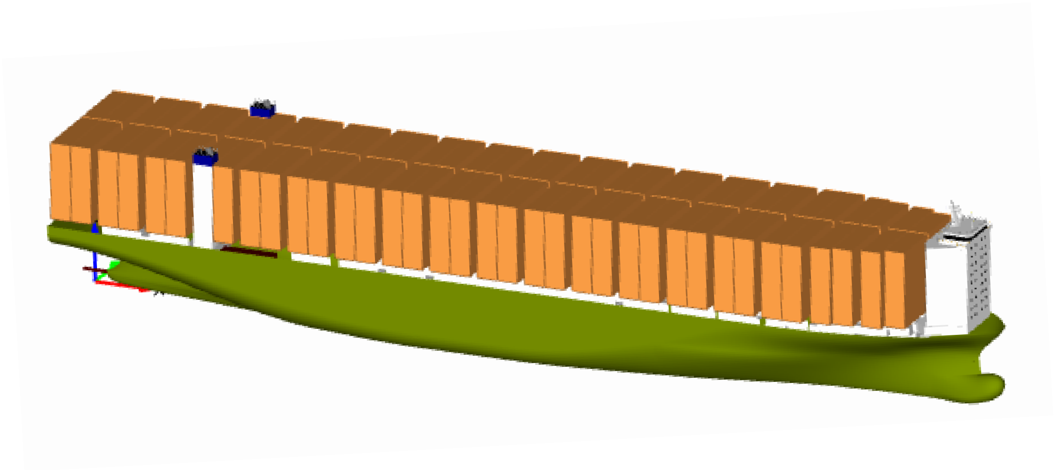
NATIONAL TECHNICAL UNIVERSITY OF ATHENS
SCHOOL OF NAVAL ARCHITECTURE AND MARINE ENGINEERING
DIVISION OF SHIP DESIGN AND MARITIME TRANSPORT

Diploma Thesis:

Parametric Ship Design and Holistic Design Optimization of a 9K TEU Container Carrier



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Abstract

Global concerns about environmental pollution, regulatory framework, the ever increasing fuel costs and the competitive container carriers industry are driving the quest for ever improved ships with higher performance efficiency, lower emissions and more attractive financially. In order to meet all these requirements, the designers need to push their conventional means to the limits and come up with new solutions and design features that improve the current solutions. Optimization seems to be the promising way to achieve the improvement goals, when applied with state of the art techniques that can identify the ship as a whole. Holistic design optimization is the way of analyzing and taking into account every system of the ship as a whole and not as synthesis of their parts and this scope leads to a more integrated approach of the ship design, contrary to the conventional ship design spiral. The most important part to materialize this approach is the fully parametric ship design model, made widely available lately though the advances of the CAD/CAE technology. Parametric modelling enables the designers to investigate their available options with regard to improvement efficiency, when combined with variation and optimization techniques. By enclosing all ship performance aspects like geometry, hydrostatics, stability, resistance and power, economics, energy and operational efficiency, as computational modules, the model gives a complete image of the design performance. Within the scope of this project, a case study of a 9000 TEU container carrier is modelled with the use of the powerful CAD/CAE system CAESES/FRIENDSHIP-Framework. The model provide the user with its performance indicators and thus allows the implementation in an iterative optimization process. Multi objective optimization with the use of Genetic Algorithms investigates the improvement margin of the ship design and provides the final Pareto-Front set of optimal designs and among them a top ranking design is chosen as representative of the whole procedure.

Keywords:

Optimization; CAD/CAE systems; Holistic Design; Parametric Modelling; FRIENDSHIP-Framework; 9000 TEU container ship; port efficiency

Περίληψη

Οι παγκόσμιες ανησυχίες για περιβαλλοντικά θέματα, το νομικό πλαίσιο, τα ολοένα αυξανόμενα κόστη καυσίμων και ο ανταγωνισμός της βιομηχανίας μεταφοράς εμπορευματοκιβωτίων, οδηγούν στην αναζήτηση νέων βελτιωμένων πλοίων με υψηλότερη αποδοτικότητα, χαμηλότερες εκπομπές και οικονομικότερα. Προκειμένου να καλυφθούν όλες αυτές οι απαιτήσεις, οι σχεδιαστές οφείλουν να ωθήσουν τα συμβατικά μέσα τους στα όρια και να βρουν νέες λύσεις και σχεδιαστικά χαρακτηριστικά που θα βελτιώσουν τις υπάρχουσες λύσεις. Η βελτιστοποίηση δείχνει να είναι πολλά υποσχόμενο μέσο για την επίτευξη αυτών των σκοπών, όταν εφαρμόζεται με σύγχρονες τεχνικές που αναγνωρίζουν το πλοίο ως σύνολο. Η ολιστική βελτιστοποίηση στο σχεδιασμό του πλοίου είναι η μέθοδος ανάλυσης και υπολογισμού όλων των υποσυστημάτων του πλοίου ως οντότητες και όχι ως σύνθεση των μερών τους και αυτή η θεώρηση οδηγεί σε μια περισσότερο ολοκληρωμένη προσέγγιση της σχεδίασης πλοίου, σε αντίθεση με τη συμβατική σπείρα σχεδίασης πλοίου. Το σημαντικότερο εργαλείο για την υλοποίηση αυτής της προσέγγισης είναι η παραμετρική σχεδίαση, που έγινε τελευταία ευρύτερα διαθέσιμη μέσω της ανάπτυξης των τεχνολογιών CAD/CAE. Η παραμετρική σχεδίαση δίνει στους σχεδιαστές τη δυνατότητα να διερευνήσουν τις διαθέσιμες επιλογές τους σχετικά με την βελτίωση της αποδοτικότητας, συνδυαζόμενη με τεχνικές προσομοίωσης και βελτιστοποίησης. Περικλείοντας όλους τους παράγοντες επιδόσεων του πλοίου όπως υδροστατικά, ευστάθεια, αντίσταση και πρόωση, οικονομικά, ενεργειακή και επιχειρησιακή αποδοτικότητα ως υπολογιστικά τμήματα, το μοντέλο δίνει μια πλήρη εικόνα των επιδόσεων του σχεδιασμού. Στα πλαίσια αυτής της εργασίας, μοντελοποιείται ένα πλοίο μεταφοράς κιβωτίων τάξης μεγέθους 9000 TEU με τη χρήση του ισχυρού CAD/CAE προγράμματος CAESES/FRIENDSHIP-Framework. Το μοντέλο παρέχει στο χρήστη τους δείκτες αποδοτικότητας και επιτρέπει την εφαρμογή μιας επαναληπτικής βελτιστοποίησης. Η πολυκριτηριακή βελτιστοποίηση με τη χρήση γενετικών αλγορίθμων διερευνά το περιθώριο βελτίωσης του σχεδιασμού και δίνει ως αποτέλεσμα το τελικό σύνολο των βέλτιστων σημείων σχεδίασης Pareto Front, μεταξύ των οποίων και ένα συγκεκριμένο σχέδιο που επιλέχθηκε ως το πρώτο στη σχετική κατάταξη, σαν αντιπροσωπευτικό της όλης διαδικασίας.

Λέξεις κλειδιά:

Βελτιστοποίηση, συστήματα CAD/CAE; ολιστική μελέτη, παραμετρική μοντελοποίηση, FRIENDSHIP-Framework, 9000 TEU container ship, αποδοτικότητα λιμενισμού

Acknowledgement

Coming to the end of my studies, this project work concludes my studies in the school of Naval Architecture and Marine Engineering at the National Technical University of Athens. I am really grateful to the professors, staff and colleagues here, who have offered me so much support, knowledge, opportunities and added so much value in my studies and myself as a person.

My supervisor Prof. Apostolos Papanikolaou has been a real inspiration, assistant and supporter throughout my last years and for this he has my deepest gratitude. I would really like to thank him for the opportunity he gave me to work on such an interesting topic and the insight he gave me in advanced ship design topic.

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Όλα αυτά δε θα ήταν δυνατά χωρίς την αμέριστη συμπαράσταση, υποστήριξη και ανιδιοτελή προσφορά των ανθρώπων που αποτελούν σημείο αναφοράς μου όλα αυτά τα χρόνια. Ευχαριστώ τους γονείς μου.

Ilias Soultanias

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PART A: Container shipping and ship design background

1 The Container Shipping Industry

1.1 Container shipping evolution

Trading and therefore shipping was one of the activities that humans developed as soon as their level of culture demanded the import of indigenous goods or the export of their products. Since all these primitive civilizations that developed so early these activities and high level of culture were located around the eastern Mediterranean and Mesopotamia area, the transport of the exchanged goods was inevitable, waterborne trade kicked off. The very first vessels to be used for the transport of goods across the Aegean Sea and eastern Mediterranean were human powered, with large storage spaces, to accommodate the stowage of the cargo. In modern terms, we would describe them as general cargo ships with no primitive handling gear consisting mainly of pulleys, ropes and levers, technology available from the construction field at the time, while liquids would be carried in clay pots and other grain products in sacks.

That was the case since ancient times and remained in principle the same all the way up to the 19th century. Of course, there have been several other ship types developed over the time course, but most of them were related to people transportation, warships or fishery. The general cargo transportation ships followed the same principles for the storage and stowage of cargo on board and some evolutions were only made on the propulsion power and construction sides. Up until the Middle Ages the volume of trade could be handled by that kind of general cargo ships, the grains could still be put in bags and liquids in pots, while in only some cases big amounts of grain cargo would be carried in the bare cargo holds. The handling gear did not evolve significantly throughout the time and only adopted to the different type of cargo transported from time to time and the larger amount of grain cargo transported over time. Industrial revolution came to change societies, technology, and the nature of the transported goods. Different ship types evolved to cater the different cargo to be transported. Tankers for the transportation of liquids and bulk carriers for the grains were the first to differentiate, although a conversion of the ship type was not difficult for those primitive designs lacking many of the late safety measures. General equipment and cargo in small amounts was still transported in general cargo ships with large holds and it was not until the 1950s, that a major change in the shipping took place.

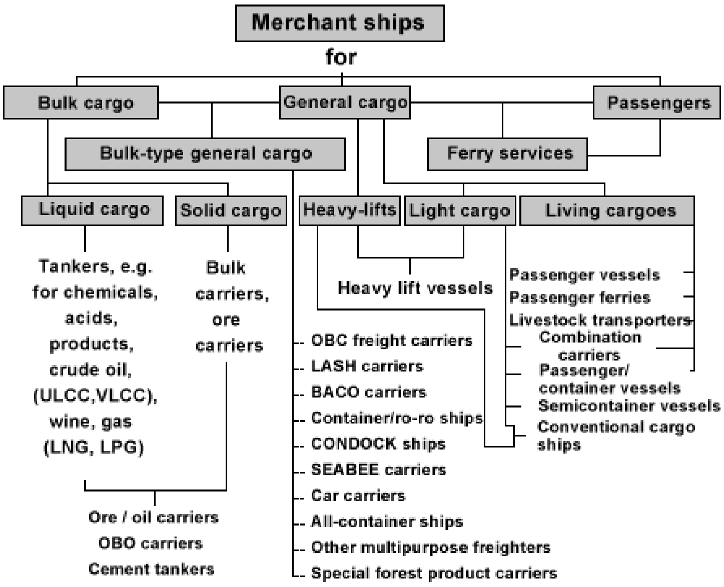


Figure A. 1 Ship Types

In 1955 a trucking entrepreneur from North Carolina, USA, introduced the idea of carrying entire truck trailers with their cargo still inside. Malcom P. McLean realized that it would be much simpler and quicker to have one container that could be lifted directly from the truck onboard the ship, without having to unload its contents and container shipping was born on converted tankers! In the following years, containers would become more popular in the states, and specific ships for their transportation were built, while around 1960s the standard dimensions of containers were set. Intermodalism, was the new era in the seaborne transportation and it would change the whole logistics chain by unifying seaborne and land transportation from end to end. The International Standardization Organization defined the standard dimensions to be used, ensuring compatibility with the Twenty-foot Equivalent Unit- TEU being the standard unit, with length of 20 ft, height and breadth of 8 ft, while the Forty-foot Equivalent Unit-FEU is the most common used today. Containers were moved onboard ships then directly to trucks or trains seamlessly and with the minimum handling costs. This new transportation system is believed to be the driver or the globalization and the tremendous growth in the second half of the 20th century.

Since early 70s this new ship type became popular and some big companies to rule the whole transportation chain emerged. By operating terminals, rail services and shipping lines, companies like Sea-Land (the offspring of Malcom McLean) and Maersk, were able to optimize the whole transportation process. At the initial development of this new market, consortia of carriers sharing space on ships and individual shareholders with shared responsibility were the main supporters and gave birth to the first shipping companies of this kind mainly in the US, Denmark and Germany. This had been the development model for this industry until recently, when more individual ship-owners active in other ship types, invest in containerships. The recent increase in the containerized trade has drawn attention to this industry and will continue evenly in the near future.

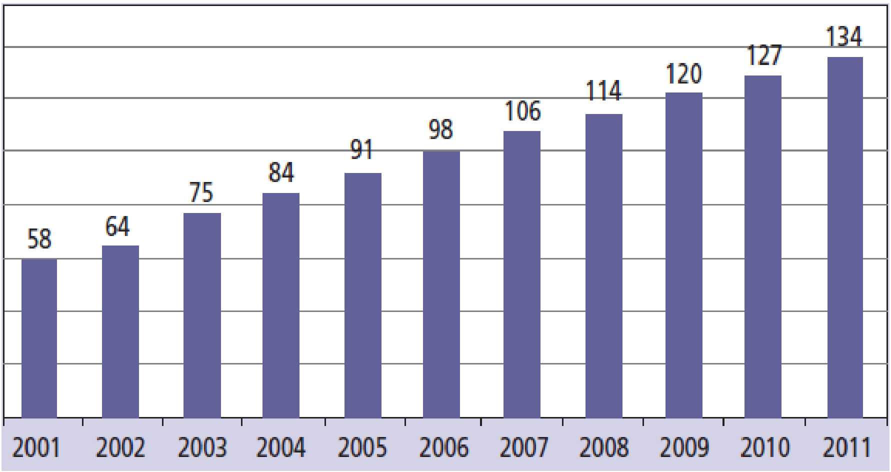


Figure A. 2 Global Containerized Trade 2001-2011 in million TEU [1]

At the beginning of this new ship type, the vessels converted or built to carry containers, could handle up to 1000 TEU, enough to cover the transportation needs at the time. As the industry changed and more commodities and cargo was shipped in containers, the need for bigger vessels to cater major trade lines, brought a growth in ship sizes and older vessel capacities now served as feeders. The quest for bigger ships has reached new growths lately that we expect the deliveries of the first 18000 TEU container ships. This work will focus on the medium category for the latest standards, at 8000-9500 TEU, vessels that operate in major shipping lines between East Asia and northern Europe.

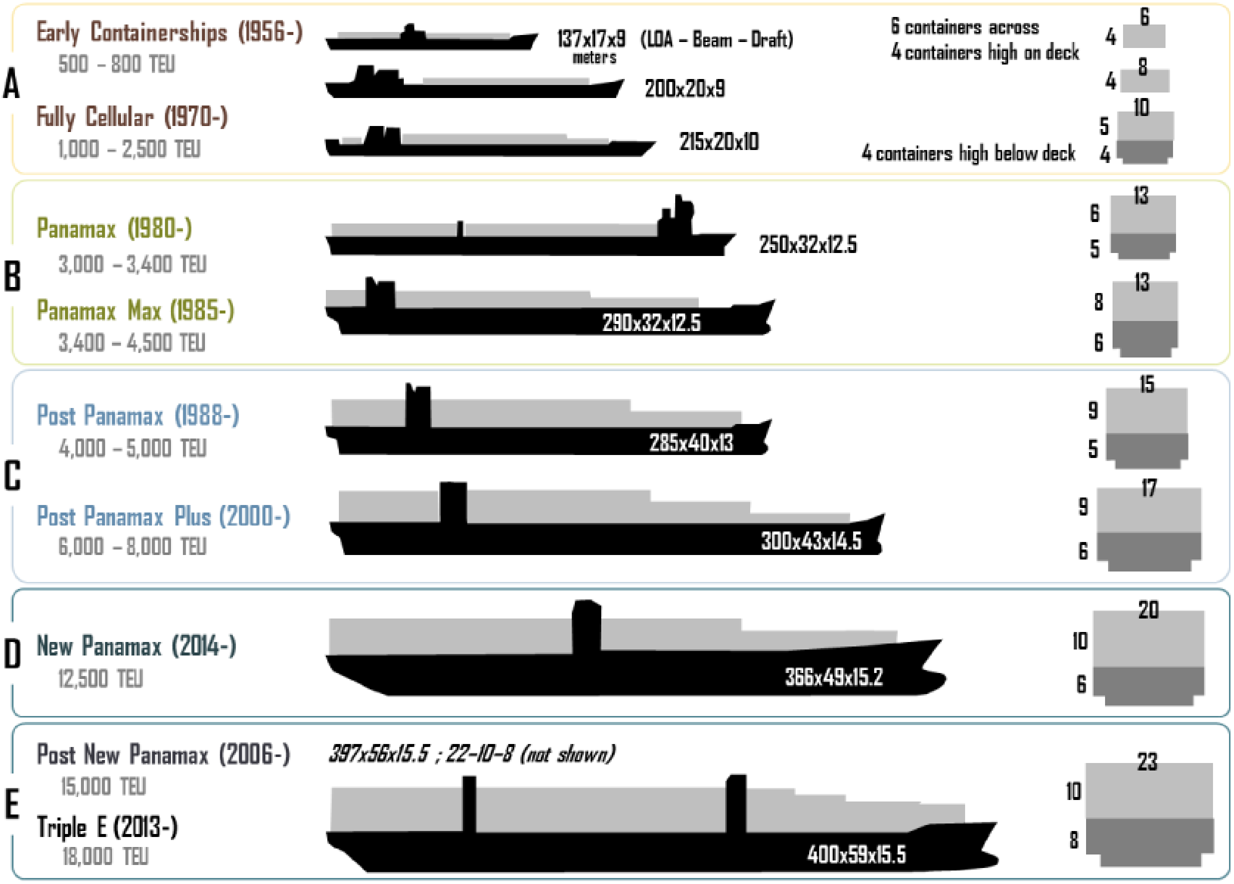


Figure A. 3 Containership size evolution [3]

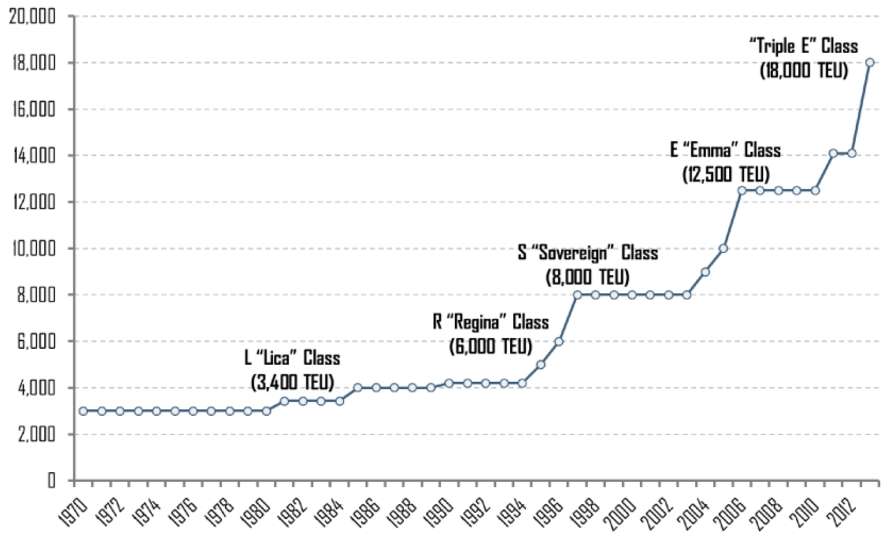


Figure A. 4 The largest available container ship [3]

1.2 Trade routes

In the era of trade globalization, the trade routes have thickened around the world over the last decades. Defined by the trading trends and the industrial production of different regions, the container shipping lines expand around the world and especially between East Asia and North Europe or North America, the most advanced areas. The main trade routes with the highest activity are depicted below:

Table A. I Top Trade Routes [2]

Top Trade Routes (TEU shipped) 2012					
Route	**West Bound**	**East Bound**	**North Bound**	**South Bound**	**Total**
Asia-North America	7,529,000	14,421,000			21,950,000
Asia-North Europe	8,959,000	4,406,000			13,365,000
Asia-Mediterranean	4,371,000	1,875,000			6,246,000
North Europe-North America	2,632,000	1,250,446			4,637,000
Asia-Middle East	2,802,151	1,250,446			4,052,597
Australia-Far East			1,072,016	1,851,263	2,923,279
Asia-East Coast South America			550,000	1,399,000	1,949,000
North Europe/Mediterranean-East Coast South America			824,000	841,000	1,665,000
North America-East Coast South America			667,000	574,000	1,241,000

