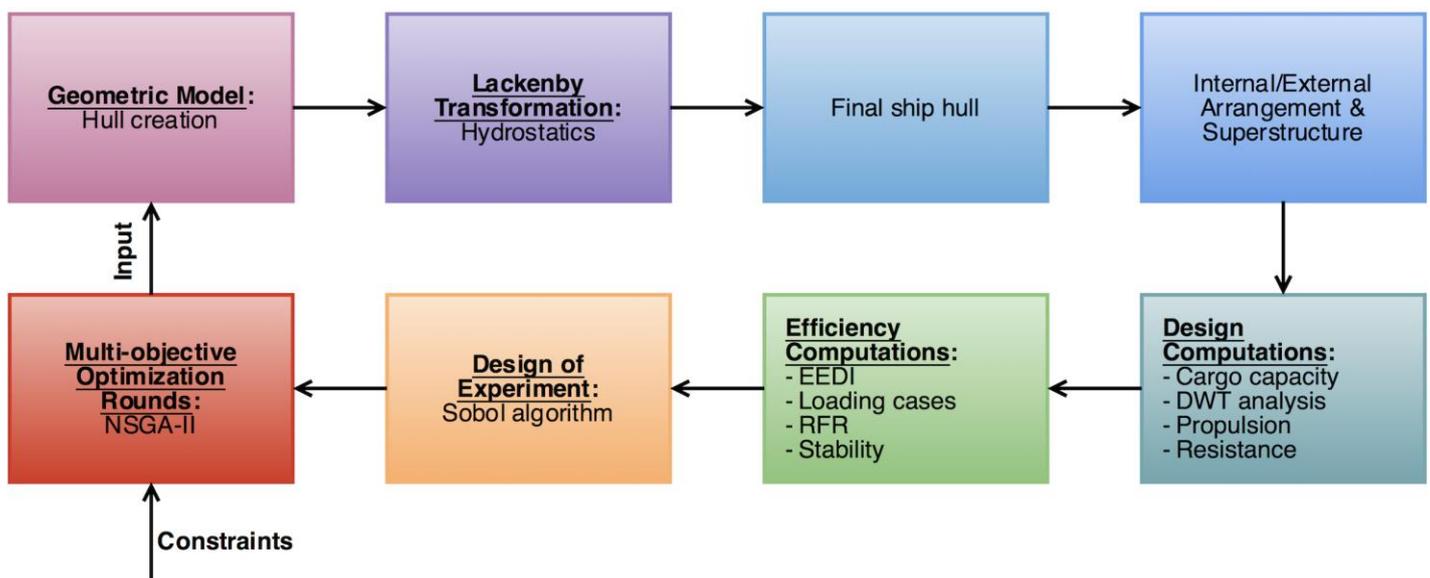

Figure 1: Design optimisation procedure

Next step is to create the superstructure and the cargo arrangements (Fig. 3). Custom programmes, or features, as they are called within the software, are developed for this purpose. Taking into account several parameters, such as the number of decks, the bay spacing, the double bottom and double side distances, as well as the IMO visibility line regulation and the deck line, the required surfaces are produced to build the deckhouse and the cargo arrangement below and above the main deck.
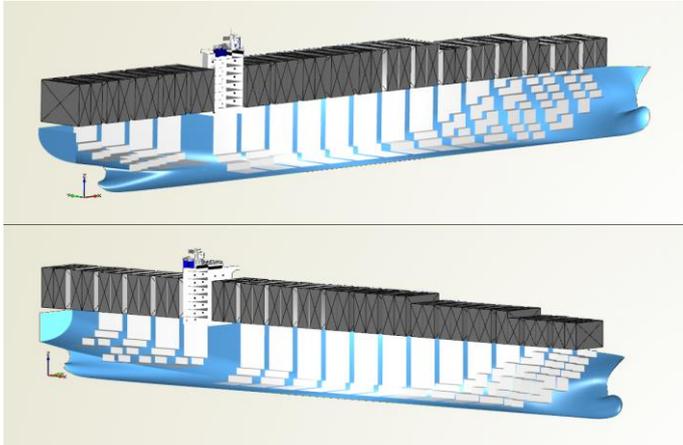

Figure 3: Geometric model

2.2 *Naval architectural computations*

After the proper definition of the geometric model, several naval architectural computations take place, in order to produce the required values, which are then used as input during the computation of the performance indicators examined in the present study.

