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Parametric design and multi-objective optimisation of containerships

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ABSTRACT

The fluctuation of fuel price levels along with the continuous endeavour of the shipping industry for economic growth has led the shipbuilding industry to explore new designs for various types of ships. In addition, the introduction of new regulations by the International Maritime Organisation frequently triggers changes in the ship design process. In this respect, proper use of computer-aided ship design systems extends the design space, while generating competitive solutions in short lead time. This paper focuses on multi-objective optimisation of the design of containerships. The developed methodology is implemented on CAESES® software and is demonstrated by the conceptual design and optimisation of a 6500 TEU containership. The methodology includes a parametric model of the ship's external and internal geometry and the development and calculation of all required properties for compliance with the design constraints and verification of the key performance indicators. The latter constitute the objective functions of the multi-objective optimisation problem. The energy efficiency design index, the ratio of the above to below deck number of containers, the required freight rate, the ship's zero-ballast container capacity and the total ship resistance were used in this study. Genetic algorithms were used for the solution of this multi-objective optimisation problem.

1. Introduction

1.1. Container shipping industry

Global containerised trade has been on constant growth since 1996. It is worth mentioning that in 2015, there was a 2.4% growth, which can be translated to a total movement of 175 million TEUs in one year (UNCTAD, 2016). 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 and Bunker, 2017). 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. In addition, the recent landmark decision by the International Maritime Organisation (IMO) Marine Environment Protection Committee to implement a global sulphur cap of 0.5% m/m (mass/mass) from 1 January 2020 has introduced a step change to the framework of designing and operating ships (IMO, 2016).

In the years before 2014 and the collapse of the fuel prices, the shipping industry was adopting several practices to reduce fuel consumption. One of them was slow steaming (SS) (Tozer, 2008) and super slow steaming (SSS) (Maloni et al., 2013; Bonney and Leach, 2010). In comparison to some years ago -when operational speeds of around 25 knots were common-containerships nowadays travel at around 18–20 knots in slow steaming and at 15 knots in super slow steaming. Ship design for lower speeds has major impact to fuel savings and may reduce their energy efficiency design index (EEDI) levels (White, 2010).

The recent improvements in technology and engineering have made the introduction of ultra large container vessels possible. A new trend, known as cascading, resulted from the high number of new building programmes initiated by many liner companies. These orders consisted primarily of very large containerships. The continued influx of such large vessels into the market has led to a large number of vessels being cascaded onto trade lines that historically have been served by smaller vessels (Köpke et al., 2014). Hence, routes where 2000–3000 TEU containerships are preferred by charterers at the moment may attract larger vessels in the near future. Since the former category of ships is mainly used for the purpose of short sea shipping, ships in the 6000 TEU

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category could become widely popular among the ship owners and the charterers. In addition, the recent opening of the new Panama Canal locks means that the Post-Panamax containerships can be utilised in more transport routes, including the trans-Panama services (van Marle, 2016).

Although container carriers do not spend considerable amount of time in ports, port efficiency is considered as one of the most important factors in containership design. The less port time they spent, the more time is available for cruising at sea, which means that vessels can operate in lower speeds and consequently reduce fuel consumption. Usually, the transport efficiency is optimised by focusing on the schedule of the ships visiting a specific port (Kurt et al., 2015). However, in our case the optimisation focuses on the ship itself, making the incorporation of the port efficiency in the holistic optimisation of containerships possible. In this study a simplified approach was used, namely monitoring the ratio of the above to below deck containers' number. As Soultanias (2014) has found, the larger the ratio, the faster the loading and unloading of containers; thus, the time spent by ships in port is reduced.

1.2. International regulatory framework

Recent developments in the international maritime regulations are going to greatly affect future ship designs and particularly containerships. One major development is the introduction of the EEDI, in 2012 (IMO, 2012a, c, b). This is a major step forward in implementing energy efficiency regulations for ships, limiting greenhouse gas emissions, through the introduction of the EEDI limits for various ship types. The EEDI relates the CO_2 emissions of a ship to her transportation work and is in fact an indicator of a vessel's energy efficiency. The determination of EEDI is based on a rather complicated looking (but indeed simple) formula, while it is required that the calculated value is below a reference line set by the IMO regulation for the specific ship type and size. The EEDI requirement for new ships started with some baseline values in 2013, and is being lowered (thus becoming more stringent) successively in three steps until 2025, when the 2013 baseline values will have been reduced by 30%. 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 will be applied to all ships as of September 2017 (IMO, 2004). Although various systems and technologies aiming at the minimisation of the transfer of organisms through ballast water to different ecosystems are currently available, their installation on board ships increases their capital and operating costs. Therefore, research has been focusing lately at solutions to reduce the amount of required ballast water. This problem is more severe for containerships, which inherently carry more ballast water, even at the design load condition, for which the ratio of the containers carried on deck to those carried under deck should be maximised. Thus, design solutions for modern containerships that consider zero or minimal water ballast capacities are very appealing to the ship owners. Nevertheless, attention should be paid to the overall cargo capacity as well, so as to maintain competitive values in all respects.

Finally, as far as safety regulations are concerned, a new generation of intact stability criteria is currently being developed by the IMO (IMO, 2015). 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 will be performance-based and will address five modes of stability failure; parametric roll, pure loss of stability, excessive acceleration, 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 (IMO, 2015) are applied as part of the optimisation process in this study.

2. Parametric CAD modelling

In recent years, several researchers have presented significant computer-aided design (CAD) methodologies dealing with ship design process and inherently its optimisation (Brown and Salcedo, 2003; Campana et al., 2009; Mizine and Wintersteen, 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 Post-Panamax, 6500 TEU containership, focusing on optimisation of the ship's arrangements, while considering all