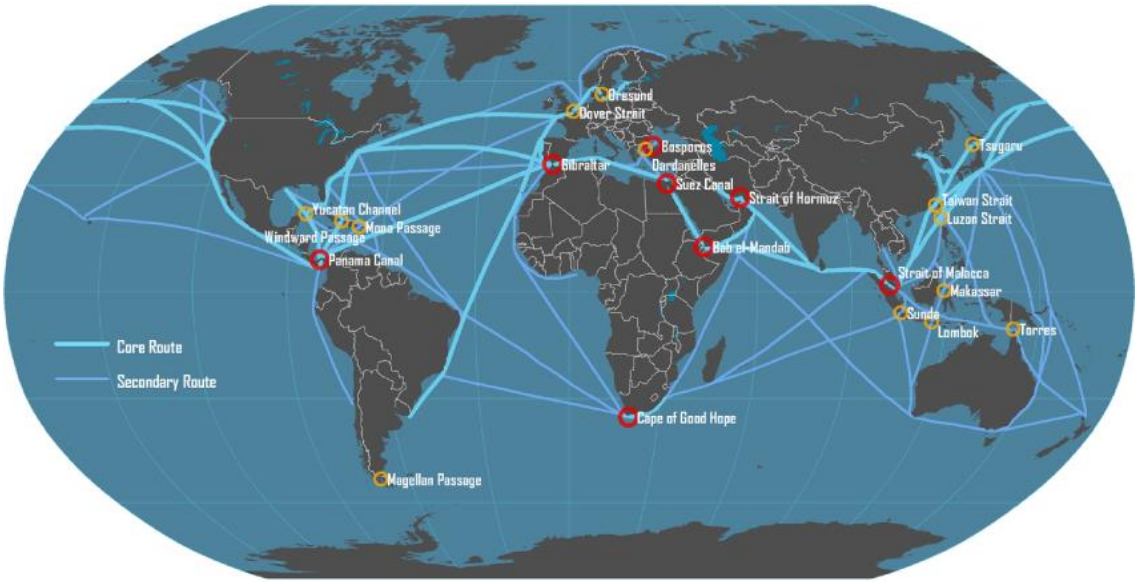


Figure A. 5 World shipping routes [3]

1.2.1 North Europe – East Asia route

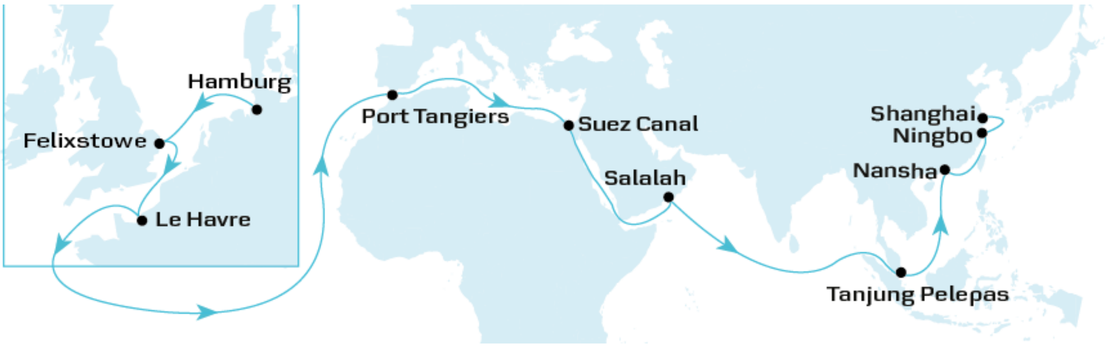
In this case study, the focus will be on the North Europe – Asia route, as implemented by some of the major liner companies. This route was chosen upon the size of container vessels used at the range of 8000-9500 TEU capacity. The same vessel category operates in the pacific route between China and the West Coast of the US. Bellow we have retrieved some interesting facts about the operation of our selected trade route by two major shipping lines.

Figure A. 6 Alternative routes between North Europe and East Asia [3]

Hapag Lloyd (Germany): Loop 4

Total transit time: 46 days
Port Calls: 8
Frequency: weekly
Ship size operating: 8000-9000 TEU

Maersk Line (Denmark): AE6 Asia-Europe



Total transit time: 47 days
Port Calls: 10
Frequency: unknown
Ship size operating: 8000-9000 TEU

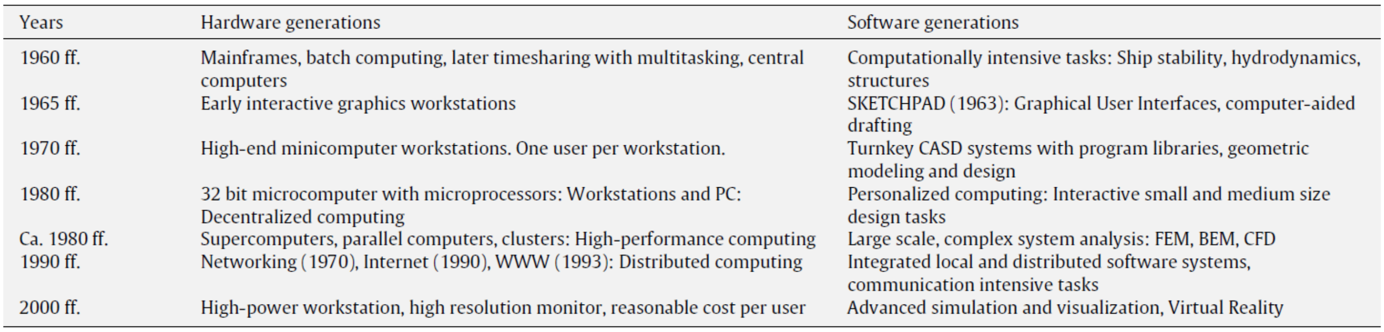
COSCO (China): CES service

Total transit time: 38 days
Port Calls: 8
Frequency: weekly
Ship size operating: 8500 TEU

2 Computer Aided Ship Design and Engineering

2.1 Evolution of CAD/CAE systems in ship design

Advances in computer technology and the evolution of Computer Aided Design Software since the 1960s, introduced new tools in the ship design industry, which enabled the designers to be more creative and effective. These new media were firstly introduced to the shipbuilding industry, through the numerical control of a flame cutting torch in part production from steel plates [4]. Early adoption of the CAD[1] in the ship design practice followed the principle of simulating the manual drafting by means of elastic curves. These early concepts were extended and based on more advanced curve definitions such as Bezier curves, B-Splines and NURBS[2], while surface modeling followed shortly after. In the years to follow, the software developed would support even more intensive applications like hydrostatic calculations, ship stability and some structural and hydrodynamic analysis of ships.



Years	Hardware generations	Software generations
1960 ff.	Mainframes, batch computing, later timesharing with multitasking, central computers	Computationally intensive tasks: Ship stability, hydrodynamics, structures
1965 ff.	Early interactive graphics workstations	SKETCHPAD (1963): Graphical User Interfaces, computer-aided drafting
1970 ff.	High-end minicomputer workstations. One user per workstation.	Turnkey CASD systems with program libraries, geometric modeling and design
1980 ff.	32 bit microcomputer with microprocessors: Workstations and PC: Decentralized computing	Personalized computing: Interactive small and medium size design tasks
Ca. 1980 ff.	Supercomputers, parallel computers, clusters: High-performance computing	Large scale, complex system analysis: FEM, BEM, CFD
1990 ff.	Networking (1970), Internet (1990), WWW (1993): Distributed computing	Integrated local and distributed software systems, communication intensive tasks
2000 ff.	High-power workstation, high resolution monitor, reasonable cost per user	Advanced simulation and visualization, Virtual Reality

Table A. II Generation of computing hardware and software design [4]

The advanced compexity of the ship designs and structures called for a system approach to the whole procedure, leading to a novel system analysis for the ship design methodology. The quest of the optimum and efficient ship design involved the introduction of optimization techniques such as Discrete or integer design variables, stohastic decision models and multiple criteria (or Pareto) optimization [4].

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[1] CAD: Computer Aided Design

[2] NURBS: Non-Uniform Rational B Splines

2.2 General Methodology of CASD systems

The introduction of Computer-Aided Design technologies in the field of ship design was primarily focused on simulating the existing approach with the new means of technology. Thus, the existing familiar approach of the design spiral remained the main guideline, defining the four design phases [5]:

- Conceptual model
- Preliminary model
- Final design model
- Detailed and faired hull form model

This linear approach though, falls mostly in line with the conventional means of ship design, while the advances in the CAD and CAE systems lead to a system-wise approach. In the core of this process lies the model, which interacts with the many different computational modules attached to it, providing results for different design phases. Based on these interrelations and the model structure, it is possible to tell apart the functions of each design phase.

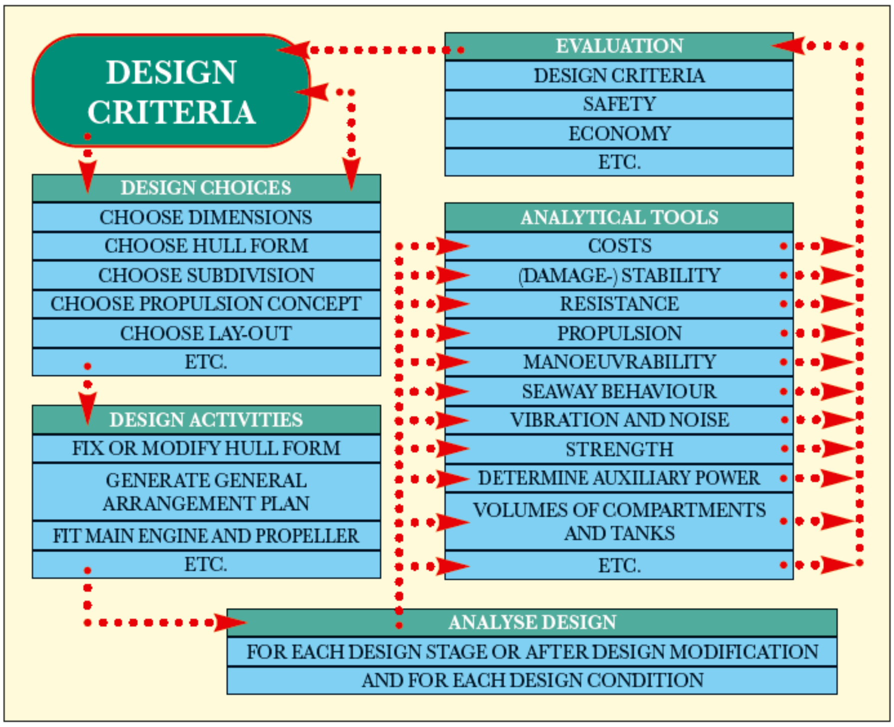

Figure A. 7 Model of Ship hull design process [5]

In the conceptual design phase, data referring to main dimensions and the hard definition of geometry are related with physical laws' functions and even empirical formulas, to provide an early estimation of basic ship particulars, e.g. displacement, propulsion power etc. Moving to the next phase, the preliminary one, the initial draft model and its topology created are used for further and more complex calculations including damage stability, oil outflow etc. among others. At this point there may be an iterative or optimization process for the development of the design. During the two final phases, the final design and the engineering one, a solid 3D visualization of the model is created, minor details get finalized, as well as all construction details, internal arrangements and building drawings are taken care of [5].

In the bottom line, the application of CAD-CAE systems in hull forms design aims to greater effectiveness and higher quality in terms of the performance and safety indexes calculated and overall more accurate preliminary results. This leads to greater overall efficiency of the ship design process, with some interesting benefits [5]:

- Shorter time to reach a certain design stage
- Fast analytical calculations
- Integration between CAD and CAE
- Fast geometric manipulations and variations
- Wider range of the design activities sequence
- Increased job satisfaction

2.3 Integrated ship design

Modern ships need to be energy efficient, economic and reliable in order to confront the operational challenges in the industry. In the quest of the above, ship design today made a little shift from the traditional procedure, to include smarter methods like parametric modelling, numerical analysis, simulations and optimization. These advanced methods enabled by our strong computational resources today can be implemented at an earlier, rather than later stage of the ship design process to achieve better designs in every way possible. As mentioned above, the “combined systems” approach within a holistic scope of the ship design, bypasses the original design spiral and leads to a more integrated solution. This integrated approach has the ship model at its core and all the computational modules interact with it in many different layers.

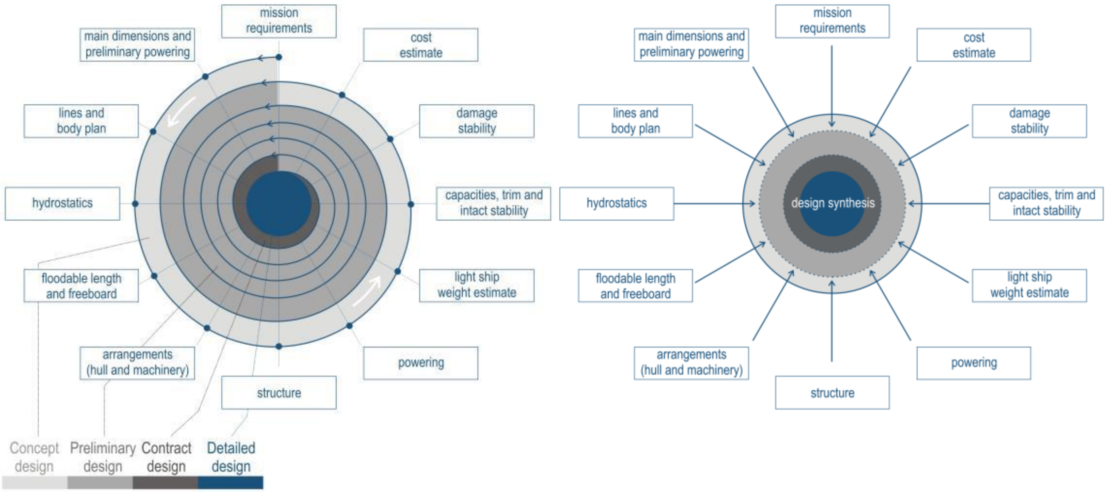

Figure A. 8 Traditional design spiral vs. integrated approach [6]

2.4 Parametric modelling

Under the holistic approach, the model interacts with the different computation modules by means of some basic parameters, values that define the model itself, its geometry and properties. In modern CAD/CAE tools, the range of the parameters defined, demonstrates three major geometric modeling concepts [7]:

- Conventional design
- Partially-parametric design
- Fully-parametric design

2.4.1 Conventional design

This case is about the simulation of the traditional design techniques, where the designer has full control of the shape by moving the essential points forming the curves. This brings also great responsibility, as the designer has to deal with fairing, meeting constraints etc. Conventional approach is a rather rigid method, where any changes to the original design are a time consuming task.

2.4.2 Semi-parametric design

CAD tools under this category are able to build on existing shapes and modify a given hull form by controlling parameters that create variants. New hull forms can be produced by advanced transformations (e.g. Lackenby transformation) or distortion based on a given parent hull form. The method is qualified as “partially parametric”, as changes apply only partially to an existing parent geometry, which in the end keeps all the shape related information unchanged. It is although favored against conventional design, as it can provide the designer some fast simple variants in the initial optimization procedure.

2.4.3 Fully-parametric design

In this last case, the model itself is generated out of relationships created by form parameters. This interaction enables creating ship hulls quickly and effectively, while many of the parameters are in many cases performance indicators, providing the designer with instant feedback. Moreover, the mathematically defined curves and surfaces yield excellent fairness by directly using the model parameters. Since all computations are highly integrated in the model, there is a wide range of variants, as soon as the model is set up.

Depending on the required level of control over the design, each approach can be chosen. As more and more designers take advantage of the CAD CAE features, they move towards the partial and full parametric modelling categories. While partially parametric models build on existing shapes and are exceptional for many short term applications, they are not compatible with more advanced and automatic procedures. Multi objective optimizations require a highly interconnected model as a fully parametric design, in order to apply iterative, AI or machine learning techniques and this is the case that this study focuses on.

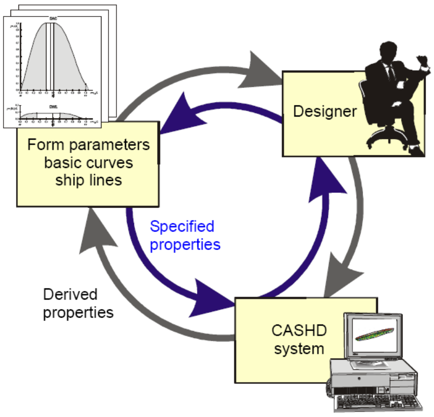

Figure A. 9 Conventional modelling (outer) vs form parameter design (inner) [8]

2.5 Containership design

As part of the transportation chain, containerships are displacement vessels following some specific constraints with regard to the containers they carry. Their main dimensions are multiplies of the original container dimensions, plus some extra spaces like double bottom, double sides, or bay spacing. The shape of the hull of these ships is rather more slender than other cargo vessels such as tankers and bulkers, and that is due to the higher Froude numbers they operate, since their operational speed is also much higher [9]. During the last years, the typical operational speed of a container ship would mount to 25 kn, while today they have reduced their speed even down to 19-20 kn. That calls for a change in the typical designs lately and this is where studies like this and formal optimizations in general come in use. In terms of propulsion, the growth of the ship size and the demand for high speed, made twin skeg configurations and two propellers typical solutions for the designers, while the demand for lower speeds lately and the slow steaming trend, call for a single shaft propeller and bulkier aft ship designs. Stability is rarely an issue, as long as the vertical centers of weights are kept as low as possible, while the consumables' changes during the trip can affect the stability and should be taken into account. High metacentric height GM can also be an issue, by causing high frequency rolling and accelerations respectively. Another interesting design feature of this ship type is the bow shape, which has a large flare angle, so that a large deck area can accommodate enough containers, while at the waterline level and below it needs to be wave piercing and of high hydrodynamic performance. The ship design procedure follows the standard design spiral procedure, as the design evolves after iterations to meet the specifications.

3 CAD/CAE Application in Ship Holistic Design Optimization

Based on holism (derivative of the greek term “holos” (όλος), meaning “the whole”, “entire”), this concept optimization takes into consideration all natural systems as wholes and not as synthesis of their parts [10]. In terms of ship design optimization, this approach addresses the whole ship’s life cycle beginning from the early stages of conceptual and preliminary design to the final design, the economic operation of the vessel and all the way down to the recycling or sell. Merging all the different parameters and indicators to take into consideration under a single model is quite hard task and leads to really complex computational models. Setting main assumptions as design specifications is a first step in working with such complex holistic models, in the quest of the optimum design, which in the end should indicate a more efficient design. Efficiency is of course a matter of economic profits and in this case, the reduced Required Freight Rate can be a major higher efficiency indicator.

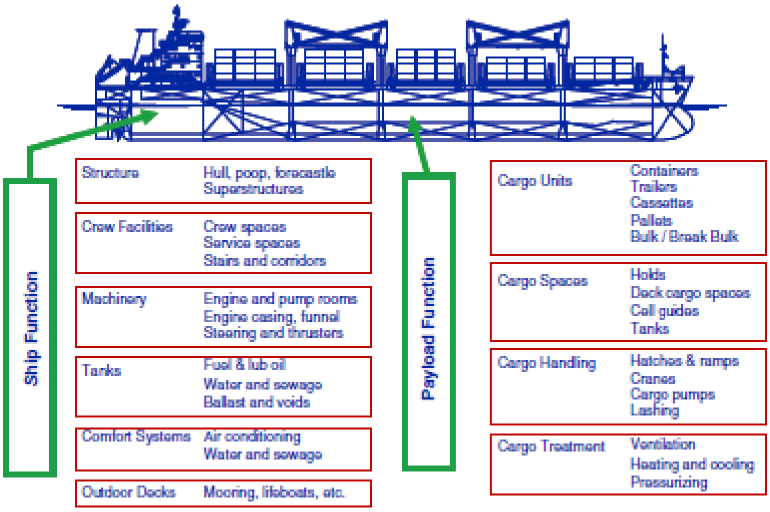

Figure A. 10 Ship functions according to Levander [10]

Optimizing the ship design in a holistic way, means to address and optimize several and gradually all aspects of ship’s life; at least the stages of design, construction and operation [10]. The implementation of all the different functional elements, design features and geometry modules in a single model, forms a nonlinear optimization problem, where unconventional optimization methods and strategies should be applied. The use of Genetic Algorithms combined with gradient based search techniques and with utility functions for the design evaluation is a popular way to deal with that kind of optimization problems. Following this procedure, the generic ship design optimization problem describes the exhaustive multi-objective and multi-constrained optimization with least reduction of the entire real design problem [10]. This definition is served by the following basic elements of the whole holistic optimization project:

- **Optimization criteria (merit functions, goals):** that could be a major performance indicator, needed to be improved in an economic efficient sense.
- **Constraints:** a list of mathematically defined criteria subject to regulations in terms of safety or the dimensions of the project.
- **Design parameters:** a list of parameters (vector of design variables) defining the design under optimization (mainly dimensions, capacities etc.)
- **Input data:** including all the major design specifications, size parameters, reference data, and all the required information for the additional calculations for the design performance
- **Output:** again a set of design parameters (vector of design variables) which deliver designs with minimized (or maximized, as defined per case) merit functions. These are supposed to be the optimal designs, although, there is a trade off at the selection of the optimum along the Pareto front, for multi-objective optimizations.

