VIENNA 2018 TRA
TRANSPORT RESEARCH ARENA
A digital era for transport
solutions for society, economy and environment

Proceedings of 7th Transport Research Arena TRA 2018, April 16-19, 2018, Vienna, Austria

Parametric design and holistic optimisation of post-panamax containerships

Alexandros Priftis [a] *, Evangelos Boulougouris [b], Osman Turan [a]

[a]*University of Strathclyde, 100 Montrose Street, G4 0LZ, Glasgow, United Kingdom*
[b]*Maritime Safety Research Centre, University of Strathclyde, 100 Montrose Street, G4 0LZ, Glasgow, United Kingdom*

Abstract

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 designs for various types of merchant ships. Moreover, the introduction of new regulations by the IMO has added further constraints to the ship design process. In this respect, proper use of modern CAD/CAE systems extends the design space, while generating competitive designs in short lead time. This study deals with the parametric design and holistic optimisation of a post-panamax containership. The methodology includes a complete parametric model of a containership's external and internal geometry, as well as the development and coding of all tools required for the determination of both the design constraints and the efficiency indicators, which are used for evaluating the parametrically generated designs. The second-generation intact stability criteria are taken into consideration in the optimisation process. The set-up multi-objective optimisation problem is solved by use of the genetic algorithms and clear Pareto fronts are generated.

Keywords: parametric design; computer-aided design; holistic; multi-objective optimisation; genetic algorithms; second-generation intact stability criteria; containership

---

* Corresponding author. Tel.: +44 (0) 141 548 4113
E-mail address: alexandros.priftis@strath.ac.uk

1. Introduction

1.1. Container shipping industry

Global containerised trade has been on constant growth since 1996. 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 318.5 $/t. Marine diesel oil (MDO) has been following similar course and can be found at prices of around 534 $/t (Ship & Bunker, 2017). However, 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. 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).

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 2,000-3,000 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 6,000 TEU 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 and a simplified approach was used, namely monitoring the ratio of the above to below deck containers' number.

1.2. International regulatory framework

Recent developments in the international maritime regulations are going to greatly affect future ship designs and particularly containerships. New rules have been recently developed regarding the control and management of ships' ballast water and sediments and is 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.

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). Pure loss of stability failure mode should also be examined, as the considerable flare found in the aft and fore parts of a containership's hull results in significant changes in the waterplane area as the ship sails through waves. These changes may result in a large roll angle or even capsize (Peters et al., 2011). Likewise, excessive acceleration failure mode should be checked in containerships' case, due to high deckhouses found in such kind of ships. Hence, the draft criteria of level 1 and 2 for excessive acceleration, pure loss of stability and parametric roll failure modes according to SDC 2/WP.4 and SDC 3/WP.5 (IMO, 2015) are applied as part of the optimisation process in this study.

2. Parametric CAD design

In recent years, several researchers have presented significant computer-aided design (CAD) methodologies dealing with ship design process and inherently its optimisation (Brown & Salcedo, 2003, Campana et al., 2009, Mizine & 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, containership, focusing on optimisation of the ship's arrangements, while considering all side effects on ship design, operation and economy (Fig. 1) (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.

