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Parametric Modelling and Optimisation of AFRAMAX Tankers

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Diploma Thesis

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Abstract

The oil tanker shipping industry has always been one of the most important branches of shipping, as crude oil is the basis of the global economy. After a series of tanker casualties with dramatic environmental, social and economical consequences, stricter rules and regulations have been applied, related to tanker design. Moreover, the awareness about the environmental impact of the greenhouse gas emissions and the energy consumption has led to the need for higher energy efficiency. At the same time, the shipping companies are constantly making every effort to ensure their economic sustainability and competitiveness. Thus, there is a need for an optimal tanker design that satisfies the shipping companies' requirements, subject to the relevant rules and regulations.

Therefore, the present thesis focuses on a new design approach encompassing parametric modelling and optimisation of oil tankers. More specifically, the project deals with the case study of a double hull AFRAMAX tanker. The first stage of the thesis includes the development of the parametric model, along with the necessary software tools performing all necessary computations for the techno-economic assessment of each design alternative. The second stage is the design optimisation. In the end of the optimisation process, the optimal design is selected out of a series of feasible designs. The parametric model is set up in Napa, a well-known computer-aided ship design software.

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Introduction

The present diploma thesis explores a non-traditional ship design approach, which focuses on parametric modelling and optimisation of oil tankers. The design space is investigated, in order to find the optimal design that achieves specific objectives, including among others increased net present value, improved energy efficiency, increased service speed, as well as enhanced environmental protection in case of accidents.

In chapter 1, the concept of ship design is analysed and traditional and modern approaches of the ship design process are described. Thereafter, the most important computer-aided ship design software packages are presented in chronological order, starting from the 1960s up to contemporary software tools, followed by a review of selected publications related to the integration of the ship design process and ship design optimisation, as well as to hydrodynamic and structural optimisation.

In chapter 2, there is a description of the history of tankers from the 19th century until nowadays. Subsequently, a classification of tankers by types of cargo and by size is presented. Then, a detailed description of the tanker design characteristics follows, along with the major hazards entailed, due to their type of cargo. Standard and alternative designs are presented, followed by a review of the most important tanker casualties that have led to adoption of new regulations and amendments.

In chapter 3, the development of the parametric model is described in full detail. At first an overview of the problem is presented and the project's objectives are explained. Then, the workflow is described step by step. The workflow includes the development of the geometric model and all the required calculations for the techno-economic assessment of each design alternative. A brief description of the most important regulations, which function as design constraints, is carried out.

In chapter 4, the application of the developed parametric model for the design and optimisation of an AFRAMAX tanker is presented. The optimisation process is described and the results from the feasible designs are presented in the form of detailed diagrams, depicting the outcome of the whole process.

A brief summary of the project, along with suggestions for further work are given in chapter 5.

1 Ship Design

Ship Design is the area of Naval Architecture that includes all the proceedings required for designing a ship, starting from a shipping company's need for a new ship and ending at the stage before the ship's production. It combines theoretical analysis with empirical data from previous designs. Traditionally ship design's main objective has been the maximisation of the ship owners' profits by increasing the ship's payload and at the same time decreasing the total building cost. Nowadays, another very important objective is safety, regarding the crew, the passengers and the environment. To accomplish all these, ship designers take into consideration among others the ship's route, environment, type and quantity of cargo and port facilities [1].

1.1 Engineering Design Process

Design can be defined as the activity that translates an idea into a blueprint for something useful, whether it is a computer, a school, a process, a sculpture or a ship [2]. In engineering, design is a process with constant decision-making, where the engineers follow a series of steps, in order to find a solution to a problem, as it is shown in *Figure 1-1*.

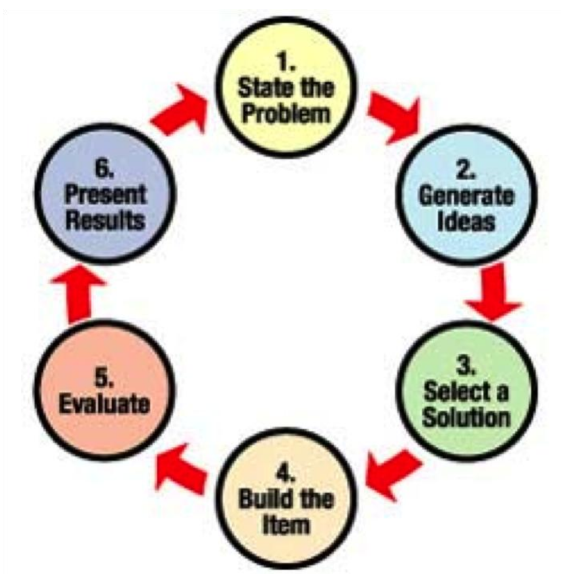

Figure 1-1: *Steps of the Engineering Design Process [3]*

The engineering design process is highly iterative, because most steps have to be repeated several times before it is possible to continue to the next steps and come to a technically sound solution.

1.2 Ship Design Process

Ship design follows a highly iterative process, especially in the early stages. The ship design process starts with the definition of the mission requirements. Those are specified by the ship owner and are related to issues, such as the definition of the ship's speed, deadweight, cargo handling equipment, flag, class, main propulsion power and automation level. During the first steps of the ship design process, appropriate values for several ship characteristics and particulars are provisionally selected based on approximate empirical formulae, educated guesses and past experience from similar designs. As better and more detailed information becomes available, the initial guesses are modified as necessary. In *Figure 1-2* J. H. Evans' design spiral is shown.

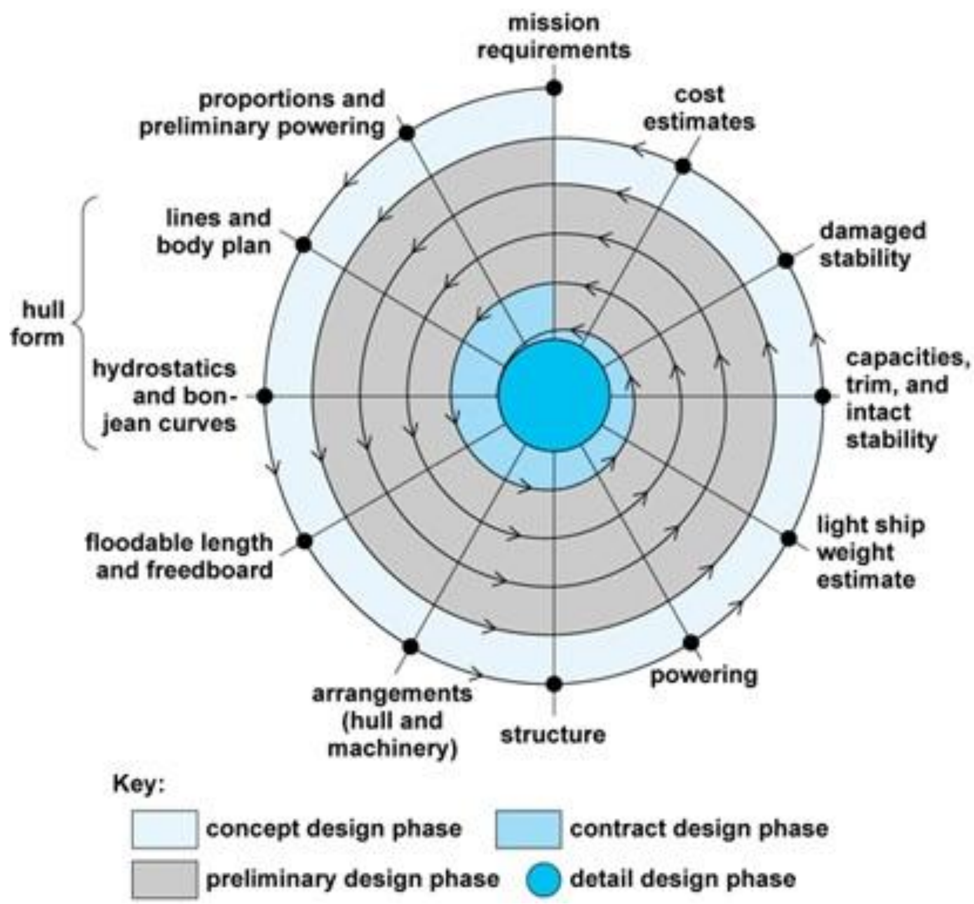

Figure 1-2: *Design spiral, J. H. Evans 1959 [4]*

As previously mentioned, the whole process starts from the mission requirements, it continues with the determination of the ship's main particulars and its preliminary powering and then step by step, as shown in *Figure 1-2* the process ends with the cost estimation. After all the steps have been completed, the design is highly unlikely to be feasible. Therefore, a second cycle begins and all the steps are repeated in the same sequence. The process will be repeated until all the requirements are satisfied. Traditionally, the ship design process is further subdivided into four phases: concept design, preliminary design, contract design and detailed design [5-8].

Concept design: In this phase, the ship designer translates the ship owner's requirements into technical ship characteristics. During the concept design, preliminary estimations are made about the ship's main dimensions according to empirical formulae and educated guesses. Economic performance and building cost estimations are carried out based on past experience and statistical data. Concept design typically corresponds to the first iteration loop of the Evan's design spiral.

Preliminary design: At this phase, calculations in further detail are made in order to determine the ship's main parameters, internal layout and the main machinery and equipment. A preliminary general arrangement plan is elaborated, the ship's stability and hydrodynamic characteristics are evaluated and preliminary plans of the steel structure are carried out. The work done during this phase is of great importance, because it has a decisive impact on the new ship's final cost and performance. Based on the outcome of this phase, conclusions may be drawn on whether the ship owner's investment is economically viable or not. This phase usually includes the second, third and fourth iteration loop of Evan's design spiral.

The combination of concept and preliminary design is traditionally called basic design.

Contract design: This is the conclusive phase of the design process, in the sense that during this phase the ship's characteristics are finalised, all technical issues are resolved and a technically sound solution in every respect is derived. Based on the outcome of this phase, the signing of the contract between the shipyard and the ship owner may take place. It includes all major drawings, material and equipment list, detailed specifications, model tests and analysis results. Documents such as the ship lines plan, the general arrangement plan, the midship section and other structural drawings, the analysis of the ship's hydrodynamic performance (resistance and propulsion characteristics, manoeuvring properties etc.), the assessment of ship's stability characteristics, life-saving and fire fighting equipment, the precise estimation of the individual ship weight components, the building cost and others are parts of the contract design. It corresponds typically to the fifth iteration loop of the Evan's design spiral.

Detailed design: During the final phase of the ship design process, production drawings are developed that comprise detailed designing of all structural parts and specifications on the ship's equipment. The drawings, parts lists and construction specifications derived during this phase are delivered to planning and production units, in order to start the ship's construction and the outfitting's installation. All the information provided in those drawings, aims to offer detailed information up to the workman level and should be highly illustrative.

An indication of the time-scale associated with each design phase is presented in *Figure 1-3*. Evan's design spiral describes the traditional design, where designers used to focus on one issue at a time. Traditional design has evolved nowadays with the aid of Computer-Aided Design, as it is further described in paragraph 1.3.

1.3 Computer-Aided Ship Design (CASD)

The rapid technological development during the 1960s influenced almost every facet of the everyday life. Engineering is one of the first sectors that were affected by computing. In the beginning, Computer-Aided Engineering (CAE) aimed to reduce the time of the iterative calculation work. Gradually, as computers became more developed, CAE was also developed and has reached its present form, offering various functions and facilitations to the engineers. In this section some of the most important innovations are described, which have contributed to the development of CAD/CAE systems and in particular of CASD. *Table 1-1* depicts a summary of the most influential hardware generations, as well as their associated software packages.

Table 1-1: *Generations of computing hardware and software in design [9]*

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

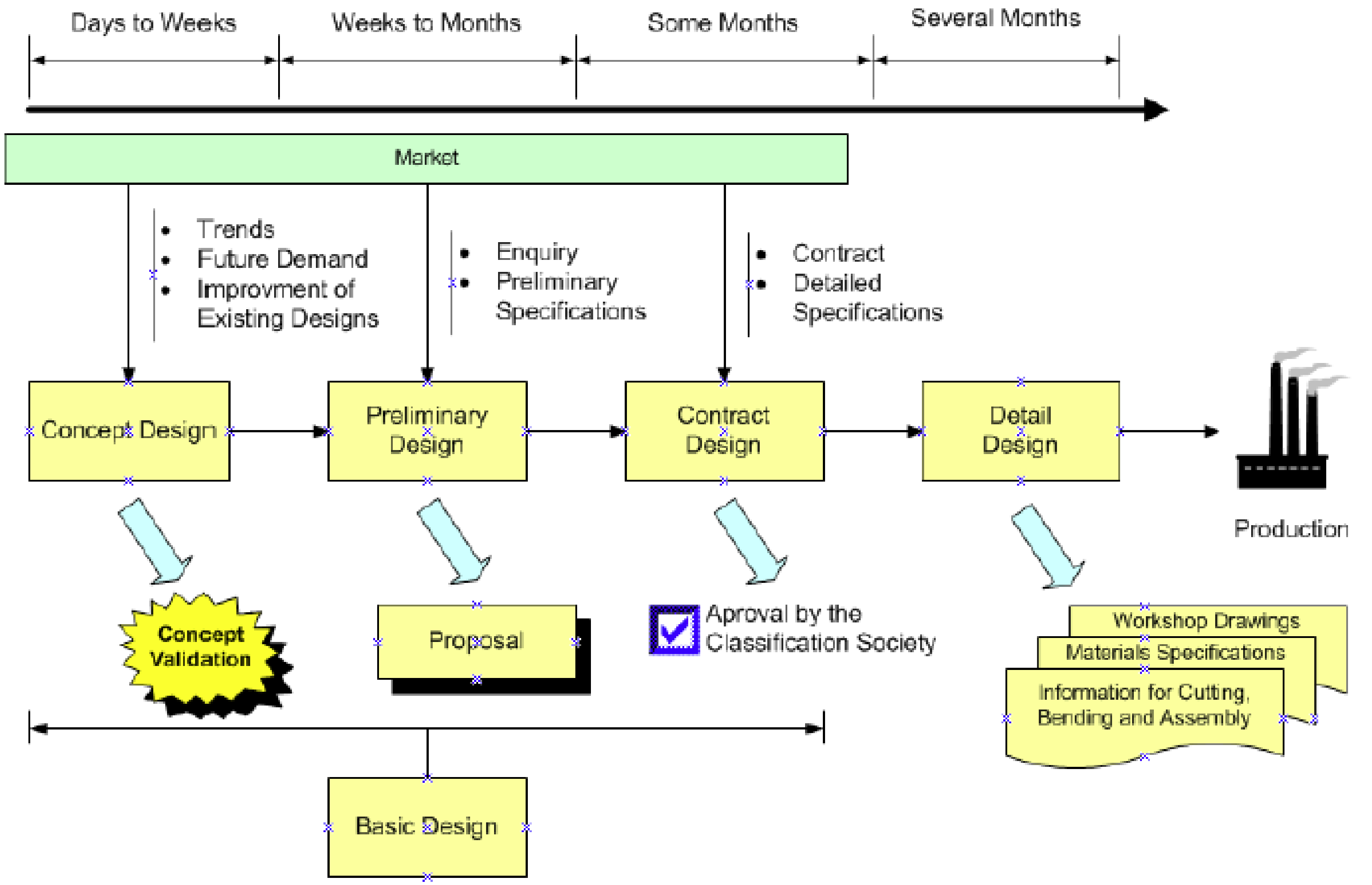

Figure 1-3: *Ship Design Process Time Scale [10]*

1.3.1 CASD/CAE Software Tools

❖ Sketchpad: I. E. Sutherland created Sketchpad, which was a pioneering computer drawing system and is considered to be the ancestor of CAD. In 1963 I. E. Sutherland submitted his thesis on "Sketchpad: a man-machine graphical communication system". He made two versions, one that was used for drafting and one that was used for the design. Sketchpad has offered a lot in human-computer interaction. It was installed on MIT Lincoln Labs' TX-2 computer, which was equipped with buttons, for entering commands, a light pen for input and a pen plotter for output. The user was able to draw on the screen, by using the buttons and the light pen. The programme's main elements were points, lines and arcs. What differed from the hand drawing was that the user could insert into Sketchpad mathematical conditions. Thus the new drawing or the existing one could take directly the desired shape. These mathematical conditions were in fact constraints and the programme included 17 different types of them. Sketchpad was a revolutionary system, because it was a combination of the graphical user interface, the non-procedural programming and the object-oriented programming [11, 12].

❖ Automatically Programmed Tools (APT): After the World War II and during the 1950's there was a huge development in the aerospace industry. Due to the demand for new technologies, parts with more complex geometries were needed. Therefore, the American Air Force funded the development of a numerical control (NC) machine tool, which was under development that period. Researchers in MIT studied further the NC problem and understood the importance of automating the entire process. D.T. Ross undertook this project and created the APT between 1955 and 1959. He was also the person who introduced the term CAD. APT was a computer programming language that simplified the process of cutting those complex parts. It enabled the programming of CNC machine tools in order to generate the parts by using a cutting tool moving in space. It basically calculated a path that the tool must follow in order to achieve the complex form. Regarding its structure, APT is very similar to Fortran [13, 14].

❖ Autokon: Autokon was a Norwegian system for the computer-aided design and construction of ships. Although APT was a pioneering language, it was purpose specific. There was a need for a programme that would cover the whole ship design process. In this respect the Autokon project started in 1960. The first version of Autokon included the following main functions:

- Hull fairing: The offsets given from a preliminary lines drawing were inserted into the fairing programme. This simulated the same spline methods as in manual fairing and it created a tape with the desirable results, which were compared to the initial offsets. Then the initial offsets were altered repeatedly, until they were close to the values of the results. The final hull form was saved and a tape was generated, in order to create the body plan.

- Shell expansion: During this function, a preliminary definition of seams, decks and longitudinals was carried out. Subsequently, these elements were faired and their intersections with transverse frames were calculated. Finally, a paper tape was created for NC marking and flame cutting.
- Part generation: The information needed, regarding the geometry of the parts, was inserted into the programme in the form of a code. Loftsmen used this information and when the relevant calculations were made, it was possible to create a tape for NC marking and cutting.
- Nesting: The parts are nested on steel formats and finally all the information, produced from the previous functions, is saved into the data bank.

The second version of Autokon simplified and made the above-mentioned functions more efficient, by doing the specifications' preparations earlier. Due to the fact that ship design requires a balance between cost and technology, Autokon followed a semi-automatic process.

Autokon was a revolutionary system, because it reduced the overall cost and time needed to complete the design process, it accomplished more detailed and accurate designs and achieved better communication and coordination between the various departments [15, 16].

❖ Prelikon: It was a system of preliminary lines design programs. Prelikon was produced in 1970 by the Bergen shipyard of the Aker Group and Det Norske Veritas (DNV). In the beginning, Prelikon was offered as part of the Autokon system, in order to produce the preliminary lines designs. Later, it became an independent system and included its own central database. Its functions were divided in three groups, the hull-form definition, the calculations' performance and output preparations and finally the performance of the data utility functions. These groups contained respectively various modules. The user inserts into the system as an input the ship's main dimensions, the owner's requirements and the ship's general arrangement. Then a parent ship was selected from the system's library, whose data are closest to the desirable design and the preliminary lines plan could be drawn. In the end, various calculations were made, such as hydrostatic and capacity. The results were checked and if they were not satisfactory, the whole process is repeated. Prelikon's main disadvantage was that among others no ship's weight, speed and freeboard calculations were made. For these calculations other independent programs were used [17].

❖ Britships: It was an integrated computer system for ship design and shipbuilding applications. It combined six ship design software, created by the British Ship Research Association (BSRA) in 1972. These software performed the following tasks:

- Routine ship design calculations
- Generation of hull-form geometry
- Lines fairing and production definition of hull-form
- Shell arrangement, longitudinal definition and plate development
- Interactive definition of steelwork piece parts and solution of design problems in geometry.
- Interactive nesting of piece parts within a rectangular plate and defining of cutting sequence.

The above mentioned tasks were organised in four phases, the concept design, the contract design, the production definition and the preparation of manufacturing information [18].

❖ Steerbear: Steerbear was a computer-aided ship design and steel processing system, which was created in 1962 in the Swedish shipyard Kockums. Initially it was built on Algol-Genius language, but later it was developed in Fortran, in order to make it compatible with more computer software and finally in PL/1, which was a language between Cobol and Fortran and offered more administrative flexibilities. The first version "Steerbear 1" included hull applications programs, like fairing, shell plate expansion and hull production activities with focus on NC steel cutting. The next versions expanded in steel drawings, description and generation of piping systems and at the same time a database was developed, in which all the useful information was saved in description form [19].

❖ Tribon: Kockum Computer Systems Company integrated the design programs Autokon, Steerbear and Schiffko and created the well-known computer-aided ship design software Tribon. It is built upon Unix C++. Tribon covers the following applications:

- Initial hull design and lines fairing
- Hydrostatics
- Stability
- Longitudinal Strength
- Steel Design
- Piping, cabling, ventilation
- Accommodation
- Product Information

Tribon was acquired by Aveva in 2004 and is widely used nowadays by shipyards, classification societies and shipbuilding offices [20].

Napa (the Naval Architectural PAckage): This is a computer-aided ship design software, which was developed during the 1970s at the Wärtsilä shipyard in Helsinki, Finland. Napa is nowadays developed and distributed by the Napa Oy company, which was established in 1989. It is written in Fortran 77 and includes tools that are related to hydrodynamic, stability and structural design. Today, Napa is used by shipyards, classification societies, maritime authorities, consultancies, ship owners, ship operators and research institutes. It covers the following design disciplines:

- Contract Design: Optimal design solution
- Hull Form and Performance: Hull design, hydrodynamics and performance optimisation
- Statutory Compliance: Compliance with rules and regulations
- Napa Steel: Structural design
- Offshore Structures: Design and analysis of offshore structures

Two of the main advantages of the Napa software, which were extensively exploited in the present thesis, are the possibility of using macros for the elaboration of a large variety of design and assessment tasks and the availability of the Napa Basic programming language. A macro is a collection of commands placed in one file or data object, from where they can later be executed. The macro language is the way of making the programme more flexible to the user, because everything in Napa can be executed using commands. When Napa Basic commands are combined with Napa commands, more efficient macros can be created. In *Figure 1-4* the design process flow in Napa is presented:

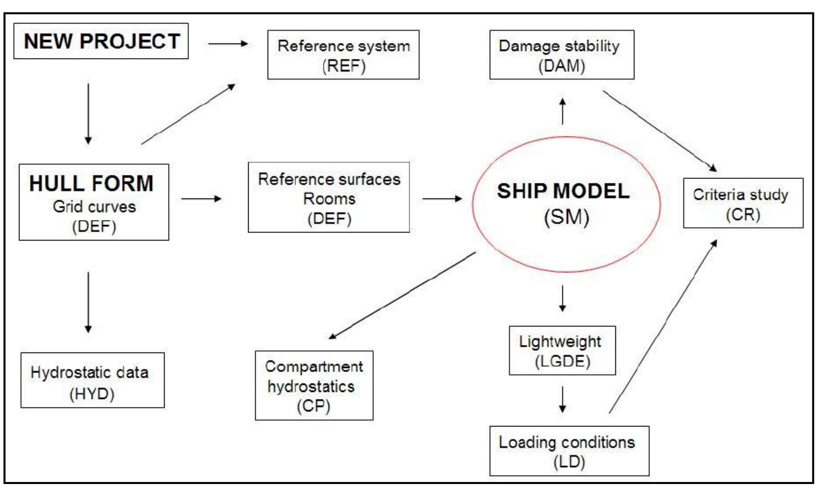

Figure 1-4: *Design process flow in NAPA[21]*

In the above figure a typical design process flow in Napa is described, but the programme is also used for more complex problems that need a further in depth study. Here, the user starts a new project and creates the reference system. Then, the hull form is defined by points, curves and surfaces. When the hull is defined, it is possible to make the hydrostatic calculations. The next step is the development of the internal arrangement. The appropriate limits are given by the user in order to create longitudinal, transverse and vertical bulkheads, decks and compartments. Each compartment's purpose is defined into the task Ship Model. The lightweight estimation follows and then the loading conditions can be determined. Finally, it is checked whether intact and damage stability are consistent with the criteria of the relevant rules and regulations [20-22].

One major issue related to CASD is the spline representation. During the 1960s intensive work was done for curve and surface representations, as they were the basis of the ship hull geometry modelling. The representations relied on the theory of splines. Firstly, the manual drafting's simulation was done with the aid of the elastic splines. Offsets were taken from a preliminary lines plan and the result was a big number of full-scale corrected offsets. In contrast to the single polynomial, these methodologies achieved the reduction of the curves' fluctuations. Later, the ships' curves were based on the Bézier curves and surfaces, which were produced by the Bernstein polynomials. At the same time the B-splines were being developed. There is a correlation between the two types of curves, as any Bézier curve can be converted in to a B-spline and the opposite. However, for the B-splines there is no relation between the degree and the number of the control points. Finally, the Non-Uniform Rational B-Splines (NURBS) are also used for the modelling of the ship hull. Their main advantage is that they can represent both curves and surfaces and standard analytic shapes, such as conics. In the area of Naval Architecture, most ship design packages today use the Bézier curves and the B-splines [23-26].