For this reason, custom features are created within the software. Cargo capacity is automatically calculated thanks to a feature that retrieves information from those responsible for the creation of the cargo arrangements. Custom features calculate the total resistance (R_T) and the propulsion, according to the Holtrop and Mennen method (Holtrop, 1978). In addition, features incorporating several semi-empirical approaches for the calculation of the lightship are also developed (Papanikolaou, 2014). Finally, custom features responsible for the deadweight analysis generate the necessary values for the determination of the loading cases examined. An operational profile is set up at this stage, so as to reckon the amount of consumables carried on board (Table 1).

Table 1: Operational profile

Operational speed (Kn)	20
One-way route distance (nm)	12,205
Number of ports	18
Average time at port (h)	15.3
Transit time (days)	63

2.3 *Design indicators*

After the definition of the features responsible for the naval architectural computations, the develop-

ment of those responsible for the determination of the design indicators takes place. These indicators will then be used as the objectives in the optimisation procedure.

A custom feature is programmed in order to calculate both the required and the attained EEDI values, according to the regulations. Apart from producing those results, an "attained/required" EEDI ratio is also calculated, to be used as a constraint during the optimisation phase.

A significant performance indicator for this study, the RFR, is also calculated by use of features. Taking the present worth of the operating and the ship acquisition costs, the number of the round trips and the TEUs into account, the freight rate is determined.

$$\text{RFR} = \sum_1^N \left[\frac{\text{PW(Operating cost)} + \text{PW(Ship acquisition cost)}}{(\text{Round trips}) \times (\text{TEUs})} \right] \quad (1)$$

One of the most important innovation elements in the model is the control of trim and stability, while optimising for maximum number of containers on deck and minimum carried ballast. Within this software module, essential ship hydrostatic and stability parameters are determined. The assessment of the initial and large angle stability of the vessel is undertaken in accordance with the IMO A.749/A.167 intact stability criteria.

In addition, the level 1 and 2 draft criteria for parametric roll failure mode according to regulations are applied (IMO, 2015). The level 1 criterion, based on the Mathieu equation, is meant to be simple and conservative, in order to quickly detect a vulnerability to parametric roll. On the contrary, level 2 criterion is more complex, thus less conservative, taking into account more detailed parameters in order to determine whether the ship is vulnerable to parametric roll or not. In order to properly define a way to perform the level 1 and 2 checks within CAESES/Friendship-Framework, multiple features are created, each one having a specific purpose. Moreover, several external software are connected with the model, so as to quickly evaluate certain parameters required for these particular computations. Maxsurf Stability Enterprise is used to produce values of the metacentric height (GM) in various wave conditions, while Matlab is responsible for the calculation of the roll amplitude, where complex equations must be solved.

Furthermore, a custom feature responsible for the determination of the examined loading cases is created. The loading conditions investigated in this study are the maximum TEU capacity and the zero ballast conditions. For the former case, the main objective is to maximise the cargo capacity. On the other hand, the latter condition is defined as a condition where no water ballast is loaded for stability reasons, with the exception of some limited water ballast in the aft and fore peak tanks, for trim bal-

ance. As in the first case, the objective is the maximisation of the number of loaded TEUs.