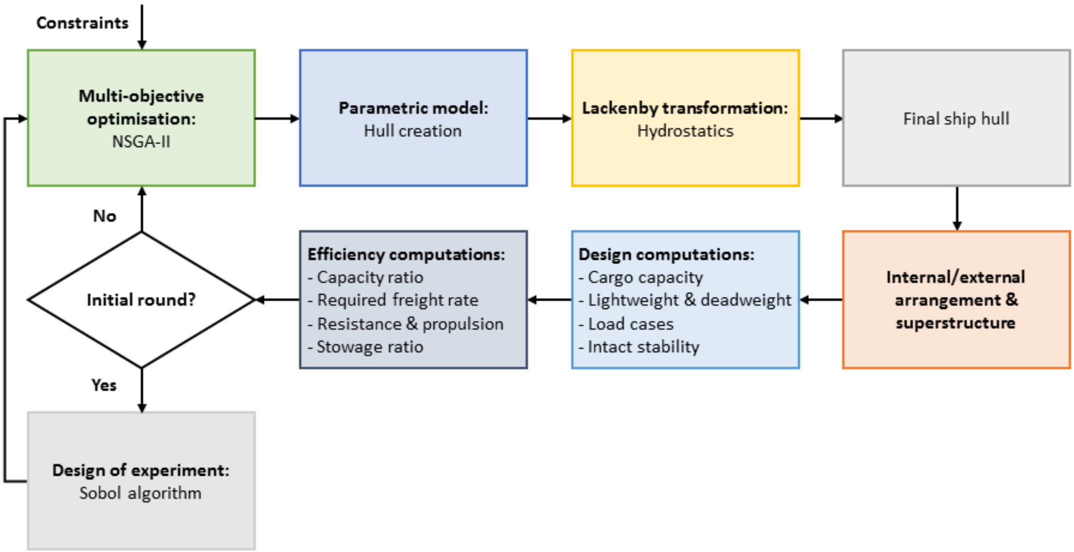

Fig. 1 Design optimisation procedure

2.1. Geometric model

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). 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 & Harries, 2007). Once the final shape of the hull is created in CAESES®, an IGES file, which contains all the geometry-related information, is generated and imported to NAPA® (NAPA, 2017) to continue with the rest of the design process. A list of in-house developed macros is run to generate the complete ship model (Fig. 2). In particular, macros which generate complex surfaces for the internal cargo arrangement definition, along with simpler ones for the oil, fresh water and water ballast tanks, are run first. The former set of surfaces take the hull surface, double bottom and double side distances into consideration in order to take advantage of as much space available as possible while defining the internal cargo arrangement.

Next, the container arrangement both below and above the main deck is defined. The surfaces generated during the previous stage are used as limits for the arrangement below the main deck. As far as the arrangement above the main deck is concerned, the number of deckhouse decks is related to the maximum number of tiers above the main deck. A plane defined in the previous stage is used to check the compliance with the minimum visibility line regulations when defining the container stacks above the main deck.

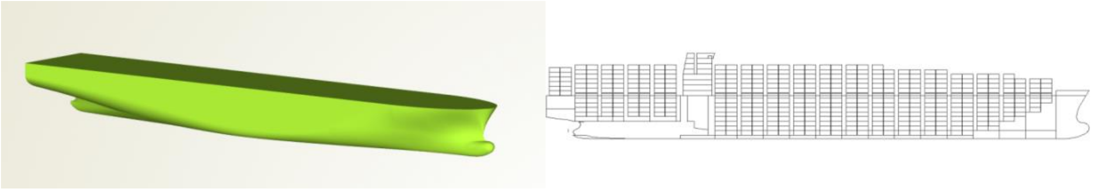

Fig. 2 (a) Modelled aft and fore body created in CAESES®; (b) Ship model created in NAPA®

2.2. Computations

Using the previously generated planes as limits, the required tanks for the consumables and the water ballast tanks are defined in NAPA®. These tanks along with the cargo holds constitute the completed ship model which is used to create the examined load case. However, before defining the latter, two computations must be run first using custom NAPA® macros; the total resistance and propulsion and the lightweight and deadweight analysis. The total resistance and the main engine's power are estimated according to the Holtrop and Mennen method guidelines (Holtrop & Mennen, 1978). The calculated value for the main engine's power then 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). At this stage, the ship's operational speed is defined and set to 22 knots. The lightweight 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). Even though the methods utilised for this step are semi-empirical approaches, and thus, an approximation of the exact values, effort is put to get the most accurate results. In this context, the formulae are calibrated using a similar 6,300 TEU containership, for which detailed lightship breakdown is available. This allows the calculation of correction factors that improve the final outcome of the model's lightship estimation. Thus, first, all required calculations for the reference ship are performed in Microsoft Excel® (Microsoft, 2010) and a custom macro is developed in NAPA®, including the methods used in the first step, to determine the model's lightship characteristics, including the correction factors in the model's lightship computation. Afterwards, custom macros responsible for the deadweight analysis are run in NAPA®, generating 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 (knots)	22
Roundtrip route distance (nm)	13567
Number of ports	18
Average time at port (h)	13.17