1.3.2 Literature Review

In this section selected publications are listed, which are related mainly to methodologies for the integration of the ship design process and for the holistic optimisation during the basic design. In addition, reference is made to publications related to the hydrodynamic and structural optimisation of ships. A great number of studies related to these subjects have been conducted, however this thesis will cover only a number of them.

<u>Ship Design Optimisation</u>

A large number of papers on the application of optimisation methods in ship design have been presented by Nowacki [9, 24, 27]. In [9] he described the influence of CAD in maritime engineering during the last 50 years and presented major advances, regarding the development of methodologies in Ship Design Optimisation. One of the most important problems in preliminary design has always been the optimum combination of the ship's main dimensions, based on specific criteria and constraints. Initially, ship design optimisation involved problems that included one objective function, usually related to an economic criterion. These problems were solved by applying systematic variations of the selected design parameters for the selection of the ship characteristics [28], or by developing algorithms that used convergent random search techniques [29]. Specific constraints, related to the cargo, the stability, the ship's strength etc., were introduced into the ship design optimisation problems. The objective functions and the constraints are non-linear functions. Therefore, techniques that applied non-linear programming were developed at that time.

In [30] Ray, Gokarn and Sha have developed a model for global optimisation in ship design following a multicriteria constrained multivariable nonlinear optimisation process. Their research focused on designing the model of a containership. Firstly, the design variables and parameters were identified. Then the system constraints were defined by the owner's requirements, the current regulations and the designer's design relations. The resistance and power were calculated using the Holtrop and Mennen's method. The lightweight consisted of the steel weight, the machinery weight, which were estimated using Schneekluth's and Watson and Gilfillan methods respectively, and the outfit weight. The building cost included the material costs, the labour costs, the indirect and overhead costs and the profit and was modelled according to MARIN. Finally, the compliance with stability requirements was evaluated. Two methods were utilised for carrying out the global optimisation, the multistart method and the simulated annealing method.

Another work on multiple-objective genetic optimisation in ship concept design was realised by Brown and Salcedo in [31]. This paper focused on the estimation of the life cycle cost and the overall measure of effectiveness (OMOE) index, which are affected by various inputs like the defence policy or the mission scenarios. In general the optimisation process was as follows: A random choice of design variables created the first populations of designs and the cost and OMOE were preliminarily estimated. Then the designs were divided into layers according to their dominance. An iterative decreasing selection of the dominant designs was made until there was only one surviving population of designs. Some characteristics of these designs were combined and new better designs were created. The final designs were presented by a Pareto frontier. This process was conducted by genetic algorithms.

Čudina's aim in [32] was to develop mathematical models for the optimisation of main ship characteristics and of commercial effects of new buildings. His work focused on increasing the ship's deadweight by choosing a full hull form with a high block coefficient and he dealt mainly with two types of merchant ships, tankers and bulk carriers. The design process started by defining the design variables and parameters, the design constraints, the dependent design attributes and the design objectives. Then a preliminary calculation of the depth and the minimum freeboard was made, which could be corrected later. The calculation of the main engine minimum power was the next step, which depended on the continuous service rating (CSR). CSR was calculated by an approximation formula and its independent parameters were determined by regression analysis. Subsequently he calculated the ship's displacement, lightship and deadweight. The ship's lightship consisted of the steel structure weight, the machinery weight and the equipment weight. Those weights were defined by empirical formulae. Finally, the cost of the newbuilding was calculated including the costs of materials and the costs of labour.

Parsons in [33] worked on various types of modern optimisation problems in early ship design. The first concerned optimal hull forms with focus on powering and seakeeping. A frigate vessel model was designed and was used as a reference design. The second case was about optimising general arrangements, in order to meet Navy requirements and design needs. In the third case, an algorithm was developed in order to decrease the total fleet cost considering two different ship classes with common characteristics. Parsons applied multicriterion optimisation and used genetic algorithms to find the optimal solutions. More specifically, genetic algorithms create groups of possible solutions, rather than developing a single solution like the traditional optimisation methods, and then they produce the Pareto frontier. Also, fuzzy functions were used to define in which extent each criterion is satisfied.

Papanikolaou in [34] discussed about two generic optimisation problems. The first one concerned the hull form optimisation of high-speed vessels. Two existing reference vessels were used, a monohull vessel and a high-speed catamaran and model tests were performed at a corresponding model scale. The study's objectives were the minimisation of the powering requirements and of the environmental impact of the generated wash waves. The wave resistance and the wash wave were calculated by a computational fluid dynamics (CFD) code, Shipflow. The optimal designs were presented by a Pareto Frontier and the designer, based on his experience, chooses the desirable solution. The second problem focused on the optimisation of the compartmentation of Ro-Ro passenger ships and aims at enhancing the damage stability. Suitable NAPA macros were created in order to develop the internal arrangement, analyse the damage stability, calculate the structural weight and estimate the transport capacity. The optimisation was made by SIMPLEX and MOGA algorithms and its analysis was aided by the modeFrontier software package.

Vasconcellos also worked in [35] on a multi-objective optimisation problem for preliminary ship design. His reference design was a high-speed catamaran and the mathematical model was built as follows. The wave and the frictional resistance were estimated by utilising the slender body theory and the flat plate theory respectively. The structure and equipments weights were calculated according to Karayannis *et al.* [36], whilst the operational weight depended on the voyage's distance and time considering among others the number of the crew, luggage weight, provisions, fuel and lubrication oil and fresh water. Finally, the cost evaluation was done, including investment, operational and infrastructure costs. This study focused on Robust Optimisation that applies Genetic Algorithms and Monte Carlo simulation. The Robust Optimisation is related to uncertainty. The uncertainty in this study was the speed reduction due to small boats in the area or night navigation. The whole optimisation process was conducted in modeFrontier software.

Nakamatsu T., Mizutani K. and Mizutani N. in [37] presented a shipyard's objective to integrate the design spiral process in initial design stage and focus on a 100000 DWT bulk carrier with 7 cargo holds, carrying coal, ore and grain. The NAPA System covered the whole design process of a 3D model and its workflow was as follows: The user defined the ship's main dimensions and according to this data a hull surface was created, which was chosen from the shipyard's database. The next step is the calculation of the powering and the fuel oil consumption. The Holtrop-84 method was used to define the hydrodynamic coefficients. Following this, the model's arrangement was created, including geometric objects and the main structural members. Further calculations were made for the estimation of the ship's freeboard, lightweight, deadweight, capacity and energy efficiency design index (EEDI). Then, it was checked whether the typical loading conditions were consistent with the regulations. The final step was the total building cost calculation, according to the model's and the shipyard's information. When the 3D model was ready, the optimisation process started with the aid of Napa's multi-objective genetic algorithm (MOGA). The specific paper presented two optimisation cases that refer to minimising the bending moment by finding the optimal bulkheads' positions and minimizing the EEDI and building cost by finding the optimal ship's main dimensions.

An extensive work in integrated design and multi-objective optimisation was done by Papanikolaou, Harries, Wilken and Zaraphonitis in [38]. An AFRAMAX tanker was used in the paper as an example. Many software packages were utilised, like Friendship-Framework (FFW), Poseidon, Napa and Shipflow. The hull was created in FFW and it consisted of the forebody, the parallel midbody and the aftbody. The tank arrangement was also created in FFW. The side shell width, the double bottom height and step, the hopper plate's angle and width were set as free variables and could be changed in each design. The main structural design was created in Poseidon, according to the common structural rules (CSR), including the scantling calculations. Resistance and propulsion were estimated by using response surface models, whilst flow and viscous calculations were performed in Shipflow. Finally suitable NAPA macros were created for the calculation of the oil outflow parameter. The multi-objective optimisation aimed at minimising the required freight rate, the energy efficiency index and the oil outflow parameter, while maximising the ship's speed.

Zaraphonitis *et al.* dealt with multi-objective optimisation of ROPAX ships in [39]. They focused on damage stability by taking into consideration the new SOLAS 2009 regulations for probabilistic damaged stability as well as the proposed formulations from the EU-funded, FP7 research project GOALDS. For this specific work, a parametric model of a typical ROPAX vessel was created in NAPA. The lightship weight and the building cost were estimated by information given from the shipyard. It was checked whether the loading conditions comply with intact stability requirements. The resistance and power were calculated using the Holtrop-84 method. The two attained subdivision indices by SOLAS 2009 and GOALDS projects were also calculated. The optimisation was done by applying Genetic Algorithms in the modeFrontier software. The optimisation aimed at the minimisation of the Potential Loss of Life and of the Gross Economic Impact of the design modifications.

Hydrodynamic Optimisation

Harries *et al.* in [40] focused on the optimisation of the hydrodynamic design from an economical perspective. Their reference vessel was a 3400 TEU container carrier. Their work aimed at three different objectives: Lower resistance for the same displacement and stability, bigger payload for the same total resistance and reduced draft for similar payload. The advanced hydrodynamic design was achieved by investigating new forebody shapes. The sectional area curves (SAC) of the common container carriers have one inflection point in the forebody, extending from the forward perpendicular to the maximum section. The new concept that they introduced was the generation of various new hull forms that produced supplementary inflections in the waterlines, in order to influence positively the free waves. The new concept is called innovative sectional area curve (InSAC). Non-linear CFD calculations were made, using the CFD code Shipflow, whilst the whole design and optimisation process was developed in FFW. The above-mentioned objectives were satisfied by many designs, developed with this method. For example, an increase of 1.5% in loaded TEU was achieved, owing to displacement increase, while the speed and the delivered power remained the same.

In [41] numerical simulation was utilised by Couser *et al.* for defining the design-space during the concept design. The process started with the development of the 3D parametric model of a mega yacht in FFW. Nine free variables were used to define the parametric model. The model initially did not include the appendages. The second part comprised the performance prediction. The calm water resistance, which used potential flow and boundary layer theory, was calculated in Shipflow, the hydrostatic stability in Hydromax and the sea-keeping characteristics in Seakeeper. The motions in waves were predicted by linear strip theory for two different sea states. Also the motion sickness incidence was calculated. Finally, it was checked, whether the intact stability met the stability criteria from the Large Commercial Yacht Code. All the data was captured by response surfaces that allow instantaneous interpolations of the performance measures for any of set of values of the free variables, in contrast with CFD or sea-keeping calculations that would be very time consuming.

Tahara *et al.* worked in [42] for the numerical optimisation of the initial design of a high-speed catamaran. The whole study focused on simulation-based design, which was based on an unsteady Reynolds-averaged Navier-Stokes (URANS) solver. The advantage of the URANS solvers is that they are able to reveal the extension of the flow distortion caused by the hulls' interaction. Three different optimisation problems were solved that include both single and multi-objective optimisation methods. The validity of the optimisation methods was proved by the experimental results regarding the resistance, the sinkage and the trim between the original and the optimal designs.

A fundamental part of the hydrodynamic optimisation is related to the propeller. Vesting and Bensow in [43] dealt with an optimisation problem of a propeller blade, aiming at the maximisation of the efficiency, while minimising the pressure pulses induced by the propeller. This was achieved by developing a parametric model of the propeller, which was built within FFW. The model's characteristics were given as a set of parameters and variables. CFD calculations were conducted in Shipflow in order to define the flow and propulsion characteristics. The best design resulting from the optimisation process offered 8.8% decrease in the pressure pulses induced by the propeller and at the same time 0.6% increase in the efficiency.

Structural Optimisation

Rigo, in a series of publications, dealt extensively with the Ship Structural Optimisation. In [44] he focused on defining the optimum scantlings and at the same time the minimum construction cost of one of the four tanks of a medium LNG tanker. LBR5 software was used, which is an integrated package for cost and weight optimisation of stiffened ship structures. The ship's main dimensions, the global structure layout and the applied loads are defined by the user. The initial scantlings were defined by the shipyard using the MARS2000 software and in the end of the optimisation procedure, the new scantlings calculated by LBR5 were compared to the initial ones. Five different load cases were assumed according to BV rules. Also, the maximum still water sagging and hogging bending moments were given by the shipyard, whilst the wave bending moments were estimated from the classification rules. Then, the mesh model of the steel structure was created. The minimisation of the construction cost can be achieved by decreasing the number of web frames, which leads to increasing the web frame spacing and by increasing the average longitudinal stiffener spacing. The optimisation process was divided into sub-optimisations, in order to understand the impact of the various parameters on the design objectives.

Žanić *et al*. dealt with an innovative design of a ROPAX ship in [45]. They focused on two directions. The first one involved general ship design optimisation and selection, whilst the second one regarded ship structural design optimisation and analysis. The objectives of the ship design optimisation were the selection of the most suitable hull form, decreased propulsion power for the same speed, less fuel consumption and increased length of cargo space. The targets of the structural optimisation included lowering the vertical centre of gravity for achieving better stability, reducing the lightweight and the maintenance cost. Regarding the structural optimisation, two superstructure alternatives were studied depending on the number of superstructure decks and the transverse and longitudinal bulkhead positions. The 3D models, as well as the optimisation were conducted by MAESTRO structural software. Many design variables were used, like the number of the superstructure decks, the lower hold's breadth and the scantlings of structural elements. It was shown that the structural optimisation can offer better material distribution, reduced weight and increased safety.

1.4 Impact of CASD on Ship Design

Ship design has been deeply influenced by CASD. The traditional design, described in paragraph 1.2 by Evan's design spiral, is considered as "ideal". It is very difficult to undertake improvements step by step iteratively, because the designers ought to take into account every function and subsystem of the design and consider every possible option. With the aid of CASD it is possible to execute the various steps of the ship design process simultaneously, as depicted in *Figure 1-5*. This is mentioned as an integrated approach to ship design. The calculation work is done faster and more efficiently. Moreover, it is possible to incorporate into the CASD programmes the assessment of the compliance with relevant rules and regulations. Thus, the designer is able nowadays to check directly whether his current design complies with the various rules and regulations and, if necessary to modify the corresponding variables and parameters. All these have led to two main advantages of the particular integrated approach. It reduces the overall cost of the design as well as the time needed for completing the whole process.

Ship design will always aim to achieve a balance between economy and safety. Using modern CASD software tools, it is easier to create new ship types or improve the existing ones in a more economically sufficient way in conjunction with the safety regulations. For example, LNG and LPG tankers, container ships and double hull tankers have been designed in this respect. CASD has also contributed to the development of more complicated methods for the ship's assessment that require a huge volume of calculation work, such as the probabilistic damage stability [9, 24].

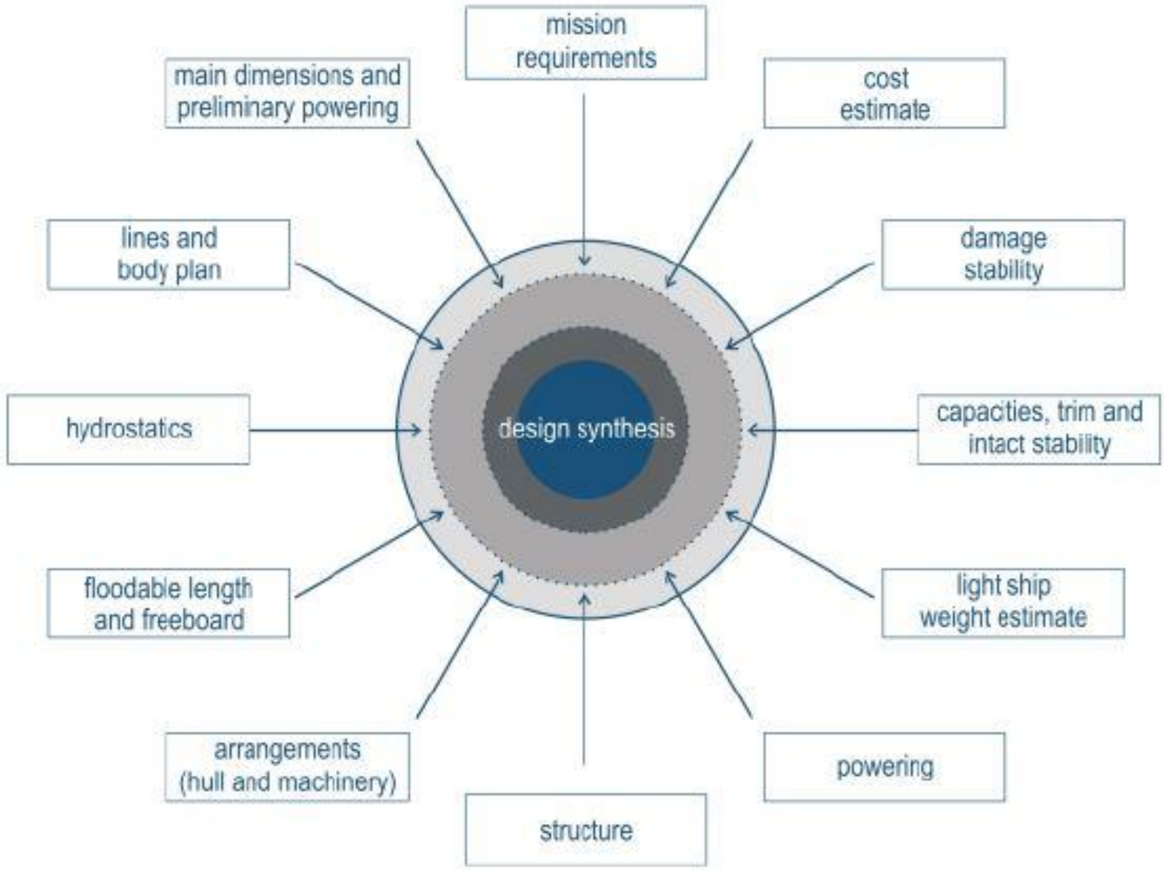

Figure 1-5: *Ship Design's Integrated Approach [46]*

2 Tankers

According to MARPOL an oil tanker is a ship constructed or adapted primarily to carry oil in bulk in its cargo spaces and includes combination carriers, any NLS (Noxious Liquid Substances) tanker and any gas carrier, when carrying a cargo or part cargo of oil in bulk [47].

2.1 History of tankers

The history of tankers as a way of transporting bulk liquids dates back to the later years of the 19th century. Before the development of tanker ships, the idea of carrying bulk liquids in ships was considered a very expensive and infeasible project. The market was also not ready for transporting and selling cargo in bulk, due to the lack of suitable infrastructure.

The modern oil tanker was developed in the period between 1877 and 1885. The Swedish engineer and businessman Ludwig Nobel was responsible for the design and construction of the world's first oil tanker. Nobel recognised that transporting oil in leaky wooden barrels was unreliable and expensive. Thus, in 1878, he signed a deal with Sven Almqvist at Lindholmen-Motala in Sweden to make the blueprints for a tanker. That same year, the first oil tanker, named Zoroaster, was built. The tanker was the first ship that used Bessemer steel and had built-in iron tanks in front and at the rear. Nobel's oil tanker revolutionised long-distance transport and distribution of petroleum.

In 1883 the oil tanker design took a large step forward. The British engineer Colonel Henry F. Swan, who was working for the Nobel Company, designed a set of three Nobel tankers. The designed tankers had several holds spanning the width or beam of the ship instead of two large holds. The holds were further subdivided into port and starboard sections by a longitudinal bulkhead. This approach of dividing the ship's storage space into smaller tanks decreased the free surface effect, which was causing stability problems in previous designs.

However, the first modern oil tanker is believed to be the Glückauf [48]. It was built in 1886 by the Armstrong Mitchell yard in Newcastle upon Tyne for the German H. Reidemann and it was the first dedicated steam-driven, ocean-going oil tanker into which oil could be pumped directly to its internally subdivided eight-compartment hull. It is considered as the first modern oil tanker, because it was equipped with systems, such as cargo main piping, valves and cofferdams and could receive ballast water when empty of cargo. Glückauf eventually grounded near Long Island, New York in fog, fortunately being almost empty of cargo. Glückauf's grounding is shown in *Figure 2-1*.

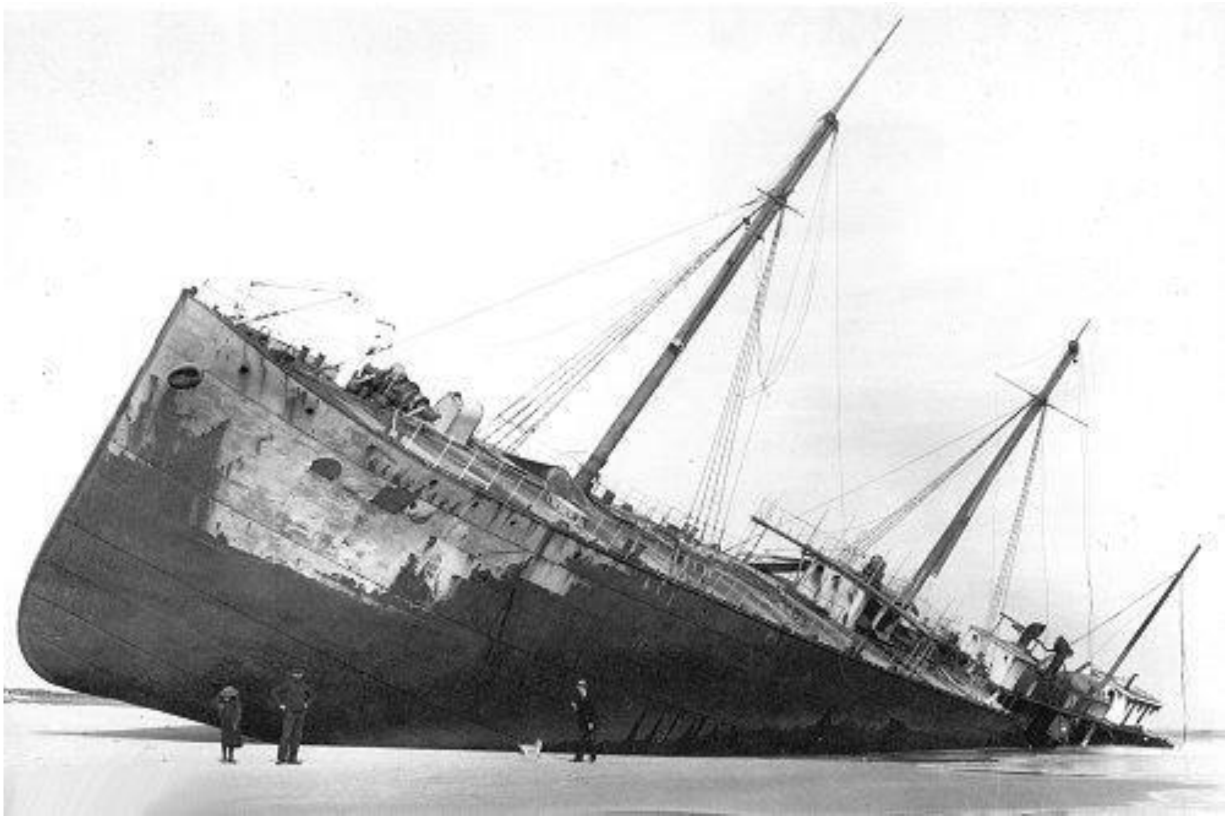

Figure 2-1: *Glückauf's grounding in Long Island, New York[49]*

The outbreak of World War I led to the development of larger ships capable of carrying more oil to warships with The USS Maumee, built in 1915, being the first "underway replenishment technique" ship. For the same reasons World War II also led to the development of larger tankers. After the end of World War II, the demand for tankers was expected to decrease. However, as it is shown in *Figure 2-2*, there was a huge demand for oil from the mid-1950s until 1980.

This increase was due to the rapid growth of the world economy. The increased oil consumption, coupled with political events including the closure of the Suez Canal in 1956 and later in 1967 until 1975, the nationalisation of oil refineries in the Middle East and the Marshall Plan, led to the demand for an increased number of larger tankers. Crude oil was transported to North America, Europe and Japan from distant, oil-producing areas, such as the Persian Gulf, Southeast Asia and South America. Therefore, there was a remarkable development in the tanker shipping industry.

More specifically, until 1955 the biggest oil tanker was the SS Spyros Niarchos with a DWT of 47,500 t. In 1958, due to the above-mentioned reasons, the first oil tanker with a DWT more than 100,000 t was delivered. The DWT increase of the oil tankers continued and during the 1970s the Supertankers appeared. In 1974, the biggest Supertanker with a DWT of 418,000 t was ordered by a Greek ship owner. Supertankers are no longer operated nowadays.