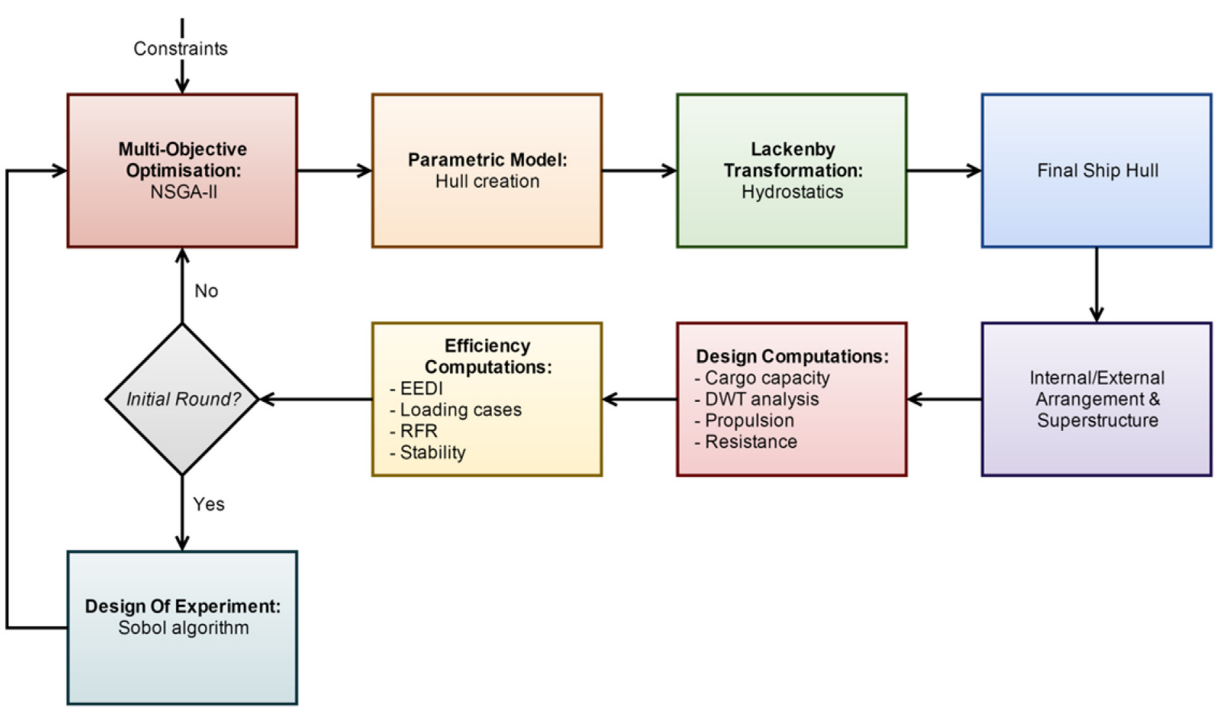

Fig. 1. Design optimisation procedure.

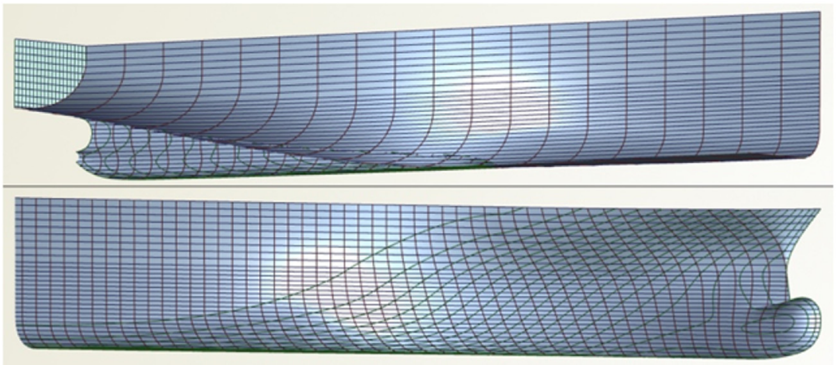

Fig. 2. Modelled aft and fore body.

side effects on ship design, operation and economy (Priftis, 2015). 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). Efforts are currently being made in the framework of the European Union funded HOLISHIP project, in that respect (HOLISHIP, 2016). According to the project's approach, a proposed model follows modern computer-aided engineering (CAE) procedures and integrates techno-economic databases, calculation and optimisation modules and software tools along with a complete virtual model which allows the virtual testing before the building phase of a new vessel. Within this context, a parametric ship model of ship's external and internal geometry is created at first, followed by a multi-objective optimisation to determine an optimal design (Fig. 1).

2.1. Parametric model

Modern CAD/CAE software tools are used to generate the parametric ship model, following the principles of a fully parametric design. The geometric model is produced within CAESES® (Friendship Systems, 2017), and consists of four main parts; the main frame, the aft body, the fore body, and the main deck (Fig. 2). An initial hull form is used as a baseline for our model and is transformed to get the desired hull shape for this study's baseline model. In order to achieve this, several parameters are defined to control certain parts of the hull. Apart from the main dimensions of the hull, parameters are introduced to control specific areas at the aft and fore ends. For example, the bilge height and width, the shape of the bulbous bow, as well as the position of the propeller tube and the transom are controlled by parameters.

In order to create an adequately faired and smooth hull surface, a Lackenby transformation is applied (Lackenby, 1950). It starts with a hydrostatic and sectional area curve calculation. These are used as input to the Lackenby transformation. By adjusting the prismatic coefficient (C_P) and the longitudinal centre of buoyancy (LCB), the final hull geometry is produced. This process allows shifting sections aft and fore, while fairness optimised B-Splines are utilised (Abt and Harries, 2007).

Next step is to create the superstructure and the cargo arrangements (Figs. 3 and 4). New programmes (or "features", as they are called within CAESES®) were 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, the required surfaces are produced to build the deckhouse and the cargo arrangement below and above the main deck. The feature responsible for the creation of the superstructure takes as input the number of tiers above the main deck, the desired position along the longitudinal direction, the height of each deck and the dimensions of the superstructure in the longitudinal and transverse directions in order to build the superstructure in the appropriate position. The feature responsible for the development of the internal cargo storage arrangement creates the surface on which the TEUs are stored, while monitoring the distance of this inner surface from the outer cell of the hull. The feature responsible for the development of the cargo storage arrangement above the main deck is designed in such a way, so as to take into account the visibility line rule imposed by the IMO (IMO, 1991). The feature automatically takes as input the visibility line and the number of deckhouse decks, both of which are defined in the model. This prevents an excessive vertical stowage of containers above the main deck. In