Next step is to define the load case examined in this optimisation study. Taking into account the recent regulations regarding the control and management of ships' ballast water and sediments, a zero-ballast "full load departure" condition is defined. The rationale for creating such a load case is to examine how the containership's cargo arrangement should be defined, so that the ship is capable of transporting as many containers as possible while its water ballast tanks are empty. A custom NAPA® macro is run for the load case definition, during which containers are being loaded while intact stability criteria are being monitored to ensure compliance with international regulations. Homogeneous TEU weight is assumed, varying between 10 and 14 tonnes. 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. Afterwards, the attained and required energy efficiency design index (EEDI) values are calculated. 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 (IMO, 2012a, c, b). Using custom NAPA® macros, both the attained and the required values are computed. Finally, the objectives of this optimisation's study are computed in NAPA®. Taking the load case's results into account, two ratios are defined; the capacity and stowage ratio. The former represents the number of loaded containers to the total container capacity. The latter represents the number of containers that can be loaded above the main deck to the number of containers that can be loaded below the main deck. This ratio represents the ship's port efficiency factor. The required freight rate is calculated using custom NAPA® macros. 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):

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

PW represents 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 (e.g. fuel and maintenance costs). As far as the ship acquisition cost is concerned, several data are used as input, including the steel mass of the vessel, cost of steel, discount rate and operation time (Soultanias, 2014). Once all the above computations are completed, a text file is automatically generated by NAPA®, after calling the required commands. This text file is then read by CAESES® to continue with the second-generation intact stability criteria level 1 and 2 checks. The latter are performed using custom made programmes (or "features" as they are called in CAESES®). Level 1 checks are meant to be simple and conservative, in order to quickly detect any vulnerability to each of the three failure modes. Level 2 checks are more complex, thus less conservative, taking into account more design-related details in order to determine whether the ship is vulnerable to either of the examined failure modes. For each failure mode, several features are developed within CAESES®, connecting various external software to quickly evaluate certain parameters required for these particular computations. Maxsurf® Stability (Bentley Systems, 2014) is run to produce the necessary metacentric height (GM) values for various wave conditions, while Matlab® (Mathworks, 2014) is used to calculate the roll amplitude, where complex equations must be solved.

3. 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 & 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. No objectives are set yet, since only the feasibility boundaries are investigated. However, several parameters are evaluated through this process.

Table 2. Design variables

Design variable	Minimum value	Maximum value
Number of bays in hold aft of deckhouse	4	5
Bays	16	18
Y-extent of bilge (m)	4	6
Z-extent of bilge (m)	4	6
Double bottom (m)	2	3
δC_P	-0.05	0.05
δLCB	-0.025	0.025
Rows	14	18
Tiers in hold	8	10
Tiers on deck	6	8
Homogeneous TEU weight (t)	10	14

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, specific hull dimensions, such as the double bottom, as well as the variation of the C_P and LCB values and the homogeneous container weight. Taking into account typical containership load cases, the weight of each container loaded in the examined load case can vary between 10 and 14 tonnes. 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 breadth of the hull is calculated by taking the number of rows and the beam of each container into account. 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. It is worth mentioning that the TEU capacity of the model is not constrained during the DoE phase, thus the maximum and minimum number of TEU capacity of the variants is limited to the 6,000-7,000 area only during the formal optimisation round.

