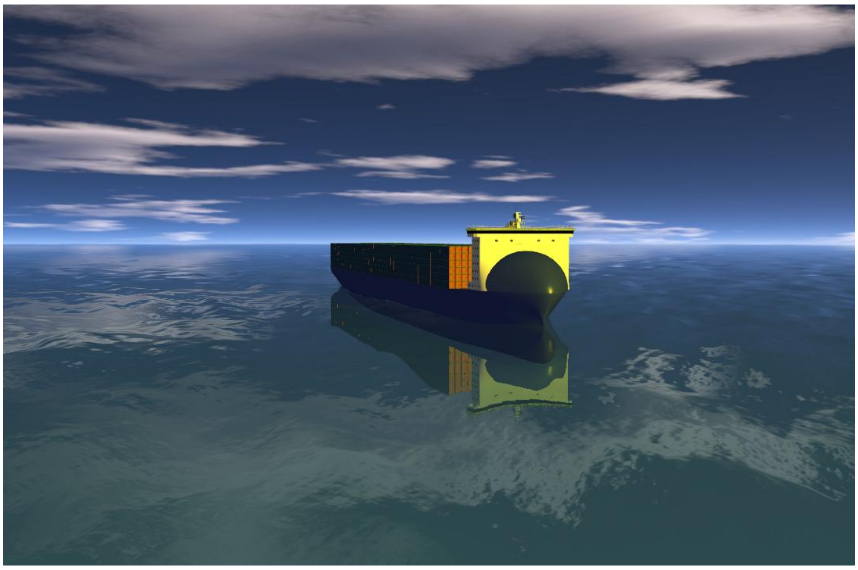
NATIONAL TECHNICAL UNIVERSITY OF ATHENS
SCHOOL OF NAVAL ARCHITECTURE AND MARINE ENGINEERING
DIVISION OF SHIP DESIGN & MARITIME TRANSPORT

Diploma Thesis:

PARAMETRIC DESIGN AND MULTIOBJECTIVE OPTIMIZATION-STUDY OF AN ELLIPSOIDAL CONTAINERSHIP



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Athens, January 2012

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Αθήνα, Ιανουάριος 2012

Abstract

Increasing international competitive pressures are motivating all industrial corporations to continually reduce cycle time, improve return on assets and reduce working capital complying also with demanding environmental regulations. Efficient and effective decision making becomes a significant factor for management of time and budget demanding the strict attention of engineers. Optimization is a process of decision making when a number of alternative choices are available and an optimal solution has to be determined. Ship design is a typical optimization problem involving multiple and frequently contradictory objective functions and constraints. When dealing with multi-criteria optimization, finding the best compromise means to define a Pareto-Frontier or else, a set of non-dominated solutions. Modern CAD/CAE systems allow a holistic design approach which aims at investigating many if not all important aspects of an optimization problem at the same time in contrast to traditional methods (design spiral, Evans). To investigate and develop innovative solutions, the designer requires a tool that does not enforce detailed definition and allows easy reconfiguration of arrangements and systems. Looking at the study case, the integrated approach is applied on a novel concept regarding containerships. A CAE environment is established combining the simulation of key measures of merit in the early phase of ship design for a considerable numbers of variants: Geometry, lightship weight, payload, capacity, stability and hydrodynamics were computed by means of simulation codes. A complete preliminary research is stated where today's needs are identified, a conceptual solution is proposed and a multi-objective optimization is performed in order to meet the targets. What is fundamentally here presented is not only an innovative design, but also a pioneering methodology of holistic investigation of ship design at the early stage.

For this purpose, a powerful CAD/CAE package based on parametric modelling techniques, the FRIENDSHIP-Framework, is employed and coupled with the commercial flow solver SHIPFLOW allowing the generation and analysis of new hull shapes leading to rapid design explorations without model testing.

Key words: <<Optimization, CAD/CAE systems, Holistic design, Parametric modelling, FRIENDSHIP-Framework, SHIPFLOW>>

Περίληψη

Οι διεθνώς αυξανόμενες πιέσεις ανταγωνιστικότητας οδηγούν όλες τις βιομηχανίες σε συνεχή προσπάθεια μείωσης των χρόνων ανταπόκρισης, βελτίωσης των ισολογισμών εσόδων εξόδων και μείωσης του κεφαλαίου κίνησης καθώς πρέπει ταυτόχρονα να συμμορφώνονται με τους απαιτητικούς κανονισμούς προστασίας του περιβάλλοντος. Οι αποδοτικές και αποτελεσματικές μέθοδοι λήψης αποφάσεων αποτελούν πλέον σημαντικό παράγοντα στη διαχείριση χρόνου και χρήματος απαιτώντας την αυστηρή προσοχή των μηχανικών. Η βελτιστοποίηση είναι μια διαδικασία λήψης αποφάσεων όταν ένας μεγάλος αριθμός εναλλακτικών επιλογών είναι διαθέσιμος και η βέλτιστη λύση εξ αυτών πρέπει να προσδιοριστεί. Η μελέτη πλοίου είναι ένα τυπικό πρόβλημα βελτιστοποίησης, το οποίο συνεπάγεται πολλαπλές και συχνά αντικρουόμενους αντικειμενικούς στόχους και περιορισμούς. Στην πολυκριτηριακή βελτιστοποίηση, η ανεύρεση της βέλτιστης συμβιβαστικής λύσης, σημαίνει τον ορισμό ενός μετώπου Pareto, η αλλιώς ενός συνόλου μη-κυριαρχούμενων λύσεων. Τα σύγχρονα συστήματα CAD/CAE επιτρέπουν την καθολική προσέγγιση της μελέτης, η οποία θέτει ως στόχο τη διερεύνηση πολλών, αν όχι όλων των πλευρών ενός προβλήματος βελτιστοποίησης συγχρόνως, σε αντίθεση με παραδοσιακές μεθόδους (Ελικοειδής καμπύλη μελέτης κατά Evans). Για την διερεύνηση και ανάπτυξη καινοτόμων λύσεων, ο σχεδιαστής χρειάζεται εργαλεία τα οποία δεν απαιτούν λεπτομερή ορισμό και επιτρέπουν την αναδιάταξη συνθέσεων και συστημάτων. Επικεντρώνοντας στην εξεταζόμενη περίπτωση, η συνολική αυτή προσέγγιση εφαρμόζεται σε μια πρωτότυπη ιδέα που αφορά σε πλοία μεταφοράς εμπορευματοκιβωτίων. Στο προκαταρκτικό στάδιο της μελέτης αυτής δημιουργείται ένα περιβάλλον CAE, στο οποίο προσομοιώνονται ταυτόχρονα πολλαπλά κριτήρια που έχουν περιθώρια βελτίωσης, για έναν ικανοποιητικό αριθμό εναλλακτικών σχεδιάσεων: Η γεωμετρία, το βάρος άφορτου πλοίου, το ωφέλιμο φορτίο, η χωρητικότητα, η ευστάθεια και η υδροδυναμική συμπεριφορά προσδιορίζονται μέσω κωδίκων υπολογιστικής προσομοίωσης. Παρουσιάζεται μια πλήρης προκαταρκτική έρευνα, όπου αναγνωρίζονται οι σύγχρονες ανάγκες, προτείνεται μια λύση και πραγματοποιείται μια πολυκριτηριακή βελτιστοποίηση ούτως ώστε να επιτευχθεί ο στόχος. Αυτό που στην ουσία παρουσιάζεται δεν είναι μόνο μια καινοτόμα σχεδιαστική πρόταση αλλά και μια πρωτοποριακή μέθοδος ολιστικής διερεύνησης της μελέτης πλοίου σε πρώιμο στάδιο.

Για αυτό τον σκοπό, χρησιμοποιείται ένα ισχυρό σχεδιαστικό πακέτο CAD/CAE,που βασίζεται σε τεχνικές παραμετρική μοντελοποίησης, το FRIENDSHIP-Framework, συζευγμένο με το εμπορικό λογισμικό επίλυσης ροών, SHIPFLOW, επιτρέποντας έτσι την γρήγορη δημιουργία και ανάλυση νέων μορφών γάστρας. Με αυτόν τον τρόπο διερευνούνται γρήγορα πολλαπλές εναλλακτικές σχεδιάσεις χωρίς την απαίτηση για δοκιμές σε πραγματικό μοντέλο.

Λέξεις-κλειδιά: <<Βελτιστοποίηση, συστήματα CAD/CAE, ολιστική μελέτη, παραμετρική μοντελοποίηση, FRIENDSHIP-Framework, SHIPFLOW>>

Acknowledgment

At this point I would like to express my deepest gratitude to my advisor Prof. A. D. Papanikolaou for giving me the opportunity to deal with such an interesting topic and for his always great support and motivation.

My sincere thanks also go to Dr. E. Boulougouris for his decisive support during the completion of this Diploma thesis, and especially for his significant contribution during the preparation of the project “E^4-Containership”, submitted by the author and A. Pavlou to the academic competition “2011 VISIONS-OLYMPICS”.

Vielen Dank also to Dr. Stefan Harries, as well as the rest of the Friendship-Systems Team for giving me valuable help during my internship there.

I am also thankful to Mrs. A. Alisafaki for providing me with all necessary information regarding containerships and Mr. D. Mourkogiannis for his assistance with CFD-configurations.

Last but not least, I would like to thank my friend and colleague, A. Pavlou for our productive collaboration and successful accomplishment at the academic competition.

Georgios L. Koutroukis
January 2012

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1. Introduction

Increasing international competitive pressures are motivating all industrial corporations to continually reduce cycle time, improve return on assets and reduce working capital. Shipbuilders face a number of strategic pressures to deliver ships in a shorter timescale, of increasing complexity and modularity, to demanding environmental rules, whilst lowering initial build and operating costs. Decision making, even at the preliminary design phase of a product has become significant and demands the strict attention of engineers, who are prompted to find efficient methods of dealing with such multidisciplinary tasks in order to realize superior performance within available time and budget resources. In this sense the decision making process becomes the target of an optimization problem, which could be simply expressed like: “choose the best possible solution/design between various alternatives”. From that point of view, the optimization process must consider several different usually conflicting objectives and the compromise obtained might not be a-priori know.

Optimization is inherently coupled with human activity and is mostly expressed in the everyday life with the “trial and error” method. Formal optimization procedures though have received enormous attention in the recent decades and have become an indispensable scientific tool implemented in most decision making tasks. The rapid progress in computer technology has increased the interest in mathematical models and algorithms that express the nature of optimization. The best known algorithms in this class include evolutionary programming, genetic algorithms, evolution strategies, simulated annealing, classifier systems, and neural networks.

Ship design is a complex endeavour requiring the successful coordination of many tasks of technical as well as non-technical nature and is tight coupled with optimization procedures since the late 1980s when the first investigations in the field of ship forward resistance, with deterministic algorithms and simplified deformation tools were undertaken. These first steps led to decisive progresses later in the 1990s when more experience about automated optimization procedures was acquired. Nowadays, further knowledge has been gained in the domain of multi-model, multi-disciplinary optimal design. The interest of this method is to handle multi-disciplinary problems in a holistic way. Ship design optimization should be examined from a holistic point of view as well, considering that ship design should actually address the whole ship’s life-cycle. Eventually, in the preliminary /concept design, an optimal ship is the outcome of advanced optimization techniques used for the computer-aided generation, exploration and exploitation.

Geometric modelling and CAD/CAE systems have evolved in parallel with optimization concepts during the recent years, since favourable geometry is significant in many optimization problems, especially in marine industry where complex shapes like ship hulls call for advanced handling. An important part of optimization projects is the generation and variation of geometry. In ship design optimization, accurate and quick hull form generation which is coupled with assessment tools in the environment of an optimization or variation algorithm constitute the Simulation-Driven Design method. This approach has no doubt the potential to surpass traditional design methods.

The parametric modeling software FRIENDSHIP-Framework, which stands in the core of this Diploma thesis, is an innovative CAD approach, providing also the *framework* for the practical implementation of Simulation-Driven Design, involving improved accuracy, automation, speed and communication of ship assessment tools, focused on CFD calculation methods.

The scope of this Diploma thesis is to explore the potentials of parametric ship design and multi-objective optimization, introducing the CAD/CAE software package FRIENDSHIP-Framework, coupled with several tools for assessment, enabling in this way Simulation-Driven Design. This thesis will start with a review of basic concepts regarding geometric modeling techniques and analytical tools for determination of flow around a vessel. It will also include a literature survey of multiple decision making, taking into account optimization fundamentals and strategies.

The development of a methodology to perform requirements-based tradeoffs will then be address in the case study of the E^4-Containership and it will demonstrate the applicability of the theory.

The E^4-project is a conceptual design of an ellipsoidal containership that needs to comply with contradictive objectives deriving from environmental regulations (EEDI, Ballast Water Treatment) and from the need for financially more efficient ships.

Last but not least, the comparative assessment of the outcome "optimized" design is presented. Several conventional and innovative designs are employed to signify the merits and weaknesses of the novel concept.

The herein presented case study is a further investigation of the project "E^4-Containership", conducted by A. Pavlou and the author, and submitted in April 2011 to the Academic Contest "2011 VISIONS-OLYMPICS". Our work received the honorary distinction of being listed amongst this year's top 3 winners. The final ranking is expected to be announced in April 2012. Credits for the core idea of this project and for their decisive contribution go to Prof A. D. Papanikolaou and Dr. E. Boulougouris.

2. CAD/CAE systems for ship design

2.1 Introduction

The tools and techniques used to design ship structures have evolved over the last forty years, from producing blueprints on the drafting board to the digital design of today. As computer technology became more powerful and less expensive, computer-aided-design (CAD) systems evolved to support the design of complex products. CAD and other related tools empower designers and engineers to create innovative products more quickly and efficiently.

During the 1990's, the single product data management systems continued to expand in scope and scale. Companies recognized that they could use these systems not just to design their products, but also to manage the product data over the entire lifecycle from concept through deployment. At the same time, CAD and computer aided engineering (CAE) technologies, which refers to the close coupling of modelling and simulation, grew in complexity and capabilities. Less expensive hardware and more powerful tools provided the incentive for many companies to move from 2D CAD to 3D, the prerequisite for many analysis techniques like the finite element method (FEM). Once limited to mainframe computers, these powerful analysis tools also moved to the desktop, putting the full range of CAE at the engineer's fingertips.

2.2 Objectives of CAD and CAE applied to hull forms

The ultimate objective of every tool used for economic human activity is to obtain greater efficiency, effectiveness and a better quality.

A greater efficiency means that less time, material and labour are necessary to obtain the desired results. Greater efficiency leads to [1]:

- A shorter time to reach a certain design stage;
- Fast analytical calculations possible;
- Integration between CAD and CAE;
- Fast geometric manipulations;
- More freedom in the sequence of design activities (e.g. stability calculation based on a preliminary CAD model returns more accurate information at the initial stage of the design);
- Increased job satisfaction.

To be of greater effectiveness implies that more topics can be dealt with, which also lead to a better quality. For example [1]:

- More design iterations, to come to an optimal design;
- Integration of analytical tools;
- 3-D visualization, to give all persons involved a better image of the vessel;
- Higher precision of the hull form definition.

On the other hand, CAD and CAE systems bring also some disadvantages with:

- The use of improper CAD/CAE systems, which force the designer into a corner;
- The usual need for very powerful hardware system to support it;
- A tendency to use always the latest CAD/CAE products, which may be unstable and error prone;
- A tendency to 'over-calculate', just because the computer gives the ability to, resulting in time-consuming procedures.

2.3 Ship Design Process

In ship design there are many domain-specific models of the design process, but Evans' design spiral (fig. 2.1) is probably the most well known. This model emphasizes that many design issues interact and must be considered in sequence, in increased detail in each pass around the spiral, until a single design that satisfies all constraints and balances all considerations is reached. Modern CAD/CAE systems allow a holistic design approach which aims at investigating many if not all important aspects at the same time. Such a synthesis model of CAE (fig.2.1) allows exploring the design space to a greater extent and provides an efficient method of handling complex systems with many relationships and dependencies at once [2].

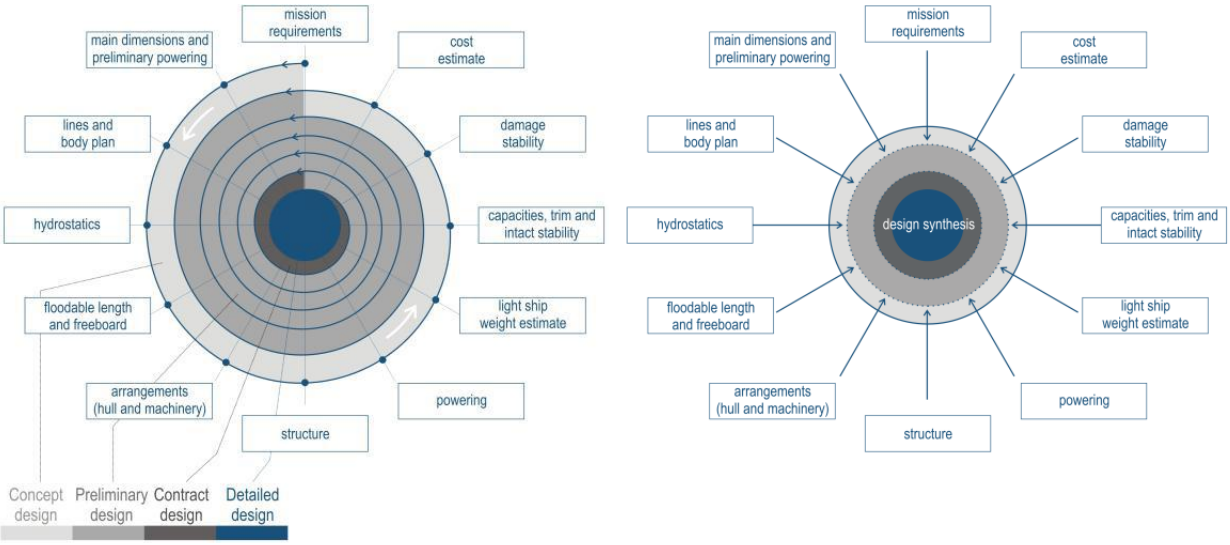


Fig2.1: Traditional design spiral (left) vs. integrated approach (right)[2]

2.4 *Geometric modeling*

A review of the existing CAD/CAE tools demonstrates three basic geometric modeling concepts [3]:

- Conventional design;
- Partially-parametric design;
- Fully-parametric design.

2.4.1 Conventional design

Traditionally, in most CAD-systems the generated hull geometry is controlled directly from low-level entities, namely points. The designer has to move separately each point in order to achieve a change in the geometry. That means that the designer has the absolute control over the shape but also requires a great experience and specific knowledge to generate and vary the geometry. However, achieving the desired form is not a trivial task, especially, if the result needs to yield suitable fairness (in a subjective manner) and/or is to meet specific constraints. In addition, once the initial design is created, it is time-consuming to alter the shape and specific manipulation is required.

2.4.2 Semi-parametric design

This category refers to CAD tools that offer the opportunity to build on existing shapes and to modify the given hull form by controlling parameters that create variants. Each new hull form will always inherit the characteristics implied by the parent form or the formulae.

The new hull form (the daughter form) is derived with mathematical transformations or distortion. Transformations can be local or global. Global transformations simply work on the basis of hull form coefficients and are therefore easier to use [1]. A well known method of this kind is the Lackenby transformation which is utilized by many CAD tools (AVEVA, FRIENDSHIP-Framework, etc).

The method discussed can be qualified as “partially parametric” because there is a standardized procedure, where changes applied to the shape are given by means of parameters that are associated with problem-specific properties. The advantages of such a procedure are its speed and simplicity for the designers, allowing them to execute optimization and creating a fast number of variants. The great disadvantages though are the inflexibility and the lack of shape control, which make variation in hull form types prohibitive. Many designers prefer an arbitrary free form method for the ab initio design, or at least free form manipulation after the initial design has been produced by a procedural method [1].

2.4.3 Fully-parametric design

Instead of moving several points in order to achieve the desired geometry, the model in parametric design is established on relationships created by form parameters, which allows creating and varying ship hulls quickly and efficiently. Form parameters are high level descriptors that reflect the functional characteristics of hulls. Variants are created by modifying the value of form parameters, which consequently update the dependent relationships and results in curves and surfaces that yield excellent fairness [4].

In figure 2.2 the different modeling concepts are presented and compared on the basis of flexibility, required knowledge, effectiveness and cost in relevance to efficiency.

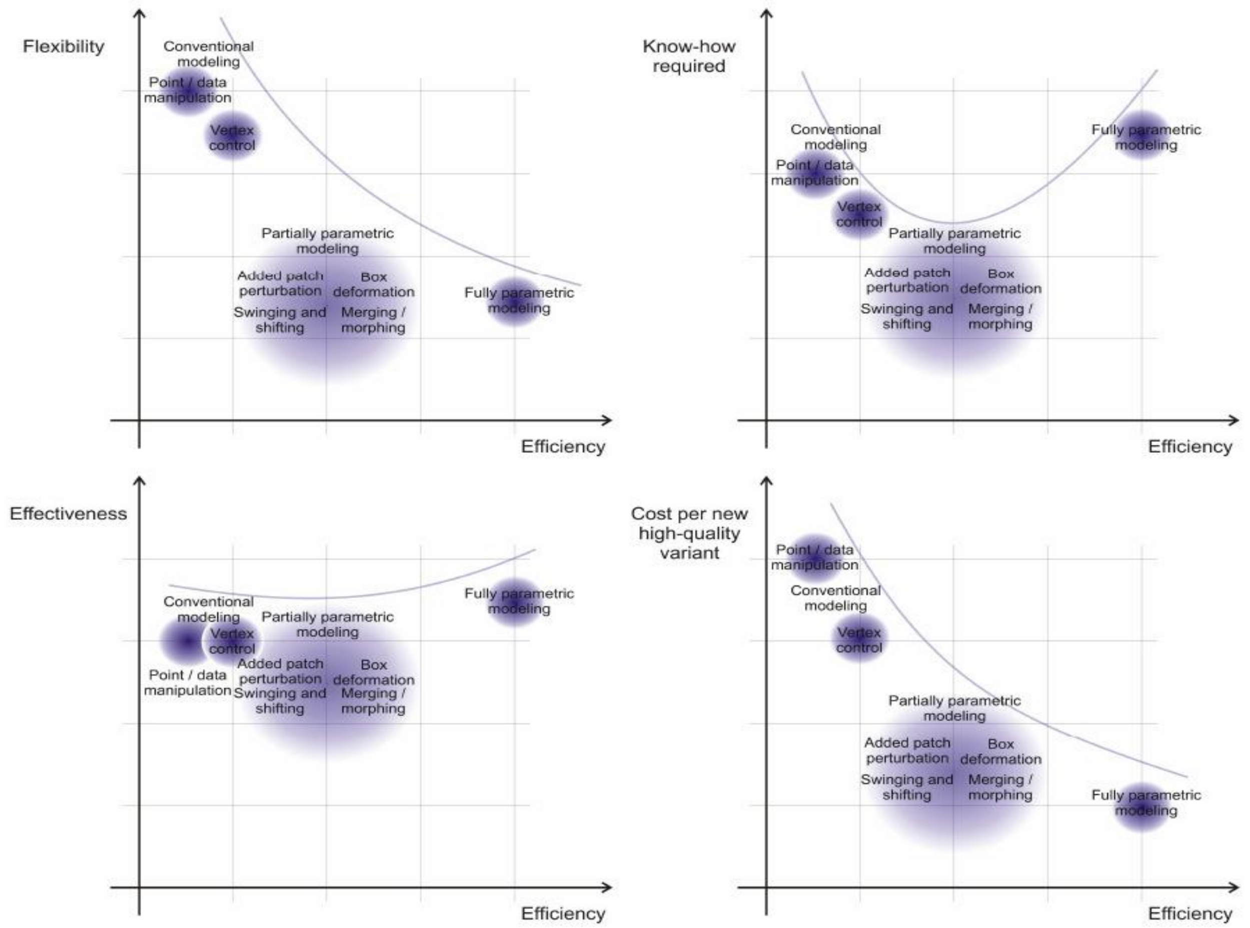


Fig2.2: Assessment of different geometric modeling techniques [5].

What can be derived by the figure 2.2 is that the fully parametric modeling technique yields excellent efficiency since only a few modifications are required in order to achieve a new fair hull form. This approach requires though a good knowledge of the basic elements of parametric modeling and the most time is consumed in order to set up the whole structure. Once the model is established, a wide variety of new designs is available, in contrast to conventional modeling where, setting up a hull form and browsing through new designs are equally time-consuming and demands experience of the designer. Partially-parametric models build on existing shapes and prove to be an easy-handled approach for numerous tasks but it is not recommended for global and multi-objective investigations since the allowed modifications of the model are restricted. According to (Harries, 1998) [4], *the great advantage of parametric modeling is the ability to find the optimal balance between variability and simplicity, more precisely the balance between the freedom to be able to do everything and the restriction to do only what you really need.*

2.5 An insight in fully-parametric ship design

Background

In the scope of this documentation, the investigated approach of parametric modeling is the one presented by Harries and Abt [5], which is adopted and utilized by the CAD/CAE system FRIENDSHIP-Framework.

2.5.1 Form Parameters

A great advantage of parametric modeling regarding marine design is that its main characteristic, the form parameters, describe the topology in naval architect's language, namely the designer specifies the curves or surfaces on the level of their properties (geometrical or physical) [6].

These established form parameters are either [3]:

- Integral (area, volume, high order moments etc),
- Positional (length, beam, draft etc) or
- Differential (tangents, curvature information, slope etc).

The form parameters definition is provided to the ship's geometry in terms of longitudinal curves – so-called basic curves like the sectional area curve and the design waterline, ideally containing all information needed to produce a hull's shape [7].

The contrast of the traditional concept of modeling versus the innovative concept of parametric design is illustrated in Figure 2.3 where the input and output are reversely handled. The designer specifies what he or she wants and the system computes the position of the vertices such that the designer's specifications are met. In this way, rather than coping with the underlying mathematics, the naval architect is free to think lines and hull form as expressed by their form parameters. Form parameters can thus be regarded as high-level design elements; they are the vocabulary with which to formulate design ideas [7]. This is also referred to as problem-oriented modeling technique.

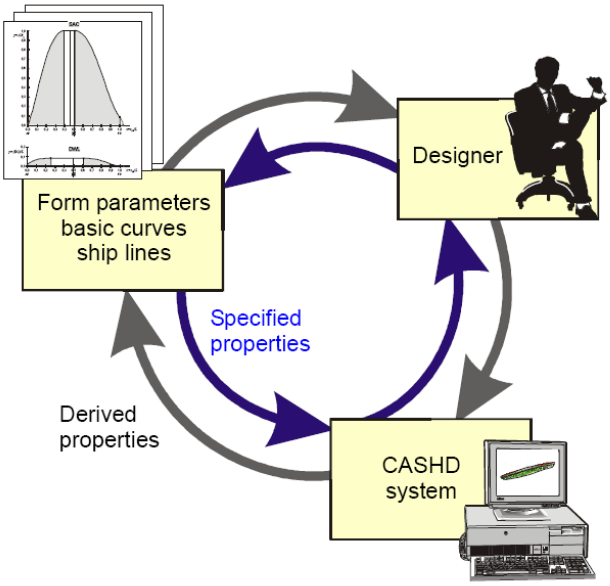


Fig2.3: Conventional modeling (clockwise) vs. form parameter design (counterclockwise) [7].

2.5.2 Parametric design of ship hull forms

Focusing on bare hulls, the modeling process is subdivided into three consecutive steps as shown below [7]:

1. Parametric design of a suitable set of longitudinal basic curves (Deck line, DWL, SAC.)
2. Parametric modeling of a sufficient set of design sections derived from the basic curves.
3. Generation of a small set of surfaces which interpolate the design sections.

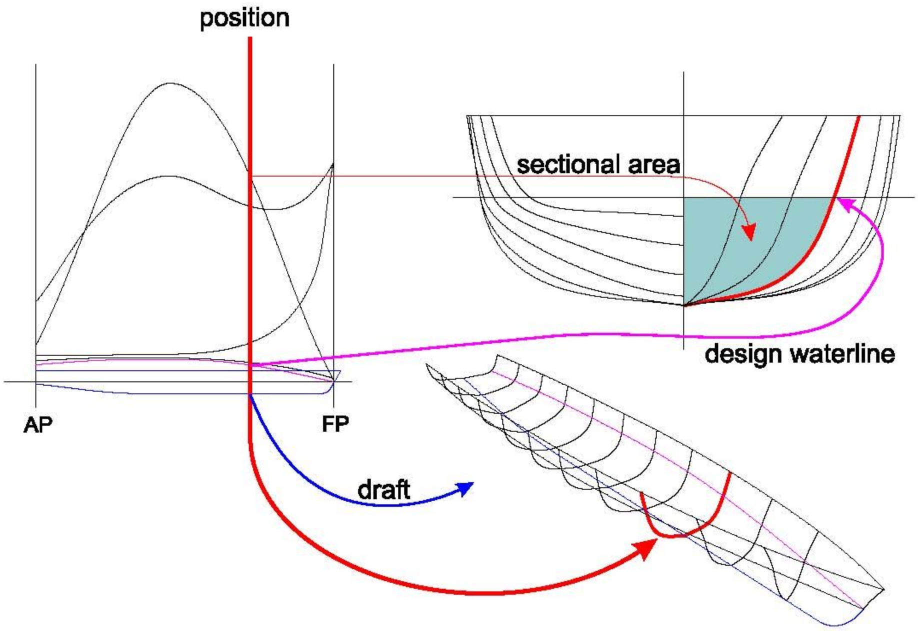


Fig2.4: Shape definition process for ship hull forms [7].

2.5.3 Fairness of Curves

Ship design software packages are based nowadays mostly on B-Spline technology, due to its advantageous characteristics with regard to local shape control, internal continuity and variability. Therefore, B-spline curves are able to represent any kind of shape. Yet, the fairness of the surface is normally realized interactively by the designer, which is a non-trivial task since vertex coordinate, weights etc. have to be controlled [6]. The parametric modeling technique developed by Harries and Abt (1997) is based on parametric curve generation, where the vertices of all B-Spline curves are computed from geometric optimization, employing fairness criteria as measures of merit and capturing global shape characteristics as equality constraints. Form parameters allow the elaboration on the level of their properties (geometrical or physical) instead of their mathematical representation [4].

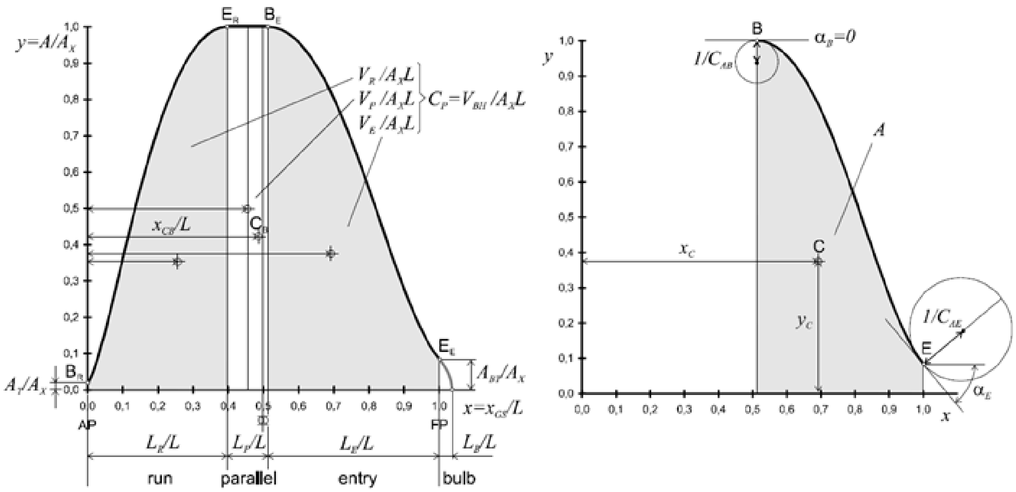


Fig2.5: Example Section Area Curve [4].

The left picture of figure 4 a well-known curve is presented, namely the Sectional Area Curve (SAC) of a containership. The SAC is composed by four separate curves, which refer to different regions of the vessel, namely the run, parallem mid body, entry and bulb. The area under the complete curve may be characterized as a form parameter and a physical form parameter of the hull. More form parameters are visible on the picture like the length of each body and the longitudinal center of buoyancy. On the right picture a planar curve with its form parameters, which represents the entry body is isolated. The set of form parameters which controls this planar curve are presented in table 1.

	Form-parameter		Mathematical description	Constraint
1	Position at beginning	x_B	$x_B = x\|_{t=0}$	h_1
2		y_B	$y_B = y\|_{t=0}$	h_2
3	Position at end	x_E	$x_E = x\|_{t=1}$	h_3
4		y_E	$y_E = y\|_{t=1}$	h_4
5	Tangent angle at beginning	α_B	for open B-spline directly via $\vec{V}_0\vec{V}_1$	h_5
6	Tangent angle at end	α_E	for open B-spline directly via $\vec{V}_{m-2}\vec{V}_{m-1}$	h_6
7	Curvature at beginning	C_{AB}	$C_{AB} = \frac{x'_B y''_B - x''_B y'_B}{\left(x'^2_B + y'^2_B\right)^{3/2}}$ with $x' = \frac{d}{dt}x(t)$, etc.	h_7
8	Curvature at end	C_{AE}	$C_{AE} = \frac{x'_E y''_E - x''_E y'_E}{\left(x'^2_E + y'^2_E\right)^{3/2}}$	h_8
9	Area between curve and x-axis	A	$A = \frac{1}{2}\left[\int_{t_B}^{t_E}(yx' - xy')dt + y_E x_E - y_B x_B\right]$	h_9
10	Centroid of area (first order moment)	x_C	$x_C A = M_y = \frac{1}{3}\left[\int_{t_B}^{t_E}(yx' - xy')xdt + y_E x_E^2 - y_B x_B^2\right]$	h_{10}
11		y_C	$y_C A = M_x = \frac{1}{3}\left[\int_{t_B}^{t_E}(yx' - xy')ydt + \frac{1}{2}y_E^2 x_E - \frac{1}{2}y_B^2 x_B\right]$	h_{11}

Table2.1: Set of form-parameters for planar curves [4].

This set of 11 form parameters makes the planar curve flexible and able to adopt any shape requested by the designer on the basis of geometric properties. It is not mandatory to provide all of them every time, on the contrary, the method is capable of handling any subset (or any possible combination) of the form parameters.

The fairness of a curve is evaluated in a subjective manner, usually by judging the smoothness of the curvature plot (usually porcupines). *In the recent years though some techniques of evaluating the fairness of a curve have been presented by incorporating energy measurement criteria.*

Since the curve fairness can now be expressed as a mathematical formula, it is now available to treat the modeling process as an optimization problem where curve fairness criteria constitute the objective function while form-parameters are viewed as equality constraints. The vertices of the B-Spline curve are the free variables of the variation problem. For more information regarding the mathematical background see [4].

Thus, the shape of the curve can be directly influenced by its properties at the end points, e.g. position, tangent angle and curvature, while retaining excellent fairness.

3. Ship resistance analysis

3.1 Introduction

The prediction of ship hydrodynamic performance according to Bertram [8] can be broken down into the general area of:

- Resistance and propulsion;
- Seakeeping;
- Manoeuvring;

In the scope of the present thesis resistance issues are high ranked, therefore an insight in resistance analysis and prediction takes place.

Resistance is one of the most significant components when it comes to ship design and there is need for accurate estimates already at the preliminary design phase. Several techniques have been developed through the years and the basic approaches can be roughly classified into [8]:

- Empirical/statistical approaches;
- Experimental approaches;
- Numerical approaches;

The first approach refers to methods developed by examining numerous similar vessels or extensive series and provides either statistical information or semi-empirical prediction tools. These methods are very popular, especially at an early stage of ship design in order to have a simple and accurate overview of power requirements. Some methods with general applicability are Holtrop-Mennen 1982, SSPA 1969, Hollenbach (1998) etc [9]. Experimental approach refers to model tests or full-scale trials. This is the most reliable method but still it cannot be integrated in a systematic investigation easily due to the time-consuming and cost effective model production process. There has been little change in the basic methodology of ship resistance since the days of Froude (1874). Nowadays, the numerical approach based on Computational Fluid Dynamics (CFD) has become increasingly important and is now an indispensable part of the design process.

Although a model of the final ship design is still tested in a towing tank, the testing sequence and content have changed significantly over the last few years. Traditionally, unless the new ship design was close to an experimental series or a known parent ship, the design process incorporated many model tests. The process has been one of design, test, redesign, test etc. sometimes involving more than 10 models each with slight variations. This is no longer feasible due to time-to-market requirements from shipowners and no longer necessary thanks to CFD developments [8].

3.2 Components of resistance

When a ship is moving through water there will be forces opposing the motion. The total resistance, R_T, of a ship is defined as the force needed to tow the ship at a constant speed and it can be divided into subcomponents in different ways (Figure 3.1).

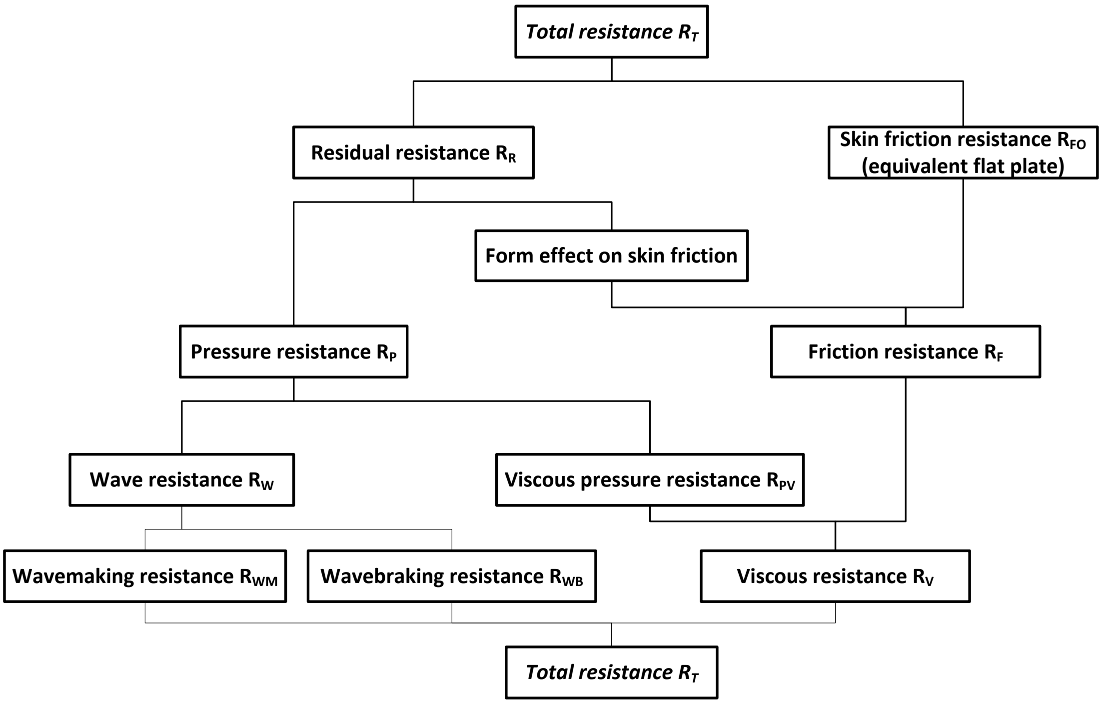


Fig3.1: Components of resistance [8]

One way is to divide it into skin friction resistance R_{FO}, and residuary resistance R_R, which includes all components related to the three dimensional form of the ship and wave-making resistance. It can also be divided according to physical phenomena into viscous resistance, R_V, and wave resistance, R_W. Further on, the viscous resistance consists of the frictional and pressure component. So the elaborated subdivision looks as follow:

The total resistance of a ship can be divided into three main parts [10]:

- wave resistance;
- frictional resistance;
- viscous pressure resistance;

For each of the parts of the total resistance different effects are primarily causative. Wave resistance depends on the lost energy due to the wave production of the ship as a partially submerged body disturbing the free surface of a fluid, thus waves are created due to water particles being removed from their equilibrium position. Secondly, sheer stresses between parts of the fluid with different velocities are the reason for the frictional resistance. These sheer stresses occur in the area close to the wall, within the boundary layer. Directly at the surface of the body, or at a wall, the fluids velocity is equal to zero, but at the outer end of the boundary layer the velocity is equal 99% of the undisturbed fluid velocity. Viscous pressure resistance consists of effects like flow separation and turbulence, which are mainly appearing in areas where the velocity of the fluid is decreasing and therewith the thickness of the boundary layers is increasing [10].

3.3 Computational Fluid Dynamics

Computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows [11]. The fundamental basis of almost all CFD problems, are the Navier-Stokes equations, which define any single-phase fluid flow.

The flow around a body can be described mathematically as a function of fluid pressure and the three components of velocity. A set of governing equations of motions can be created, like the Range Average Navier-Stokes equations (RANSE) for turbulent flow, and solved in association with specific boundary conditions. These equations are often complex to solve and rely on the use of Computational Fluid Dynamics (CFD). Several methods have been developed based on simplifications of the RANSE [8].

Typically inviscid free-surface methods based on the boundary element approach are used to analyse the forebody, especially the interaction of bulbous bow and forward shoulder. Viscous flow codes often neglect wave making and focus on the aftbody or appendages. Flow codes modelling both viscosity and the wave-making are at the threshold of practical applicability [8].

As viscous CFD codes become more robust and efficient to use, the reliance on experimentally derived coefficients in the equations of motions may be reduced. In an intermediate stage, CFD may help in reducing the scaling errors between model tests and full scale [8].

3.4 CAD-CFD Coupling

Combining CAD (computer-aided design) to generate new hull shapes in concert with CFD to analyse these hull shapes allows for rapid design explorations without model testing. CFD allows the preselection of the most promising design. Then often only one or two models are actually tested to validate the intended performance features in the design and to get a power prediction accepted in practice as highly accurate. As a consequence of this practice, model tests for shipyard customers have declined considerably since the 1980s. This was partially compensated by more sophisticated and detailed tests funded from research projects to validate and calibrate CFD methods.

3.5 Zonal-Approach

When using RANS in CFD-tools there are two different approaches available; Global and zonal. With the global approach where RANS equations are applied to the entire computational domain, it is possible to predict all quantities, however it is very time consuming and demands a great computational power. The zonal approach, proposed by Larsson (1993), reduces the computational time by utilizing three major methods, each applied in its most efficient zone of fluid condition:

i. Zone1: *Potential flow* method.
ii. Zone2: *Boundary layer* method.
iii. Zone3: *Navier-Stokes* method.

Potential flow method is used to analyze the fluid-flow in the outermost area of the free surface designated as Zone 1 in Figure 3.2. In this zone the fluid-flow is treated as continuous streamlines starting from fore end of the ship, and extending up to the aft end.

The region of free surface that describes the thin boundary layers along the ship hull is defined as Zone 2. The nature of fluid-flow change as the fluid moves along the hull in this region. The *boundary layer* theory is used to compute the fluid characteristics in zone 2. The laminar flow starts from the stagnation point, diverge gradually as it moves downstream, and when they reach the transition point where the viscous force is insufficiently strong to bond the streamlines, it breaks down and become turbulent.

The remaining region of the free surface is fully turbulent and will have wakes. It is specified as zone 3 and extending far aft from the transition point which is usually about amidships. *Navier- Stokes* theory is applied in this zone to calculate the energy and hence the corresponding resistance incurred. [12].

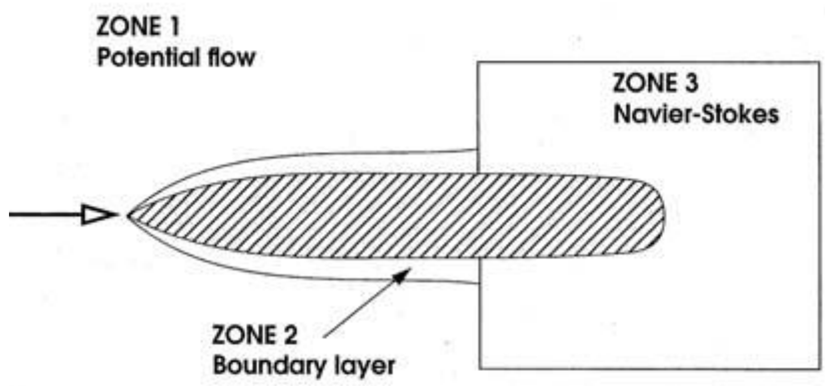


Fig3.2: The different flow regions assumed by Zonal Approach

The following potential flow techniques are used in Zone 1 to predict pressures, velocities and streamlines. By assuming non-viscous (ideal) and irrotational flow the governing equations produced are the linear, partial differential Laplace equations based on mass continuity. The non-linear free-surface boundary conditions are linearised and solved by using an iterative process until satisfactory convergence is reached.

In Zone 2 the development of the boundary layer is investigated using momentum integral equations for the thin viscous layer along the hull. By ignoring cross flow in the boundary layer, which is created due to a pressure gradient in the vertical direction of the ship hull the results are ordinary differential equations which are solved by Runge-Kutta techniques. This prediction cannot be used at the stern of a ship where a thick viscous region occurs due to convergence of the streamlines.