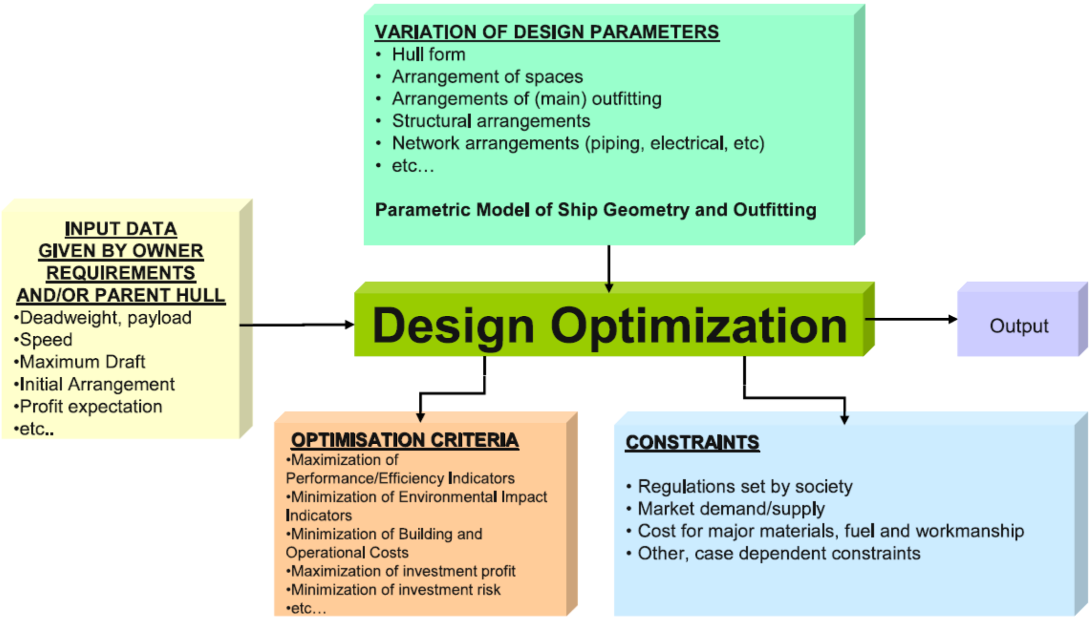

Figure A. 11 Generic Ship design optimization problem breakdown [10]

4 Port Efficiency of Container Vessels

In the frame of a holistic ship efficiency optimization, targeting for reduced fuel consumption at lower speeds, lower emissions and enhanced port efficiency, the time spent in port is an important ship design characteristic. The pursue of more efficient designs is calling for any kind of design optimization with objectives ranging from resistance and sea keeping performance to EEDI and required freight rate. Within the ship design holistic optimization context, many objectives are taken into consideration, aiming to a better over-all performance of the ship in operation.

Vessels operate at lower speeds, trying to keep the same voyage times, reducing fuel costs, while not compromising on services' quality. The only way to achieve that is by eliminating the time spent in port for loading operations and save it to compensate additional voyage time at lower speeds, following an old saying that goes: "The fastest trip is made in Port". In that case, Port Efficiency of a ship design in terms of port operations speed, is of particular interest and shall be an optimization objective of its own. In this case, container ship designs are studied and optimized, so the container ships' port efficiency is our focus.

In that sense, the phenomenon can be addressed in many different ways. As a side project of this thesis, an extensive loading simulation study has tried to take a look into the matter by analyzing statistical data that simulate the actual ship operations. At a later stage, that simulation configuration could possible evolve into one of the computational modules within fully parametric models and taken into account under the umbrella of holistic design optimization. A more simple approach was chosen for the scope of this project though, by looking into one particular design characteristic that is rather important and has an interesting correlation with the actual port efficiency of container vessels and that is the stowage ratio: $\frac{containers\ on\ deck}{containers\ in\ hold}$. It seems that the more containers stowed on deck over the ones stored in the holds, the more efficient and fast for loading operations the ship becomes. This is an assumption that follows the common sense.

PART B: Parametric Modelling and Design Optimization

1 Case Study: 9000 TEU Class container carrier and transport scenario

The study conducted in the scope of this thesis is focused on the case of an 8000 TEU class container carrier employed in the North Europe – East Asia line, as described in PART A:1.2.1 and is thoroughly presented below. Given the initial design specifications, a research of similar ships' data from available databases was conducted, in order to set up some basic design parameters. At the core of this project lies the complex parametric model, which was built from scratch, based on similar models from previous studies of the Ship Design Laboratory [11, 12]. Several new features and computation modules were originally developed and included in this model, in an attempt to develop the existing parametric model library of the SDL[1], make the whole optimization procedure more robust, faster and get more independent from costly external software deployed in the computations.

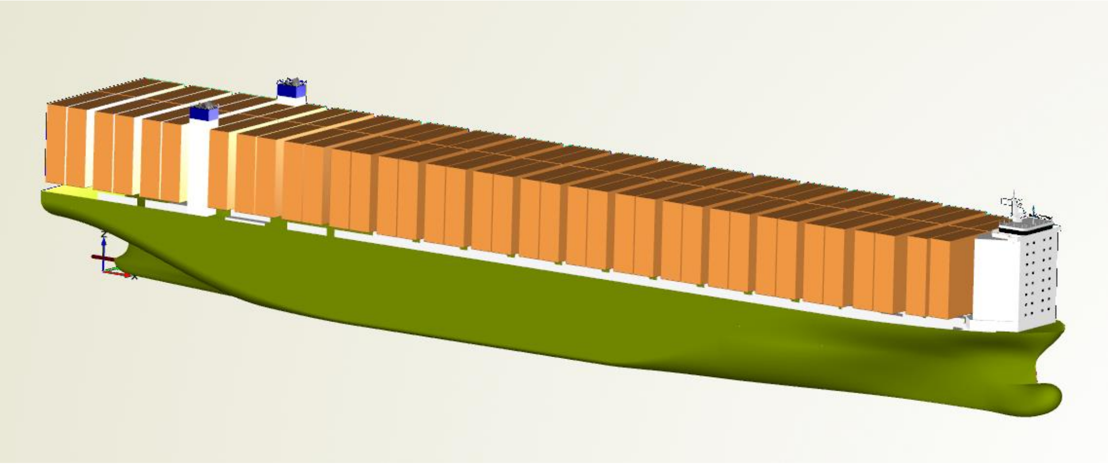

Figure B. 1 Baseline model configuration

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[1] SDL: Ship Design Laboratory; National Technical University of Athens

1.1 Operational profile

As explained above, the Asia – Europe route was studied because of the operational scenario involving the specific size of containerships. After studying the differences of the implementation of the route from 3 companies as described in PART A:1.2.1, the basic parameters for our operational profile were set. The main concept behind the optimal speed choice and the range of capacities to look at was to keep the transit time pretty much around the industry standards and cater the same capacity. More specifically, as a median number of transit days of the investigated scenario, 40 days was identified as a feasible and satisfactory time for the round trip voyage of our case. The total route length assumed in our model was actually measured on a designed route based on the above. Based on these two fixed parameters, an initial investigation for different speeds was undertaken, in order to identify a satisfactory speed range and any other model sensitivities with regard to speed change and this is elaborated later on.

Containership operational profile		
Transit time	40	days
Vessel speed	20	knots
Ship capacity	8000-9500	TEU
Route Length	13810	sea miles

Table B. I Operational profile data for round trip

1.2 Similar ships

For the preliminary design of this model, there were not any parent ships to be based on their drawings and characteristics. What was really intuitive though, was a list of similar ships' particulars, for the initial investigation of main dimensions etc.

	TEU	L_{oa}	L_{pp}	B	D	T_d	T_s
1	8063	323.00	308.00	42.80	24.6	13.00	14.50
2	8100	334.00	319.00	42.80	24.6	13.00	14.50
3	8500	334.00	319.00	42.80	24.6	13.00	14.50
4	8830	299.90	288.50	48.20	24.60	12.50	14.50
5	8957	299.90	283.30	48.20	24.80	14.00	14.50
6	9200	336.70	321.00	45.60	27.2	13.00	15.00

Table B. II Similar ships' particulars

1.3 Scope of work

Reading from the title of this study: “Parametric Modelling of Container ship and Holistic Design Optimization”, the two main objectives are clarified straight forward. The first leg deals mainly with the construction of the parametric model itself, the mathematical modelling of all the subsystems as computational modules attached to the main geometry and the challenges within. Once the model is completed, it can be used to produce many different design variants or perform simulations of the overall design process and in that sense it is coupled with the deployed optimization algorithm to drive the holistic design optimization of the second leg. In between there is a wide range of design parameters and variables, constraints, tests and experimenting in the quest of the optimum design. The optimization process is iterative and consists of several optimization runs, the results of each one of them are post processed, evaluated and ranked by means of the utility functions approach. In the following chapters, there is an extensive description of the methods applied and the work conducted under this scope.

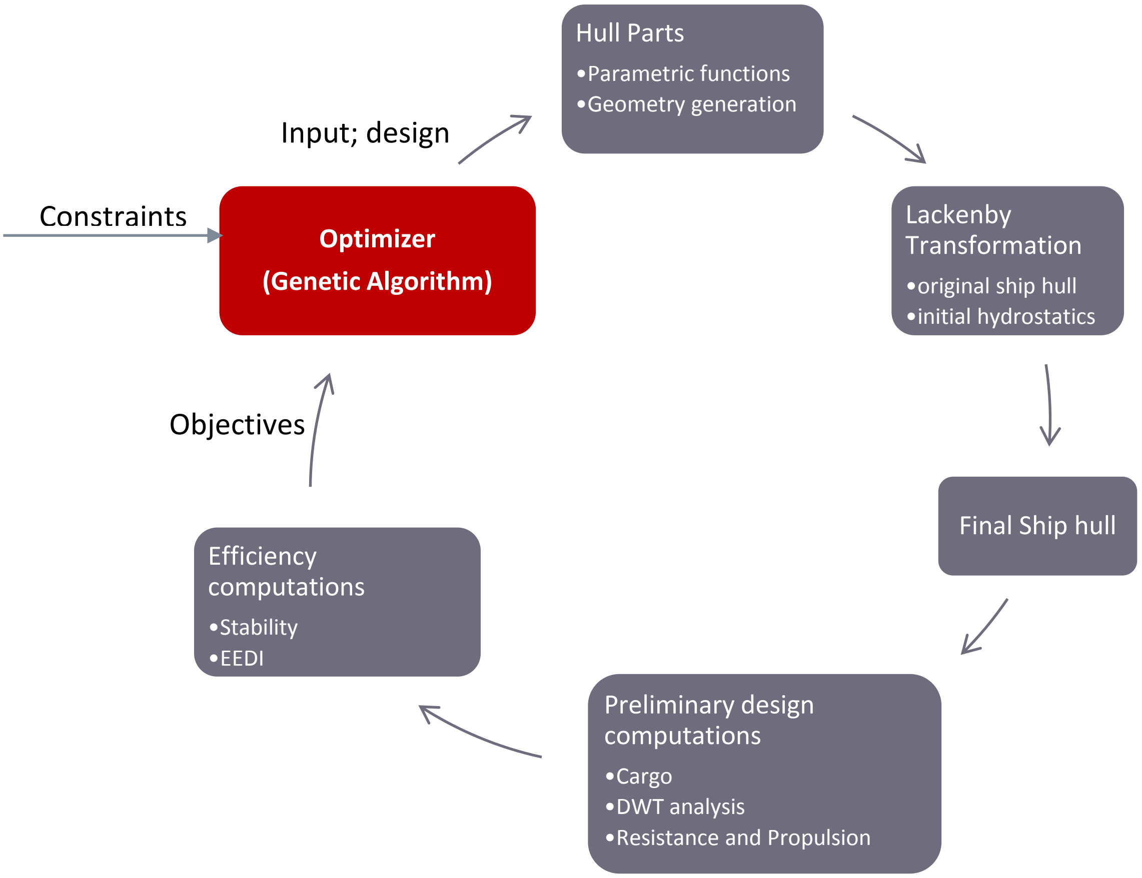

Figure B. 2 Schematic of the work procedure

2 Building the Parametric model

In this chapter there will be an extensive description of the model setup, the structure of the model, the methods used and the additional computations involved.

2.1 CAD/CAE Framework

The whole procedure of parametric modelling of the ship design (including hull form-geometry and additional computations) can only be materialized in an advanced CAD/CAE system, a framework. In this case, the system used is **“CAESES[1]/FRIENDSHIP-Framework”**, developed by Friendship Systems GmbH. The software was originally developed for advanced ship design and optimization applications, bringing some novelties in the CAD part, by introducing new types of curves and mathematical definitions for surface topologies and hull forms. Later on it evolved into a powerful simulation and optimization tool by including the software connector to communicate with external software and codes, and driving optimization with the built-in algorithms.

Using the CAD part of the program and its drawing capabilities, the initial Main Frame is created and the rest of the model is build up based on that section as reference. The ship hull is constructed in parts, which take as parametric input some function curves tailored to the local geometry. After the whole hull is completed, it is transformed using the Lackenby method the basic Hydrostatic computation at this point is the connection to most of the computations that follow. On the completed hull, there are several other subsystems to fit into, such as the internal compartments, the containers on deck, the engine room and the deckhouse, in order to have a complete ship model. The last stage of computations involves the performance simulations and indicators calculation. While the initial reference geometry is built straight forward, most of the surfaces, as well as almost all the computations are conducted via “features”, small pre-programmed modules within the model. The “Feature programming language” of the FRIENDSHIP-Framework, a simple script programming language similar to JavaScript, is used to define these computational modules inside the model. Most of these features can be exported and used in other parametric models almost straight forward, conducting a part of the design stages. Another important functionality of such a parametric design software are the interrelations between parameters, curves, points, and other geometric elements, that make our model fully parametric.

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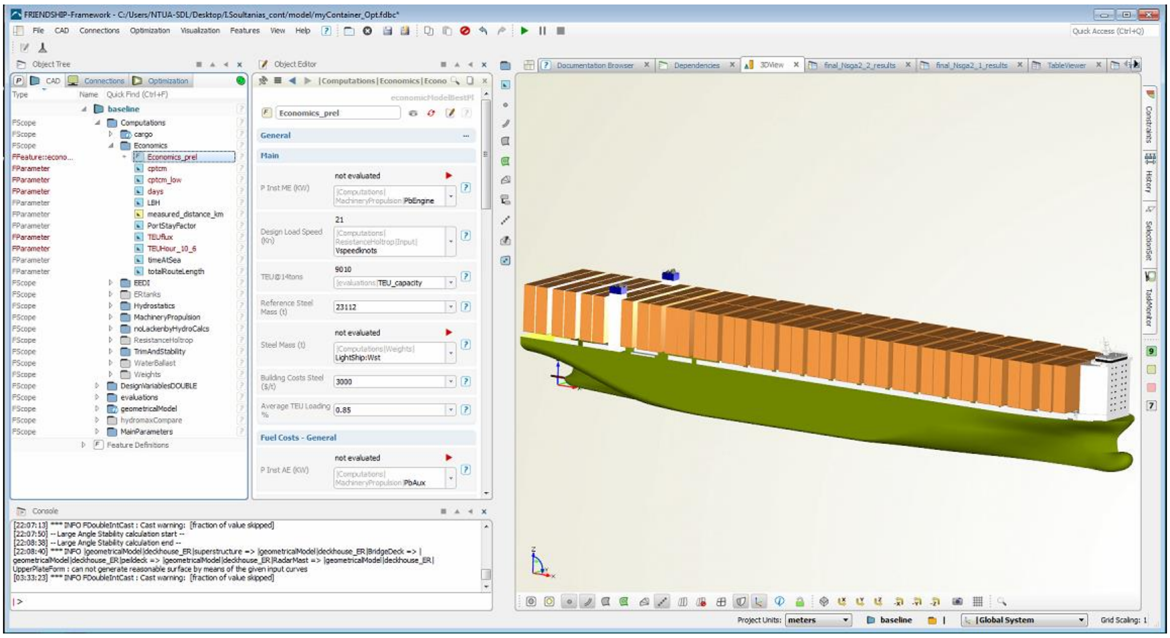
[1] CAESES: Computer Aided Engineering Software for Empowered Simulations



|Computations|Economics|Econo

Economics_prel

General

Main

P Inst ME (KW): not evaluated — |Computations|MachineryPropulsion|PbEngine

Design Load Speed (Kn): 21 — |Computations|ResistanceHoltrop|Input|Vspeedknots

TEU@14tons: 9010 — |evaluations|TEU_capacity

Reference Steel Mass (t): 23112

Steel Mass (t): not evaluated — |Computations|Weights|LightShip:Wst

Building Costs Steel ($/t): 3000

Average TEU Loading %: 0.85

Fuel Costs - General

P Inst AE (KW): not evaluated — |Computations|MachineryPropulsion|PbAux

```
[22:07:13] *** INFO FDoubleIntCast : Cast warning:  [fraction of value skipped]
[22:07:50] -- Large Angle Stability calculation start --
[22:08:38] -- Large Angle Stability calculation end --
[22:08:40] *** INFO |geometricalModel|deckhouse_ER|superstructure => |geometricalModel|deckhouse_ER|BridgeDeck => |
geometricalModel|deckhouse_ER|peildeck => |geometricalModel|deckhouse_ER|RadarMast => |geometricalModel|deckhouse_ER|
UpperPlateForm : can not generate reasonable surface by means of the given input curves
[03:33:23] *** INFO FDoubleIntCast : Cast warning:  [fraction of value skipped]
```

Project Units: meters

Figure B. 3 FRIENDSHIP-Framework interface

2.2 Geometrical model

As described above, the whole geometrical model builds up on the midship section, which holds some basic dimensional parameters. This is the geometry definition on the one side of the aft and the forward part, which connect with a ruled surface to form the parallel mid body. Apart from this basic geometry, some essential dimensional parameters are necessary to define the hull shape.

Meta surface technology

The geometry is mainly constructed out of surfaces, which are already of high fairness and they are mainly of two kinds; ruled surfaces and meta-surfaces; the integrated surface construction technology within FRIENDSHIP-Framework. Constructing the meta-surface starts with a feature definition; a pre-programmed module that could draw a cross sectional curve of the surface to be constructed. Since the surface is fully parametric, the user actually gives a varying input to the parameters to design the cross section curves. This input is basically the distribution of the parameter over a specific length (e.g. one dimension of the surface) and actually a function curve. After the function curves are constructed, a “curve engine” makes use of the pre-programmed feature definition creating the potential development of the cross sectional curves in the space, without really creating any curve and the meta-surface module materializes this “curve potential” into the actual surface. This technology enables the user to create complex surfaces with pretty much control on their shape with the use of function curves as parametric input. Of course, such a powerful tool should be used responsibly and be checked for its results, as the incompatibility of local parameter values can give some bizarre surfaces not to be acceptable.

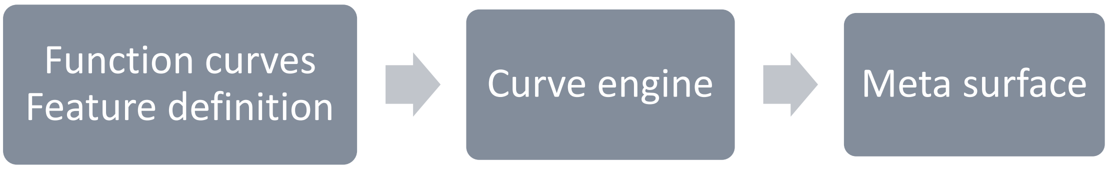


Figure B. 4 Meta surface construction

Main Parameters and Frame

For the initialization of the ship design, a set of essential parameters (vector of design variables) is given as input. Most of these parameters are defining dimensions such as beam, depth, draft, size of bilge, etc. and are necessary for the construction of the hull geometry which follows, while a broader range of more specific parameters defining the main frame includes: bilge height and width, deadrise and flare angles, and the longitudinal position of many different geometry transition positions. As expected, the main dimensions of a containership are usually defined as integers; number of bays, number of rows, number of tiers and the final dimensions are always a function of these integers respectively.