Table 3. Design constraints

Constraint	Value
Excessive acceleration criteria	= 1
Pure loss of stability criteria	= 1
Parametric roll criteria	= 1

“Attained/required” EEDI ratio	$\leqslant 1$
Load case draught	$\geqslant 0.925 \cdot T_{Design}$
Maximum TEU capacity	$\leqslant$ 7,000
Minimum TEU capacity	$\geqslant$ 6,000

4. 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, 80 generations are created, having a population size of 16, each. This results in a total of 1,280 produced variants. The design variables’ range remains the same, as the design space proved to be well defined. Contrary to the previous phase, apart from the evaluation of the model’s various parameters, four objectives are defined:

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

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 & Yang, 1998). In scenario 1, all four objectives are considered to be equally important; hence each one is assigned a weight at saturation of 25%. On the other hand, in scenarios 2 and 3, the RFR and stowage ratio are chosen respectively to be more significant for the decision maker (designer, operator) by assigning to them a weight of 50% and 25% for the most important and the second most important objective in both cases, whereas the rest are assigned a weight of 12.5%. 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 variant dominates in every scenario.

Table 4. Case scenarios

Objective	Scenario 1	Scenario 2	Scenario 3
Capacity ratio	25%	12.5%	12.5%
RFR	25%	50%	25%
Ship resistance	25%	12.5%	12.5%
Stowage ratio	25%	25%	50%

5. Discussion of results

5.1. 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
Number of bays in hold aft of deckhouse	4
Bays	17
Y-extent of bilge (m)	5.5
Z-extent of bilge (m)	5.5
Double bottom (m)	2
δC_P	0
δLCB	0
Rows	18
Tiers in hold	9
Tiers on deck	6
Homogeneous TEU weight (t)	10

Table 6. Base model design objective values

Objective	Base model value
Capacity ratio	1.0000
RFR ($/TEU)	377.81
Ship resistance (KN)	2395
Stowage ratio	0.9612

5.2. 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.

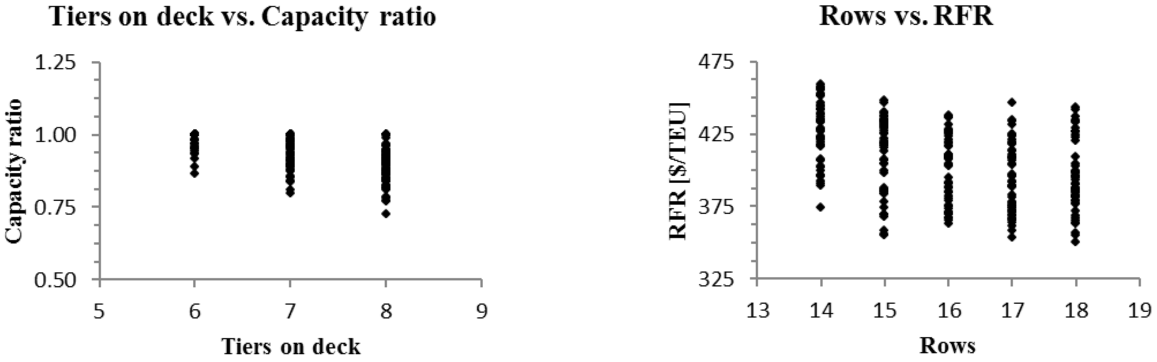

Fig. 3 (a) Number of tiers above the main deck vs. capacity ratio; (b) Number of rows vs. RFR