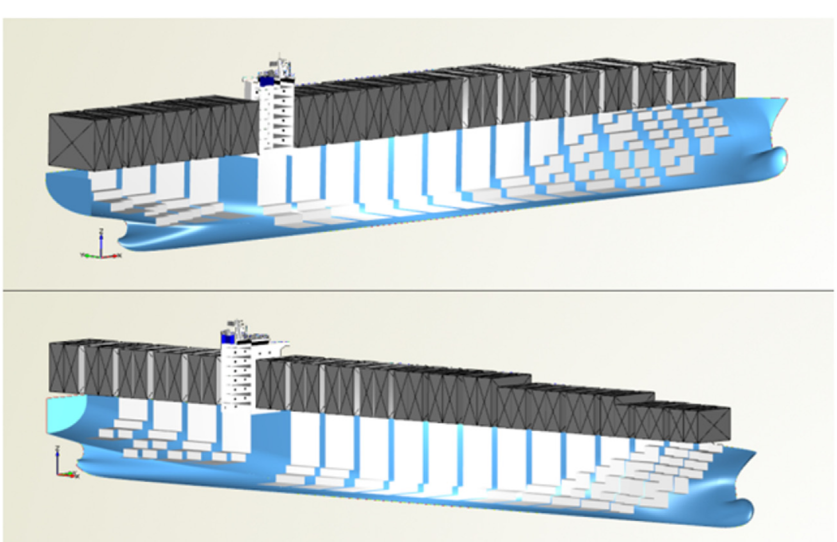

Fig. 3. Parametric model.

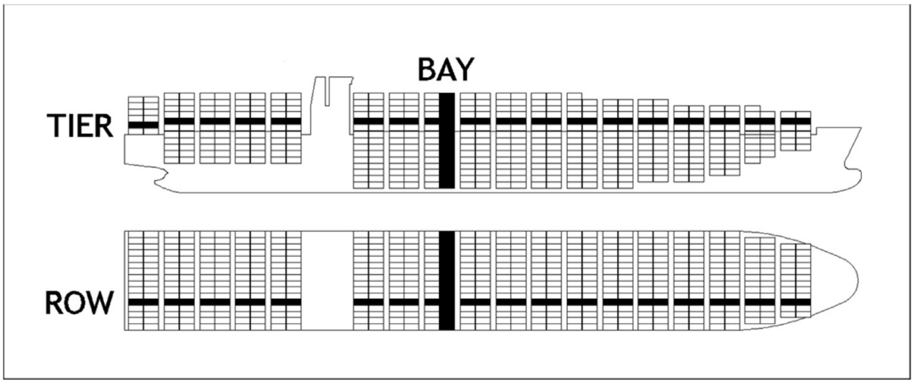

Fig. 4. Definition of bays, rows and tiers in a containership cargo arrangement.

addition, the feature follows the deck line and monitors the available space along the beam of the ship to define the proper amount of TEU rows above the main deck.

In both cases, several parameters are used to define the cargo space, such as the bay spacing and the dimensions of the standardised TEU unit. The computations are performed separately for each bay, so that maximum cargo storage capacity is guaranteed by taking advantage of every available space within the hull, especially in the regions where the complexity of the geometry is higher (e.g. the bow area).

2.2. Computations

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

For this reason, custom features are created within the software. Cargo capacity is automatically computed thanks to a feature that retrieves information from those responsible for the creation of the cargo arrangements. Apart from the actual measurement of the TEUs below and above the main deck, these features are designed to calculate the vertical and longitudinal moments, as well as the vertical and longitudinal centres of gravity, which are used as input in other computations.

Before proceeding to the remaining computations, a hydrostatic calculation is run first. Earlier, the same action took place; however, it was before the final hull was generated. Since its characteristics have changed after the last hydrostatic computation, a new run is necessary for the following steps of the project.

Custom features estimate the total ship resistance (R_T) according to the Holtrop and Mennen method (Holtrop and Mennen, 1978). Holtrop and Mennen method is one of the mostly used empirical methods to estimate the resistance and propulsion requirements. It is believed to produce satisfactory results. The aim of this study is to find an optimal containership design using a fast optimisation procedure, hence CFD was not utilised in this case, although it would be preferred over an empirical method as more accurate results would be produced through CFD. Since the method is programmed within the core software tool, the calculations are done fast and an estimation of the total resistance of the hull is obtained without having to run time-consuming CFD analyses. The overall resistance is divided into categories as defined by the aforementioned method. At this stage, the service speed of our model is determined, since it is required for the calculations. Taking into account the recent trend of slow steaming, the operational speed is set to 20 knots.

The Holtrop and Mennen method includes formulas for the estimation of the effective horsepower (EHP) and the shaft horsepower (SHP) (Holtrop and Mennen, 1978). First, the EHP is calculated, since both the total resistance and the vessel's speed are known. Having already found the necessary propulsion and efficiency factors from the resistance computations, the calculation of SHP is then possible. The final result is increased by 20% to include a sea margin as well as the impact of hull fouling, representing the common practice in the shipping industry (MAN Diesel & Turbo, 2011). Next, the estimation of the auxiliary power follows. Finally, the fuel consumption is estimated. Next, the estimation of the auxiliary power follows, using the following formula:

$$P_{B_{Aux}} = 100 + 0.55 \cdot P_{B_{ME}}^{0.7}$$

The next step is to calculate the lightship of the modelled ship. The lightship weight is divided into three categories; the steel weight, outfitting weight, and the machinery weight. Steel weight is computed using the Schneekluth and Müller-Köster methods. Outfitting and machinery weights are calculated using existing formulas, taking as input several parameters, such as the main dimensions of the ship, as well as the main engine's power (Papanikolaou, 2014). In addition, longitudinal and vertical centres of gravity are estimated, to be used later at the generation of the examined loading cases.

Even though the methods utilised for this step are semi-empirical approaches, and thus, an approximation of the exact values, we aim at the most accurate results. In this context, it should be noted that several parameters needed for the computations are derived from applications and detailed calculations performed by the CAESES®, such as the enclosed volume of the hull, which is very important for the rest of the process. Moreover, the formulae were calibrated using a similar 6300 TEU containership, for which detailed lightship breakdown and other data were available. This allowed the calculation of correction factors that would improve the final outcome of the model's lightship estimation, since the actual lightship weight and centre of gravity of the reference ship were known. Thus, first, all required calculations for the reference ship were performed in Microsoft Excel® (Microsoft, 2010) and a customised code was developed in CAESES®, including the methods used in the first step, so as to determine the model's lightship characteristics. It should be noted that this feature takes as input the data from the computations performed in Microsoft Excel®, so as to include the correction factors in the model's lightship computation.

Afterwards, 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).

The final design computation that has to be performed is the allocation of the necessary tanks in the model's hull. The tanks created in the model are mainly the ones containing the fuel, diesel and lube oil, as well

Table 1
Operational profile.