Towards the stern of the vessel, Reynolds-averaged Navier-Stokes (RANS) equations along with mass continuity equations describe the flow in Zone 3. The solution of the complex Navier-Stokes equations requires a lot of computational time and is therefore restricted to the stern of the vessel only, where a denser panelisation is created. The unsteadiness of the turbulent region is averaged out and instantaneous values of pressure and velocity are separated into a mean with fluctuations by the introduction of Reynolds stresses. In order to solve the closure problem the turbulent flow a κ-ε model is used in which the kinetic energy, κ and the rate of dissipation, ε are modelled (Larsson 1993).

3.6 Determination of the Wave Resistance

There are two ways to determine the wave resistance of the ship: pressure integration and wave cut analysis [13].

3.6.1 Pressure integration

The pressure integration method determines the wave resistance by integrating the pressure on the hull panels. The pressure on the hull consists of the hydrostatic and the hydrodynamic pressure. For the linear solution the hydrostatic pressure sums to zero and this makes it possible to integrate only the dynamic pressure to get the wave resistance. For the non linear solutions the hydrostatic pressure does not cancel and thus both pressures need to be integrated. The magnitude of the hydrostatic pressure is often larger than that of the hydrodynamic pressure and this can cause some problems concerning the accuracy of the pressure integration method. The solution to this problem is to use a sufficient number of panels on the hull surface.

3.6.2 Wave cut analysis

The wave cut analysis technique determines the wave resistance by analyzing the wave pattern. Longitudinal or transverse wave cuts can be used but the transverse method is preferred because it puts less demand on the size of the free surface. The method determines the wave elevation in a number of transverse wave cuts behind the ship. The first requirement with respect to the location of the wave cuts is that the wave cuts need to be in a region where the wave pattern is relatively smooth. This means that the first wave cut cannot be too close to the stern of the ship. The second requirement is that the wave cuts cover at least one wavelength and the distribution of the wave cuts cannot be equidistant. The wave cut method approximates the wave elevation in each wave cut by the sum of a series of elemental waves. The wave resistance is determined with the result of this approximation. The advantage of the wave cut analysis is that it is less dependent on the number of panels on the hull. This will make the wave cut method more robust than the pressure integration method for hulls with a complicated geometry (high curvature areas).

CFD tools like SHIPFLOW usually provide quantities of both approaches. Coefficients of wave cut method though are preferred in optimization processes due to its robustness compared to pressure integration method.

4. Optimization

4.1 Introduction-The generic ship design optimization problem

Optimization is a process inextricably linked with human activity. The desire to consciously optimize the outcome of decisions is a uniquely human character trait (Nowacki, 2003) [14].

In a few words, optimization is the process of decision making when a number of alternative choices are available and an optimal solution has to be determined with regard to specific criteria, while taking into account the restrictions and constraints set by the environment.

In more details, decision making of all kinds involves the choice of one or more alternatives from a list of options. The list of options would normally all be more or less acceptable solutions for the problem at hand and consequences, both good and bad, flow from the exercise of choice. The aim of rational decision making therefore, is to maximize the positive consequences and minimize the negative ones. As these consequences are directly related to the decision made or opinion set, it is not unreasonable to treat the consequences as aspects of performance. The decision problem then becomes a matter of considering these aspects of performance of all the options available simultaneously so that the decision maker (DM) can exercise his choice. In other words, rational decision making involves choice within the context of multiple measures of performance or multiple criteria [16].

Ship design is a typical optimization problem involving multiple and frequently contradictory objective functions and constraints [16]. With a system as complex as a ship, composed of many subsystems that are complicated on their own right, a naval architect is faced by a multiplicity of requirements, from the owner's needs and desires, engineering feasibility, imperatives of technological advancement, environmental considerations.

Solving the requirements of the sub-systems alone will often not produce an ideal result; the interactions amongst the sub-systems must be analyzed, leading to a ship design that truly is a multi-criteria decision problem. These MCDM methods can vary in complexity depending on not only the amount of parameters analyzed, but also how many of their interactions are thought out. In addition, subjectively becomes a factor into determining which criteria stand out above the others. How these criteria are weighted is up to the individual method itself [15]. Thus, the difficulty lies in formulating the objective and all the constraints. For this reason, *the main requirement when dealing with the generic ship optimization problem is that the designer has a picture of his objective, what he really wants to achieve* [8].

4.2 Single Objective- vs. Multi-Objective Optimization (Decision Making)

In the classical optimization where there is only a single criterion and a set of satisfiable constraints, decision making approaches lead naturally to the solution. Once the criterion of interest is agreed upon –cost, for example- the choice of the most attractive action is not a matter of opinion. There can be some argument as to how the objective –cost, for example- may be computed but in any meaningful problem the method of computation is obviously a part of the definition of the criterion itself. In other words, the choice of criterion leads directly to the solution in the mono-criterion paradigm and it is a solution that all parties can agree with [15].

However, sometimes a system must perform more than one mission or must meet multiple objectives simultaneously or consecutively, which without special assumptions may not be easy to accommodate in a single measure of merit. Therefore, in the case of multiple criteria formulation, decision makers can and will, in general, have different value systems leading to different priority orderings of the multiple, potentially conflicting performance criteria [14].

Ten or fifteen years ago, standard available optimisation tools would focus on a single and limited aspect (e.g. shape, scantlings, propeller, ultimate strength, etc.) and a single objective would be targeted (weight, resistance, cavitation, etc.). Nowadays optimisation tools tend to adopt a more generic approach and coupled with the fact that they have also become much more reliable this has made them more likely to be part of the standard design tool set that each designer uses on a day to day basis.

4.3 PARETO Optimality

When dealing with MCDM situations, it is necessary to consider how systems perform in a range of plausible conditions. This is why most of the sensitivity studies that accompany optimization are done. Finding a robust optimum whose performance is good and also relatively insensitive to changing conditions is a very important concern for engineering designers [15].

From that observation it is a short route to the assertion that requirements in design of any kind are often potentially in conflict. This is because there are few, if any systems that can combine the best of all performance aspects for all possible scenarios in the same design. If such utopian solutions exist then the obvious answer would be to go for them. But life being, the way it is, good values of some criteria inevitably go with poor values of others. The aim in multiple criteria decision making is then to find the best compromise solution [15]. The Pareto optimality expresses exactly this formulation, *namely the Pareto optimal solution is a set of possible solutions, a set of non-dominated solutions, in which no single objective can be improved without degrading the achievement of at least one other objective.*

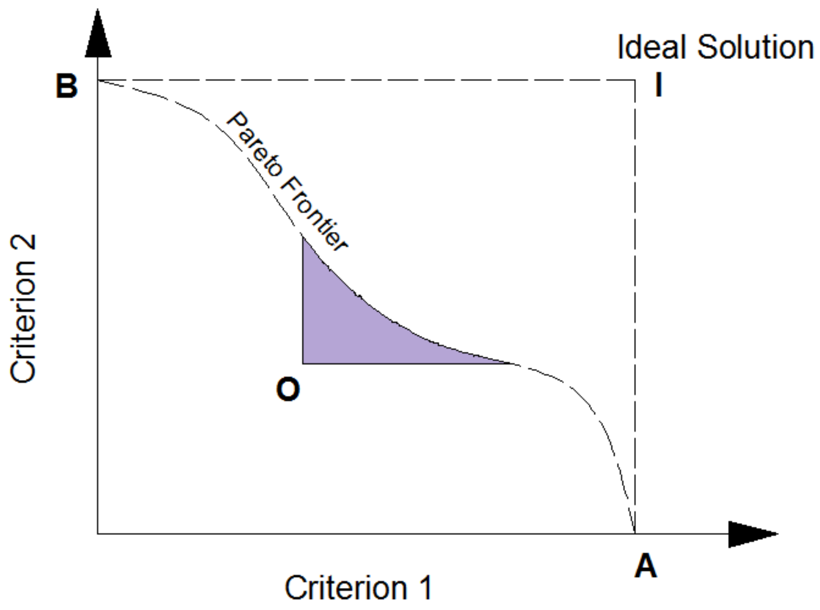


Fig4.1: The Pareto-Frontier

Without loss of generality all criteria in multiple criteria decision making can be thought of as maximizing, as is implicit in Figure 4.1, given that it is easy to convert a minimizing criterion to a maximizing one by changing the sign of the criterion in question. In figure 4.1 it is clear that if each criterion is maximized in turn the solutions obtained would be A and B respectively. The ideal solution of the combination of the two would be I. This solution is nearly always unattainable, due to physical and modeling constraints. Thus, considering O as a baseline design, the “best” solution may be found within the feasible region, shown shaded in Fig.4.1. This is a region, defined by the functional constraints. All solutions included in the shaded region will be superior to baseline O. this is because all solutions within this region are better than O at least with respect to one criterion if not in terms of both. Therefore, solution O may be considered to be dominated, but as the point O moves towards the boundary separating the feasible from the infeasible solutions, the set of dominating solutions represented within the shaded region reduces. Thus, when point O lies on the boundary, there is no solution that can be said to dominate it. This is true for every point that lies on the boundary. This boundary is referred to as the Pareto front and contains all solutions of interest because no point anywhere except on this boundary can be anything other than either dominated or infeasible [15]. With the Pareto set of non-dominated designs in hand, the designer can select an optimal solution according to his preferences. This can be done in a number of ways, such as:

- Using a utility function to rank the different designs;
- Using scatter 2D and 3D diagrams to visually identify the more attractive designs, comparing them on the basis of the designer’s preferred criteria and experience-based selection;
- Using other visual tools (parallel plots, histograms, frequency plots, etc.), and deciding according to the designer’s experience.

4.4 Formulation of the generic optimization problem

The formulation of optimization problems is a conceptual modeling process that follows certain standard procedures and results in a specific problem definition, tailored for an application, e.g. in design [14].

From the viewpoint of information flows, the generic optimization problem and its basic elements may be defined as follows (see Fig.4.2):

- Input $\mathbf{E_I}$: prescribed data, for example, requirements of the owner (DWT capacity, service speed etc).
- Output $\mathbf{E_O}$: result of the evaluation of the system performance for given input (techno-economical characteristics of the ship,- optimal solution based on criterion/-a.
- Design variables **D:** free variables of the optimization problem (under the designer's control), for example, ship's main dimensions.
- Design parameters **P**: restriction parameters, constraints (extraneous influences, scenarios, side conditions, not under the designer's control).
- Merit functions **M**: measure of merit, expression of evaluation criterion/-a, objective function (M(**D,P**)).
- Constraints **G:** boundary conditions of equality and/or inequality type, function of design variables and parameters (G(**D,P**)).

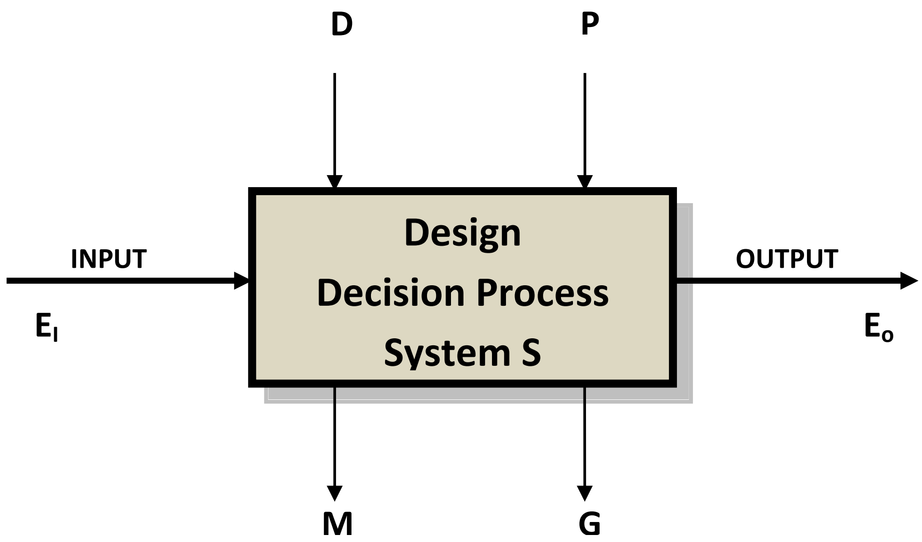


Fig4.2: Optimization System

The following list (according to Nowacki, 2003 [14]) gives a menu of modeling options, setting the choices for certain problem classes, in which the simpler and more routine alternatives, which usually predominate in ship design, are printed in italics.

- *Continuous* vs. discrete design variables.
- *Deterministic* vs. stochastic models
- *Single objective* vs. multiple objectives
- *Single-stage* vs. multiple-stage system model

Another mathematical expression of the multi-objective optimization problem presented by Sen and Yang [15] may generally be formulated as the following problem:

$$MOP\begin{cases} optimize\ F(X) = \{f_1(X) \cdots f_i(X) \cdots f_k(X)\} \\ \\ subject\ to\ X \in \Omega \end{cases}$$

$$\Omega = \left\{ X \left| \begin{array}{ll} g_j(X) \le 0 & i = 1, \cdots, m_1 \\ h_l(X) = 0 & j = 1, \cdots, m_2 \\ X = [x_1 \cdots x_n]^T & \end{array} \right. \right\}$$

Where x_i is a design variable, X denotes a solution, $f_i(X)$ is generally a nonlinear objective function, respectively, and $g_j(X)$ and $h_l(X)$ are nonlinear inequality and equality constraint functions. These objectives are usually incommensurate and in conflict eith one another. Therefore there normally exists infinite number of efficient (noninferior, non-dominated or Pareto-optimal) solutions in the multi-objective problem. The task is how to search for a best compromise solution with these multiple objectives being considered simultaneously.

4.4.1 Existence and uniqueness of solutions

An output-solution of the previously analyzed procedure is called feasible design, if it does not violate any constraint. The variable space that comprises all feasible solutions is called feasible space [14].

At least one solution exists (local optimum=global optimum) or several local optima may exist, if a nonzero feasible space exists, i.e., if the constraints are not in absolute conflict and if the objective (merit) function is defined everywhere in this space. These conditions are usually reasonably easy to test before an optimization.

An optimization problem in which either the measure of merit function or at least one of the constraint functions is a nonlinear function of the free variables in the set of the solution, is denoted as a Nonlinear Programming problem (NLP).

Only if the objective function and all the inequalities constraints –in the absence of equalities- are linear functions of the component of the solution, do we encounter the special case of LP. In design applications the linear case is very rare so that in practice we are usually faced with problems of NLP type.

In the NLP case it depends on the type of nonlinear functions whether only unique optimum exists (unimodal case) or whether several local optima occur (multimodal case) among which the global optimum can be found [14].

4.5 Design of Experiment

Design of Experiment (DoE) is a method by which a user can examine multiple design parameters and quantitatively understand their effect on the whole design (response). The best implementations begin with the use of a design of experiment where the space of feasible design is explored and the feasibility boundaries are detected. DoE's are very effective to gather information about the optimization problem at hand and about the whole design space. DoE tables are useful to detect trends of the optimization variables with regard to the objectives of the problem. Alternatively, a DoE database may be searched to detect a suitable starting point for a subsequent focused optimization process. Or a DoE may serve as a database for response surface fitting, or for checking the response sensitivity of a design candidate.

A design of experiment is used to identify which factors are statistically significant and practically important to the overall design. Statistical significance refers to the mathematical test to distinguish between whether a design variable influences the change in the mean value of the outcome due to an effect described in the model and whether the change could have been observed in the data by chance alone. In essence, a design of experiment is a research method that contributes to identify the changes, the local minima/maxima, to get an idea about the shape of the objective functions and is used as a preliminary tool for exploration of the design space and exploitation of the best regions according to criteria in order to obtain a reasonable initial design for the subsequent optimization.

4.6 Multi-Objective Optimization and Genetic Algorithms (MOGA)

Genetic algorithms (GA) are stochastic, nonlinear optimization methods that apply the principles of biological evolution [17]. In particular, they utilize populations of solutions and apply selection, reproduction and mutation methods, in contrast to more traditional optimization methods which use gradient information to move between (successively better) points in solution space. That makes them uniquely adaptive to multi-objective problems such as finding Pareto frontiers.

A good definition provided by Koza (1998) is:

"The genetic algorithm is a highly parallel mathematical algorithm that transforms a set (population) of individual mathematical objects (typically fixed-length character strings patterned after chromosome strings), each with an associated fitness value, into a new population (i.e. the next generation) using operations patterned after the Darwinian principle of reproduction and survival of the fittest and after naturally occurring genetic operations (notably sexually recombinations)".

Actually, the genetic algorithm derives its behavior from a metaphor of one of the mechanisms of evolution in nature which is called hard selection. Under this scheme, only the best available individuals are retained for generating descendants. This contrast with soft selection, which offers a probabilistic mechanism for maintaining individuals to be parents of future progeny despite possessing relatively poorer objective values.

A genetic algorithm for a particular problem must have the following five components:

1. A representation for potential solutions to the problem.
2. A way to create an initial population of potential solutions.
3. An evaluation function that plays the role of the environment, rating solutions in terms of their "fitness".
4. Genetic operators that alter the compositions of children.
5. Values for various parameters that the genetic algorithm uses (population size, probabilities of applying genetic operators, etc).

Some of the basic terminology referred to GA is the following:

The **fitness** of an individual is a value that reflects its performance (i.e. how well solves a certain task). A fitness function is a mapping of the **chromosomes** (data structure that holds a "string" of task parameters or genes, analogous to the base-4 chromosomes present in our DNA) in a population to their corresponding fitness values. A fitness landscape is the hyper-surface obtained by applying the fitness function to every point in the search space.

If the solution of a problem can be represented by a set of N real-values parameters, then the job of finding this solution can be thought of as a search in an H-dimensional space. This region is simply referred to as the **search space** of the problem.

Exploitation is the process of using information gathered from previously visited points in the search space to determine which places might be profitable to visit next. Hill climbing is an example of exploitation, because it investigates adjacent points in the search space, and moves in the direction giving the greatest increase in fitness. Exploitation techniques are good at finding local minima (or maxima). The GA uses crossover as an exploitation mechanism.

Exploration is the process of visiting entirely new regions of search space, to see if anything promising may be found there. Unlike exploitation, exploration involves leaps into unknown regions. Random search is an example of exploration. Problems which have many local minima (maxima) can sometimes only be solves using explorations techniques such as random search. The GA uses mutation as an exploration mechanism.

Elitism is a mechanism which ensures that the chromosomes of the highly fit member(s) of the population are passed on to the next generation without being altered.

The basic operation of a GA is presented in the following segment of pseudo-code:

```
Generate initial population, G(0);
Evaluate G(0);
t:=0;
repeat
    t:=t+1;
    generate G(t) using G(t-1);
    evaluate G(t);
until a solution is found
```

First, an initial population, where the individuals are set of chromosomes representing all possible solutions to the problem, is randomly generated. Then a fitness function is applied to each one of these chromosomes in order to measure the quality of the solution encoded. Knowing each chromosome’s fitness, a selection process takes place to choose the individuals that will be parents of the following generation.

4.7 *Non-dominated Sorting Genetic Algorithm (NSGA-II)*

Non-dominated Sorting Genetic Algorithm II (NSGA-II) developed by Prof. K. Deb et al. (2000, KanGal Report No. 200001) at Kanpur Genetic Algorithms Laboratory, is a fast and elitist multi-objective algorithm. Its main features are [18]:

- A fast non-dominated sorting procedure is implemented. Sorting the individuals of a given population according to the level of non-domination is a complex task: non-dominated sorting algorithms are in general computationally expensive for large population sizes. The adopted solution performs a clever sorting strategy.
- NSGA-II implements elitism for multi-objective search, using an elitism-preserving approach. Elitism is introduced storing all non-dominated solutions discovered so far, beginning from the initial population. elitism enhances the convergence properties towards the true Pareto-optimal set.
- A parameter-less diversity preservation mechanism is adopted. Diversity and spread of solutions is guaranteed without use of sharing parameters, since NSGA-II adopts a suitable parameter-less niching approach. It is used the crowding distance, which estimates the density of solutions in the objective space, and the crowded comparison operator, which guides the selection process towards a uniformly spread Pareto frontier.
- The constraint handling method does not make use of penalty parameters. The algorithm implements a modified definition of dominance in order to solve constrained multi-objective problems efficiently.
- NSGA-II allows both continuous ("real-coded") and discrete ("binary-coded") design variables. The original feature is the application of a genetic algorithm in the field of continuous variables.

5. *Utilized Software Programs*

5.1 FRIENDSHIP-Framework

The FRIENDSHIP-Framework is a CAE package for the design of functional surfaces. It offers a wide range of CAD functionality for conventional NURBS-modeling, partially parametric modeling with various transformations and fully parametric modelling.

This software comes with a set of embedded variation and optimization strategies. These algorithms can be comfortable linked to the geometry and perform automatic variant creation. For that purpose, comprehensive variant and constraint management are provided [19].

Any program or tool which is needed for geometry design and analysis can be coupled. Convenient integration mechanisms make the external program an inherent part of the FRIENDSHIP-Framework. By doing so, design and analysis expertise is centralized in order to streamline the design process. CFD solvers are coupled to the CAD through various levels of integration; tool- or project specific integration or by a common data interface. Therefore, results of CFD computations can be easily used as measures of merit for optimization procedures, driving the design process.

In addition to configuration and execution of external programs, comprehensive post-processing functionality is available. Result data gets visualized and tables are generated so that the entire design process finally takes place within a single workbench.

5.1.1 Design principles

A typical design procedure within the FRIENDSHIP-Framework starts with a fully-parametric model of the considered shape. During the geometry setup, objects are related to each other via introducing dependencies. Changes that are applied to one object are internally passed to dependent objects for update purposes. Surfaces are no longer described via basic point data. More intuitive descriptors (e.g. user-defined distributions which describe product properties) help to modify geometry smartly in a way that the resulting surfaces cover high fairness for geometrically feasible designs. Note that no “black-box” models are used, the engineer is completely free to set up any individual design. In the second step, parts of the geometry are linked to variation engines. Any floating-point number of the model setup can be varied. The user chooses a specific engine and defines bounds for variables as well as constraints and objectives. In order to be able to assess the manual or automatic variants, external software is coupled and configured. The engines simply evaluate parameters that request an external value. This transfers external data into the *FRIENDSHIP-Framework*. Based on this integration – along with parametric geometry variation – sophisticated formal optimizations can be carried out [19].

5.1.2 Basic elements

The FRIENDSHIP-Framework allows designing with a wide variety of point, curve and surface types. Curve intersection point, NURBS curve, lofted surface, Coons patch etc., are already known from other CAD programs and are fully-functional. Within the FRIENDSHIP-Framework there are some special entities, which make the software a unique fully-parametric CAD tool.

F-Splines allow the generation of fair curves with flexible (and possibly small) sets of parameters such as start and end points, tangents and area values (see section 2.5.3).

Meta-Surfaces are novel surface entities developed for collecting information available in two distinct directions. They yield the Cartesian coordinates of any point on the surface for any pair of surface coordinates u and v, basically giving an unambiguous mapping from 2 to 3 as would, say, Bézier or B-Spline surfaces, too. However, they are more flexible as they do not assume any particular representation with regard to the curves they capture.

5.1.3 Feature modeling

Features encapsulate any user-defined command sequence and that makes it available for writing macros and subroutines. They are high-level entities that can offer readily shaped and parameterised elements, as opposed to primitive elements like points, lines and "normal" curves and surfaces and represent specific work processes which can be stored externally and reused [19].

Features work on the base of an editor where the necessary input parameters and types are specified as arguments and then a process is described via commands. Thins script is finally evaluated and returns the produced output that makes up the feature’s attribute.

Features are flexible and can be combined with each other providing sophisticated objects. The advantage of this modelling technique is that complex geometries are stored in a library and can be produced with a little more than a click of the mouse instead of modelling them from the scratch every time which would take quite a while. On the other hand, the user has to be quite familiar with script writing, especially when difficult geometries and concepts are required [20].

5.1.4 Curve engine

The parametric geometric model is created using features as a basis for surface generation. More specific the methodology that is followed in the present project is that of defining within a feature an arbitrarily oriented cross section of the surface which is topologically described. As input data are used some parameters used which are easily perceived by a ship designer and there is no worry on mathematical representation as in traditional ship design. The definition so far refers to a two-dimension depiction of a section which varies according to the input parameters. Along a third axis a number of parameterised curved may be defined, which store the distribution of every input parameter along this direction. In this way and via the curve engine several cross-sections are generated at arbitrary positions within the range of the basic curves based on the template stored in the feature [20]. The Meta-Surfaces then uses this Curve Engine in a specified range.

5.1.5 Design engine

These entities enclose several variation-optimization algorithms, embedded in FRIENDSHIP-Framework, which are available for Design of Experiments, single-objective and multi-objective optimizations. To name some: Sobol, TSearch, NSGA-II, etc. Design variables are chosen from the project which shall be involved in the variation/optimization. For the most engines the lower and upper bound need to be set, as well as the current value. Then, the evaluations are chosen, which are parameters involved in the project. After the run, all these entries are listed in a result table with the corresponding value. The evaluations can be set as objectives which then are minimized. Equality or inequality constraints may also be involved. According to the underlying algorithm, these constraints may be considered or not [19].

5.2 SHIPFLOW

SHIPFLOW, the CFD program used in this work, is a commercial flow solver developed by FLOWTECH International AB in Gothenburg [21].

SHIPFLOW was developed as a pioneering effort to address the complication of fluid flow characteristics around moving objects both in fully submerged situation and in free surface situation.

Even though SHIPFLOW is intended specially for marine applications, it has also been extended to sufficiently solve closely related problems such as highly turbulent flow around automobiles.

Major areas in which SHIPFLOW has been found to be highly applicable include calculation of ship hull resistance both viscous and wave-related, development of wave profiles and sequential matters consisting of trim and sinkage characteristics, changes in velocities and pressure field around objects such as propellers. Some of these problems remain a challenge to researchers in order to produce more sophisticated CFD program to handle the complex phenomenon of fluid and object interactions.

To investigate the flow around a ship or ship model, SHIPFLOW splits the flow into three regions according to zonal approach, as described above.

SHIPFLOW uses the zonal approach in order to reduce computational time. The programming is split into six modules and SHIPFLOW considers each module at a time. The method is unidirectional, in other words the results of the last module do not affect, for example, the second module. These six modules are listed below, in the order in which SHIPFLOW assesses them.

5.2.1 Modules

XFLOW

Defines the general physical properties of the surroundings, for example the fluid, characteristics, initial ship position, ship speed, etc.

XMESH

XMESH is the mesh generator that creates panels for the hull and free surface for the potential flow solver, XPAN. If non-linear calculations are made XMESH will be called upon during the potential flow calculations to update the mesh between each iteration. XMESH is also executed when sinkage and trim is considered.

XPAN

While only considering the wave-pattern resistance, it seems to be reasonable to make several assumptions leading to the possibility to apply the potential flow theory. The working fluid, in marine application water, is treaded to be incompressible an isothermal, the depth of the water is not changing and the flow velocity is constant. Further on the flow is assumed to be steady and irrational which excludes all kinds of turbulence. Therewith and while using $\vec{q}$ as the disturbed velocity, it is possible to define a potential Φ that will satisfy the equations:

$$q = \nabla\Phi, \qquad \nabla^2\Phi = 0$$

XPAN computes the potential flow around the model (i.e. Zone 1) and free-surface, which are made up of quadrilateral panels each containing Rankine sources. XPAN can operate under linear or non-linear free-surface boundary conditions. Results obtained from XPAN are displayed by the post processor and listed in output files. The results include wave-pressure coefficient (C_W), wave-cut coefficient (C_{WTWC}) wave pattern, potential streamlines, pressure and velocity contours. The result from XPAN is stored in a database file required to execute XBOUND.

XBOUND

XBOUND is concerned with the thin turbulent boundary layer surrounding the hull (i.e. Zone 2). Using momentum integral equations SHIPFLOW provides the frictional resistance coefficient (C_F), boundary layer thickness δ, as well as other parameters associated with the boundary layer. XBOUND creates a database file required to execute XCHAP.

XGRID

XGRID creates the grid used for viscous computations in XCHAP. With XGRID it is possible to create grids for ship or submarine hulls and the module is capable of handling twin skeg hulls and bulbous bows. Appendages however are not possible to handle with XGRID.

XVISC

This module of SHIPFLOW solves the Reynolds-averaged Navier-Stokes equations (Zone 3). XVISC provides the viscous pressure resistance coefficient (C_{VP}) and therefore the total resistance C_T can be estimated. XVISC can also be used to investigate the wake and values such as axial, radial and tangential velocities at various planes towards the stern are obtained.

XCHAP

XCHAP is a module that using one of several available turbulence models (EASM, k-ω BSL, k-ω SST). XCHAP uses the grid generated by XGRID but it is also possible to import grids created by other software. By using this solver it is possible to get the time-averaged velocity, pressure and turbulent quantities. The total resistance can be computed by combining the results from XPAN, XBOUND and XCHAP.

5.3 MS-EXCEL 2007

Excel is a well-known commercial spreadsheet application written and distributed by Microsoft. It features calculation, graphic tools, pivot tables and a macro programming language.

Spreadsheets present an easy way of using a computer for a wide variety of tasks without having to write or purchase special-purpose programs. One advantage of using a spreadsheet is that a user will generally write the program himself and will therefore know exactly what formulae are included in his calculations and what confidence can be given to the answer [22].

5.3.1 Coupling with FRIENDSHIP-Framework

Component Object Model (COM) is an interface standard for component based development. COM in combination with the FRIENDSHIP-Framework is primarily used for integration of MS Excel or MS Word applications. The integration of COM objects usually takes place within Features. This provides a comfortable access to the integrated application and the integration can simply be reused in other projects. Excel integration follows the same procedures as writing macros in Excel with MS Visual Basic. The aim is to insert data from FRIENDSHIP-Framework into an Excel sheet for further elaboration and then to retrieve data from Excel into a table [19].

6. CASE STUDY- The E^4-Containership

In the following chapters a case study will be presented, combining the simulation of key measures of merit in the early phase of ship design. The integrated approach is applied on a novel concept regarding containerships. A complete preliminary research will be stated, where today's needs are identified, a conceptual solution is proposed and a multi-objective optimization is performed in order to meet the targets. What is fundamentally here presented is not only an innovative design, but also a pioneering methodology of holistic investigation of ship design at the early stage.

6.1 Introduction- "2011 VISIONS OLYMPICS" Competition- Set up the Design Problem

The work presented herein is developed based on the project "The E^4-Containership", which was submitted to the European competition "2011 VISIONS-OLYMPICS" and received the honorary distinction of being listed amongst this year's top 3 winners. The final ranking is until this moment unknown. The aim of this contest was to propose an innovative design, providing solutions to problems that arise in the current financial and environmental state.

6.1.1 Container transportation by ships

Liner services play a central part in the global trading network, carrying about 60 per cent of the value of goods shipped by sea. They provide fast, frequent and reliable transport for almost any cargo to almost any foreign destination at a predictable charge.

Container transport has obtained such a central role in world trade that the significant growth continues even through economic crises, as we have seen with the recent global financial crisis the last 3 years.

As of 2010 [23], container ships made up 13.3% of the world's fleet in terms of deadweight tonnage. The world's total of container ship deadweight tonnage has increased from 11 million DWT in 1980 to 169.0 million DWT in 2010. The combined deadweight tonnage of container ships and general cargo ships, which also often carry containers, represents 21.8% of the world's fleet. As of 2009, the average age of container ships worldwide was 10.6 years, making them the youngest general vessel type, followed by bulk carriers at 16.6 years, oil tankers at 17 years, general cargo ships at 24.6 years, and others at 25.3 years [23]. According to [24] a chart with the change in world TEU container fleet for period 1990-2014 is presented based on statistical estimation and a projected profile (see Fig. 6.1).

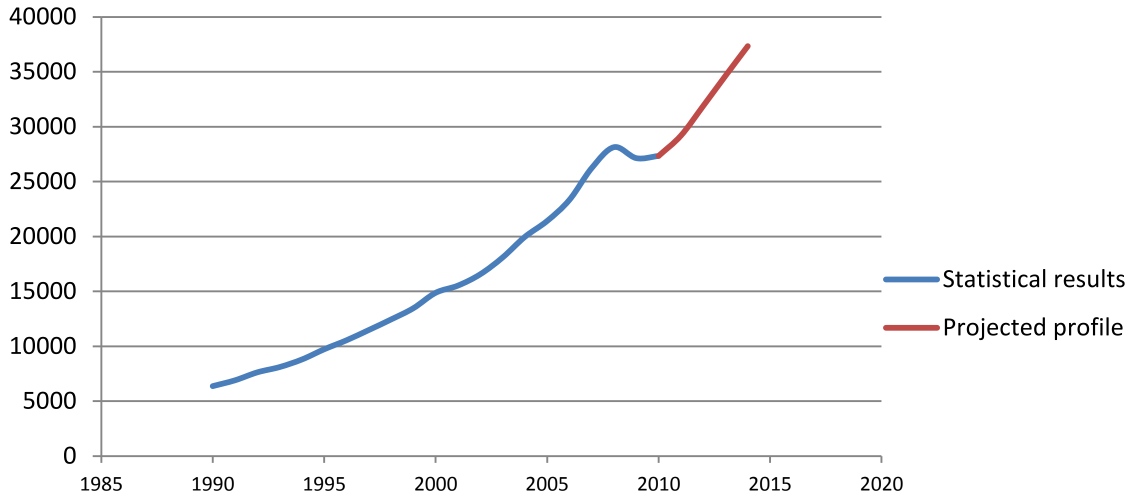


Figure6.1: World TEU container Fleet for Period 1990-2014

In recent years, oversupply of container ship capacity has caused prices for new and used ships to fall. From 2008 to 2009, new container ship prices dropped by 19–33%, while prices for 10-year-old container ships dropped by 47–69% [25]. In 2009 11,669,000 gross tons of newly built container ships were delivered. Over 85% of this new capacity was built in the Republic of Korea, China, and Japan, with Korea accounting for over 57% of the world's total alone. New container ships accounted for 15% of the total new tonnage that year, behind bulk carriers at 28.9% and oil tankers at 22.6%. In the Figure6.2 [24] are shown the container ships as a percentage of the top market.

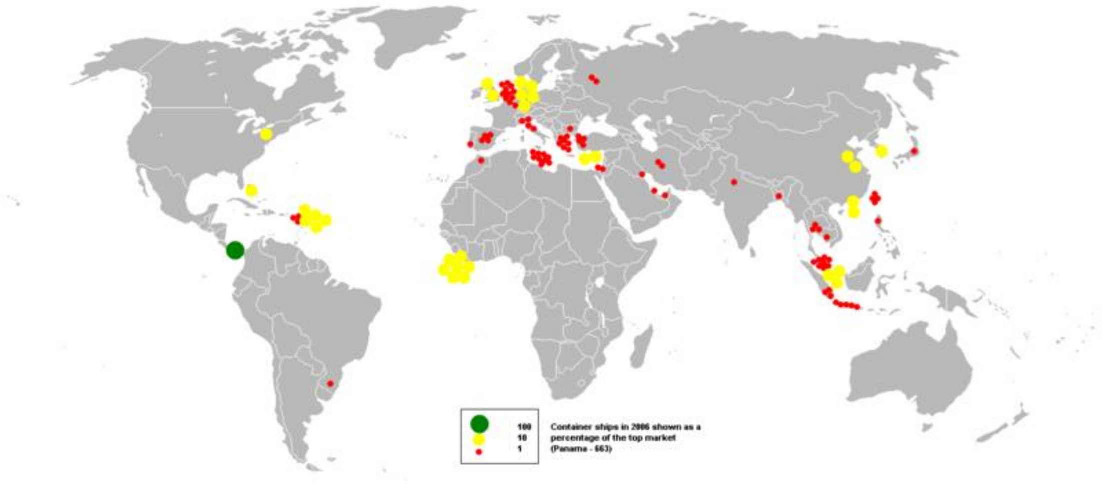


Figure6.2: Container ships as a percentage of the top market

The global economic downturn of 2008–2009 resulted in more ships than usual being sold for scrap [26]. In 2009 364,300 TEU worth of container ship capacity was scrapped, up from 99,900 TEU in 2008. Container ships accounted for 22.6% of the total gross tonnage of ships scrapped that year. Despite the surge, the capacity removed from the fleet only accounted for 3% of the world's containership capacity. The average age of containerships scrapped in 2009 was 27.0 years.

Liner companies responded to their overcapacity in several ways. For example, in early 2009, some container lines dropped their freight rates to zero on the Asia-Europe route, charging shippers only a surcharge to cover operating costs. They decreased their overcapacity by lowering the ships' speed (a strategy called "slow steaming") and by laying up ships. Slow steaming increased the length of the Europe-Asia routes to a record high of over 40 days.

In the present market situation, main engines will not be as much of a limiting factor for vessel growth either. The steadily rising cost of fuel oil has prompted most container lines to adapt a slower, more economical voyage speed, of about 21 knots, compared to earlier top speeds of 25 or more knots. Subsequently, new-built container ships can be fitted with a smaller main engine. Engine types fitted to today's ships of 14,000 TEU are thus sufficiently large to propel future vessels of 20,000 TEU or more.

6.1.2 Environmental issues

Considering the staggering percentages of world trade vessels transport (80%), it is remarkable to note that shipping is already the most environmentally friendly mode of transport and that emissions emitted from ships are small (3%). Operational pollution has been reduced to a negligible amount. MARPOL 73/78 is the most important set of international rules dealing with the environment and the mitigation of ships pollution. However, there have also been considerable improvements in the efficiency of engines, ship hull designs, propulsion, leading to a decrease of emissions and increase of fuel efficiency. The environmental footprint of shipping has been significantly improved through inputs from the marine equipment industry, which adopts a holistic approach when looking at the maritime sector. The equipment suppliers are a valued contributor and innovator within the maritime cluster. The shipbuilding sector encompasses the shipyards and the marine equipment manufacturers including service and knowledge providers. The European marine equipment industry is the global leader in propulsion, cargo handling, communication, automation and environmental systems [27].

Air pollution from ships has been at the center stage of discussion by the world shipping community at least during the last decade. Looking at developments at the International Maritime Organization (IMO) level, thus far progress as regards air pollution from ships has been mixed and rather slow. As the goal of environment-friendly shipping is high on the agenda of the IMO, the European Commission and many individual coastal states, reduction of emissions, both from greenhouse gases (GHG) such as CO_2 , and also from SO_x, NO_x , and other gases, is an important and urgent target.

Emissions from commercial shipping are currently the subject of intense scrutiny by the world shipping community and society at large. According to the Kyoto protocol definite measures to reduce CO_2 emissions are necessary in order to curb the projected growth of greenhouse gases (GHGs) worldwide. Shipping has thus far escaped being included in the Kyoto global emissions reduction target for CO_2 and other GHGs. But it is clear that the time of non-regulation is rapidly approaching its end, and measures to curb future CO_2 growth are being sought with a high sense of urgency. CO_2 is the most prevalent of these GHGs, and it is therefore clear that any set of measures to reduce the latter should primarily focus on CO2. Various analyses of many aspects of the problem have been and are being carried out and a spectrum of measures is being contemplated [6].

According to the results of IMO, the three most fuel consuming categories of ships (and thus, those that produce most of CO2 emissions) are Container vessels of 3,000-5,000 TEUs, Container vessels of 5,000-8,000 TEUs and RoPax Ferries with cruising speed of less than 25 knots.

The answer to why these three categories produce that huge amount of CO2 emissions is not the large number of ships – obviously not for the case of container vessels. Their common denominator is their high speed.

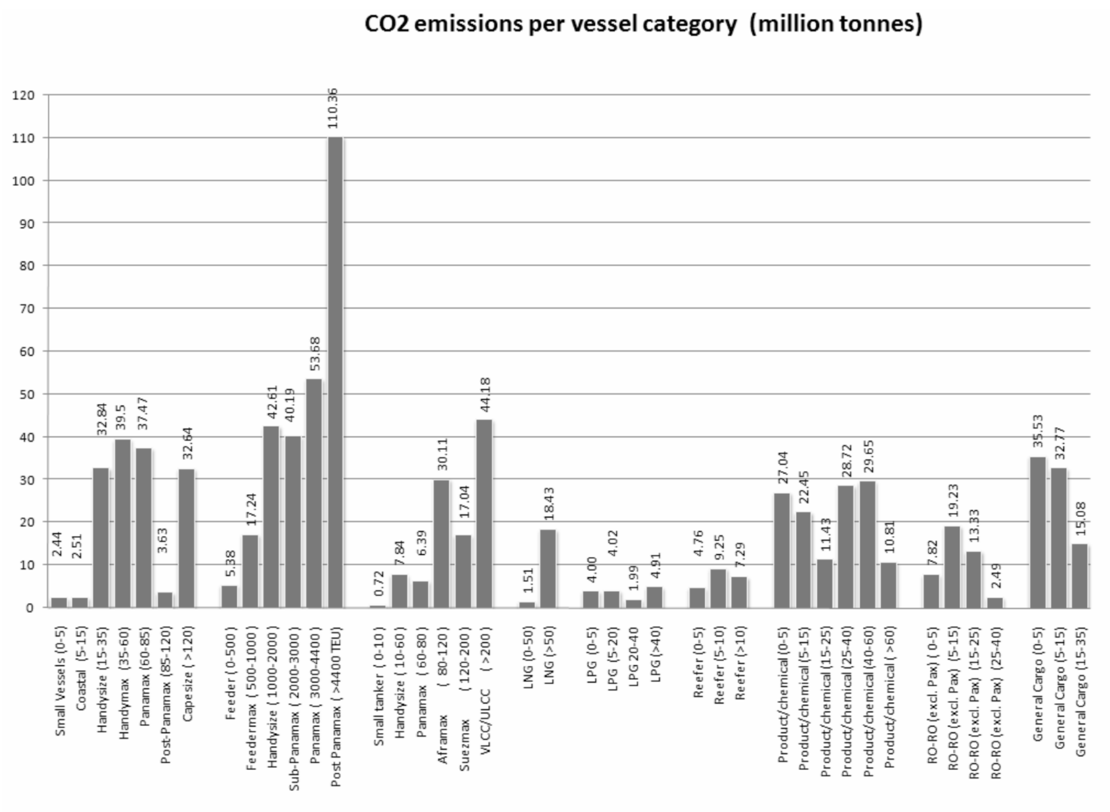


Figure6.3: CO2 emissions, world fleet (Psaraftis and Kontovas, 2009a)

6.2 *Review of research area*

With the significant improvement of the global market situation and the important shipbuilding capacity consolidation that took place during the past two years in Europe the major challenges that need to be faced during the next years are on the one hand the increased legislative pressure towards CO2 and NOx reduction, as well increasing fuel price requiring alternative fuels and reduction of fuel consumption. On the other hand the European shipbuilding companies need to meet financing challenges in a world of increasing trade which consequently results to higher transportation capacities.

European shipping industry is on the search for opportunities and ways out of the crisis but to do that, an overview of the current situation has to be done.

In a world where the population is growing fast, the trading blocks, together with new economies in countries like India, China and Brazil will increase in importance.

Many issues come up regarding energy sources, environmental impact and business trends [29].

- The energy-related threats that the world is facing are the inadequate secure supplies of energy and the cost of them. In addition, concern should be taken about the environmental damage which is caused by the increased energy consumption.
- Environmental issues are highly ranked and humanity must prepare for the consequences of the ongoing climate change and work together to slow down and reverse these adverse effects.

The growing numbers of consumers in emerging economies will have a great impact on global market and is a factor of uncertainty for the future.

The research areas that have been agreed by the VISIONS-Olympics-Team enclose all these concerns and expect feasible solutions and proposals that could have a positive influence on these matters.

<u>The E^4 Container Ship anticipates being an efficient ship that can increase the position of the European market and on the same time focuses on the minimization of its environmental impact.</u>

The research area that has been selected is the Green Logistics and the Energy Efficient Ship.

6.2.1 Green Logistics

There is growing concern over the impact of discharges to sea and ballast water management will be stricter, with new international requirements. Ship owners will be obliges to use Ballast Water Treatment (BWT) units on their vessels and that mean energy consumption and reduction of the payload.

<u>The E^4 container ship, based on its innovative hull form design requires a minimum amount of ballast water, almost 1/3 compared to a typical container ship.</u>

6.2.2 Energy Efficient Ship

As a consequence of increased fuel cost and the introduction of environmental taxes and legislation, shipping must become more efficient. In addition, stricter environmental regulations are pushing the shipping industry towards more environmentally-friendly designs and operations. Incentives for emission reduction for shipping, including emission trading schemes and tax mechanisms, will increasingly be deployed and a CO2 Emission Indexing Scheme is under preparation by IMO.

Taken all the above mentioned into account an innovative container ship design concept is proposed that achieves to reduce fuel consumption and emissions through ship design and optimization.

6.3 Review of literature

6.3.1 Slow Steaming

Most container ships trading today, and on order, were designed for a world of relatively low energy prices. Nearly all of the world's shipping lines are using slow steaming at least part of the time. Companies are more focused on reducing costs, not speed of delivery and the trend will continue even after the global economy comes back.

Slow steaming sees vessels pare back their cruising speeds from 22-25 knots to 18-20 knots, or in the case of extra slow steaming, as low as 8-12 knots. The practice caught on in 2008 when oil prices hit record levels and shipping operators' bunker bills skyrocketed. When the global financial crisis soon followed, and oil prices dropped, slow steaming survived, helping shipping lines to manage overcapacity as demand fell.