Parameter	dependent on
Beam	no rows
draft	-
Engine room aft extent	bays aft
Engine room fwd extent	bays aft, ER length
hatch height	no tiers in hold
Length b.p.	no of bays
Length of cargo space	no of bays, ER length
length of deckhouse	-
Tiers in hold	-
Tiers on deck	-

Table B. III Main Parameters

The main frame consists of the vertical sides and the horizontal bottom part, since there is no deadrise or flare angle at the midship section. The special feature of this containership design though, is the elliptic bilge, a concept design investigated at similar studies of SDL in the past. It was investigated originally [12] as an optimal volume exploitation, combining the shapes of a full rectangle, which would provide plenty of cargo space, and a triangular section, which would minimize the wetted surface.

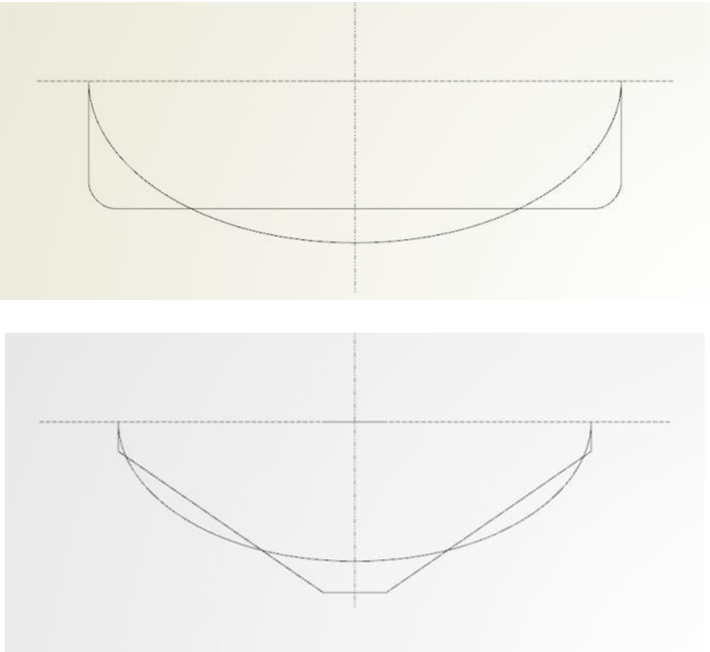


Figure B. 5 Rectangular and Triangular sections vs the elliptic one [12]

For the case of this study, a more conservative approach is adopted, with regard to the section shape. Instead of the whole section, only the bilge profile is defined as elliptic and the parameters of its size and shape are design variables, to vary during the optimization.

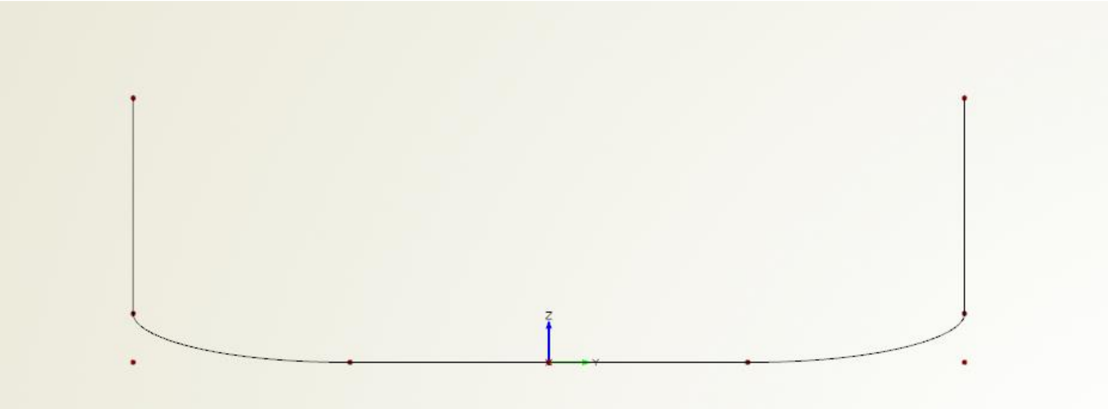


Figure B. 6 The main frame with the elliptic bilge

Aft part

The aft part starts with the definition provided by the main frame and develops all the way to the transom by combining a simple geometry with a specially defined skeg surface. More specifically, the bare hull part is mainly a meta-surface consisted of the elliptic bilge as an f-spline, while the skeg is a rather complex NURBS curve defined by five points, which are distributed along their respective function curves. These two surfaces are joined, after the initial “trim” of the bare hull by keeping just the wanted sub-surfaces of the bare hull. Sub-surfaces can be extracted by interception of a surface curve on the surface and the transformation through the parametric domain.

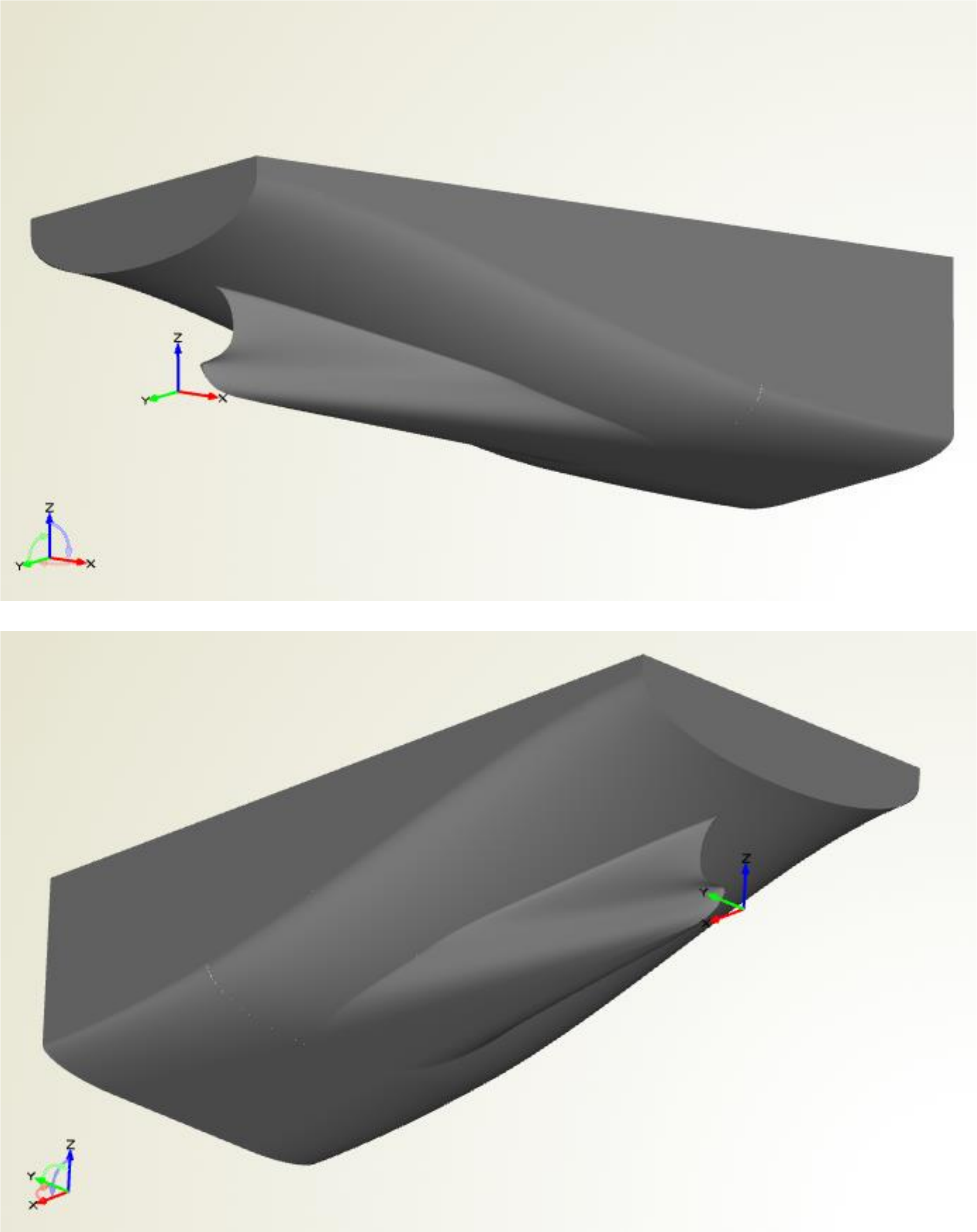


Figure B. 7 Aft part geometry

Forward part

In the forward direction, the geometry is not that simple, which calls for more complex surfaces and more creative definitions of the respective meta-surfaces. At the first parts, they generally follow the same construction principles by using and extending the bilge spline part, while at later stages, meta-surfaces are based on differently defined splines or NURBS curves. At the very fore part, the bulbous bow crated as a meta surface is connected to the previous surface with a COONS patch and on the upper side, a small surface of revolution forms the bow.

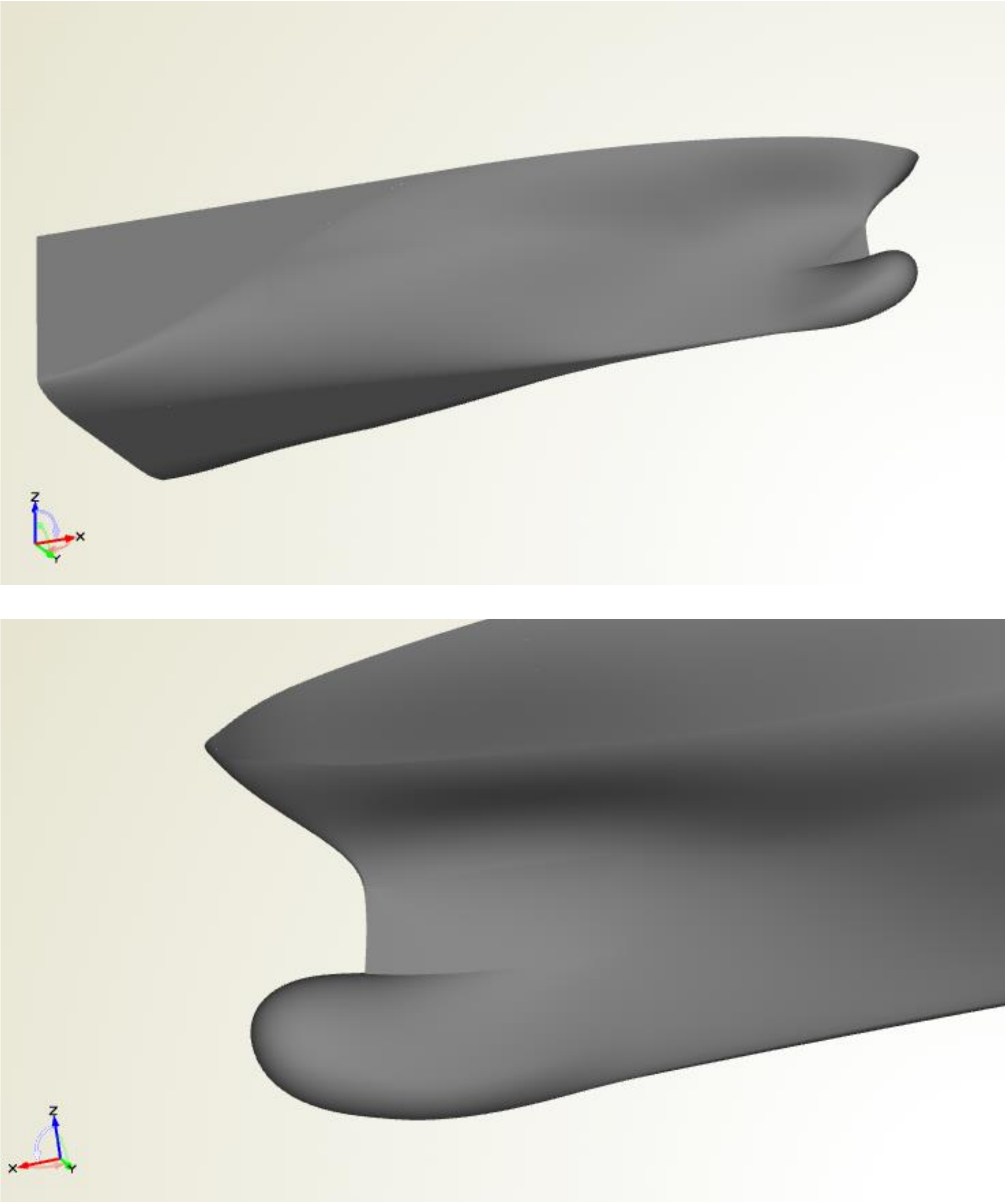


Figure B. 8 Forward part geometry

Lackenby transformation

After the two parts get connected with a ruled surface, the parallel mid body, the ship hull is completed and an initial hydrostatic calculation is performed, to determine the basic properties of the hull. The Sectional Area Curve and the center of Buoyancy are used at the next stage to the final hull formation. Fixing the ship hull to meet the coefficients and parametric input is the main function of the Lackenby Transformation. In this case the Generalized Lackenby method is applied in the way it is adopted within FRIENDSHIP-Framework [13].

The original Lackenby method used in partially parametric models is creating hull variants by taking the parent hull and modifying it according to four parameters:

- Change in prismatic coefficient ΔCp
- Change in longitudinal center of buoyancy ΔXcb
- Change in forward position of parallel mid body ΔLpf
- Change in aft position of parallel mid body ΔLpa

The transformation itself modifies the Sectional Area Curve by using some polynomial shift functions, which may cause dysfunctions, in case length-restricted Lackenby transformations (they are usually applicable to the length between perpendiculars). In order to confront this issue and apply the method to fully parametric models, this approach employs B-splines instead of quadratic transfer functions, enabling the model to control the regions of application and the slopes at either end of the shift functions [13].

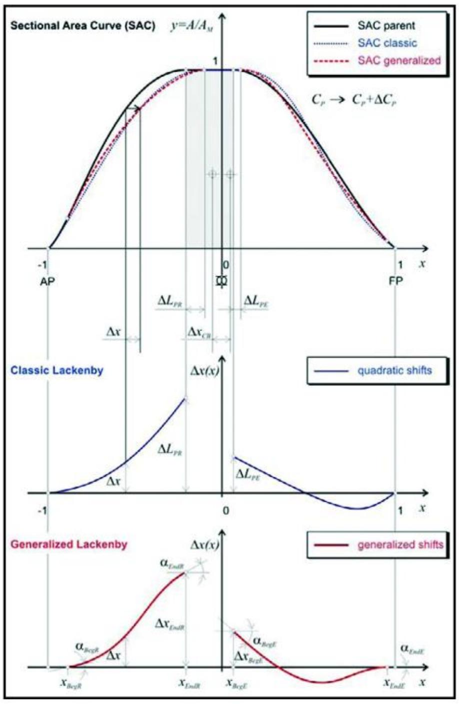


Figure B. 9 Generalized Lackenby method illustration

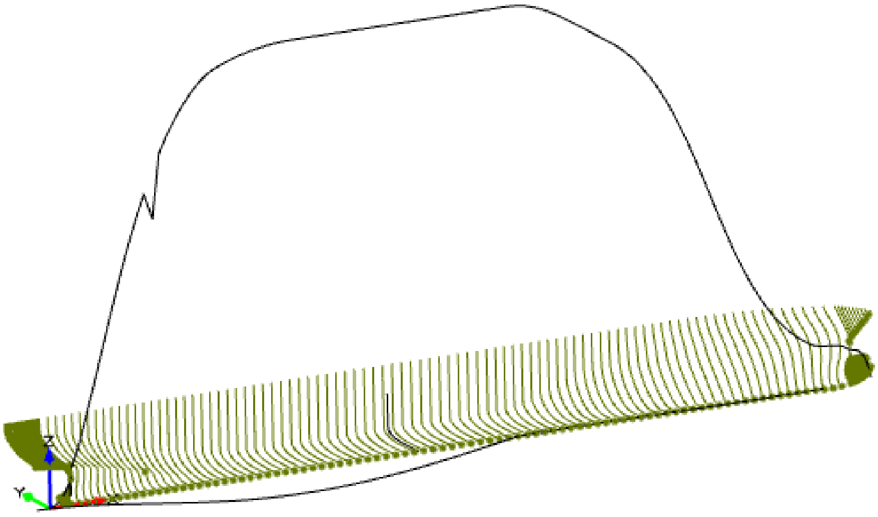


Figure B. 11 Lackenby transformation curves and sections

The transformed and final ship hull looks like this:

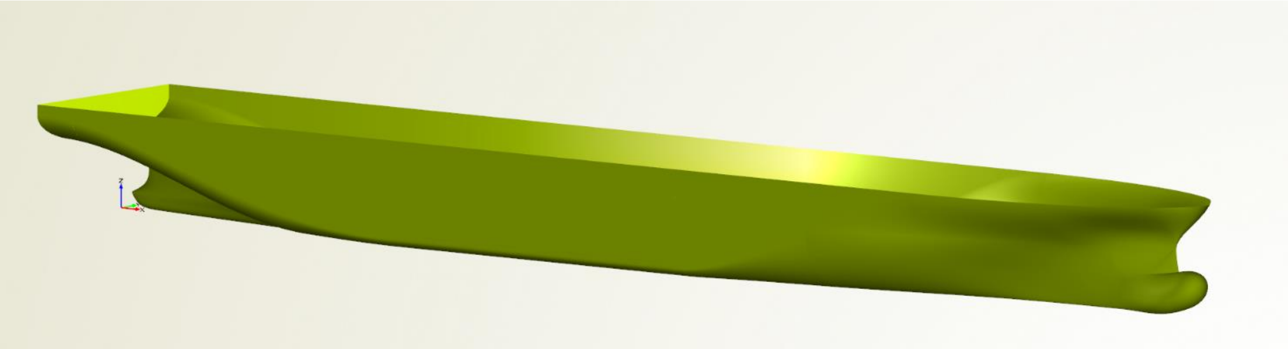


Figure B. 10 Final hull form

Deckhouse, engine room and funnels

These parts of the construction are created by the dedicated features provided within the FFW[1], according to the design strategy that will be described later on. The main input needed by the features is the position and the size of each element. At this point, it is worth mentioning that the features design more conventional deckhouses and funnels being connected, but since the choice was to put the deckhouse all the way to the front, the features were pretty much elaborated to separate the two structures. Another major change was the separation of the funnel in two pieces to be put along the sides of the ship in order to cater the strategy described below. Since some properties of the deckhouse like deck areas, volumes or even wall length are used for some additional weight computations, all this information had to be

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[1] FFW: FRIENDSHIP-Framework

extracted from the features, which led to digging into the design and programming philosophy of them.

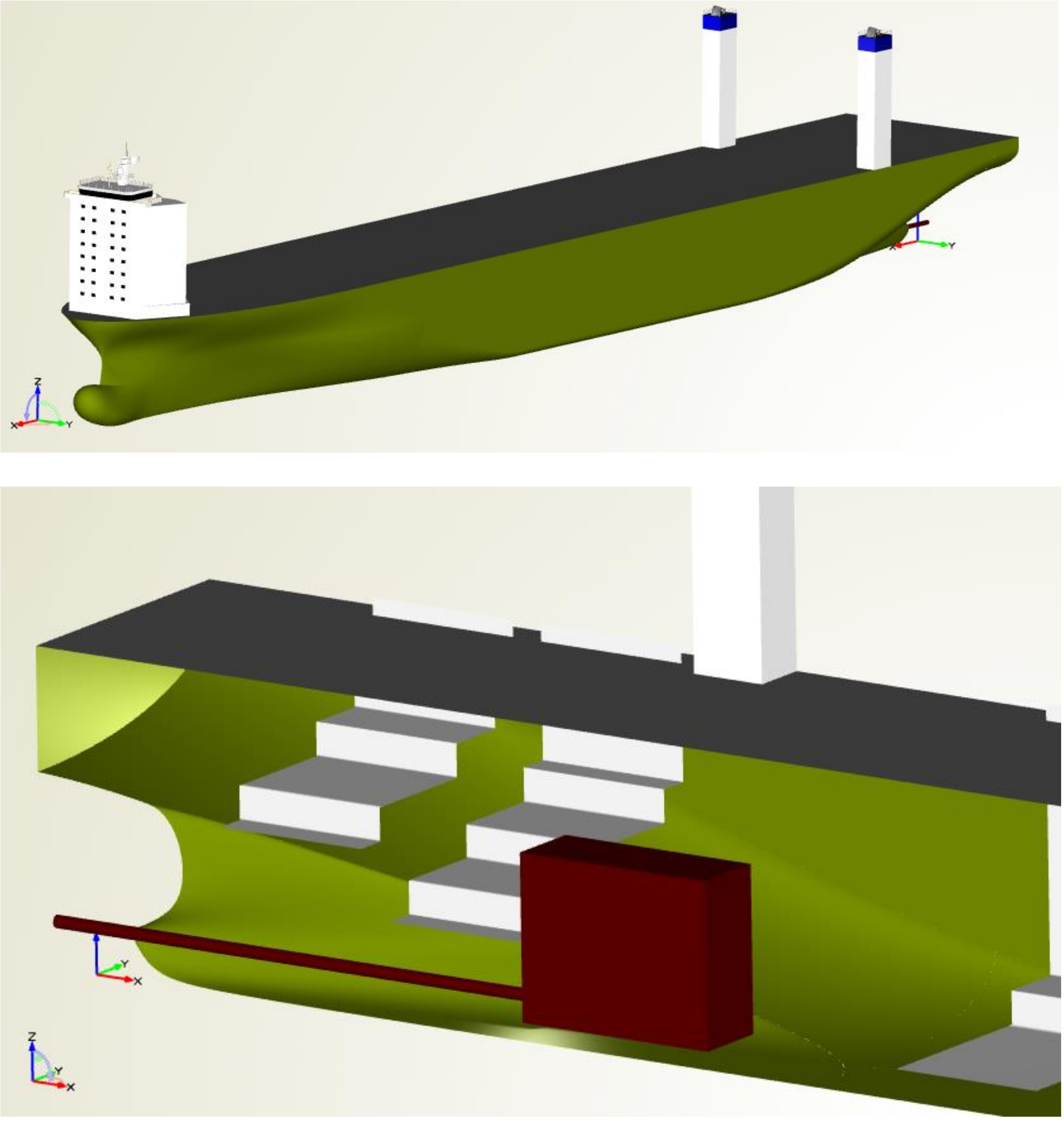

Figure B. 13 Deckhouse, Funnels and Engine Room Arrangement

2.3 Computational modules

After the initial geometrical model construction, the procedure continues with all the necessary preliminary design phases. That means calculation and construction of some essential ship parts like the internal compartmentation, the cargo stowage on deck, Lightship weight estimation and Deadweight analysis, tanks allocation and basic Hydrostatics. At a later stage further computations regarding resistance and propulsion, trim and stability, energy efficiency and economic profitability are carried out to provide the overall performance indicators. It should be noted that even though there were no parent ships available for thorough review, some of the calculations are roughly based on data extracted out of a couple drawings of similar vessels that we obtained.