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

as the water ballast tanks. At first, sections which represent the tanks are generated. Then, hydrostatic calculations are performed to determine the basic properties of the tanks, such as the volume, weight, and their centre of gravity.

2.3. Performance indicators

Following the definition of the features responsible for the naval architectural computations, the development 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.

One of the optimisation criteria in our project is the minimisation of the EEDI. A custom feature is programmed in order to calculate both the required and the attained EEDI values, according to the regulations (IMO, 2012c). The required EEDI value is calculated based on the following formula:

$$EEDI_{req} = a \times b^{-c} \times \left(1 - \frac{x}{100}\right)$$

Where a and c are equal to 174.22 and 0.201, respectively, according to the IMO in case of containerships, b stands for the deadweight of the vessel, and x is a reduction factor. The feature is programmed in such way to include the reduction factor as a parameter that can change within the creation of the model. In the present study, the optimisation is run for the current conditions, i.e. the reduction factor is considered to be equal to 10%. However, the designer can select the desired value, depending on the conditions that have to be met in a particular study.

On the other hand, the attained EEDI value is calculated using the following conceptual formula (measured in gr CO_2/tonne mile):

$$EEDI_{att} = \frac{(\text{Ship emmisions}) - (\text{Ship emmisions reduction by efficiency technologies})}{(\text{Transport work})}$$

The ship emissions include that of the main engine, auxiliary engines, as well as the shaft generators, and motor emissions. The efficiency technologies include several arrangements, modifications, or installations to the hull or the propulsion system, which result in increased efficiency. Hence, these technologies should be taken into account in the calculation of the attained EEDI as a reduction factor. Finally, the transport work takes into account the cargo loading of the ship, as well as its service speed (DNV GL, 2013, MAN Diesel & Turbo, 2015).

Apart from producing the values mentioned above, an “attained/required” EEDI ratio is also calculated, to be used as a constraint during the optimisation phase.

Another significant performance indicator for this study, the required freight rate (RFR), is also calculated by use of newly developed features in CAESES®. This value indicates the minimum rate that evens the properly discounted ship's expenses. The main formula used to calculate the RFR is the following (Watson, 1998):

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

where PW is the present worth of the respective cost. The overall cost is divided into two categories; the operating cost and the ship acquisition cost. The former is mainly based on the running costs of the ship, such as cost for the fuel, crew, stores, maintenance, insurance, administration, and port costs. As far as the fuel cost is concerned, a review is made first, so as to identify the HFO and MDO costs. Then, taking into account the route length and the fuel consumption of the model, the total fuel cost is reckoned. As far as the ship acquisition cost is concerned, to perform the calculations, several data are used as input, including the steel mass of the vessel, cost of steel, discount rate, operation time, main dimensions, and engines' power (Soultanias, 2014).

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. This step is essential for the implementation of the next one, namely the generation of the loading cases. Within this software module, essential ship hydrostatic and stability parameters are determined, such as the values of the restoring arm lever GZ-ϕ curve, the trim of the ship, as well as the vertical centre of mass KG and longitudinal centre of mass LCG values that are used in the loading cases computation. The stability is evaluated by assuming a homogenous stow. The assessment of the initial and large angle stability of the vessel is undertaken for common type loading conditions in accordance with the IMO A.749/A.167 intact stability criteria. The code used in this project generates the GZ-ϕ curve, by running several hydrostatic computations at various heeling angle values. A continuous check is performed, to ensure that the model complies with the IMO intact stability criteria. If the latter is not the case, the stowage of cargo, ballast and fuel, along with the associated KG and LCG values are modified and the whole process is repeated, until the criteria are met. The ultimate goal of this iterative procedure is to minimise the amount of carried water ballast and identify “zero ballast” loading conditions. During this procedure, the payload weight, calculated based on the homogenous weight per TEU, as well as its vertical centre of gravity are taken into account.

A new element introduced in this optimisation problem, compared to previous similar studies (Priftis et al., 2016b) is the consideration of the imminent changes in the stability regulations. In particular, the level 1 and 2 draft criteria for parametric roll failure mode according to the IMO are applied in this project (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 and accurate, taking into account more detailed parameters so as 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®, multiple features are created, each one having a specific purpose. Moreover, several external software programmes are connected with the model, so as to quickly evaluate certain parameters required for these particular computations. Maxsurf Stability Enterprise® (Bentley Systems, 2014) is used to produce values of the metacentric height (GM) in various wave conditions, as proposed by the regulations, while Matlab® (Mathworks, 2014) is responsible for the calculation of the roll amplitude during the level 2 criterion check, where complex equations must be solved.

The last computation required is the generation of the loading conditions. A custom feature was developed for this purpose. The loading conditions investigated in this study are the maximum TEU capacity and the “zero ballast” conditions. Both of them require several parameters and elements determined in previous stages. These parameters consist of various weight groups, as well as their longitudinal and vertical centres of gravity which represent the data used as input in this computation. These groups include the displacement, the lightship, the payload, divided into the below and above main deck TEUs, the consumables, and the water ballast. As far as the water ballast is concerned, several groups are defined, to fill only the minimum required space with sea water.

For the maximum TEU capacity case, the main objective is to maximise the cargo capacity. On the other hand, the “zero ballast” condition is defined as a condition where no water ballast is loaded for stability

Table 2
Design variables.

Design variable	Minimum value	Maximum value
Bays	18	20
Rows	14	18
Tiers in hold	8	10
Tiers on deck	6	8
Double bottom (m)	2.00	3.00
Double side (m)	2.00	3.00
δC_P	−0.06	0.06
δLCB	−0.026	0.026
Bilge radius (m)	4	6

reasons, with the exception of some limited water ballast in the aft and fore peak tanks, for trim balance. As in the former 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, which takes as input the number of containers stacked above and below the main deck, calculated in a previous computation. The objective is to maximise the ratio i.e. the number of TEUs stored on deck. As far as the zero ballast condition is concerned, a performance indicator, which is also one of the objectives of the optimisation procedure, is defined at this stage. Instead of using the actual TEU capacity of the zero ballast condition, a parameter representing a capacity ratio is used. This ratio is defined by dividing the number of containers the ship can transport while in zero ballast to the maximum TEU capacity of the ship. As in the case of stowage ratio, 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 the examination of 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 and Stobart, 2015). Through the DoE, the investigation of the feasibility boundaries is ultimately achieved, allowing the detection of the trends of the design variables (Table 2) with regard to the optimisation objectives. In our case, the design engine is assigned to create 250 variants of the initial model. At this point, no objectives need to be determined, since only the feasibility boundaries are investigated. However, several parameters are evaluated through this process.