Following the definition of the loading cases, two performance indicators are created; the port efficiency and the zero ballast water indicators. The former is represented by an "on deck/in hold" stowage ratio. The objective is to maximise the ratio i.e. the number of TEUs stored on deck. The zero ballast water indicator is represented by a capacity ratio, which is defined by dividing the number of TEUs the ship can transport while in zero ballast condition to the maximum TEU capacity. As in the port efficiency indicator's case, the higher the capacity ratio, the more competitive is the vessel.

2.4 *Design exploration*

Before proceeding to the formal optimisation round, a design of experiment (DoE) is conducted first. This process allows us to examine the design space and the response of several parameters to the change of the model's main characteristics. The algorithm utilised is the Sobol algorithm, a quasi-random sequence which secures the overall coverage of the design space, while overlapping of previous set of sequences is avoided (Mohd Azmin, 2015). Through the DoE, the investigation of the feasibility boundaries is ultimately achieved, allowing us to detect the trends of the design variables (Table 2) in regard to the optimisation objectives. In our case, the design engine is assigned to create 250 variants of the initial model.

Table 2: Design variables

Design variable	Min. value	Max. value
Bays	18	20
Rows	14	18
Tiers in hold	8	10
Tiers on deck	6	8
Double bottom (m)	2.00	2.75
Double side (m)	2.00	2.75
Δc_P	-0.06	0.06
ΔLCB	-0.026	0.026
Bilge radius (m)	4	6

Moreover, the constraints are set (Table 3), so as to have a clear view of which of the subsequent variants violate criteria that must be met.

Table 3: Design constraints

Constraint	Value
"Attained/Required" EEDI	≤ 1
GZ area (0-30 deg)	≥ 0.055 m-rad
GZ area (0-40 deg)	≥ 0.09 m-rad
GZ area (30-40 deg)	≥ 0.03 m-rad
Initial GM	≥ 0.15 m
Angle at GZ_{max}	≥ 30 deg
GZ_{max}	≥ 0.2 m
Homo weight/TEU (max. TEU capacity)	≥ 6 t
Homo weight/TEU (Z.B. condition)	≥ 7 t
Trim at full load departure condition	$\leq 0.5\%$ L_{BP}
Parametric roll criteria	$= 1$ (pass)

2.5 *Multi-objective optimisation*

The last step to complete our work is to run the formal optimisation round. To achieve that, the non-dominated sorting genetic algorithm II (NSGA-II) is utilised (Deb et al., 2002). In particular, during each run, five generations are created, having a population size of fifty-two, each. The design variable extents remain the same, as the design space proved to be well defined, following the DoE phase. As far as the constraints are concerned, apart from the ones defined in the previous stage, two additional are set to delimit the maximum TEU capacity of the ship variants. Therefore, an upper (7,000 TEUs) and lower (6,000 TEUs) limit is defined. Unlike the previous phase, in this case, apart from the evaluation of various parameters of the model, several objectives are defined:

- Minimisation of the RFR
- Maximisation of the capacity ratio
- Minimisation of the EEDI
- Maximisation of the stowage ratio
- Minimisation of the overall ship resistance

The results of a multi-disciplinary optimization procedure might not provide a straightforward solution to a problem. For this reason, several case scenarios are created, so as to determine the optimal of the top solutions to the problem. In our project, three distinctive scenarios are defined, where the significance of each objective is acknowledged differently by assigning specific "weights" following the utility functions technique of decision making theory (Table 4). In scenario 1, all 5 explored objectives are considered to be equally important. On the other hand, in scenarios 2 and 3, the RFR and capacity ratio are chosen to be more significant for the decision maker (designer, operator).

After obtaining the results of each run, the data is normalised according to the scenarios. Afterwards, the normalised data is ranked, in order to find the optimal variant of our model.

Table 4: Case scenarios

Objective	Scenario 1	Scenario 2	Scenario 3
RFR	20%	50%	20%
Capacity ratio	20%	20%	50%
EEDI	20%	10%	10%
Stowage ratio	20%	10%	10%
Ship resistance	20%	10%	10%

3 DISCUSSION OF RESULTS

3.1 *Base model*

Before proceeding to the actual results, some essential information about the base model is presented, in order to have a clear perspective of the initial hull (Tables 5-6).