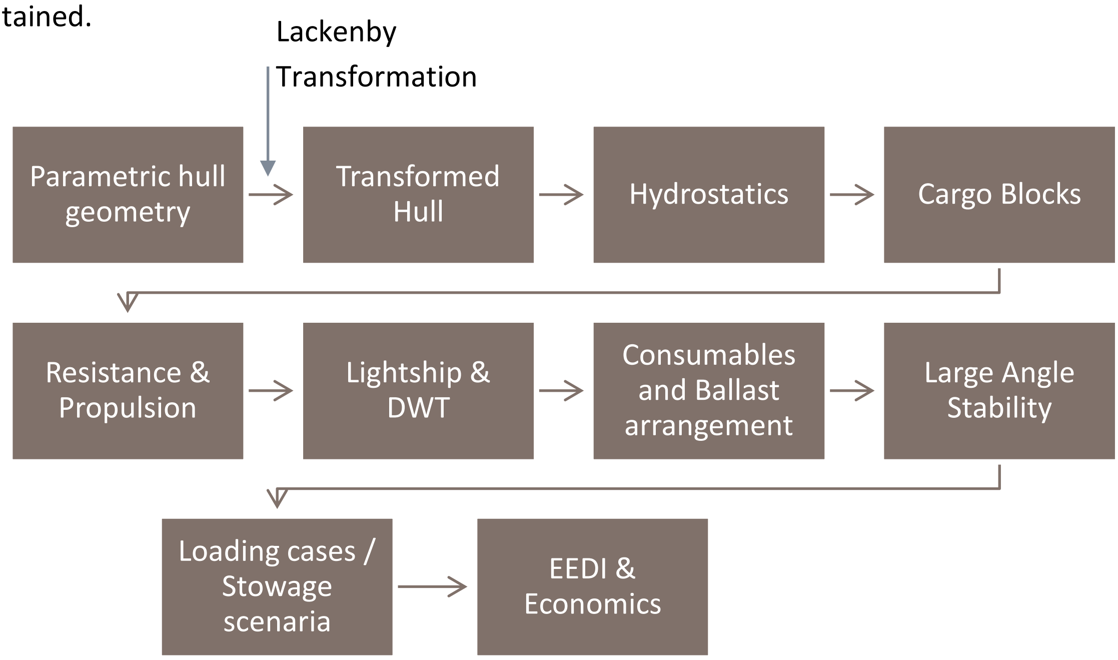

Figure B. 14 Computational modules’ interrelations

2.3.1 Cargo stowage and internal compartmentation

As soon as the ship hull form is finalized, the internal compartments surfaces and the cargo stowage surfaces on deck are generated with an advanced pre-programmed feature. The stowage feature was developed earlier during other studies of the SDL [12, 11], but tailoring it to different projects ended up with some errors when used out of some confidence area with regard to dimensions. So, the feature was basically re-written from scratch, improved and some extra functionalities were added to make it more robust. The containers are stowed in bays with length of two TEU[1] (FEU[2]) with a gap of 0.394 m between them, while the space between two bays is 2.5 m. Creating

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[1] TEU: Twenty foot Equivalent Unit

[2] FEU: Forty foot Equivalent Unit

the inner stowage surfaces begins with the construction of a step curve along the depth of the hull with the offset of the double side distance and goes all the way to the double bottom top, adding a new step, each time the hull moves inwards more than the required distance (double side). This curve is extruded to create the inner surface. On deck, the feature keeps track of the deck line to define the available beam of the area and constructs a solid box for the container stowage. All these features provide all the necessary information about volumes, capacity (TEU) and moments, to other computations involving cargo at a later stage.

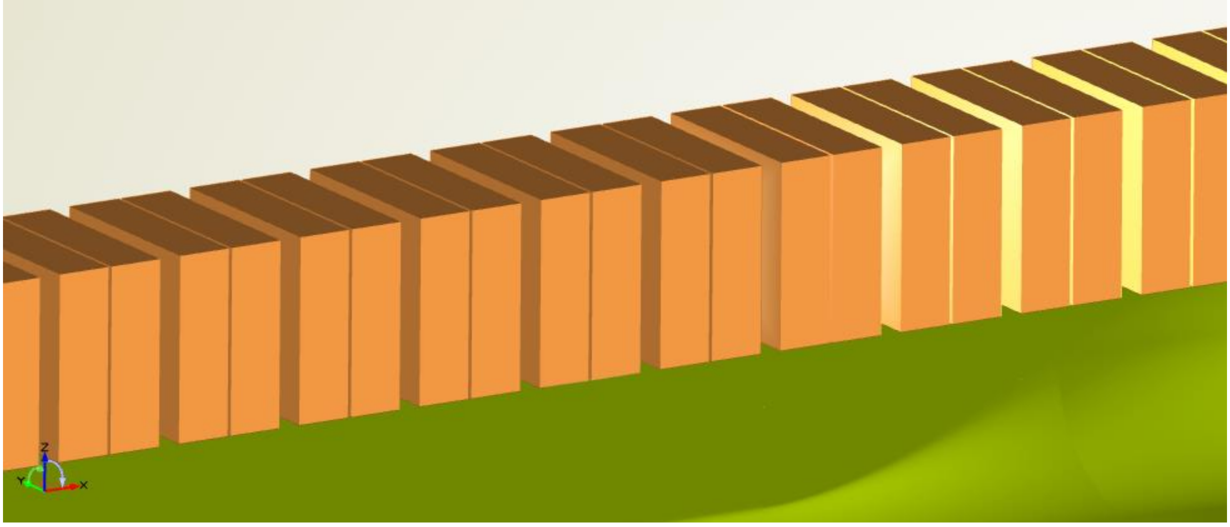

Figure B. 16 Deck stowage surfaces; Bays on deck

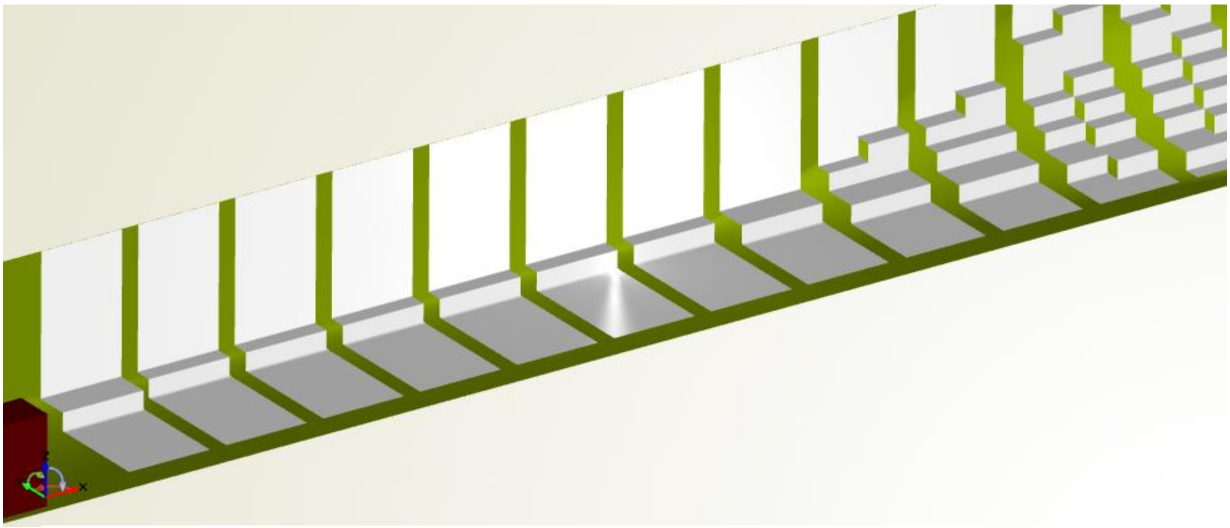

Figure B. 15 Inner stowage surfaces; Bays in hold

After the creation of all these stowage bays, a purpose-built feature takes all their output regarding capacity, volumes and moments and calculates cargo centers of gravity, total capacity and even distribution of Gravity Centers over the volume added on deck.

2.3.2 Hydrostatics

Right after the finalization of the ship hull form, we can proceed to the Hydrostatics computation, which will provide all the necessary hydrostatic properties of our vessel to be used in other stages of the design later on. This computation is a feature that comes already with the software installed. The required input is set up in the Hydrostatic configuration and contains the draft, the length of the ship and most importantly, section offsets, out of which the volume is calculated. The results are given in a table and they contain displacement volume, center of buoyancy, wetted surface, center of flotation and both transverse and longitudinal moments of inertia, while it provides the actual Sectional Area Curve. This computation can also be used with a heel angle, which is the case at the custom made stability feature.

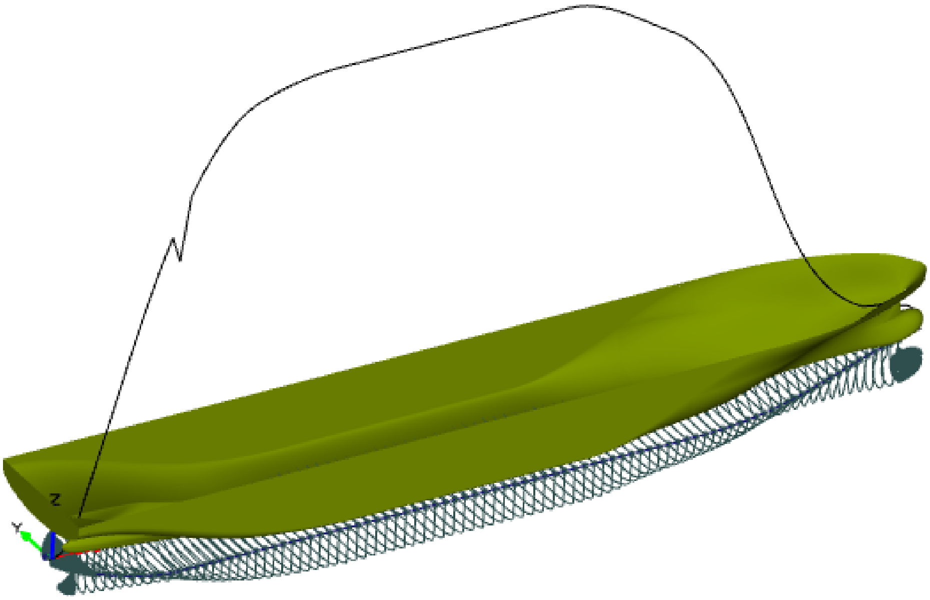

Figure B. 17 Visualization of the hydrostatic computation within FFW

2.3.3 Resistance and Propulsion

As long as the resistance and propulsion approximation is concerned, our approach adopts the approximation method of Holtrop & Nennen [14]. The resistance analysis of this method provides some propulsion parameters such as wake rotation and hull efficiency to be used along with the resistance to calculate the actual power. The auxiliary power is also calculated with empirical formulas as advised in [15].

2.3.4 Lightship

The Lightship weight estimation, essential part of the preliminary design is modelled within a pre-programmed feature by breaking down the weight categories. The main lightship categories taken into account are:

- W steel
    - W hull structure
    - W superstructures
- W outfitting
- W machinery

Machinery and outfitting weights are calculated according to [15] empirical formulas, fine-tuned to contemporary data [11]:

$$W_M = 0.541 * Pb^{1.0241}$$

$$W_{OT} = 0.309 * L * B + W_{lashes}$$

$$W_{lashes} = TEU_{on\ deck} * 0.043$$

Steel weight is a sum of the respective weights of the hull structure and the superstructures, while we also calculate the hatches weight and add them to the total steel sum. Hull structural weight is calculated by the analytical method of Schneekluth [15] and the weight of superstructures is calculated with the Mueller Kostner method [15], by extracting all the required data from the deckhouse features in the model. All the centers of the weights are calculated with analogy ratios with regard to a couple of similar ships that had some of their drawings.

2.3.5 Deadweight Analysis

At this stage, we set and calculate a full set of consumables, constant weights, crew, provisions etc. The calculations are based on the operational profile defined above, 30 crew members and the propulsion and auxiliary power installed on board, both of which are calculated at another module. The centers of all these weights are assigned to positions according to their allocation on board the ship.

Tanks allocation

As part of the deadweight analysis, the allocation of all kind of tanks is included. Water ballast tanks are mainly placed at the fore and aft peak for trimming purposes, in the double bottom, in the first step and the double sides. Fuel and other consumables' tanks are interestingly allocated between the central bays in the transverse direction. The advantage of such a configuration is the lower VCG as the voyage goes on, when the consumables are reduced and lower their overall contribution to the rather high KG, being on the safe side at the Arrival Condition.

2.3.6 Trim and Stability

Our model is required to fulfil the stability criteria set in the Intact Stability Code 2008 of IMO – MSC 267(85), where there is a special mention to container carriers and the tailored criteria that they should meet. Apart from the designated values to meet with regard to the area of the GZ curve, an angle of maximum righting arm GZ above 30 degrees is required and a maximum trim of 0.5% of the ship length.

The brand new stability feature in this project calculates the righting arm – heeling angle curve (GZ-ϕ) and exports all the indicating values from it, such as areas, heeling angles and righting arms. Although in previous similar projects [12] an external stability calculation software was used, we opted for a new approach built inside the framework, in order to cut down on costs and expand the library of available computation features, thus making the model more simple and robust. This feature employs the existing hydrostatic computation for different heeling angles, while keeping the displacement constant with the use of a tangent search optimization method. It is an iterative process for a range of heeling angles, in order to draw the GZ-ϕ curve. If the criteria are not met, another iterative process reduces the overall center of gravity to be applied at the loading cases calculation and that happens almost always because of the relatively high center of gravity of the cargo. In case the trim exceeds the limitation mentioned above, there is also a movement of the overall longitudinal center of gravity.

2.3.7 Loading cases – stowage scenarios

At this last stage, after the stability check, where requirements are met even by changing the expected centers of gravity, we proceed to the loading cases or stowage study. This computation module takes as input all the weights and their position calculated previously, the tanks, the deadweight items and the distribution of the cargo centers of gravity over the capacity. After setting the modified expected overall centers of gravity (according to the stability analysis before), the only items that can vary are the payload weight and the cargo center of gravity, in order to achieve lower overall VCG, that would comply with the stability requirements.

Two cases are investigated:

1. Total TEU capacity available
2. Zero Ballast condition

In the first case, all available container slots are filled, so the change of the payload reduces the homogenous weight per container. Ballast is only loaded for trimming purposes, in case the trimming requirement is not met.

The Zero Ballast condition, a conceptual condition originating from other SDL projects in the past; [11], is defined as a condition in which only the required ballast for trimming is loaded and no extra ballast for stability purposes. In that case, containers are loaded on deck up to a certain tier, so that the overall center of gravity complies with the required one in terms of stability. The number of containers loaded in this condition is also an objective or our optimization.

2.3.8 Energy Efficiency

Last but not least, two modules that are more relevant to the ship life-cycle analysis are calculated. The first one, the Energy Efficiency Design Index, is already a part of the design procedure. The implementation of the index calculations for this project follow the guidelines issued by Germanischer Lloyd. EEDI should be lower than a required value, dependent on the ship displacement. Thus both values are calculated and their ratio is taken into account as a performance indicator, since the required EEDI changes for every design variant. It should be noted that the low limit of 10% required reduction of the index was calculated, although all of the results had a larger margin below that limit, so we are still on the safe side for the next years.

2.3.9 Economics

One of the most important life cycle indicators and eventually one of the objectives of the optimization, is the result of this module. This feature, takes into account all the costs of the ship during its lifetime, and calculates the Required Freight Rate for a break even investment upon building this ship. The lower this rate gets, the higher are the profit margins for operating this ship, making the investment worthwhile and fulfilling the purpose of the container carrier. In terms of value levels, the RFR is calculated per FEU for a roundtrip. Another more indicative parameter is the cost per container mile, which was also implemented in our economic analysis.

2.3.10 Other parameters

Apart from the above mentioned dedicated computational modules, there are several other parameters define within the fully parametric model that calculate individually many different properties and design characteristics of each variant. One notable parameter that is also serving as one of the optimization objectives is the **Stowage ratio**, namely the ratio of containers stowed on deck over the containers stowed in holds. The main assumption in the scope of this project is the positive influence of this ratio towards the actual port efficiency and the speed of the loading operations, as described above in 0.

$$stowage\ ratio = \frac{containers\ on\ deck}{containers\ in\ hold}$$

2.4 The 9000 TEU Container Carrier model

From the beginning of this thesis project, some guidelines for the design of the vessel were set. This design was meant to differentiate from previous projects in terms of size and capacity, some design features and the approach of new systems in the scope of the life-cycle holistic analysis. After investigating the Panamax class of 3700 TEU for another project of the SDL, the goal was set for the New Post-Panamax category of 8500-9500 TEU, operated according to the industry common practice nowadays. Another interesting experiment to be investigated in this project is the deckhouse position, decided to be placed all the way to the front. In this way the visibility line requirement of IMO has no effect on the deck stowage of the containership, leading us to a more compact vessel for this class.

A special feature to be implemented on this design in particular, is the superstructures arrangement. We have opted for a twin island arrangement, where the deckhouse is placed all the way forward, while the engine room and the funnels are placed at the aft part of the ship. The aim of this arrangement is to investigate the advantage of such a configuration because of the lack of the IMO visibility line limitation for the container stowage. The engine room remains at a more conventional position, while the space above can be loaded with containers on deck normally. The funnels are placed at the sides of the ship allowing the stowage of containers between them, while the emissions during loading operations coming from auxiliary engines can be directed only to one of the two and above the other, the crane could easily operate.

2.5 Design variables and limitations

This whole complex parametric model is defined of 15 appointed design variables, 3 of which are fixed after thorough investigation of their impact on the performance of the design and the respective sensitivity. The rest 12 design variables are the ones defining each new variant and they affect primarily the main dimensions of the ship hull.