The design variables used in this study are presented in Table 2. They consist of TEU arrangement elements, such as the number of bays and rows, certain hull dimensions, such as the double bottom, as well as the variation of the C_P and LCB values. Since the main dimensions of containerships are highly dependent on the container arrangement, the main dimensions of the model derive from these design variables. For instance, the beam of the hull is calculated by taking the number of rows, the beam of each container and the double side dimension into account. As far as the variation of the C_P and LCB values are concerned, the range selected in this case represents the percentile change in the values used in the baseline model, in order to apply the Lackenby transformation on the hull to create a new variant.

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.

When the run ends, a wide variety of results are displayed, which provide information about the design space. It is worth mentioning that the TEU capacity of the model is not constrained, thus the maximum and minimum number of TEU capacity of the variants is not limited to the 6000–7000 area.

Table 3
Design constraints.

Constraint	Value
EEDI ≤1, "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 metacentric height GM	≥0.15 m
Angle at GZ_{max}	≥30 deg
GZ_{max}	≥0.2 m
Homo weight/TEU (maximum TEU capacity)	≥6 t
Homo weight/TEU (zero ballast condition)	≥7 t
Trim at full load departure condition	≤0.5% L_{BP}
Parametric roll criteria	= 1 (pass)

2.5. Multi-objective optimisation

The last step to complete the procedure is to set up 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, 300 generations are created, having a population size of twelve, each. This results in a total of 3600 produced variants. The design variable extents remain the same, as the design space proved to be well defined, following the DoE phase. In addition, the design variables' range remains the same, as the design space proved to be well defined. 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 (7000 TEUs) and lower (6000 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 optimisation procedure define the Pareto front of the non-dominated designs. As the decision maker needs to select one design, Multi Attribute Decision Making (MADM) is applied. Several case scenarios are created, so as to determine the optimal of the top solutions to the problem. In this study, 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) (Sen and Yang, 1998). In scenario 1, all five objectives are considered to be equally important; hence each one is assigned a weight at saturation of 20%. On the other hand, in scenarios 2 and 3, the RFR and capacity ratio are chosen respectively to be more significant for the decision maker (designer, operator) by assigning to them a weight of 50% and 20% for the most important and the second most important objective in both cases, whereas the rest are assigned a weight of 10%. After obtaining the results of each run, the data are normalised according to the scenarios. Next, the normalised data are ranked to find the optimal variant of our model. The maximum score that can be achieved after this process for each design, in each case scenario, is 1, whereas the lowest is 0. In most cases, a specific

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%

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 (gr CO_2/tonne mile)	8.80
Stowage ratio	0.9451
Ship resistance (kN)	1559

variant dominates in every scenario.

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 and 6).

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 attained EEDI is concerned, it is evident that as the former increases, the latter decreases (Fig. 5). As the number of the bays gets higher, since the total TEU capacity is not constant, the number of containers carried on board also rises, resulting in a higher deadweight value. Since the latter is inversely proportional to the attained EEDI value, it can be understood that there is a strong relation between the number of bays and the EEDI value. Similar behaviour can be observed in the correlation between the number of rows and the attained EEDI –the total TEU capacity is variable in this case as well (Fig. 6).

Furthermore, the relation between the tiers below the main deck and the stowage ratio is presented in Fig. 7. The higher the number of the container stacks, the lower the stowage ratio. This trend is expected, as the increase in the number of TEUs below the main deck results in a lower number of containers stacked above the main deck, for a given TEU capacity range.

Finally, as far as the dependency of the RFR on the number of tiers above the main deck is concerned, it is evident that the RFR decreases, as the latter increases (Fig. 8). As previously mentioned the number of tiers below and above the main deck is interdependent. Moreover, it can be understood that a tier located above the main deck contains more TEUs than one below the main deck, due to the hull shape restrictions. Hence, by increasing the number of tiers above the main deck, a larger cargo capacity can be achieved for the same main dimensions of the ship, which

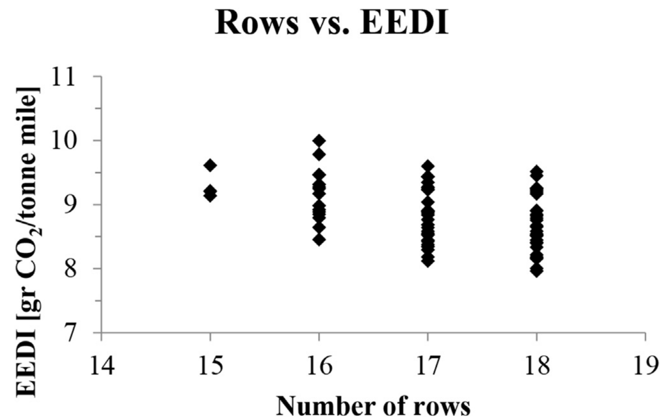

Fig. 6. Rows vs. EEDI.

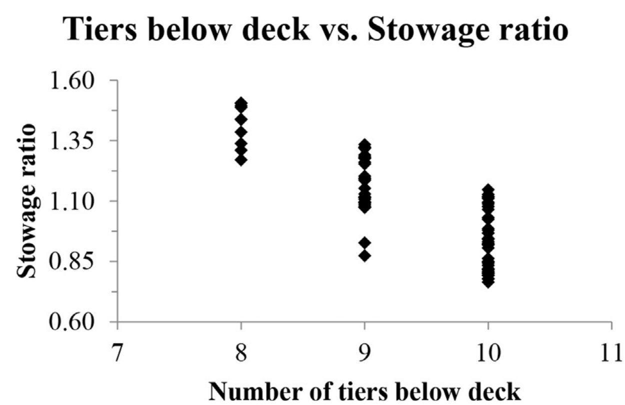

Fig. 7. Tiers below deck vs. stowage ratio.