Table 5: Base model design variable values

Design variable	Base model value
Bays	19
Rows	16
Tiers in hold	9
Tiers on deck	6
Double bottom (m)	2.0
Double side (m)	2.1
Δc_P	-0.01125
ΔLCB	-0.00375
Bilge radius (m)	5

Table 6: Base model design objective values

Objective	Base model value
RFR ($/TEU)	582.35
Capacity ratio	0.5206
EEDI	8.80
Stowage ratio	0.9451
Ship resistance (kN)	1559

3.2 *Design of experiment*

The DoE phase enables the exploration of the huge design space, which is impossible in traditional ship design procedures. The following observations can be made.

As far as the correlation between the number of bays and the number of TEUs is concerned, it is evident that as the former increases, the latter gets also higher. The same behaviour can be observed as to the dependency on number of rows (Figs 4-5).
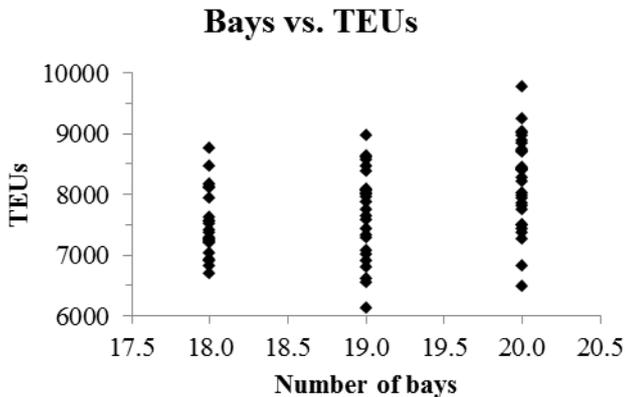
Figure 4: Bays vs. TEUs

Furthermore, since the formula used to calculate the attained EEDI contains the transport work, which is relative to the deadweight of the vessel, it is clear that changes in the displacement of the model result in variation of the attained EEDI. An increase in the displacement of the model normally leads also to an increase of deadweight. Since the deadweight is inversely proportional to the attained EEDI, as the displacement of the model increments, the index trivially declines, which is expected by the economy of scale (Fig. 6).
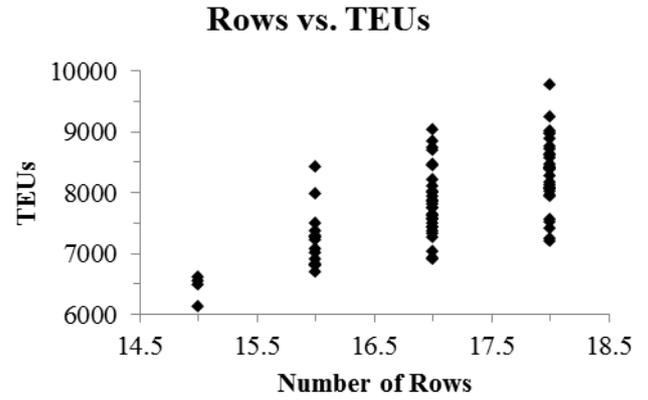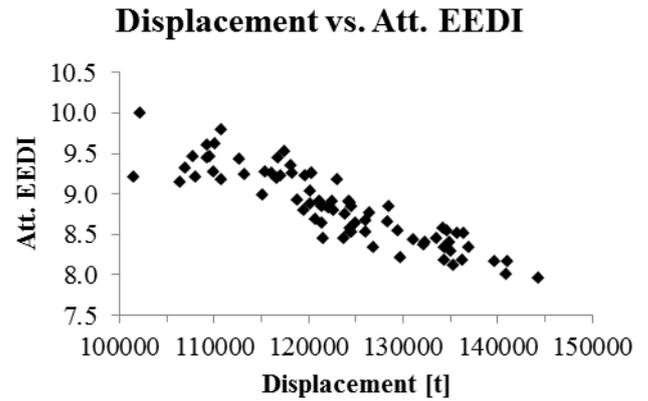