According to DnV [30] about 80% of the loops from Asia to Europe are currently slow steaming and that illustrates to what extent the industry has embraced the concept. The majority of the Asia–Europe services are running at speeds of 17–19 knots.

Maersk Line [31] reported that from 2007 to 2010 they reduced their CO2 emissions per container moved by 14.5 per cent by improving their operational efficiency, most importantly through the application of slow steaming, which alone has cut CO2 emissions by approximately 7 per cent in just 18 months. Slow steaming began as a cost-saving initiative in 2008 but is now a core operating principle of Maersk Line, in spite of the market turn-around in 2010. A typical 8,000-container ship traveling at 21 knots will burn 125 metric tons of fuel to go 500 nautical miles. The same ship will need just 80 metric tons of fuel to travel the same distance if the speed drops to 15 knots.

As the industry continues a sluggish recovery, slow steaming practices are here to stay because it cuts costs and lowers CO_2 emissions and that is where the pressure is going to build on ship operators in coming years.

According to the Lloyd's Register [32], there are technical considerations, when reducing speeds to below 20 knots, which means running at reduced power outputs. To ensure reliable operation from engines designed to run optimally at higher outputs, closer surveillance of engine performance and operating parameters, fuel quality, lube oil consumption and power-speed conditions will be required. For example, a relatively straightforward calculation demonstrates that, for a large container ship designed for 25 knots at 70,000kW main engine power, speed reduction to 20 knots would require just 50% power. Given that voyage time will increase as a consequence of the reduced speed, the fuel saving will be somewhat less, about 40%. So slow steaming can offer a large saving in fuel consumption; however, it can be calculated that total NOx emissions increase - by up to 40 tonne per voyage – when steaming between 20 and 25 knots.

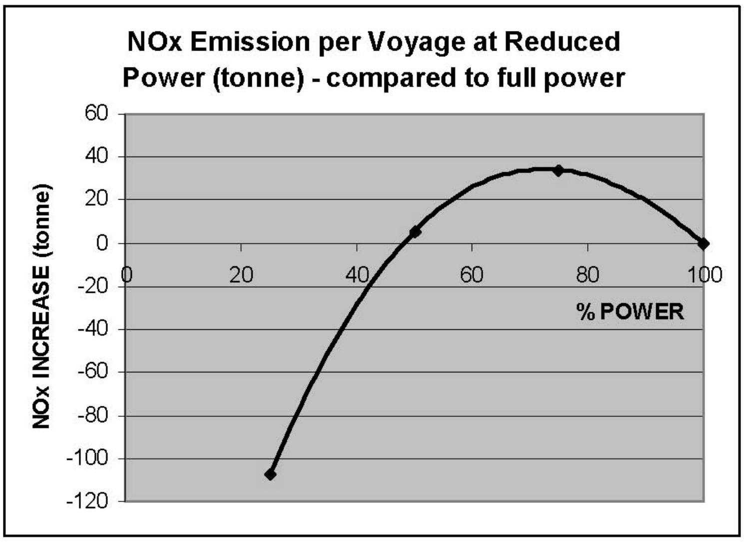


Figure6.4: NOx emission increase in tones per Voyage at reduced power compared to full power [32]

In addition it is a waste of capacity and a capital cost penalty to carry unused power potential. Factors to be taken also into account are:

- Possible loss of effectiveness of heat recovery systems.
- Loss of turbocharger efficiency.
- Loss of propeller efficiency.
- Fouling of hull and propellers due to reduced ship speed.
- Increased compensatory fuel consumption of auxiliary engines to supplement loss of heat recovery capability.
- Increased lubricating oil consumption.
- Possible increased vibration levels and detrimental effects.

6.3.2 Ballast Water Treatment

When dealing with ballast two are the main unwanted effects [33]:

- Ballast water contains organisms that can cause damage when released to different ecosystems; Invasive organisms can bring about changes to the marine flora and fauna and cause damage to marine industries such as fishing – this is a concern not only of environmentalists, but also of international society (recent IMO regulations)
- The additional fuel to carry the ballast water, while it is not part of payload – this is concern of the ship operator.

A conventional 90k DWT Containership in lightship condition will typically float with a mean draft of 3-4 meter- with the bow and propeller almost out of the water. For this reason ballast water is needed in order to increase displacement; besides, any conventional containership with a significant number of deck-containers will need to carry a substantial amount of ballast water as part of her deadweight in the design condition for keeping the vertical position of ship's mass centroid (and of GM) at acceptable levels.

According to the current legislation all ships have to be fitted with ballast water treatment systems [34]. There are various technologies currently available employing different methods such as, chemical treatment, heating, filtration, ultraviolet light, etc. The International Convention for the Control and Management of Ships' Ballast Water and Sediments also allows for the adoption of prototype technologies in certain ships if agreed upon by the IMO. There are effective technologies already in existence with the scope for further innovation and research. Removing organisms from ballast water goes a long way to ensuring that alien species do not invade fragile marine ecosystems [34].

The aim is to clamp down the transfer of organisms in ballast water –and the subsequent damage potentially caused by alien species entering unfamiliar regional ecosystems- by specifying that each tone of ballast water should contain less than 10 living organisms larger than 50 microns (μm) and that each tone must contain less than 10 such organisms of between 10-50μm per milliliter of ballast water.

The shipping industry will have to comply with these new regulations in the near future and that could happen in two ways. The first and more direct one is the ship owners to purchase ballast water treatment (BWT) systems for their fleet. That would mean a considerable initial capital for retrofitting and in the long terms great operational cost for maintenance and extensive energy consumption.

The second, more delicate solution –but still hard to apply on the spot– is to build vessels that require less or even no ballast. Efforts have already being done e.g. from the Shipbuilding Research Centre of Japan with remarkable results. The NOBS (non-ballast water ship) and MIBS (minimum ballast water ship) are the proposed designs and have been taken into consideration throughout this project. It is intended to design a vessel that could maintain adequate draft while in the unloaded condition in order to prevent bow slamming and propeller racing (immersion) without or with minimum use of ballast water .

The NOBS design contains a few flaws. In essence, the NOBS would employ a slanted V-shaped ship bottom but it was found that the design would result in a vessel with a far greater breadth and a narrow keel than conventional ship designs, raising queries about the practicality of building and operating such a vessel type- amounts of cargo would have had to be drastically slashed, making an unprofitable venture to say the least, while the narrow keel would have required special measures to be taken during construction and docking.

The innovative MIBS design that substituted the SRC's NOBS concept will reduce the amount of ballast water required by approximately 60-80% while increasing overall propulsion efficiency and reducing horsepower output by some 10% [34]. By cutting the amount of ballast water stored onboard, the MIBS design will also require fewer BWT units or at least the installation of smaller and less powerful units capable of thoroughly treating water while consuming less shipboard energy.

6.3.3 Energy Efficiency Design Index (EEDI)

The Energy Efficiency Design Index (EEDI) is conceived as a future mandatory instrument to be calculated and made as available information for new ships. EEDI represents the amount of CO2 in gram emitted when transporting one deadweight tonnage of cargo one nautical mile [35].

For container vessels, the EEDI value is essentially calculated on the basis of 65% of the maximum cargo capacity in dwt, propulsion power, ship speed, SFOC and fuel type. However, certain correction factors are applicable, e.g. for installed Waste Heat Recovery systems. To evaluate the achieved EEDI, a reference value for the specific ship type and the specified maximum dwt cargo capacity is used for comparison. The final calculation method of the EEDI and how to award compliance (or penalize non-compliance) has not yet been determined.

The main engine's 75% SMCR (Specified Maximum Continuous Rating) figure is as standard applied in the calculation of the EEDI figure, in which also the CO2 emission from the auxiliary engines of the ship is included.

According to the rules under discussion, the EEDI of a new ship is reduced to a certain factor compared to a reference value yet to be decided. Thus, ships built after 2025 is proposed to have a 30% lower EEDI than the reference line. This new regulation will compel ship owners to take the energy saving issue more seriously.

There has been an increasing interest in waste heat recovery systems and other systems to recover energy in order to reduce the CO2 footprint which will be a factor of great importance especially in the years to come considering also the continuously rise of fossil fuels price. Thus, EEDI is still at a very early stage so it is still under discussion and new proposals are rising up every day in order to result in a reliable energy efficiency index.

6.3.4 DNV'S QUANTUM

Innovative concepts for future containerships are envisaged in DNV's Quantum projects. Namely the Quantum 6000 and 9000 propose many novel features and some of them will certainly be found in future commercial designs. As a container ship of the future, it strives to achieve the aim of transporting more cargo with less fuel for a low impact on the environment. DNV follows the trend of slow steaming by reducing the speed and implements gas fuel combined with hull optimization resulting in high efficient designs.

6.3.5 NOBS-MIBS-QUANTUM

Our proposed E^4 containership concept is targeting similar goals like the NOBS-MIBS and QUANTUM concepts in designing an efficient ship with minimum environmental impact; however, in achieving the set goals we explored and implemented a variety of new ideas, which will be elaborated in the following. The Quantum and NOBS-MIBS projects should be used as good reference points (yardsticks) for our proposed E^4 designs.

6.4 Proposed solution

6.4.1 E^4 Concept

E^4 is an innovative containership with a view to the future of container shipping. It is the answer to the demand for slow steaming. In the long term the oil price is expected to remain high and there is also a steadily increased environmental awareness. Everything points to the fact that a tax on carbon emission will be probably introduced. With the rapid development of huge markets like China and India, a greater demand for transportations of goods comes from the East. After recognizing all these factors that define the current situation and foresee the next day we designed the E^4 containership which is hopefully a good solution and may provide an answer for the future demands. In the world of uncertainty it is a prudent strategy to be fully prepared to adapt to market changes and environmental legislation.

The E^4 container ship is a pioneer for its class since the whole design concept is tuned around a lower design speed range between 16-19 knots (the specified speed may change to a certain degree, in the range of +/- 10 to 15%, w/o loss of generality for the obtained results and findings.), perfectly matching the slow speeding era requirements. Adopting elements from traditional slender monohulls and from full designs of bulkcarries and oil tankers, E^4 is unique compared to any other existing container ship. The main goal of the E^4 project is to gain efficiency through hull optimization. A number of innovative design elements enable this vessel to transport more cargo while using less fuel, thus reducing its environmental impact.

The name of the project “E^4” stands for the words:

-Elliptic. Main characteristic of the hull is the elliptic midship section that is dominating the whole design and provides the ship with many green advantages.

-Efficiency. This ship is designed to carry more boxes than a conventional ship at a low freight rate.

-Energy saving. It is energy saving because it is designed to steam slower and the leading scope of this concept is to reduce the power needed via hullform optimization.

-Environmental friendly. Due to sophisticated design it has a very low carbon footprint identified on a very low EEDI and has a minimum need for ballast water.

The E^4 is a ship with features that are likely to be built based on current technology. The intelligent arrangement of the E^4 allows the future installation of power systems based on new technologies such as LNG or fuel cells without redesigning the plant.

6.4.2 Slow Steaming

Slow steaming is already established among the global fleet and as mentioned above it comes together with a number of complications. The E^4 tends to cover the possible future demand for slower ships and introduces some new concepts that can be adapted to future designs. This containership has been designed completely out of the typical speed range for its capacity, which is between 22 and 26 knots. The design speed of 19 knots has been selected as adequate speed at which the ship can be considered a “slow steamer”. At this speed the EEDI is definitely below the reference line, which means that it has a satisfactory CO2 footprint and also the liner can easily keep up with the schedule and remain competitive in the containership market.

Ship’s resistance is typically divided into viscous and wave-making resistance. Wave-making resistance becomes important when the speed and the ship’s Froude number increases. *Since the design regards to a slow ship (Froude number 0.15-0.18) more emphasis should be given on the reduction of frictional resistance that dominates the total resistance (about 80-85%) and that leads consequently to minimization of the wetted surface through optimization of the hull shape.* For this reason an investigation has taken place in order to find a midship section that reduces the submerged area for given volume. Finally, the ellipse seemed (and could be expected) to include all these characteristics and in addition, the elliptic section has excellent characteristics in ballast conditions since it provides less volume at low draughts.

6.4.3 Elliptic Section

For slow ships the aim should be to minimize the wetted surface as mentioned above. In this case the optimum midship area coefficient C_M is approximately 0.80. *When the midship section coefficient is significantly reduced provides the overall design with benefits according to Schneekluth since in the case of very broad ships, keeping C_M smaller leads to a greater decrease in the wetted surface, length of streamlines and resistance [8] and it also reduces the cross-flow drag.* Going back to the basics, it is obvious that the circle is the plane curve enclosing the maximum area for a given arc length (C_M=0.780). But the circle’s ratio B/T equals to 2, something that is not feasible at least among large containerships. The next best option is the ellipse. In the following paragraphs a brief description of the ellipse will be presented.

An ellipse (from Greek ἔλλειψις - *elleipsis*) is a smooth closed curve which is symmetric about its horizontal and vertical axes. The distance between antipodal points on the ellipse, or pairs of points whose midpoint is at the center of the ellipse, is maximum along the **major axis** or **transverse diameter**, and a minimum along the perpendicular **minor axis** or **conjugate diameter** [36].

The **semi-major axis** (denoted by *a* in the figure) and the **semi-minor axis** (denoted by *b* in the Figure6.2) are the half beam and the draught of a ship, respectively in the language of naval architecture.

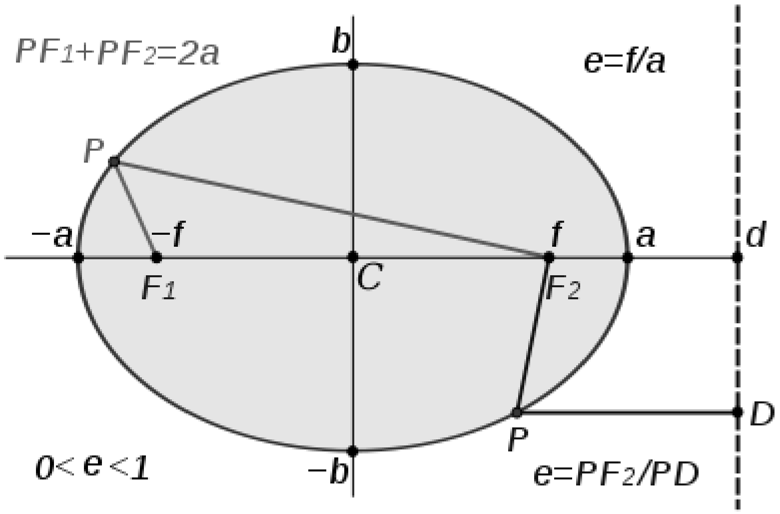


Figure6.2: Ellipsis definition

The eccentricity of an ellipse, usually denoted by *ε* or *e*, is the ratio of the distance between the two foci, to the length of the major axis or $e = 2f/2a = f/a$. For an ellipse the eccentricity is between 0 and 1 ($0<e<1$). When the eccentricity is 0 the foci coincide with the center point and the figure is a circle. As the eccentricity tends toward 1, the ellipse gets a more elongated shape.

Eccentricity should be carefully investigated since it can conclude in opposite results than expected regarding the minimum perimeter for specific enclosed area. In this project an eccentricity of 0.79 has been decided after the optimization process which gives remarkable results as it seems in the following comparisons.

The area enclosed by an ellipse equals to π*a*b and the circumference C is: C=4*a*E(e) , where again e is the eccentricity and the function E is the complete elliptic integral of second kind. In this project though, the circumference of the ellipse is calculated automatically from the design program.

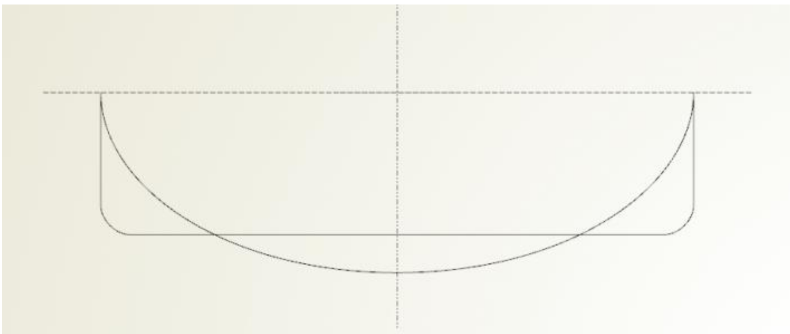


Figure6.3: E4-Conventional. Same Area and Same Beam

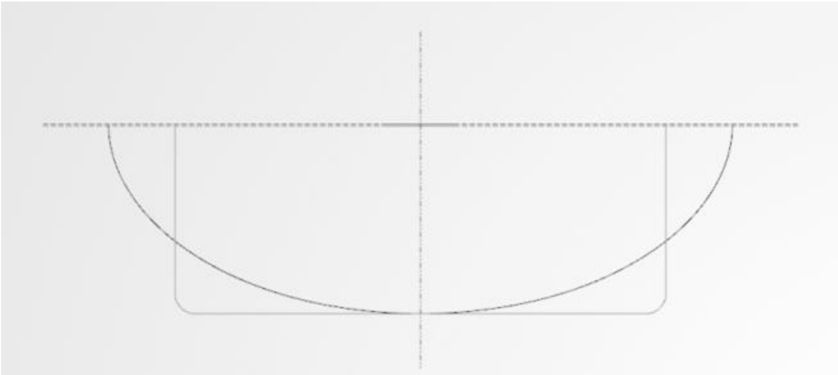


Figure6.4: E4-Conventional. Same Are and Same Draft

In Figure6.3 and Figure6.4 the elliptic section is compared to the conventional. As can be seen it has reduced arc length for the same enclosed area. The transverse center of buoyancy is higher and that means that for low drafts less volume of water is displaced.

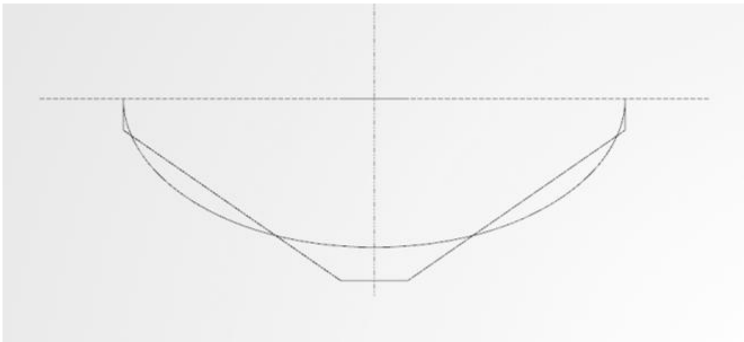


Figure6.5: For same Area and same Beam

As seeing in Figure6.5 the NOBS cross section dominates regarding ballast water requirement but for same enclosed area it has definitely larger arc length. In the case of containership the smooth ellipse permits a better distribution of cargo. Elliptic section allows a smoother distribution of containers leading to reduced center of gravity (VCG) compared to the NOBS and that is significant in the case of containerships where stability issues are high ranked.

The MIBS cross section can be considered almost identical to an ellipse approaching the min length for constant area enclosed. Nevertheless ellipse incorporates more efficiently the box-shaped settlement of cargo allowing lower KG values.

At low draughts the elliptic hull displaces less water than conventional which means that the ship spends less energy on carrying ballast when travelling unloaded. In addition, less Water Ballast Treatment (BWT) units are needed in order to comply with ballast water requirements.

Ellipse seems to be a good combination of the known V- and U-shaped midship sections

Nevertheless -nothing can be flawless- the ellipse as a main choice for hull design has some drawbacks too. It is common sense that a box-shaped hull facilitates the placement of the boxes utilizing the most possible space. But in this case the beamer design compensates the loss of TEU's in holds since more cargo can be loaded on deck. In addition the speed of loading/unloading is higher because it takes less time to deal with the containers on deck rather than in holds.

Another disadvantage of the elliptic section is the reduced damping ability along the longitudinal axis rendering it vulnerable to rolling motions. However, there are ways to address this issue using anti-rolling tanks, bilge keels, or even retractable anti-rolling fins.

Ellipse seems to be a promising feature and therefore it has been selected for the current design.

6.4.4 Propulsion and Machinery

The propulsion of E^4 is provided by an azimuth podded system. Due to the azimuthing propulsion its maneuverability is excellent; it saves space inside the vessel hull because of the lack of an axial system and gives a lot of freedom for ship design and inside arrangement. The installation of azimuth propulsors means simpler hull form and structure and far easier machinery installation. Fewer sub-suppliers, less parts and large saving in weight and space are all elements that have significant effects on construction time and cost. This system eliminates the need for aft thrusters and a rudder, thus it contributes to the minimization of wetted surface and additionally improves the performance in shallow draught conditions.

For the E^4 container ship two **Azipods** of series XO2100 by ABB are selected [37]. The diameter of each propeller is decided to be the larger one offered by this type, namely 6.4m. This decision is based on the fact that a large propeller diameter with low blade area ratio and fewer blades, give a high efficiency.

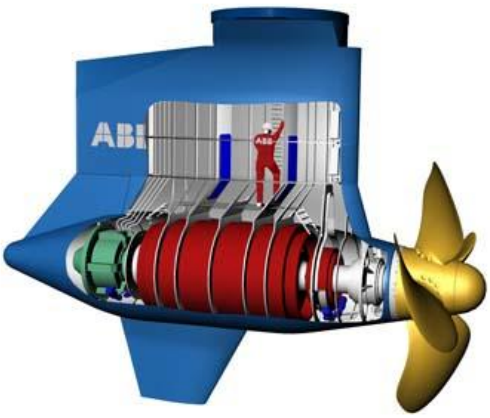


Figure6.6: ABB's Azipod [37]

Diesel-Electric Power Plant

The electrical-driven Azimuth Pods are powered by a diesel-electric plant. In general the advantages of diesel-electric propulsion can be summarized as follows [38]:

- Lower fuel consumption and emissions due to the possibility to optimize the loading of diesel engines / gensets. The gensets in operation can run on high loads with high efficiency.
- High reliability, due to multiple engine redundancy. Even if an engine / genset malfunctions, there will be sufficient power to operate the vessel safely. Reduced vulnerability to single point of failure providing the basis to fulfill high redundancy requirements
- Reduced life cycle cost, resulting from lower operational and maintenance costs.
- Improved maneuverability and station-keeping ability. Precise control of the electrical propulsion motors controlled by frequency converters.
- Increased payload, as diesel-electric propulsion plants take less space.
- More flexibility in location of diesel engine / genets and propulsors. The propulsors are supplied with electric power through cables. They do not need to be adjacent to the diesel engines / gensets.
- Low propulsion noise and reduced vibrations.
- Efficient performance and high motor torques, as the system can provide maximum torque also at slow speeds, which gives advantages for example in icy conditions.

6.5 Address potential technology gaps

The E^4 proves its feasibility throughout this report. Although there are still some important issues that are unsolved or may cause trouble in the whole design.

As mentioned, ellipse is a basic element of the E^4 containership and is considered to have many advantages. There still exists though the problem of seakeeping that is undiscovered by this project. Because of the fact that so big vessels of this shape are not yet manufactured we cannot tell to what extend the ellipse affects negatively the seakeeping. It is a matter of facts that the vessel cannot damp so efficiently to roll movements but the anti-rolling tank system that is installed reduces the impact to great degree.

Anti-roll tank systems operate on the principle that a fluid, usually water, moves from one tank to another and generates a moment on the ship that counteracts the motion. These two tanks are located as far out on the beam of the ship as possible to give the largest moment arm possible.

They are preferred because of their great efficiency and furthermore because they are not increasing the wetted surface of the hull –like fins and bilge keels do- and this is something crucial for our survey.

The active anti-rolling tank, nevertheless consume energy in order to operate. But the characteristic elliptic section may proof beneficial regarding the energy demand of this system.

If we install the active anti-rolling tanks along the parallel body where the hull shape is clearly elliptical, the transverse moving water will flow in an elliptic orbit which means that there will be reduced energy losses. We may take advantage of this smooth flow by adjusting a double pole hydroelectric pump on the bottom of the ship in the midway of the anti-rolling tank so that we can regenerate a part of the energy used to activate the system.

Another disadvantage of the E^4 is the big amount of curved surfaces. Because of the lack of flat sides more manufacturing work has to be done. And that is translated also into building cost raise.

On the other hand the E^4 has a long parallel body in contrast to a typical containership which means that for 1/3 of the vessel only one design pattern will be needed. In addition there is a lack of skeg which takes normally a long time to shape.

There should definitely be a further investigation in this design but on a first glance the E^4 containership seems to be very promising.

6.6 *Designing the E⁴-Containership*

Due to the fact that a containership like E^4 has never been designed before, it was impossible to estimate its main particulars based on similar vessels. For this reason the investigation of the hull shape should start from the scratch. The modeling technique is based on parametric curve generation and automated optimization of bare hull.

As a basis for our conceptual design a maximum beam at the new Panama dimensions is assumed, namely 49 m and a design speed between 16-21 knots so that the vessel becomes a “slow steamer”. Moreover the contemporary trend of moving the superstructures forward is taken to the limits by placing it over the fore peak providing the design with many advantages, like the increased and homogenously distributed cargo on deck and better visibility. Consequently two engine rooms are established, one is set aft near the azipod room to provide the propulsors with sufficient power and the second is installed below the deckhouse to serve the rest power demands of the ship and crew. The design speed determines definitely the fullness of the hull, the shape and the main dimensions. The task is to obtain the best possible combination of them. By a beamer design accommodating ellipsoidal midship section what is expected is a lower C_M leading to reduced wetted area and increased stability allowing more container stowage on deck. As a result, reduced demand on ballast water and power are achieved leading to a greener product with low EEDI.

6.7 *Set up of the optimization model*

To investigate and develop innovative solutions, the designer requires a tool that does not enforce detailed definition and allows easy reconfiguration of arrangements and systems. Looking at the case of a novel containership, a CAE environment is established to examine key measures of merit for a considerable numbers of variants simultaneously: Geometry, lightship weight, payload, capacity, stability and hydrodynamics were computed by means of simulation codes.

In the case of this diploma thesis, the definition “optimization model” implies a whole system that is built up by several subsystems in order to approach the design of a novel containership in a holistic way. The target of this holistic approach is to create a fully parametric model able to vary in a wide range of dimensions and form parameters and to return a large number of valuable information predicting numerous features and properties of the subject. Further on an optimization process takes place in several steps based on the collected data, obtained from a large number of design variants.

Based on simulation driven design the designer is able to handle as many issues as possible simultaneously. Obviously this is not a trivial task, therefore a number of assumptions have to be made and the design problem has to be viewed by specific perspectives, in order to define the boundaries and the targets of the investigation. The main idea is to set up a large flexible model that is able to predict automatically and accurately a large number of properties regarding geometry, weight, stability, resistance and capacity. Therefore a number of specialized tools and semi-empirical methods have been integrated that allow a thorough insight and increase the efficiency of the results. Thus, a numerous designs are achieved quickly and accurately that enable comparisons and optimization.

In this chapter all subsystems and their effects are described individually. First to come is the geometric parametric model, which is the core of the project and is developed with fully parametric definition within the FRIENDSHIP-Framework. When the geometry is determined some important characteristics of the vessel, regarding the hydrostatic and hydrodynamic respond and the container stowage are derived utilizing integrated as well as newly developed for the need of this projects, tools of FRIENDSHIP-Framework. All the necessary data are exported to MS-EXCEL for further analysis. Excel performs a number of automated computations within parametric spreadsheets based on semi-empirical methods and valuable information returns to the optimization environment of FRIENDSHIP-Framework. . The integrated semi-empirical methodologies that are later on explained in detail, regarding weight and resistance prediction function under several conditions, so conditional programming within Excel, as well as in FRIENDSHIP-Framework, is necessary. The term conditional programming refers to conditional expressions which perform different computations or actions depending on whether a programmer-specified Boolean condition evaluates to true or false. Last but not least is the activation of an external CFD calculation, resulting in comparison-worthy resistance estimations and allows interesting visualization of wave patterns and pressure distribution along the hull.

The optimization model has been developed through two main phases. The first, during the preparation for the submission of the project E^4-ContShip to the academic competition Visions-Olympics 2011 and the second phase took place during the internship at Friendship Systems and was a further investigation, integrating CFD codes and several sophisticated features. This differentiation will be mentioned from now on, since there are significant improvements.

6.7.1 Parametric geometric model

The hull form is developed within the FRIENDSHIP-Framework as a fully parametric model and in any case it forms the fundamental basis from which various kinds of information are obtained. Due to the fact that a containership like E^4 has never been designed before, this new design deviates considerably from any available parent. For this reason the investigation of the hull shape should start from the scratch. The modelling technique is based on parametric curve generation and automated optimization of bare hull. The properties that characterize the uniqueness of the hull form in this project are:

- The adaption of fully ellipsoidal mid-ship section until design draft.
- Global dimension limits set by new Panama Canal (T_{max}=15.2m, B_{max}=49m, L_{max}=366m).
- Lack of Flat of Bottom (FOB).
- Reduced Area of Flat of Side (FOS).
- Range of design speed between 16kn-21kn.
- Implement of twin azimuth propulsion that leads to no or reduced need for a skeg.

The model is divided into fore-body, mid-ship body and aft-body. While the aft-body and fore-body are created using Meta-surfaces, the mid-ship body is a simple ruled surface for connection. For the hull shape definition some basic curves for representation of points, tangents and integral values are employed. The basic curves depend on global parameters such as beam and height and local parameters such as flare, which influence only local characteristics. These basic curves are created as a combination of Lines and F-Splines and their form is specified by controlling start-, end- position and respective tangents as well as specific areas between the curve and a reference axis. The definition curves which are employed in order to build up the meta-surfaces, utilizing the curve engines are also a combination of Lines, F-Splines and B-Splines following the same process as the basic curves. Within the following chapters a detailed description of the parameterization and geometry definition is given. The center of the coordinate system is set to the aft perpendicular with x pointing forward and y pointing to portside.

Name	Description
beam	Beam of the ship
draft	Draft of the ship (trim=0)
height	Height of the deck
i(Bays)	Number of bays along L_{cargo} defining L_{BP}
xParAft	x position of aftbody end (begin midbody)
xParFwd	x position of forebody begin (end midbody)

Table6.1: Global Form-Parameters

The model is initially controlled by a set of global parameters such as draft, beam, length between perpendiculars, length of parallel body, which are described in Table 6.1. There are also some more specific parameters regarding the aft- and fore- body and they are described in the respective sections.

Fore-body

The fore-body is realized using an F-Spline from bottom until draft design, associated with a B-Spline from its end point until deck. Two Meta-surfaces which are smoothly connected to each other derive from these two planar definition curves and are developed along x-axis, that begin at the fore position of parallel mid-ship body and their definition is set to end at fore peak perpendicular. In fact the lower surface (WET) of the fore-body end up sooner, so there is some space for a smooth surface connection between main hull and bulbous bow to take place. The upper surface (DRY) ends up at fore perpendicular, where some work needs to be done in order to shape the stem region. The start point of the lower curve of the cross section definition is given at every x-Position by the Center plane curve (CPC) while the end position is set by the design water line curve (DWL). The start tangent is given the value zero as a follow-up of the elliptic definition of the mid-ship body. At DWL height the parameter for end tangent is given by a flare curve which begins with 90 degrees at the end x-position of mid-ship body and then it differentiates so, that favourable hydrodynamic characteristics are obtained. For the fullness of the wet part a definition of sectional area curve is being used. Start position of the SAC is automatically determined by after hull part. The upper cross section is determined by DWL at start position and Deck line at end position, while the transverse angle at both positions is defined by flare curves DWL flare and Deck flare respectively. As a B-Spline, the upper part needs a special treatment, so two additional points are implemented in between and their coordinates are given by parametric tangential definition, where also a distance factor has to be given.

Bulbous bow

The bulbous bow is a separate surface body which is designed based on Kracht analysis. It consists of a wide variety of parameters, but in this case study only some main characteristics will be examined namely, beam, length and height of bulbous bow at the fore perpendicular. The overall shape is formed in a way so that the streamlines created around the bulb are as smoothly transited to the main hull as possible. In other words, the designed bulb has to face a number of arbitrary designs and it should respond smoothly without attaching to the whole design favorable characteristics, but also it should not provoke much deteriorated hydrodynamic response. The bulb is primarily created at the origin of the coordinate system and then translated to the proper position, namely at the fore perpendicular. Between the fore-body and the bulbous bow a fillet surface [19] is created. This part is the weaker of the whole design since its creation depends only on the edge positions of fore- and aft- surfaces and the derivative tangential information at these positions in two dimensions of surface development. In order to achieve the less negative effect of such a weakness and due to the fact that the range of geometry variation is pretty large, a dependency between the main hull part and the bulb is created. This refers to the beam and height of bulb which respectively depend on end position of fore-body beam (ratio) and draft.

Aft-body

For the aft-body design, several alternative approaches have been browsed. The basic assumption that affected the final form of the aft-body are the twin-srew propulsion, namely two Azipods of max propeller diameter= 6.4m, the ellipsoidal mid-ship section where the aft body derives, the lack of skeg (potential implementation of a skeg in order to optimize the stream lines along the aft body is possible though without defective influence on the total design and the aim of reducing the W.S.), the lack of axial system. The requirements that such an aft-body has to meet are mainly the reduction of WS, smoothening of stream lines leading to hydrodynamic benefits, the ability to increase/reduce the waterplane area and the L_{WL} with the less possible transom immersion. Finally, the aft-body should comply with the overall character of this project, which is the holistic approach that should facilitate a quick and adaptive modification of the aft-body by changing and controlling global parameters mainly. The design of the aft-body is pretty easy, yet capable to adapt with low sensitivity to a wide range of geometric modifications. The basic curves that control the surface creation are a CPC a FOS, Deck line. The cross section that is defined by these curves follows the pattern of the mid-ship body, adapting the fully elliptic form, where an F-Spline from CPC to DWL attributes fullness according to ellipse area function and from FOS to Deck with a vertical line.

Characteristic points that play significant role on the form and the properties of the design are the aft positions of CPC and FOS, which define an ellipse and are able to move vertically so that immersion of transom and fullness of aft water plane area are controlled in order to achieve a favorable combination of stability, loading, capacity, hydrodynamic response.

In the object tree, all constructive data are stored in a scope under the name “Factory”. The global and local parameters which are involved in the optimization process are stored in a distinct folder under the name Parameters.

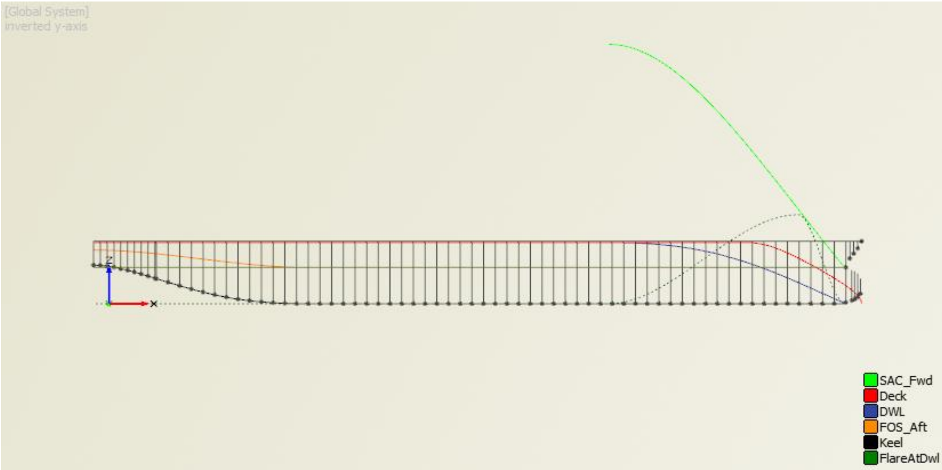


Figure6.10: Longitudinal basic curves on XZ-plane.

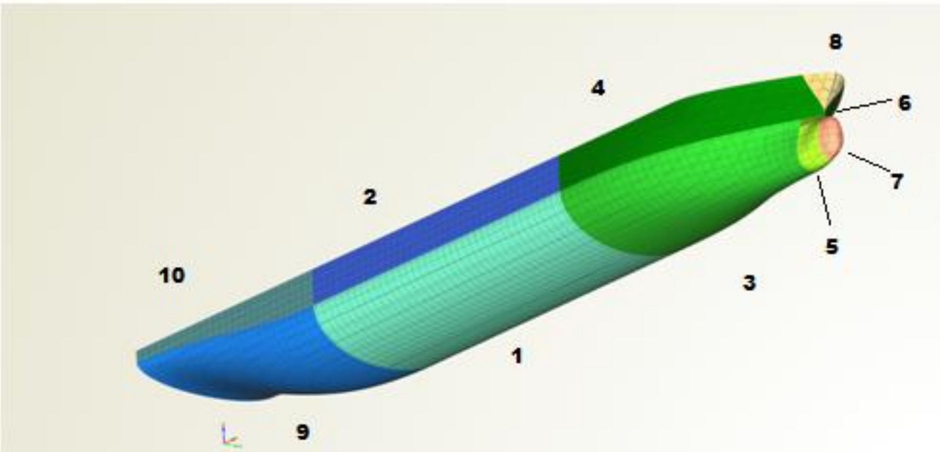


Figure6.11: Set of surfaces interpolating the design sections

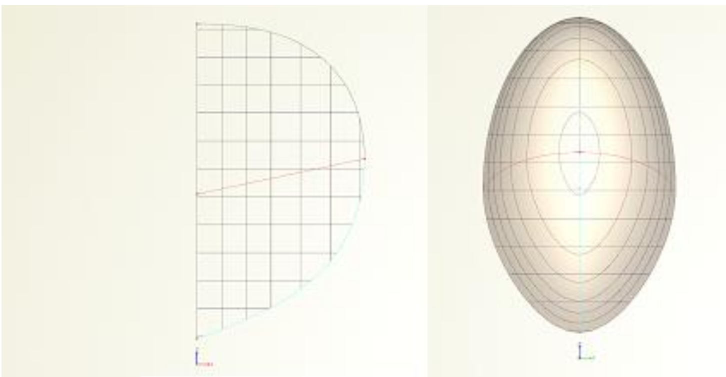


Figure6.12: Bulb generation at origin.

In Table 6.2 a summary of all positional, integral and differential curves used to produce the parametric model are shown.

Basic Curve	Description	Associated Form-Parameters
DWL	Design Waterline	fullness, tanAtFP, xParFwd
Deck	Deck-line	Fullness, xBeg, xEnd,
SAC_Fwd	Section Area Curve	areaAtFP, tanAtFP
FlareAtDWL	Flare at DWL	flareAtFP, xMaxFlare, MaxFlare, tanAtFp
CPC	Center Plane Curve	xAftPeak, zAftPeak, xParAft, tanAtxAftPeak, fullness
FOS_Aft	Flat of Side	xAftPeak, zAftPeak_factor

Table6.2: Basic curves and associated local form-parameters

In Table 6.3 a summary of all surfaces used to produce the parametric model are shown. (See also Appendix A.)

No.	Surface Name	Description
1	MidBodyBelowDWL	F-Spline from CPC to DWL.
2	MidBodyAboveDWL	FLine from DWL to Deck
3	ForeBodyBelowDWL	F-Spline from Keel to DWL.
4	ForeBodyAboveDWL	B-Spline from DWL to Deck
5	Fillet	Fillet between 3 and 7
6	TopFillet	Coon patch
7	MovedBulb	FSplines
8	StemTube	Fillet between 4 and Stem Contour
9	AftBodyBelowFOS	Fspline from CPC to FOS_Aft
10	AftBodyAboveFOS	FLine from FOS to Deck

Table6.3: Global Form-Parameters

6.7.2 Hydrostatics

The calculation of the hydrostatic quantities of every design is realized within the FRIENDSHIP-Framework based on an embedded computation for a given configuration. The configuration receives as input the hull in form of offset groups through a mechanism of automated adaption. Usually 3-4 offset-groups are enough regarding the complexity of the design. It is recommended to create a single offset-group for bulb, main hull and stern respectively as a default option. An offset-group assembles the created cross section of the involved bodies in the form of offset data which are parametrically defined according to variation. Additionally, the sinkage and heel of the vessel are required input as well. In this case no heel is considered. When the configuration is ready the FHydroComputation [19] is triggered which returns a table with all basic hydrostatic quantities for every separate offset group that can be shown in the following exemplary table, where explanation is included. Further properties that derive from hydrostatic calculation such as coefficients KM, BM etc are manually defined and are automatically updated for every computation. An illustration of SAC and of the submerged body in the form of section is also given, pointing out the position of LCB and LCF. In the case of the ellipsoidal containership investigation two conditions are examined hydrostatically, full load condition at Draft design, which is also one of the global variables later on and the ballast condition. Another important quantity is the estimation of the wetted surface, which is also set as a main objective in our optimization problem. For this estimation an appropriate feature, embedded in FRIENDSHIP-framework is used. This feature executes the computation of the wetted surface for a given section group at specific draft. For this feature a section group of 90 sections that derive from the hull body, is utilized, returning an accurate wetted surface estimation. In the following pictures are presented some illustrations of the hydrostatic properties and the SAC.

All these properties are stored in the folder "Hydrostatics".

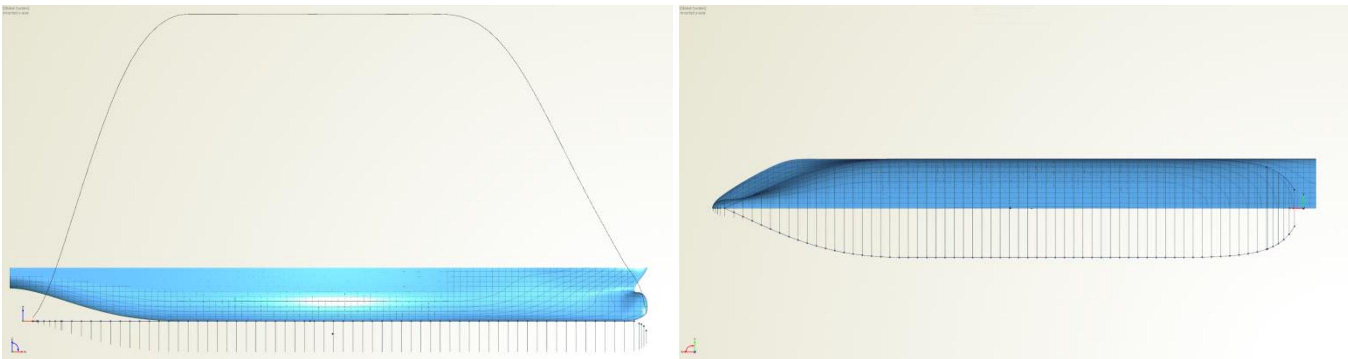


Figure6.13: Profile and top view of hydrostatic properties.

6.7.3 Arrangement and dimensioning within the hull

The global parameters of the model are tight bound to the specific purpose of the vessel. In this case the length between perpendicular L_{BP}, breadth B, draft T and height D are attributed as global parameters. All four are associated with the optimization process and are close connected with the arrangement of container since a specific number of TEU's has an integer value of breadth, height and beam and the "housing" ,in that case the hull, has to comply also with other aspects like the hydrodynamic response and safety. Beam, height and draft are in the following chapters arbitrarily defined and the interaction between these factors and some objectives is evaluated. On the other hand, the length definition is stricter and a description of the arrangement within the hull longitudinally is presented:

$$L_{BP} = L_{aft} + L_{ER} + L_{CARGO} + L_{fore}$$

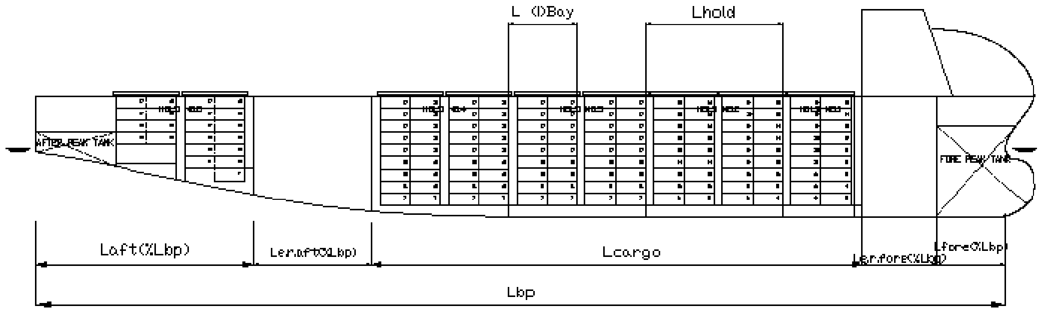
L_{aft}: length aft of Engine Room, including the length of one hold plus the length of aft peak tank. (%L_{BP})

L_{ER}: Engine room length (aft&fore). (%L_{BP})

L_{cargo}: length of cargo subdivided in bays ([number of bays] X[bay length])

L_{fore}: fore peak tank length according to regulation (%L_{BP})

For a given number (i) of bays, where bay is assumed the length of two TEU's plus margins (2xi=1 hold).



Based on this configuration, the Length between perpendiculars (L_{BP}) is defined directly by the desired number of bays along L_{cargo}.