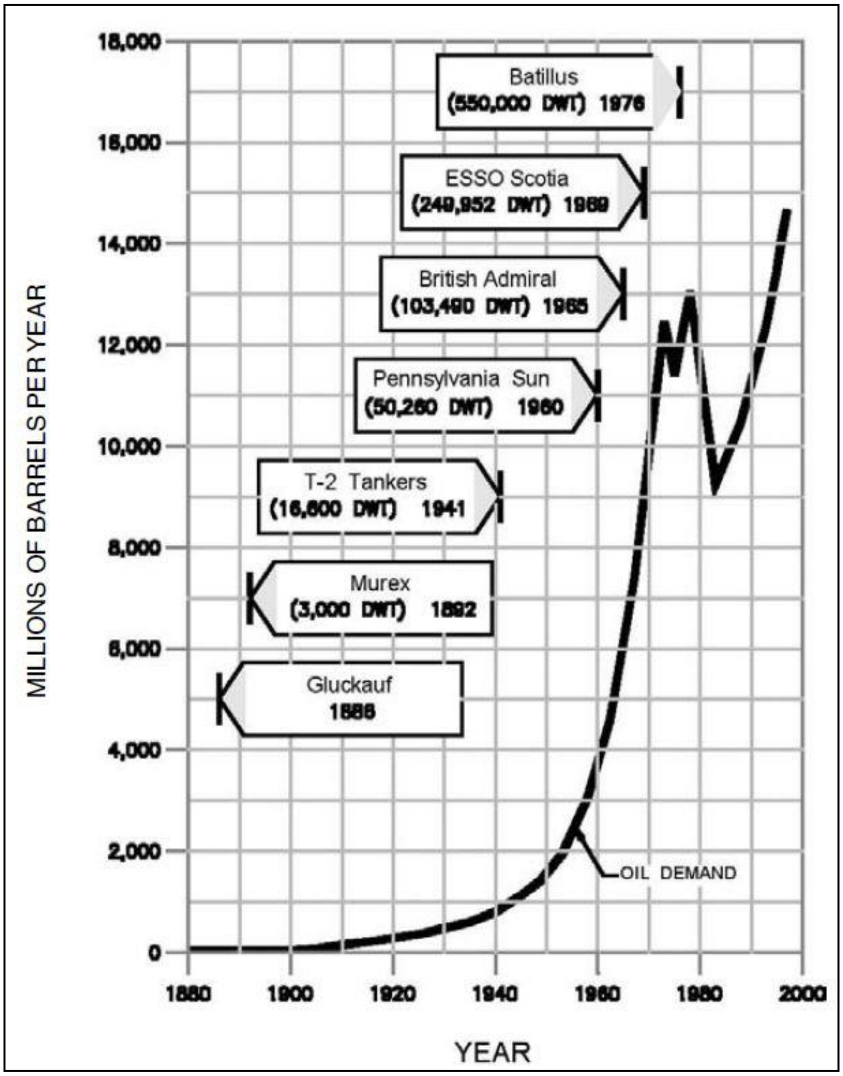

Figure 2-2: Growth of oil demand and tanker size [5]

2.2 Classification of tankers by type of cargo

2.2.1 Crude Oil Tankers

These vessels carry crude oil from a production oil field to a refinery. The crude oil, which is the raw product pumped from the earth without sand and water, is loaded from shore pumps into the vessel through pipelines and hoses. These hoses are connected with manifolds, from which the oil goes vertically down to the ship's bottom lines. From there, the oil is delivered through longitudinal pipelines, equipped with several branches, to the cargo tanks. Respectively, to unload the cargo, the oil is pumped out from the cargo tanks and pressed to the manifolds. Loading and unloading can last between 24 to 36 hours per operation.

2.2.2 Product Tankers

These vessels carry refined products from the refineries to the customer. The product tankers are designed to carry several different types of cargo and therefore they are equipped with more tanks than the other types of tankers. As they carry different types of cargo, their piping system is very complicated. Every cargo tank has separate loading and unloading lines to the manifolds and separate cargo pumps. The types of cargo that can be transported by these tankers are:

- oil products such as gasoline, kerosene, naphtha, diesel oil, lubricating oil
- vegetable oil
- wine
- orange juice

2.2.3 Chemical Tankers

These vessels carry cargo with high toxicity and flammability and therefore careful handling is required. That is the main reason they have to comply with stricter rules and regulations. For example, there is a wider distance between the cargo tanks and the outer shell or the bottom. The cargo is divided into classes (A, B, C or D) depending on its toxicity, where A is the most toxic and D the least. These vessels are specifically designed to maintain the consistency of the chemicals transported. Possible cargo can include acids, alkaline, alcohol, edible oils, chlorinated alkenes, monomers and chemical substances.

2.2.4 Liquefied Gas Tankers

Liquefied gas tankers are used to transport liquefied gas from gas fields to the customer. By definition liquefied gas is the liquid form of a substance, which at normal ambient temperature and atmospheric pressure would be gas. At low temperatures and under pressure, this cargo can be stored in its liquid state. The particular tanker subtypes are divided into 3 categories:

- Fully pressurised ships, where the cargo is under pressure at the ambient temperature. These ships are used mostly for transferring Liquefied Petroleum Gas (LPG) between smaller terminals. The term fully pressurised means that the cargo is carried in closed cylindrical tanks under ambient temperature and at a certain pressure in order to ensure that the cargo will remain in its liquid state.

- Fully refrigerated ships, where the cargo is carried under atmospheric pressure and at very low temperatures. For example, LPG is carried at -42 ^{o}C. They are used mostly for transferring Liquefied Natural Gas (LNG) at a temperature of -162 ^{o}C.
- Semi Pressurised/Semi Refrigerated ships, which are a hybrid type between fully pressurised and fully refrigerated. These vessels carry a variety of different types of cargoes [5, 50, 51].

2.3 Classification of tankers by size

Handysize: These vessels have a maximum of 10,000-30,000 DWT. They are easily manoeuvrable and have a shallow draft.

Handymax: Vessels of 30,000-50,000 DWT. These are a larger version of the Handysize vessels. Handysize and Handymax tankers usually enter small port and they operate within regional trade routes.

Panamax: These vessels are the largest that can transit through the Panama Canal. They range in length between 200 and 250 m with a deadweight tonnage between 50,000 and 80,000 t.

AFRAMAX: AFRA stands for Average Freight Rate Assessment. They are medium-sized oil tankers with capacity between 80,000 and 120,000 t. They are ideal for short to medium trade routes and they are usually used in ports that are not well equipped to accommodate bigger tankers and in regions with low crude oil production.

Suezmax: The largest ships that can pass through the Suez Canal and have a capacity of 120,000 to 200,000 DWT.

Very Large Crude Carriers (VLCC): They have a size ranging between 200,000 to 320,000 DWT. They are designed to deliver crude oil on very large voyages and they can also operate in ports with depth limitations. VLCCs are used extensively around the North Sea, Mediterranean and West Africa.

Ultra Large Crude Carriers (ULCC): They are the largest shipping vessels in the world and their size exceeds the 320,000 DWT. These vessels are not easily manageable, as only a limited number of ports can accommodate them. ULCCs are used for long distance trade routes from Middle East to Europe, Asia, and North America. Nowadays, new ULCC tankers are not being built and in general their operation is confined.

The terms Handysize and Handymax are usually used to describe bulk carriers, but nowadays they are also used for the description of product tankers. The most important tankers described above are shown in *Figure 2-3*.

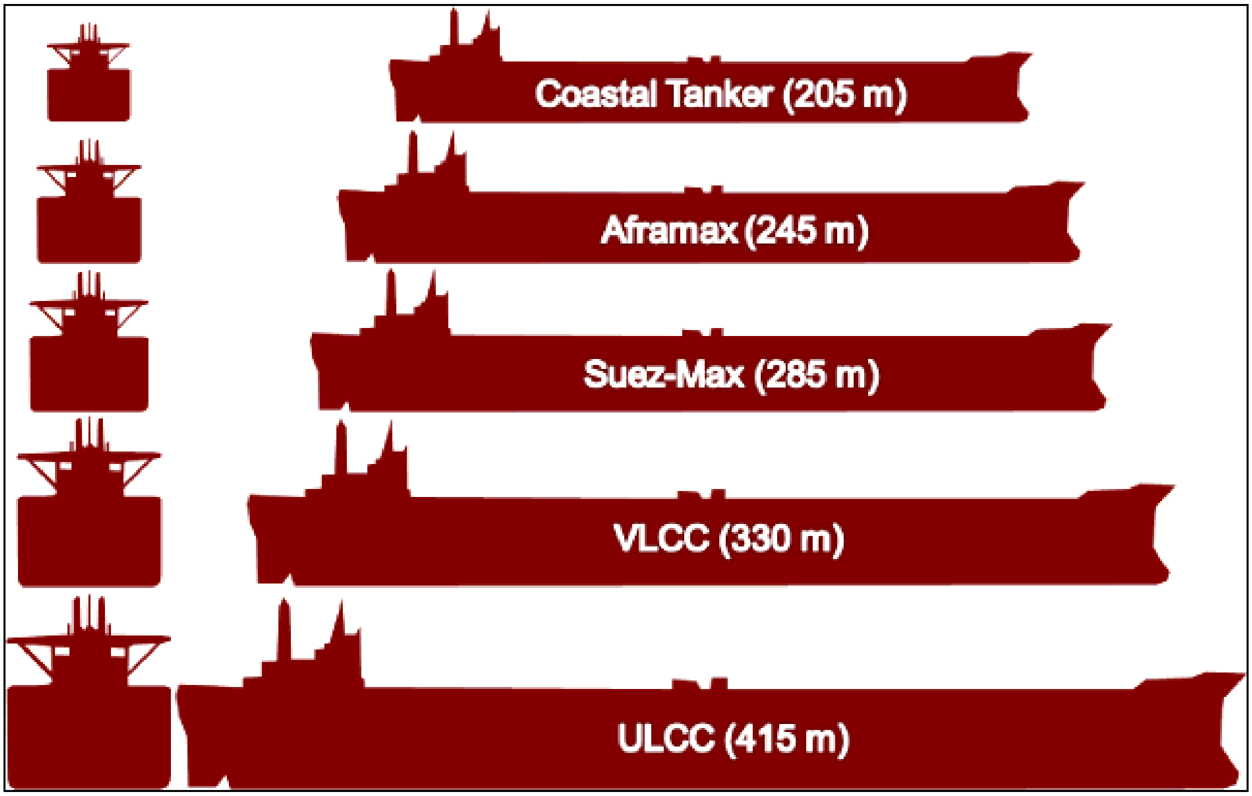

Figure 2-3: *Tanker ship size[52]*

In general, crude oil tankers carry large amounts of crude oil, which are transported from distant areas. They have a minimum DWT of 50000 t, whereas the product tankers are smaller and their DWT ranges from 5000 t to 80000 t [5, 51, 53].

2.4 <u>Tanker Design Characteristics</u>

The general arrangement of a crude oil tanker is as shown in *Figure 2-4*.

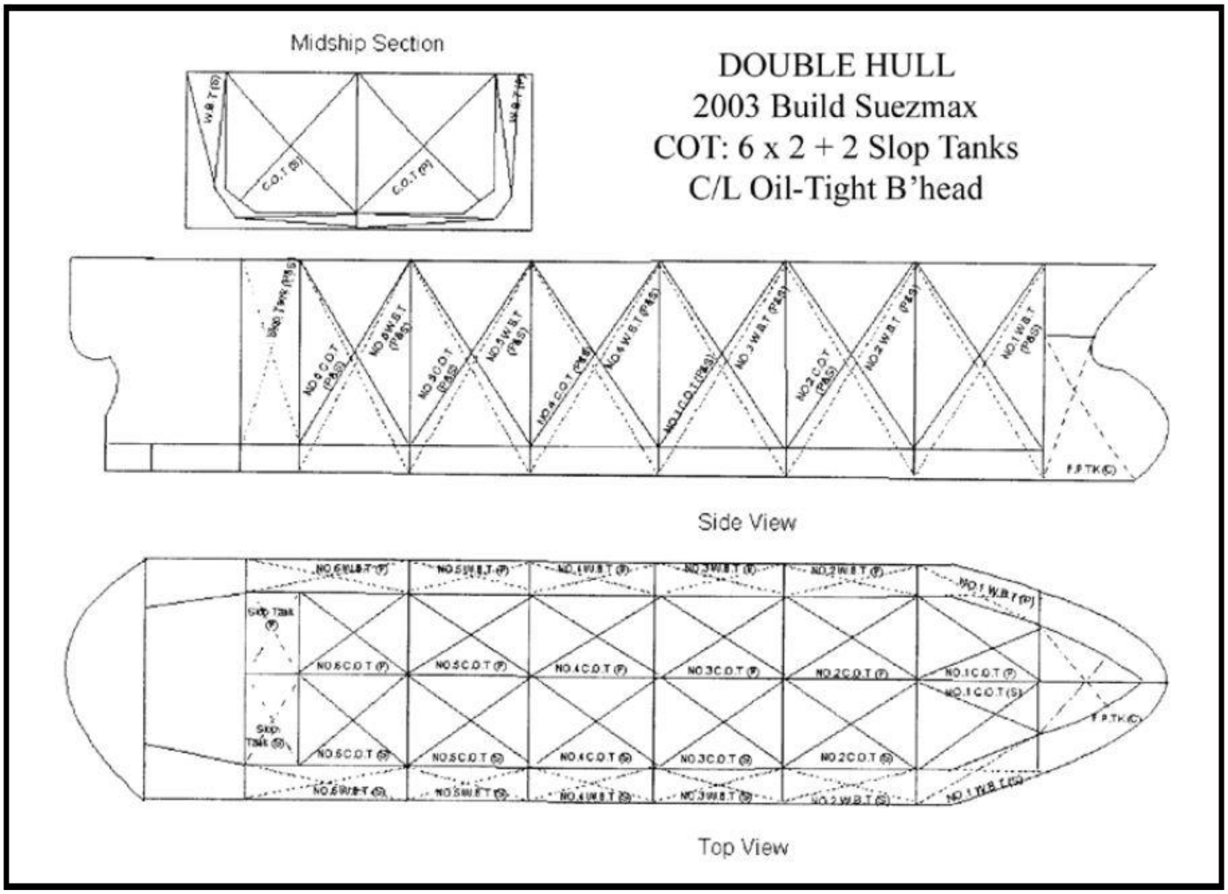

Figure 2-4: *General Arrangement of Suezmax COT[54]*

The tankers nowadays are described by the following elements [32]:

- high block coefficient
- one main deck
- cross-section with double bottom and double sides
- plane or corrugated bulkheads in cargo holds
- high cubic capacity of cargo tanks
- accommodation and engine room positioned aft
- short engine room
- freeboard exceeding minimum requirements

There are many factors that have influenced the design of the present tankers. Carrying bulk liquids entails some important disadvantages and hazards.

- Free surface effect: When a tanker with a partially filled tank is heeled, the liquid in the tank moves across it in the same direction as that of heel. As a result, the centre of gravity of the ship moves away from the centreline, which reduces the righting lever GZ and the height of the metacentre. This further increases the angle of the heel and is known as the free surface effect.
- Oil spill: Accidents resulting from an explosion, grounding or collision increase the possibilities of a marine oil spill. This is defined as the release of a liquid petroleum hydrocarbon into the ocean and coastal waters. Oil spills have serious environmental, social and economical consequences.
- Fire/Explosion: While the cargo is being discharged, the percentage of oxygen entering the tank increases which can lead to a fire or an explosion.

The designers have developed various ideas to avoid the hazards mentioned above.

Longitudinal Bulkheads: The vessel's cargo area is divided into two parts with a main longitudinal bulkhead. These two parts are further subdivided into smaller parts by the transverse bulkheads. This configuration decreases the free surface effect. In larger tankers such as the VLCCs or ULCCs double longitudinal bulkheads can be used, which offer greater flexibility with cargo loading options.

Hull Designs: As it was previously mentioned, in case of a marine oil spill there are disastrous consequences. MARPOL has introduced operational and constructional regulations for avoiding accidental oil pollutions, a number of which have been applied over the last 30 years. Until the 90s single-hulled tankers represented the status quo and carried 80% of the crude oil and refined products. The main disadvantage of the single-hulled tankers is that the cargo oil is separated from the seawater by a thin layer of 20 mm steel. In case of a collision or grounding, there is a great threat of an oil spill. An improvement that has been made through the years in the single-hulled tankers is that they are equipped with segregated ballast tanks. Earlier, the single hull tankers carried the water ballast into the empty cargo tanks, which still contained an amount of residuals that remained after the unloading of the cargo. When the water ballast was emptied from the cargo tanks, these cargo residuals were also thrown to the sea, causing an extensive marine pollution. MARPOL adopted new regulations in order to eliminate this pollution and water ballast is being carried into segregated ballast tanks. However, this measure provides only minimal protection regarding the oil spills. Another design is the mid-deck concept. The mid-deck tankers have a very high double bottom, which loads cargo, and very wide double sides, which load only ballast. Under MARPOL the mid-deck design is considered an acceptable solution. During a collision there is a low possibility for a full penetration of the wider side tanks. However, the main disadvantage of this design is that in case of grounding, accident oil will be released to the sea. The dominant and "best" design is considered the double hull concept. A double hull is essentially a hull within a hull. The cargo is carried inside the inner hull with a space dividing it from the outer hull. The cargo space is protected from the environment by the double hull, which consists of a double side and double-bottom space and is intended for the carriage of ballast. The ballast space extends for the full length of the cargo carrying area. It is required for an unloaded tanker, to load the ballast space between the hulls with seawater, in order to gain stability and propeller immersion. An obvious advantage of the double-hulled tankers is that in case of an accident the cargo is prevented from leaking into the sea. The main disadvantage is that the construction cost is higher in comparison with the single-hulled tankers. It is also difficult to reach the ballast tanks, due to their special geometry. In *Figure 2-5* it is shown that in case of grounding, the double hull design achieves enhanced safety.

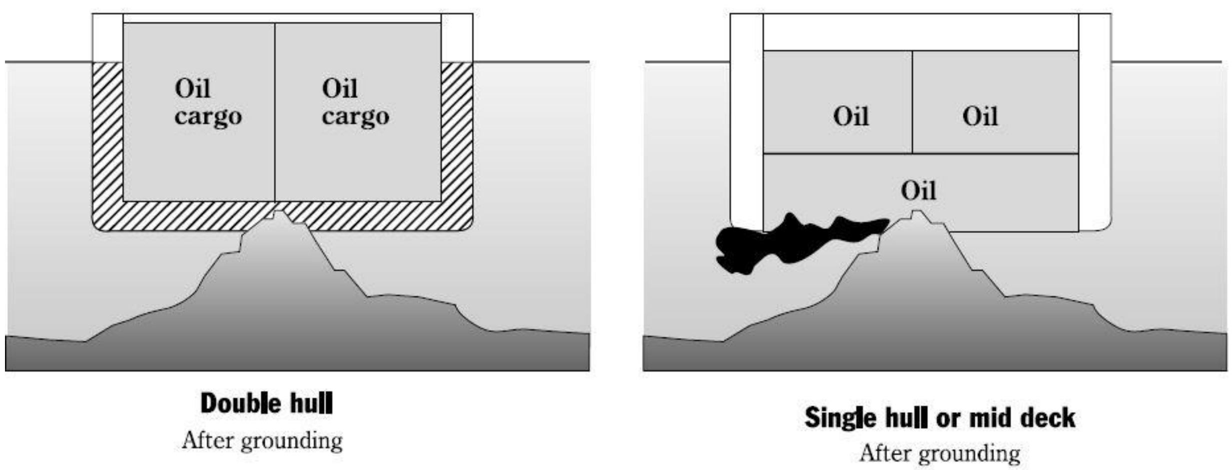

Figure 2-5: *Double Hull, Single Hull, Mid-deck after grounding[55]*

Apart from the classic hull designs there are also some alternative tanker designs, such as the "Coulombi Egg". The doubled-hull concept is nowadays regarded as the standard design. However, an oil spill is still possible, but with a relatively reduced probability of occurrence. The choice of the best design depends on the criterion that is taken into account. If the criterion chosen is the prevention from oil spill, then the double-hulled design is preferred. If the purpose is to decrease the overall volume of oil entering the ocean, mid-deck and double-hulled designs are preferred. If the criterion is the minimisation of the construction and maintenance cost, then the single-hulled designs come first. In general, there is such a wide range of circumstances related to marine accidents that no design seems to be the only possible solution [55, 56]. In *Figure 2-6* the various hull designs are presented.

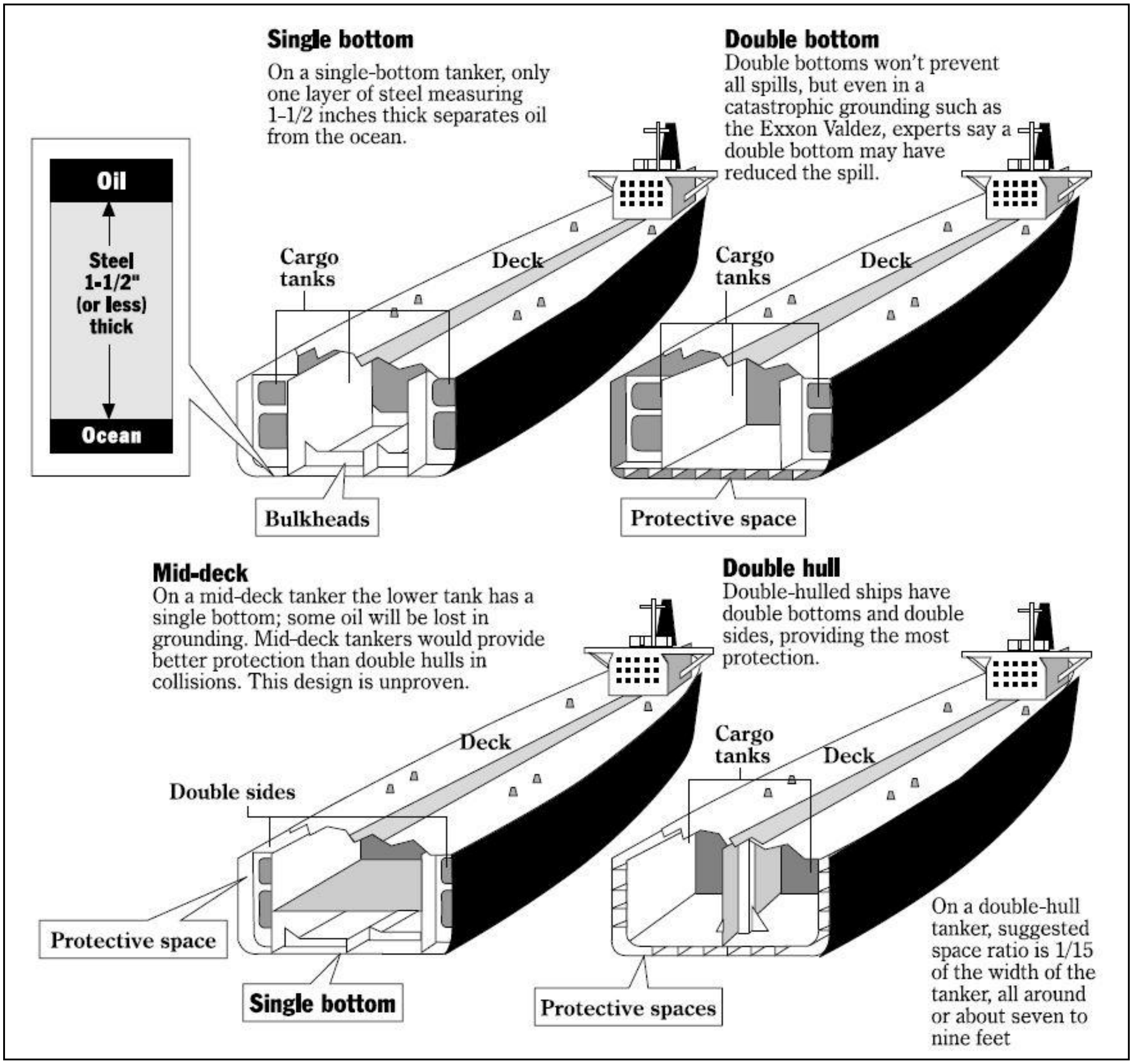

Figure 2-6: *Tanker Hull Designs [55]*

The basic advantages and disadvantages of the three designs, described above, are shown in *Table 2-1*.

Table 2-1: *Advantages and disadvantages of the designs*

Design Comparison			
	Single-Hull	Mid-Deck	Double-Hull
Advantages	+Lower construction cost	+Safer in collisions +Better performance in high speed groundings	+Halves the oil volumes spilled in accidents +Reduction of oil spills
Disadvantages	-Highest possibility of oil spill in accidents	-Some oil will be spilled in low speed groundings -Lack of operating experience	-High construction cost

Inert gas system: All tankers are equipped with an inert gas system, in order to eliminate the risk of fire and explosion. While a tank is being discharged from its cargo the amount of oxygen increases in the tank. The inert gas system basically maintains an oxygen deficient atmosphere in the cargo and slop tanks, so that combustion of vaporised hydrocarbon gases does not occur. Oil will not burn as long as the percentage of oxygen stays remains 5% [50].

2.5 Review of major tanker accidents

It is a fact that each accident occurs under very different circumstances and most of the times accidents are caused due to a combination of reasons. Therefore, it is very difficult to predict measures to be taken, in order to avoid a possible accident, before this accident happens. For example, the well-known "Exxon Valdez" oil spill was caused by the ship's grounding on Prince William Sound's Bligh Reef. Many reasons led to this grounding, such as the failure of the Exxon Shipping Company to supervise the master and the crew, the lack of specific monitoring equipment, the vessel's route outside the normal sea lane in order to avoid small icebergs and among others the fact that the captain was reported to be drunk. The grounding of the single hull crude oil tanker "Exxon Valdez" led to the first major regional agreement for tanker operations in US waters through the Oil Pollution Act in the USA in 1990. This agreement was in fact the introduction of the double-hull tanker concept. It can be assumed that if the "Exxon Valdez" was double hulled, the oil spill would have been avoided, which is not necessarily true. There is a considerable probability that the oil spill could have been avoided, but the accident would still have occurred. However, the regulations aim to not only minimise the probability of such incidents, but also to reduce the consequences of the incident, such as oil spills. In *Table 2-2* there is a list with the major tanker casualties, which led to the introduction of new regulations and amendments of the existing ones. The "Deepwater Horizon" was not an oil tanker, but an oil rig. It is mentioned in this section, because it had dramatic environmental consequences. It is considered the largest accidental marine oil spill in the history of the petroleum industry. The regulations, which are related to offshore platforms, are certified by classification societies and governmental authorities and do not comply with international safety regulations [48].