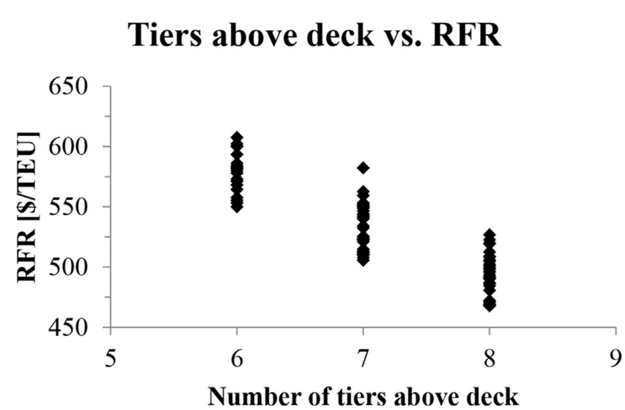

Fig. 8. Tiers above deck vs. RFR.

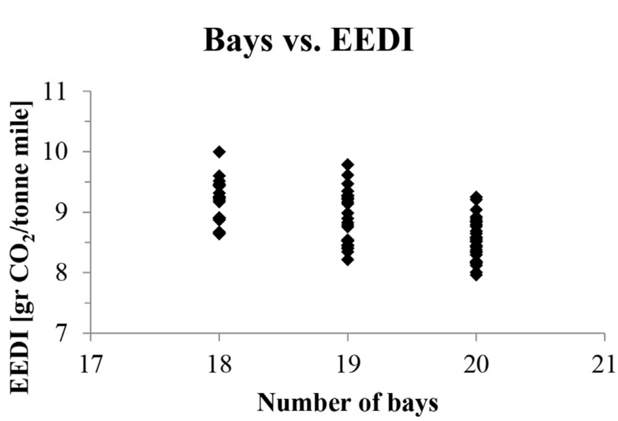

Fig. 5. Bays vs. EEDI.

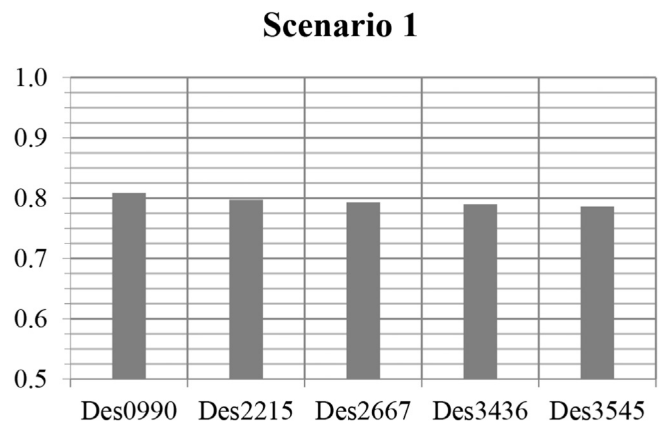

Fig. 9. Scenario 1 ranking.

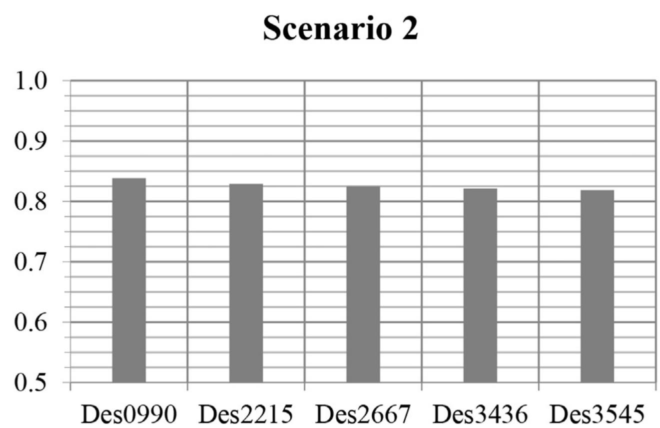

Fig. 10. Scenario 2 ranking.

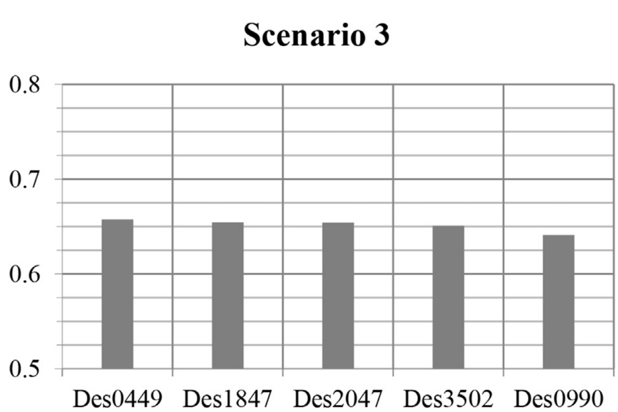

Fig. 11. Scenario 3 ranking.

in turn leads to a lower RFR.

3.3. Multi-objective optimisation

Following the NSGA-II run and the evaluation of the results, an improved design, named Des0990, is identified. Des0990 ranked first in the first two case scenarios. A second variant, named Des0449, ranked first in the third scenario. Following the decision making process, Des0990 is ultimately selected as the optimal design (Figs. 9–11). Below, some principal information of the optimised design can be found (Fig. 12, Tables 7 and 8).

A set of graphs containing the relation between the optimisation objectives is presented below. The Pareto front is demonstrated by a solid black line in each case.

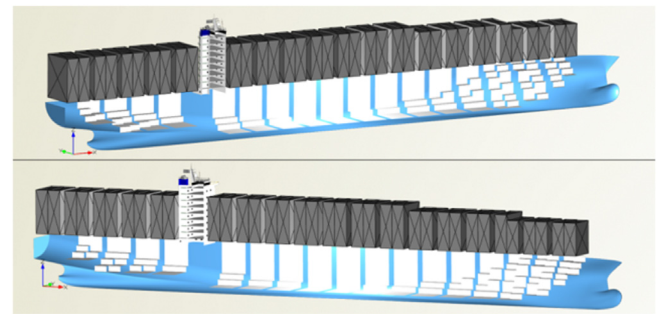

Fig. 12. Des0990 model.

As far as the values of the RFR and the stowage ratio are concerned, a favourable trend can be observed. In particular, it can be understood that the higher the stowage ratio, the smaller the freight rate. As one would expect, as the stowage ratio rises, the total number of containers transported is increased for a given set of main dimensions. Hence, the deadweight is increased and the RFR value gets lower (Fig. 13).

In case of the two examined ratios –capacity and stowage– an inversely proportional trend can be observed. 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, Des0990 and Des0449 (Fig. 14).