Design Variable	Baseline value
num. of Bays	19
num. of Rows	18
num. of Tiers in hold	8
num. of Tiers on deck	8
double side	2.14
double bottom	2.3469
relative bilge height (wrt. Depth)	0.18
relative bilge width (wrt. Beam)	0.52
relative parallel body length	0.25
relative parallel body position (from AP)	0.46

ΔCp change of prismatic coef.	0.0113
ΔXCB long. center of buoyancy move	-0.00375

Table B. IV Design Variables

Each new variant produced from the parametric model, should meet some statutory and safety requirements, while also being within a reasonable range for the scope of the present project. For this reason, there are a series of constraints set up mainly for the optimization process, which will validate or reject each new variant according to the following rules:

Constraint	Comparator	Limit
EEDI ratio attained/required	less than	1
GM initial	greater than/equal	0.15
GZ area 30 to 40 deg	greater than/equal	E 30-40
GZ area up to 30 deg	greater than/equal	E 30
GZ area up to 40 deg	greater than/equal	E 40
angle at max GZ	greater than/equal	30 deg
Trim at FLD	less than/equal	0.5% L_{BP}
homogenous weight per TEU max capacity	greater than/equal	6 t
homogenous weight per TEU zero ballast	greater than/equal	7 t

Table B. V Constraints

Please note that the stability constraints with regard to the properties of the righting arm vs. heeling angle are defined as functions of ship dimensions in the Intact Stability Code 2008 of IMO for the case of container carriers as follows:

$$E_{30} = \frac{0.009}{C} \quad E_{40} = \frac{0.016}{C} \quad E_{30-40} = \frac{0.006}{C}$$

Where: $C = T * \frac{D^*}{B^2} * \sqrt{\frac{T}{KG}} * \left(\frac{C_b}{C_{WP}}\right)^2 * \sqrt{\frac{100}{L_{BP}}}$ and $D^* = Height + h * \frac{2b-Bd}{Bd} * \frac{l_H}{L_{BP}}$

$$b = Beam - 2 * double\ side \quad Bd = Beam \quad h = 1.25 \quad Bm = beam\ at\ draft$$

$$l_H = \frac{L_{BP}}{2} - \frac{L_{BP}}{4} * \frac{bay\ Spacing}{bay\ Length\ incl.\ space}$$

3 Sensitivity Analysis

After setting up successfully the fully parametric model and before proceeding to the formal optimization, an initial investigation of the model validity and feasibility of the produced variants needs to be undertaken. This initial investigation is called "sensitivity analysis", as it is used to show the sensitivities of the model with regard to the design variables. In such a complex model with many design variables, we need to check a wide range of them in order to set up the optimization correctly. As it is mentioned above, apart from the 12 design parameters, which will be used for the optimization, there are a couple design variables more (defined as such in the model), which are fixed to chosen values and do not vary. The most notable fixed variables are the draft and the vessel's speed. Before the general design of experiment, these two need to be set and for that we should investigate the respective model sensitivities.

3.1 Draft investigation

The draft is a design variable that was meant to be fixed from the beginning. As a matter of consistence, draft should be fixed, so that variants can be comparable. Changing the draft has a strong effect on many other parameters, as it increases the resistance, thus it influences the creation of new variants and could be a problem for the optimization.

3.2 Speed investigation

When it comes to the speed selection, it is clear that it affects many different aspects of the design, most of which like fuel consumption or resistance straightforward, while the effect on others is clearly prominent, while not directly connected, like the Required Freight Rate. The selection of speed at a specific level will eventually be a compromise for some other performance indicator obviously, but since the scope of this work is optimizing a design, the relative results would be essentially the same for different speeds. This leads to the main constraint that was taken into account, the voyage duration. After studying the liner services commercially available today in PART A:1.2.1 , a total round trip time of 40 days was chosen, thus leading to the speed selection of 20 knots.

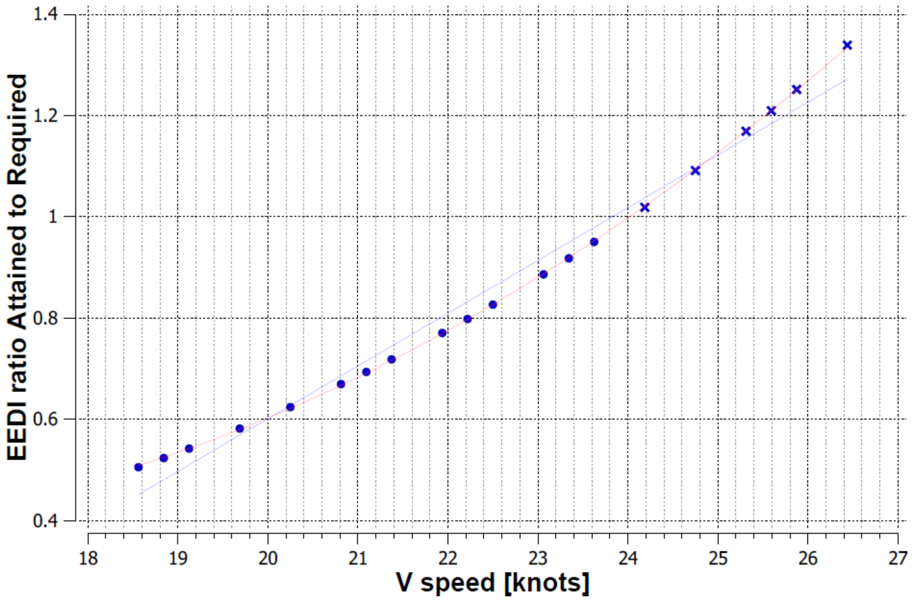

Figure B. 18 Speed vs. EEDI ratio

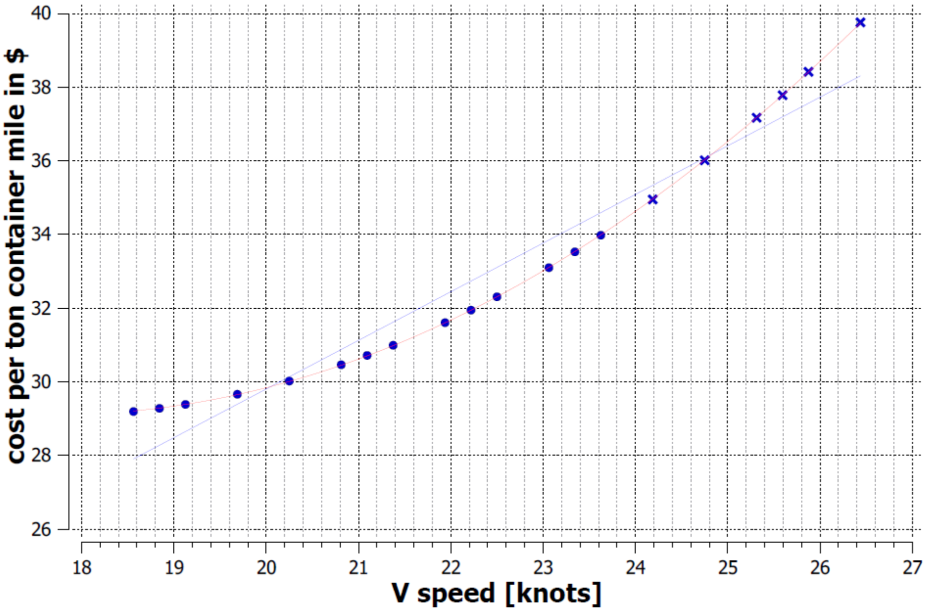

Figure B. 19 Speed vs. cost per ton container mile

3.3 Design of Experiment – DoE

The Design of Experiment, as this investigation is formally known, aims to explore the limits of the model feasibility in the design space defined by the design variables vector. Driven by a pseudo-random Sobol design engine within the Framework, the design variables change in a quasi-random way as they are evenly distributed all over the design space defined, to create every possible combination of design vectors and produce new variants. The design engine is assigned to create 500 design variants, which are more than sufficient to give an image of the model sensitivities, as the common practice for such investigations is the creation of variants depending on the number of free variables as follows:

$$number\ of\ variants = (number\ of\ design\ variables)^2$$

As it is expected, most of these new variants do not comply with the constraints, thus only a percentage of the variants are valid and they show the range of applicability of the parametric model for the specified application. In other words, this is a sensitivity test of the model itself against the change of the design variables. It is a great opportunity to check the applicability limits and restrict or widen the range of the design variables at the next stage, the optimization.

The initial design of experiment was set up with the 12 original design variables described before within the following limits:

Design Variable	Upper Limit	Lower Limit
num. of Bays	17	20
num. of Rows	15	20
num. of Tiers in hold	7	10
num. of Tiers on deck	7	9
double side	2	2.5
double bottom	1.8	3
relative bilge height (wrt. Depth)	0.1	1
relative bilge width (wrt. Beam)	0.1	1
relative parallel body length	0	0.3
relative parallel body position (from AP)	0.4	0.55
ΔCp change of prismatic coef.	-0.06	0.06
ΔXCB long. center of buoyancy change	-0.02	0.02

Table B. VI DoE design variables definition

The useful output of this trial run are the diagrams, which show the actual domain areas for the design variables and the validity of each variant. In this way we can have a quick evaluation of the design space and possibly recognize a behavioral pattern to focus our next run. A first impression about the robustness of our model can be obtained from some key diagrams, while a wider variety of them is still available for further study.

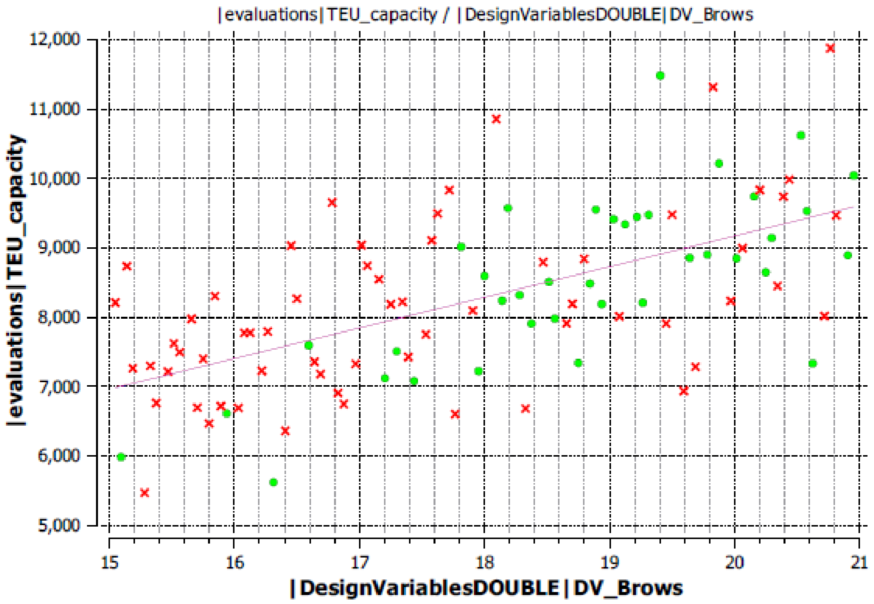

Figure B. 20 DoE: Rows vs. TEU capacity

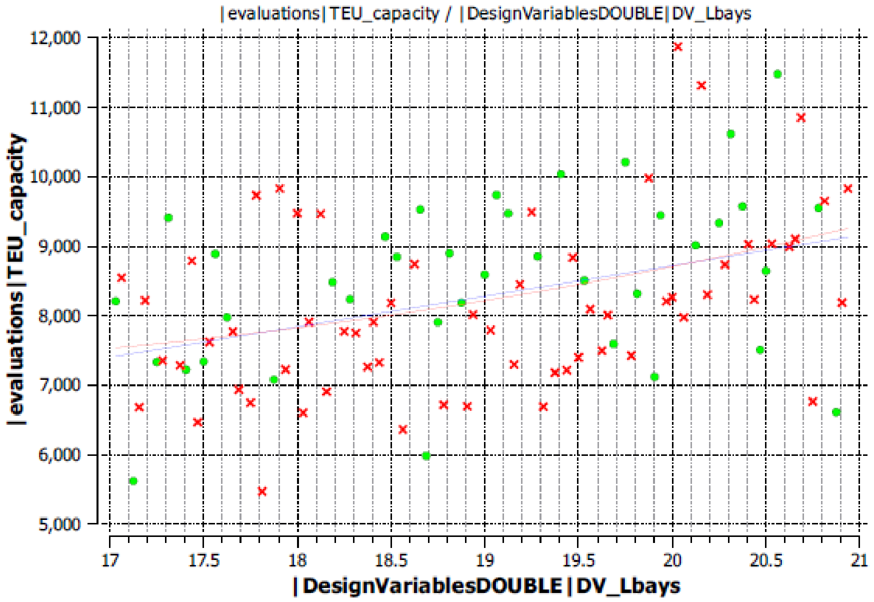

Figure B. 21 DoE: no of Bays vs. TEU capacity

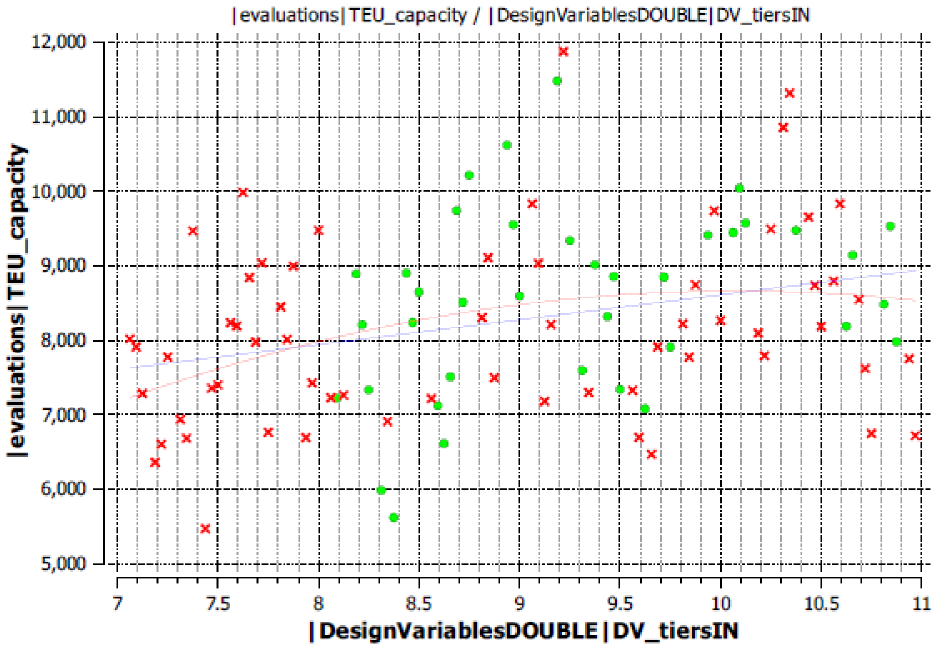

Figure B. 22 DoE: tiers in hold vs. TEU capacity

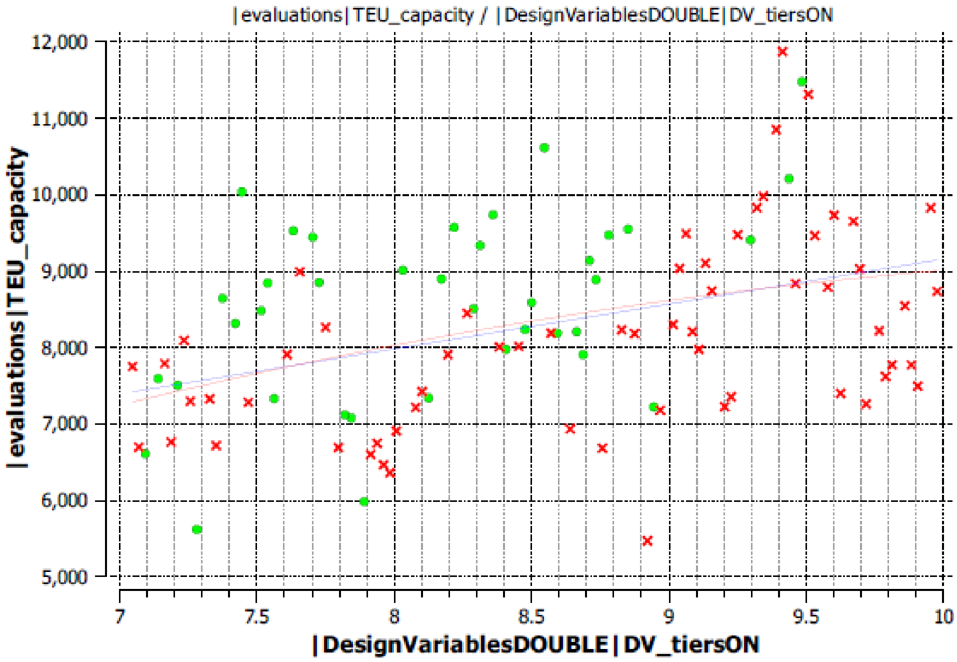

Figure B. 23 DoE: tiers on deck vs. TEU capacity

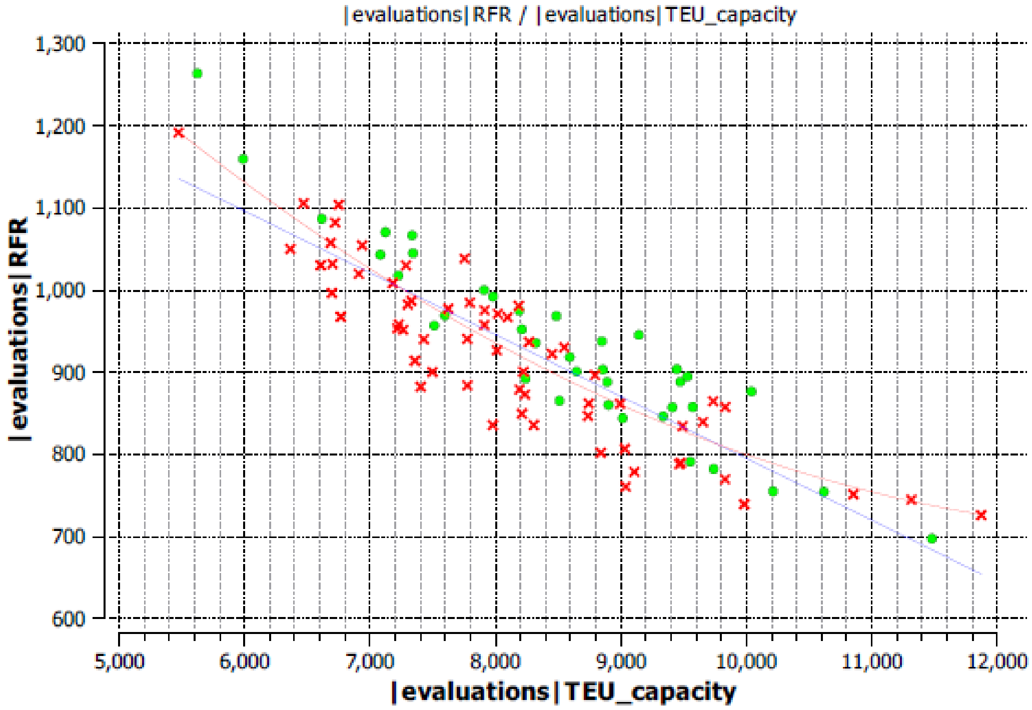

Figure B. 24 DoE: RFR vs. TEU capacity

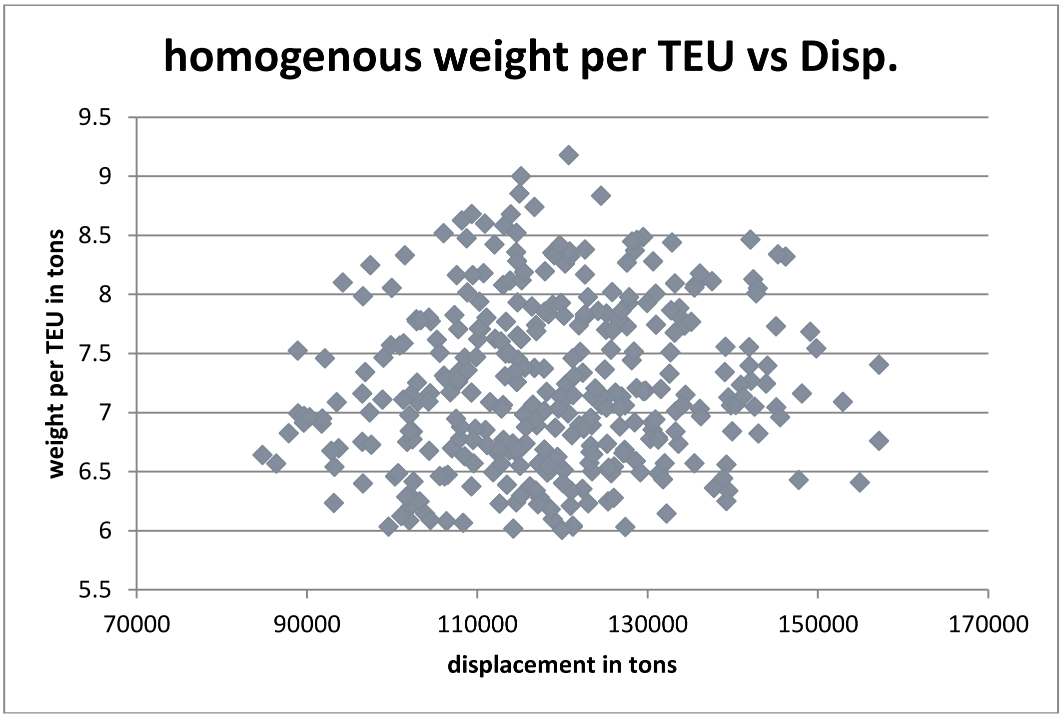

Figure B. 25 Weight per TEU vs. Displacement

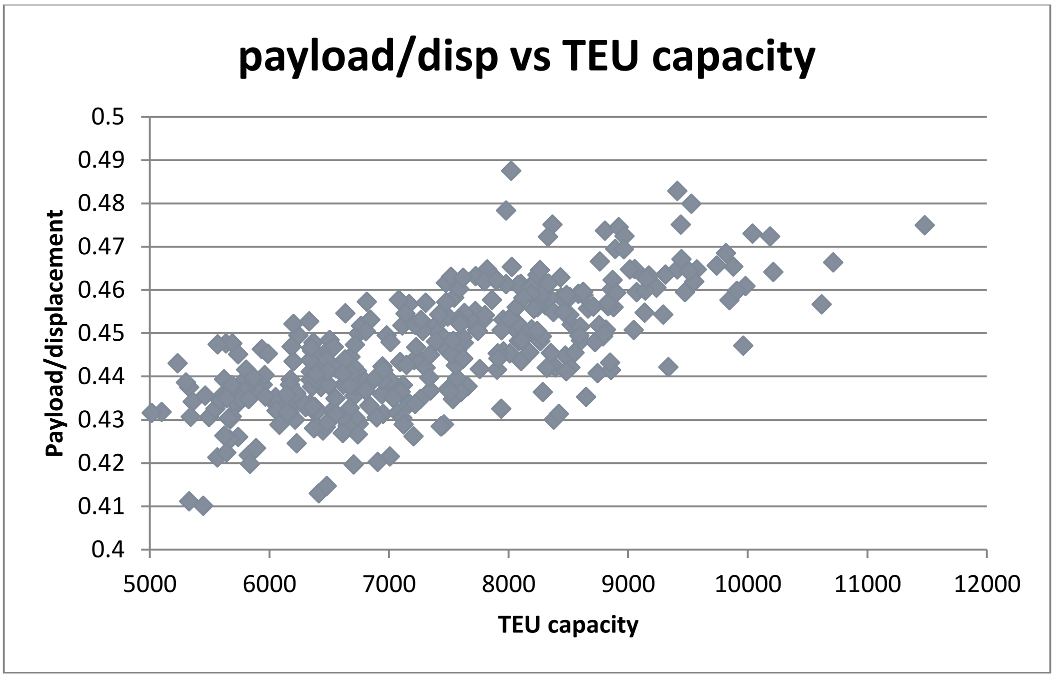

Figure B. 26 DoE: Payload/displacement vs. TEU capacity

What is quite interesting to look into, in the figures above, is the range of the design variables with higher concentration of valid designs (green). It is worth mentioning that no constraint to the ship size or the TEU capacity is set at this stage, so designs out of our focus area ~9000 TEU are still valid. As it seems, the design variables space is well defined regarding the main dimensions at least. Only the number of tiers in hold seems that it should be more than 8, but after some feasible designs at the early trial stages of the optimization were found in that area too, this low limit remained unchanged.