Table 2-2: *Major tanker casualties*

Ship's name	Date	Cause of the accident	Oil released in tonnes	Adoption of new regulations/amendments
Torrey Canyon	1967	Grounding	119,000	- MARPOL 1973 - STCW 1978 - SOLAS 1974
Argo Merchant	1976	Grounding	28,000	- Development of Protocol 1978 of MARPOL
Amoco Cadiz	1978	Grounding	227,000	- Implementation of Protocol 1978 of MARPOL - Introduction of Paris MOU
Exxon Valdez	1989	Grounding	37,000	- OPA 90
Erika	1999	Extreme weather conditions	20,000	- Revision of MARPOL 73/78 - Adoption of ERIKA I, ERIKA II
Prestige	2002	Hull damage in heavy seas	77,000	- Adoption of regulation 1726/2003 - Amendments to regulations 13G and 13H of MARPOL
Deepwater Horizon	2010	Drilling rig explosion	600,000	

3 Parametric Modelling of Oil Tankers

Whenever there is a request for a new ship, the traditional approach is to design a static model, in order to study it, create the relevant drawings and make the necessary computations. During this process, designers are relying extensively on the use of modern CASD software tools, while at the same time they are benefitting from past experience gained from similar designs.

The present thesis on the other hand is exploring a non-traditional approach, focusing on the development of parametric models. Through this approach, a ship model is created, which enables the production of a multitude of similar designs. Parametric modelling aims at generating a series of designs that fulfil specific objectives, in order to select the most efficient ones, based on prescribed criteria. Many designs can achieve some of the objectives separately, but the optimal solution is to develop a number of designs that accomplish all the objectives combined in the best possible way. Thus, ship designers are able to offer the best solution, according to the mission requirements that have been set. Possible objectives of parametric modelling of oil tankers can be:

- maximisation of cargo capacity (payload)
- maximisation of speed for a given main engine
- minimisation of propeller power
- minimisation of the oil outflow parameter
- minimisation of the energy efficiency design index
- minimisation of building cost
- maximisation of net present value

In Napa, parametric modelling can be achieved by developing suitable Napa macros that elaborate a large variety of design and assessment tasks. The efficiency of these macros is substantially enhanced by using the Napa Basic programming language, which is embedded in the Napa system. Alternative designs are derived by assigning values to a series of design variables and design parameters. Design parameters are kept constant, whilst design variables are treated like free variables, as they vary between a lower and an upper boundary. Moreover, there are two types of design constraints. The first type is related to relevant rules and regulations. The second type is related to the ship's environment, such as its route weather, restrictions regarding the ship's main dimensions, for example if it is passing through the Panama Canal, or it needs to be berthed in specific ports, posing limitations to the ship's dimensions.

Although Parametric Modelling offers several advantages, it comprises also some limitations. First of all, parametric modelling allows for relatively limited flexibility. When a unique static model is designed, the designer has full control over all special characteristics and particular features of the design. When using the parametric modelling approach, the designer is confined within the limitations offered by the parametric model. For example, designing a double-hull tanker is a completely different concept from designing a mid-deck tanker. Furthermore, parametric modelling is highly demanding, because it requires extensive programming and as a result its development is very time consuming. However, parametric modelling offers the advantage of repeating the design process for a high multitude of variables in almost zero time.

In *Figure 3-1* the process of the development of the 3D parametric model is presented and is described in further detail in the following paragraphs of this chapter.

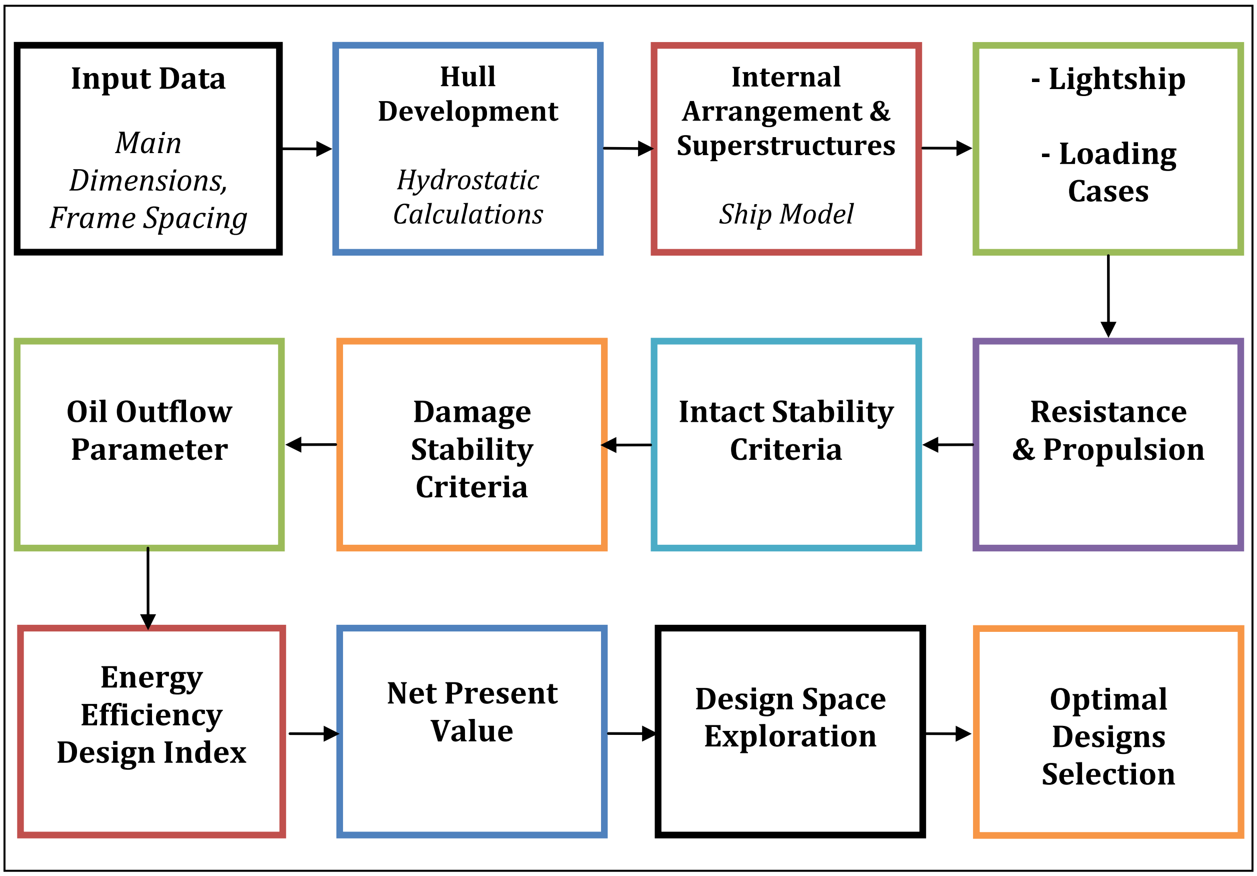

Figure 3-1: *Thesis Workflow*

3.1 Input Data

The parametric model's necessary input data are read from specific input files. These data may include the ship's main dimensions, the frame spacing, information on machinery and outfitting, such as the ship's main engine power and others.

3.2 Hull Development and Hydrostatic Calculations

The present parametric model uses a predefined hull form, from which alternative designs can be derived by changing chosen dimensions. The transformation of the hull is performed using available Napa tools. It is possible to change the following dimensions:

- L: Length between perpendiculars
- B: Breadth at the design water level
- T: Draught to the design water level
- D: Moulded volume at the design water level
- C_B: Block coefficient
- LCB: Longitudinal centre of buoyancy
- PA: Length of the aftbody
- PF: Length of the forebody

When only the main dimensions L, B, T are changed, the result is an affine transformation. Other transformations are also possible, such as a displacement transformation, or a piecewise linear transformation, changing the values of PA and PF. It is also possible to combine an affine with a displacement transformation. The predefined hull is called the parent hull. The new one that is derived from the transformation is saved in a new version of the project.

The hull surface consists of the forebody, the parallel midbody and the aftbody. Each of these surfaces is created by a grid of curves, including basic curves, sections and waterlines, which are presented in the following figures by the colours black, blue and red respectively. In the end of this paragraph the final hull surface and the lines plan are presented in *Figure 3-2* and in *Figure 3-3*.

Forebody

The forebody includes the following basic curves:

- FRF: fore frame (fore section of the parallel midbody)
- CLF: fore centre line and stem profile
- FSF: fore flat of side
- FBF: fore flat of bottom
- DECKF_UP: fore deck line

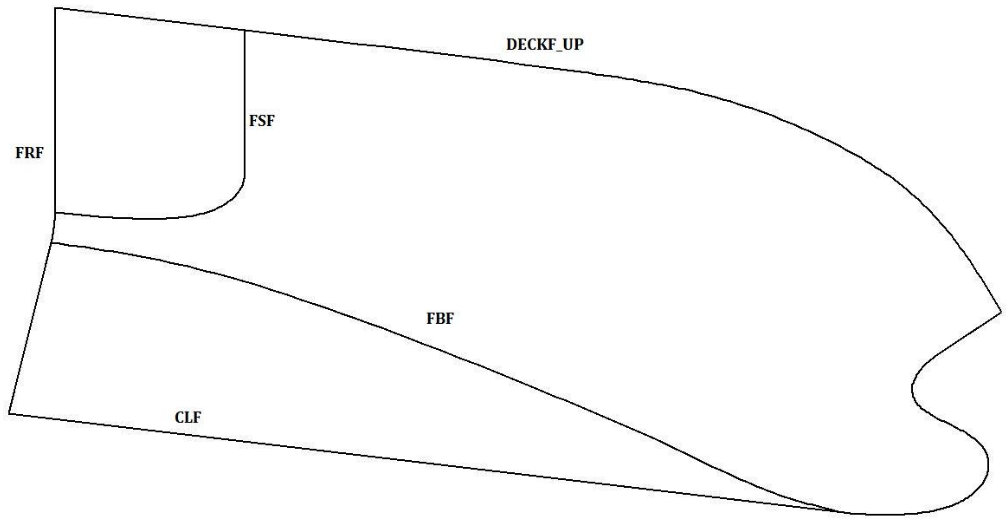

***Figure 3-2**: Forebody's basic curves*

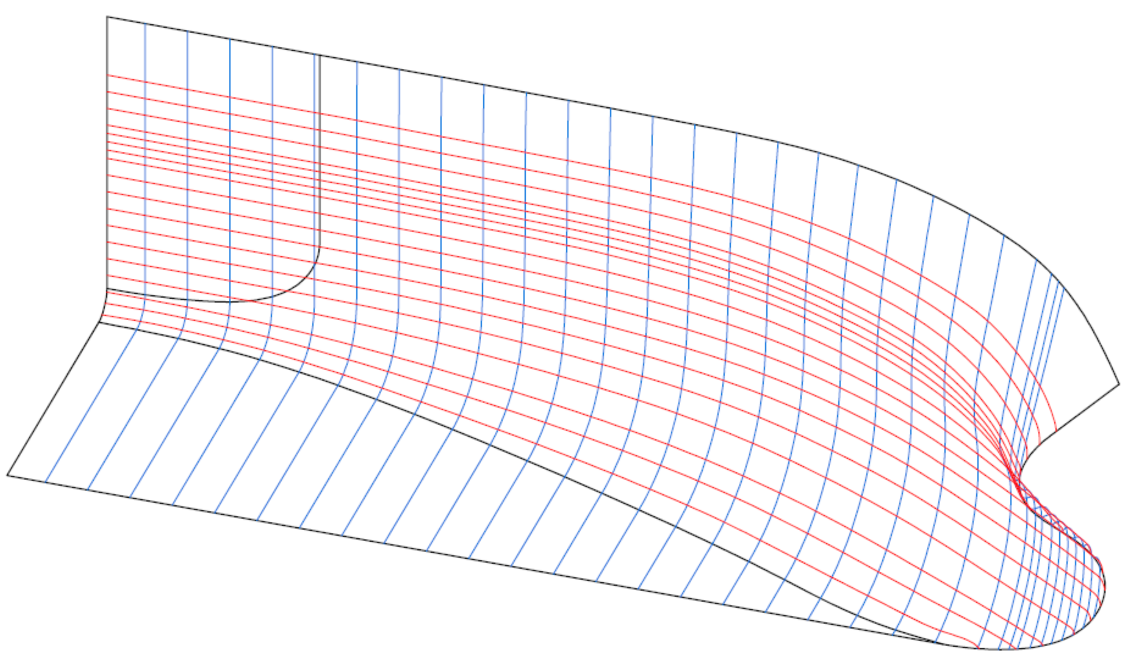

***Figure 3-3:** Forebody's set of definition curves*

Parallel Midbody

The parallel midbody includes the following basic curves:

- FRF: fore frame (fore section of the parallel midbody)
- FRA: aft frame (aft section of the parallel midbody)
- CLM: centre line
- FSM: flat of side
- FBM: flat of bottom
- DECKM_UP: deck line

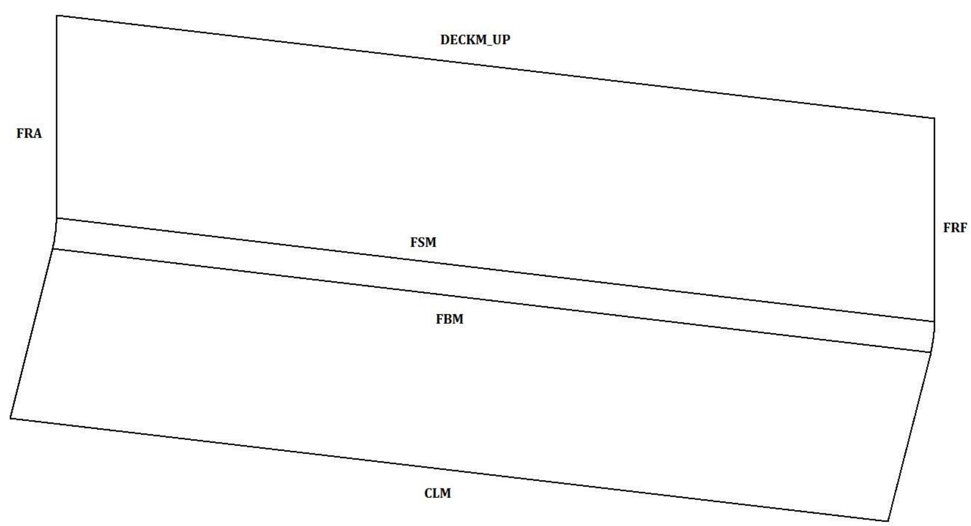

Figure 3-4: *Parallel midbody's basic curves*

Aftbody

The aftbody includes the following basic curves:

- FRA: aft frame (aft section of the parallel midbody)
- CLA: aft centre line and stern profile
- TRANSOM: transom line
- SHAFT_END: shaft line
- FSA: aft flat of side
- FBA: aft flat of bottom
- DECKA_UP: aft deck line

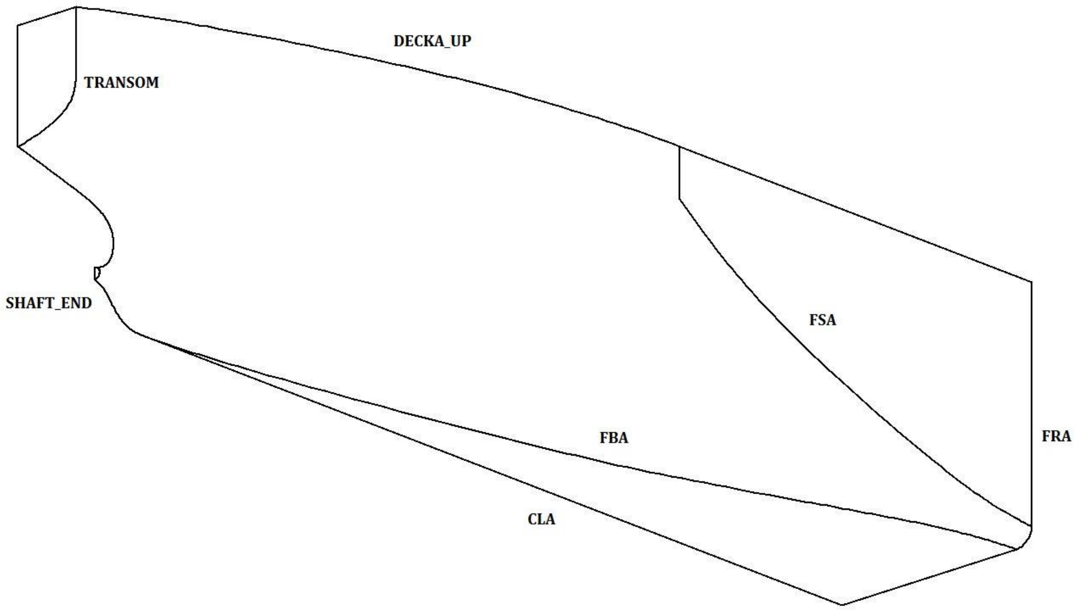

Figure 3-5: *Aftbody's basic curves*

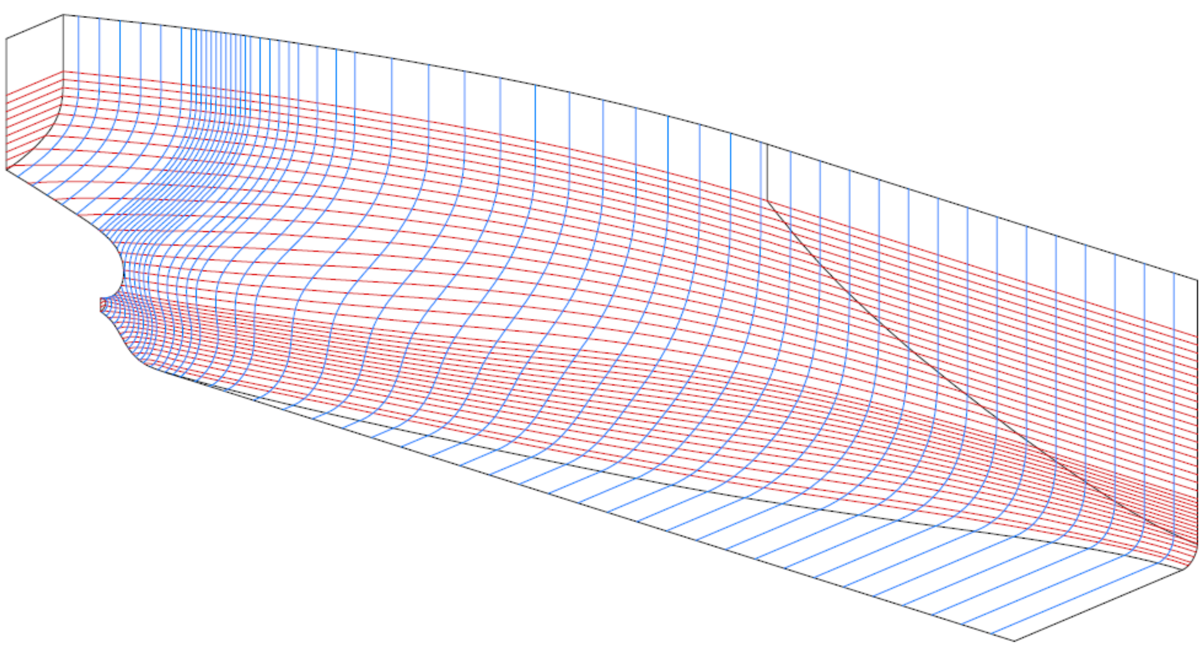

Figure 3-6: *Aftbody's set of definition curves*

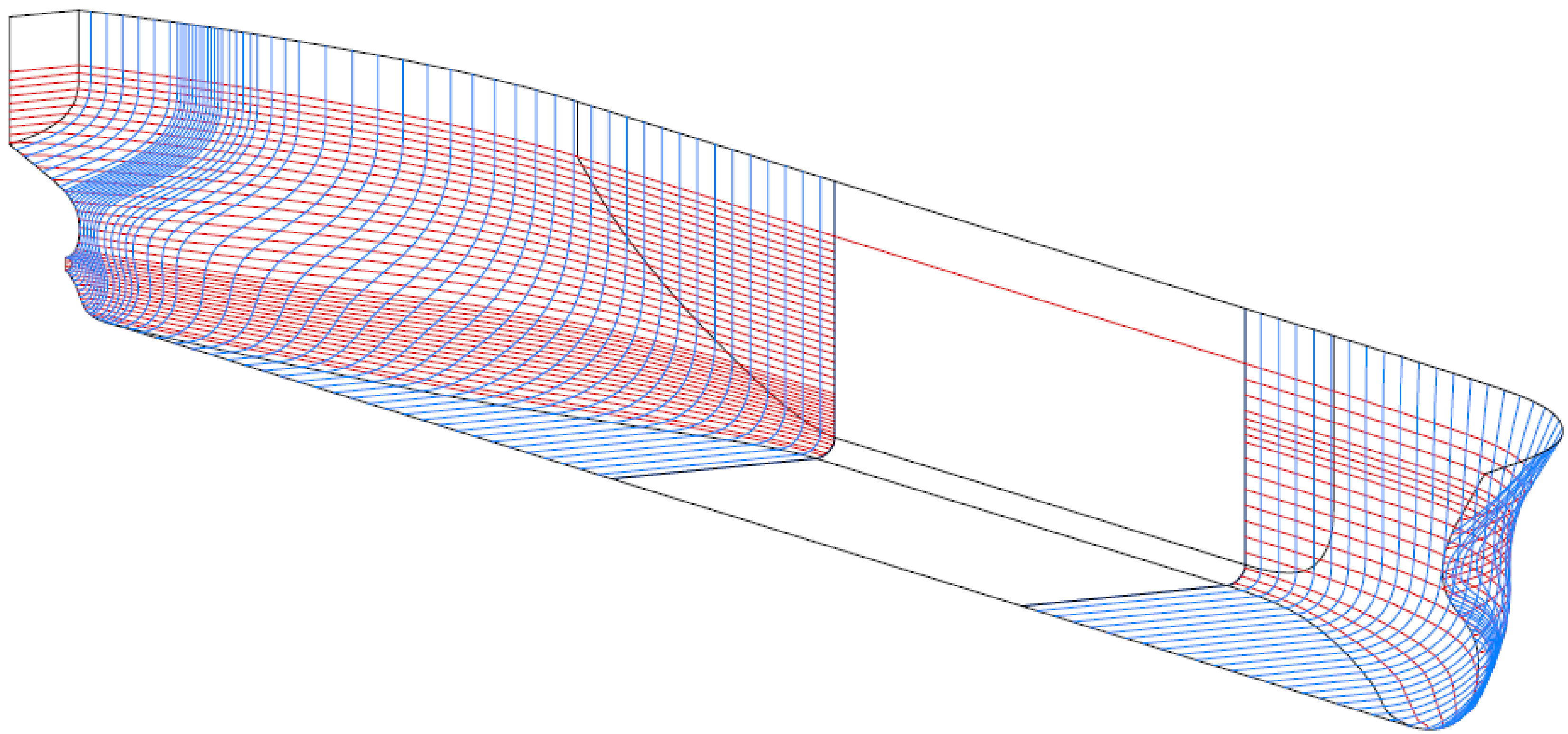

Figure 3-7: *Hull's set of definition curves*

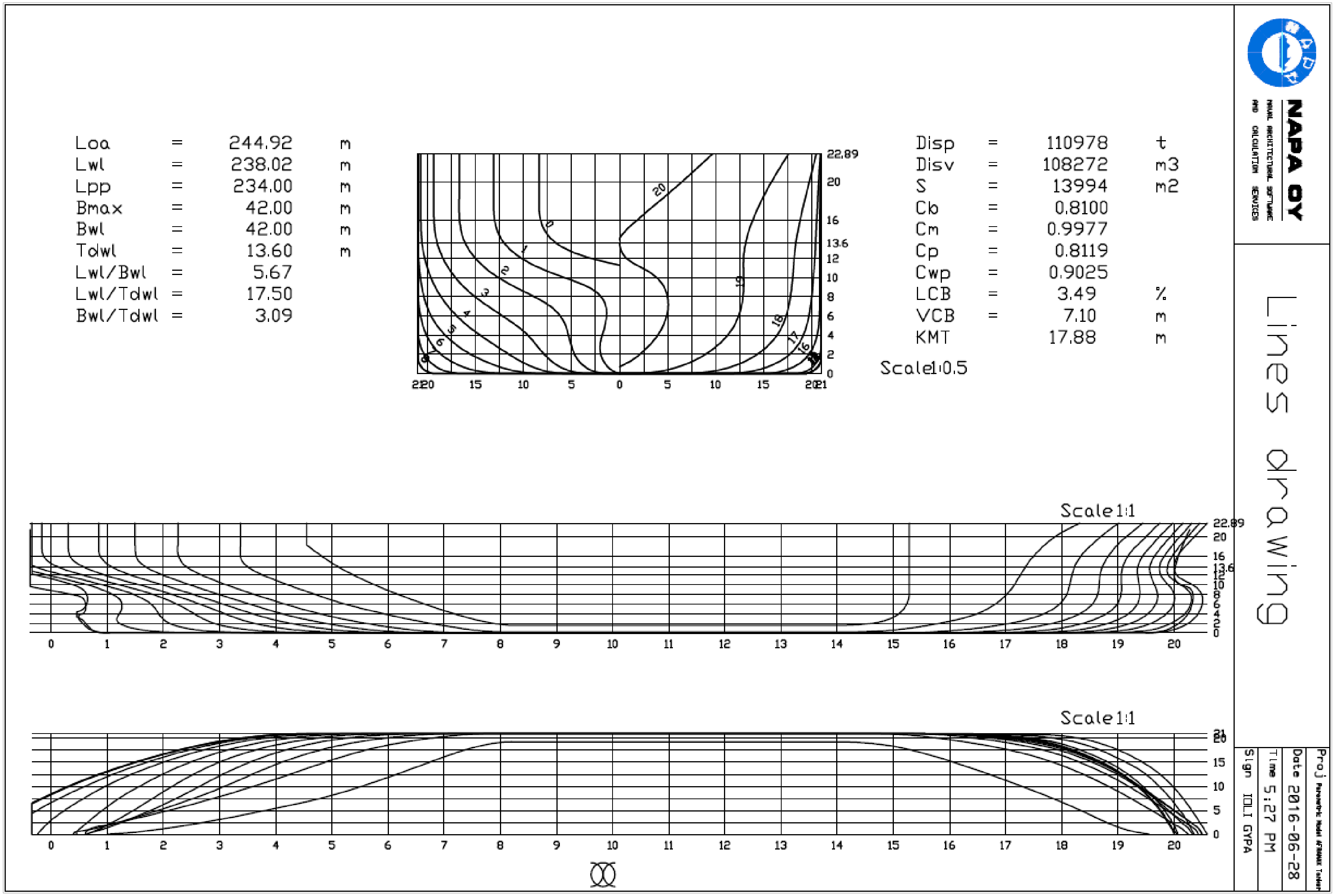

Figure 3-8: Lines Drawing

After the development of the hull form it is possible to make the hydrostatic calculations. In Napa, this is done in the task HYD, where the calculations' results are given in the form of a list. A range of draughts is read from an input file and the output is a list of values, such as the displacement, the moulded volume, the longitudinal centre of buoyancy, the longitudinal centre of flotation, as well as the various coefficients.