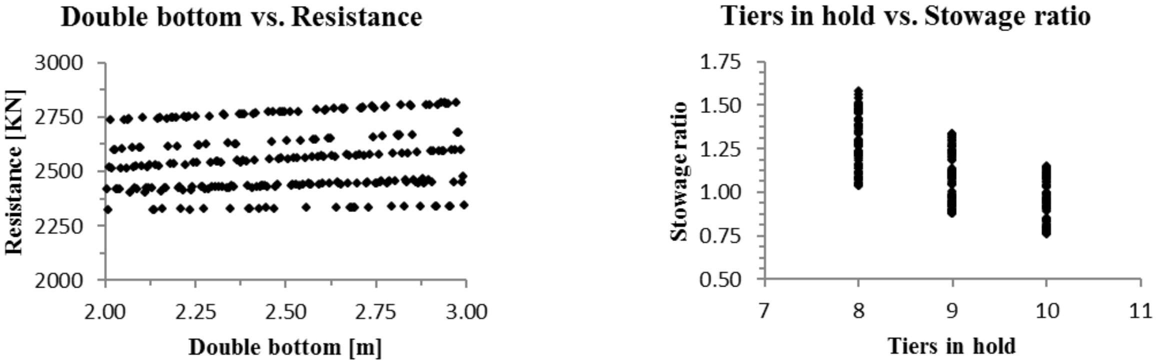

Fig. 4 (a) Double bottom vs. total resistance; (b) Number of tiers below the main deck vs. stowage ratio

As far as the relation between the capacity ratio and the number of tiers above the main deck is concerned, it is evident that in all possible scenarios, the capacity ratio can reach 100%, meaning that in some cases, in the examined load case, the maximum number of TEUs that can be loaded can be equal to the maximum TEU capacity of the ship. However, as the number of tiers above the main deck increases, the ratio can reach lower values (Fig. 3). When the RFR is compared with the number of rows, an inverse proportion can be spotted. In particular, as the number of rows gets higher, lower RFR values are achieved. The trend is more noticeable between the 14 and 16 rows range (Fig. 3). In Fig. 4, the relation between the total resistance and the double bottom distance is illustrated. A slight increase in the total resistance can be identified, as the double bottom distance rises. Finally, as far as the relation between the stowage ratio and the number of tiers in hold is concerned, a steep decrease in the ratio can be observed, as the number of tiers below the main deck increases. The amount of cargo space in cargo holds increases as more tiers become available below the main deck, hence the number of TEUs stored below the main deck gets higher, leading to a low stowage ratio (Fig. 4).

5.3. Multi-objective optimisation

Following the NSGA-II run and the evaluation of the results, an improved design, named Des0573, is identified. Des0573 ranked first in the first and third scenarios. A second variant, named Des0576, ranked first in the second scenario. Both designs respond similar to the objective functions and following the decision-making process, Des0573 is ultimately selected as the optimal design. Below, some principal information of the optimised design can be found (Fig. 5, Tables 7, 8).

Table 7. Des0573 design variable values

Design variable	Des0573 value
Number of bays in hold aft of deckhouse	5
Bays	17
Y-extent of bilge (m)	4.071
Z-extent of bilge (m)	4.033
Double bottom (m)	2.254
δC_P	-0.028
δLCB	0.003
Rows	15
Tiers in hold	8
Tiers on deck	8
Homogeneous TEU weight (t)	10

Table 8. Des0573 design objective values

Objective	Des0573 value
Capacity ratio	0.9931
RFR ($/TEU)	358.01
Ship resistance (KN)	2325
Stowage ratio	1.5527