4 Multi Objective Optimization

This is the actual stage of the second part of this thesis project; design optimization. After the investigation runs and the design of experiment, there is a solid design baseline to start the optimization procedure.

4.1 Employed Methods and set up

The simulation is driven by the genetic algorithm NSGA II, suitable for multi-objective optimization. Design of Experiment showed that the design space was well defined, so the design variables range remained the same for all the 12 variables used for the variants production. In terms of limits and constraints, the same as before are also here applicable, with two additions of the upper and lower limit for the nominal TEU capacity, in order to direct the search in the designated size category of 9000-9500 TEU.

The design of experiment was followed by the first optimization round with 6 generations of 50 variants population size each one, starting from the baseline, since it was a good design compared with the results of the Design of Experiment. After the conclusion of this round, the valid designs were evaluated according to the method described below and the top ranked one was chosen as a starting point for a second round. The optimization was eventually run for a second time, again with 6 generations of 50 variants population size each.

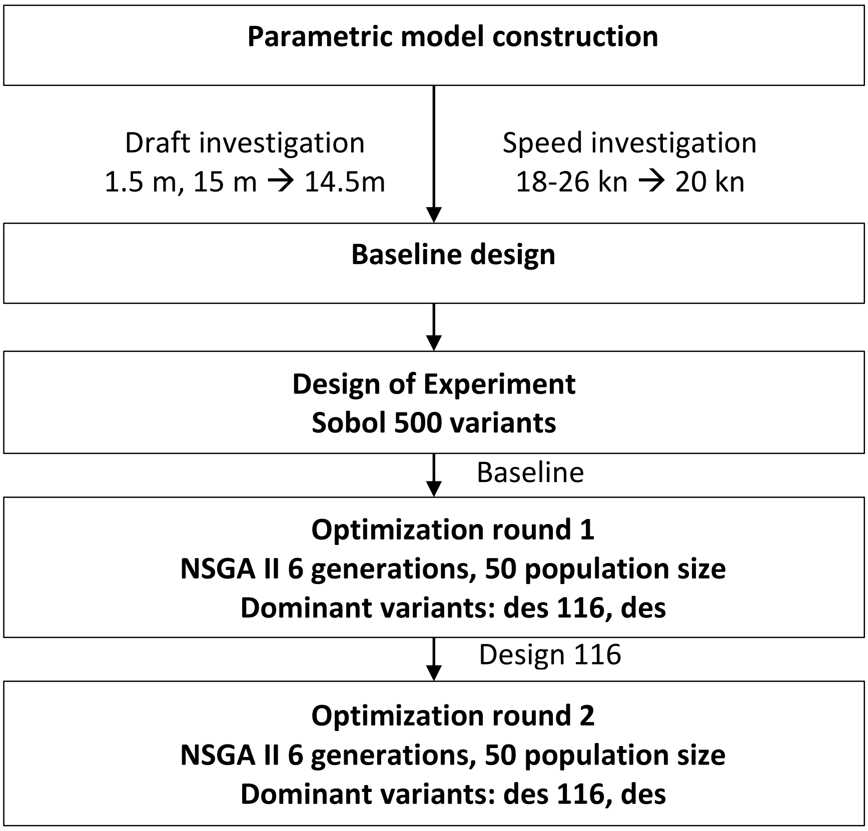

Figure B. 27 Optimization strategy schematic

4.2 Objectives – Merit functions

Within the scope of this project, three main objectives were defined:

- Minimum Required Freight Rate
- Maximum Zero Ballast capacity in TEU
- Maximum stowage ratio $\frac{containers\ on\ deck}{containers\ in\ hold}$

All the three objectives are actually parameters that are calculated within a different computation module of the model, thus providing a value for each variant and that can be used as a performance indicator. For this multi criteria optimization problem, the utilized genetic algorithm NSGA II, is always minimizing the defined objectives simultaneously and this is our case as well. The parameters needed to maximize, are simply changed to differences from a bigger value, the minimization of which, maximizes the actual objective.

4.3 Variants evaluation – Utility Functions

The optimization run, governed by the "design engine", an integrated program to drive the optimization by use of the NSGA II algorithm, provides a set of variants as a result with no special ranking, although at later stages, the designs improve. Here is where the decision making part of the multi objective optimization comes in. The designer has to review the result table and select the preferred solution. As expected, multi objective optimization problems do not have a straightforward solution. Thus a compromise between the different objectives is to be made by the designer, who selects a design fulfilling the aims of the project.

Our approach towards the evaluation of the optimization results is a rather complex procedure that ensures the independency of a particular design from any specific objective bias. Firstly, we defined a number of scenarios of different significance for each objective as follows:

Scenario	**1**	**2**	**3**
Zero Ballast capacity	33%	40%	20%
Stowage ratio	33%	40%	20%
Required Freight Rate	33%	20%	40%

Table B. VII Utility scenarios

After obtaining the performance parameters' values for each design, we normalize the values, to get actual indicators and have a clearer image of the relative performance among the designs. In the end, these normalized indicators are combined into a weighted average for each particular scenario. According to this averaged indicator for each scenario, the designs are ranked and below we can see the ranking for the 3 different scenarios. Please notice that the designs cited bellow are coming from both 2 rounds of optimization.

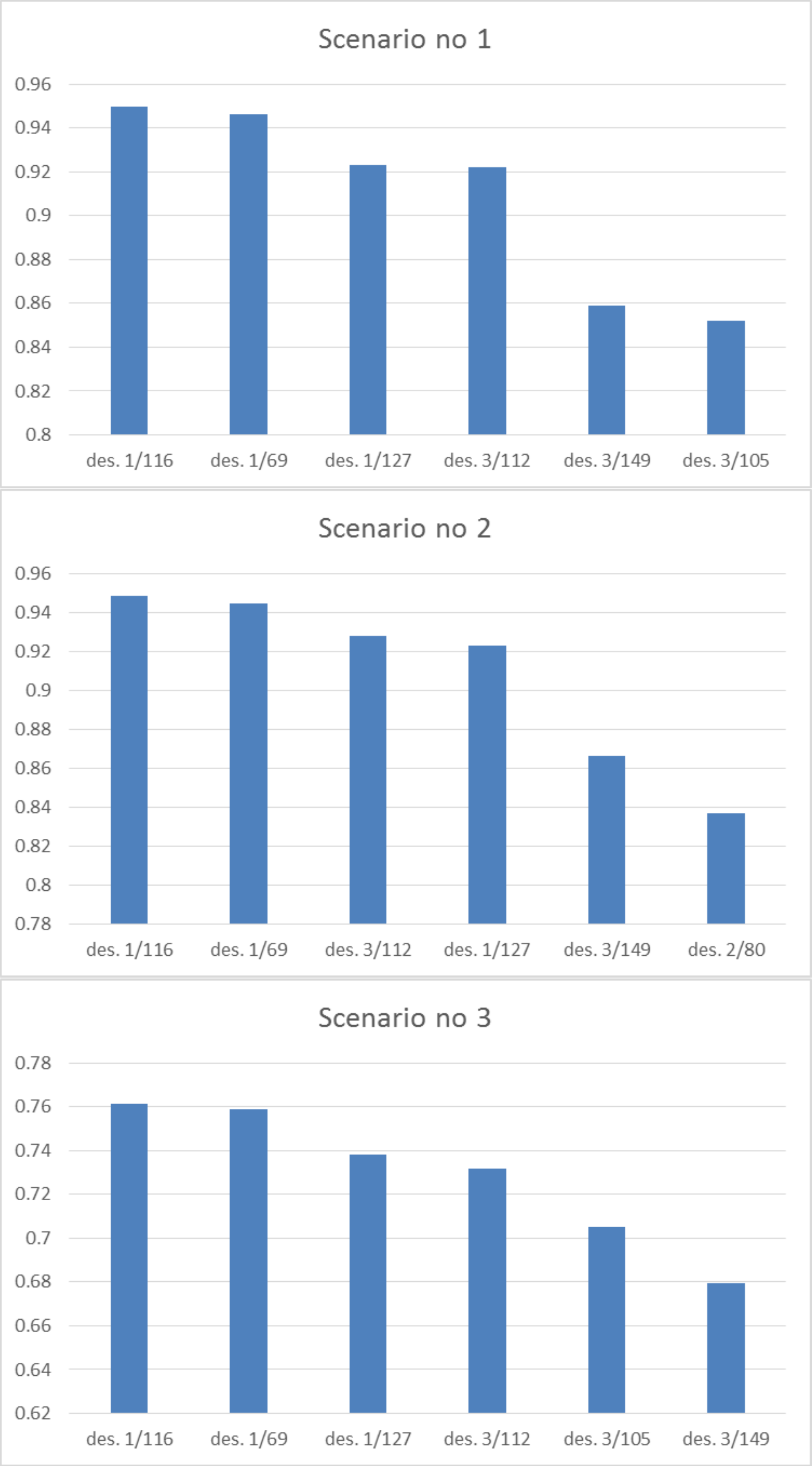

Figure B. 28 Designs Ranking according to different scenarios

From the figures above, it is crystal clear that one particular design, “design 1/116” is ranked as top performing for the 3 different scenarios. This shows the overall exceptional performance of the design independently from the scenario followed. Design 1/116 was a result from the first optimization round and it was set as a starting point for the second optimization round. However, there was no better design from that second round, which leads us to identify design 1/116 as the dominant one in our analysis.

PART C: Optimization Results and Conclusion

1 Behavior of different design variables

Coming to an end, after conducting the optimization runs, a look into the design variables behavior and variation during the whole process could be really intuitive. As expected from an optimization algorithm, the variation of the design variables is strongly oriented, since the model is pushed to its boundaries in the quest for local and global minimum values of the objectives.

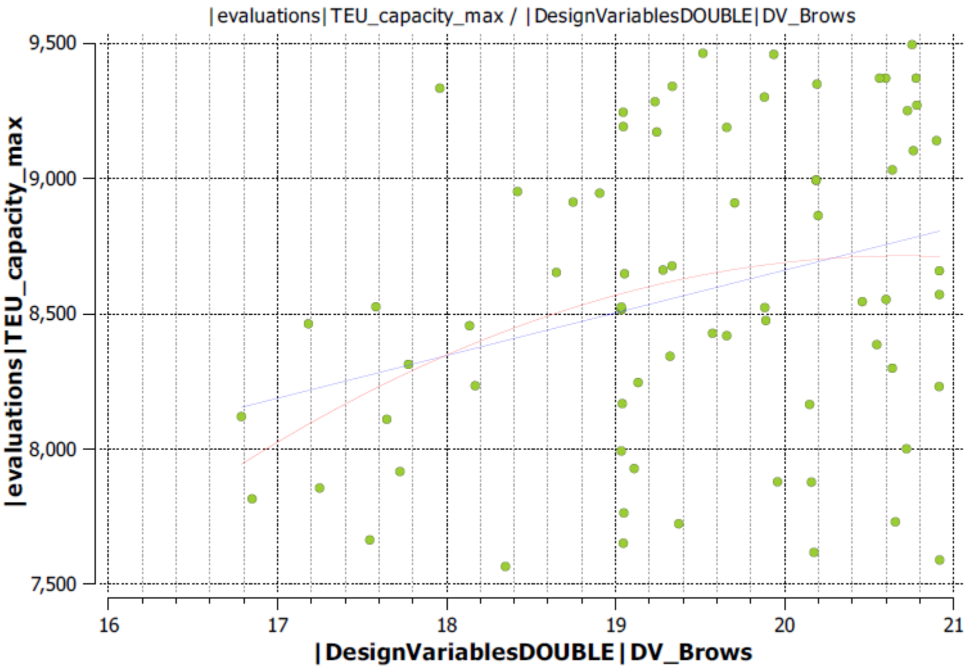

Figure C. 1 Optimization: TEU capacity vs. Rows (refers to the integer part)

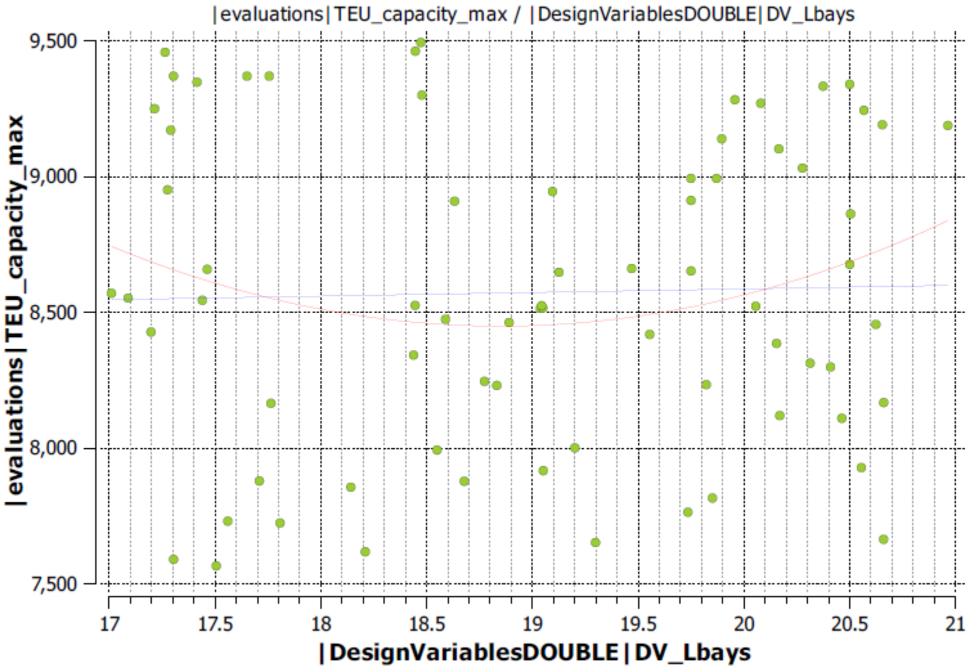

Figure C. 2 TEU capacity vs. Bays (refers to the integer part)

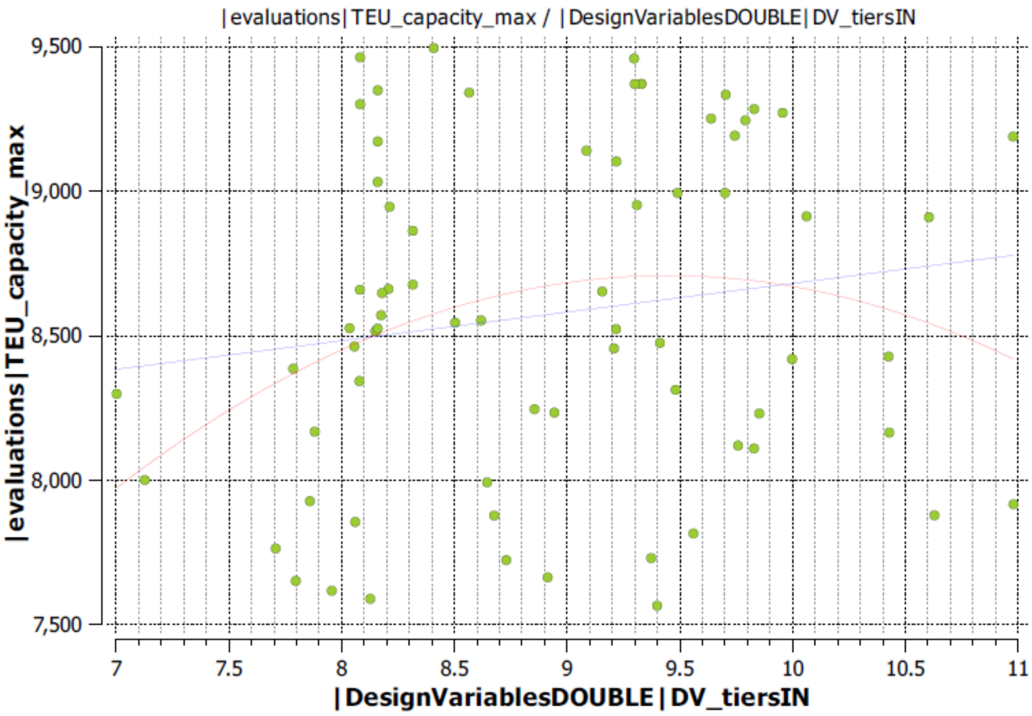

Figure C. 3 TEU capacity vs. Tiers in hold (integer part)

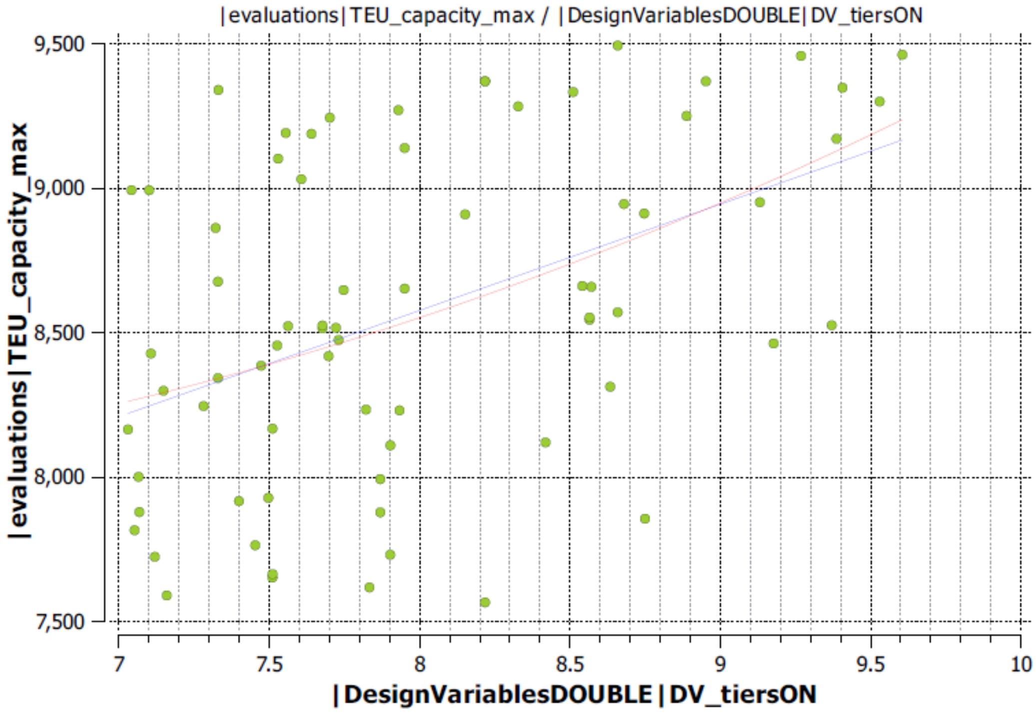

Figure C. 4 TEU capacity vs. Tiers on deck (integer part)