3.3 Internal Arrangement & Superstructures

After creating the ship's hull form, the next step for the development of the parametric model is the definition of the internal arrangement and the superstructures. The internal arrangement includes the main inner structures, such as bulkheads and decks, the inner hull and the compartmentation. There are specific constraints, derived from relevant rules and regulations, determining the development of these elements.

3.3.1 Bulkheads and Decks

Bulkheads are defined in specific frames. Ships are equipped with at least one collision bulkhead, one after peak bulkhead and one watertight bulkhead at each end of the machinery space. *Table 3-1* shows the total number of bulkheads according to [57].

Table 3-1: *Total Number of bulkheads [57]*

Length, *L*, in metres	Total number of bulkheads	
	Machinery amidships	Machinery aft, *see* Note
≤ 65	4	3
> 65 ≤ 85	4	4
> 85 ≤ 90	5	5
> 90 ≤ 105	5	5
> 105 ≤ 115	6	5
> 115 ≤ 125	6	6
> 125 ≤ 145	7	6
> 145 ≤ 165	8	7
> 165 ≤ 190	9	8
> 190	To be considered individually	
NOTE With after peak bulkhead forming after boundary of machinery space.		

A longitudinal bulkhead, which is positioned in the ship's centreline and is extending throughout the whole cargo area, separates port from starboard tanks.

When, the positions of the bulkheads are defined, the next step is to define the decks. Oil tankers are equipped with one main deck and a number of platform decks within the engine room area. The main deck has usually camber and sheer.

In Napa, the above-mentioned elements are described by surfaces, called planes and cylinders. The main inner structures are used as reference objects for the development of the compartmentation.

3.3.2 Inner Hull

As described in Chapter 2, the cargo is carried inside the inner hull with a space dividing it from the outer hull. The inner hull was developed according to Chapter 4 of MARPOL 73/78, which specifies the requirements for the cargo area of oil tankers. More specifically, Regulations 18 and 19 were applied.

Regulation 18 "Segregated Ballast Tanks": For crude oil tankers of ≥20,000 t DWT and product carriers of ≥30,000 t DWT, delivered after 1 June 1982, segregated ballast tanks shall be provided. The capacity of the segregated ballast tanks should offer safety for ballast voyages without the need of loading the cargo tanks with water ballast. Moreover, under ballast condition, the following requirements should be followed, regarding the ship's draughts and trim:

- ❖ Moulded draught amidships: $d_m \geq 2.0+0.02\,L$
- ❖ Trim by stern: $\leq 0.015\,L$
- ❖ Draught at the aft perpendicular should obtain full immersion of the propeller

Regulation 19 "Double hull and double bottom requirements for oil tankers delivered on or after 6 July 1996": It is required for oil tankers ≥5,000 t DWT delivered on or after 6 July 1996, to be equipped with ballast tanks or spaces other than tanks that carry oil as follows:

- ❖ Wing tanks or spaces: They extend for the full depth of the ship's side or from the top of the double bottom to the main deck. Their distance from the outer shell should be $w = min\,\{0.5+DWT/20{,}000;\ 2.0\text{ m}\} > 1\text{m}$.
- ❖ Double bottom tanks or spaces: The distance between the bottom shell and the upper limit of the bottom tank or space, at any cross section, should be $h = min\,\{B/15;\ 2.0\text{ m}\} > 1\text{m}$.

Developing the inner hull of the parametric model in Napa is a demanding task. For every different hull form, a new inner hull must be created, which should comply with the above-mentioned regulations. The inner hull is extending throughout the whole cargo area. It is comprised transversely of three planes, the double bottom, the double side and the hopper plate. The hopper plate is an inclined plane, which connects the two other planes. The transverse section of the inner hull is kept constant for a length approximately equal to the

45% of L_{BP} around amidships and becomes more slender towards the forward and aft end of the cargo block area, adapted to the shape of the hull. The process of the inner hull's development is as follows:

The double bottom's height is specified by the user in accordance with the regulations. The inner hull geometry is defined at a series of longitudinal positions. The following figures are used to describe the whole process. In *Figure 3-9*, the section of the outer hull in a specific longitudinal position, the main deck, the centreline and the double bottom are shown.

In each longitudinal position the points A and B are created with the following coordinates:

<u>Point A</u>

- x_A=longitudinal position
- y_A=0 (centreline)
- z_A=height of double bottom

<u>Point B</u>

- x_B=longitudinal position
- y_B=y_s-d, where y_s is the y position of the outer hull at the height of the double bottom and d is a distance specified by the user (d is equal to the horizontal distance from the lower point of the hopper plate to the outer hull at midships).
- z_B=height of double bottom

The endpoints A and B create a line segment, which is divided into smaller parts by a specific number of points. These points are called B_i, with 1≤ i ≤n and n is read from the data input file.

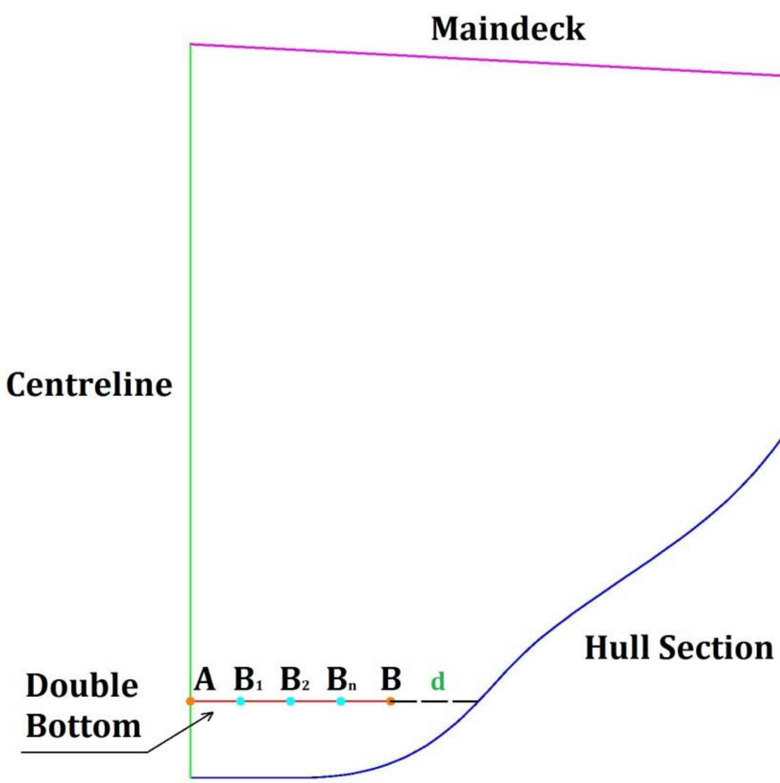

Figure 3-9:*Points A, Bi, Distance d*

Each B_i point is the starting point of a new line with a specific inclination, equal to the angle φ of the hopper plate, which is specified by the user. A new line segment is defined, with its starting point at B_j and its end point at the intersection of the hull and the inclined line. The new line segment is also divided into smaller parts, as depicted in *Figure 3-10*, by a specific number of points, which are called C_j, with $1 \leq j \leq m$ and m is read from the data input file.

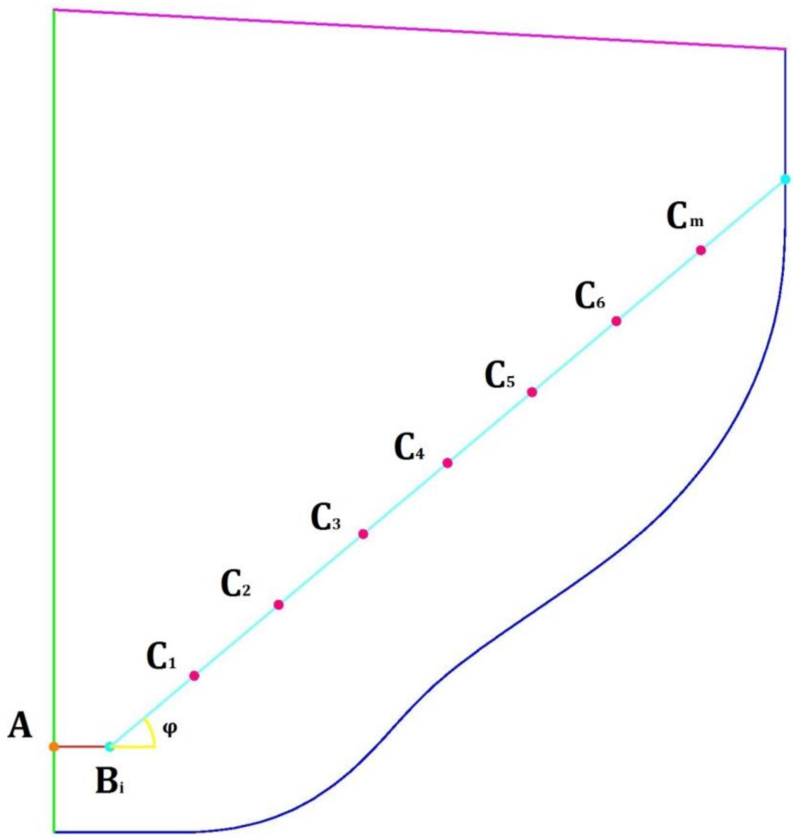

Figure 3-10: *Points C_j, $1 \leq j \leq m$*

For each C_j point, it is checked whether the horizontal distance between the C_j and the outer hull is greater than the distance w, specified by the regulations. The coordinates of the last C_j point for which this distance is greater than w are saved. Two new points with the following coordinates are created and are presented in *Figure 3-11*.

<u>Point D</u>

- ❖ x_D=longitudinal position
- ❖ y_D=same y with final C_j
- ❖ z_D=height of maindeck at y

Point E

- x_E=longitudinal position
- y_E=0 (centreline)
- z_E=height of maindeck at y_E

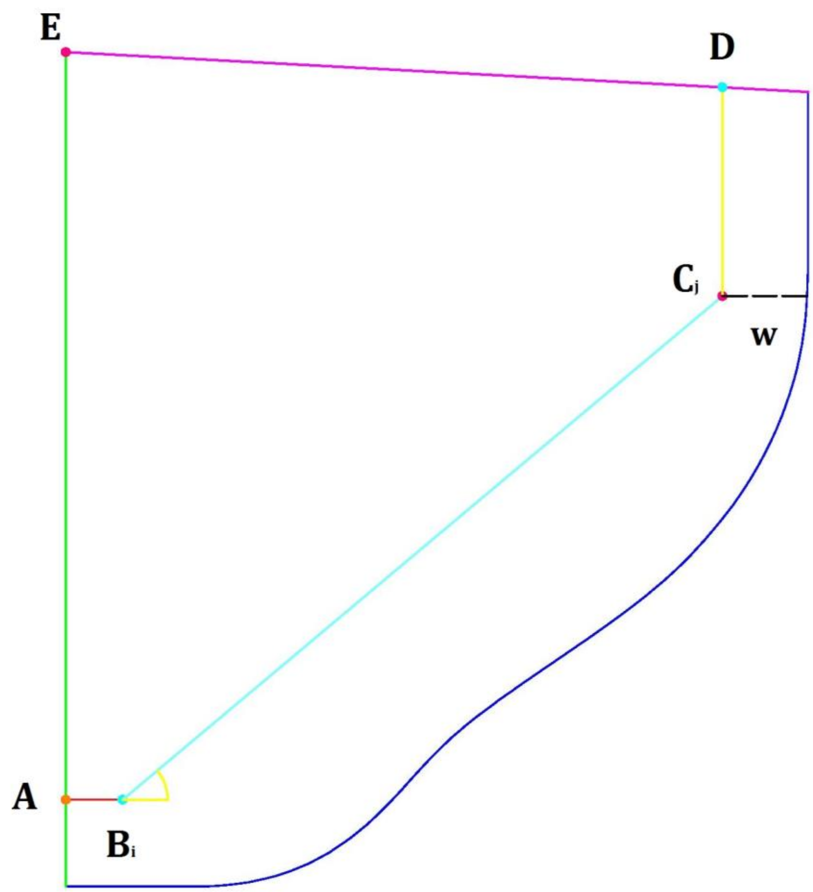

Figure 3-11: *Points D, E, Distance w*

The points A,B_i,C_j,D and E create a surface and the area of the surface is measured. The exact same process is repeated for all the B_i points and the areas of the A$B_i$$C_j$DEA surfaces are measured. In the end, the combination of $B_i$$C_j$ points maximising this area is selected and the surface's characteristics are saved. For example, in *Figure 3-12* two surfaces have been developed and the one with the biggest area is saved.

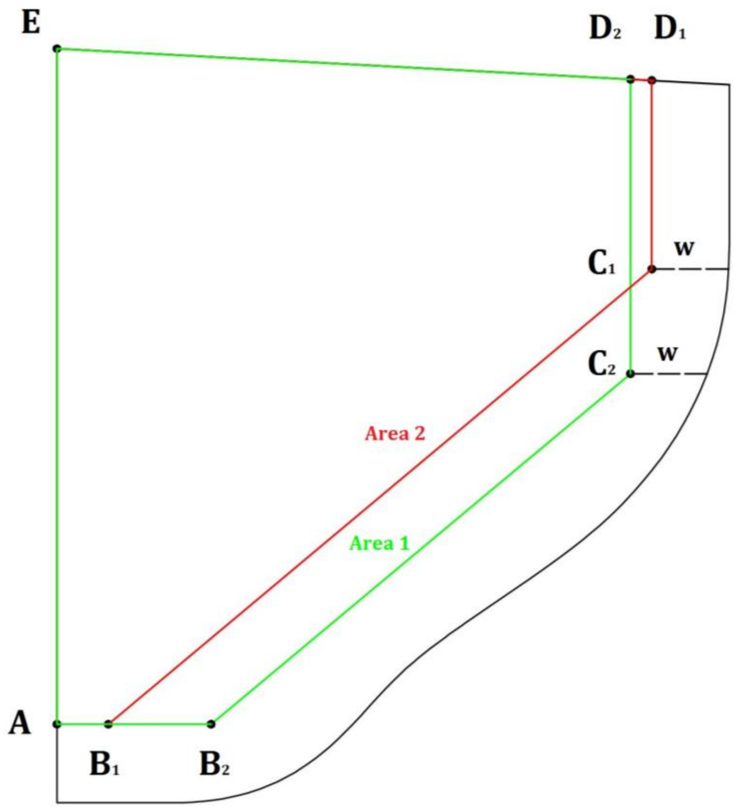

Figure 3-12: *Area 1, Area 2*

The same methodology is followed at the longitudinal position of the forward and aft limit of every segment of the inner hull. Then a facet surface is created in Napa, consisting of three planar sections (double bottom, hopper plate and inner side) for each segment. The final inner hull is shown in *Figure 3-13*.

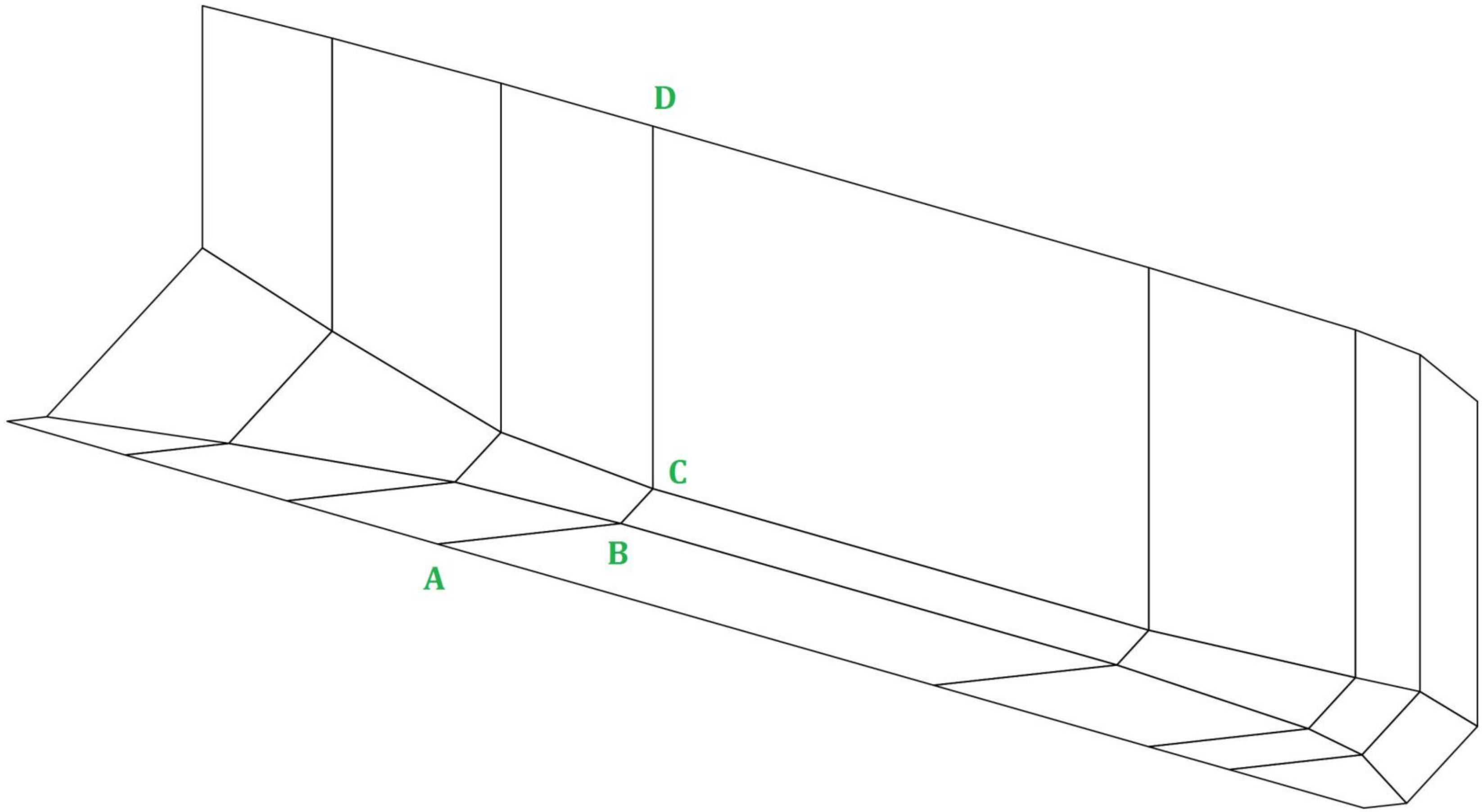

Figure 3-13: *Inner Hull*

3.3.3 Compartmentation and Superstructures

With the outer hull, decks, longitudinal and transverse bulkheads and the inner hull already defined, it is possible to develop the model's compartmentation. The compartmentation consists of all the watertight compartments (tanks, rooms and voids). In Napa, all these elements are created as room objects. A room is a space totally enclosed within a series of surfaces [21]. These surfaces are the room's limits. Room objects are used to model the watertight spaces below the main deck, as well as the spaces in the ship's superstructures.

3.3.4 Ship Model

The Ship Model is the core of the parametric model, as it is used for the majority of the workflow's next steps, such as the determination of the loading conditions, the check of the intact stability criteria and others. The Ship Model is related directly to the functional aspects of the ship.

When the model's compartmentation is determined, the purpose of each room should be defined. Purpose is the role of each compartment in the ship. For example, if a compartment is intended for carrying Water Ballast, then the purpose is Water Ballast. If a compartment is intended to remain empty, then its purpose is Void. There is a multitude of predefined purposes in the Napa system database, but it is also possible to create new project-specific purposes in the project database. Thereafter, other characteristics of the compartments are defined, like the class, the type, the density of the compartment's content, the steel reduction, the compartment's maximum filling degree, and the permeability [21].

When the special features of all the compartments have been determined, an arrangement (also called the Ship Model in Napa) is created. The arrangement consists of a group of compartments, occupying the entire enclosed volume of the ship. In *Figure 3-14*, a drawing of the Ship Model of a tanker, developed by the parametric model is shown, including its compartments with their purposes.

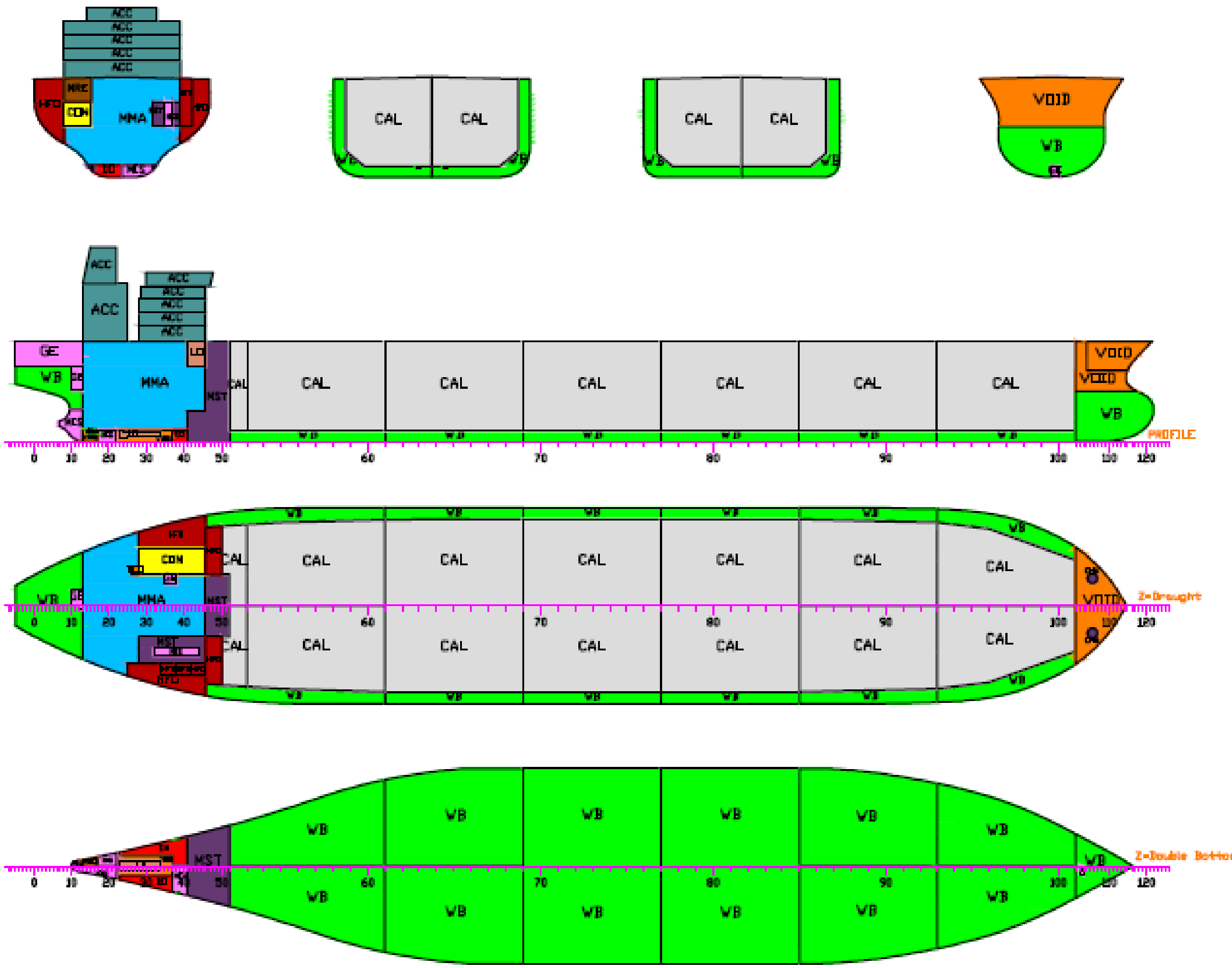

Figure 3-14: *Ship Model*

As depicted in the drawing of the Ship Model, the parametric model contains 9 transverse bulkheads. There is one collision bulkhead, two bulkheads on each side of the engine room and six bulkheads that divide the cargo space. There is one longitudinal bulkhead in the centreline, which is extending through the whole cargo area. The ship has one main deck and two platform decks within the engine room.