Figure 5: Rows vs. TEUs
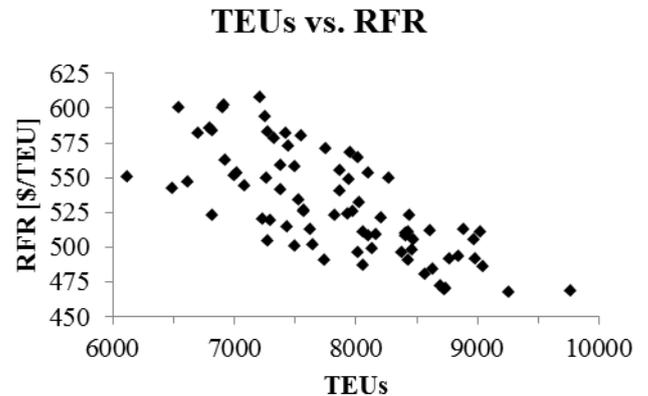

Figure 6: Displacement vs. Attained EEDI

Figure 7: TEUs vs. RFR

Finally, as far as the dependency the RFR on the TEU capacity is concerned, it is evident that the RFR decrease, as the ship size and capacity increases, which is a clear indication of the economy of scale (Fig. 7).

As far as the draft criteria for parametric roll failure mode are concerned, it should be mentioned that 6% of the variants created during the DoE phase did not pass either of the two levels.

3.3 *Multi-objective optimisation*

Following the NSGA-II run and the evaluation of the results, an improved design, named Des0156, is

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identified. Des0156 ranked first in the first two case scenarios. A second variant, named Des0242, ranked first in the third scenario. Following the decision making process, Des0156 is ultimately selected as the optimal design. Below, some principal information of the optimised design can be found (Fig. 8, Tables 7-8).
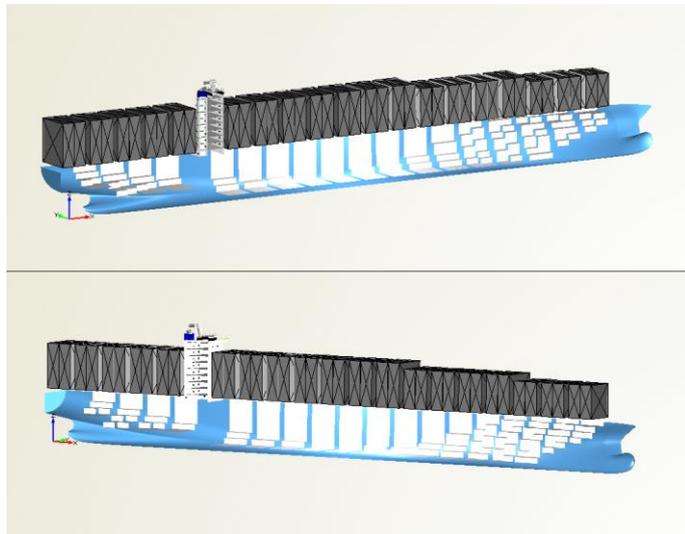

Figure 8:Des0156 model

Table 7: Des0156 design variable values

Design variable	Des0156 value
Bays	20
Rows	15
Tiers in hold	8
Tiers on deck	8
Double bottom (m)	2.50
Double side (m)	2.42
Δc_P	-0.04662
ΔLCB	-0.01680
Bilge radius (m)	4.242