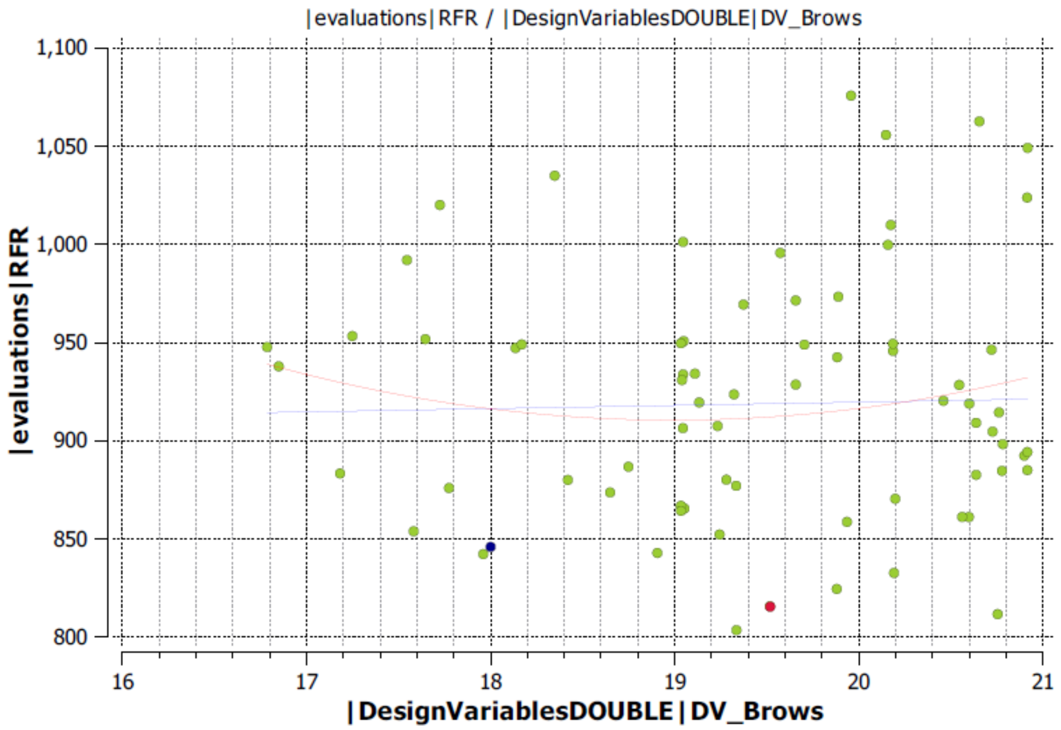

Figure C. 5 RFR vs. Rows (integer part)

2 Pareto Optimality

Multi objective optimization is not expected to provide a single result, an optimum design. As described above, a compromise between the individual objectives should be achieved from the designer’s point of view, at some point. This principle is identified best in the Pareto Front analysis approach.

Starting with the depiction of two objectives at a time in a single scatter diagram, we can clearly see the relation between the two of them and their possible combinations to reach a compromise. The designs depicted show the limits of the model with regard to each objective. Trying to maximize one of the two objectives will restrict our options for the possible combination regarding the other objective. Following this procedure, the designer would reach a point where the further improvement of one objective would degrade the performance of the other one. The set of all these points forms the Pareto-Front, a curve which shows the limits of the optimization study. The best designs that could be achieved are on this curve and then it is up to the designer to choose the most applicable for their case.

Bellow we can clearly see the correlation between the objectives of this optimization and distinguish the respective Pareto front for each case.

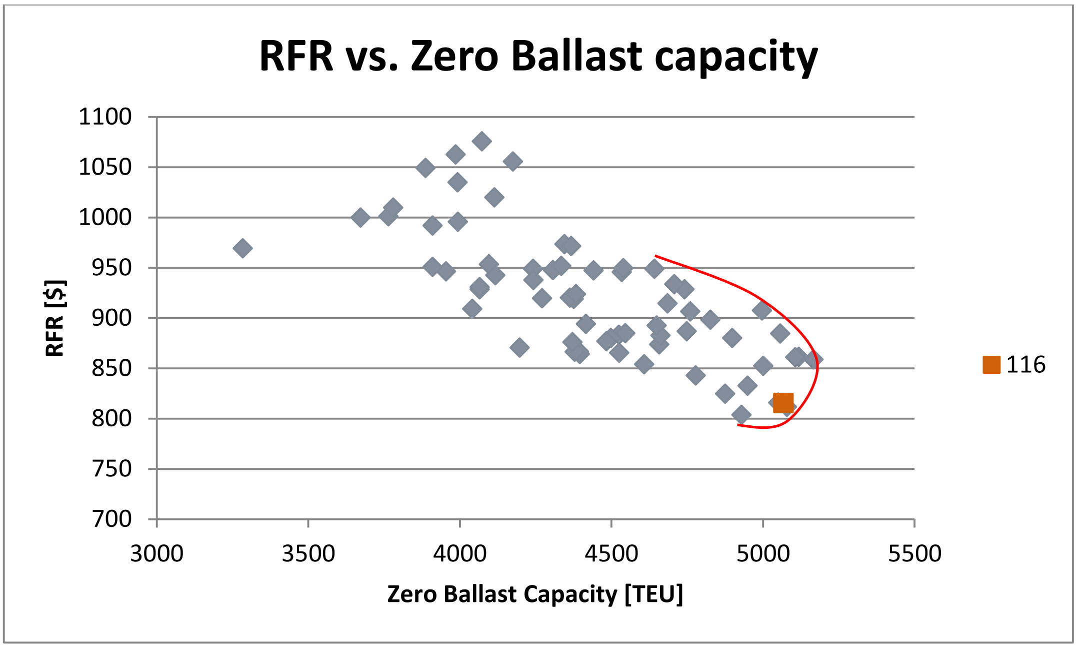

Figure C. 6 Required Freight Rate vs. Zero Ballast capacity and Pareto Front

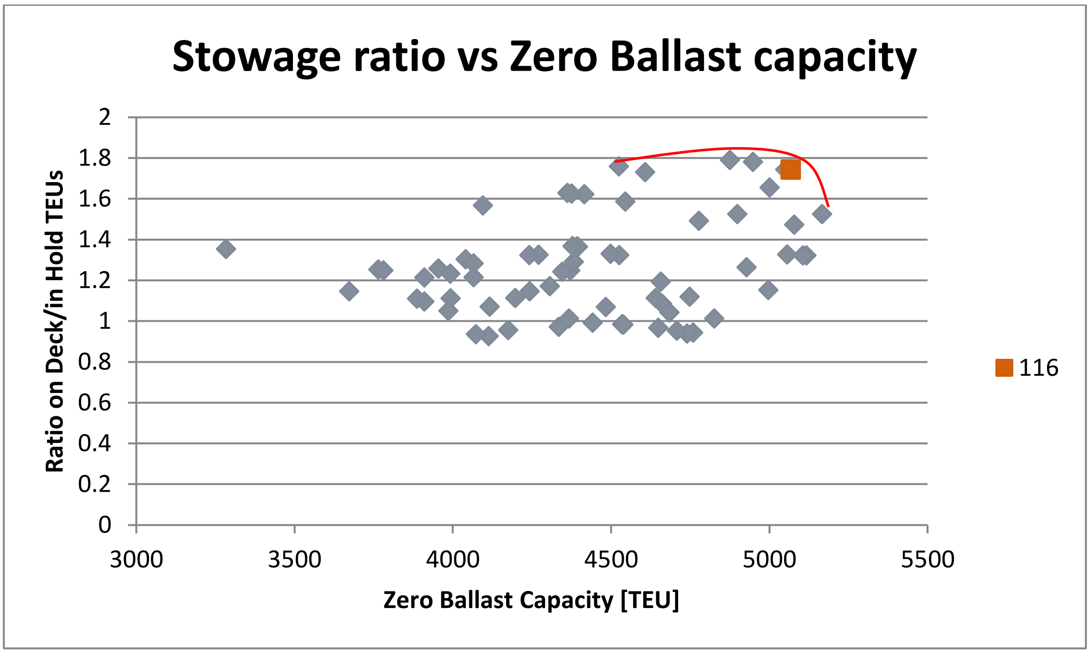

Figure C. 7 Stowage ratio vs. Zero Ballast capacity and Pareto Front

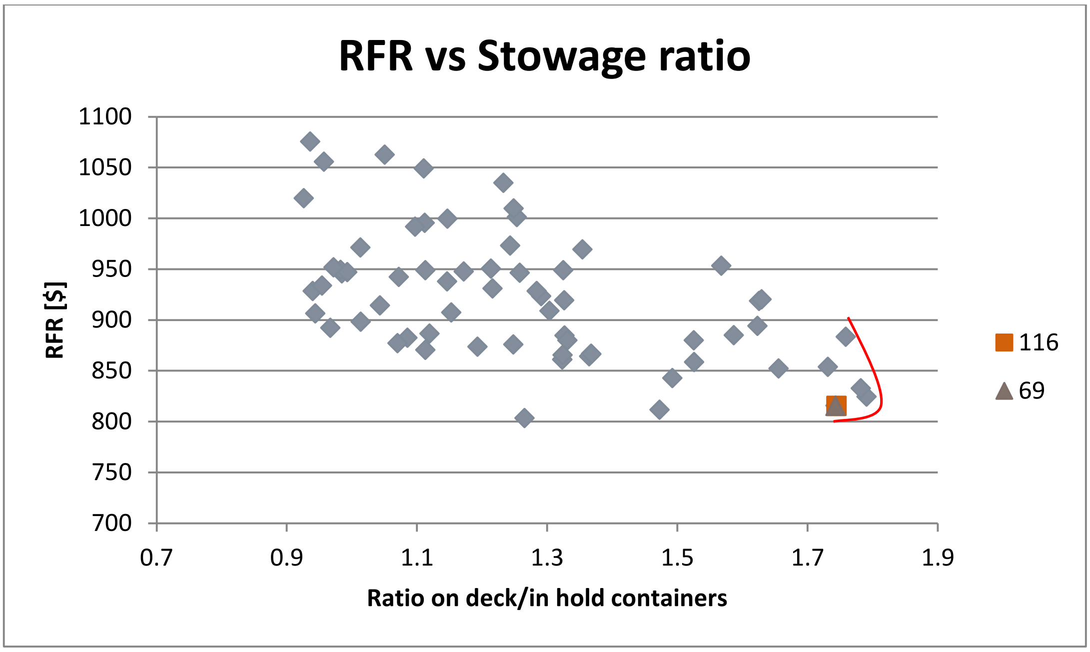

Figure C. 8 Required Freight Rate vs. Stowage ratio and Pareto Front

3 Design Comparisons

As mentioned before, within the scope of this work and after concluding the optimization process, apart from the identification of the Pareto Fronts, we chose a single design, which was top ranked in all the scenarios studied, showing an overall independent performance. This is design no. 1/116 and we can compare it to the original baseline model.

As far as the design variables are concerned:

Design	baseline	des. 1/116
Rows	18	19
Bays	19	18
Tiers in hold	8	8
Tiers on deck	8	9
double bottom [m]	2.347	2.569
double side [m]	2.140	2.244
relative bilge height	0.184	0.481
relative bilge width	0.522	0.410
relative parallel body length	0.253	0.098
relative parallel body position	0.46	0.442

Table C. I Design Particulars' Comparison

Their performance and design characteristics (parameters computed):

Design	baseline	des. 1/116	change
L bp [m]	18	19	
Beam [m]	295.19	280.18	
Depth [m]	45.558	48.089	
Displacement [t]	142326	129548	-8.98%
TEU capacity	9010	9456	+4.95%
weight per TEU [t]	7.35	6.39	-13.06%
Cost per ton container mile [$]	30.66	29.53	-3.69%
EEDI ratio	0.685	0.718	4.82%
Zero Ballast TEU capacity	4833	5067	+4.84%
Required Freight Rate [$]	845.99	815.54	-3.60%
Stowage ratio	1.466	1.744	+18.96%

Table C. II Performance Indicators Comparison

As a general comment, the overall improvement of the original design is obvious in most of the performance indicators and crystal clear at the three optimization objectives. Regarding the reduced weight per container indicator, it is not quite troublesome or annoying, since the parameter refers to the ideal loading case, when the ship has reached full capacity, which rarely if ever happens. Another assumption for this indicator is that all containers are supposed to be loaded with the same weight ~6-7 tons, which of course cannot be the case. This parameter has been kept pretty low, so that the vertical center of gravity of the cargo is kept low enough to fulfil the stability requirements. Following the common practice of loading heavier containers at lower tiers and keep the light or empty ones at the top, achieves the same effect with regard to stability, without the need to keep the homogenous weight per TEU so low. Another change that seems quite unwanted is the slight increase of the EEDI ratio (attained to required), but since both values are far below 0.8, it seems that the designed vessels meet even the third phase criteria, so this increase is not really of any interest.

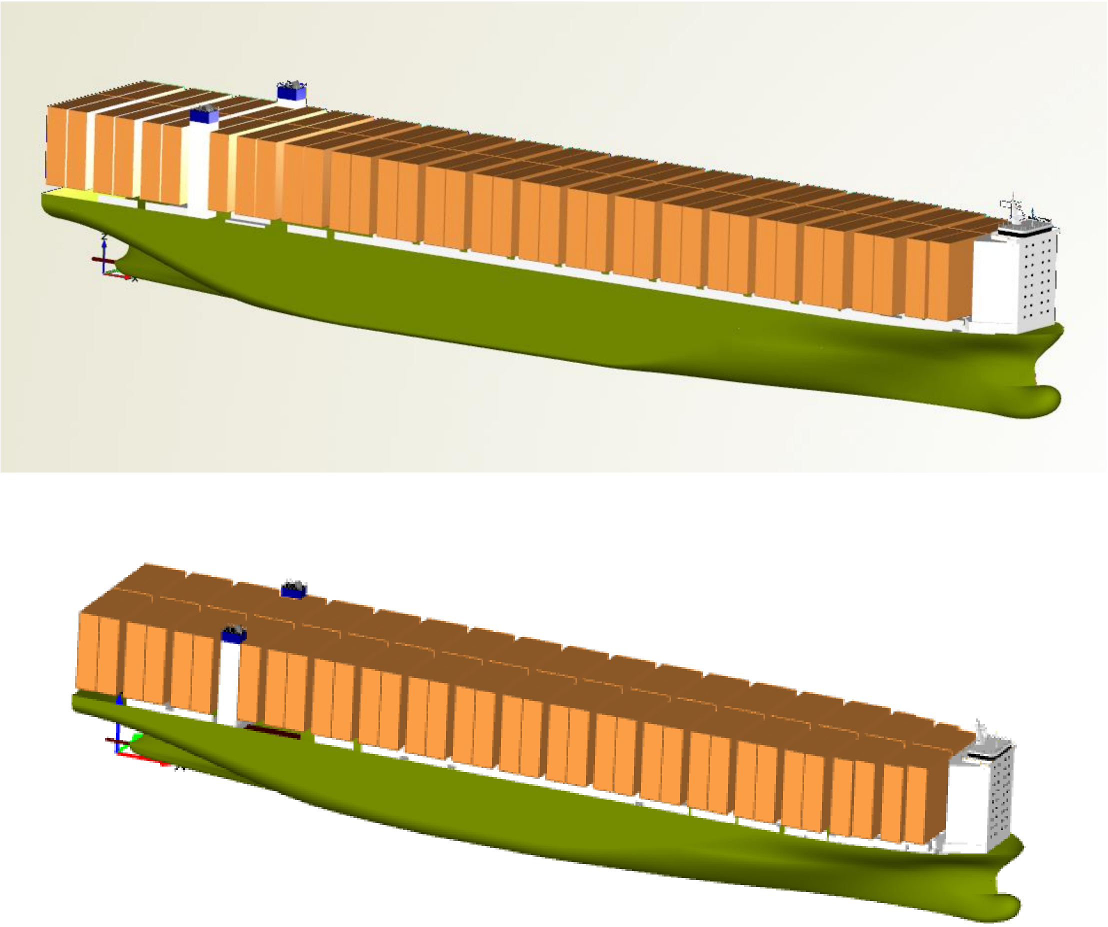

Figure C. 9 Baseline design (above) and des. 1/116 (bellow)

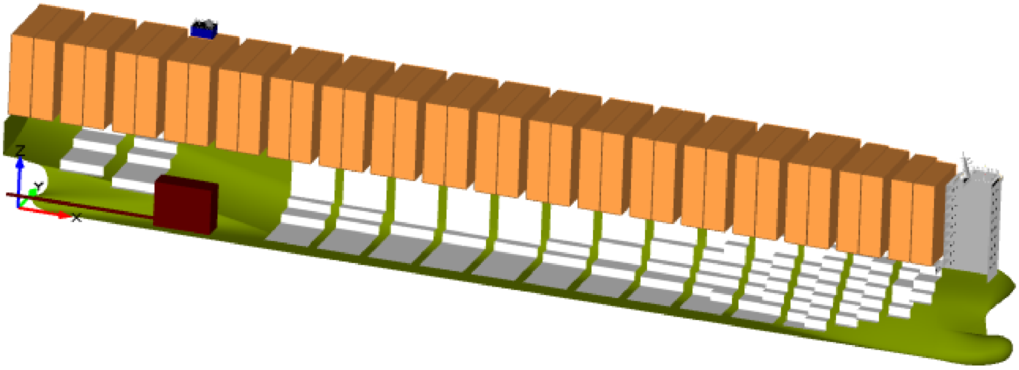

Figure C. 10 Design 1/116 half-model

4 Conclusion

Coming to an end, the application of the holistic design optimization for the case of a 9000 TEU container carrier had successful results. Since the multi objective optimization is a procedure that does not provide an optimum design, but rather a set of optimal designs on the Pareto Front, the respective analysis presented above, provides enough insight in the improvement margin of this container carriers' class design. Talking about single solutions, the design no 1/116, which was identified one of the best and with constant top ranking for our different scenarios, seems to be a good solution and improved over the original baseline model.

This parametric model has some peculiarities identified from the beginning, the most important being the position of the deckhouse all the way front at the bow. It was meant to be an experiment to check the feasibility of such a design for this class, discovering eventually any benefits it would have. After this extensive study, it can be concluded that there is enough margin to reduce the length of the ship and improve a series of performance factors that depend on the length, lightship or wetted surface, by eliminating the visibility line requirement and achieving the same capacity with less bays. This configuration though brings some other difficulties caused by the relatively higher center of gravity of the cargo in general, which calls for extra ballast for the full loaded condition, and subsequently lower weight per container. Under circumstances that is not really a problem, as explained above.

Taking into account all the above comments and results of the optimization, we can safely conclude that the benefits of positioning the deckhouse all the way forward are outnumbering any drawbacks and that can be justified by holistic design optimization techniques that push the limits of the model to the Pareto front designs.

Regarding the first part of this study, the parametric modelling of an integrated containership model, the deliverable files consist a really elaborate fully parametric model. This new version is far improved over older versions used for projects of the SDL, while the addition of many custom made computational modules can be a really valuable resource for future projects.

5 Further steps

This study was focused on Holistic Ship Design Optimization techniques for a specific ship size category of 9000 TEU capacity with an attempt to investigate some elements of novelties in the deckhouse arrangement. Of course there is a whole area of design optimization that could be applied in different ship sizes. In some cases it could be also interesting to investigate some special design features, like the deckhouse position in this project, or even others like the tanks arrangement. The deckhouse positioning at the front may also be further investigated for its feasibility in terms of structural strength, or even sea keeping performance, aspects that were not studied in this project.

An area that seems really promising in terms of optimization margins, is the port efficiency of container vessels. In the scope of this project, it was confronted in a simple way, by using the stowage ratio and according to the assumption: “the more containers on deck, the faster gets the (un)loading”, which may follow the common sense, but remains rather simple and not proven yet though. In that direction there has been some research, in which the author of this thesis was also involved, focusing on actual loading simulations of many different loading cases for each design and many designs altogether. A statistical approach of the simulation results might give some insight on the phenomenon itself and provide the designers with a port efficiency evaluation tool.

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