In total, 12 (2x6) cargo tanks are created, (with 6 tanks along the longitudinal direction and 2 tanks transversely). The slop tanks are positioned aft from the cargo tanks and forward from the engine room. The water ballast is loaded into the water ballast tanks, which are positioned in the space between the inner and the outer hull. There is also one water ballast tank forward from the collision bulkhead and one aft from the engine room. The majority of the remaining tanks is positioned within the engine room, such as the heavy fuel oil tanks, diesel oil tanks and lubricating oil tanks. The fresh water tanks are positioned aft from the engine room, port and starboard of the steering gear room.

Finally, the superstructures are positioned aft of the cargo space, consisting of 4 decks. The funnel is positioned aft of the superstructures.

3.4 Lightship Calculation and Definition of Loading Conditions

Regression analysis was applied in [58] for the calculation of the ship's lightship (LS). The regression analysis was based on a database of 76 oil tankers, of which 12 were small oil tankers, 9 Handymax, 15 Panamax, 9 AFRAMAX, 25 Suezmax and 6 VLCC.

The following approximation formula was used:

$$LS=0.07422*L_{BP}*B*D+2297$$

Where L_{BP}=Length between perpendiculars, B=Beam and D=Depth.

As depicted in *Figure 3-15*, the correlation between the LS and the variables L_{BP}, B, D is satisfactory [58].

Moreover, the lightship's longitudinal centre of gravity (LCG_{LS}) and vertical centre of gravity (KG_{LS}) are calculated proportionally, according to the data derived from reference ships.

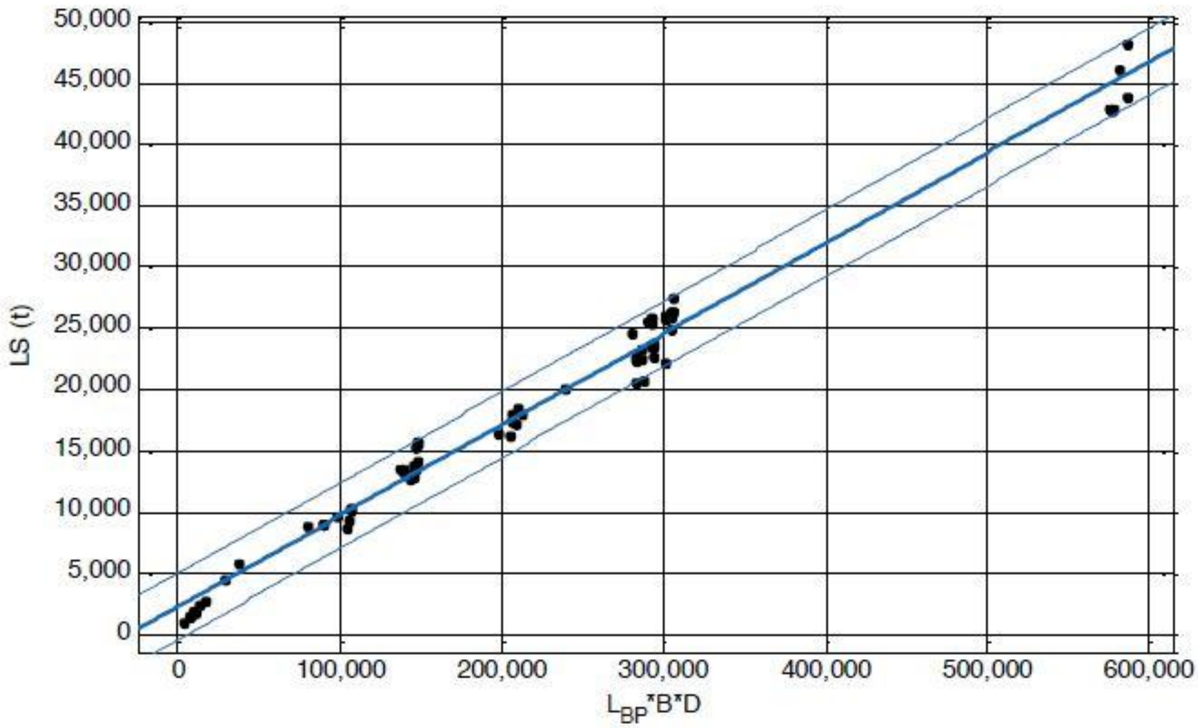

Figure 3-15: *LS vs. L_{BP}, B, D [58]*

The LS calculation is necessary in order to define the ship's loading conditions and perform relevant analyses. More specifically, a loading condition is a situation, where the ship's weights are determined regarding their quality, quantity and location [21]. In each loading condition, the following quantities are being examined:

- Moulded Draught
- Fore Moulded Drauht (T_F)
- Aft Moulded Draught (T_A)
- Trim
- Heeling Angle
- Longitudinal Centre of Buoyancy (LCB)
- Longitudinal Centre of Gravity (LCG)
- Vertical Centre of Gravity (VCG)
- Metacentric Height (GM)
- Uncorrected Metacentric Height (GM_0)
- Metacentric Height Correction (GM_{corr})
- Total Displacement
- Deadweight

3.5 Resistance and Propulsion

The resistance of each design alternative is calculated in Napa through the Holtrop-84 method. This power prediction method has been derived applying regression analysis, based on results from a multitude of model tests. A brief description of the Holtrop-84 method is carried out below:

The ship's total resistance is given by the formula: $R_{total}=R_F*(1+k_1)+R_{APP}+R_W+R_B+R_{TR}+R_A$, where:

R_F: frictional resistance

R_{APP}: appendage resistance

R_W: wave resistance

R_B: additional pressure resistance of bulbous bow

R_{TR}: additional pressure resistance due to transom immersion

R_A: model-ship correlation resistance

$1+k_1$: form factor of the hull

Each component is calculated from specific formulae, while the form factor of the hull and the wetted surface come from regression analysis [59].

Once the ship's main engine is selected, the corresponding engine power is used in order to optimize the propeller and to calculate the ship's speed using the corresponding tools available in Napa. It should be noted that the Holtrop-84 method is quite old, while nowadays the hydrodynamic design of the hull forms is more efficient than 30 years ago. Therefore, the above procedure is expected to underestimate the service speed. Thus, the obtained speed value is corrected by an appropriate correction factor, based on comparisons with the reference design.

During a propeller optimisation, carried out in Napa, there are three performance parameters that can be optimised; the propeller diameter, the speed of rotation and the pitch ratio. One of the performance parameters should remain fixed, while the other two can be optimised. In the present parametric model, the maximum propeller diameter, the rotation frequency and the propeller power are given. Based on this input, Napa identifies the optimal propeller and the corresponding ship's speed.

The above-described process is applied with the ship at the Full Load Departure condition. Then for the selected propeller, the required propulsion power for the same ship's speed at the Normal Ballast Departure condition is calculated.

3.6 Intact Stability Criteria

For each design alternative, compliance with Chapter 4 of MARPOL 73/78 and more specifically the Regulation 27 “Intact Stability” [47] is evaluated. According to this Regulation, every oil tanker of 5,000 t DWT and above should comply with the following criteria:

- The area under the righting lever curve (GZ curve) up to 30° angle of heel should be more than 0.055 mrad.
- The area under the GZ curve up to 40° angle of heel should be more than 0.09 mrad.
- The area under the GZ curve between 30° and 40 ° angle of heel should be more than 0.03 mrad.
- The righting lever (GZ) should be at least 0.2 m at an angle of heel equal or greater than 30°.
- The maximum GZ should occur at an angle of heel greater than 25° and preferably greater than 30°.
- The initial GM_0 should be equal or greater than 0.15 m.

In addition to the above, compliance with the "Severe wind and rolling criterion" of Chapter 3.2 of IMO Res.749 is evaluated.

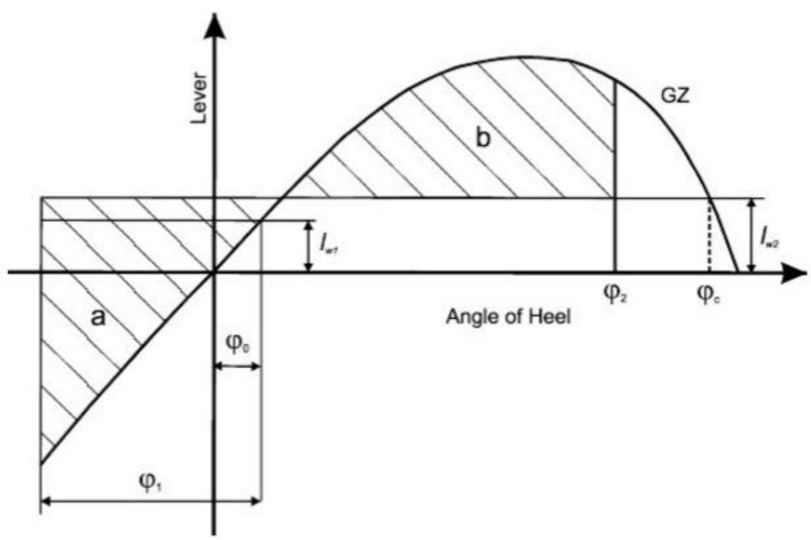

Figure 3-16: *Severe wind and rolling[60]*

According to this criterion, the area "a" in *Figure 3-16* should be less than area "b". Moreover, the angle of heel under steady wind (φ_0) should be less than 16° or less than the 80% of the angle of deck edge immersion [60].

3.7 Damage Stability Criteria

Each design alternative should be in accordance with Chapter 4 of MARPOL 73/78 and more specifically with Regulation 27 "Subdivision and damage stability". For every oil tanker of 150 gross tonnage and above, delivered after 31 December 1979, the following provisions related to the dimensions of the assumed damage extents should be taken into consideration [47]:

Side damage

- Longitudinal extent: $min\{1/3*(L_{BP}^{2/3})\ ;\ 14.5\ \text{m}\}$
- Transverse extent: $min\{B/15\ ;\ 11.5\ \text{m}\}$
- Vertical extent: from the bottom shell until upwards without limit

Bottom damage

- x-position: 0.3 L from the forward perpendicular
  - Longitudinal extent: $min\{1/3*(L_{BP}^{2/3})\ ;\ 14.5\ \text{m}\}$
  - Transverse extent: $min\ \{B/6\ ;\ 10\ \text{m}\}$
  - Vertical extent: $min\ \{B/15\ ;\ 6\ \text{m}\}$

- x-position: any other part
  - Longitudinal extent: $min\{1/3*(L_{BP}^{2/3})\ ;\ 5\ \text{m}\}$
  - Transverse extent: $min\ \{B/6\ ;\ 5\ \text{m}\}$
  - Vertical extent: $min\ \{B/15\ ;\ 6\ \text{m}\}$

The above-mentioned dimensions of the assumed damage extent are used to check, whether the ship, given the damage, would comply with the following criteria:

- No progressive flooding should occur through openings, including weathertight doors, hatch covers, man holes, air pipes. This means that the final waterline after the damage should be under the lower edge of the openings.
- During the final stage of flooding, the maximum angle of heel should be less than 25° or less than 30° provided there is no deck immersion.
- During the final stage of flooding, the GZ curve should have a range of at least 20° beyond the equilibrium position.
- The minimum GZ should be at least 0.1 m for the above-mentioned range.
- The minimum area under the GZ curve should be at least 0.0175 m*rad for the above-mentioned range.

In case that a space is flooded, due to side or bottom damage, the assumed permeabilities of the spaces are shown in *Table 3-2*.

Table 3-2: Permeabilities of the Flooded Spaces

Spaces	Permeabilities
Stores	0.60
Accommodation	0.95
Machinery	0.85
Voids	0.95
Consumable liquids	0-0.95
Other liquids	0-0.95

Finally, the free surface effect of the flooded spaces should be calculated for 5° angle of heel.

3.8 Oil Outflow Parameter

For each design alternative, compliance with with Chapter 4 of MARPOL 73/78 and more specifically with Regulation 23 "Accidental oil outflow performance" is evaluated. According to this Regulation, the mean oil outflow parameters of every oil tanker of 5,000 t DWT and above, should be:

- $OM \leq 0.015$, for $C \leq 200{,}000$ m^3, where C: total volume of cargo oil, in m^3, at 98% tank filling
- $OM \leq 0.012+(0.003/200{,}000)*(400{,}000-C)$, for $200{,}000 \leq C \leq 400{,}000$ m^3
- $OM \leq 0.012$, for $C \geq 400{,}000$ m^3

OM is calculated separately for side and bottom damage. When the mean outflow for side damage (O_{MS}) and mean outflow for bottom damage (O_{MB}) are calculated, the OM is given from the formula:

$$OM=(0.4\ O_{MS}+0.6\ O_{MB})/C$$

O_{MB} is calculated separately for tide conditions of zero and -2.5 m and an average value is calculated by the following formula:

$$O_{MB}=0.7\ O_{MB(0)} + 0.3\ O_{MB(2.5)}$$

Where $O_{MB(0)}$ is the mean outflow for 0 m tide condition and $O_{MB(2.5)}$ is the mean outflow for -2.5 m tide condition.

The calculation of O_{MB} and O_{MS} is based on a probabilistic approach. More specifically, O_{MS} is estimated by the formula:

$$O_{MS} = C_3 \sum_{1}^{n} P_{S(i)} O_{S(i)}$$

Where $P_{S(i)}$ is the probability of penetrating cargo tank i from side damage, $O_{S(i)}$ the corresponding oil outflow and C_3 a coefficient regarding the number of longitudinal bulkheads.

Respectively, O_{MB} is calculated for every tide condition by the following formulae:

$$O_{MB(0)} = \sum_{1}^{n} P_{B(i)} O_{B(i)}\, C_{DB(i)}$$

$$O_{MB(2.5)} = \sum_{1}^{n} P_{B(i)} O_{B(i)}\, C_{DB(i)}$$

Where $P_{B(i)}$ is the probability of penetrating cargo tank i from bottom damage, $O_{B(i)}$ the corresponding oil outflow and C_{DB} a coefficient regarding the oil capture.

3.9 Energy Efficiency Design Index

The Energy Efficiency Design Index (EEDI) represents the energy efficiency of a ship in terms of gCO_2/tonne.mile.

The ship's actual EEDI (Attained EEDI) should be less or equal to the Required EEDI, which is given from the formula:

Required EEDI=(1-X/100)(Reference EEDI)*

Where X is a reduction rate, related to the ship's building year, and the Reference EEDI is a reference value for the EEDI, which is calculated by the formula:

*Reference EEDI=a*b*$^{-c}$

Where a and c are constants, related to the ship's type, and b is the ship's capacity. The Required EEDI is calculated four phases; Phase 0 includes the period 1 January 2013-31 December 2014, phase 1 the period 1 January 2015-31 December 2019, phase 2 the period 1 January 2020-31 December 2024 and finally phase 3 the period 1 January 2025 and onwards.

The Attained EEDI is calculated by the following formula:

$$\text{Attained EEDI} = \frac{\left(\prod_{j=1}^{M} fj\right) * \left(\sum_{i=1}^{nME} Pme * Cfme(i) * SFCme(i)\right) + (Pae * Cfae * SFCae)}{fi * Capacity * Vref * fw} + \frac{\left(\prod_{j=1}^{M} fj * \sum_{i=1}^{nPTI} Ppti(i) - \sum_{i=1}^{neff} feff(i) * Paeeff(i)\right) * Cfae * SFCae}{fi * Capacity * Vref * fw} - \frac{\sum_{i=1}^{neff} feff(i) * Peff(i) * Cfme * SFCme}{fi * Capacity * Vref * fw}$$

Where C_F is a conversion factor between fuel consumption and CO_2 emission, *Vref* is the ship's speed, *P* is the power of main and auxiliary engines, *SFC* is the specific fuel consumption, f_j, f_i, f_w, f_{eff}, f_l are factors related to design elements, weather, efficiency technology, cubic capacity and equipment. Finally, for each design alternative, it is checked whether the Attained EEDI is lower or equal to the Required EEDI [61, 62]:

$$Attained\ EEDI \leq Required\ EEDI$$

3.10 Net Present Value (NPV)

The last step for the assessment of each design alternative consists of the ship's economic evaluation and more specifically the calculation of the Net Present Value. NPV is the difference between the present value of the amount of the investment and the present value of the future cash flows from the operation of the ship. NPV is calculated by the following formula:

$$NPV = \sum_{i=1}^{T} \frac{Ri}{(1 + \frac{p}{100})^{i}} - Io$$

Where:

- R_i : Cashflow for year i
- p : Interest Rate
- T : Years of the project
- I_0 : Initial investment

If the NPV is positive, it means that the earnings of the investment exceed the foreseen costs. If the NPV is negative, the project does not meet a minimum required return and should be rejected. In general, positive NPV shows a profitable investment. In case there are more investments with positive NPV, the one with the higher NPV should be chosen.

Moreover, the internal rate of return (IRR) can be calculated. IRR is the interest rate, which makes the difference between the present value of the amount of the investment and the present value of the future cash flows from the investment equal to zero. More specifically:

$$NPV = \sum_{i=1}^{T} \frac{Ri}{(1 + \frac{p}{100})^{i}} - Io = 0$$

The NPV is set equal to zero and the equation is solved with p as the unknown. The internal rate of return (IRR) is the set equal to p [63, 64].

4 Case Study and Results

4.1 Case Study: AFRAMAX tankers

The development of the parametric model is based on a reference design of an existing AFRAMAX tanker. It is a typical double-hulled AFRAMAX tanker with 6 tanks along the cargo space and 2 cargo tanks transversely. The engine room, the crew accommodation and the navigational bridge are positioned aft of the cargo tank area.

The inner hull has the following characteristics in accordance with the regulations and the reference design:

- ❖ w = 2.5 m
- ❖ h_{DB}=draught*0.17 >= $min\ \{B/15;\ 2.0\ \text{m}\}$
- ❖ hopper inclination = 40 °

The powering is provided by a propeller directly coupled to a two-stroke diesel engine. The main engine of the reference ship is the MAN B&W 6S60MC. The same engine is used for all the design alternatives created by the parametric model. The engine's maximum continuous rating (M.C.R.) is equal to 12240 kW at 105 rpm, while the normal continuous rating (N.C.R.) is 10170 kW at 93.7 rpm. The fuel and lubricating oil consumption is shown in *Table 4-1*.

Table 4-1: *Fuel and lubricating oil consumption*

<table>
<tr><th rowspan="3">At load
Layout point</th><th colspan="4">Specific fuel oil consumption
g/kWh</th><th colspan="3">Lubricating oil consumption</th></tr>
<tr><th colspan="2">With high efficiency
turbocharger</th><th colspan="2">With conventional
turbocharger</th><th rowspan="2">System oil
Approximate
g/kWh</th><th colspan="2">Cylinder oil
g/kWh</th></tr>
<tr><th>100%</th><th>80%</th><th>100%</th><th>80%</th><th>Mechanical
cyl. lubricator</th><th>MAN B&W
Alpha
cyl. lubricator</th></tr>
<tr><td>L_1</td><td>170</td><td>167</td><td>172</td><td>169</td><td rowspan="4">0.15</td><td rowspan="4">1.0-1.5</td><td rowspan="4">0.7</td></tr>
<tr><td>L_2</td><td>158</td><td>156</td><td>160</td><td>158</td></tr>
<tr><td>L_3</td><td>170</td><td>167</td><td>172</td><td>169</td></tr>
<tr><td>L_4</td><td>158</td><td>156</td><td>160</td><td>158</td></tr>
</table>

The input data required by the parametric model are given in specific input files. The free variables of the parametric model vary between a lower and an upper boundary, as depicted in *Table 4-2*. In the final run, 2000 AFRAMAX tankers will be designed.

Table 4-2: *Free Variables Boundaries*

Free Variable	**Lower Bound**	**Upper Bound**	**Increment**
Length BP (m)	229.5	239	0.5
Beam (m)	40.4	44	0.4
Design Draft (m)	13.2	14.1	0.1

The frame table of the reference design is also given in the input file, as shown in *Table 4-3*:

Table 4-3: *Frame Table*

Frames	**Frame Spacing (m)**
- #46	0.8
#46-#52	0.85
#52-#101	3.7
#101 -	0.8

For each design alternative, the frame spacing is proportionally modified, based on the corresponding length ratio. For the definition of the Ship Model, the characteristics of the compartments should be described, as shown in *Table 4-4*:

Table 4-4: *Compartments' Characteristics*

Purpose	Density (t/m3)	Steel Reduction (%)	Capacity (%)	Permeability (%)
Cargo	0.7905	2	0.98	0.95
Water Ballast	1.025	2	1	0.95
Heavy Fuel Oil	0.99	2	0.98	0.95
Diesel Oil	0.9	2	0.98	0.95
Lubricating Oil	0.9	2	0.98	0.95
Fresh Water	1	2	1	0.95
Accommodation	1	2	1	0.95
Miscellaneous	1	2	1	0.95

The following four loading conditions have been defined for the specific parametric model:

- Full Load Departure
- Full Load Arrival
- Normal Ballast Departure
- Normal Ballast Arrival

Full Load Departure (FLD)

It is the Loading Condition at which the vessel sails with its cargo and fuel tanks fully loaded and with full supplies, while the water ballast tanks are empty. The cargo and fuel tanks are loaded at the 96.04% of their moulded volumetric capacity: the net volume of each tank is equal to 98% of the moulded volume due to a 2% steel reduction and filling is assumed at 98% of the net volume. The steel reduction is defined in the Ship Model task. Therefore, here only the 98% filling with respect to the net volume is defined. The tanks are loaded as shown in *Table 4-5*:

Table 4-5: *Full Load Departure Tank Capacity*

Tank Purpose	Fill Ratio (%)
Cargo Oil	98
Water Ballast	0
Fresh Water	100
Heavy Fuel Oil	98
Diesel Oil	98
Lubricant Oil	98
Miscellaneous	55

Full Load Arrival (FLA)

In this Loading Condition the cargo tanks are fully loaded, while the consumables (fresh water, heavy fuel oil, diesel oil and provisions) are loaded at 10% of their capacity. The lubricant oil tanks are filled at 75% of their capacity. Only the Aft Peak Tank is loaded with water ballast. The crew weight remains the same in every loading condition. The tanks are loaded as shown in *Table 4-6*:

Table 4-6: *Full Load Arrival Tank Capacity*

Tank Purpose	Fill Ratio (%)
Cargo Oil	98
Water Ballast	5
Fresh Water	10
Heavy Fuel Oil	10
Diesel Oil	10
Lubricant Oil	75
Miscellaneous	50

<u>Water Ballast Departure (WBD)</u>

During this loading condition, the cargo tanks are empty and the water ballast tanks are fully or partially loaded. The rest of the tanks are loaded in the same way as in the FLD loading condition. The tanks are loaded as shown in *Table 4-7*:

Table 4-7*: Water Ballast Departure Tank Capacity*

Tank Purpose	Fill Ratio (%)
Cargo Oil	0
Water Ballast	90
Fresh Water	100
Heavy Fuel Oil	98
Diesel Oil	98
Lubricant Oil	98
Miscellaneous	55

Water Ballast Arrival (WBA)

In this loading condition, the water ballast tanks are loaded as in the WBD loading condition. The cargo tanks are empty and the consumables have the same capacity as in the FLA loading condition. The tanks are loaded as shown in *Table 4-8*:

Table 4-8: *Water Ballast Arrival Tank Capacity*

Tank Purpose	Fill Ratio (%)
Cargo Oil	0
Water Ballast	98
Fresh Water	10
Heavy Fuel Oil	10
Diesel Oil	10
Lubricant Oil	75
Miscellaneous	50

Economic Assessment

Finally, each design alternative's techno-economic evaluation is carried out through the NPV calculation. The investment is composed of two stages.