6.7.4 Parametric stowage calculation

In order to run an integrated approach for simulation driven design in the early stage of a containership, it is of crucial importance to take into account as much of the key aspects as possible and additionally to achieve a good level of accuracy. When designing a containership at an early stage, the estimation of the payload characteristics is not as easy as in bulk carriers or tankers due to the complex arrangement of containers within the bays. So if the number of TEU's , the payload per container and the stability are necessary to be considered for every variant of an optimization process, then the right tools have to be developed. In this project two approaches are established. The first one is based on excel spreadsheets and geometrical elements import via COM integration and the second one is fully defined within the FFW based on a sophisticated algorithm.

Approach A: Stowage Calculation with Excel

A parametric box stowage tool is developed in order to monitor the number of boxes and to retrieve information about stability such as the center of gravity of containers for homogenous of different weight distribution (See Appendix B). The parametric excel sheet functions based on the following method:

It collects data that represent the geometry of the hull within the L_{cargo} at the x-position of every bay, as defined formerly in order to export them to EXCEL-sheet in a tabular form. Afterward these data are further elaborated, namely a minimum double distance is set so that the maximum number of containers at every x- and z-position that fits in the selected breadth and height to be estimated. Then, the bottom position of Containers' on deck is mathematically defined, where a minimum hatch thickness of 0.5m is included. This parametrically defined spreadsheet has the following form where the number of TEU's at every tier and bay is available for further elaboration, namely to calculate the center of gravity of Payload in hold and on deck. An illustration of the parametric excel sheet may be found in Appendix A.

Approach B: Stowage calculation with TEU feature

This parametric tool serves generally the same scope as the one presented previously. The difference stand in the fact that an automated procedure for container calculation and arrangement prediction has been developed within the FRIENDSHIP-Framework, allowing the method to save time, since an external calculation featuring excel sheets is more tedious. An elaboration of this feature is presented also in Appendix D, where also further information about capabilities of the created feature is available.

6.7.5 Weight prediction

Lightship

The most precise prediction of the several weight groups of a ship, as well as the center of gravity of these, is a several step in preliminary design phase as also in the final stage. If there is a severe miscalculation of the vessel's lightship weight, the attained deadweight capacity will be significantly violated. Likewise, speed, resistance, stability and more importantly safety will have to be reconsidered and redesigned in such a case. Hence, the more accurate the weight groups prediction in the preliminary design stage, the safer is the proceeding in further design phases [39].

Displacement Δ of the ships is decomposed as:

$$\Delta = W = W_{LS} + DWT$$

Where:

Δ =Displacement

W =Total weight

W_{LS}=Lightship

DWT =Deadweight

$W_{LS}$is further split into the ship's steel weight (St), the outfit weight (OT) and the machinery weight (M):

$$W_{LS} = W_{St} + W_{OT} + W_M$$

By far the greatest part of the hull weight is made up by the steel weight. For this reason, more precise weight calculation methods are applied to better determine this quantity. One way of prediction is based on semi-empirical methods which is very popular among the designers, when it comes to conventional ships. Another approach is with the help of construction-oriented software such as POSEIDON of GL, but this requires greater experience, is more time consuming and as mentioned above, special software is cost-effective and computing power demanding. The first approach complies with the purpose of a preliminary design but the second is of course necessary in further stages. The method, utilized in this containership project was developed by Schneekluth (1972) and takes special care of the type of the vessel. It is the only acknowledged method for containership's weight initial prediction which takes into account several properties of the vessel although it has as reference conventional ships. The advantages over other methods are [9]:

- Provides a wider range of variation, even for unusual ratios of cargo ship main dimensions.
- Efficient and easy to program.
- Effect of C_B considered.

The method (Schneekluth, 1985) is based on the evaluation of systematically varied ship forms and sizes of a containership type corresponding to the level of development at the early 1980s. To isolate the influence of the main data and ratios on the hull steel weight, the construction and building method was kept as uniform as possible over the entire variation range. Checked using statistical investigations, this corresponds reasonably consistently to practical reality and the building method applied in shipyard.

Due to the special characteristics of the E5-Containership and the lack of similar vessels, the steel weight prediction has below:

- Correction for bulbous bow.
- No use of light metal correction (conservative approach).
- Center of Gravity has been specially defined beyond usual boundaries (conservative approach).

The weight of Superstructures is also included in W_{St} and its estimation is based on the methodology presented by Mueller Koster [9].

For the estimation of the outfit weight W_{OT}, the methodology of Schneekluth and other approach formulae have been compared and it is concluded to apply the first one since that results each time in higher values and this is essential in this project since a novel design with no calibration using data of comparable ships, has to be conservatively composed at some aspects.

Machinery weight prediction has been conducted according to typical formulae.

<u>DWT Analysis</u>

$$DWT = W_{fo} + W_{lo} + W_{fw} + W_{st\&pr} + W_{crew} + W_{misc} + PAYLOAD$$

W_{fo}= Weight of fuel oil

W_{lo}= Weight of lub oil

W_{fw}= Weight of fresh water

$W_{st\&pr}$= Weight of stores and provisions

W_{crew}= Weight of crew

For this study a constant range has been selected: 15,000 sm.

In this section the important factor PAYLOAD is calculated. Assuming a homogenous distribution of the payload weight within the containers, the factor γcargo is introduced to describe the weight capacity per TEU. It is used later on as a hard constraint and plays significant role in the problem formulation. Centre of gravity of each component of DWT are estimated based on thorough study of the overall arrangement and comparison to conventional vessels, taken into account the specific characteristics on the ship under study, expect from the payload factor, which center of gravity is estimated using the stowage tools.

6.7.6 Resistance prediction

Approach A: Semi-Empirical Method

The Holtrop-Mennen method has proved to be highly effective at the initial design stage to establish the still water performance and for estimating the required propulsive power. The pair worked on developing a numerical description of ship resistance and propulsion using basic hull dimensions. The total ship resistance is subdivided into components and each component has been evaluated by multiple regression analysis. Holtrop and Mennen examined almost a thousand model tests and a few hundred trial measurements from the MARIN database [40].

The prediction method is programmed with excel sheets (Appendix B) and receives from the FRIENDSHIP-Framework several input data which appear in the following table. In fact, the Holtrop sheet is used as "entrance" for the several parameters exported from FRIENDSHIP-Framework via COM integration.

Some basic assumptions have been made within the methodology regarding the scope and the basic characteristics of the vessel, namely the fact that the vessel has twin-screw azipod propulsion; the propellers are fixed to the higher diameter available by azipod propeller standards. Beside these assumptions all other factor were parameterized within excel according to method's modification regarding dimension ratios. According to Holtrop&Mennen [40] the total resistance R_T of a ship is subdivided into:

$$R_T = R_F \cdot (1 + K) + R_W + R_{APP} + R_B + R_{TR} + R_A$$

Where

R_F	= frictional resistance according to ITTC 1957
(1+K)	= form factor
R_W	= wave-resistance
R_{APP}	= appendage resistance
R_B	= additional pressure resistance of a bulbous bow near the surface
R_{TR}	= additional pressure resistance of an immersed transom stern
R_A	=model-ship correlation resistance

The model-ship correlation resistance R_A is supposed to describe primarily the effect of the hull roughness and the still-air resistance.

Approach B: CFD Method

In this approach which is considered more accurate, a CFD computation is involved, namely the potential flow solver XPAN launched by SHIPFLOW. In this case the total resistance of a ship under service conditions, as described by Schneekluth [9] is given by:

$$R_T = R_F \cdot (1 + K) + R_W + R_{APP} + R_A + R_{AA}$$

R_F	= frictional resistance according to ITTC 1957
(1+K)	= form factor (different approach)
R_W	= wave-resistance by XPAN
R_{APP}	= appendage resistance (same as in approach A)
R_A	= correlation allowance regarding resistance due to roughness
R_{AA}	= wind resistance

Resistance will be defined in terms of force coefficients, which are non-dimensional values of the total resistance and its subcomponents. The total resistance coefficient is formed as:

$$C_T = \frac{R_T}{\frac{1}{2} \cdot \rho \cdot V^2 \cdot S}$$

Where:

R_T= total resistance, in N

ρ= mass density of tank water, in Ns^2/m^4

V= speed, in m/s

Total resistance in terms of coefficients is found to be:

$$C_T = C_F \cdot (1 + k) + C_W + C_{APP} + C_A + C_{AA}$$

The frictional resistance coefficient, CF, is calculated according to ITTC-57 method based on Reynolds number. According to equation RRR:

$$C_F = \frac{0.075}{(log_{10} R_n - 2)^2}$$

In this case the correction for wind and roughness are given individually, where the correlation allowance with ITTC line according to the length is presented in the following table [9]:

L_{wl} [m]	100	180	235	280	325	400
C_A	0.0004	0.0002	0.0001	0	-0.0001	-0.00025

Table6.14: Correlation coefficient according to length [9].

6.7.7 *Propulsion and powering prediction*

Since the total resistance of the ship under service conditions is estimated, the interaction between the propulsion system (Azimuth propulsion in this case) and the ship hull has to be considered. These effects and the open-water efficiency of the propeller determine the propulsive efficiency η_D:

$$\eta_D = \eta_H \cdot \eta_O \cdot \eta_R = \frac{R_T \cdot V_S}{P_D}$$

η_H	= hull efficiency
η_O	= open-water propeller efficiency
η_R	= relative rotative efficiency
P_D	= delivered power at propeller
R_T	= total calm-water resistance
V_S	= ship speed

Propulsion coefficients are computed according to Holtrop's formulae with respect to twin-screw propulsion but they have found to be inadequate since they are not meant to compute azimuth propulsion coefficients, therefore they are assumed constant after a while. Open-water propeller coefficient may be set constant at 70%, similar to the assumption of Quantum 6000 made by DNV which employed also Azipods for propulsion.

Mechanical losses in shafting are considered minor since the Azipod propulsors have a very short axial system. The ratio between delivered power at propellers and shaft power is set:

$$\eta_S = \frac{P_D}{P_S}$$

Where the used shaft efficiency is assumed $\eta_S = 0.995$

The engines of a Diesel-electric power plant are designed to cover all power need of the vessel, namely, propulsion and electric power for the ship. Special care should be taken regarding the efficiencies and the electrical losses as mentioned before. According to MAN guidelines for Diesel-electric drives, a slightly modified table is presented where the installed power P_{INST} is calculated, denoting the Maximum Continuous Rating MCR [38].

No.	Item	Unit
1.1	Shaft power on propulsion motors (incl. 15% Sea Margin)	$1.15xP_S$
1.2	Electrical transmission efficiency	η_{ET}= 0.92
1.3	Engine power for propulsion	P_{B1}(= 1.1/1.2)
2.1	Electric power for ship (E-Load)	0.025x P_{B1}+250
2.2	Alternator efficiency	η_A= 0.96
2.3	Engine power for electric consumers	P_{B2}(= 2.1/2.2)
3.1	Total engine demand	P_B (=1.3+2.3)
3.2	Total engine power installed (incl. 85% Engine Margin)	$P_{INST} = P_B/0.85$

Table6.15: Configuration of installed power.

6.7.8 EEDI calculation

In the EEDI framework, ships with diesel electric propulsion systems are not included yet. The main reason is that the formula is based on the installed propulsion power, which cannot be determined in a straightforward manner for diesel electric propulsion systems. The generator sets are designed to provide power to a number of applications with varying demand of electric power, including the ships main propulsion. Therefore the power of these generators may not be taken as equivalent to the main engine power in the calculation of the EEDI.

For E^4 the EEDI was estimated using the following procedure:

The power needed for the propulsors and the power for auxiliary form together the Maximum Continuous Rating MCR as elaborated above. Therefore the EEDI in case of a Gen-Set is assumed:

$$EEDI = \frac{C_f \cdot SFOC \cdot (0.75 \cdot MCR)}{V_{ref} \cdot (0.65 \cdot DWT)}$$

Where:

- C_F is a non-dimensional conversion factor between fuel consumption measured in g and CO_2 emission also measured in g based on carbon content. For Heavy Fuel Oil it is equal to 3.1144 [35]
- SFOC is the specific fuel oil consumption, measured in g/kWh, of the engines. It is retrieved from following table provided by IMO [41]:

Engine year of build	2-stroke low-speed	4-stroke medium-/high-speed (>5000kW)	4-stroke medium-/high-speed (1000-5000kW)	4-stroke medium-/high-speed (<1000kW)
2001-2007	165-175	175-185	180-200	190-230

Table6.16: SFOC according to engine size [9].

- V_{ref} is the ship speed, measured in knots, on deep water in the maximum design condition at the shaft power of the engines assuming the weather is calm with no wind and no waves.
- For containerships, the capacity parameter should be established at 65% of the deadweight (0.65xDWT)

6.7.9 Stability prediction

Stability issues are high ranged when it comes to containerships. Especially when the aim is to stack more containers on deck, the centre of gravity increases with adverse effects. The prediction of stability is quite a complex task and is difficult to integrate a full stability analysis within an optimization process. Since the project refers to preliminary design phase, only the initial transverse metacentric height GM will be examined. There are also semi-empirical formulae for the GZ curve prognosis, but in the case of the E5-Containership they are not applicable due to the fact that vertical sides are required. Nevertheless, the initial stability prediction is very accurate because it is based on information retrieved from the actual geometry of the ship. The initial metacentric height is decomposed as follow:

$$\overline{GM} = \overline{KM} - \overline{KG}$$

The height of the center of gravity is retrieved by the stowage and weight analysis as described above. It can be split into a part due to the ship’s hull, a part due to the ship’s cargo or payload and a part due to consumables weigths (fuel oil, lube oil, etc):

$$\overline{KG} = \frac{\Delta_{ls} \cdot \overline{KG}_{ls} + \Delta_{cargo} \cdot \overline{KG}_{cargo} + \Delta_{consum.} \cdot \overline{KG}_{consum.}}{\Delta}$$

The height of the center of buoyancy as well as the waterplane moment of inertia I_T are obtained by the hydrostatics calculation within the FRIENDSHIP-Framework. Therewith the metacentric height can be calculated as:

$$\overline{KM} = \overline{KB} + \overline{BM}$$

$$\overline{KM} = \overline{KB} + \frac{I_T}{\nabla}$$

6.8 Optimization strategy, objective functions and constraints

Throughout the investigation a basic structure regarding the optimization process occurs in two stages as listed below:

- Automated and systematic exploration of the multidimensional design space with analysis sequences for more than 1000 designs.
- Automated deterministic detailed optimization of best selected range from exploration, with multi-objective genetic algorithms, utilizing many form parameters.

At the very beginning, the design engine called, Ensemble Investigation is used. This is an algorithm used in designs of experiments, where objectives are only evaluated and constraints are not considered. This method of identification of the problem is used only at the early stage.

Later, in order to gain a better insight into the design space and obtain a reasonable subsequent optimization, a design of experiment is set with a SOBOL Design Engine, embedded in FRIENDSHIP-Framework.

The deterministic SOBOL algorithm is a so-called quasi-random or low discrepancy sequence and imitates the behaviour of a random sequence. It is more efficient and less random than a (pseudo) random number sequence, which spreads points randomly in the design space. These sequences use a base of two to form successively finer uniform partitions of the unit interval, and then reorder the coordinates in each dimension [43]. In this way, a uniform sampling of the design space is attained, offering a better overview of the design space, depending on the density of available variants. Sobol type algorithms are known to have superior convergence than random sequences [19].

For the multi-objective optimization, the Non-dominated Sorting Algorithm II (NSGA-II) is utilized. The main advantages of this algorithm are that it applies Pareto-based ranking schemes and avoids “trapping” between local maxima (or minima). More information about the NSGA-II may be found in previous chapters.

The main objectives that are monitored and optimized during the optimization procedure reflect clearly the scope of this project. The holistic design approach is implemented to this design problem with the following objectives:

- Minimization of the wetted surface.
- Maximization of the TEU’s capacity.
- Minimization of the EEDI.
- Minimizations of the required ballast water in ballast condition.

<u>Several constraints should be introduced in order to get feasible designs. The main constraints (hard and soft) used were:</u>

- Stability (initial GM).
- Minimum weight per TEU (Payload/TEU) in full load condition.
- Maximum beam and draft restrictions (New Panamax).
- Maximum draft restriction in ballast condition according to the requirement for propeller immersion.
- Control of geometric irregularities.

At every stage of the investigation process, different constraints are employed in the optimization, according to specific needs. Stability is controlled through the initial metacentic height (GM) and is one of the major constraints that influence the total design. It is required that GM holds a value, higher than an indicative one, which is determined by similar vessels or regulations. As a restriction is set also the carrying weight of every TEU container that validates the maximum container number according to specific needs. Some soft constraints regarding main dimensions according to physical restrictions are also available and are set as design variable boundaries. Of great importance is the control of geometric irregularities that occur very often in the case of arbitrary parametric design where large variation is required. These constraints ensure that the developed geometry will remain within feasible boundaries regarding its shape and contributes in avoiding system crashes which are not rare when dealing with sophisticated holistic systems. Constraints will be discussed in detail at the respective chapters.

The optimization process is set up gradually in two main different phases. It is divided into a preliminary investigation (Phase A) and a secondary more thorough (phase B). A brief overview may look like this:

PHASE A- The E4-containership

The first phase includes an initial parametric study and a first attempt to determine whether it is physically possible to achieve a hull form complied with specific criteria. The exploration is based inclusively on semi-empirical methods. The design speed is fixed at 16kn so that the non-trivial effects of wave resistance to be avoided. This study included a design of experiment and an initial step to the multi-objective approach by employing an evolutionary algorithm [42].

PHASE B- The E5-Containership

As it looks, the name of the project has been changed in order to point out the evolutionary character of the overall project. A reference design is obtained by the Phase A and is utilized for further and more thorough investigation. Now, an accurate and more robust methodology is employed, that gains a substantial benefit from more sophisticated sub-systems, that are integrated and a more comprehensive exploration of the design space is attained, leading to a firm exploitation with the help of genetic algorithms. Now the range of the design speed is increased between 16 and 21 knots, so that the concept design becomes more competitive and flexible to speed fluctuation. The following map helps the reader to clarify the steps of the optimization process that will follow.

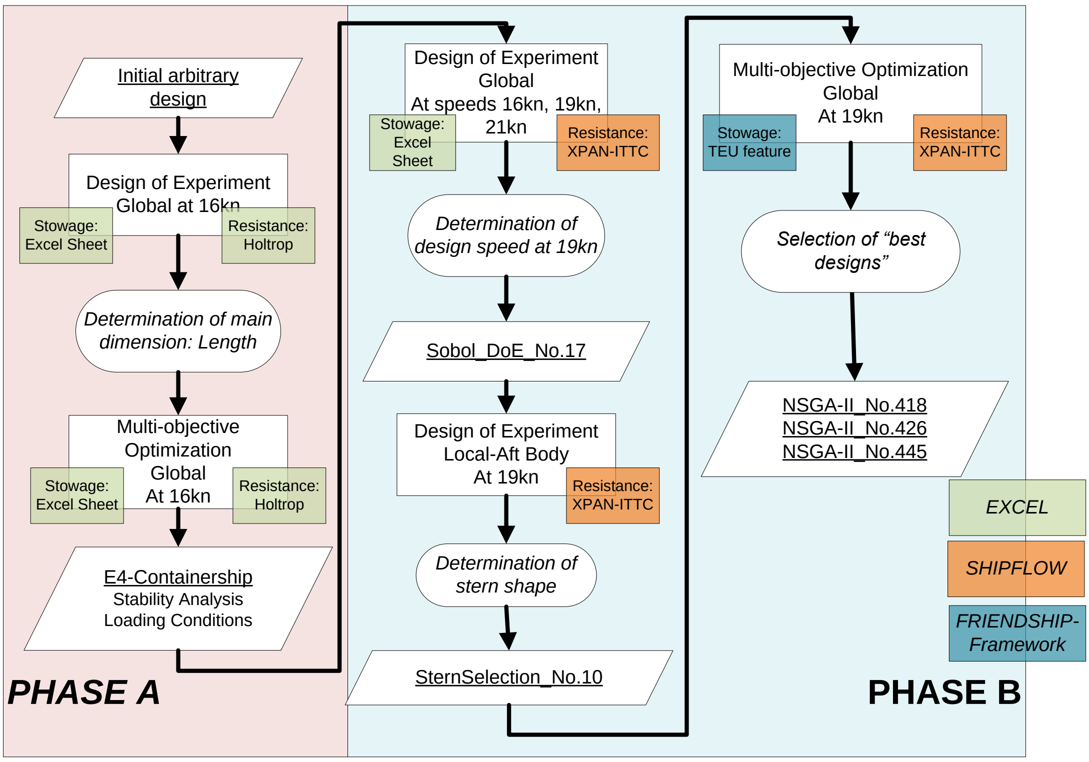


Figure6.14: Optimization process map.

6.9 Phase A: The E^4-Containership

This stage may be characterized as the initial conceptual design phase. In this phase two kinds of data can play a role. At first, we have shape knowledge, which at this stage mainly consists of mental images, or rough sketches, of important layout items. Examples of shape data are deck contours and plan contours. Secondly, we have non-shape data, which are based on relationships between parameters. Out of the many types of relations, for hull design the most relevant ones are physical, definitional and empirical relations. In the preliminary design phase the body of the vessel gets shape, often in a rather rough form. It might be that in the conceptual phase insufficient empirical relations are available. For example, the hull form to be designed may fall outside the domain of available empirical methods. In that case, the preliminary model can be utilized by analytical calculations such as damage stability or potential flow calculations to derive numerical qualities from the hull form.

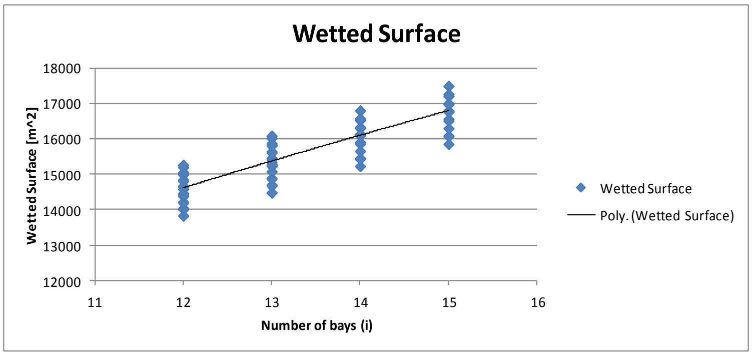
6.9.1 Application of DoE

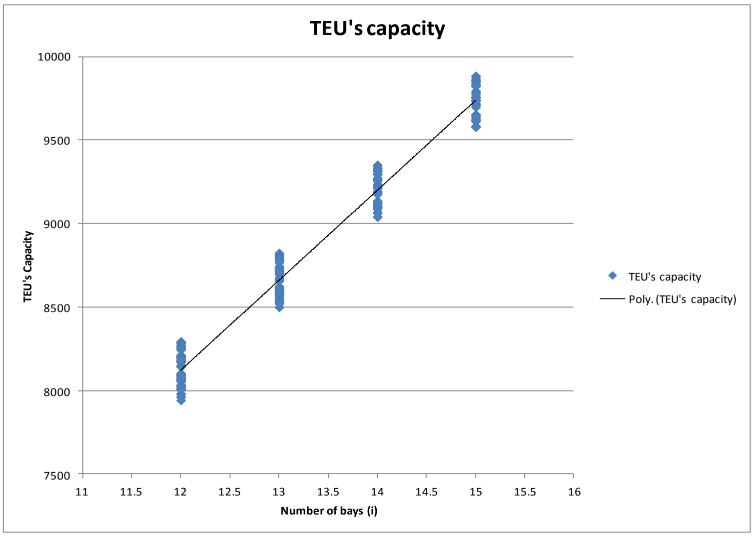
At this stage the initial dimensions and parameters do not play significant role, since they have to be somehow evaluated within a simulation process. Therefore the Ensemble Investigation design engine is employed to run a variation of 1000 designs where only the four global parameters and the basic objectives and properties are monitored. Special care has been given, so that the shape of the vessel does not meet any irregularities while varying. The range of the design variables and the results are presented in the following tables and diagrams:

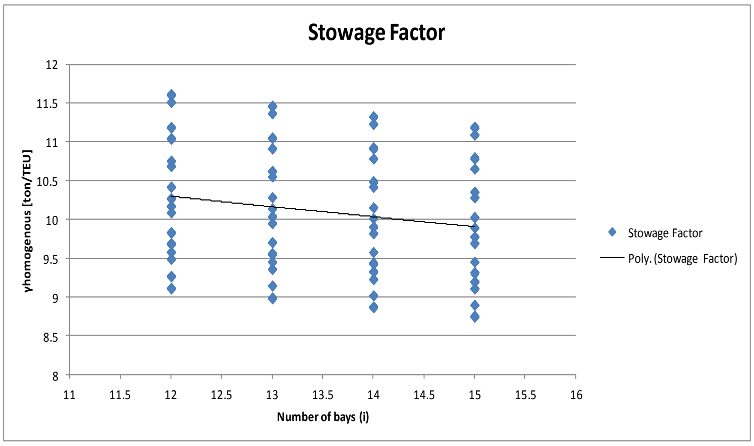
Ensemble Investigation		***Boundaries***
No. of designs (feasibility)	1000 25.7%	(of feasible designs)
i(bays)		12-15
Draft T [m]		13.2-15.2
Height D[m]		22.5-25
Beam B[m]		45-49

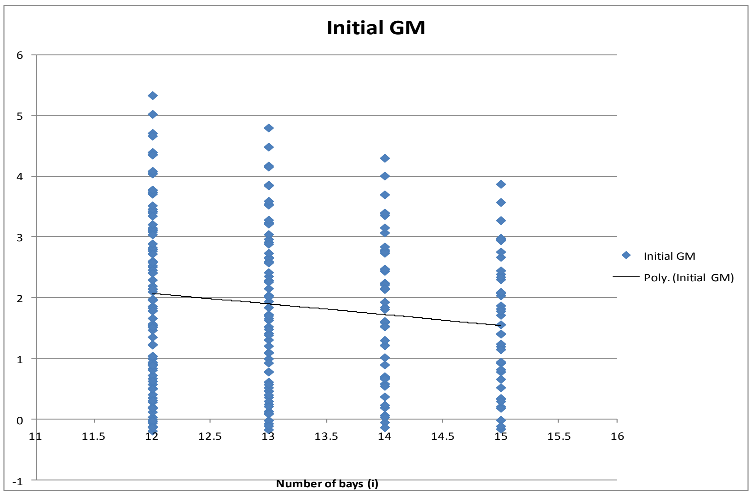
Table6.17: Results of DoE.

As mentioned before, length is included in terms of number of bays along the L_{cargo}, where a bay refers to the total length of two TEU's in row, plus appropriate margins. Alternative expression is: Number (i) = half the length of a hold. So in this case the range of the length is between 6 to 7.5 holds (L_{BP}= 266- 313m) along L_{cargo}. Table A presents also the boundaries of the feasible designs. In other words, this first investigation sets the boundaries of the main dimensions of the vessel. Breadth is examined between 45m and the new Panama restriction 49m. The range of draft is determined between 13.2 m and 15.2m (new Panamax).









__Results of Ensemble-Investigation__

The diagrams of the left column present an overview of the investigation. They consist of the feasible design variants (circa 250) that were created by the design engine.

A rough exploration of some basic properties of the examined vessel is depicted allowing the comparison between variants regarding their performance. A characteristic differentiation lies in the fact that four different length values have been taken into account according to settings (Variation of length is respective to increase/decrease of holds number along L_{cargo}).

Every diagram has its respective trendline that enables the visualization of the influence of the main particular "Length" to the total design. in the next paragraph the determination of length between perpendicular is discussed.

6.9.2 Determination of length L_{BP}

Taken into account the results of the previous analysis it is concluded that from now on the global parameter that refers to the length between perpendiculars *will be kept constant at i=13 bays, namely* L_{BP}*= 281.74 m*. The trend lines in the above diagrams converge to the fact that the vessel at this length has moderate results regarding the evaluation. It allows the vessel to be ranged among the category of 8000-9000 TEU's which is a rather competitive group. The initial stability at this length is rather good and not excessively high. In addition a vessel of this range keeps an adequate Payload/TEU factor.

6.9.3 Multi-objective optimization

Based on the data obtained by the initial investigation, a multi-objective optimization is undertaken. The design variables, constraints etc, are presented in brief. From this process, the final design of E4 is selected and further investigated. The selected geometry –best according to some criteria- is imported in TRIBON-AVEVA in order to examine and verify the arrangement and to conduct thorough stability calculations. The NSGA-II is utilized for the optimization. The process of the optimization is illustrated in figure 6.15 in the form of a flowchart:

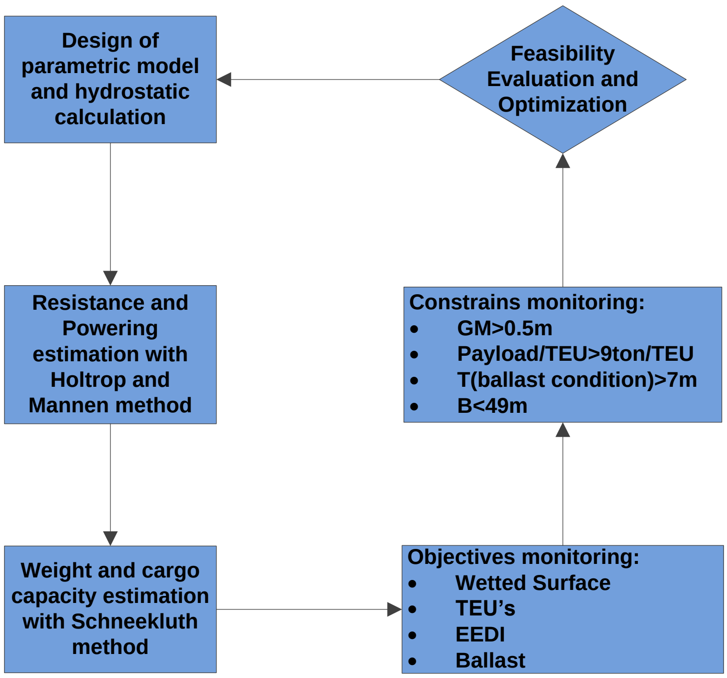


Figure6.15: Multi-objective Optimization process flow.

The optimization process results in 600 designs with 83% feasibility and it is up to the designer which one to choose by prioritizing his demands and weighting the benefits and the drawbacks of every design.

In figures [6.16], [6.17] the results of the multi-objective optimization are illustrated and the Pareto-Frontier is visible.

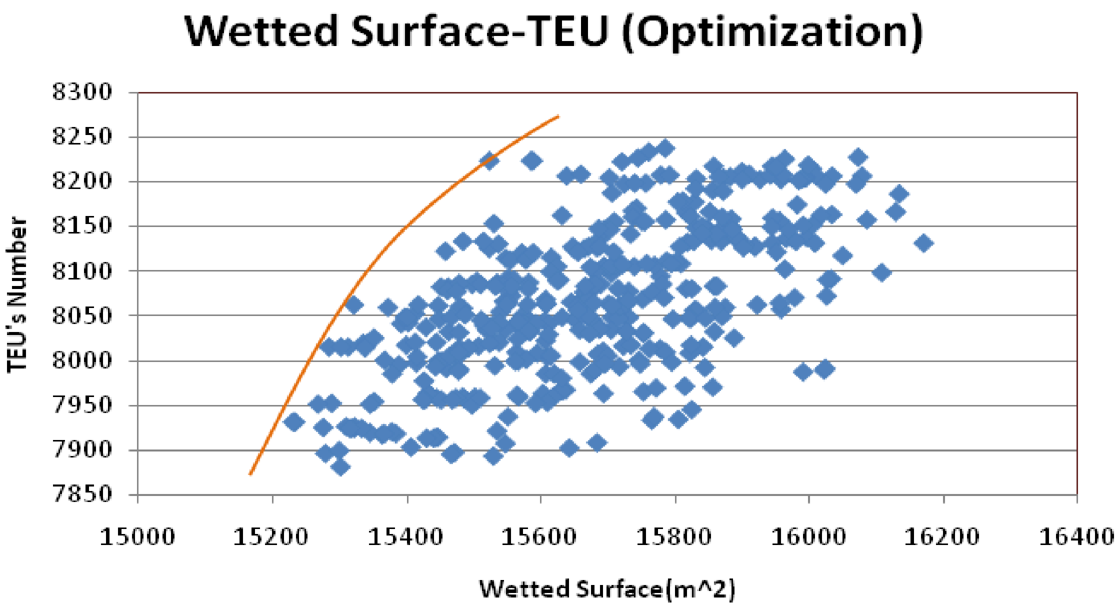


Figure7: TEU capacity vs. Wetted surface

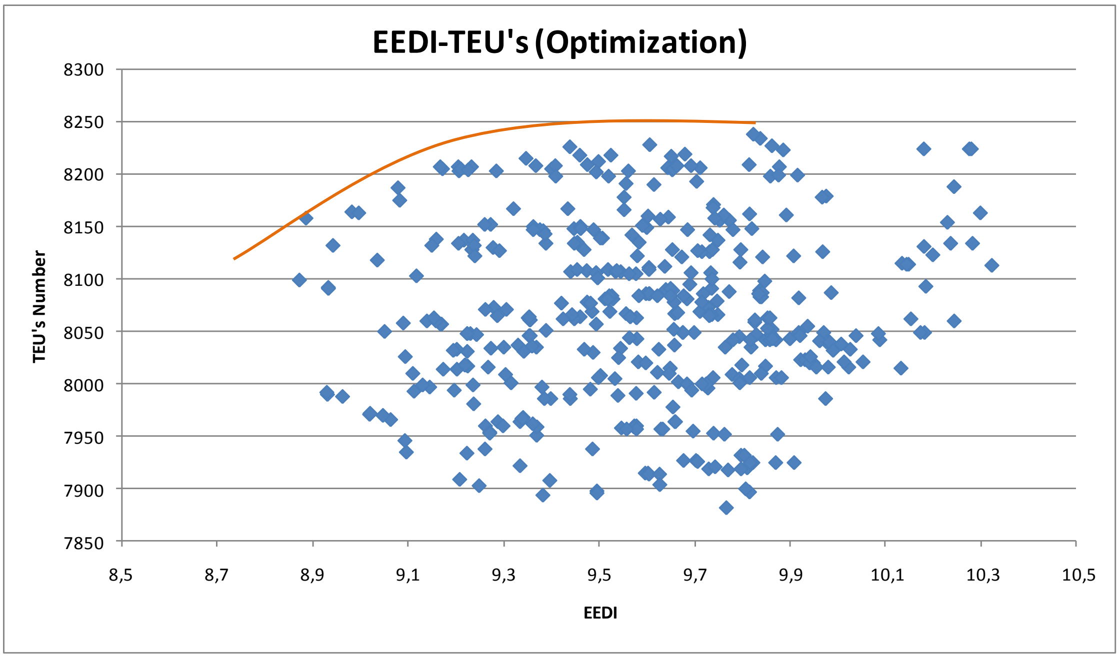


Figure6.17: TEU number vs. EEDI

6.9.4 *Selection of E4 variant*

The final design is selected based on prioritized criteria. Minimum wetted surface is the first demand. Then a reduced EEDI is of great importance and of course a sufficient number of TEU's. The hydrostatics and loading conditions of the E^4 are computed with the help of the naval architecture program AVEVA Tribon.

The Stability criteria applied (Appendix E) were those of IMO 749 Intact Stability Criteria for non – passenger ships [44].

The main particulars of the selected design for E^4 are shown in the following table:

Name		***E^4-Containership***	
L_{OA} [m]	287.7	**C_{WP}**	0.837
L_{BP}[m]	281.7	**DWT [ton]**	90,221
Beam (deck) [m]	47.5	**Lightship [ton]**	28,207
Beam (draft) [m]	47.2	**Container Tot.**	8,012
Draft[m]	14.25	**Container Max.**	8,449
Depth[m]	25	**Engine Power [kW]**	18,045
Δ [ton]	118,428	**Tiers on Deck/in Hold**	7(max.8)/9
C_B	0.596	**Rows on Deck/ in Hold**	19/17
C_M	0.785	**Bays**	67
C_P	0.759	**Design speed [kn]**	16

Table6.18: Main particulars of E4-Containership

6.9.5 *Full Load Conditions of the E4-Containership*

It is worth to examine three remarkable full loading conditions (arrival) which are distinguished and presented (all refer to homogenous cargo distribution):

	Baseline Condition	**Max. Loading of TEU's**	**Non-Ballast Condition**
Actual TEU's Capacity	8,012	8,449	7,062
Payload/TEU (ton/TEU)	10	9	12
Ballast required (ton)	7,510	10,006	0
Max. Tiers on Deck	7	8	6

Table6.19: Loading conditions of E4-Containership

For the above loading conditions, an initial GM has been computed within the range of 2-4.4 m. The value of initial GM that was predicted based on the developed tools during the optimization is about 0.5m and is only indicative since proper stability estimation needs a GZ-curve to be generated. Such an option has not been employed yet because formal stability calculation has to be integrated via expert software such as Hydromax. For a preliminary design phase though, integration of such an instrument is not an easy task, since containerships require a sophisticated approach when it comes to stability issues. For an initial approach of the GZ-curve some semi-empirical formulae could probably be used, predicting the curve at low angles, but this method has been tested and failed to meet the requirements due to the fact that such empirical formulae are designed to address conventional ship's stability with vertical parallel sides.

6.9.6 Discussion

The survey that was conducted in the first phase of this investigation enriched the study with valuable information. Now, there is a "parent" vessel, to be set as reference, or baseline design for the next level of the optimization process. In addition, very important information regarding the loading conditions and the required ballast has been gained. The data presented at the last chapter of this study regarding ballast required will be used later for comparison to conventional designs and their superiority will be identified.

6.10 Phase B: The E5-containership

During this phase a more comprehensive approach of the optimization task is realized. A robust optimization system is set up, utilizing advanced tools regarding the containership concept, as described previously. The highlight of this multi-criteria decision making is the fact that CFD code is employed, offering significant information about resistance coefficients. The current study has set the target in finding, not a single good design, but a range of best designs as a result of the Pareto analysis. Therefore, a design of experiment (DoE) takes place at first place and then a genetic algorithm is utilized to perform the global multi-objective optimization. What will be discussed in this chapter is the methodology that leads to that final task.

6.10.1 Comments on resistance prediction

Until now, resistance was computed according to Holtrop and Mennen method. Now the total resistance will have to be composed manually as described previously.

Correction of the Form Factor k

Some local transformations of the shape of E4 took place after recognizing some problematic areas (stern immersion), without loss of the general characteristics. A CFD-computation (potential + viscous flow) was run for this model. More information about this task may be found in Appendix C. An important fact that was found by comparing the results of the semi-empirical resistance method and the numerical approach was that the form factor k was overestimated by the prediction tool:

	Holtrop&Mennen	***SHIPFLOW XCHAP***
Form factor k	0.28	0.114

Table6.20: Comparison of form factor k results.

The reason for this overestimation lies on the fact that the semi-empirical method is created based on statistical analysis of conventional vessels. The E^4 concept though, adopts elements from slender as well as bulkier hulls. The prismatic coefficient C_P of E^4, which is rather increased due to low mid-ship coefficient C_M, is similar to tankers and bulk-carriers, which hold a high C_P due to increased block coefficient C_B. The formula of the form factor in this method is based on C_P, therefore the results for E^4 are misleading and the resistance (viscous pressure coefficient) is overestimated and consequently the power demand is increased. This fact justifies the use of CFD-tools for, at least, verification of the results.

In this study from now on, the form factor k will be obtained by different empirical formulae, which base their prediction on block coefficient. There is already a feature embedded in FRIENDSHIP-Framework that computes the form factor by means of formulae and it has been examined in order to find which formula converges to the real form factor k, according to SHIPFLOW.

Name	Formula	Form factor k
Granville 1	$18.7 \cdot (C_B \cdot \frac{B}{L})^2$	0.195
Granville 2	$-0.03 + 32.8 \cdot \frac{{C_B}^2}{(\frac{L}{B})^2 \cdot \frac{B}{D}}$	0.064
Watanabe	$-0.095 + 25.6 \cdot \frac{C_B}{(\frac{L}{B})^2 \cdot \sqrt{\frac{B}{D}}}$	0.139
Holtrop	$-0.07 + (\frac{D}{L})^{0.22284} \cdot (\frac{B}{L})^{0.92497} \cdot (1.7 + 6 \cdot {C_B}^5$	0.143
Mewis	$0.4 \cdot C_B - 0.11$	0.130
SHF-XCHAP	-	0.117

Table6.20: Formulae predicting the form factor k.

From the formulae, it can be concluded that, discarding the extreme value of Granville 1, the mean value of the rest may converge to the real form factor, estimated by SHIPFLOW-XCHAP. So:

Mean value from formulae	k=0.119
SHF-XCHAP	k=0.117

To sum up, a correction of the form factor prediction took place and from now on the mean value from formulae will be employed in both resistance prediction approaches, as described in former chapter.

6.10.2 Application of DoE

As already mentioned, the parametric model consists of several form parameters. Until now, only the major variables have been determined or boundaries have been set. But all the other parameters, global and local are still unexplored and there is also need to investigate the performance of the vessel in a wider range of speeds [16kn, 19kn, 21kn]. In addition more constraints have to be set, especially those one that refer to geometrical irregularities, since the variation type that is chosen leads often to abnormal shapes. The aim of this investigation is to find the relationships and understand the dependencies of the form parameters that lead either to a violation of constraint, or to unacceptable values of the merit functions. In this DoE, three speeds of the vessel are going to be tested. Within the FRIENDSHIP-Framework a SOBOL algorithm is accessible and used in this work for the design space exploration producing 400 variants for every speed. Each of the variants flow characteristics is calculated with SHIPFLOW. The objective functions remain same as previously. Considered parameters, constrains and boundaries are discussed in the following topic.

The eleven (11) Design Variables, the constraints and boundaries, which are used in DoE, are presented in the following tables:

Design Variables	Upper-Lower Value
Draft [m]	13.2-15.2
Height [m]	24-27.6
Half-beam [m]	22-24.37
AreaAtFP_SAC [m^2]	7-14.8
zAftPeak_factor_FOS	0-1
Fullness_DWL	0.62-0.75
zAftPeak_CPC [m]	-2.1-0.5
tanAtFP_DWL [deg]	110-135
tanAtFP_SAC [deg]	139-151
xParAft [%L_{BP}]	0.25-0.35
xParFwd [%L_{BP}]	0.58-0.79

Table6.21: Design Variables of DoE.

Constraints	Type of constraint	Description
controlDWL_area>0	Soft	Geometric irregularity
controlDWL_curvature>=0	Soft	Geometric irregularity
controlKEELaft_curvature<=0	Soft	Geometric irregularity
controlStern>=0	Soft	Geometric irregularity
controlGM>0.3m	Hard	Minimum acceptable value
controlStowageFactor>9ton/TEU	Hard	Minimum acceptable value

Table6.22: Constraints applied in DoE.

Process Flowchart

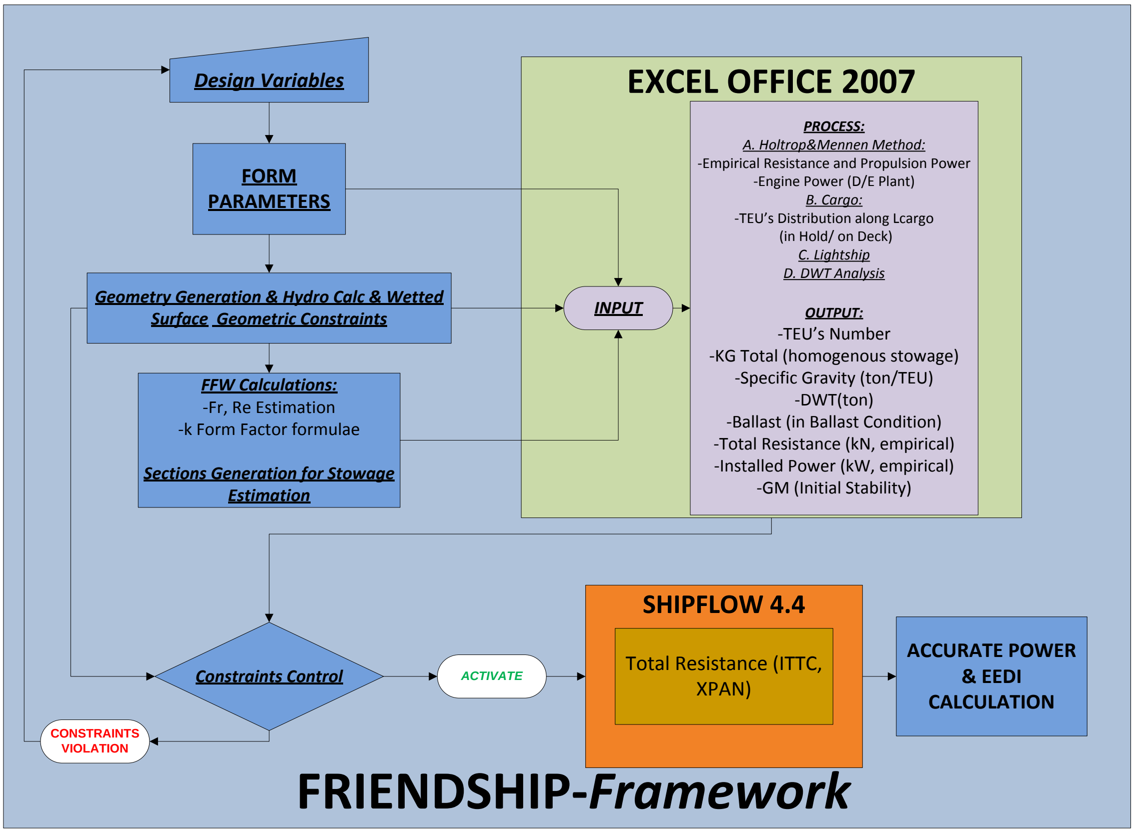


Figure6.18: Flowchart of internal Loop A.