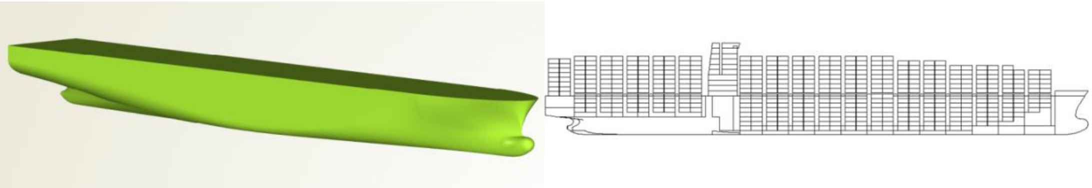

Fig. 5 (a) Des0573 hull; (b) Des0573 ship model

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. As far as the values of the RFR and the capacity ratio are concerned, a favourable trend can be observed. In particular, it can be understood that the higher the capacity ratio, the lower the freight rate. A higher capacity ratio means more containers are loaded in the examined load case, which increases the transported payload and consequently results in lower RFR values (Fig. 6). The relation between the stowage ratio and the RFR is demonstrated also in Fig. 6. There are many designs generated in the 1.40-1.60 range regarding the stowage ratio values, which feature various RFR values. However, the identified improved designs are described by both low RFR and high stowage ratio values. As far as the relationship between the RFR and the resistance is concerned, two main groups of the generated designs can be defined, one described by a total resistance value of around 2300 KN and one described by a total resistance value of around 2450 KN. Des0573 and Des0576 are part of the first group (Fig. 7). Regarding the relation between the two examined ratios, a clear trend towards an optimal point can be observed. The optimal point is described by a capacity ratio of one and a stowage ratio of around 1.60. The identified designs are both close to that point featuring both high capacity and stowage ratios (Fig. 7).

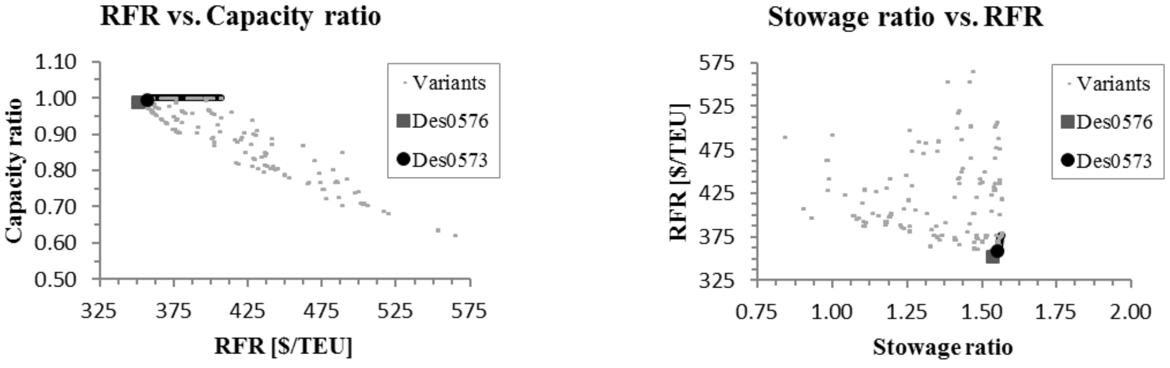

Fig. 6 (a) RFR vs. capacity ratio; (b) Stowage ratio vs. RFR

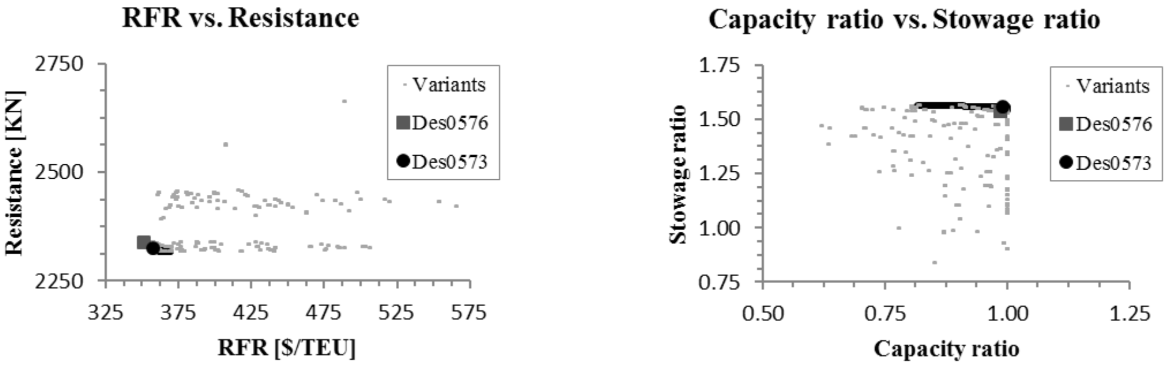

Fig. 7 (a) RFR vs. resistance; (b) Capacity ratio vs. stowage ratio

Below, the baseline model and Des0573 are compared, showing the differences in the objective values (Table 9).