During the first stage, the construction cash outflows are calculated. The construction of the ship will last for 2 years. The machinery weight and the corresponding cost and the accommodation outfitting weight and cost are the same for all the designs, because the main engine and the superstructures remain the same during the development of the parametric model. Since the variations of the size of the ship are kept small, it might be assumed that the variations of the weight and cost related to the hull outfitting are not significant. Therefore, the total building cost variation depends on the ship's steel weight and the price of steel. The shipping company is assumed to receive a loan, which equals to the 60% of the total building cost and the remaining amount is paid by the company's capital. The loan should be repaid in 10 years and the repayment starts in the first year of operation. At the end of this stage, the annual loan's instalments and interests have been calculated.

During the second stage, the operational cash flows are calculated. It is considered that the ship will be in operation for 20 years. The assumed ship's route for the specific case study is Fujairah-Singapore and the distance is 6680 nautical miles per roundtrip. The operational cash flows are determined by the annual costs and incomes. The costs are divided into fuel, port, crew, maintenance and other costs. The income depends on the ship's deadweight, the worldscale and the address commission.

More specifically, the worldscale is a standardised rate system in the tanker industry that allows comparison of freight rates for various size tanker routes and is divided in two parts. The first one is the flat rate, which represents a base rate for similar ship sizes performing similar voyages. The second part is the worldscale index/multiplier that when coupled with the flat rate, reflects the state of the current market. The address commission is a payment to the charterer by the shipping company as a percentage of freight or hire. Appropriate values for the above quantities have been defined, according to data derived from a series of reference designs [65].

An inflation rate of 2 % has been defined for the quantities of the operational stage, while the inflation rate for the fuel costs is 3.5 %. In the end of the operation time, the ship is sold for a value of 12.5% of the building cost.

The NPV is calculated subsequently, as the cash flows for each stage are now available. The designs with a positive NPV show that the investment is profitable and they are considered as feasible designs. The designs with a negative NPV are rejected.

4.2 Results

The free variables that have been used in this particular study are the length between perpendiculars, the beam and the draught. An exhaustive search is carried out for 20 different values of L_{BP}, 10 of beam and 10 of draught.

In total 2000 designs were produced, 1192 of which were feasible. The remaining 493 designs are rejected, because the NPV is negative and as previously mentioned, negative NPV shows an unsuccessful investment. In addition, 315 designs are also rejected because the index NPVI is very low. NPVI is given by the formula: *NPVI=NPV/Building Cost.* For example, if the building cost is 40 million Euros and the NPV is 200,000 Euros, then the investment is also considered unsuccessful, because the shipping company’s profit is very low. Therefore, a lower boundary is set for NPVI, equal to 0.05. The design should be within the limits of the constraints, defined during the development of the parametric model; it should comply with the regulations, mentioned in the previous chapter, meet the intact and damage stability criteria, achieve the suitable oil outflow parameter and EEDI and finally offer a positive NPV.

The optimal design is selected out of the 1192 feasible designs on the basis of an objective. The objective of the optimisation process in this case is the maximisation of the NPVI. The optimal design's characteristics are shown in the Appendix.

In *Table 4-9* the minimum and maximum values of some important quantities of the 1192 feasible designs are shown:

Table 4-9: *Feasible Designs Minimum – Maximum Values*

Quantities	Min	Max
Deadweight (t)	93293	104187
Cargo Capacity (m^3)	115480	129819
Water Ballast Capacity (m^3)	36878.3	40701.1
GM Full Load Departure (m)	3.720	6.188
Trim Full Load Departure (m)	-1.138[1]	-0.929
GM Full Load Arrival (m)	3.781	6.274
Trim Full Load Arrival (m)	-0.373	-0.212
GM Normal Ballast Departure (m)	12.235	17.429
Trim Normal Ballast Departure (m)	-1.357	-1.186
GM Normal Ballast Arrival (m)	12.142	17.401
Trim Normal Ballast Arrival (m)	-0.942	-0.765
KG margin intact stability (m)	2.508	3.947
KG margin damage stability (m)	0.448	1.401
Oil Outflow Parameter	0.01284	0.01378
EEDI Margin	0.249	0.385
Building Cost (million euros)	39.88	40.73
Net Present Value (million euros)	2.00	14.59
NPVI	0.05	0.358

The KG margin is given by the formula: *KG margin* = $KG_{allowble}$-KG_{actual}. Compliance of intact and damage stability requirements is evaluated by the values of the corresponding KG margin. In case there is a negative value of KG margin, then the design alternative should be rejected.

The EEDI margin is given by the formula: *EEDI margin = Required EEDI - Attained EEDI.* In *Table 4-9* the EEDI margin is presented for Phase 1.

[1] trim by the stern

The following diagrams present the correlations between the various quantities of the feasible designs.

The relation between cargo volume and DWT is shown in *Diagram 4-1*. As expected, increased cargo capacity is combined with increased values of DWT.

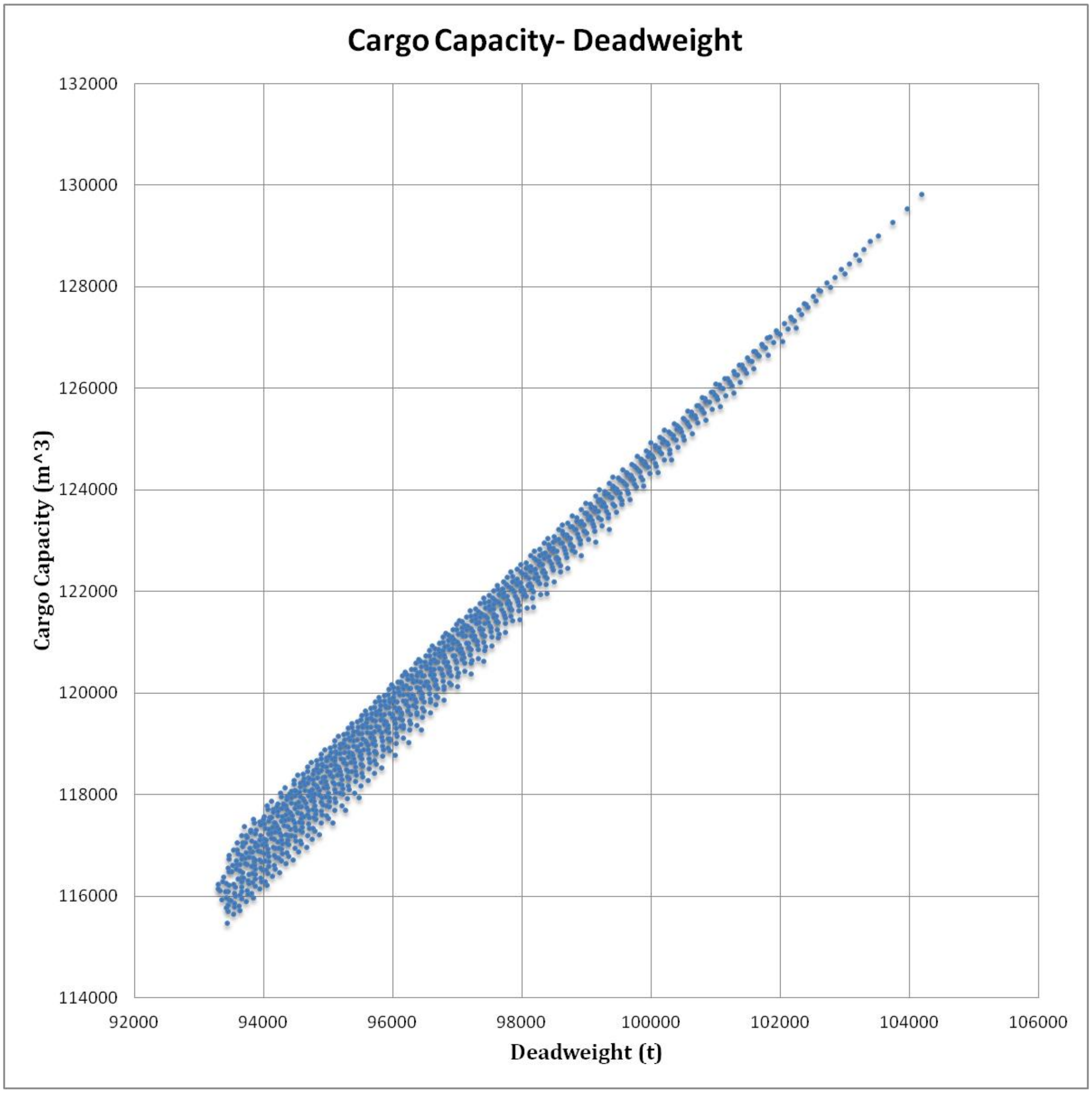

Diagram 4-1: *Cargo Capacity vs. DWT*

The relation between water ballast capacity and DWT is shown in *Diagram 4-2*. Increased water ballast capacity corresponds to designs of increased DWT. Points in this scatter diagram are shown to be grouped along certain straight lines with almost constant inclination. Each line corresponds to a specific value of beam. The leftmost line has the narrowest beam and the rightmost line the widest.

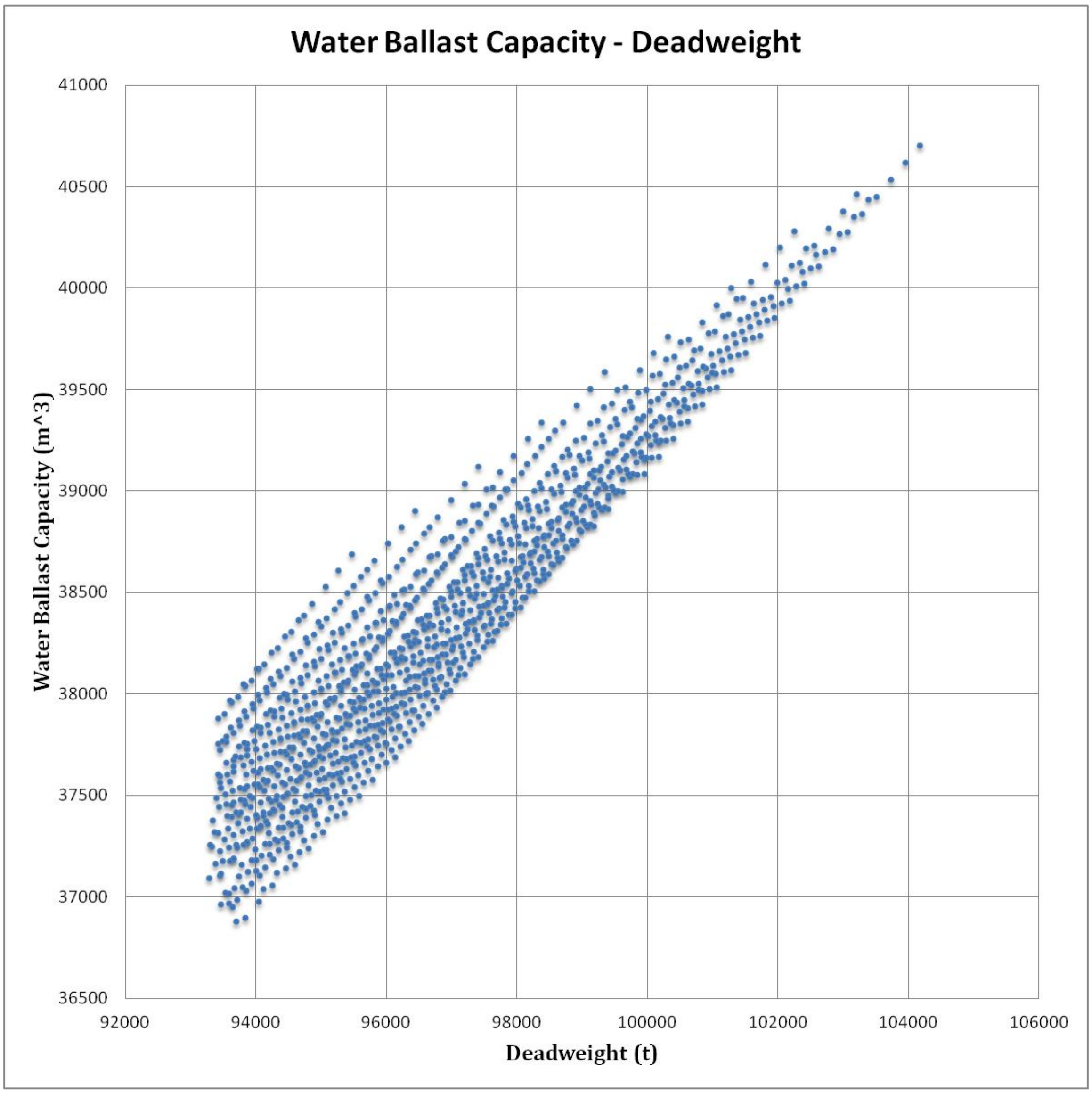

Diagram 4-2: *Water Ballast Capacity vs. DWT*

As depicted in *Diagram 4-3* there is a linear correlation between the building cost and lightship. It was previously mentioned that the main engine and the superstructures remain the same for all the designs. Therefore, the lightship change of every design depends only on the steel weight, as the machinery and the outfitting weight are the same. With the machinery and outfitting costs assumed constant, the building cost variations depend solely on the steel price, which is a constant value, and on the steel weight that is given from a linear formula.

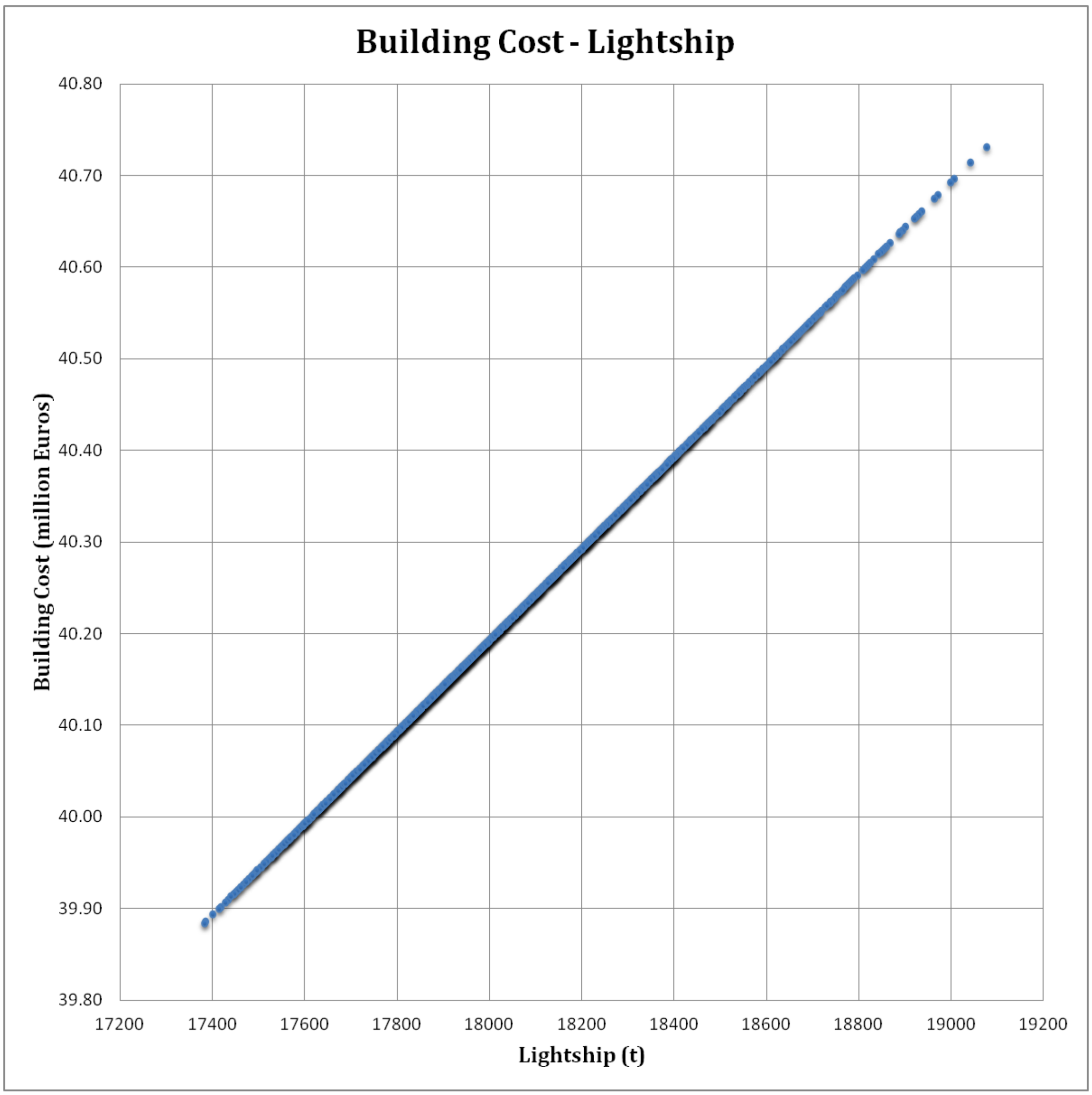

Diagram 4-3: *Building Cost vs. Lightship*

The relation between building cost and DWT is shown in *Diagram 4-4*. As expected, building cost generally increases with increased DWT. Once again, points in this scatter diagram are shown to be grouped along certain straight lines with almost constant inclination. Each line corresponds to a specific value of draught. For the same draught, there is a linear correlation between building cost and DWT. The points of the leftmost line have the lowest draught, which is equal to 13.2 m and respectively the points of the rightmost line have the highest draught, equal to 14.1 m.

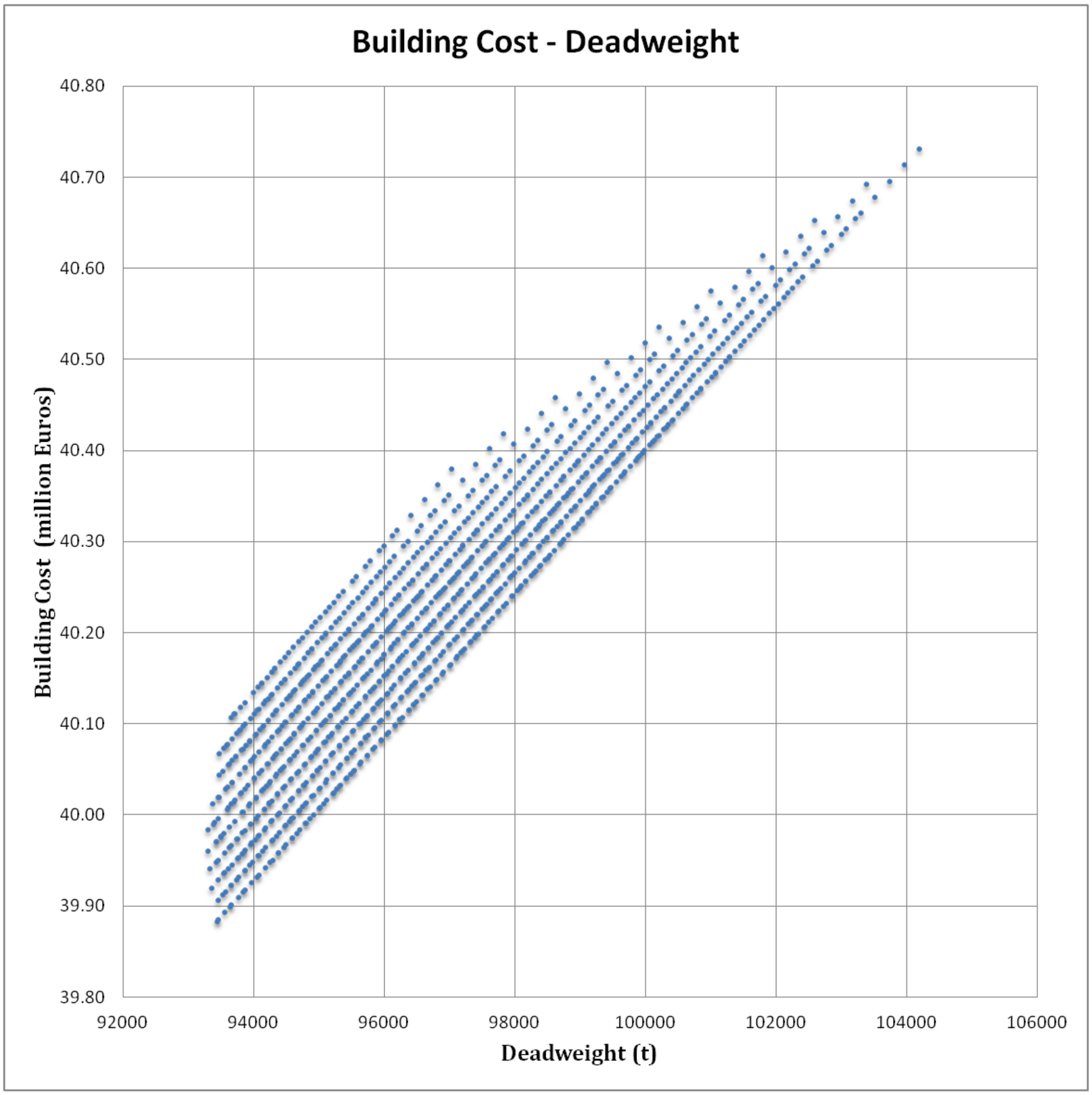

Diagram 4-4: *Building Cost vs. DWT*

The relation between speed and displacement is shown in *Diagram 4-5*. Since all designs are equipped with the same engine, speed is shown to decrease for increased displacement. Points in the diagram are following some discrete groups along certain almost straight lines, which present some common characteristics. Each separate group of lines has the same beam. Moreover, within the same group, designs with the same draught are following separate lines. Lines located lower in the diagram correspond to higher beam values. Ships with lower length are generally located at the left end of the group.

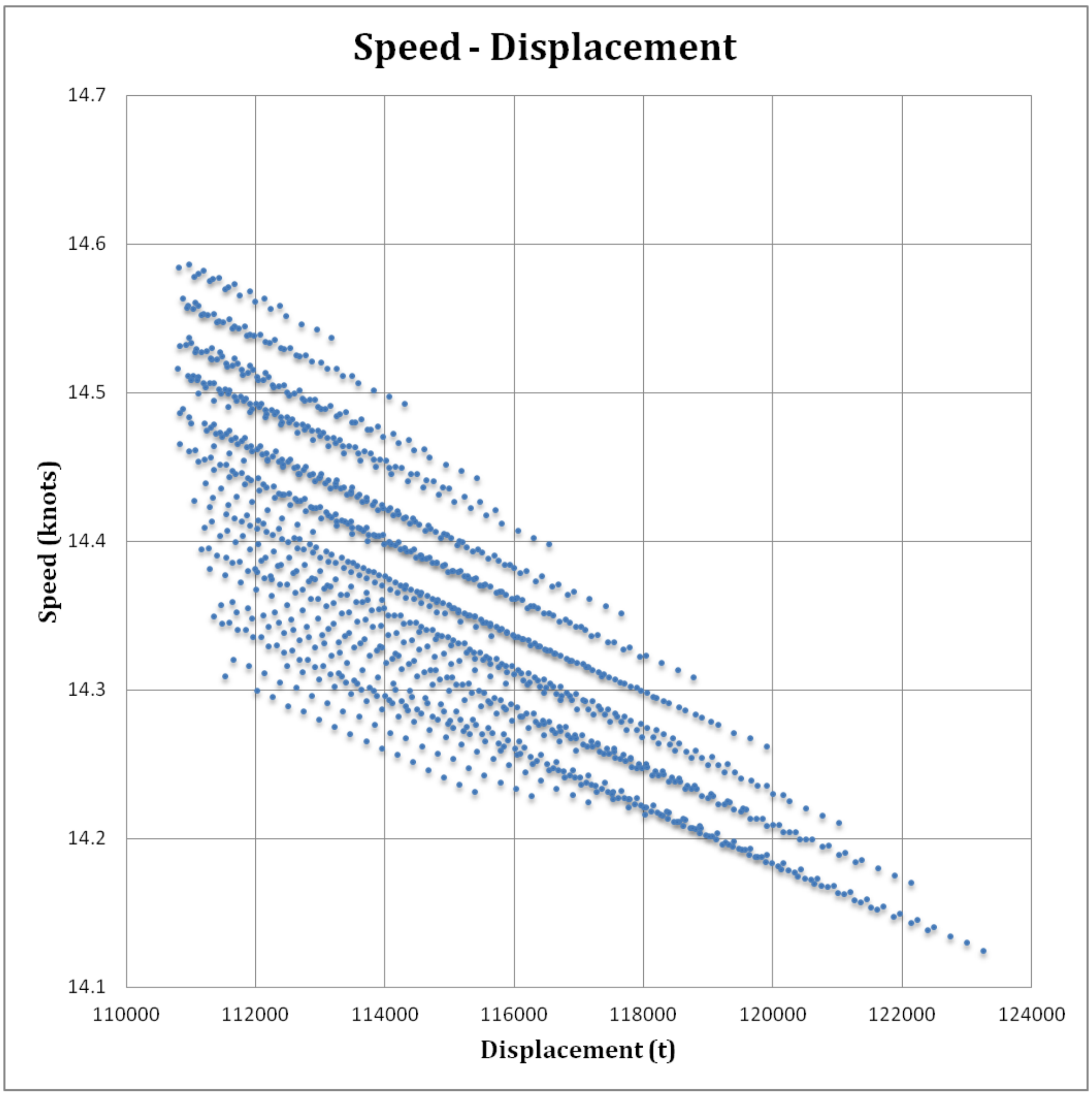

Diagram 4-5: *Speed vs. Displacement*

In general, it is known that the longest ships are faster, as their decreased Froude number, results in lower wave resistance. However, this is not proved in *Diagram 4-6*. This happens, because the values of the Froude number are already quite small, ranging between 0.15 and 0.158. Thus, the effect of the frictional resistance is more important than that of the wave resistance. Each inclined parallel line of the diagram is comprised of points, which have the same beam. The speed is reduced as the beam increases, because the immersed volume and the wetted surface are increased, resulting to an increased resistance.