The flowchart presented in figure 6.18 describes the process that is followed in order to result in an acceptable variant that is forwarded to evaluation. It is significant in order to conceive the collaboration between the different software, in other words, it gives a clear picture of the integration technique. This process refers to an inner loop (LOOP A) that is executed before the objective functions and constraints are evaluated by a decision-making algorithm.

As presented, the design variables trigger the procedure, by giving value to the form parameters, which manage to create the hull-form, compute the hydrostatic elements and wetted surface and formulate the geometry-control formulae. The latter are sent to “constraint control” for evaluation. Further computations take place within the FRIENDSHIP-Framework based on the shape generation. All the appropriate information produced is sent to EXCEL OFFICE 2007 via COM integration for further elaboration. Since the processes and the output are achieved, a result-file is sent back to FRIENDSHIP-Framework for evaluation (GM and stowage factor). *If the “constraint control” detects any violation the process is not going to further steps (SHIPFLOW computation and then optimization/variation algorithm), but it returns to design variable variation in order to create a new hull form. On the other hand, if the constraints control is successful, then a SHIPFLOW calculation is executed and then accurate results regarding resistance, power and EEDI are received. If this procedure is fulfilled then the system may progress into the optimization (NSGA-II) or variation (SOBOL) process. This formulation contributes in discarding quickly the unacceptable or infeasible designs without burdening the system with pointless and time-consuming SHIPFLOW calculations.*

Results of DoE

The DoE is executed for three speed values: 16kn, 19kn and 21kn. Each run consists of 400 variants. The feasibility of the total 1200 variants is up to 33%. What will be further elaborated from the large number of produced information and discussed are the resistance values from Holtrop Method in contrast to CFD-calculation and the objective values. The target at this level is to restrain the number of design variables and their range in order to focus on a beneficial region of designs (global maximum/minimum). Therefore, this process will lead us to the next step which is the formal multi-objective optimization.

Figure 6.19 presents the estimated total resistance at the three speeds for some designs. Designs are sorted from minimum to maximum resistance at 16 kn. It can be observed that for some designs the total resistance is lower at all speeds.

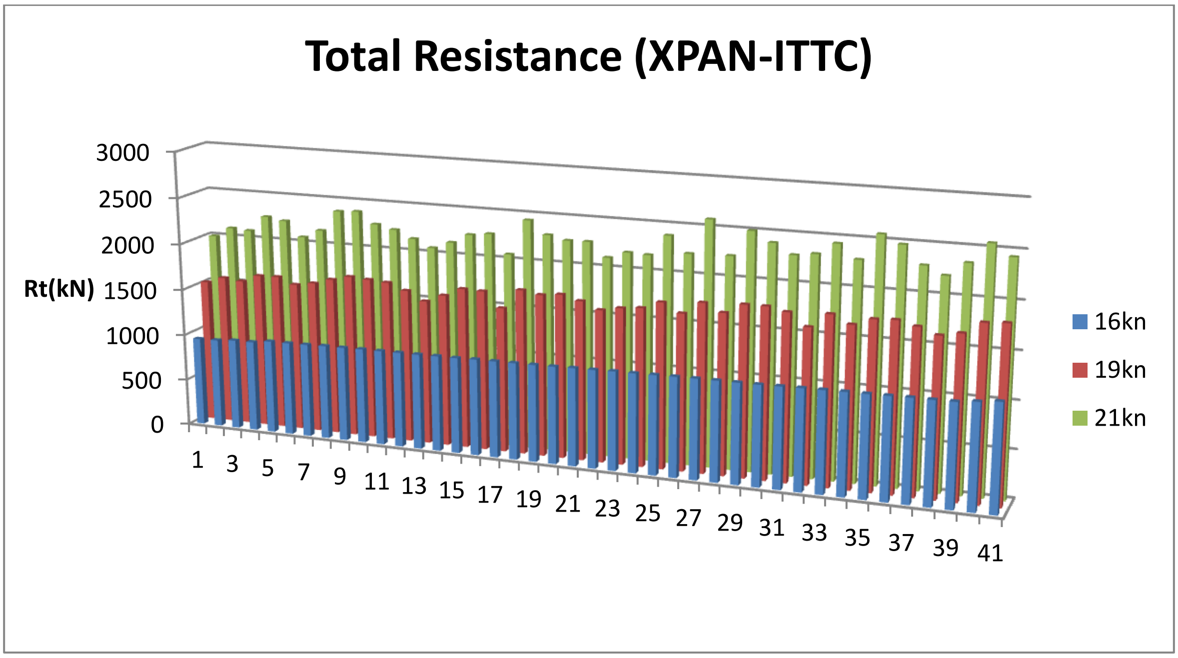


Figure6.19: Results of DoE. Total resistance at three design speeds.

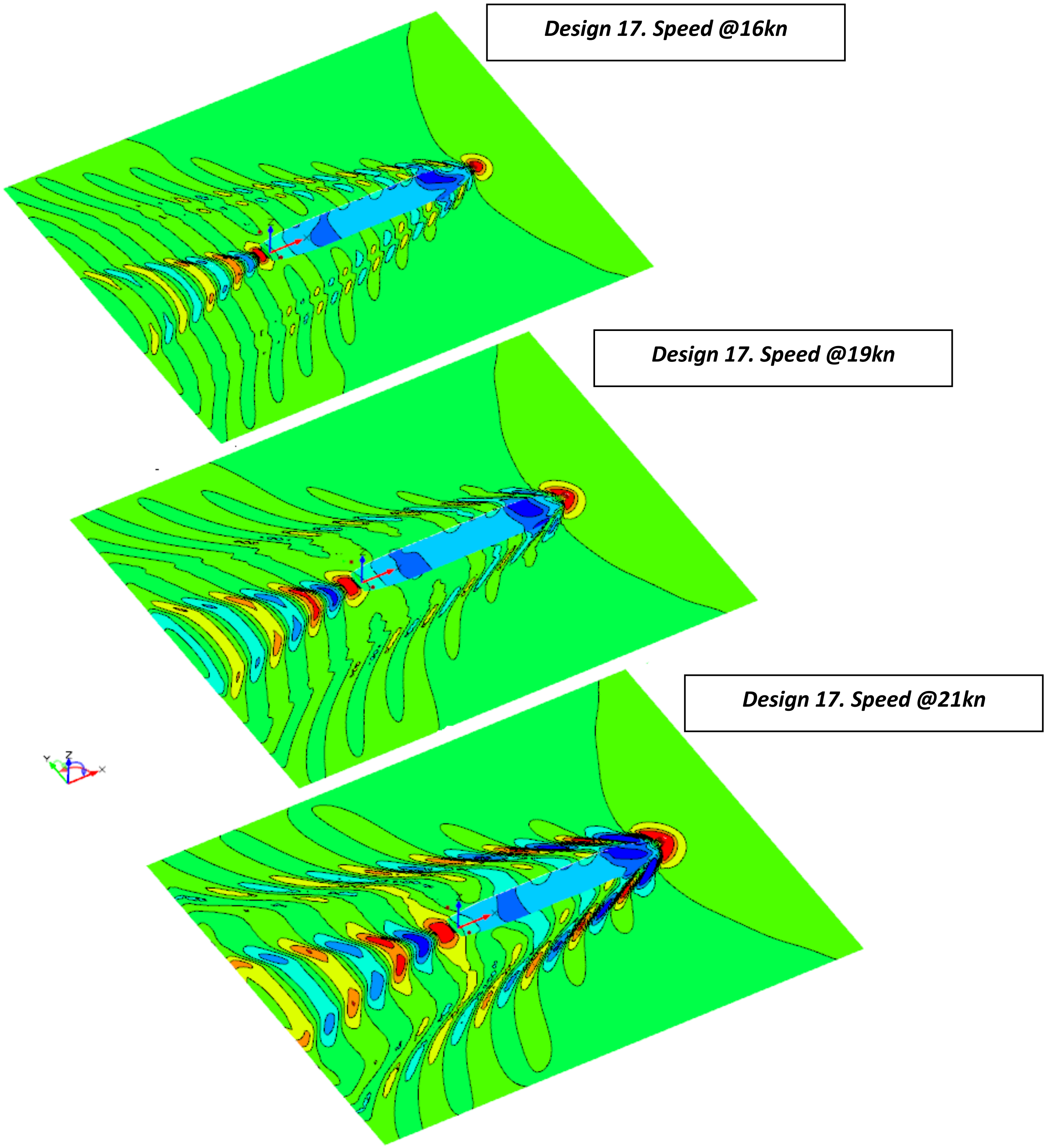
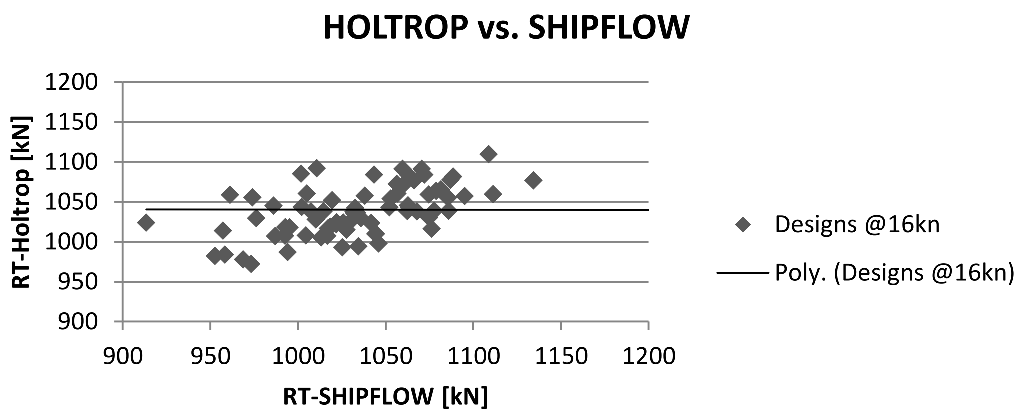
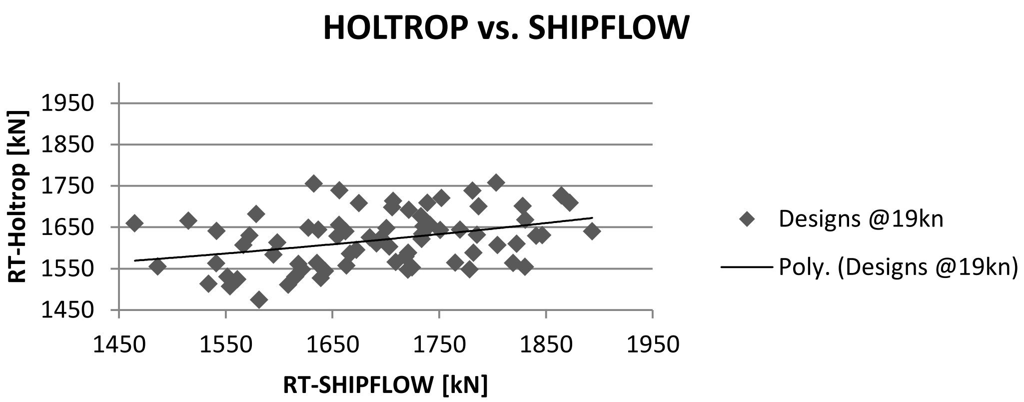


Figure6.20: Wave pattern of Sobol_DoE_No.17 at three speeds.

In figure 6.20 the wave pattern of a design variant (des. 17 from figure 6.19) at the three speeds is visualized. As it seems, the design variant with the best overall resistance response has still some problems regarding the wave elevation at stern. Therefore, at a next step, a variation with SOBOL algorithm of a restricted region will be executed in order to minimize the wave resistance due to transom immersion. The depicted design will be set as reference.

At this level a comparison between the efficiency of the resistance prediction methods may be presented. The following charts show the estimated total resistance at the three speeds using the Holtrop&Mennen method and comparatively the SHIPFLOW estimation based on XPAN module for the wave resistance and ITTC-57 for friction resistance. The form factor in both cases is estimated as previously described.





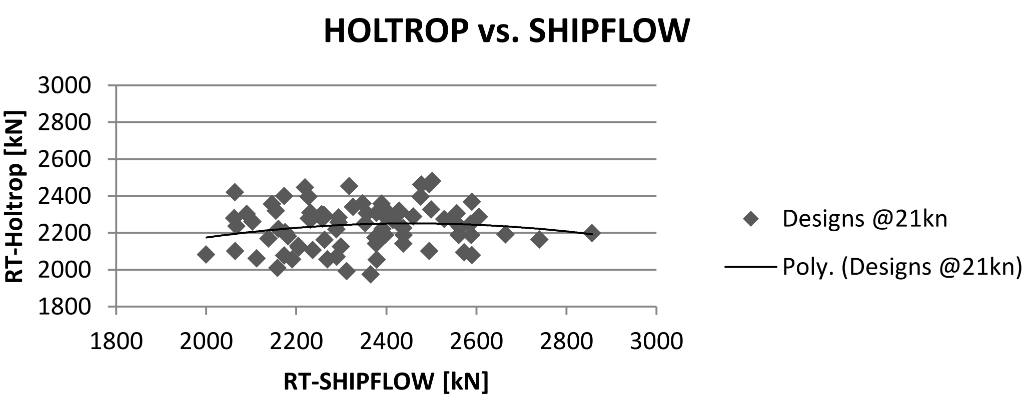


Figure6.21: Holtrop results vs. SHIPFLOW results at three speeds.

The ideal result would be, the values of the two methods to coincide exactly, providing a linear analogy. In that case the method of Holtrop&Mennen would be preferred due to the time-saving procedures. But this is obviously not true; therefore SHIPFLOW integration will be present also at the multi-objective optimization. What can be concluded form the above charts, is that the two approaches reach a relatively good convergence throughout the explored design space, at the speed of 19kn. *Therefore, 19kn is set as design speed from now on.* It is chosen because a reliable convergence between Holtrop and CFD-code is necessary, since the values from the semi-empirical method are used at first place as a preliminary resistance prediction in order to determine weights (machinery, fuel oil etc.).

The results that refer to the objectives are listed below:

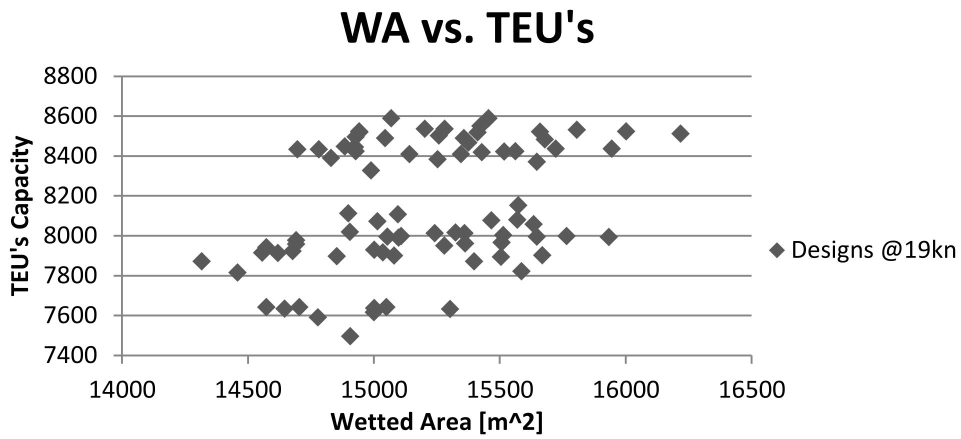
Objective/Design Speed	16kn	19kn	21kn
Wetted Area(m^2)	13,824-16,365	13,824-16,365	13,824-16,365
EEDI	9.01-11.71	13.25-16.75	17.26-25.6
TEU's Capacity	7,347-9,056	7,347-9,056	7,347-9,056
Ballast(ton)	8,100-18,069	7,145-16,891	6,138-15,715
DWT(ton)	77,413-105,816	78,020-104,686	77,189-103,565
GM(m)	0.30-4.15	0.35-4.48	0.31-4.83

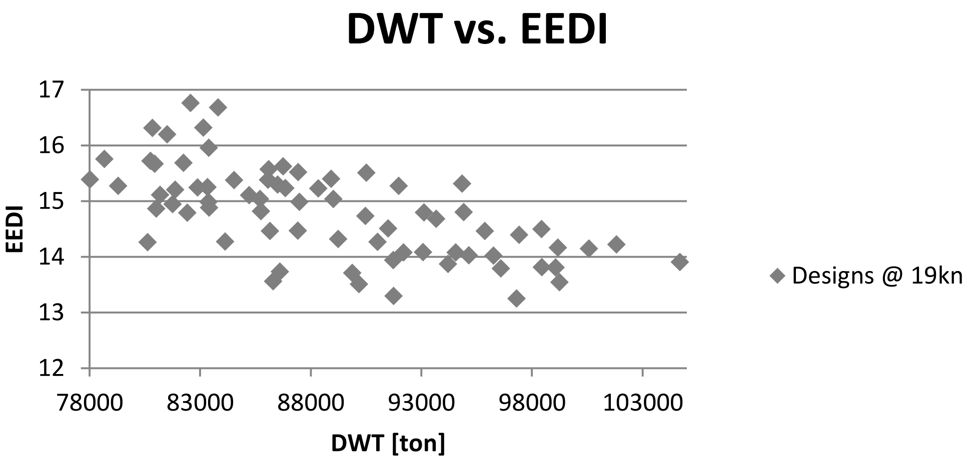
Table6.23: Results of DoE.

The created designs seem to have an adequate initial stability in terms of GM, calculated within the study. The range of the initial GM varies between 0.3-4.5m, with most designs (>50%) holding an initial GM greater than 1m.

Attention: The stability factor may only be seen as an indicative value, since no GZ-curve is produced for every design due to lack of tools. It may be compared to the E4 design, which was subjected to stability analysis.

The charts of the objectives at 19kn will be presented in order to compare the result of this variation with that of the formal optimization (next chapter).





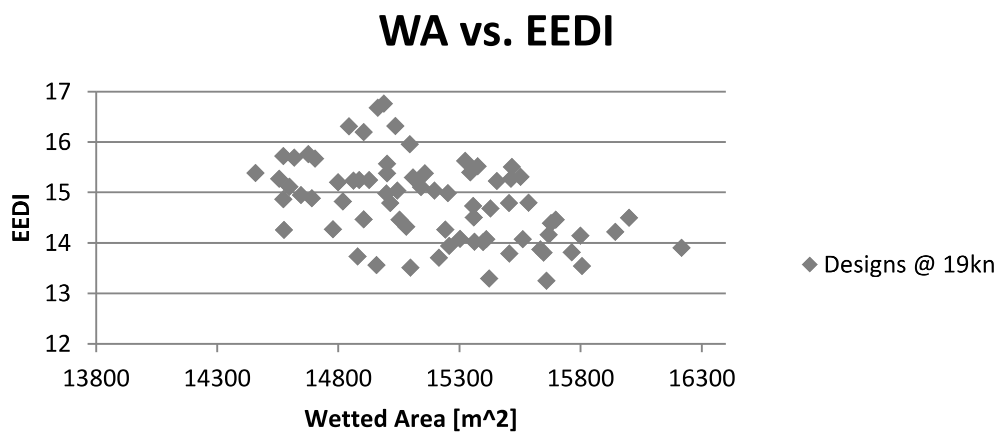


Figure6.22: Objectives at 19kn.

It can be concluded that the SOBOL-variation leads to the formulation of a Pareto-Frontier. By close investigation of the best designs at the three speeds, a "good" region for analytical multi-objective optimization has been detected.

6.10.3 Determination of the Stern form-parameters

The stern form influences greatly two main factors: resistance and stability. An immersed stern, increases the water-plane area, the waterline length L_{WL} significantly thus stability raises, accompanied by all the known benefits (increased capacity, low need for ballast water etc). But doing so, it is unavoidable the fact that the transom area beneath the waterline will take on, leading to a steep increase of wave resistance. Therefore a good compromise of the two factors has to be investigated. Formally, such an investigation would require exploitation of Navier-Stokes equations, since the aft-body is dominated by viscous flow phenomena. Considering the fact that in this study only potential flow is used, an investigation using the SOBOL algorithm again is utilized in order to determine some basic form parameters, regarding the stern shape that will comply well with the two objectives, stability and resistance.

There are going to be used 3 design variables, which locally describe the shape of the stern. They are listed below with reference of their boundary values:

Design Variables	Boundaries
zAftPeak_factor_FOS	0.4-1
tanAtxAftPeak_CPC [deg]	90-110
zAftPeak_CPC [m]	-2.5-0.31

Table6.24: Design variables and their boundaries for stern form variation.

The design Sobol_DoE_No.17 from the former investigation is set as reference. The design speed is determined at 19kn. Its properties that are of interest are:

Reference design	No. 17
zAftPeak_factor_FOS	0.7843
tanAtxAftPeak_CPC [deg]	101.56
zAftPeak_CPC [m]	0.090
Wetted Area [m^2]	15098
EEDI	13.3
DWT [ton]	90191
Total Resistance [kN]	1542
Wave Resistance [kN]	414.7
GM [m]	0.9

Table6.25: Properties of reference design Sobol_Doe_No.17.

The SOBOL was set to run 60 variants and achieved 70% feasibility. The following diagram presents the two contradictive objectives, total resistance R_T and initial stability GM. With red color is pointed the reference design and with green color the finally selected variant.

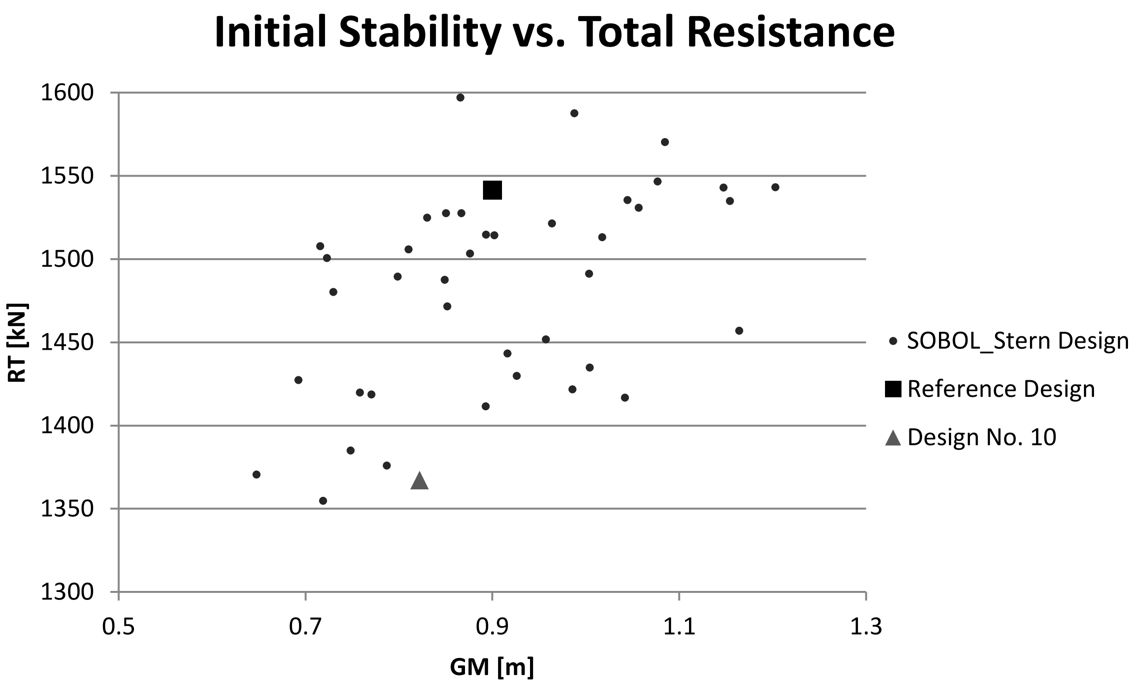


Figure6.23: Objectives of Stern from variation.

Design SternSelection_No. 10 has been finally selected which holds 12% less total resistance than the reference design and an adequate initial GM. The following table summarizes the design variables and evaluated properties of this design, which will be used later as reference for the formal multi-objective optimization.

Design SternSelection_No.10

Design Variables	Value
Draft [m]	14.28
Height [m]	24.94
Half-beam [m]	23.28
AreaAtFP_SAC [m^2]	14.28
Fullness_DWL	0.6387
tanAtFP_DWL [deg]	131.777
tanAtFP_SAC [deg]	147.203
xParAft [%L_{BP}]	0.333
xParFwd [%L_{BP}]	0.787

Table6.25: Properties of final design Sobol_Doe_No.17.

Evaluations	
Wetted Area [m^2]	15209 (+1%)
Volume [m^3]	117033
DWT[ton]	91318(+1.2%)
TEU	7990
EEDI	11.5 (-13%)
R_{TOTAL}[kN]	1367.12(-11%)
GM[m]	0.822(-8%)
Payload/TEU [ton/TEU]	10.2
C_B	0.611
C_P	0.7786

Table6.26: Design variables and properties of final design SternSelection_No10.

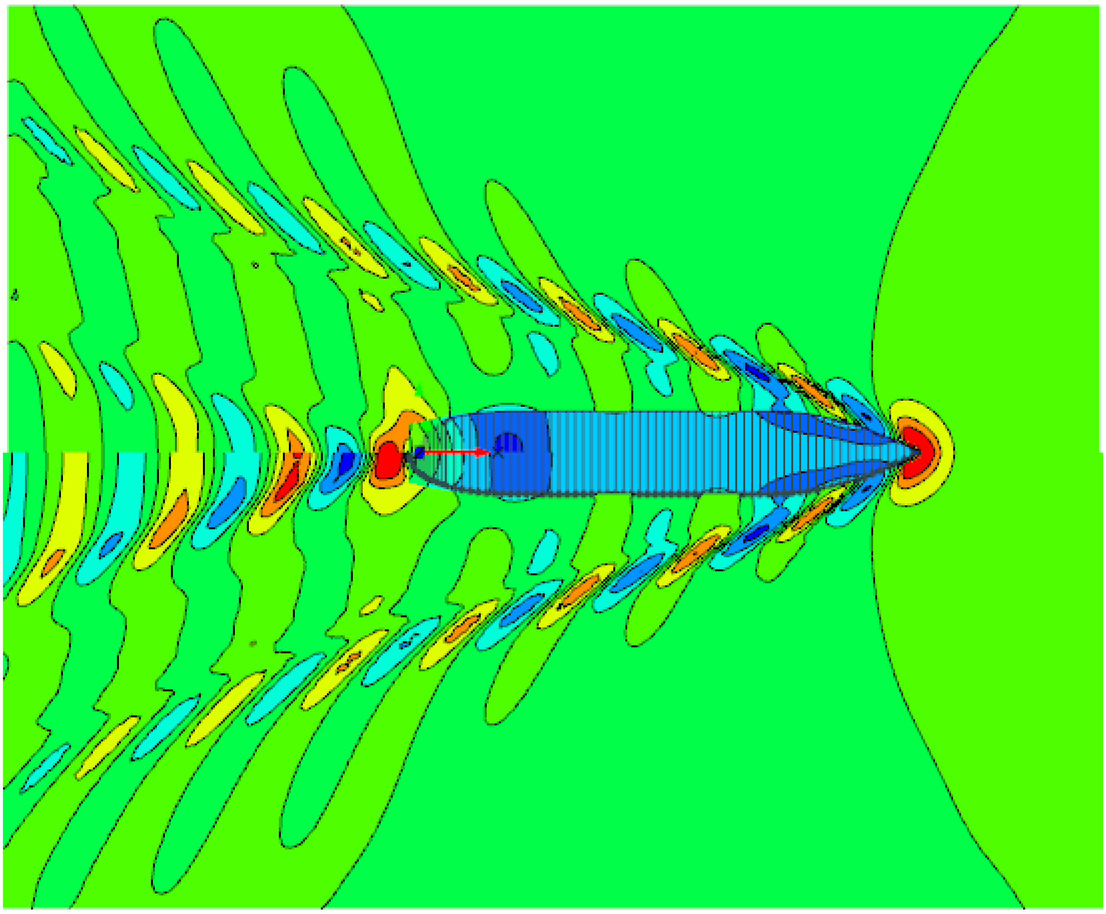


Figure6.24: Wave pattern assessment of reference and final design.

The qualitative change between the reference and the new selected design is visible on the wave pattern as shown above.
On the top half is depicted the wave pattern of design SternSelection_No. 10, while on the lower half stands the reference design Sobol_DoE_No.17.

6.10.4 Multi-Objective Optimization

Since the design of experiment has provided us with a lot of feedback regarding the response of the E5-containership while varying, it is time now to proceed to the formal multi-objective optimization. The design No. 10 from the previous investigation has been selected as reference design and the number of design variables has been reduced by two, because the form parameters regarding the stern shape are already determined and will be kept constant. In addition the range of the rest design variables has been significantly reduced after a thorough examination of the best designs of the DoE. As a result, a region of good variants within the space of feasible design has been identified. In this area, the optimization will be executed in order to find the best design and provide the Pareto-Frontier. *The NSGA-II will be utilized to perform the multi-criteria optimization. In this process, the stowage calculation sheet, regarding the TEU's number and arrangement will be replaced by the parametric feature that predicts the inner arrangement of containers more accurate and quick since a major part of the external computation is avoided. This approach is more robust and offers better prognosis of the total TEU's arrangement within curved hulls.*

The optimization runs at full scale factors, at design speed of 19kn where the Froude number is $F_n = 0.1872$ and Reynolds number is $Re = 2.47 \cdot 10^9$.

Design Variables, Constraints and Boundaries

Design Variables	Upper-Lower Value
Draft [m]	13.9-14.9
Height [m]	24-27.6
Half-beam [m]	24.1-27.21
AreaAtFP_SAC [m^2]	7.06-14.28
Fullness_DWL	0.63-0.72
tanAtFP_DWL [deg]	111.1-133.6
tanAtFP_SAC [deg]	140-150
xParAft [%L_{BP}]	0.255-0.333
xParFwd [%L_{BP}]	0.652-0.787

Constraints	Type of constraint	Description
controlDWL_area>0	Considered in Loop A	Geometric irregularity
controlDWL_curvature>=0	Considered in Loop A	Geometric irregularity
controlGM>0.3m	Considered in Loop A	Minimum acceptable value
controlStowageFactor>9 ton/TEU	Considered in Loop A	Minimum acceptable value
controlGM>0.5m	Considered in NSGA-II	Minimum acceptable value
controlStowageFactor>9.5ton/TEU	Considered in NSGA-II	Minimum acceptable value

Table6.27: Design variables, constraints and boundaries considered in M.O. Optimization

As it seems in the table where the used constraints are described, there is a slight modification of the design process of the multi-objective optimization. As mentioned before there is a Loop A, an inner process, where the design variant is evaluated before the SHIPFLOW calculation is activated, in order to avoid the time-consuming CFD-code when the geometry or stability or weight/TEU are not acceptable. When it comes to geometric irregularities, the model is automatically discarded. Regarding GM and stowage factor, a lower limit has been set in Loop A, so that designs which are completely out of range to be discarded before proceeding to the evaluation stage of the NSGA-II. Since the process of the genetic algorithms always requires the input of the objective function, to be evaluated and based on the result, to create the new variants*, the discarded designs are been given a value, which is though way out of the range of feasible results, so that the genetic algorithm considers of them but they cannot influence the process since they are evaluated as very bad designs. What is achieved in this way is to control whether feasible designs enter the CFD-computation or not, without disturbing the process of the genetic algorithm.*

Comments about resistance and propulsion coefficients

As described in the respective chapter, when CFD-code is utilized, then resistance is composed manually. The components of resistance are described below:

- Friction resistance coefficient is retrieved from ITTC-57 formula.
- Wave resistance is calculated in terms of wave cut analysis.
- Resistance of appendages is describes according to assumptions and formula of Holtrop method.
- The coefficient of roughness is not taken into account according to Schneekluth because at the length of 281.7 m, it is considered to be zero.

About the propulsive coefficients:

- Hull efficiency is constant at 0.99, as a mean value of former experiments.
- Relative-rotative efficiency is kept constant at 1.05 as a mean value of former experiments.
- Open-water efficiency is assumed 0.68, while the comparative concept Quantum 6000 with azipod propulsion considers it 0.7.

Evaluation of the Results

The NSGA-II created 480 designs with 89% feasibility. The range of the particulars, the evaluation and the objectives are listed below:

Particulars	Boundaries
L_{BP}(m)	281.7
B(m)	46-48.68
T_{Design}(m)	13.9-14.87
D(m)	24.2-27.2
C_B	0.586-0.651
C_P	0.746-0.828
C_{WP}	0.842-0.906

Evaluations	Boundaries
DWT(ton)	80,988-100,030
R_{Total} (XPAN-ITTC)(kN)	1,226-1,496
$Power_{Total}$ (kW)	25,881-31,272
PAYLOAD/$TEU_{homogenous}$ (t/TEU)	9-11
$GM_{initial}$ m	0.5-3.2

Objectives	Boundaries
Wetted Area(m^2)	14,353-15,784
EEDI	8.98-10.96
Nominal TEU's Capacity	7,604-8,814
Ballast(ton)	9,236-15,161

Table6.28: Results of M.O. Optimization.

The following diagrams depict the scatter of the objectives per two. It is shown that the best compromises have been achieved since the Pareto-Frontier is apparent in every diagram. Except from the feasible optimized designs, there are also illustrated the reference design (red) and the designs, which violated the constraints (reduced GM or low weight/TEU factor).

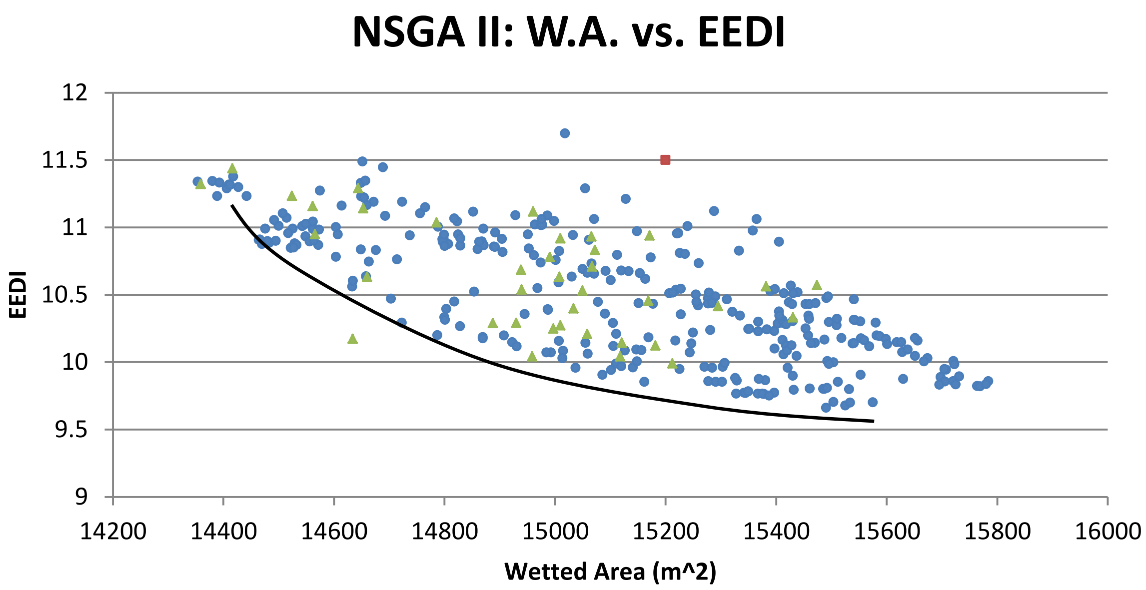


Figure6.25: Design variants of M.O. Optimization. Wetted area vs. EEDI.

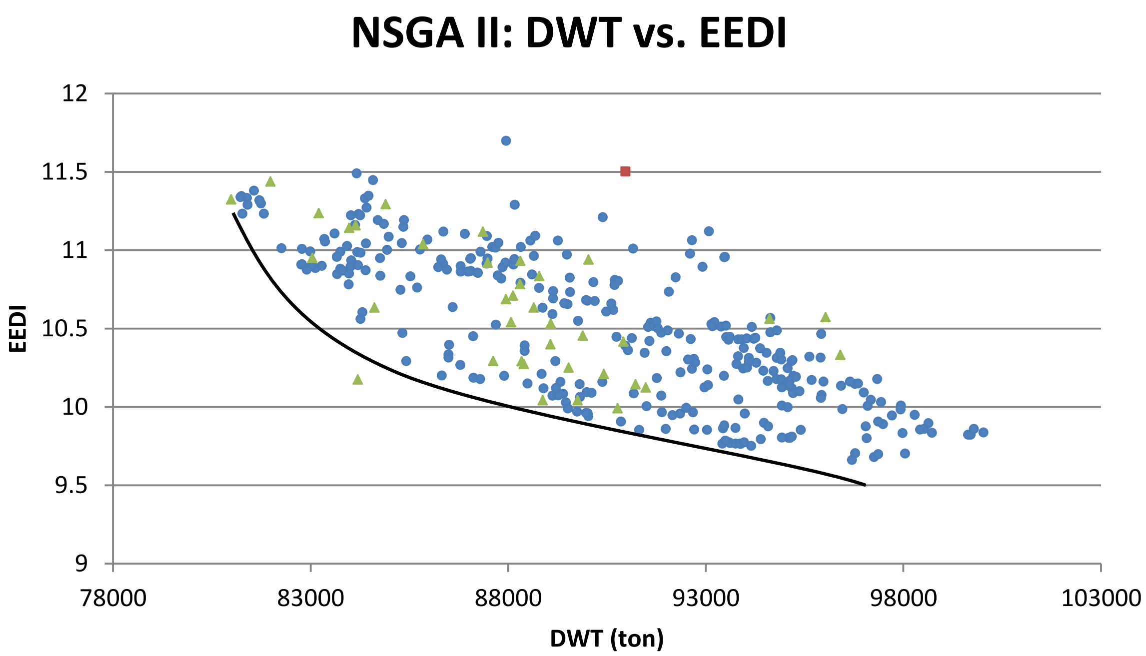


Figure6.26: Design variants of M.O. Optimization. DWT vs. EEDI.

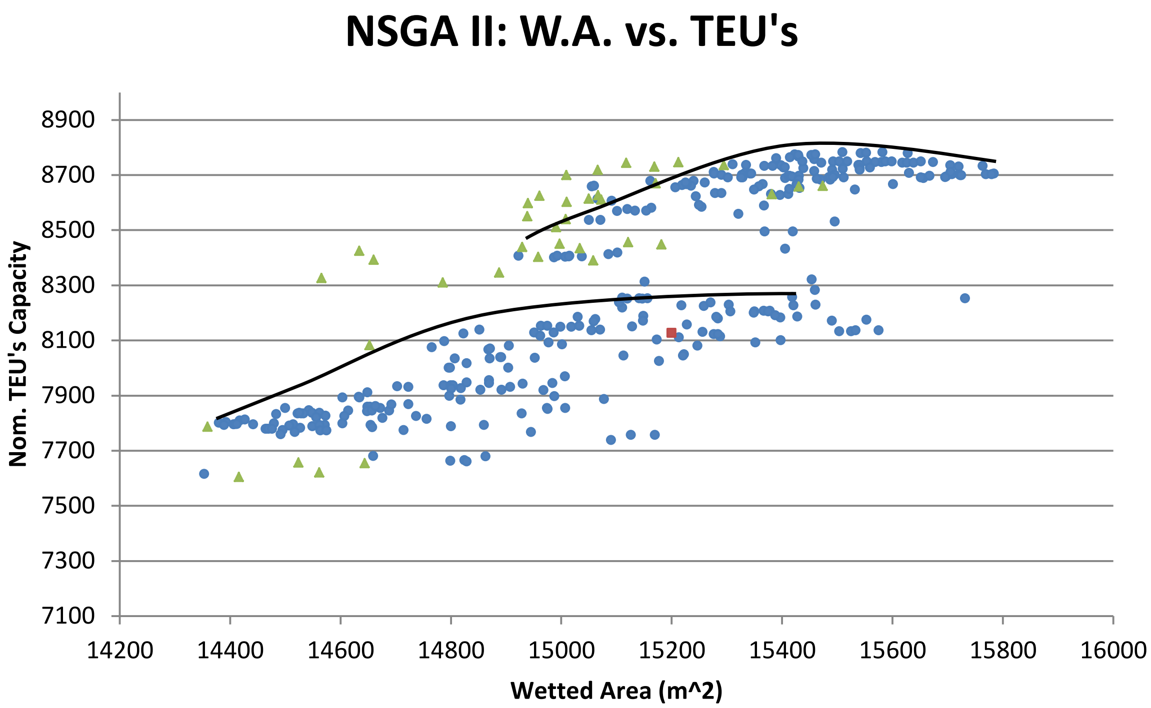


Figure6.27: Design variants of M.O. Optimization. Wetted Area vs. TEU.

Chart legend

The blue circle stands for the feasible optimized designs.

The red square stands for the baseline design (SternSelection_No. 10).

The green triangle stands for the designs that violated the constraints.

The black line represents the created Pareto-Frontier.

Comments

In every diagram, the reference design is not close to the Pareto-Frontier in terms of the objectives. That proves the fact that there was a merit, and that the genetic algorithm has completed its task successfully. In two of the diagrams the majority of the violating designs are within the feasible space. That may be explained by the fact that the constraints were set in a subjective manner and had a soft influence. In the third diagram seems like there are two Pareto Frontiers (two lines where the density of design appearance is increased) and that can may be explained by the fact that the variation of the beam on deck beam allowed either 18 or 19 rows of containers, and that may be characterized as a steep change. Therefore it can be assumed that the NSGA-II found the best compromises for two categories, one with 18 rows of TEU's on deck and one with 19.

6.10.5 Selection of "best" designs

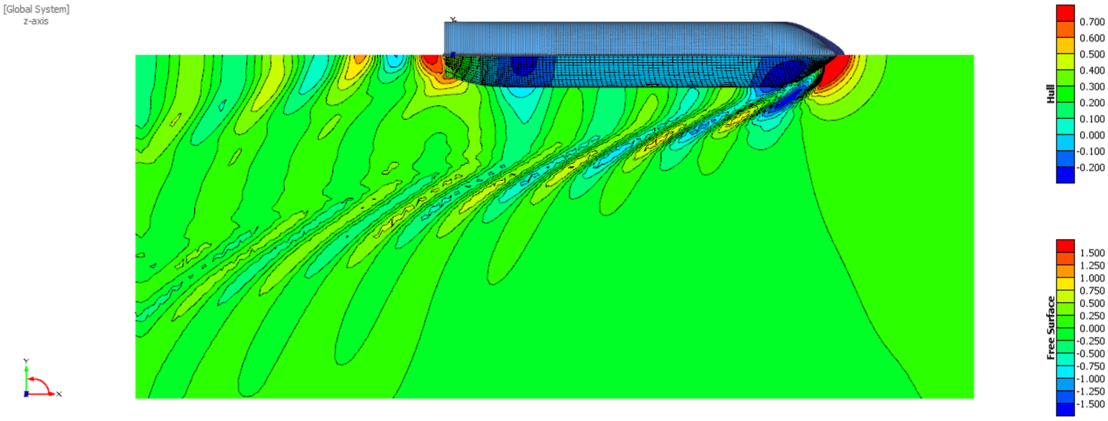
The multi-objective optimization created a wide variety of feasible designs. It also achieved to develop designs of best compromise regarding two objectives each time, while keeping the constraints in an acceptable range. Pareto frontiers in the above tables prove this fact. In order to choose some best variants, prioritized criteria should be implemented in order to meet specific needs. There are formal procedures for this task like Multiple Attribute Decision Making (MADM) presented by Sen and Yang [15]. In this case, a manual exploitation of the design space is conducted.

The aim is to discover three designs that best compromise the main objectives (Wetted surface, EEDI, TEU capacity). The desired variants should have an initial GM>1m so that intact stability with a small amount of ballast water required, is ensured. This assumption is based on the fact that the E4-containership, which was subjected to stability analysis, held an initial GM of 0.5m and required a total ballast water of 7000tons that raise GM to 4m and new designs do not differentiate significantly from this baseline. Therefore an initial GM>1m (without ballast water) may be considered adequate and conservatively approached.