As far as the relationship between the attained EEDI and the capacity ratio is concerned, a clear Pareto front can be identified. There are many designs in the range between 0.625 and 0.650 (as far as the capacity ratio is concerned) that feature an attained EEDI value of 8.75 up to 10.50 gr CO_2/tonne mile. The identified improved design Des0990 has one of the lowest EEDI values but a relatively small capacity ratio. Nevertheless, Des0990 performed better than the baseline ship in that respect (Fig. 15).

Regarding the relation between the stowage ratio and the total resistance, a slight decline in the overall resistance can be observed, as the stowage ratio rises. Des0990 marks a great improvement as far as the stowage ratio is concerned, while it manages to achieve a lower total resistance (Fig. 16).

Finally, it is worth commenting on the relation between then total resistance and the RFR. As in previous observations, it can be concluded that the resistance gets lower as the freight rate values become smaller (Fig. 17). Resistance influences directly the required power for propulsion. In addition, the fuel costs are taken into account in RFR estimation. Since fuel cost is proportional to the main engine's power, lower resistance means lower required power, which in turn can be translated to reduced fuel costs and lower RFR values.

The results presented above can be compared with previews optimisation runs on the same setup as above (Priftis et al., 2016a). In particular, a less extensive NSGA-II run within CAESES® produced a similar improved design, named Con156. During this run, 260 variants were created. Judging from the graphs of these two optimisation results, similar Pareto fronts can be observed, which shows that NSGA-II can get a uniform high-quality Pareto front in multi-objective optimisation problems with excessive targeting. Details of the selected improved design produced during the less extensive optimisation run can be found in Tables 9 and 10:

Con156 features 20 bays, whereas Des0990 has one bay less than that. The number of rows and tiers above and below the main deck is the same in both cases. As far as the rest of the design variables are concerned, the differences are relatively small (Tables 7 and 9). With regard to the objective values, a few similarities can be observed. For instance, both improved variants attained the best RFR values among the design variants in each run. In addition, both designs feature a

Table 7
Des0990 design variable values.

Design variable	Des0990 value
Bays	19
Rows	15
Tiers in hold	8
Tiers on deck	8
Double bottom (m)	2.78
Double side (m)	2.07
δC_P	−0.05624
δLCB	0.02376
Bilge radius (m)	4.877

Table 8
Des0990 objective values.

Objective	Des0990 value
RFR ($/TEU)	501.55
Capacity ratio	0.5314
EEDI (gr CO_2/tonne mile)	8.51
Stowage ratio	1.4553
Ship resistance (kN)	1429

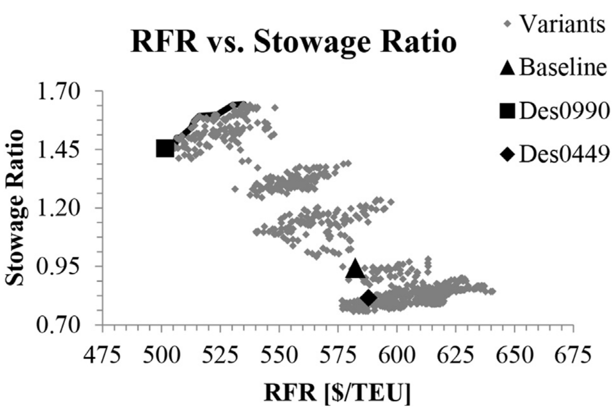

Fig. 13. RFR vs. stowage ratio.

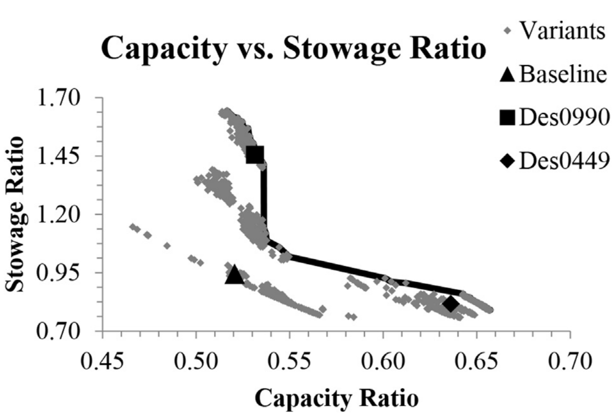

Fig. 14. Capacity vs. stowage ratio.

relatively high stowage ratio; however, their capacity ratio is not one of the best that occurred during the optimisation runs. This can be explained by the fact that the stowage ratio has a greater impact in the optimal design selection during the MADM process. In both runs, the relation between the two ratios can be described as inversely proportional. Hence, a design with a high stowage ratio –and consequently a low capacity ratio value– was declared as the best among the produced

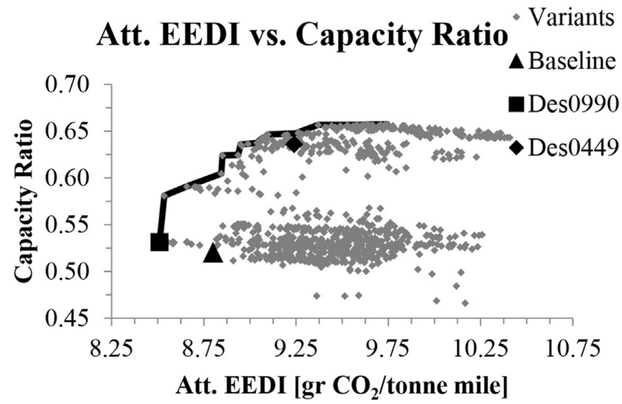

Fig. 15. Att. EEDI vs. capacity ratio.

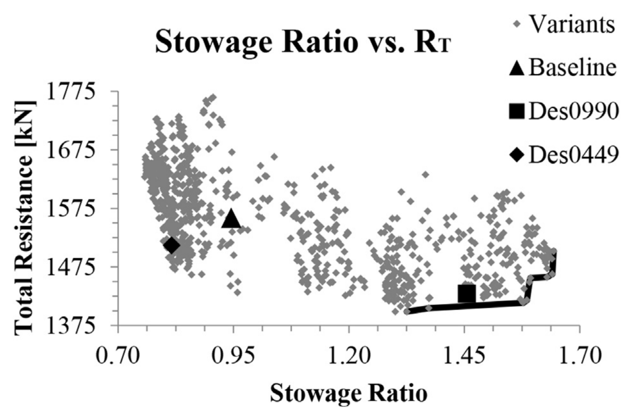

Fig. 16. Stowage ratio vs. total resistance.