Table 9. Baseline design vs. Des0573

Data	Baseline	Des0573	Difference
Capacity ratio	1.0000	0.9931	-0.69%
RFR ($/TEU)	377.81	358.01	-5.24%
Ship resistance (KN)	2395	2325	-2.92%
Stowage ratio	0.9612	1.5527	+61.54%

As far as the main dimensions are concerned, the improved design features the same number of bays, while the number of rows and tiers below the main deck are decreased by three and one, respectively. Also, two extra tiers above the main deck are carried in the improved design. The extra tiers found in Des0573 offer the advantage of an increased stowage ratio, as well as a reduced RFR, due to the higher total number of TEUs carried on board. Furthermore, the double bottom distance is higher in Des0573's case, while the bilge radius is reduced compared to the baseline design. Overall, Des0573 manages to outperform the original in every objective but the capacity ratio. Nevertheless, the difference in the latter between the two designs is minimal. In addition, the "attained/required" EEDI ratio for Des0573 for the current state of the rules is equal to 0.92, providing a safety margin from the maximum allowed value set by regulations. A notable improvement can be observed in the port efficiency factor, where an increase of 61.54% is achieved.

6. Summary and concluding remarks

The work presented in this paper is part of the HOLISHIP project, where concepts for ship design and operation are implemented in integrated design platforms (Marzi et al., 2018). The objective is to turn this integration into a seamless and flexible design process, where the user can adjust a set of design parameters and get results for the conceptual or contract design. Some of the software tools presented in this paper are to be integrated in the holistic ship design platform currently being developed as part of the HOLISHIP project. In addition, the developed software tools are applied and tested in more cases, which are not part of the HOLISHIP project, in order to be further validated.

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 excessive acceleration, pure loss of stability and parametric roll failure modes. 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 affect the above. The methodology presented in this study can be also applied to other containership sizes or other ship types (Koutroukis et al., 2013). More phases of the ship's life cycle can be integrated to future studies, resulting in more comprehensive holistic ship design investigations (Papanikolaou, 2010).

Acknowledgements

This work was partially funded by the H2020 European Union project "HOLISHIP-Holistic Optimisation of Ship Design and Operation for Life Cycle" (contract 689074).

References

Abt, C. & Harries, S. 2007. Hull variation and improvement using the generalised Lackenby method of the FRIENDSHIP-Framework. The Naval Architect, 166-167.

Bentley Systems 2014. Maxsurf Stability. Windows Version 20 ed.

Brown, A. & Salcedo, J. 2003. Multiple-objective optimization in naval ship design. Naval Engineers Journal, 115, 49-62.

Campana, E. F., Liuzzi, G., Lucidi, S., Peri, D., Piccialli, V. & Pinto, A. 2009. New global optimization methods for ship design problems. Optimization and Engineering, 10, 533-555.

Deb, K., Pratap, A., Agarwal, S. & Meyarivan, T. 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Transactions on Evolutionary Computation, 6, 182-197.

Friendship Systems 2017. CAESES. 4.2.1 ed.

HOLISHIP 2016. Holistic optimisation of ship design and operation for life cycle. EU.

Holtrop, J. & Mennen, G. G. J. 1978. An approximate power prediction method. International Shipbuilding Progress, 25, 166-170.

IMO 2004. BWM - international convention for the control and management of ships' ballast water and sediments. In: INTERNATIONAL MARITIME ORGANISATION (ed.). London, United Kingdom.