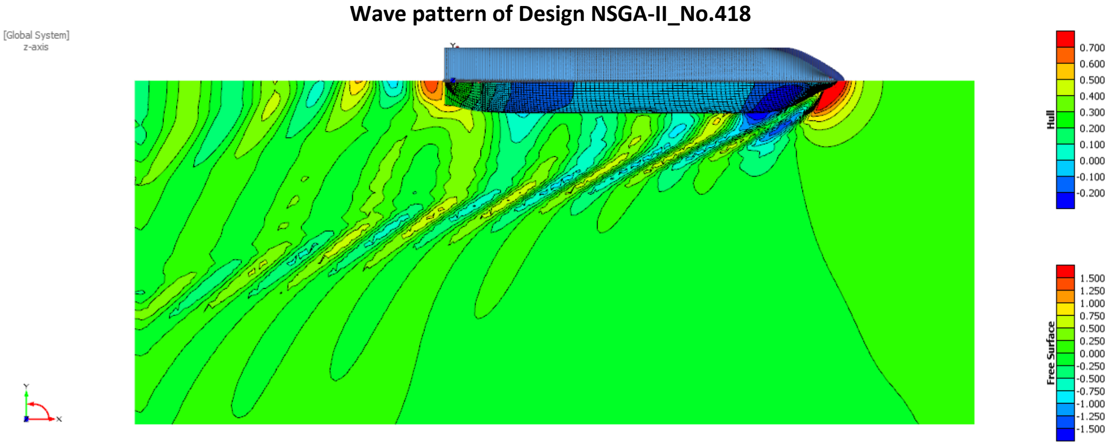
The three design variants which are considered "best" are listed in the following table with all their main dimensions and particulars:

Item	NSGA-II_No.418	NSGA-II_No.426	NSGA-II_No.445
L_{BP}[m]	281.7	281.7	281.7
B[m]	48.3	48.56	46.68
T[m]	14.07	14.87	13.95
D[m]	27.2	24.72	24.7
LCB[m]	146.5	147.67	145.74
C_b	0.649	0.622	0.596
C_p	0.827	0.792	0.759
C_{WL}	0.903	0.888	0.866
W.S. [m^2]	15569	15551	14458
Volume[m^3]	123886	125091	107999
DWT[ton]	95055	97555	81344
TEU	8814	8136	7854
EEDI	10.12	9.62	11.01
Payload/TEU[ton/TEU]	9.82	11.02	9.44
BHP[kW]	29076	28369	27069
GM[m]	1.32	2.47	1.79

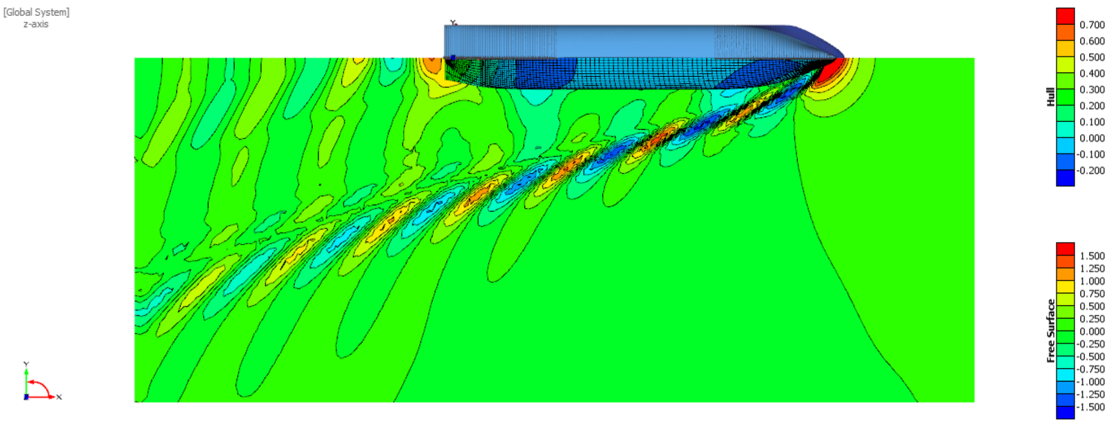
Table6.29: Selected "best" designs.



Wave pattern of Design NSGA-II_No.418

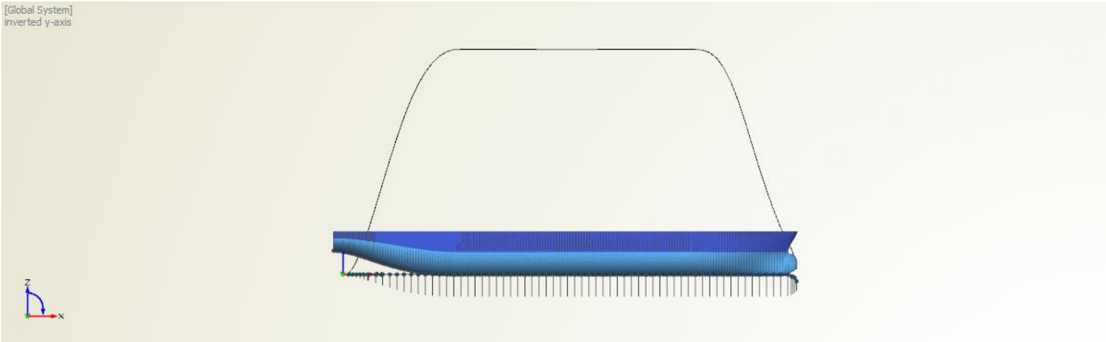


Wave pattern of Design NSGA-II_No.426

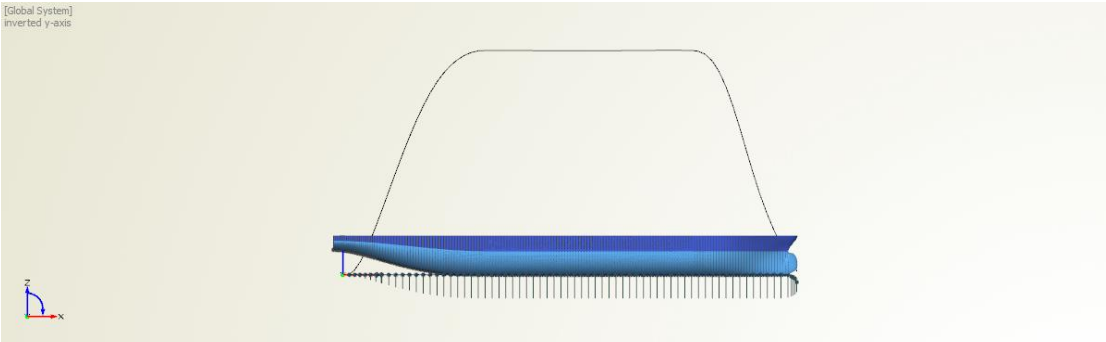


Wave pattern of Design NSGA-II_No.445

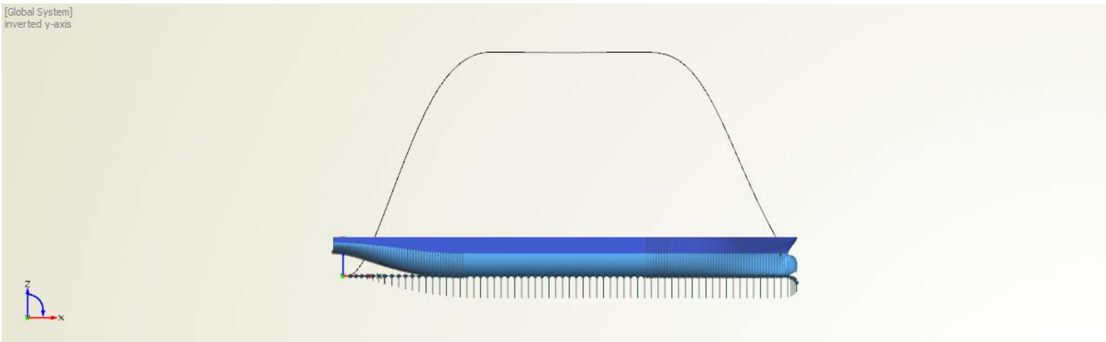
Item	NSGA-II_No.418	NSGA-II_No.426	NSGA-II_No.445
$R_W(\%R_R)$	46.2	43.5	58.4
$R_R(\%R_T)$	21.4	19.9	22.4



Sectional Area Curve of Design NSGA-II_No.418

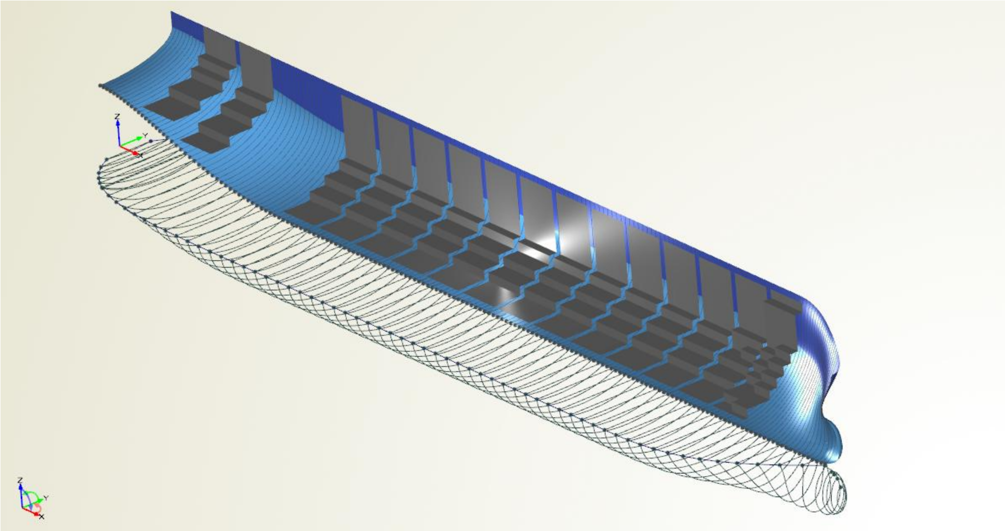


Sectional Area Curve of Design NSGA-II_No.426

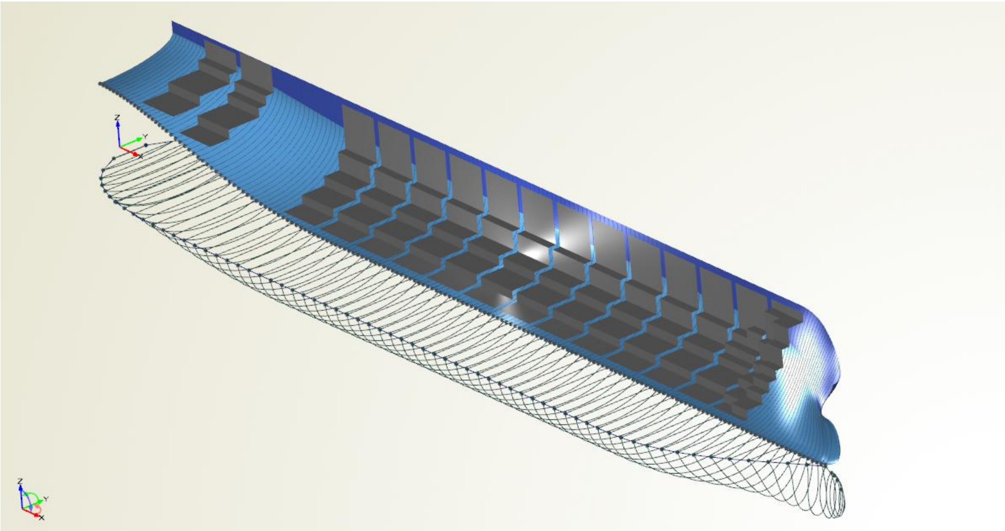


Sectional Area Curve of Design NSGA-II_No.445

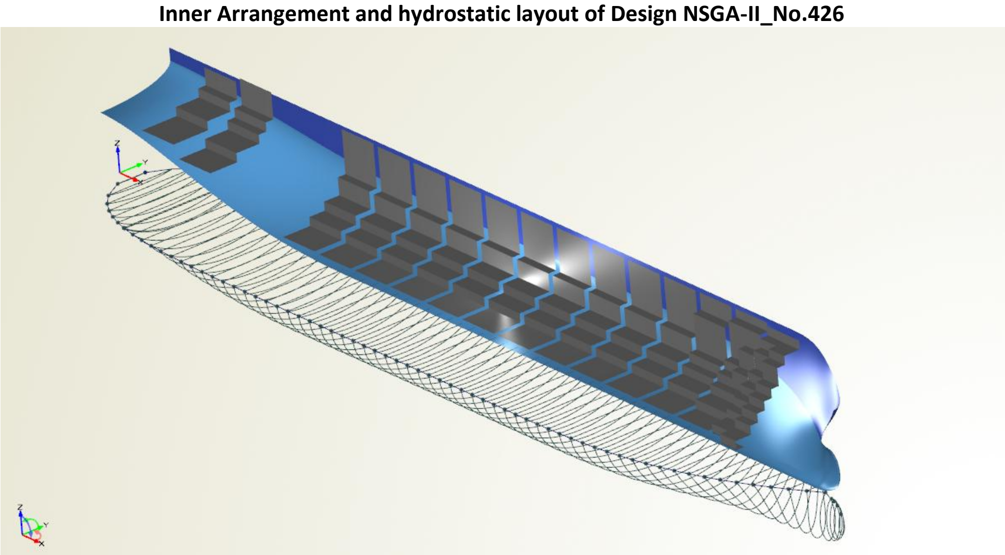
Item	NSGA-II_No.418	NSGA-II_No.426	NSGA-II_No.445
Length of Parallel Body [m]	148.4	131.65	98
$L_{PAR.BODY}(\%L_{BP})$	52.7	46.7	34.8



Inner Arrangement and hydrostatic layout of Design NSGA-II_No.418

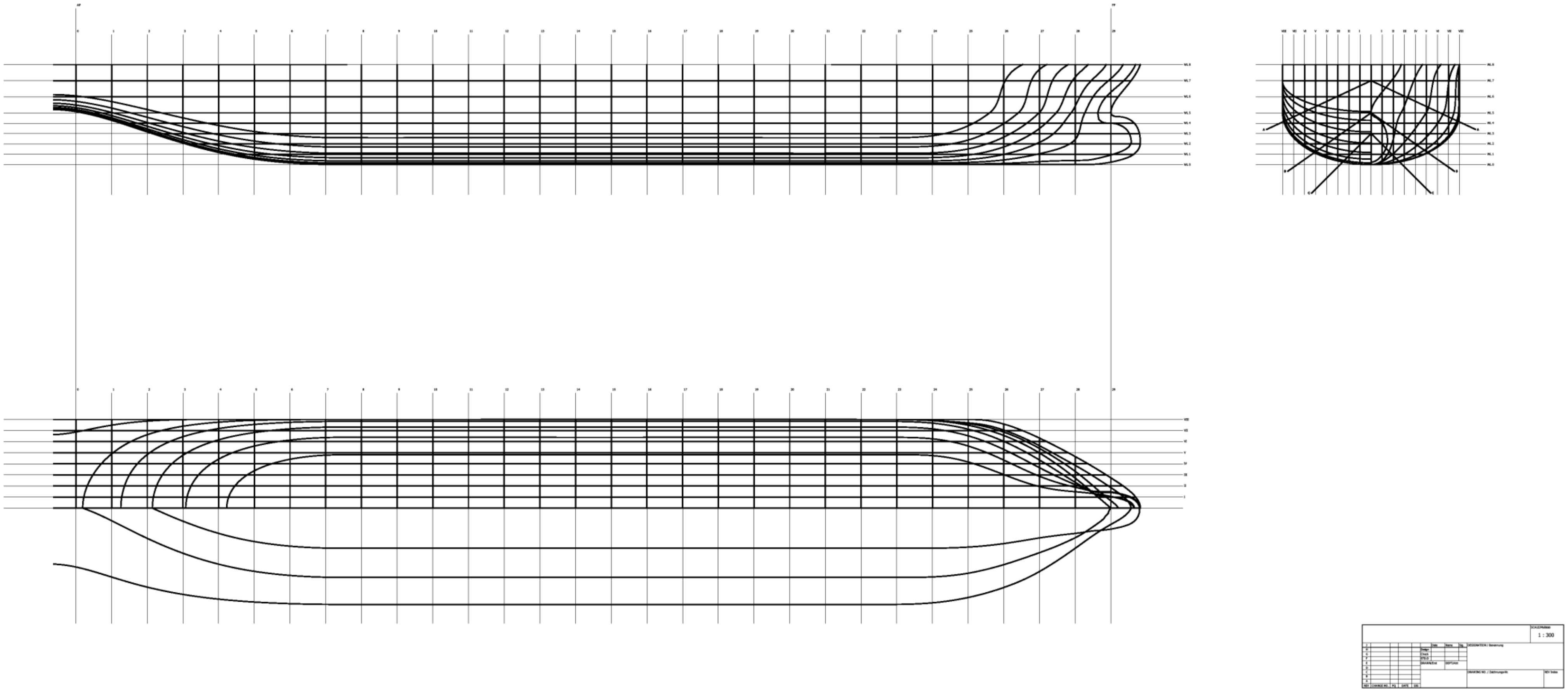


Inner Arrangement and hydrostatic layout of Design NSGA-II_No.426

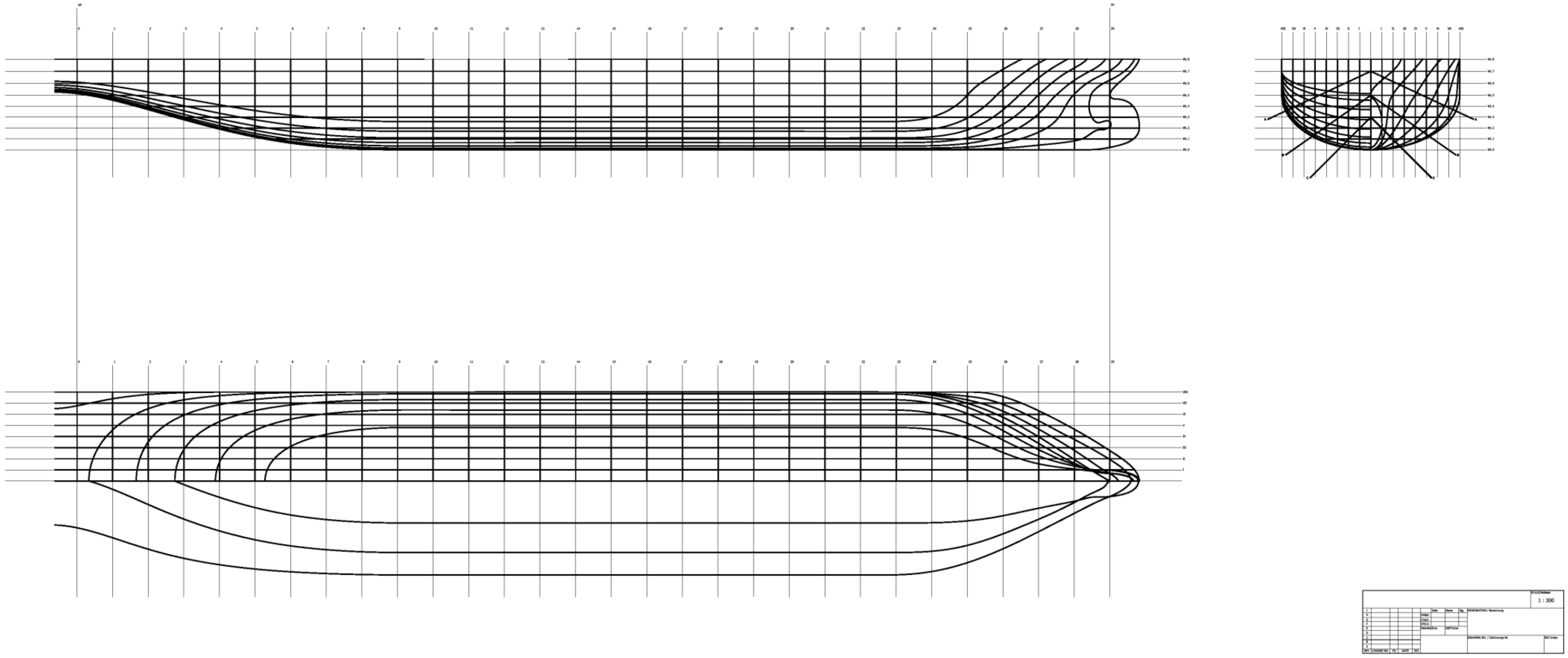


Inner Arrangement and hydrostatic layout of Design NSGA-II_No.445

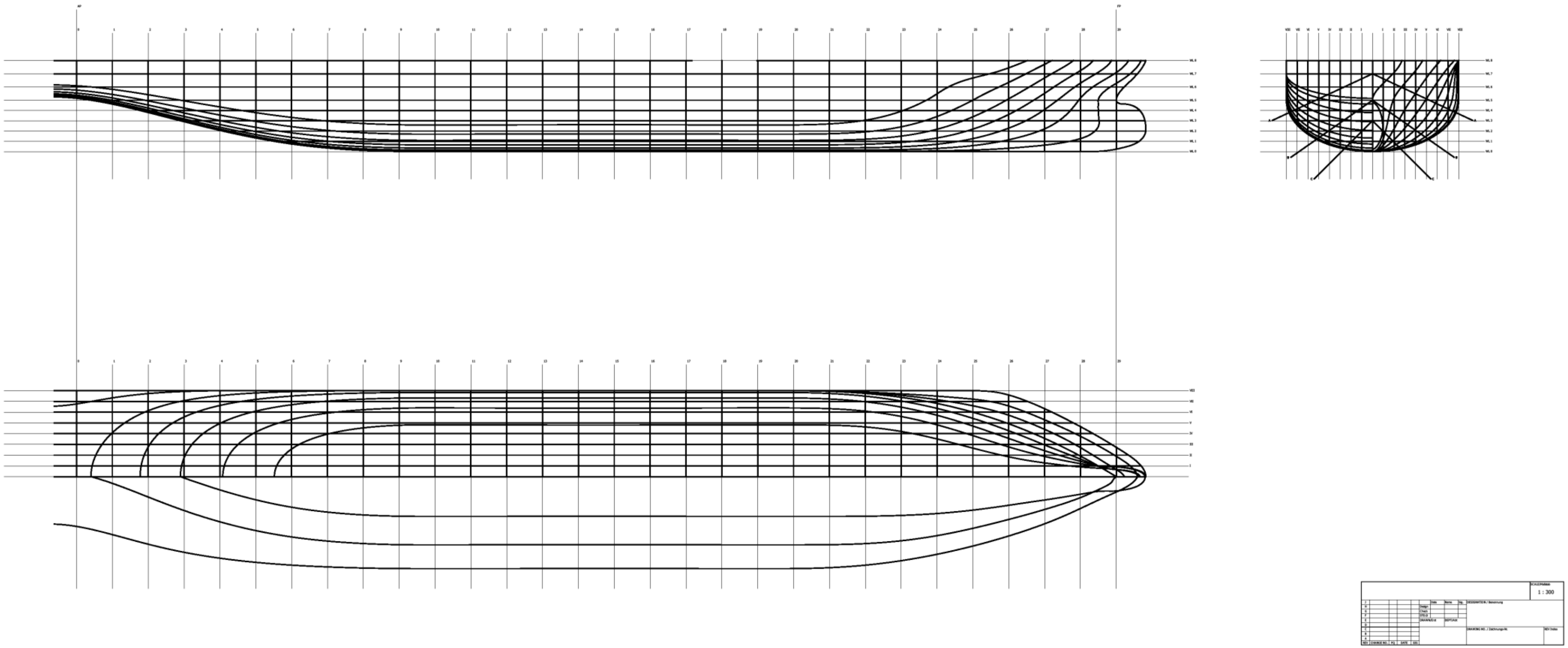
Item	NSGA-II_No.418	NSGA-II_No.426	NSGA-II_No.445
TEU in Hold (%Total)	4292 (48.7)	3614 (44.4)	3570 (45.5)



Lines-Plan of Design NSGA-II_No.418



Lines-Plan of Design NSGA-II_No.426



Lines-Plan of Design NSGA-II_No.44

6.10.6 Discussion over the results of Resistance

If we focus on the results of the SHIPFLOW calculation, valuable information may be exported. The well known fact that moving the longitudinal center of buoyancy (LCB) forward in ships of low Froude number, leads to a reduction of the wave resistance, may be proved by the following diagram. The wave resistance is expressed in terms of the non-dimensional coefficient C_{WTWC}, of the wave cut analysis and lcb expresses the LCB as a percentage of L_{BP}. The performance of the previously selected "best" designs is also depicted.

With respect to block coefficient C_B, it has been found that the wave resistance is reduced for the values of C_B=0.62-0.63.

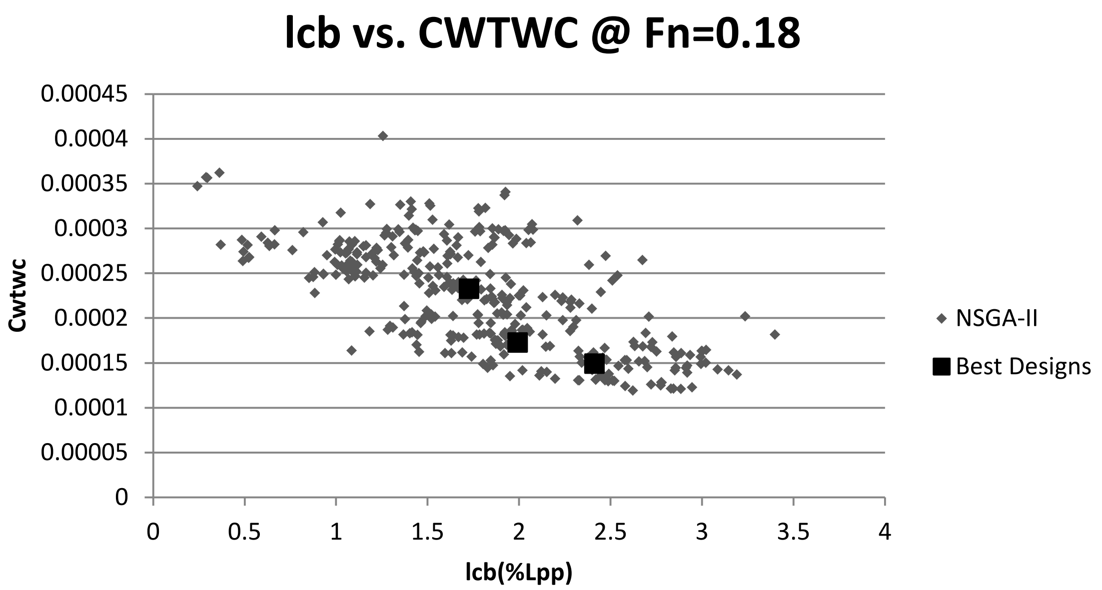


Figure6.28: Resistance results of M.O. Optimization. Lcb vs. Cwtwc

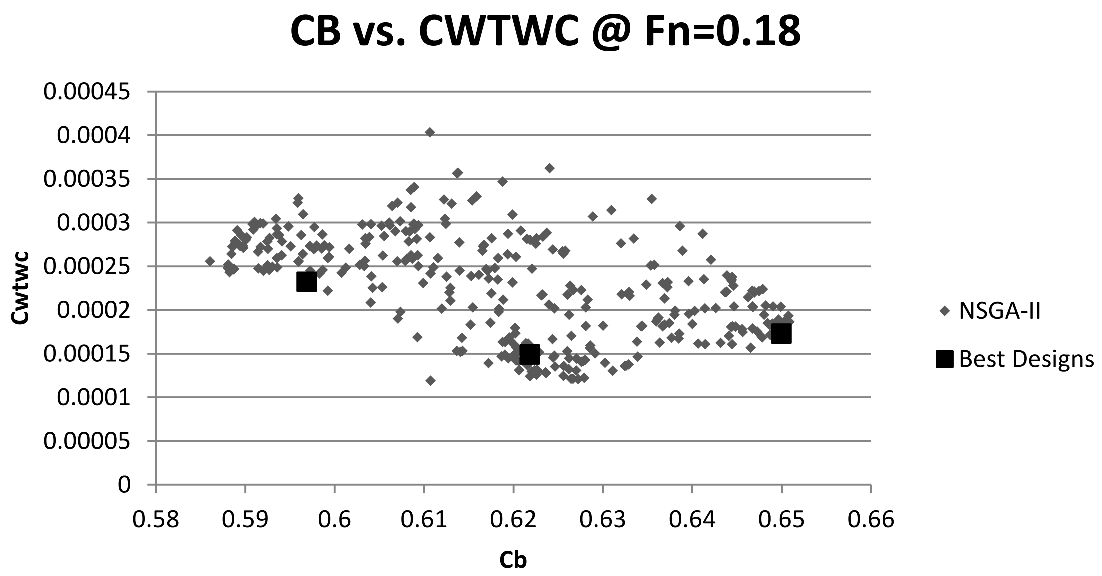


Figure6.29: Resistance results of M.O. Optimization. Cb vs. Cwtwc

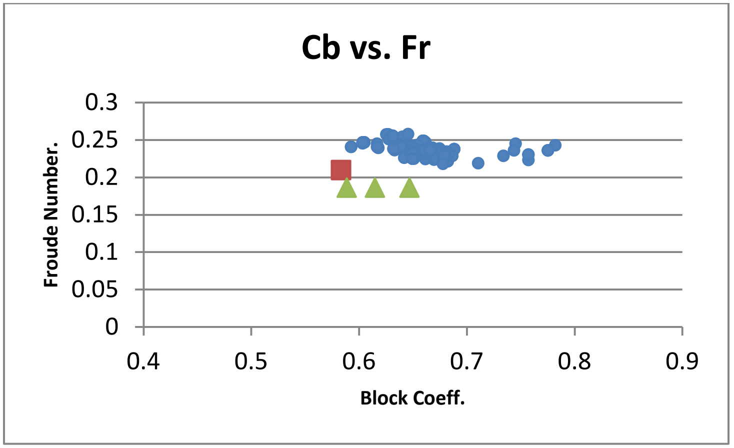
6.11 Results-Comparative assessment

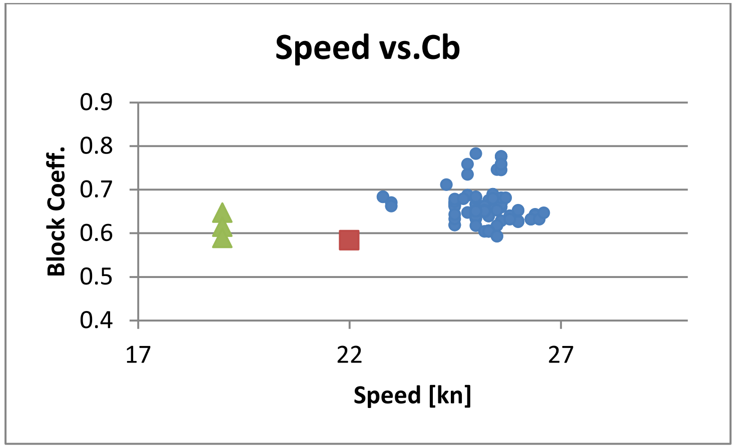
In the previous chapter, the methodology that led to a multi-objective optimization was analyzed, focusing on the potentiality of parametric design.

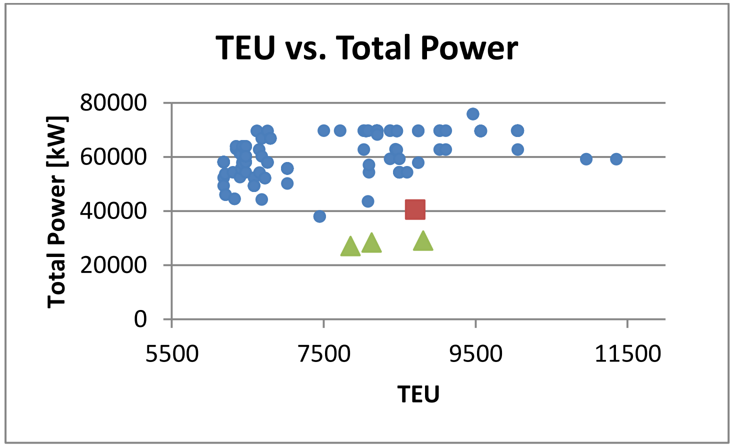
In this chapter the resultant designs will be evaluated in terms of main particulars and efficiency compared to existing ships and other innovative designs. For this task, a list of conventional containerships within the range of 6,000-11,000 TEU capacity [45] is employed. In addition, the parametric sample containership, included in FRIENDSHIP-Framework [19], is utilized. This is a fully parametric design of a 2700 TEU containership and it will be regenerated with appropriate modifications of some global parameters in order to simulate the hull form of existing ships and allow thorough comparisons with the E5-Containership on the basis of hull shape.

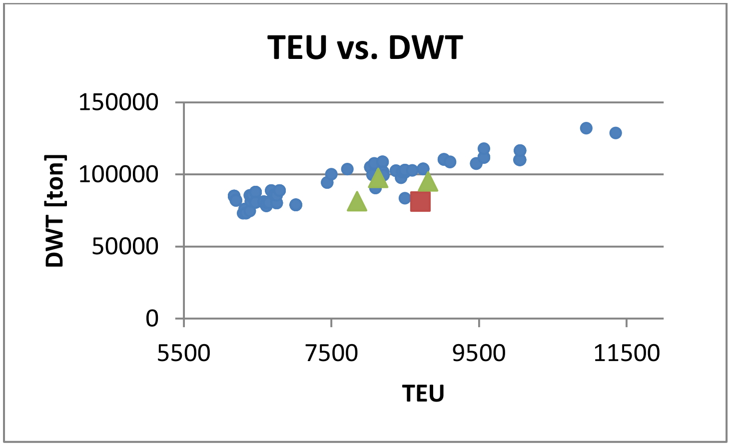
6.11.1 General Particulars

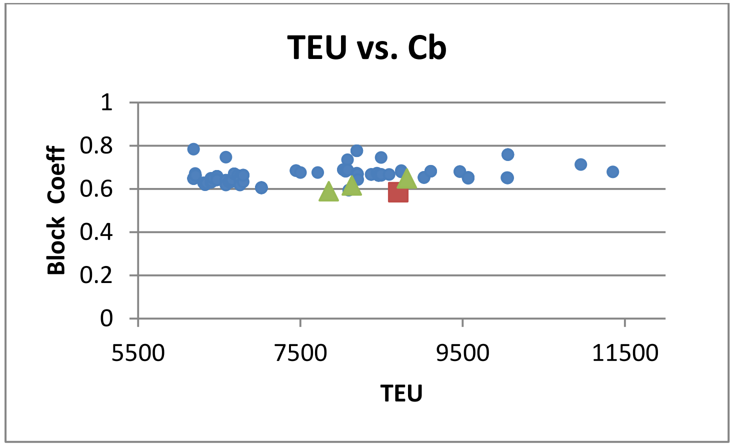
In the following tables a comparison between existing ships, the innovative design Quantum9000 (DNV) [46] and the selected as “best” variants from the optimization, is presented.

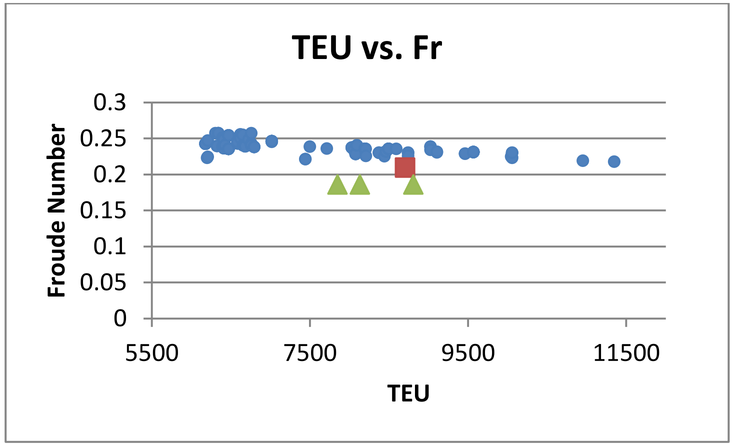

Cb vs. Fr
Froude Number.
0.3
0.25
0.2
0.15
0.1
0.05
0
0.4
0.5
0.6
0.7
0.8
0.9
Block Coeff.

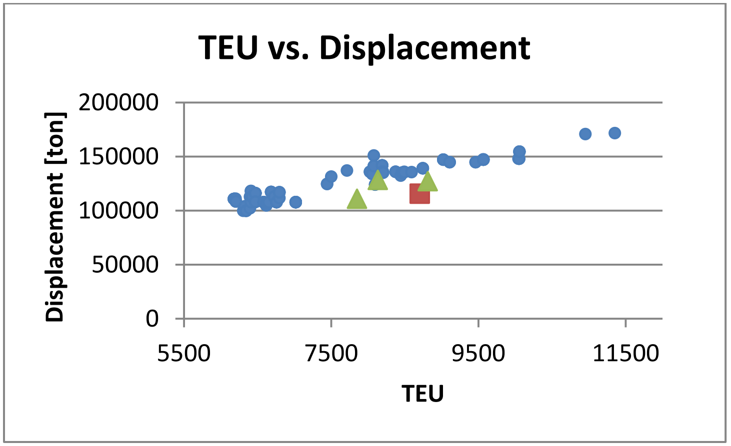

Speed vs.Cb
Block Coeff.
0.9
0.8
0.7
0.6
0.5
0.4
17
22
27
Speed [kn]

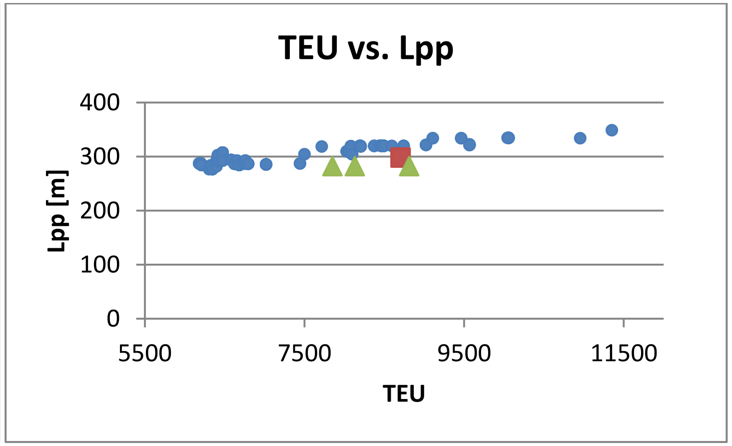

TEU vs. Total Power
Total Power [kW]
80000
60000
40000
20000
0
5500
7500
9500
11500
TEU

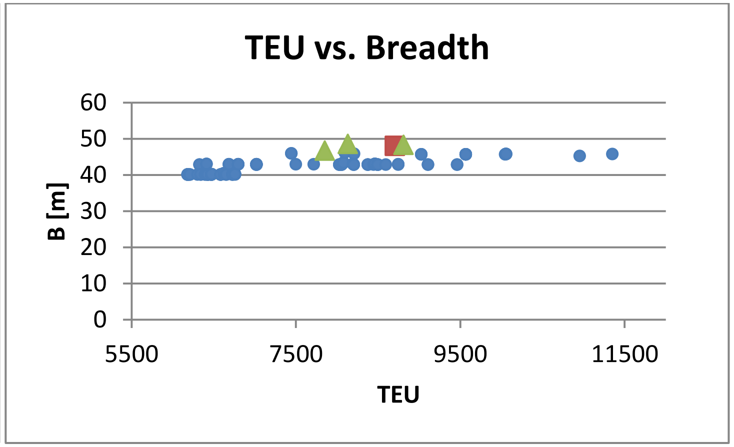

TEU vs. DWT
DWT [ton]
150000
100000
50000
0
5500
7500
9500
11500
TEU

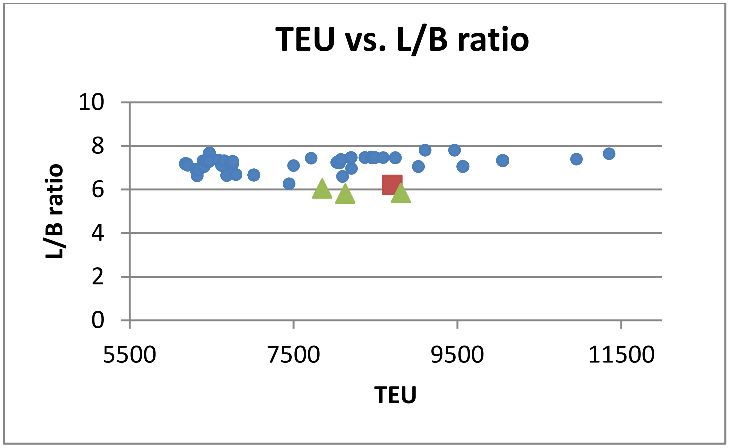

TEU vs. Cb
Block Coeff
1
0.8
0.6
0.4
0.2
0
5500
7500
9500
11500
TEU

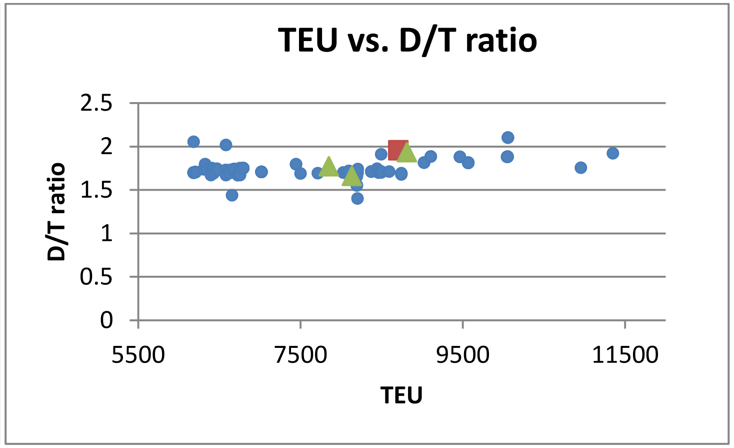

TEU vs. Fr
Froude Number
0.3
0.25
0.2
0.15
0.1
0.05
0
5500
7500
9500
11500
TEU

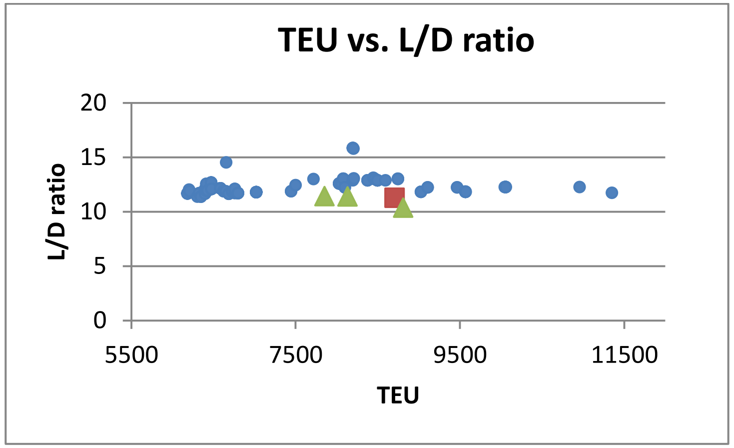

TEU vs. Displacement
Displacement [ton]
200000
150000
100000
50000
0
5500
7500
9500
11500
TEU

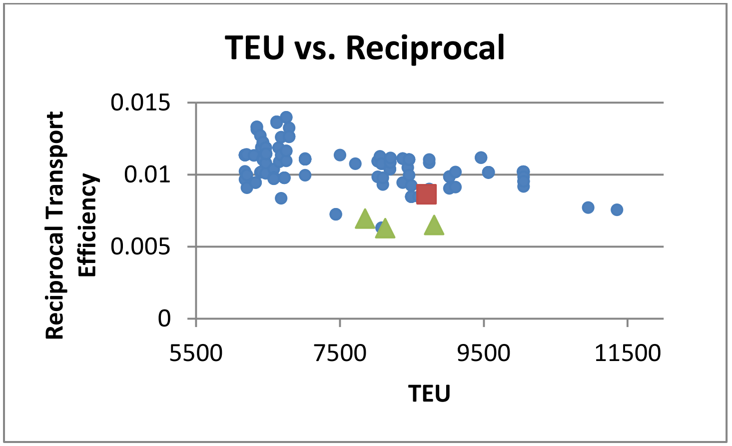

TEU vs. Lpp
Lpp [m]
400
300
200
100
0
5500
7500
9500
11500
TEU

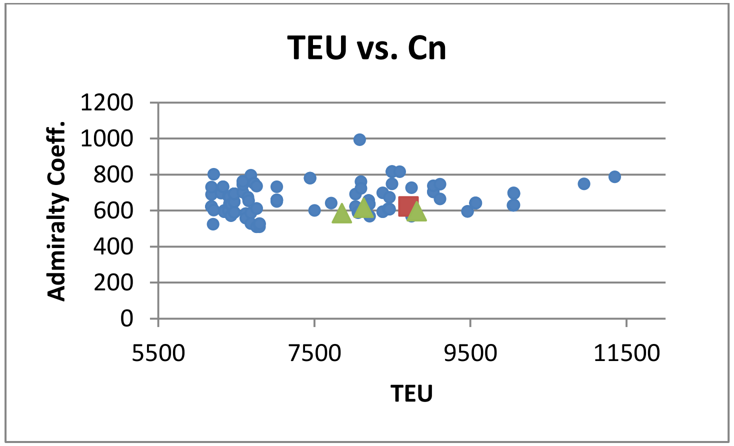

TEU vs. Breadth
B [m]
60
50
40
30
20
10
0
5500
7500
9500
11500
TEU

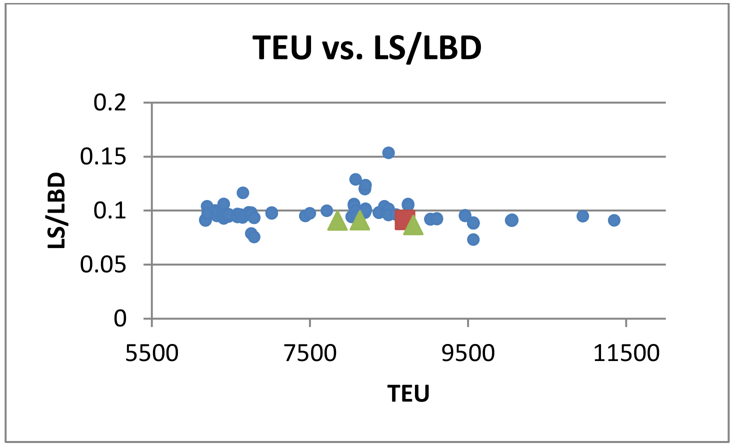












Charts legend

The blue circle stands for the feasible optimized designs.