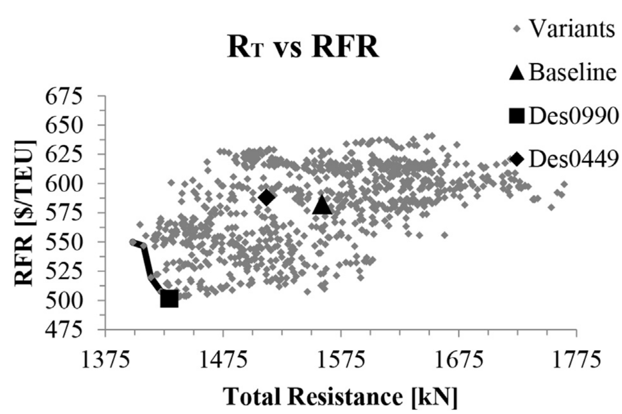

Fig. 17. Total resistance vs. RFR.

Table 9
Con156 design variable values.

Design variable	Con156 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 10
Con156 objective values.

Objective	Con156 value
RFR ($/TEU)	504.86
Capacity ratio	0.5233
EEDI (gr CO_2/tonne mile)	9.04
Stowage ratio	1.5186
Ship resistance (kN)	1496

Table 11
Baseline design vs. Des0990.

Data	Baseline	Des0990	Difference
Bays	19	19	0
Rows	16	15	−1
Tiers in hold	9	8	−1
Tiers on deck	6	8	+2
Double bottom (m)	2.0	2.78	+0.78
Double side (m)	2.1	2.07	−0.03
Bilge radius (m)	5	4.877	−0.123
Total resistance (kN)	1559	1429	−8.33%
Maximum TEU capacity	6487	6789	+4.65%
Zero ballast TEU capacity	3377	3608	+6.84%
Capacity ratio	0.5206	0.5314	+2.07%
Stowage ratio	0.9451	1.4553	+53.98%
RFR ($/TEU)	582.35	501.55	−13.87%
EEDI (gr CO_2/tonne mile)	8.80	8.51	−3.29%

variants in both cases. Finally, it should be mentioned that both Des0990 and Con156 achieved one of the lowest resistance values during the NSGA-II runs.

A one-to-one comparison between the baseline model and Des0990 is made, to show the percentage differences in several elements (Table 11).

As far as the main dimensions are concerned, the improved design features the same amount of bays, while the number of rows and tiers below the main deck are decreased by one. Also, two extra tiers above the main deck are carried in the improved design. It should be noted that Des0990 is one of the few produced variants that feature eight tiers above the main deck. Due to stability restrictions, most of the successful design variants can carry only up to six or seven tiers of containers above the main deck. The extra tier found in Des0990 offers the advantage of an increased stowage and capacity ratio, as well as a reduced RFR, due to the higher total number of TEUs carried on board. In addition, the homogenous weight of each TEU in the maximum TEU capacity loading condition is 7.48 t, while in the zero ballast loading condition it is 22.15 t. Hence it is ensured that the containers will not collapse due to overstacking, since the maximum number of tiers under and over the main deck is eight and the maximum superimposed load each ISO container can withstand is 192 t, according to regulations (IMO, 2014). Furthermore, the double bottom distance is higher in Des0990's case, while the double side distance and the bilge radius are reduced compared to the baseline design.

Overall, the improvement of the initial containership design is obvious. Des0990 manages to outperform the original in every objective. In addition, it should be noted that the attained/required EEDI ratio for the current state of the rules is equal to 0.53, providing a safety margin from the maximum allowed value set by regulations. On top of that, Des0990 manages to be a future-proof design, as the attained EEDI value of 8.51 gr CO_2/tonne mile is in fact well below the value of 12.47 gr CO_2/tonne, which represents the reference line EEDI value when the reduction factor reaches the most conservative level of 30% in 2025 (Table 12). A notable improvement can be observed in the port efficiency factor and the RFR objectives, where an increase of 54% and a decrease of 14% are achieved, respectively.

Table 12
EEDI reference values.

Design	Phase 1 (10%)	Phase 2 (20%)	Phase 3 (30%)
Baseline	15.87	14.10	12.34
Des0990	16.03	14.25	12.47
Des0449	16.11	14.32	12.53

4. Summary and concluding remarks

Through the work presented in this paper, the advantages of the utilisation of modern design optimisation in the shipbuilding industry have been 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 optimisation can include other areas of ship design as main objectives, such as structural strength or seakeeping, allowing naval architects to achieve a greater degree of holism in the design process (Papanikolaou, 2010).

It is evident that the relation of the design process with statutory regulations should be included in the optimisation process as well, as new rules are introduced every year. The present study incorporated new tools for the newly developed second generation criteria for parametric roll failure mode. The results indicate how the model should be designed to pass certain criteria to comply with international regulations, while it becomes clear that specific design parameters, such as the bilge radius and consequently, the midship coefficient, affect the above.

Compared to previous studies (Priftis et al., 2016b), the present paper shows that the consideration of newly developed intact stability criteria, such as the parametric roll check, influences the characteristics of the optimal containership design. Since these criteria have been recently developed, there are limited optimisation studies that take them into account. However, their consideration in a multi-objective design optimisation is important, as containership design will be affected once these criteria come into force. When parametric roll failure mode is not considered, an optimal containership would feature a different containership arrangement, compared to the optimal design identified in the present study. The introduction of new design parameters that extend the control over the hull increased the flexibility of altering the hull shape and led to new findings after the optimisation was run. In addition, some parameters, such as the oil prices, differ between several optimisation studies, due to the fluctuation in prices throughout time and indicate that an optimal design can potentially be affected by such parameters. Future work could of course include the rest of the second generation intact stability criteria as part of the optimisation procedure, while uncertain parameters need to be treated accordingly to get more accurate results.

As far as the results of the current application are concerned, some general observations can be made and conclusions drawn.

The majority (71%) of the feasible variants produced during the optimisation process feature 15 rows. Since wider designs may be more prone to increased transverse accelerations in seaways, this observation seems to be valid, as the parametric rolling is taken into account in this optimisation study. The optimal design is characterised by the same number of row. Moreover, the highest ranked designs feature the minimum allowed number of tiers in hold. This can be explained by the fact that the maximisation of the stowage ratio is desired in this study. Hence, the number of TEUs below the main deck has to be minimal.

The methodology presented in this study can be also applied to other containership sizes or other 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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