IMO 2012a. Consideration of the energy efficiency design index for new ships - minimum propulsion power to maintain the maneuverability in adverse conditions. In: INTERNATIONAL MARITIME ORGANISATION (ed.). London, United Kingdom.

IMO 2012b. Guidelines for calculation of reference lines for use with the energy efficiency design index (EEDI). In: INTERNATIONAL MARITIME ORGANISATION (ed.). London, United Kingdom.

IMO 2012c. Guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships. In: INTERNATIONAL MARITIME ORGANISATION (ed.). London, United Kingdom.

IMO 2015. Development of second generation intact stability criteria. In: INTERNATIONAL MARITIME ORGANISATION (ed.). London, United Kingdom.

IMO 2016. Marine environment protection committee. In: INTERNATIONAL MARITIME ORGANISATION (ed.). London, United Kingdom.

Köpke, M., Papanikolaou, A., Harries, S., Nikolopoulos, L. & Sames, P. 2014. CONTiOPT - Holistic optimisation of a high efficiency and low emission containership. Transport Research Arena 2014. Paris, France.

Koutroukis, G., Papanikolaou, A., Nikolopoulos, L., Sames, P. & Köpke, M. 2013. Multi-objective optimization of container ship design. 15th International Maritime Association of the Mediterranean. A Coruña, Spain: Taylor & Francis Group (CRC).

Kurt, I., Aymelek, M., Boulougouris, E. & Turan, O. 2015. A container transport network analysis study on the offshore port system case of west North America coast. International Association of Maritime Economists. Kuala Lumpur, Malaysia.

Lackenby, H. 1950. On the systematic geometrical variation of ship forms. Transactions of RINA, 92, 289-316.

MAN Diesel & Turbo 2011. Basic principles of propulsion. Copenhagen, Denmark.

Marzi, J., Papanikolaou, A., Corrignan, P., Zaraphonitis, G. & Harries, S. 2018. Holistic ship design for future waterborne transport. 7th Transport Research Arena. Vienna, Austria.

Mathworks 2014. MATLAB. R2014a ed.

Microsoft 2010. Microsoft Excel.

Mizine, I. & Wintersteen, B. 2010. Multi-level hierarchical system approach in computerized ship design. 9th International Conference on Computer and IT Applications in the Maritime Industries. Gubbio, Italy.

Mohd Azmin, F. & Stobart, R. 2015. Benefiting from Sobol sequences experiment design type for model-based calibration. SAE Technical Papers, 1.

NAPA 2017. NAPA.

Papanikolaou, A. 2010. Holistic ship design optimization. Computer-Aided Design, 42, 1028-1044.

Papanikolaou, A. 2014. Ship design: methodologies of preliminary design, Netherlands, Springer.

Peters, W., Belenky, V., Bassler, C., Spyrou, K. J., Umeda, N., Bulian, G. & Altmayer, B. 2011. The second generation intact stability criteria: an overview of development. Annual Meeting of the Society of Naval Architects and Marine Engineers. Houston, Texas.

Priftis, A. 2015. Parametric design and multi-objective optimization of a 6,500 TEU container ship. Diploma, National Technical University of Athens.

Sen, P. & Yang, J. B. 1998. Multiple criteria decision support in engineering design, London, United Kingdom, Springer.

Ship & Bunker. 2017. Ship & bunker [Online]. Available: http://shipandbunker.com/prices [Accessed September 2017].

Soultanias, I. 2014. Parametric ship design and holistic design optimisation of a 9K TEU container carrier. Diploma, National Technical University of Athens.

Spyrou, K. J. 2005. Design criteria for parametric rolling. Oceanic Engineering International, 9, 11-27.

UNCTAD 2016. Review of maritime transport. Geneva, Switzerland.

van Marle, G. 2016. Intra-Asia beckons for panamax ships. Container Shipping and Trade. Enfield, United Kingdom: Riviera Maritime Media Ltd.

Watson, D. G. M. 1998. Practical ship design, United Kingdom, Elsevier.