Table 8: Des0156 objective values

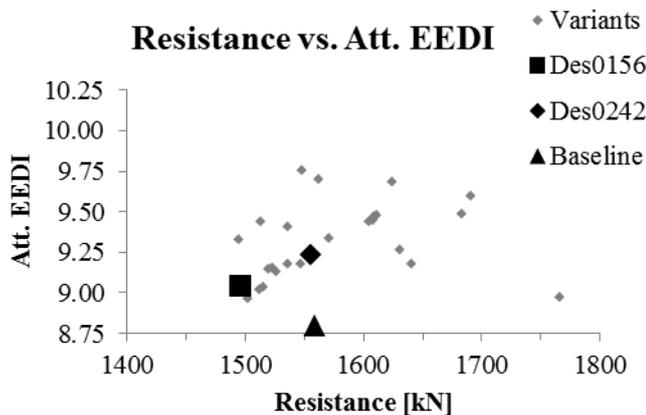| Objective	Des0156 value
RFR ($/TEU)	504.86
Capacity ratio	0.5233
EEDI	9.04
Stowage ratio	1.5186
Ship resistance (kN)	1496

Figure 9: Resistance vs. Attained EEDI

As far as the values of the resistance and the attained EEDI are concerned, low values for both objectives are desired. Des0156 has a total resistance of 1496 kN, the second best value among the successful variants, as well as one of the lowest attained EEDI values (Fig. 9).
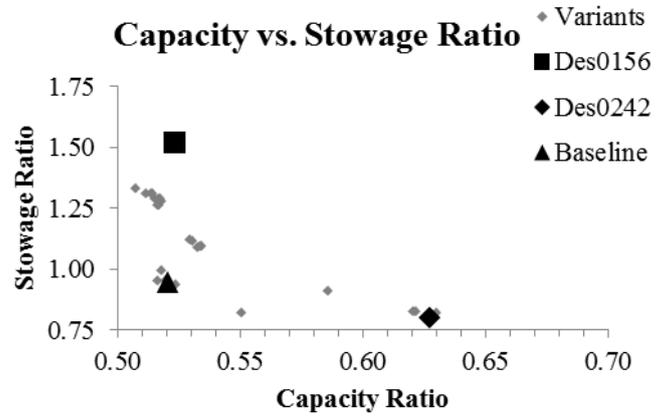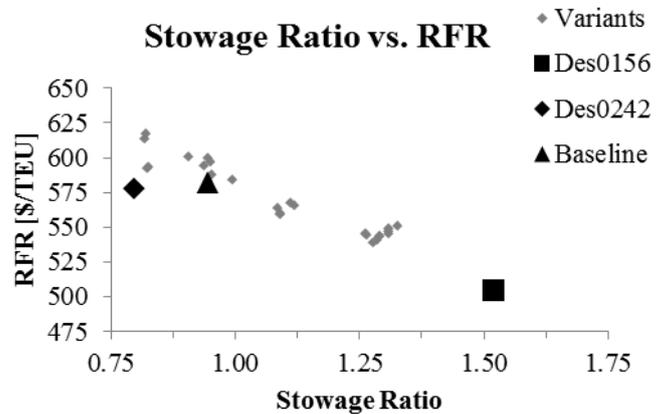

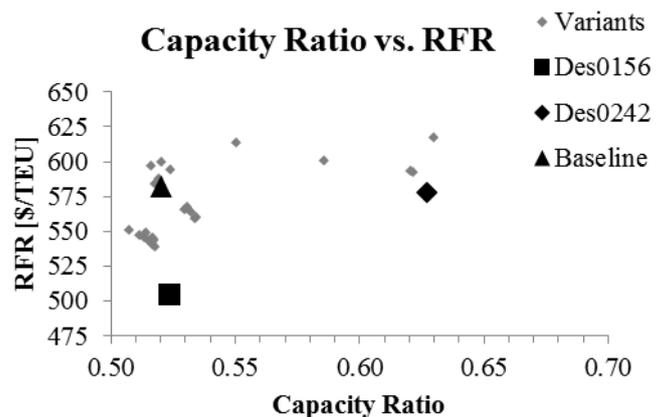Figure 10: Capacity vs. stowage ratio

Figure 11: Stowage ratio vs. RFR

Figure 12: Capacity ratio vs. RFR

In case of the two examined ratios −stowage and capacity− we can observe an inversely proportional trend. Variants which feature high stowage ratio are characterised by low capacity ratio and vice versa. This is the main difference between the two identified designs, Des0156 and Des0242 (Fig. 10).