The red square stands for Quantum9000 (DNV).

The green triangle stands for the selected “best” designs.

From the tables above it may be concluded that the design NSGA-II_No.426 is rather competitive against the novel conceptual containership Quantum9000. In the following table a thorough comparison between these designs and additionally an existing containership COSCO NINGBO providing an insight in the properties and features is presented on the following table.

ITEM	*Cosco Ningbo*	*Quantum 9000*	*NSGA-II_No.426*
L_{bp}(m)	333.4	297.7	281.7
B(m)	42.8	48.0	48.6
T_D(m)	14.5	13.5	14.9
D(m)	27.3	26.4	24.7
C_b	0.68	0.58	0.62
C_M	0.97	0.96	0.79
C_P	0.70	0.60	0.79
C_{WP}		0.76	0.89
Wetted Area(m^2)	18,010	15,640	15,551
Displacement(ton)	144,227	115,587	128,343
DWT(ton)	107,277	81,155	97,555
L.S. (ton)	36,950	34,432	30,788
TEU(total)	9,469	8,708	8,136
TEU(on Deck)	4,796(8 TIER)	5,570(9 TIER)	4,522(7 TIER)
TEU(in Hold)	4,673	3,138	3,614
Design Speed(kn)	25.4	22.0	19.0
EEDI		8.5 (approx.)	9.6
DWT/TEU	11.3	9.3	11.9
BHP(kW)	74,800	(@19kn&T13m& Δ109,996ton) 20,772	28,369

Table6.29: Comparison between COSCO Ningbo, Quantum 9000 and design NSGA-II_No.426

The created design No.426 may well compete with the other candidates in the field of its purpose. It should be noted that the E5-Containership project refers to ships of lower and yet competitive speed.

The distinctive geometric properties of the elliptic ship are obvious. It is a shorter and beamer ship, while prismatic and waterplane coefficients remain high, providing the vessel with a large parallel body and increased initial stability.

From available information it is shown that the Quantum9000 for the same speed and lower displacement requires proportionate power as the examined variant. *It should be also noted that the BHP of E5-Containership consists of propulsion and consumers' power demands due to the installation of D/E plant, while the annotated BHP of the other vessels refer only to propulsion.*

Quantum9000 has a low EEDI due to the usage of the efficient LNG fuel.

It should be clarified also that the nominal TEU capacity of the DNV project and the COSCO vessel are considered to be too increased compared to their actual capability and do not comply with stability regulations. Additionally the ratio DWT/TEU reveals the insufficient capacity of Quantum, while the variant of E5 hold a ratio, which is even better than that of the existing ship. More information and evaluation about stowage and container capacity is presented in the respective chapter.

6.11.2 Wetted Surface

The E5-project had as objective the reduction of wetted surface, based on the assumption that the resistance of a slow speeding ship is dominated by frictional resistance, and this component is proportional to the wetted area.

In order to have a clear picture of the existing ships compared to the E^5, a database of containerships is formed. Ships of the range between 8,000 and 12,000 TEU's were collected and put together creating the design space of the existing designs.

With elaboration of the results a table is created that illustrate the features of E^5 compared to the conventional container ships and to the innovative Quantum 9000.

The calculation of the wetted surface is based on the reliable empirical formula that Holtrop-Mennen proposed.

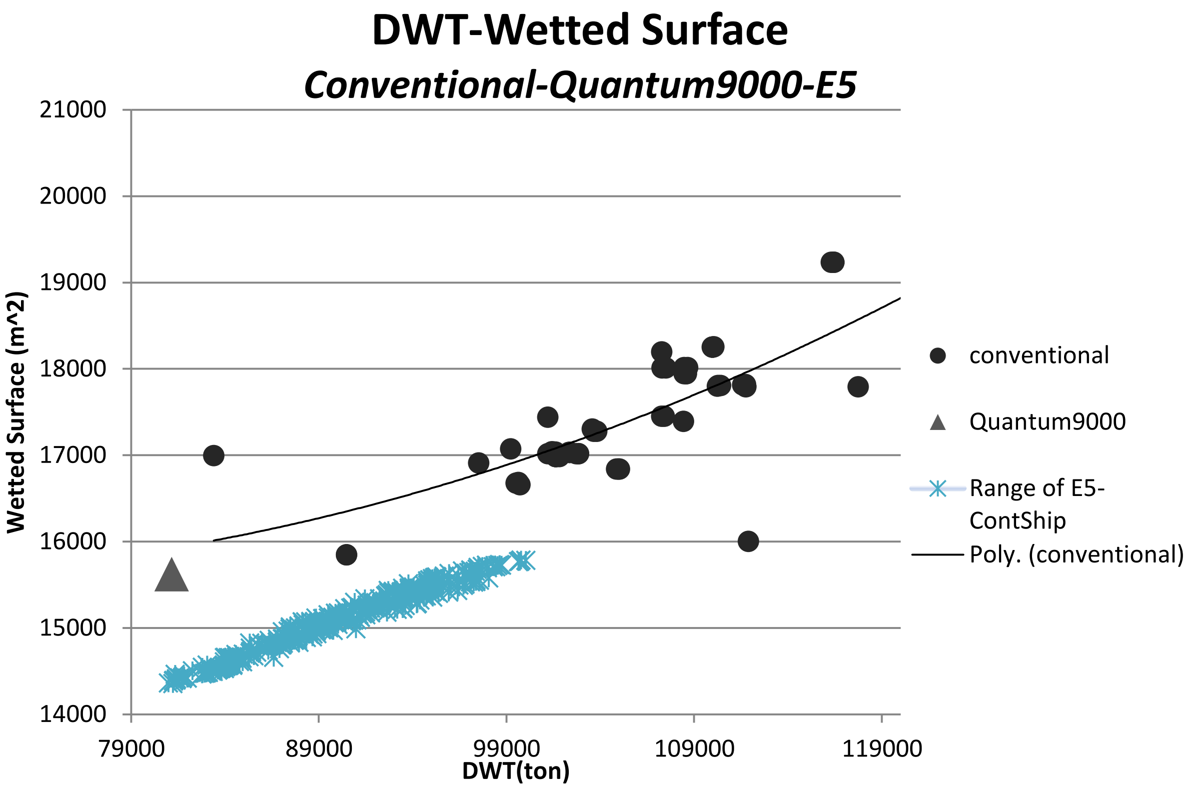


Figure6.30: Comparison of Wetted surface vs. DWT for E^4, Q9000 and conventional designs

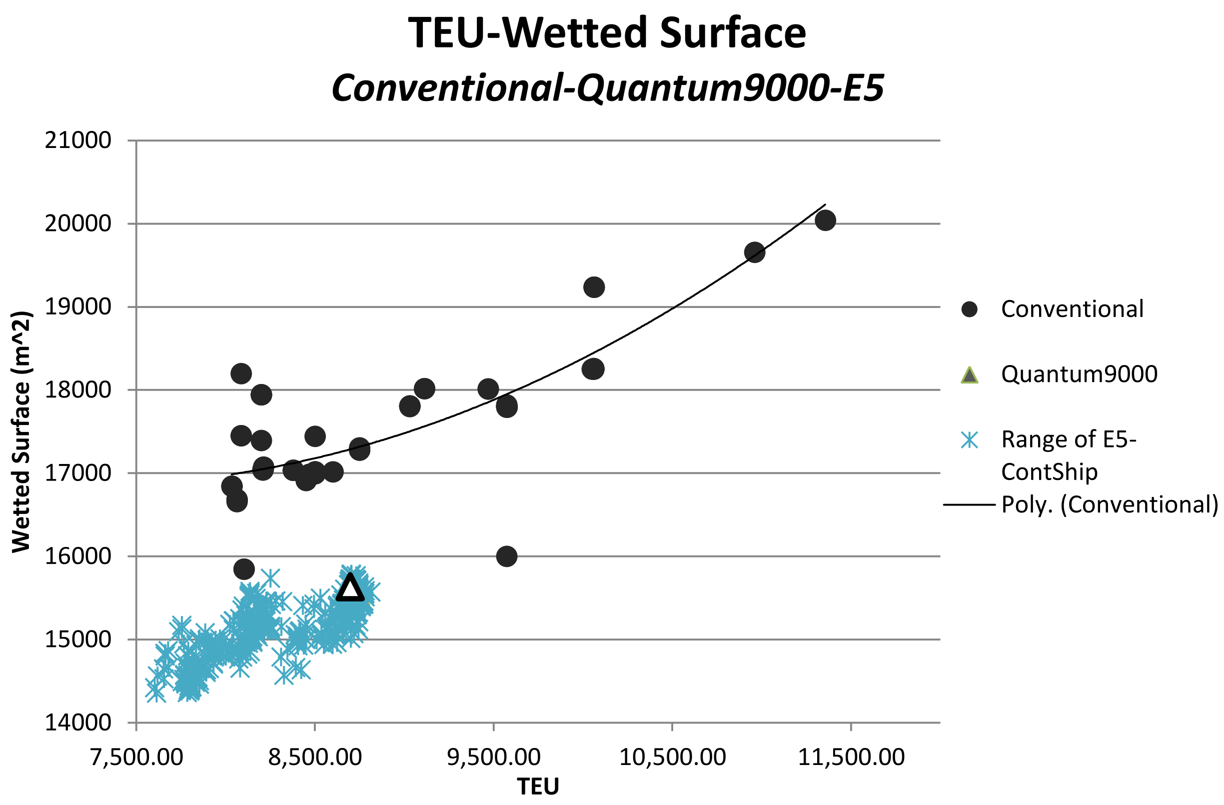


Figure6.31: Comparison of Wetted surface vs. TEUs for E^4, Q9000 and conventional designs

From figures [6.30, 6.31] it can be concluded that the target of minimizing the wetted surface has succeeded. The E^4 has about <u>*12% less wetted surface* that the conventional vessels</u> and a comparatively increased capacity. That is mainly due to the large beam, the long parallel body and the translation of the deckhouse close to the fore peak.

Thus, the novel design will be compared to conventional containerships regarding the wetted surface at same displacement. The point is to show that the conventional containerships which are normally designed to sail at higher speed are inferior when it comes to slow steaming due to comparably increased wetted surface. Two conventional vessels were parametrically remodelled within the FRIENDSHIP-Framework, the COSCO-Ningbo and the APL-FINLAND.

ITEM	***<u>COSCO-Ningbo</u>***	***<u>APL-Finland</u>***	***<u>E5-ContShip Des.426</u>***
Lbp(m)	333.44	300	*281.7*
B(m)	42.8	46	*48.6*
Td(m)	13	14.1	*14.87*
D(m)	27.3	27.3	*24.7*
C_B	0.643	0.595	*0.622*
C_M	0.97	0.9899	*0.7853*
C_P	0.662	0.6	*0.792*
C_{WP}	0.78	0.7953	*0.888*
WS(m^2)	17,146	15,800	*15,550*
Δ(ton)	122,469	122,056	*128,343*
TEU	9469	8102	8136

Table6.30: Comparison between COSCO Ningbo, APL-Finland and design NSGA-II_No.426

The wetted area of the E5-containership Des.426 is slightly reduced compared to APL-Finland but for a higher displacement. In addition the elliptic vessel holds about 10% lower wetted area than the COSCO-Ningbo while its total weight is greater. In the following topic where loading conditions and required ballast are considered, the superiority with respect to certain objectives (capacity, wetted surface and additional ballast etc) will be clarified.

The following illustrations present the shape of Des.426 compared to the shape of COSCO-Ningbo. COSCO Ningbo was parametrically remodeled within the FRIENDSHIP-Framework [1], based on data retrieved from its Capacity Plan in order to calculate the Wetted Surface.

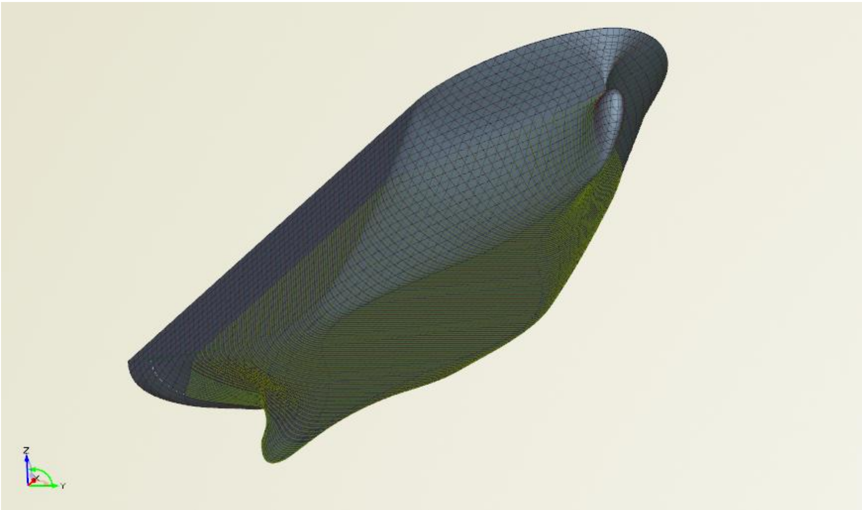


Figure6.32: COSCO-Ningbo

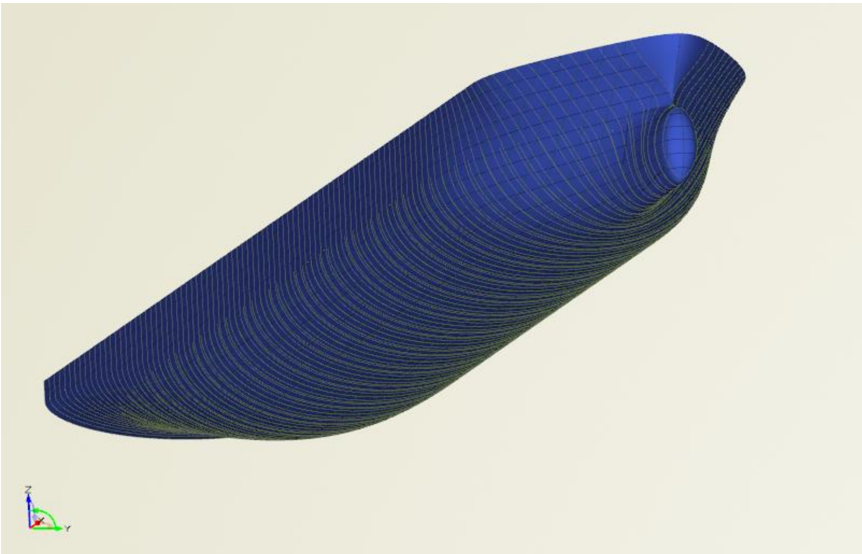


Figure6.33: NSGA-II_No.426

6.11.3 Arrangement and Machinery

The effects of unique arrangement and machinery are listed below:

- More containers on deck (at best navigational vision)
- D/E power plant in two engine rooms offering:
    - High reliability (redundancy).
    - Exploitation of the space below deckhouse.
    - Better power distribution.
    - Lower operational and maintenance costs (on kind of engines).
    - More cargo space.
- Twin Azimuth propulsion:
    - Drop of propulsion axial system. More space. Freedom in design.

A profile view of the E4-Containership derived from its General Arrangement plan is presented in the following figure. All the properties, mentioned above, may well be visualized.

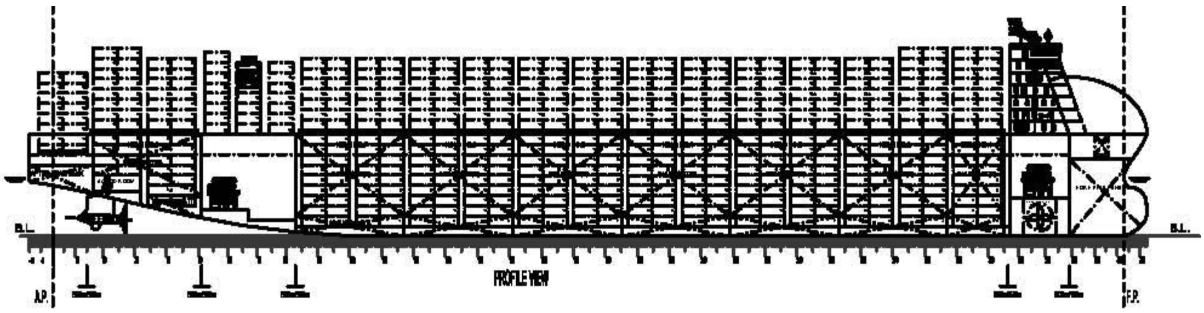


Figure6.34: Profile view of E4-containership

<u>*Engine Selection:*</u>

For the diesel-electric propulsion system, it is recommended to choose two sets of Marine Gen-Sets by MAN:

- 2 MAN 14V32/44CR of maximum power 11,200kW to be installed in the after engine room serving the main load of power needed for propulsion. It hold a specific fuel oil consumption (SFOC) of177g/kWh at 85%MCR.
- 2 MAN 8L32/40 of maximum power 4,500kW to be installed in the fore engine room under the deck house serving mainly the consumers need and powering the retractable bow thruster. These engines are also contributing to the main propulsion system and have a SFOC=185g/kWh at 85%MCR.

6.11.4 Loading conditions and Ballast water management

In order to clarify the similarity of the compared vessels regarding capacity and loading, the following table presents a comparison based on available information between COSCO-Ningbo, Baby Post Panamax (GL) [47]. The candidate variant that will compete the two others, is the E4-Containership (Phase A, Visions-Version), for which a thorough stability calculation took place and its results may be characteristic for a wide range of created variants without loss of generality.

Homo. Loading	9 ton/TEU		14 ton/TEU	
NAME	**Cosco Ningbo**	**E4-Visions**	**BPP**	**E4-Visions**
Lpp (m)	333.4	281.7	246	281.7
B (m)	42.8	47.2	37.3	47.2
T (m)	14.5	14.25	13	14.25
DWT (ton)	107,277	90,221	58,233	90,221
TEU	8,255	8,449	3,630	6,054
TEU on Deck (%Total)	3,582(43%)	4,908(58%)	n/a	2,513(42%)
Ballast (ton)	Half-Bunker	Arrival	Arrival	Arrival
	20,454	10,006	4,913	0

Table6.31: Comparison between COSCO Ningbo, Baby-Post Panamax and E4-containership over full load condition.

In the above comparison, the limited amount of carried ballast for the E4 may be noted, which is attributed to its unique hull form. *The E4 requires half the ballast water than the COSCO-Ningbo,* and it is a non-ballast vessel compared to Baby Post Panamax. *It is also remarkable the fact that in a loading condition complied with stability regulations (IMO), the E4 may carry 58% of the containers on deck, while the COSCO has the ability for 43% TEU's on deck.* That is attributed mainly to the well stability that the E4 hold. More containers on deck lead to reduction of loading/unloading procedure while being on port.

The increased stability derives from the fact that the metacentric radius (BM) is very high, due to the increased waterplane area. The long parallel body has contributed to that, as well as the low mid-ship area coefficient, because it provides a good compromise of displacement and waterplane area. The unique arrangement of E4 allows more stowage on deck, so that the stability advantage to be exploited.

6.11.5 Energy Efficiency Design Index (EEDI)

Figure 6.35 illustrates the EEDI for containerships, using 65% of their deadweight as measure for the utilization. From this table it is obvious that for a given deadweight requirement, the EEDI may vary significantly in terms of ship size. The range of all variants of E5-Containetship at 19kn appears also in the graph (blue ellipsoidal surface) and is much lower than the reference line proposed by MEPC.1/Circ.681. The sea margin has been assumed at 15% and the loading of engines at 85% MCR, while the power losses due to D/E plant are up to 8%. For the EEDI calculation a SFOC of 175 g/kWh, is considered.

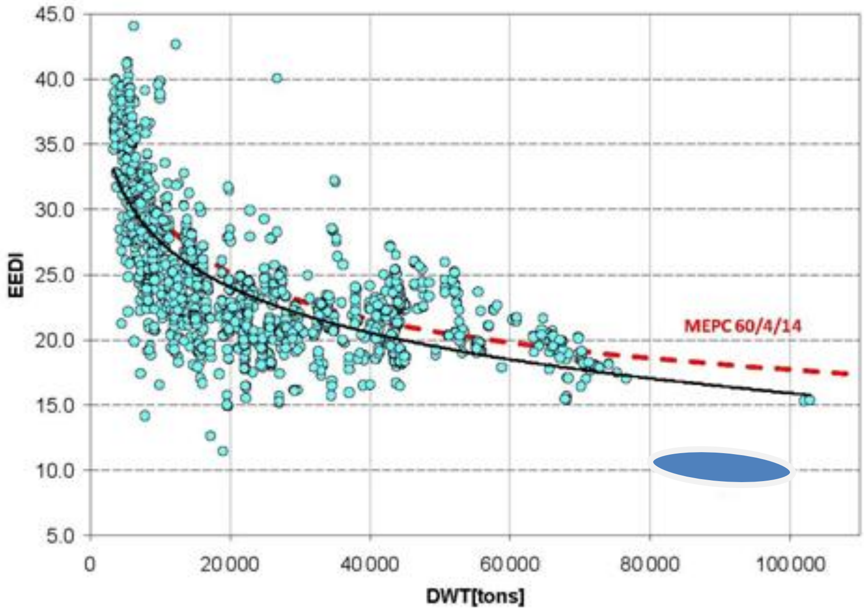


Figure6.35: E5-Containership range compared to existing ships over EEDI.

As a comparative ship is set the Baby-Post-Panamax, designed by GL. Although it is a significantly smaller ship (about 60,000 DWT), the following graph allows comparison. In figure 6.36 the range of the optimized designs remains below these lines, complying with the regulations for the first and second phase. It has been achieved due to the lower design speed and the reduced power demand.

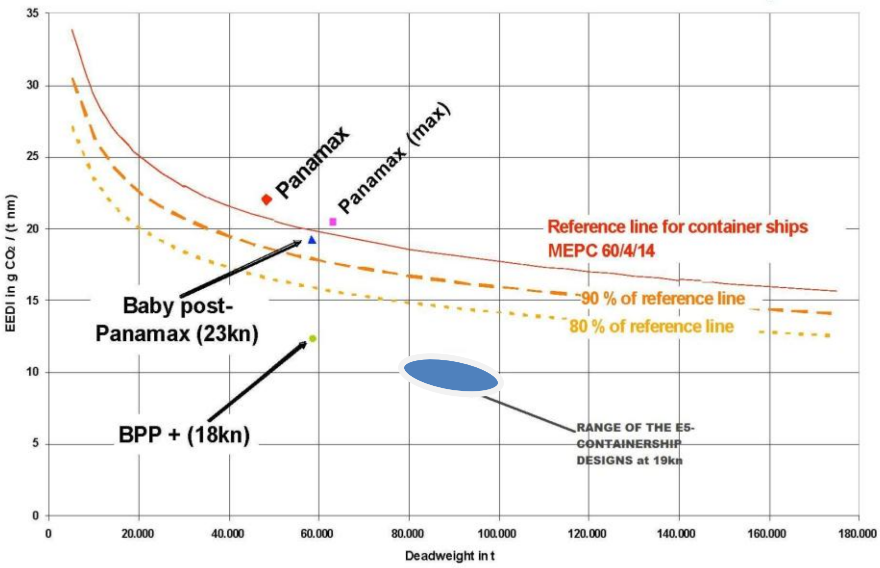


Figure6.36: E5-Containership range compared to existing ships over EEDI.

6.12 Discussion and proposals

The container ship market is an increasingly important and attractive transport market segment, which may be expected to become of even greater importance in the future. The future although is very fog and the shipping industry should be ready to adapt to any unexpected evolution. The global economy has proven unstable during the last years. The return to the good old days seems difficult if the contributing component continue to be unwilling to do the big step forward. The increasing concern about environmental issues pushes the ship owners to comply with more strict legislation. The continuously increasing oil prices make the alternative energy sources even more tempting but the new technologies are still too expensive. The new markets that boom in the East tend to change the balance.

The E^4 containership is an effort for greener, more efficient ships and the big advantage of it is that it is ready to be build based on available and proven technology. The importance of the issues that concerns the E^4 design may reflect on the fact that significant organization like the DNV and the GL are already involved in the investigation of these research areas.

Some proposals for further investigation, regarding the unique characteristics of the E4-Containership and the optimization model are:

- Investigation of the response in rolling motions.
- Examine the installation of more conventional power plant. A two-stroke engine would be more appealing according to current manufacturing trends.
- Increase of the flat side in order to reduce manufacturing cost. Examine the hull form design also from production aspect.
- Optimization of the vessel for more than one design speeds so that the ship's flexibly confronts the market fluctuations.
- Integration of specialized software in the optimization process, in order to cover more tasks of the ship design problem. Coupling with software regarding structural analysis, intact/damaged stability, economic model, etc would form a more accurate model.
- Coupling the optimization model with viscous flow computation. This application is still avoided due to the time-consuming procedures, but significant improvement has been noted in the late years.
- Cross-flow analysis on the E4-Containership, to examine the merits of ellipsoidal shape.
- Application of the ellipsoidal concept to other ship types (bulk carries, tankers...)
- Alternative optimization strategies.

7. Conclusion

The work presented herein, demonstrated the applicability of a holistic ship design approach using parametric design tools for optimization at the conceptual design phase.

The preliminary design phase of an ellipsoidal containership has been realized, utilizing parametric modeling tools in the framework of simulation-driven design.

In this case study, it has been achieved to build up a robust optimization model in a unique holistic approach. Several sub-systems have been developed in order to cover many aspects of the design optimization problem that compose a fully automated package regarding the design of a novel, unconventional containership. The core of this method is found in the parametric model, which is applicable to a wide range of global dimensions and local characteristics, retaining its fairness of shape and feasibility of its properties. It is generated using the tight coupling of the computer aided engineering tool FRIENDSHIP-Framework, the flow solver SHIPLFLOW and the computational spreadsheets of EXCEL.

Since the designer has developed all the subsystems and has carefully examined the interaction and dependencies that occur between the different factors, an extensive parametric variation study was undertaken in order to explore the feasible boundaries of a multi-dimensional design space. The final stage of multi-objective optimization, led by a Genetic Algorithm provided many favourable designs with rather competitive characteristics compared to existing ships of the same type and range, and other conceptual designs.

Regarding the investigated design concept, it was shown, that a wider, beamer containership design with ellipsoidal midship section, larger parallel body and lower design speed has many advantageous characteristics regarding powering demands, environmental footprint, required ballast water, container stacking and stability.

Still, there are many unexplored regions. In order to achieve a greater degree of holism and improve the decision making process at the preliminary phase, more aspects of the ship design problem have to be integrated in the automated optimization process.

It seems that the multi-discipline task of ship design enters a new era, where the naval architect and the designer will have to embrace a totally new perspective. Parametric modeling and simulation-driven design have the potential to change radically the traditional way of thinking and acting in marine industry.

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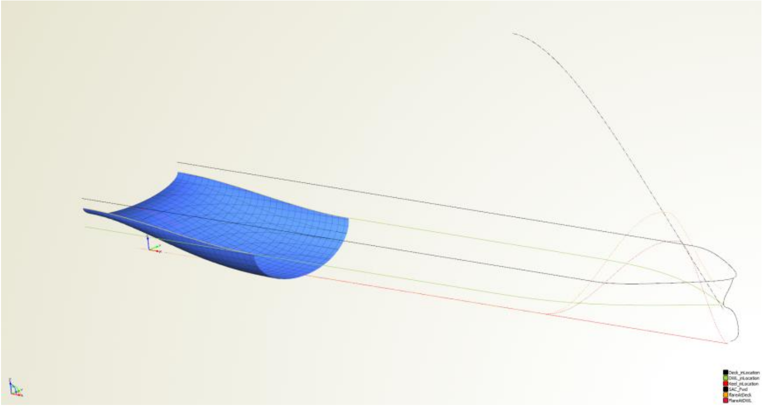
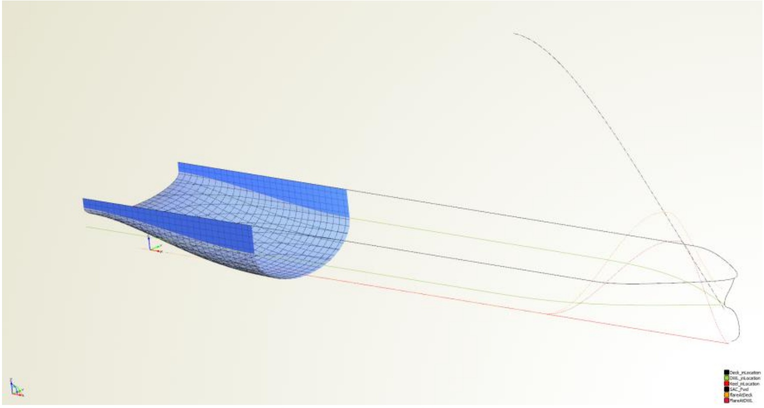
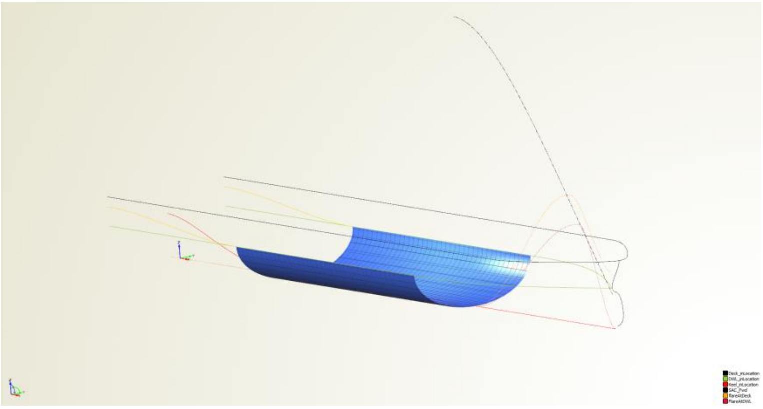
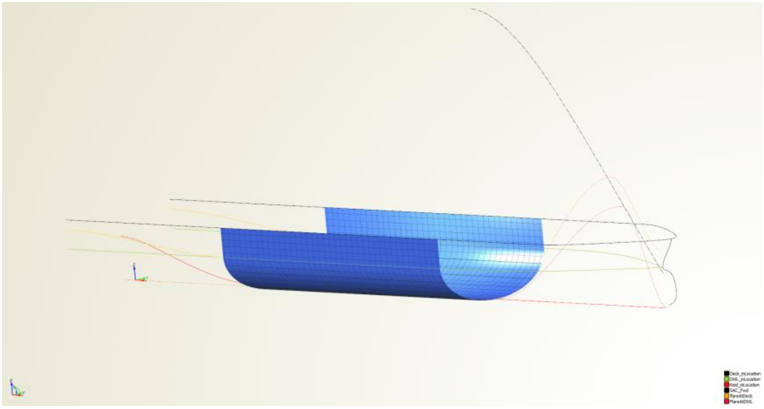
9. *Appendices*

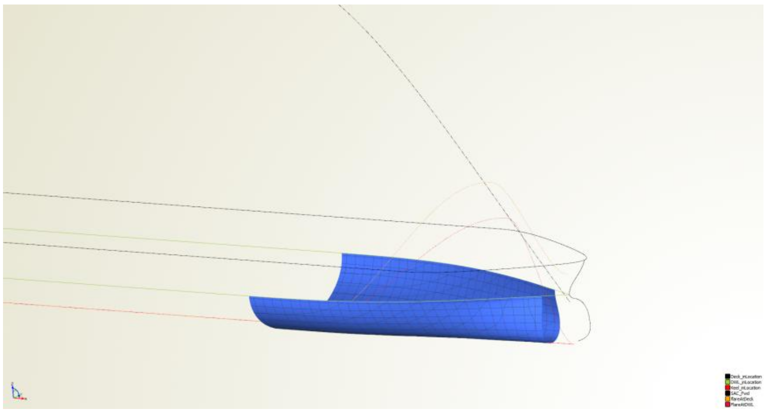
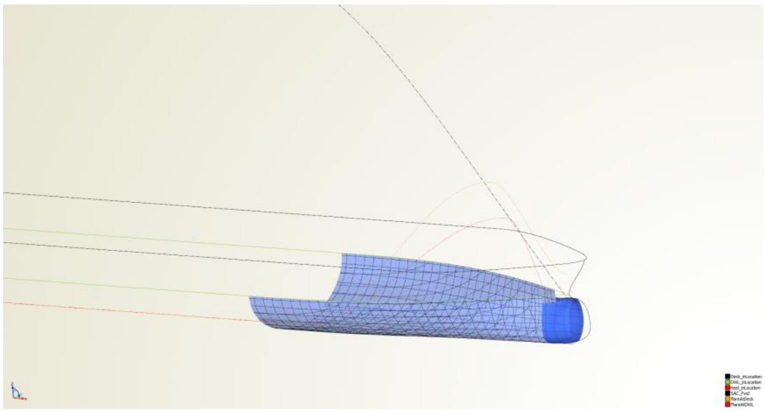
A. HULL SHAPE DEVELOPMENT

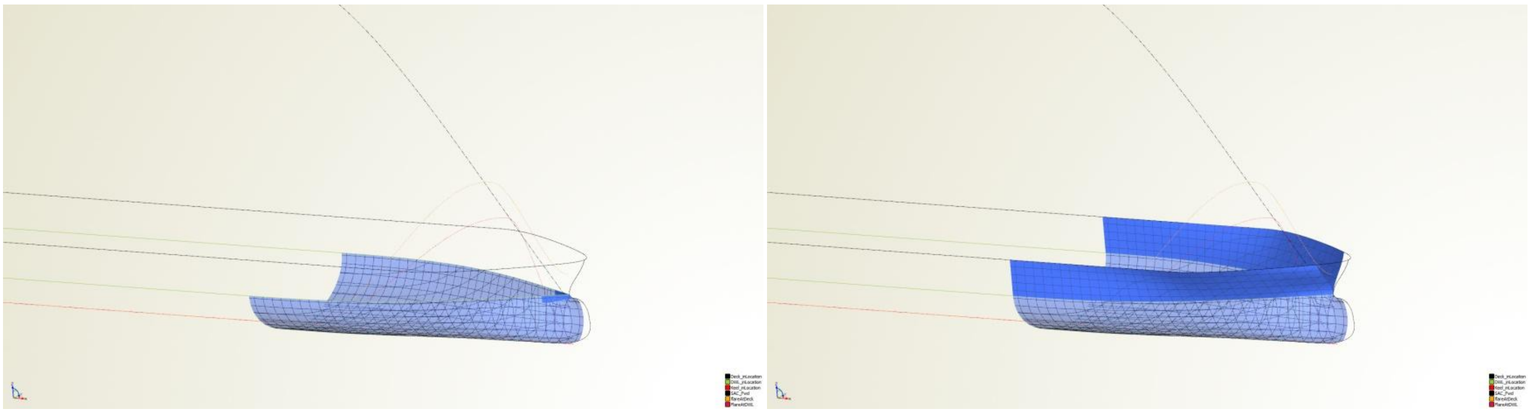
AftBodyBelowFOS (left)-AftBodyAboveFOS (right)

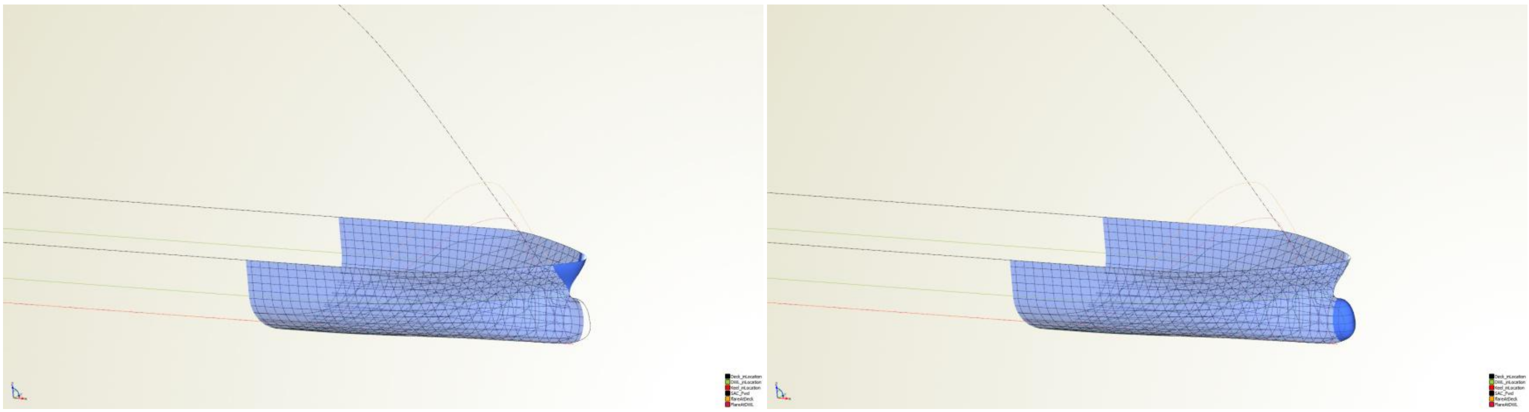
MidBodyBelowDWL[ellipse] (left)-MidBodyAboveDWL (right)

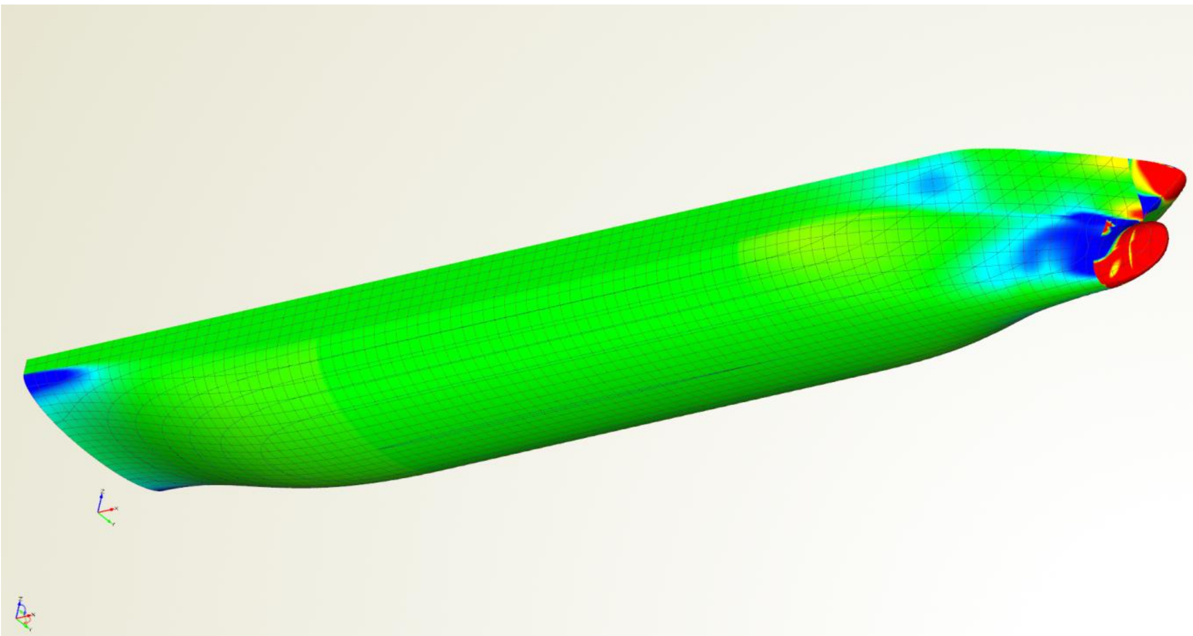
ForeBodyBelowDWL (left)-Fillet (right)



TopFillet (left)-ForeBodyAboveDWL (right)



StemTube (left)-MovedBulb (right)



Total Gaussian Curvature of the hull

B. EXCEL INTEGRATION

HOLTROP & MENNEN SEMI-EMPIRICAL PREDICTION METHOD

HOLTROP AND MENNEN RESISTANCE AND PROPULSION PREDICTION (1982)

(pink)	>	Indicates assumed values
(green)	>	Indicates input data from FRIENDSHIP-Framework
(blue)	>	indicates conditional values within the method

Principal Particulars

	VALUE		DESCRIPTION
L_{WL}	281.3713235	m	Waterline length
L_{BP}	281.744086	m	Between Perpendiculars
B	47.98	m	Moulded
D	25.68	m	Moulded
T	13.2	m	Average moulded
VOLUME	106969.8972	m^3	Volumetric diplacement
Δ	109751.1145	t	Displacement
D_{prop}	6.0192	m	Propeller diameter
V	21	kn	Service Speed
h_B	6.422048659	m	Centre of bulb area above keel line
$A_{BULB\ TR}$	49.22094198	m^2	Transverse bulb area at FP
i_E	41	deg	Half-angle of entrance of the load waterline
$A_{TRANSOM}$	50	m^2	Submerged transom area
lcb	2.602271452	%	Longitudianl centre of buoyancy forward (+), or abaft (-) of midship as a percentage of L
W.S.A	14490.43131	m^2	Wetted Surface Area
Fn	0.205628523		Froude Number
Rn	2763407453		Reynolds number
C_M	0.785398163		Midship Coeff.
C_B	0.600271287		Block Coeff.
C_P	0.76428914		Prismatic Coeff.
C_{WL}	0.837005416		Waterplane Coeff.
ρ	1025.9	$kg.m^{-3}$	Density of sea water
ν	1.16E-06		Kinematic Viscosity of water
g	9.81	$m.s^{-2}$	Acceleration due to gravity

Viscous Resistance Calculations

	VALUE		DESCRIPTION
c_{stern}	10		Stern shape Coeff. (10 for U-shaped sections)
L_R	82.64430106	m	Length of the run
C_{FO}	1.35E-03		Friction Coeff. (ITTC 1957)
C12	0.506281679		Coeff. Used in 1+K1 determination
C13	1.03		Coeff. Used in 1+K1 determination
$1 + K_1$	1.283861587		Effective form factor of bare hull
$R_{V\ Bare\ Hull}$	1508.210	kN	Viscous resistance of bare hull
$1 + K_2$	2.80		Effective form factor of appendages(azipod propulsors and bilge keels included)
S_{app}	260.8277636	m^2	Total wetted surface of appendages(18% W.S.A)
$R_{V\ Appendages}$	59	kN	Viscous resistance of appendages
R_{VTotal}	1567	kN	Total viscous resistance

Wave-making Resistance Calculations

	VALUE		DESCRIPTION
C_1	3.222225087		Bulbous bow Coeff.
C_7	0.2		Bulbous bow Coeff.
C_2	0.705367407		Bulbous bow Coeff.
C_5	0.99983917		Bulbous bow Coeff.
λ	0.929231715		Bulbous bow Coeff.
m_1	-2.00680781		Bulbous bow Coeff.
C_{16}	1.193077416		Bulbous bow Coeff.
m_2	-0.0929563		Bulbous bow Coeff.
C_{15}	-1.69385		Bulbous bow Coeff.
d	-0.9		Bulbous bow Coeff.
C_3	0.034104996		Bulbous bow Coeff.
R_W	594.5349706		Wave resistance

Additional Resistance due to presence of bulbous bow

	VALUE		DESCRIPTION
P_B	1.101460088		Emergence of the bow Coeff.
F_{nt}	1.321803044		Froude number based on bulb immersion
R_B	27.10797033	kN	Add. resistance due to bulbous bow

Additional Resistance due to immersed transom

	VALUE		DESCRIPTION
F_{nT}	3.237957106		Froude number based on transom immersion
C_6	0.070481716		Transom Coeff.
R_{TR}	210.941493	kN	Add. resistance due to transom

Model-Ship Correlation Resistance

	VALUE		DESCRIPTION
C_4	0.04		
C_A	0.000268118		Correlation allowance Coeff.
R_A	232.5535906	kN	Correlation resistance

Total Resistance

	VALUE		DESCRIPTION
R_T	2633	kN	Total Resistance

Propulsion Factors and Efficiencies (twin screw)

	VALUE	DESCRIPTION
w	0.141482968	Wake fraction
t	0.150003068	Thrust deduction
n_R	0.9982	Relative rotative eff.
n_H	0.99	hull eff.
n_O	0.7	Open water prop. eff.
n_S	0.99	Shafting eff.