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As far as the relationship between the RFR and the two ratios is concerned, an optimal design would feature a low RFR value and high stowage and capacity ratios. Des0156 features the lowest RFR between the successful variants, at 504.86 $/TEU, as well as one of the highest stowage ratios (Fig. 11). On the other hand, Des0242 achieved one of the highest capacity ratios (Fig. 12).

As far as the draft criteria for parametric roll failure mode are concerned, it should be noted that 8.1% of the produced variants did not pass either of the two levels.

Finally, a one-to-one comparison between the initial and the improved design is made, to show the percentage differences in several elements (Table 9).

As far as the main dimensions are concerned, the improved design features an additional bay, while the number of rows and tiers below the main deck are decreased by one. Also, an extra tier above the main deck is carried in the improved design. This justifies the higher stowage ratio in Des0156's case, as more containers can be stacked above the main deck compared to the baseline design. Furthermore, the double bottom and double side distances are higher in Des0156's case, while the bilge radius is reduced compared to the baseline design.

Overall, the improvement of the initial containership design is obvious. Des0156 manages to perform better in every objective, apart from the attained EEDI value. Nevertheless, the design complies with the current regulations regarding the EEDI. As a matter of fact, the attained/required EEDI ratio is equal to 0.563, providing a safe gap from the maximum allowed value set by regulations. A notable improvement can be observed regarding the port efficiency factor and the RFR, where an increase of 61% and a decrease of 13% are achieved, respectively.

Table 9: Baseline design vs. Des0156

Data	Baseline	Des0156	Difference
Bays	19	20	+1
Rows	16	15	−1
Tiers in hold	9	8	−1
Tiers on deck	6	8	+2
Double bottom (m)	2.0	2.50	+0.50
Double side (m)	2.1	2.42	+0.32
Bilge radius (m)	5	4.242	−0.758
R_T (kN)	1559	1496	−4.04%
Max. TEU capacity	6487	6984	+7.66%
Z.B. TEU capacity	3377	3655	+8.23%
Capacity ratio	0.5206	0.5233	+0.52%
Stowage ratio	0.9451	1.5186	+60.68%
RFR ($/TEU)	582.35	504.86	−13.31%
EEDI	8.80	9.04	+2.73%

4 SUMMARY AND CONCLUDING REMARKS

Through the work presented in this paper, the advantages of the utilisation of modern design optimi-

sation in the shipbuilding industry are demonstrated. By incorporating this type of parametric optimisation process in the early stages of ship design, a much improved design can be produced, providing numerous benefits to a potential builder and end user (ship owner). Furthermore, it is demonstrated that using modern CAD/CAE systems, it is possible to explore the huge design space with little effort, while generating excellent/partly innovative results within very short lead times. The presented methodology and the implemented CAD system allow the integration of more advanced tools for the improved modelling of e.g. ship's hydrodynamics or ship's strength. The areas of optimisation are of course not limited to the objectives examined in this project. Aspects such as structural strength or seakeeping can become main objectives of design optimisation as well, as necessary, allowing naval architects to achieve a greater degree of holism in the design process (Papanikolaou, 2010).

The methodology presented in this study can be also applied to other containership sizes and ship types (Koutroukis et al., 2013, Soultanias, 2014). More phases of the ship's life cycle can be integrated to future studies, resulting in more comprehensive holistic ship design investigations (Papanikolaou, 2010).

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