PARAMETRIC SRPEADSHEET FOR STOWAGE CALCULATION

HEIGHT BOTTOM LINE	-2		-1		0		1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		HEIGHT CENTER LINE	SUM	MOMENT
SUM PER BAY ON DECK	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	0	0	0	0			
21.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**21.75**	0	0
19.25	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	0	0	0	0	**19.25**	646	12435.5
16.75	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	0	0	0	0	**16.75**	646	10820.5
14.25	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	0	0	0	0	**14.25**	646	9205.5
11.75	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	0	0	0	0	**11.75**	646	7590.5
9.25	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	0	0	0	0	**9.25**	646	5975.5
6.75	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	0	0	0	0	**6.75**	646	4360.5
4.25	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	0	0	0	0	**4.25**	646	2745.5
	HATCHES																																								
	DECK																																								
32.5	0	0	0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**33.75**	0	0
30	0	0	0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**31.25**	0	0
27.5	0	0	0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**28.75**	0	0
25	17	17	17	17			17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	16	15	12	0	0	0	0	**26.25**	468	12285
22.5	17	17	17	17			17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	16	16	16	15	15	13	11	0	0	0	0	**23.75**	459	10901.25
20	17	17	17	17	ENGINE ROOM		17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	16	16	15	14	14	13	11	9	0	0	0	0	**21.25**	448	9520
17.5	17	17	17	17			17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	16	16	15	14	13	12	11	10	8	0	0	0	0	**18.75**	438	8212.5
15	15	15	15	15			17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	16	15	14	13	12	11	10	8	7	0	0	0	0	**16.25**	429	6971.25
12.5	13	15	15	15			17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	16	15	14	12	11	10	8	7	5	0	0	0	0	**13.75**	421	5788.75
10			9	13			15	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	15	15	14	13	11	10	8	7	5	4	0	0	0	0	**11.25**	389	4376.25
7.5				7			14	14	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	14	14	12	12	10	9	8	7	5	4	0	0	0	0	**8.75**	363	3176.25
5							11	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	11	10	10	9	8	7	6	4	3	0	0	0	0	**6.25**	295	1843.75
2.5							7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	7	7	7	6	6	5	4	2	1	0	0	0	0	**3.75**	195	731.25
SUM PER BAY IN HOLD	96	98	107	118	0	0	149	151	153	153	153	153	153	153	153	153	153	153	153	153	153	153	153	153	151	146	139	134	123	116	107	97	80	64	0	0	0	0			

ON DECK	TOT	KG	MOMENT
	4522	12	53133.5

IN HOLD	TOT	KG	MOMENT
	3604	15	63806.25

C. FLOW SIMULATION- ZONAL APPROACH

A hydrodynamic analysis of the model E^4-Containership using FLOWTECH's CFD tool, SHIPFLOW is about to be presented.

In this work all flow simulations were done at full scale with a Froude number of and a Reynolds number of Rn= $2.1*10^9$. The ship speed is 16kn.

Since the Froude number is low, the containership is considered to be a "slow steamer", which results in the dominance viscous resistance over the wave-making energy loss. For this reason it is worth to run the potential and the viscous flow code as well, in order to get an accurate estimation of the required power and also to compare the computational approach with the empirical methods that are widely used for resistance prediction, but this exceeds the limits of this project. This is mandatory to be done in optimization procedures, since the empirical prediction tools are shaped on the basis of existent vessels which are conventionally designed and in the case of novel concepts the accuracy of such methods is highly disputed.

Within this project a potential flow simulation using non-linear free surface boundary conditions was used due to a much higher reliability of these calculations. Only first order panel discretization is employed. A maximum number of iterations of 20 were allowed.

In this work 10 streamlines were traced on the forward part of the hull distributed from 0.05 to 0.9 of the length in girth-wise direction while zero represents a location at the keel and one the topmost edge of the panels. In the aft part the evaluation of the frictional resistance will be done by XCHAP. The boundary layer is assumed to be turbulent from the start, but with a cross-flow angle of zero degree at the first point of the streamlines. An initial momentum thickness was set to be 1.0*10-4 at the first point and the initial form factor was assumed to be 0.22 according to Holtrop and Mennen semi-empirical method.

Within the flow simulation twelve processor threads were used and a maximum number of 4000 iterations were fixed for the baseline computation.

The position and size of the propellers of the twin screw azipod system are defined but the actuator disks are assumed to be turned off. In this way, the wake is computed for inactive propellers. If the propeller disks were set to be active, then the effective wake field would be computed, but this would exceed the limits of our project. Nevertheless this setup comprises a well feedback for future investigation.

GRID GENERATION

The potential flow solver XPAN needs a defined body mesh consisting of several groups and a free surface mesh optionally consisting of a transom and a free surface group.

The meshes are produced by the mesh generator XPAN within SHIPFLOW. The input file for the SHIPFLOW computation consists either of offsets or meshes. The conventional approach is to create a grid from the offsets of the surfaces. This is the simplest way and fits perfect to our case since the hull form is very smooth and there is a lack of skegs. Grid generation from offsets is suitable for global surface generation and a time-saving solution for potential flow codes because grids occupy less memory space by creating a default mesh. On the other hand, manual input of meshes are more sophisticated, they need more computational power but they are more accurate when complex geometries are taken into account. Manual mesh generation is mostly employed for local geometry analysis. For example skegs, twin-skegs, ducts are generated with meshes because in these regions more viscous effects take place and a different panelization is required.

In case of the grid approach, offsets are used as geometry input to SHIPFLOW. The input consists of 3 offsetgroups, forward bulb, mid hull and aft overhang as shown in fig. 1.

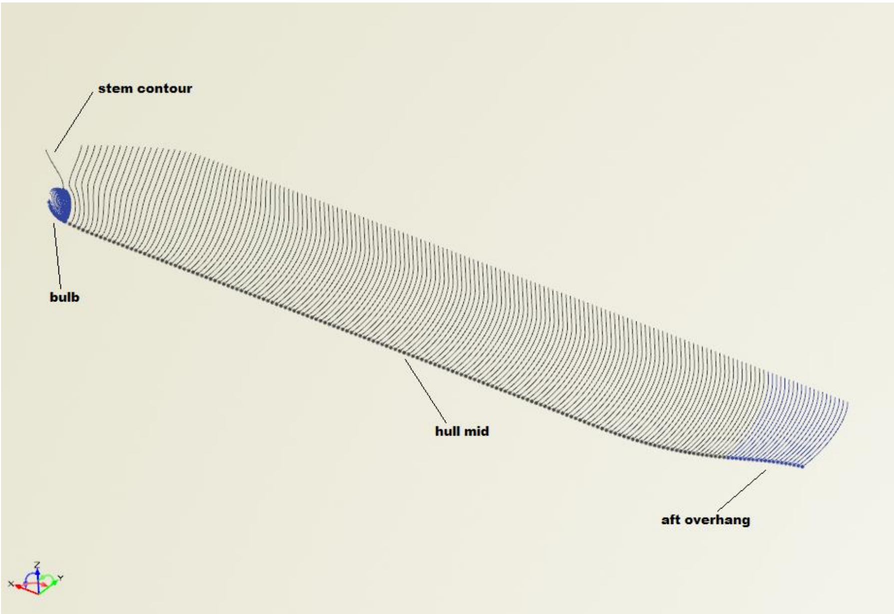


Figure 1. An overview of the input for the component grid approach

When using the conventional grid approach, specific requirements on the offset file have to be taken into account [12].

Within one group the offsets must be sorted from bow to stern, in most cases antipodal to the x-axis direction. It appears that the grid and generator are very fragile regarding bad conditioned offset data, e.g. double points. In order to avoid the violation of the offset file, certain steps should be done:

1. Reverse groups if not oriented from bow to stern.
2. Check all offset for orientation inner to outer.
3. Remove double offsets, attach offsets at the same x positions.
4. Check all offsets for double points.
5. Optional: approximate offsets with a second degree b-spline curve.

In case of the fore-ship offsets, and also the mid hull offsets in the component grid approach, the tasks are a bit different. The first offset should be changed in order to fulfill the requirement to model a stem contour all other offsets must be checked like before. A simple line will be introduced and attached to the cutted first offset in order to model the stem contour.

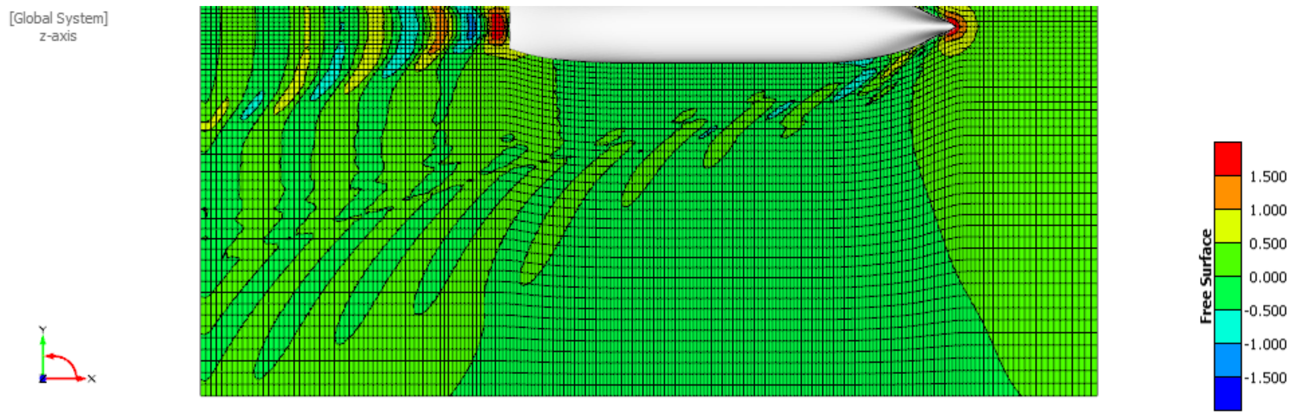


Figure 2. Wave pattern and free surface

The dimensions of the free surface mesh, as seen in fig. 2 were fixed to an upstream boundary of 0.5 LPP, a downstream boundary of 0.8 LPP and a side boundary of 0.9 LPP. Therewith it is guaranteed that the mesh behind the ship is longer than a fundamental wavelength and that the waves are not leaving the mesh on the side. Both are requirements for the use of a transversal wave cuts for the resistance approximation. The free surface behind the transom is also estimated by special command.

All computations were done using an Intel(R) Core(TM) i7 CPU at 3.20GHz and memory at 24GB RAM

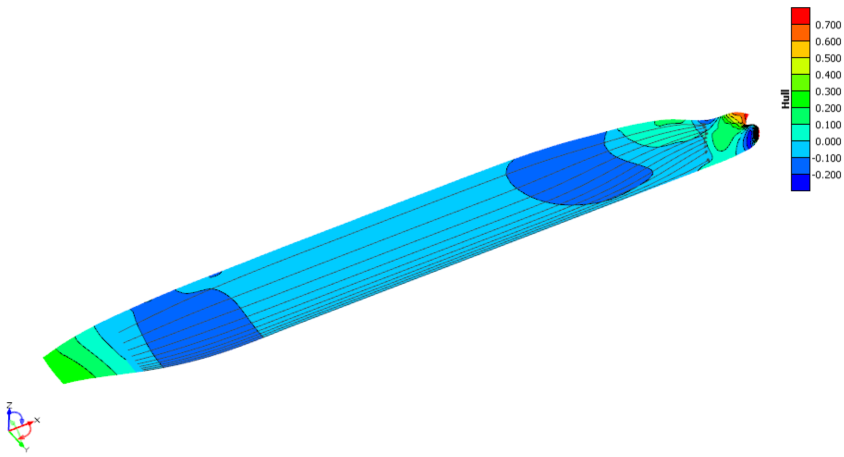


Figure 3. Visualization of streamlines and distribution of pressure

In figure 3 are presented the distribution of pressure on hull body as it has been calculated by XPAN is visualized with colour mapping and the potential flow streamlines as formulated by XBOUND.

The disc was situated one meter behind the bulb tip point with a normal direction corresponding to the longitudinal angle of the skeg (fig.4).

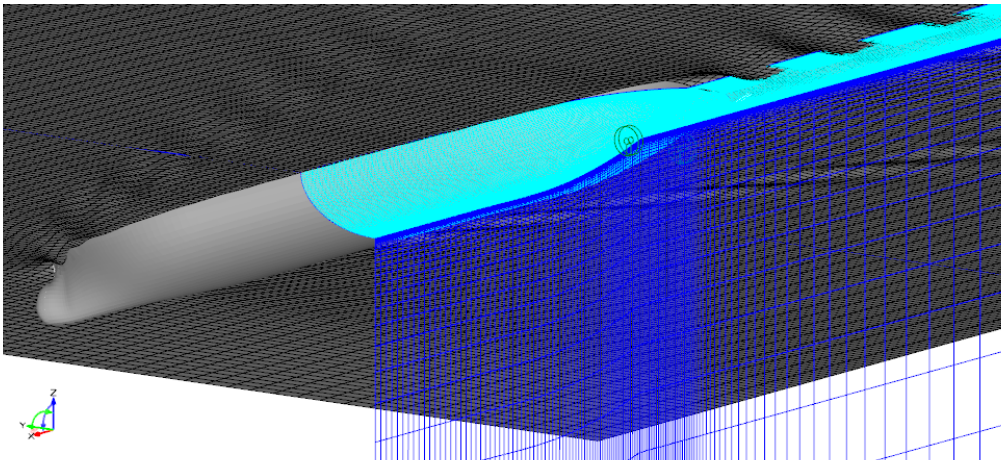


Figure 4. Generated grids from XCHAP and Propellers position

The iteration histories of the viscous flow simulations for the viscous pressure forces are shown in figure 5. On the x-axis of the iteration history plots the iterations divided by ten are shown.

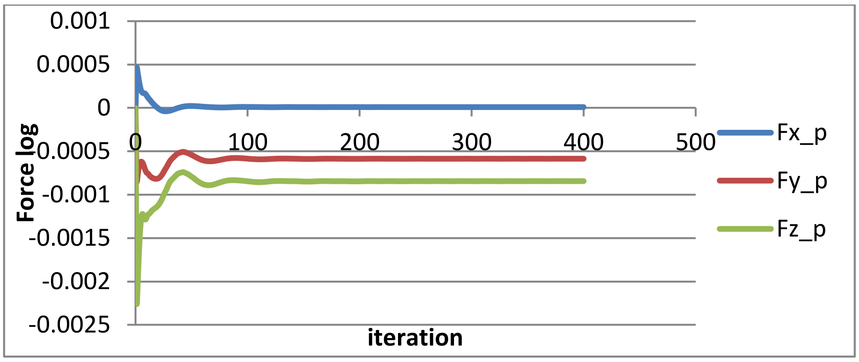


Figure 5. Iteration history of the viscous example computation

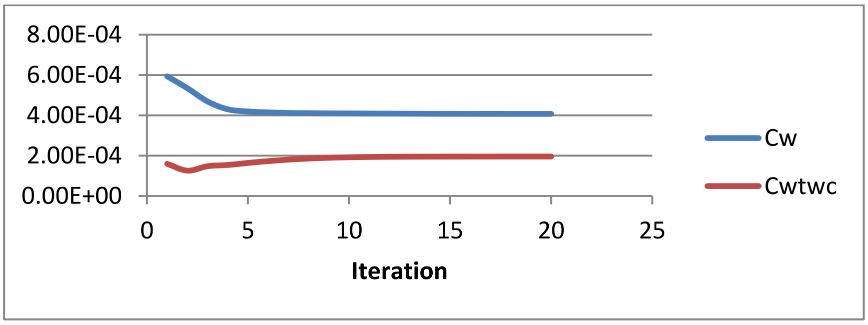


Figure 6. Iteration history of the potential computation

CF (Frictional resist. coeff.)	1.366E-03
CPV (Viscous pres. resist. coeff.)	1.957E-04
CV (Viscous resist. coeff.)	1.561E-03
CW (Wave resist. coeff.)	4.064E-04
CT (Total resist. coeff.)	1.968E-03
K (Form factor)	0.117
S (Wetted surface / L**2)	0.192

Table 1. Shipflow results from Zonal Approach

D. FEATURE: TEU's stacking

Feature: Topology of Inner Structure

This is a feature that includes a routine which automatically generates the topology of TEU's distribution each time the surface geometry is updated. The user provides the hull form, its main dimensions (height, beam) and a couple of requirements. These requirements refer to the minimum allowed distance between the outer shell and inner structure asides and the double bottom distance that is defined according to the rules. Then an algorithm has been set up which performs the following actions:

- Estimates the maximum number of containers (specified dimensions) that fit inside the hull (at max beam) in horizontal direction on transverse plane, taking into account the geometry and the required space asides and returns the actual length of double side distance.
- Estimates the maximum number of containers that fit in vertical direction on transverse plane with regard to double bottom and deck heights. If an even number of TEU's cannot be stacked within the distance (Height-DB), an extra layer of containers is considered, part of which remains exposed.
- A repeated process (Loop A) begins which is "sketching" a line from top to bottom that depicts the inner topology. The length of it increases by a constant value (height of a container) and at the end of every loop a control takes place. This control assures that the minimum distance between the end point of the line and the outer shell is lower than a predefined value, namely a percentage of the actual double side distance. This is handled with an approximation factor which is set as input too. If this constraint is violated a second process (Loop B) begins.
- Loop B continues tracing in horizontal orbit with direction, center plane. It also increases stepwise by a standard value (beam of container) and at the end of every loop the same control as before is performed. In this case if the requirement is satisfied, the process returns to Loop A.
- All these are repeated until the sketched inner shell ends up at center plane, at double bottom height.

This is how the topology is created. From this feature the number of containers and several other properties (KG, volume, moment, etc) are provided. In figure 7 an explanatory drawing is depicted and in figure 8 we see an illustration of FRIENDSHIP-Framework.

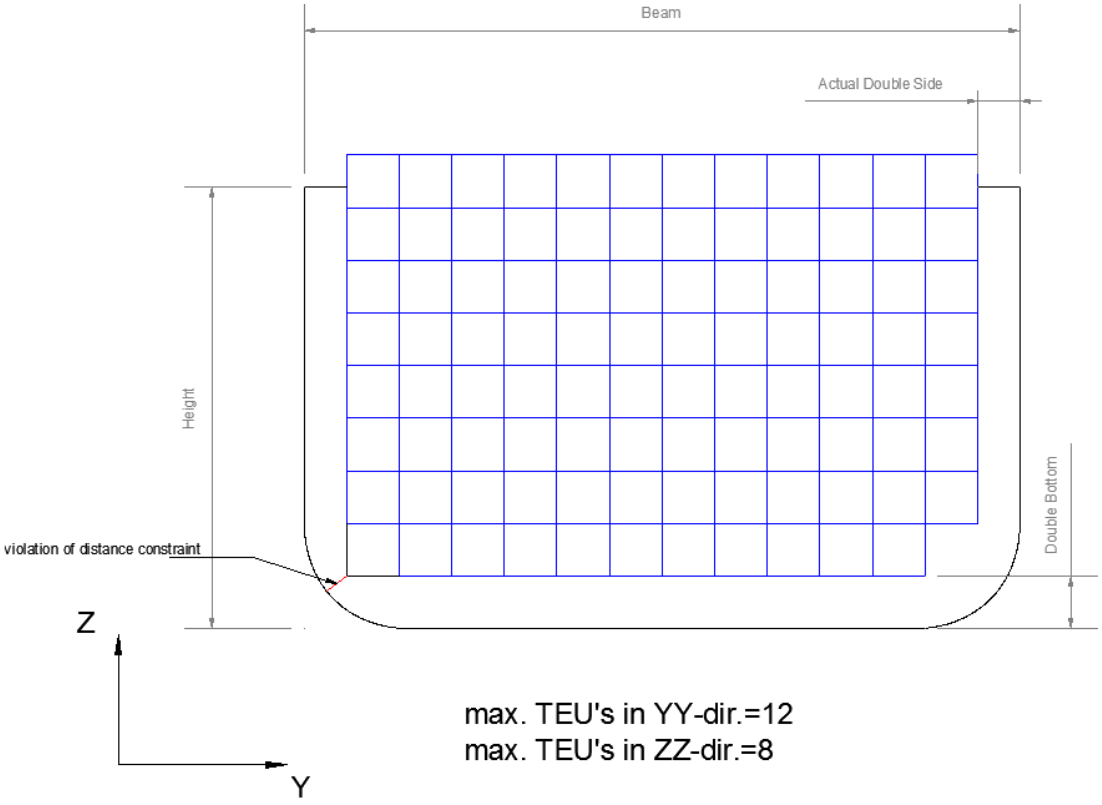


Figure 7. Examplary illustration

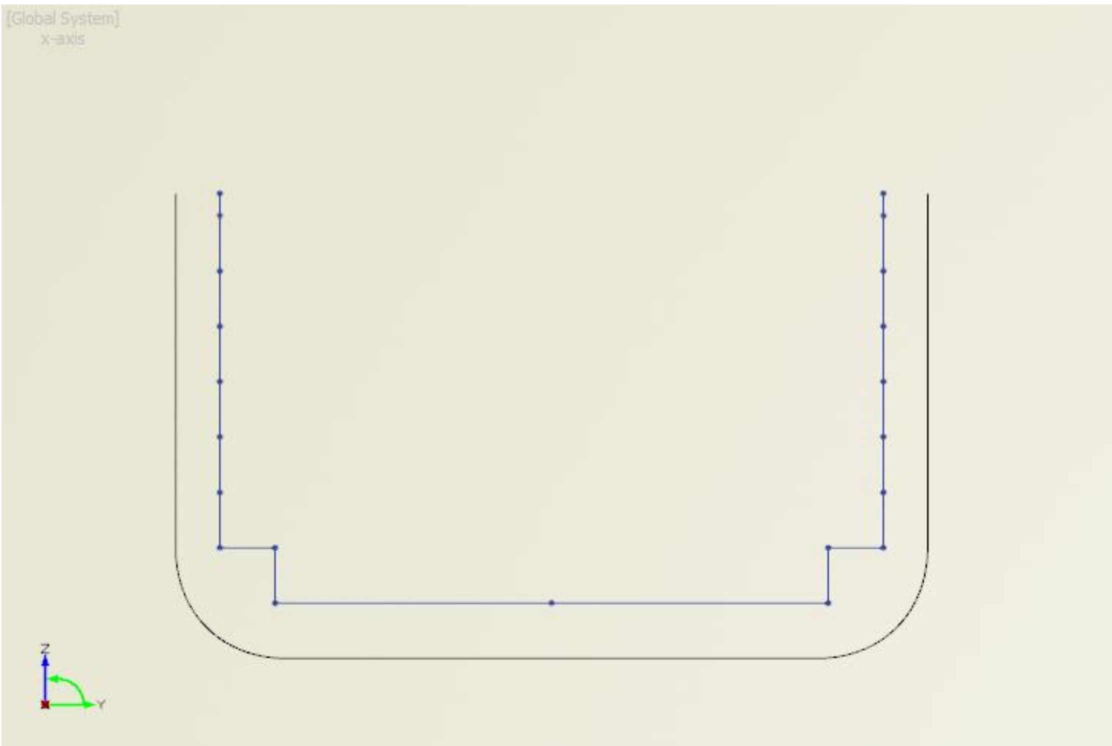
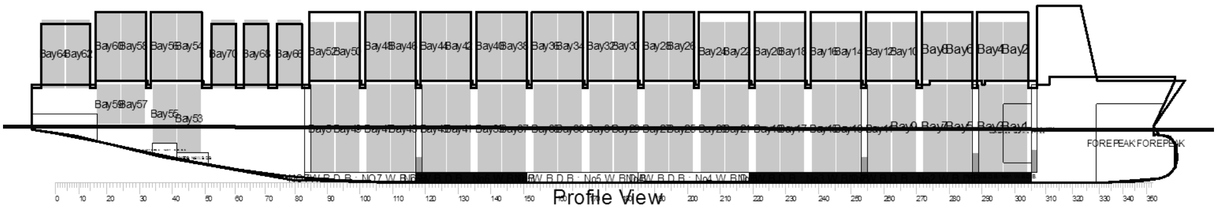


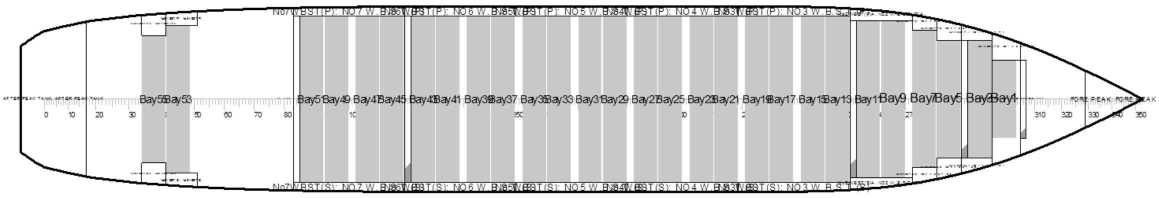
Figure 8. Illustration from FRIENDSHIP-Framework

E. FULL LOAD ARRIVAL CONDITION (E[4]-CONTAINERSHIP)

FULL LOAD ARRIVAL CONDITION

Intact State





Deck at 14.25 metres

Name	Density (t/m3)
WB	1.0250
FW	1.0000
FO	0.9700
LO	0.9000
MISC	1.0000

Intact State

Intact State

Title	Frames	Cargo	% full	SG (t/m3)	Weight (t)	LCG (m)	TCG (m)	VCG (m)	FSM (t-m)
WATER BALLAST									
No1W.B.D.B.: No1 W.B.D.B.	287-305	WB	100.0	1.025	745.2	242.47	0.00	2.68	0.0
No2W.B.D.B.: No2 W.B.D.B.	253-287	WB	100.0	1.025	2111.2	220.12	0.00	2.57	0.0
No3W.B.D.B.: No3 W.B.D.B.	219-253	WB	100.0	1.025	2324.2	192.37	0.00	2.53	0.0
No6W.B.D.B.: No6 W.B.D.B.	117-151	WB	100.0	1.025	2329.9	106.73	0.00	2.54	0.0
Total WATER BALLAST					7510.5	178.57	0.00	2.56	0.0
FUEL OIL									
IFO.TANK2: I.F.O.TANK2	117-119	FO	10.0	0.970	132.8	93.28	0.00	4.68	2767.7
IFO.TANK3: I.F.O.TANK1	253-255	FO	10.0	0.970	121.8	207.52	0.00	4.78	2079.4
IFO.TANK4: I.F.O.TANK4	287-289	FO	10.0	0.970	97.8	236.08	0.00	5.20	449.2
IFO.TANK5: I.F.O.TANK4	305-307	FO	10.0	0.970	71.4	251.13	0.00	5.98	411.7
Total FUEL OIL					423.8	185.67	0.00	5.05	5708.0
FRESH WATER									
DRINK WATER: DRINK WATER	67-83	FW	10.0	1.000	15.1	57.72	-16.25	10.13	125.8
WASH WATER: WASH WATER	67-83	FW	10.0	1.000	15.1	57.72	16.25	10.13	125.8
Total FRESH WATER					30.2	57.72	0.00	10.13	251.6
LUB OIL									
LUB OIL(P): LUB OIL(P)	67-83	LO	10.0	0.900	13.6	57.72	-12.50	7.75	14.1
LUB OIL(S): LUB OIL(S)	67-83	LO	10.0	0.900	13.6	57.72	12.50	7.75	14.1

Title	Frames	Cargo	% full	SG	Weight	LCG	TCG	VCG	FSM
				(t/m3)	(t)	(m)	(m)	(m)	(t-m)
Total LUB OIL					27.2	57.72	0.00	7.75	28.2
MISCELLANEOUS									
MISC(P): MISC(P)	67-83	MISC	100.0	1.000	226.4	57.72	-10.00	8.75	0.0
MISC(S): MISC(S)	67-83	MISC	100.0	1.000	226.4	57.72	10.00	8.75	0.0
Total MISCELLANEOUS					452.8	57.72	0.00	8.75	0.0
Cont Set 0									
Bay1					755.0	246.25	0.00	16.70	0.0
Bay10					1101.2	217.69	0.00	33.50	0.0
Bay11					1178.5	211.39	0.00	15.14	0.0
Bay12					1101.2	211.39	0.00	33.50	0.0
Bay13					1284.8	203.41	0.00	14.95	0.0
Bay14					1101.2	203.41	0.00	33.50	0.0
Bay15					1284.8	197.11	0.00	14.95	0.0
Bay16					1101.2	197.11	0.00	33.50	0.0
Bay17					1284.8	189.13	0.00	14.95	0.0
Bay18					1101.2	189.13	0.00	33.50	0.0
Bay19					1284.8	182.83	0.00	14.95	0.0
Bay2					1101.2	246.25	0.00	33.50	0.0
Bay20					1101.2	182.83	0.00	33.50	0.0
Bay21					1284.8	174.85	0.00	14.95	0.0
Bay22					1101.2	174.85	0.00	33.50	0.0
Bay23					1284.8	168.55	0.00	14.95	0.0
Bay24					1101.2	168.55	0.00	33.50	0.0
Bay25					1284.8	160.57	0.00	14.95	0.0
Bay26					1284.8	160.57	0.00	34.75	0.0
Bay27					1284.8	154.27	0.00	14.95	0.0
Bay28					1284.8	154.27	0.00	34.75	0.0
Bay29					1284.8	146.29	0.00	14.95	0.0
Bay3					946.7	239.95	0.00	16.10	0.0
Bay30					1284.8	146.29	0.00	34.75	0.0
Bay31					1284.8	139.99	0.00	14.95	0.0
Bay32					1284.8	139.99	0.00	34.75	0.0
Bay33					1284.8	132.01	0.00	14.95	0.0
Bay34					1284.8	132.01	0.00	34.75	0.0
Bay35					1284.8	125.71	0.00	14.95	0.0
Bay36					1284.8	125.71	0.00	34.75	0.0
Bay37					1284.8	117.73	0.00	14.95	0.0
Bay38					1284.8	117.73	0.00	34.75	0.0
Bay39					1284.8	111.43	0.00	14.95	0.0
Bay4					1101.2	239.95	0.00	33.50	0.0
Bay40					1284.8	111.43	0.00	34.75	0.0
Bay41					1284.8	103.45	0.00	14.95	0.0
Bay42					1284.8	103.45	0.00	34.75	0.0
Bay43					1284.8	97.15	0.00	14.95	0.0
Bay44					1284.8	97.15	0.00	34.75	0.0
Bay45					1284.8	89.17	0.00	14.95	0.0
Bay46					1284.8	89.17	0.00	34.75	0.0
Bay47					1284.8	82.87	0.00	14.95	0.0
Bay48					1284.8	82.87	0.00	34.75	0.0
Bay49					1284.8	74.89	0.00	14.95	0.0

Bay5					1024.0	231.97	0.00	15.68	0.0
Bay50					1101.2	74.89	0.00	33.50	0.0
Bay51					1284.8	68.59	0.00	14.95	0.0
Title	Frames	Cargo	% full	SG (t/m3)	Weight (t)	LCG (m)	TCG (m)	VCG (m)	FSM (t-m)
Bay52					1101.2	68.59	0.00	33.50	0.0
Bay53					975.7	34.29	0.00	17.24	0.0
Bay54					1284.8	34.29	0.00	34.75	0.0
Bay55					850.1	27.99	0.00	18.27	0.0
Bay56					1284.8	27.99	0.00	34.75	0.0
Bay57					618.2	20.01	0.00	20.16	0.0
Bay58					1284.8	20.01	0.00	34.75	0.0
Bay59					598.9	13.71	0.00	20.28	0.0
Bay6					1101.2	231.97	0.00	33.50	0.0
Bay60					1284.8	13.71	0.00	34.75	0.0
Bay62					1284.8	5.85	0.00	32.75	0.0
Bay64					1284.8	-0.57	0.00	32.75	0.0
Bay66					1284.8	59.98	0.00	32.75	0.0
Bay68					1284.8	51.51	0.00	32.75	0.0
Bay7					1178.5	225.67	0.00	14.98	0.0
Bay70					1284.8	43.04	0.00	32.75	0.0
Bay8					1101.2	225.67	0.00	33.50	0.0
Bay9					1178.5	217.69	0.00	15.14	0.0
Total Cont Set 0					77397.5	130.48	0.00	25.58	0.0
PROVISIONS ARRIVAL									
PROVISIONS					1.6	250.00	0.00	25.00	0.0
Total PROVISIONS ARRIVAL					1.6	250.00	0.00	25.00	0.0
CREW									
STORES					3.4	270.00	0.00	25.50	0.0
Total CREW					3.4	270.00	0.00	25.50	0.0
Lightweight					28207.0	152.89	0.00	15.86	0.0
Deadweight					85846.8	134.53	0.00	23.36	5987.9
Total Displacement					114053.8	139.07	0.00	21.51	5987.9
Buoyancy					114053.8	139.03	0.00	8.34	1976394.7
Total Buoyancy					114053.8	139.03	0.00	8.34	1976394.7

Intact State

Drafts at equilibrium angle

Draft at LCF	13.894	metres
Draft aft at marks	14.267	metres
Draft fwd at marks	13.443	metres
Draft at AP	14.267	metres
Draft at FP	13.443	metres
Mean draft at midships	13.855	metres

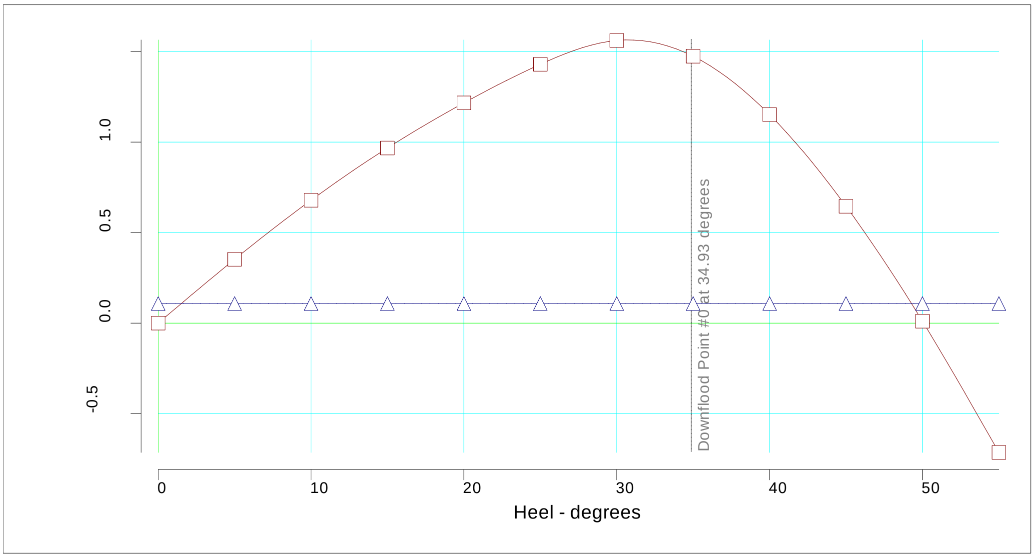
Hydrostatics at equilibrium angle

Density of water	1.0250	tonnes/cu.m
Heel	No heel	
Trim by the stern	0.824	metres
KG	21.508	metres
FSC	0.053	metres
KGf	21.560	metres
GMt	4.104	metres
BMt	17.329	metres
BMl	586.960	metres

Density of water	1.0250	tonnes/cu.m
Waterplane area	11803.79	sq.metres
LCG	139.071	metres
LCB	139.032	metres
TCB	0.000	metres
LCF	127.363	metres
TCF	0.000	metres
TPC	120.989	tonnes/cm
MTC	2376.127	tonnes-m/cm
Shell thickness	0.000	mm

Intact State

FULL LOAD ARRIVAL: Intact State



Righting Lever (GZ) Curve

Heel to Stbd (deg)	GZ (m)	Slope (m/rad)	Trim (m)	WLrad (m)	Freeboard (m)	Unprotected (m)	Wind (m)
0.00	0.0000	4.1040	-0.824	13.855	10.15[0]	13.68[0]	0.1082
5.00	0.3525	3.9239	-0.793	13.782	8.07[0]	11.81[0]	0.1082
10.00	0.6788	3.5605	-0.677	13.555	5.98[0]	9.86[0]	0.1082
15.00	0.9673	3.1352	-0.470	13.160	3.91[0]	7.87[0]	0.1082
20.00	1.2161	2.7242	-0.186	12.589	1.89[0]	5.86[0]	0.1082
25.00	1.4292	2.4030	0.158	11.836	-0.06[0]	3.88[0]	0.1082
30.00	1.5612	0.0124	0.525	10.921	-1.94[0]	1.92[0]	0.1082
35.00	1.4742	-2.2968	0.842	9.924	-3.80[0]	-0.03[0]	0.1082
40.00	1.1514	-4.7989	1.148	8.888	-5.67[0]	-2.02[0]	0.1082
45.00	0.6454	-6.5558	1.447	7.820	-7.54[0]	-4.02[0]	0.1082
50.00	0.0104	-7.7880	1.747	6.717	-9.37[0]	-6.03[0]	0.1082
55.00	-0.7142	-8.6298	2.051	5.581	-11.15[0]	-8.01[0]	0.1082

IMO Wind heeling

Property	Value	Units
Length WL	290.192	metres
Profile area above WL	7629.029	sq.metres
Area to leeward (Area b)	0.54348	m-radians
Area to windward (Area a)	0.00143	m-radians
GZc	0.108	metres
Gust angle	1.513	degrees
Rollback angle	18.784	degrees
Steady state angle	1.008	degrees

Property	Value	Units
Max. angle to leeward	34.926	degrees
B/d'	3.428	
X1	0.814	
Cb	0.597	
Ar	0.000	
K	1.000	
Og	7.706	metres
r	1.064	
T	15.338	seconds

Intact State

IMO 749 Intact Stabilty Criteria non - passenger

#	Criterion	Actual Value	Critical Value
1	Area under GZ curve up to 30 degrees > 0.055	0.476	0.055
2	Area under GZ curve from 30 to 40 deg. or downflood > 0.03	0.132	0.030
3	Area under GZ curve up to 40 deg. or downflood > 0.09	0.608	0.090
4	Initial GM to be at least 0.15 metres	4.104	0.150
5	GZ to be at least 0.20m at an angle > 30 degrees	1.561	0.200
6	Max GZ to be at an angle > 30 degrees	30.043	30.000
7	IMO Weather Criterion (Maximum Initial Angle Of Heel)	1.008	16.000
8	IMO Weather Criterion (Areas)	380.905	1.000

Condition complies with the regulations

Intact State

Immersion Particulars
State of Openings = X-ray: Normal condition
Unprotected Openings

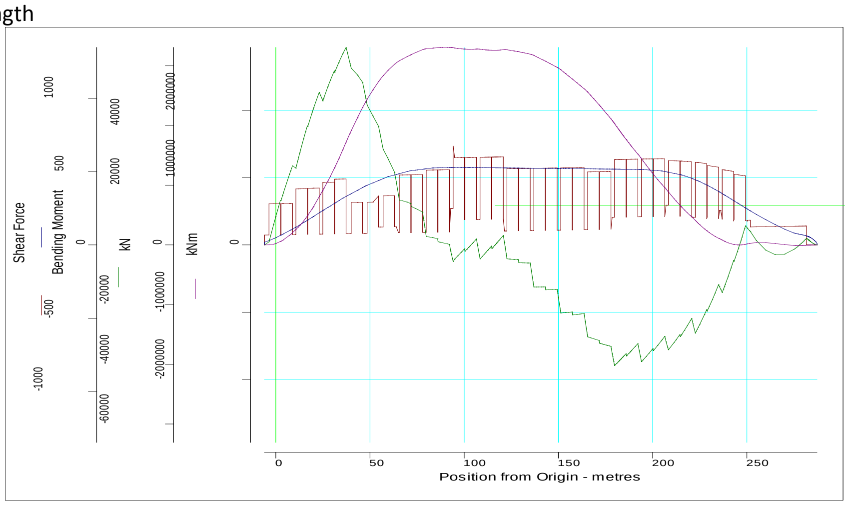
Point #	X position (m)	Y position (m)	Z position (m)	Ht. above WL (m)	Flood Angle (deg)
0	255.000	21.000	27.200	13.679	34.926
1	255.000	21.000	27.200	13.679	34.926

Deck Edge

Point #	X position (m)	Y position (m)	Z position (m)	Ht. above WL (m)	Flood Angle (deg)
0	140.870	23.600	24.000	10.145	24.855
1	140.870	-23.600	24.000	10.145	Not immersed

Intact State

Longitudinal Strength

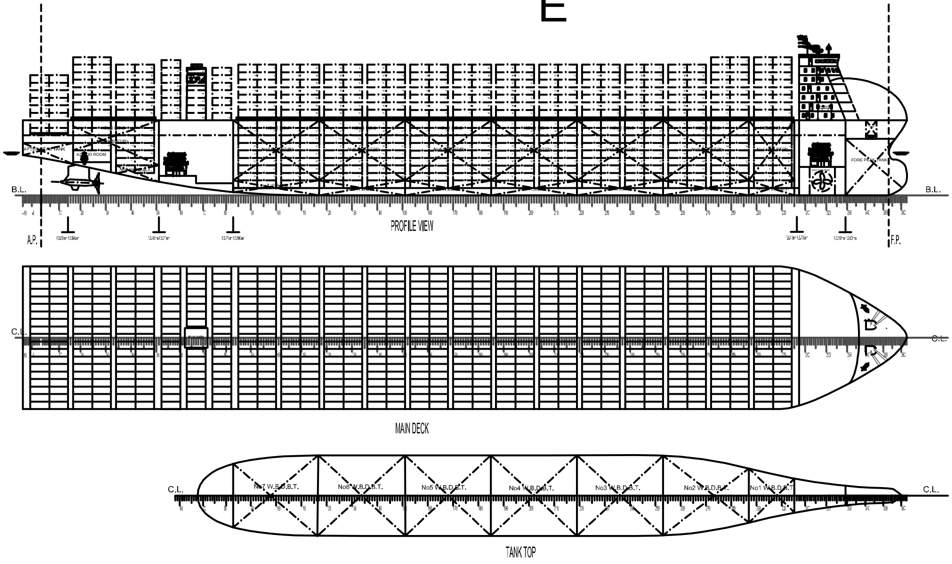


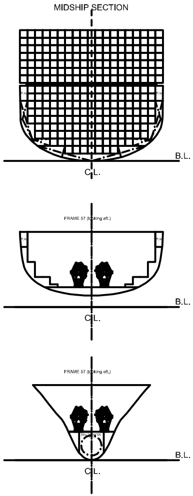
Shearing Force and Bending Moments

Distance from Origin (m)		Shearing Force (kN)	Bending Moment (kNm)
8.88	--	26503.8	182820.0
16.74	--	39901.6	430190.8
23.04	--	51131.4	716263.0
31.02	--	58281.6	1136138.2
37.31	--	66176.1	1527075.1
92.25	--	0.0	2935397.3
94.12	#119	-5590.4	2930106.7
100.42	--	-2130.5	2910455.8
103.58	--	0.0	2907628.1
106.47	--	1985.5	2910794.7
107.05	--	0.0	2911372.9
108.40	#136	-4687.2	2908469.9
114.70	--	-1226.4	2893732.0
116.40	--	0.0	2892970.0
120.76	--	3189.2	2900568.1
121.57	--	0.0	2901994.4
138.24	--	-14096.7	2798065.5
143.26	--	-15048.5	2728168.7
151.24	#187	-22807.8	2602733.0
157.54	--	-23449.9	2461318.1
179.80	#221	-40422.7	1801259.2
186.10	--	-37198.2	1561108.9
194.08	#238	-39155.9	1280661.0
200.38	--	-35460.3	1049934.3
208.36	#255	-35155.9	788159.3
214.66	--	-30718.8	584630.7
222.64	#272	-29541.1	366274.5
228.94	--	-22179.1	206710.8
236.92	#289	-15949.8	72001.7
243.22	--	-5489.5	6903.6
246.15	--	0.0	-406.6
249.28	--	6416.3	9630.7
257.35	--	0.0	33464.8
265.00	--	-3240.4	20502.3
277.96	--	0.0	-9389.2
281.70	#353	2247.6	-5159.1
Maximum BM			
92.19			2935445.4
Maximum SF			
37.31		66176.1	

GENERAL ARRANGEMENT

E^4





GENERAL PARTICULARS

Length Overall	L_{OA} =287.70	m
Length Bet. Perp.	L_{BP} =281.70	m
Breadth Mld.	B =47.50	m
Depth Mld.	D =25.00	m
Designed Draught	T_d =14.25	m
Block Coefficient	C_B =0,59	
Service Speed	V_S =16.00 kn	
Frame Spacing	600/840/770/840/770/600	mm

CONTAINER CAPACITY: 8448 TEU(3541 in holds)

MAIN ENGINE

NATIONAL TECHNICAL UNIVERSITY OF ATHENS
DEPARTMENT OF NAVAL ARCHITECTURE AND MARINE ENGINEERING
SHIP DESIGN LABORATORY

Title:	GENERAL ARRANGEMENT	
Type of Ship:	CONTAINERSHIP	
Name:	E^4	
Scale: 1/400	The Naval Architects:	Drawing No:
Designed: KOUTROUKIS GEORGE,PAVLOU ANTONIS	PAVLOU ANTONIS KOUTROUKIS GEORGE	
Drawn: KOUTROUKIS GEORGE,PAVLOU ANTONIS		
Checked:		