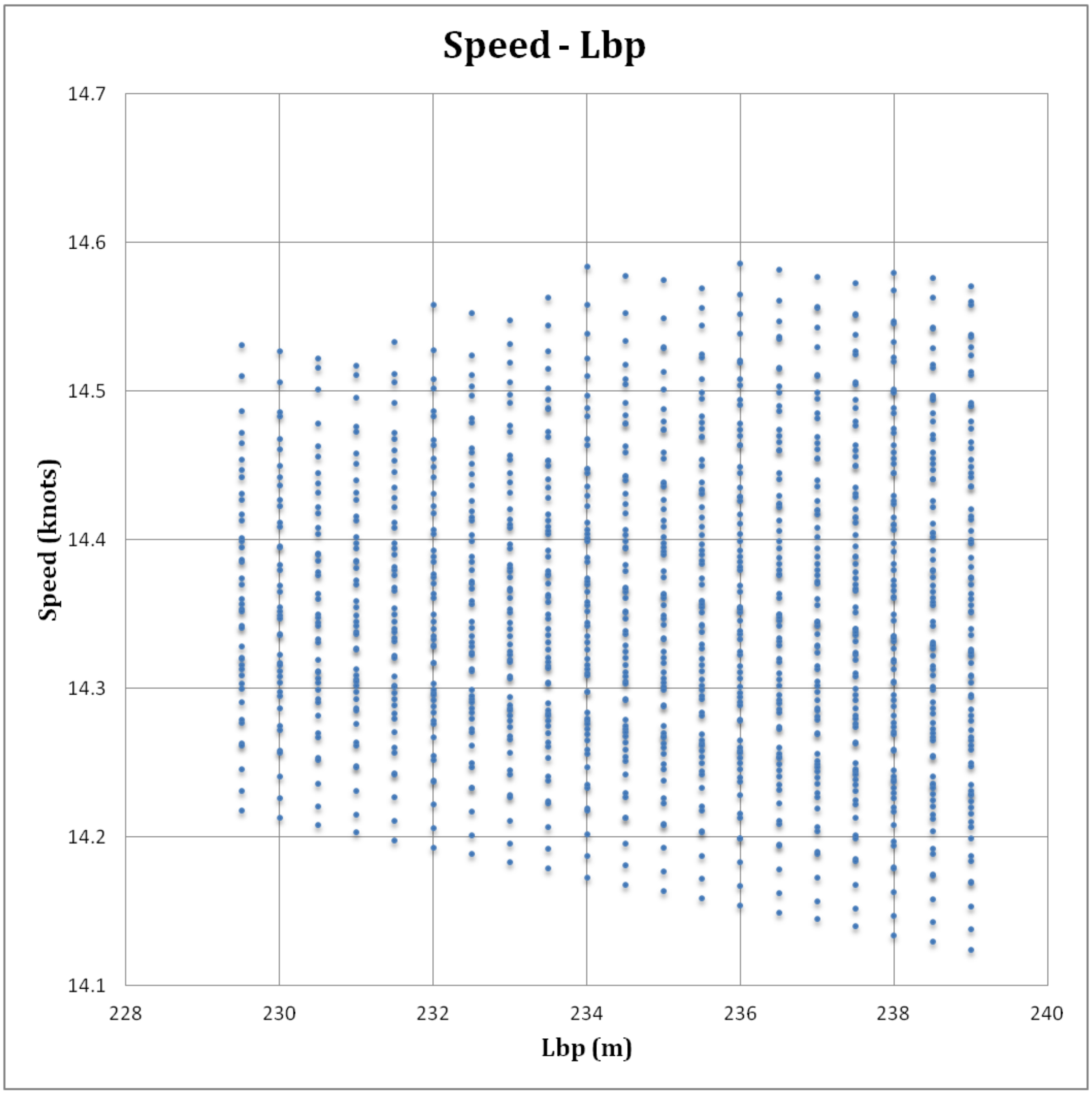

Diagram 4-6: *Speed vs. L_{BP}*

In *Diagram 4-7*, the KG margins of the intact and damage stability are shown. The intact stability's margin varies between 2.5 and 3.9 m, while the damage stability's margin is between 0.4 and 1.4 m. It is observed that while the ship's beam is increased the mean KG margin values are also increasing. This is of course expected, since an increase of beam results in an even higher increase of BM and consequently of the metacentric height.

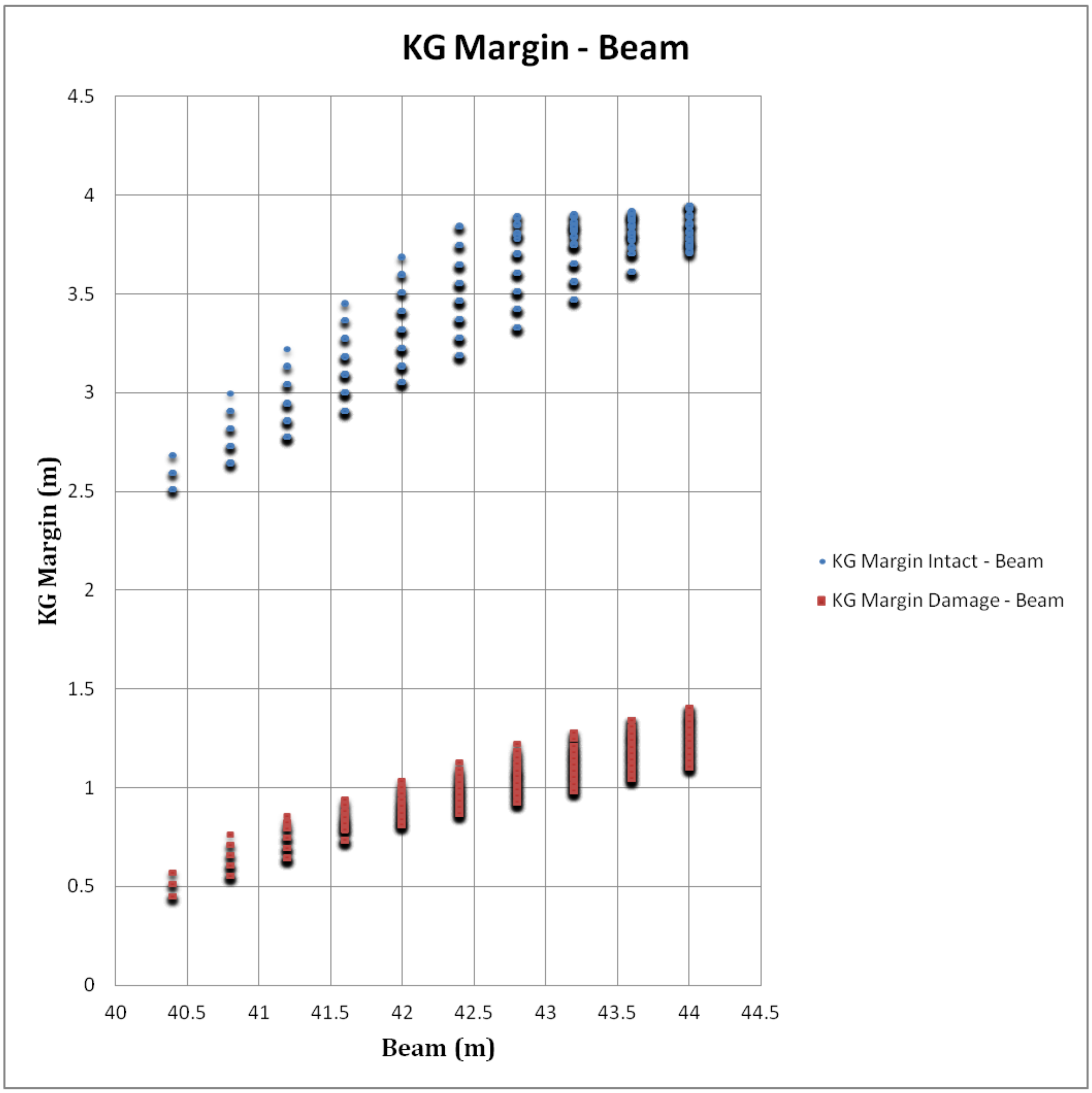

Diagram 4-7: *KG Margin (Intact & Damage Stability) vs. Beam*

As depicted in *Diagram 4-8* the feasible designs of the parametric model fulfil the requirement of Phase 1 of the EEDI, which is in force from January 1st 2015 until December 31st 2019. In the above diagram, twenty groups of points are clearly visible, each one of them corresponding to a constant value of length.

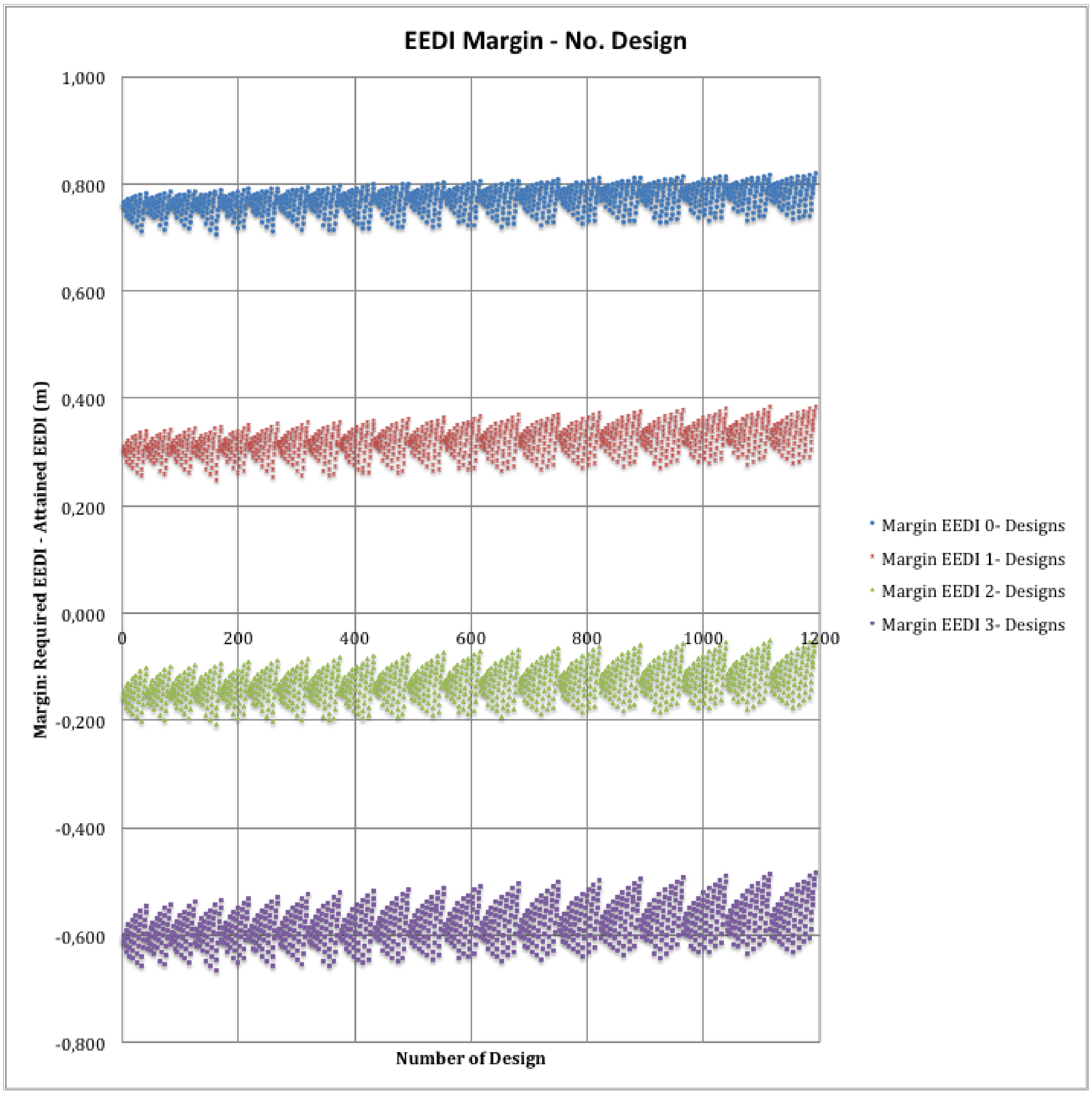

Diagram 4-8: *EEDI Margin vs. No. Design*

Diagram 4-9 shows that as the DWT increases, the EEDI Margin increases as well, which means that the ships with bigger DWT tend to be more efficient concerning the energy.

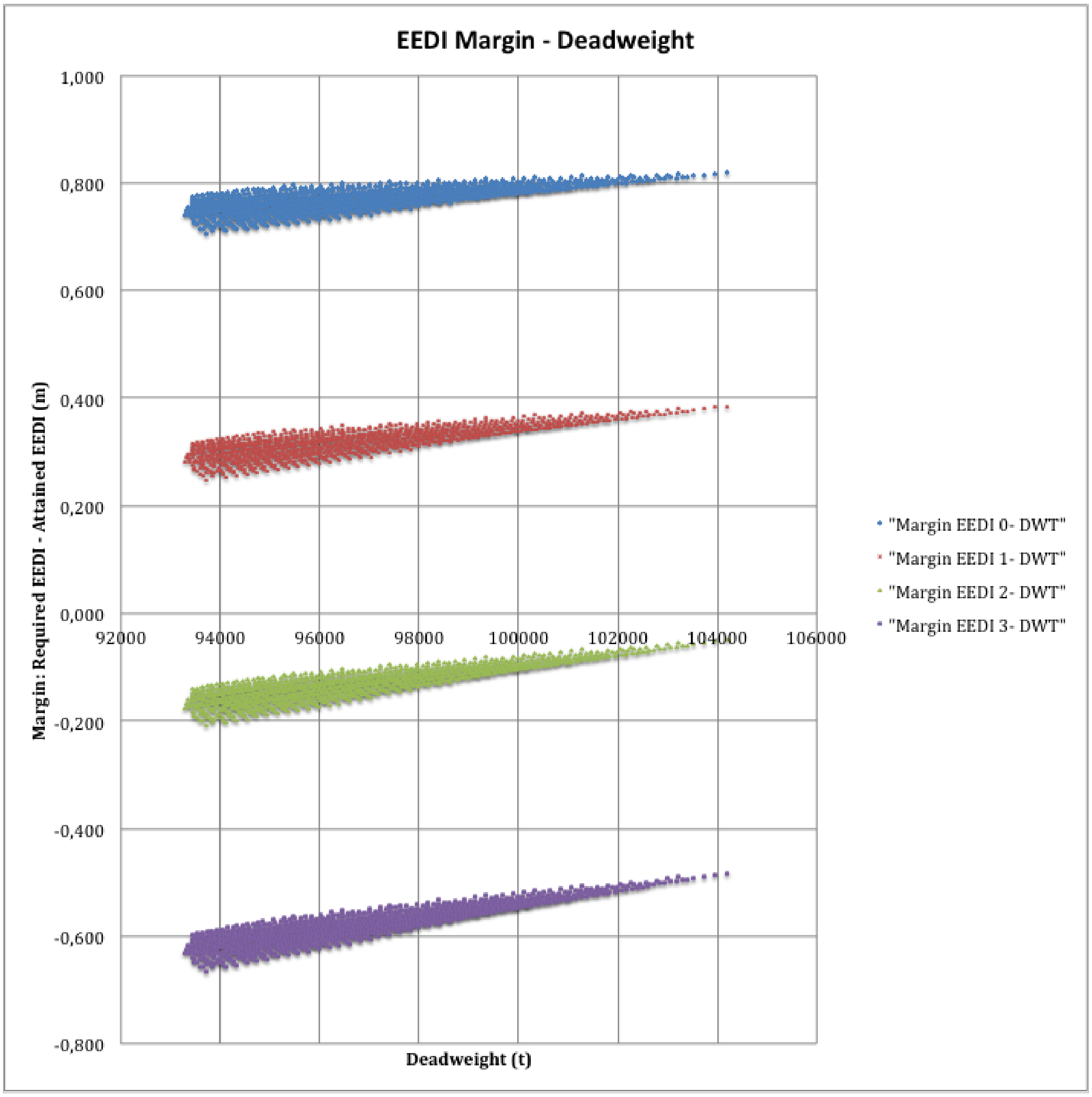

Diagram 4-9: *EEDI Margin vs. Deadweight*

Diagram 4-10 is comprised by groups of lines. All points belonging to the same line have the same pair of beams and draughts. Each group of lines consists of designs having the same beam. Ships with lower length are generally located at the left end of the group. It is shown that as the deadweight increases, by keeping the beam and draught constant and increasing the length, the oil outflow is decreased.

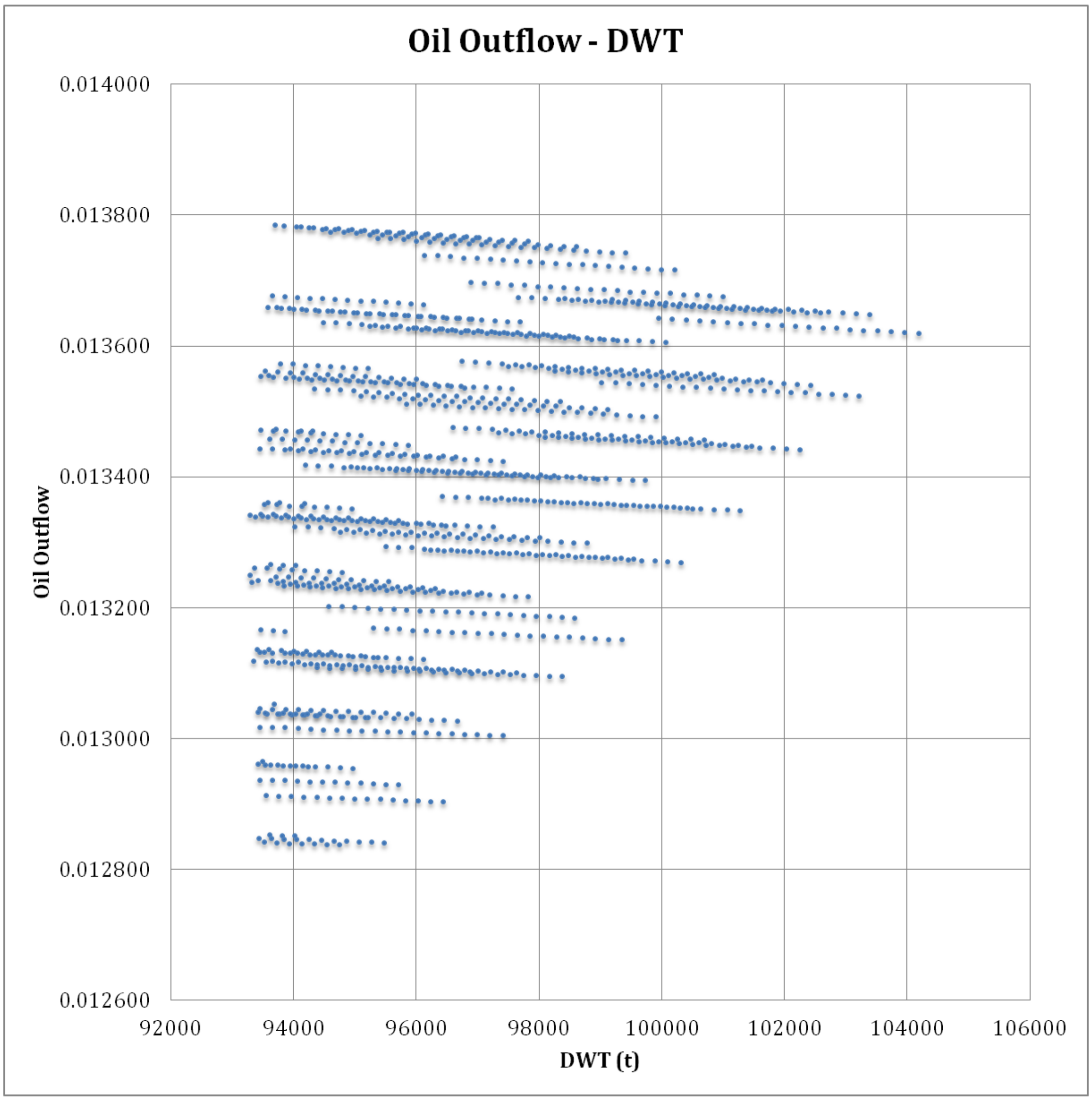

Diagram 4-10: *Oil Outflow vs. DWT*

In the following diagrams the correlation between the oil outflow and the ship's main dimensions is shown. In *Diagram 4-11*, it is shown that a change of length has no significant influence on the value of the oil outflow.

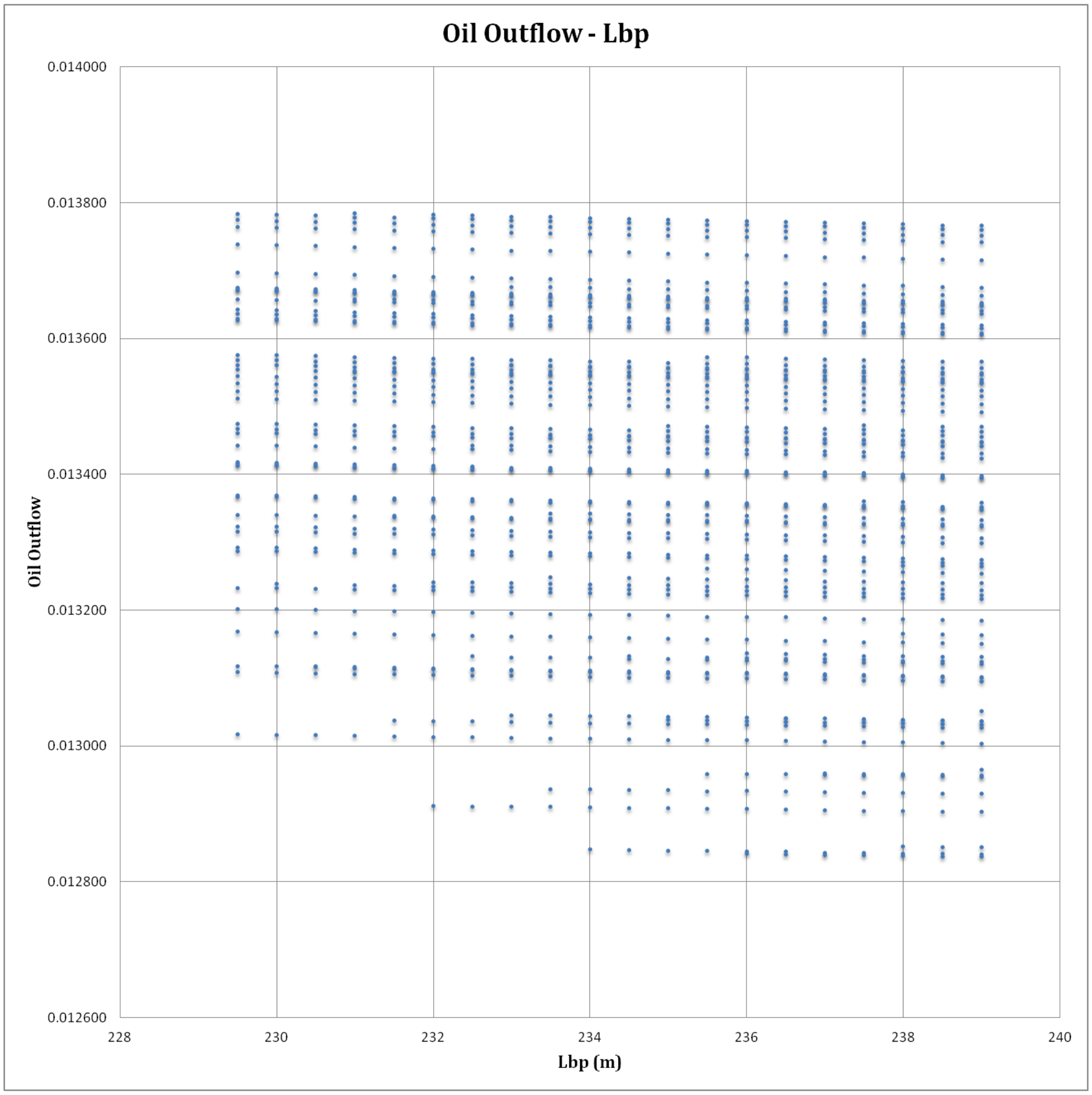

Diagram 4-11: *Oil Outflow vs. Lbp*

As observed from *Diagram 4-12*, by increasing the ship's beam, there is a significant increase of the oil outflow parameter as well. In the following three diagrams, the effect of the beam change on each component of the oil outflow is shown.

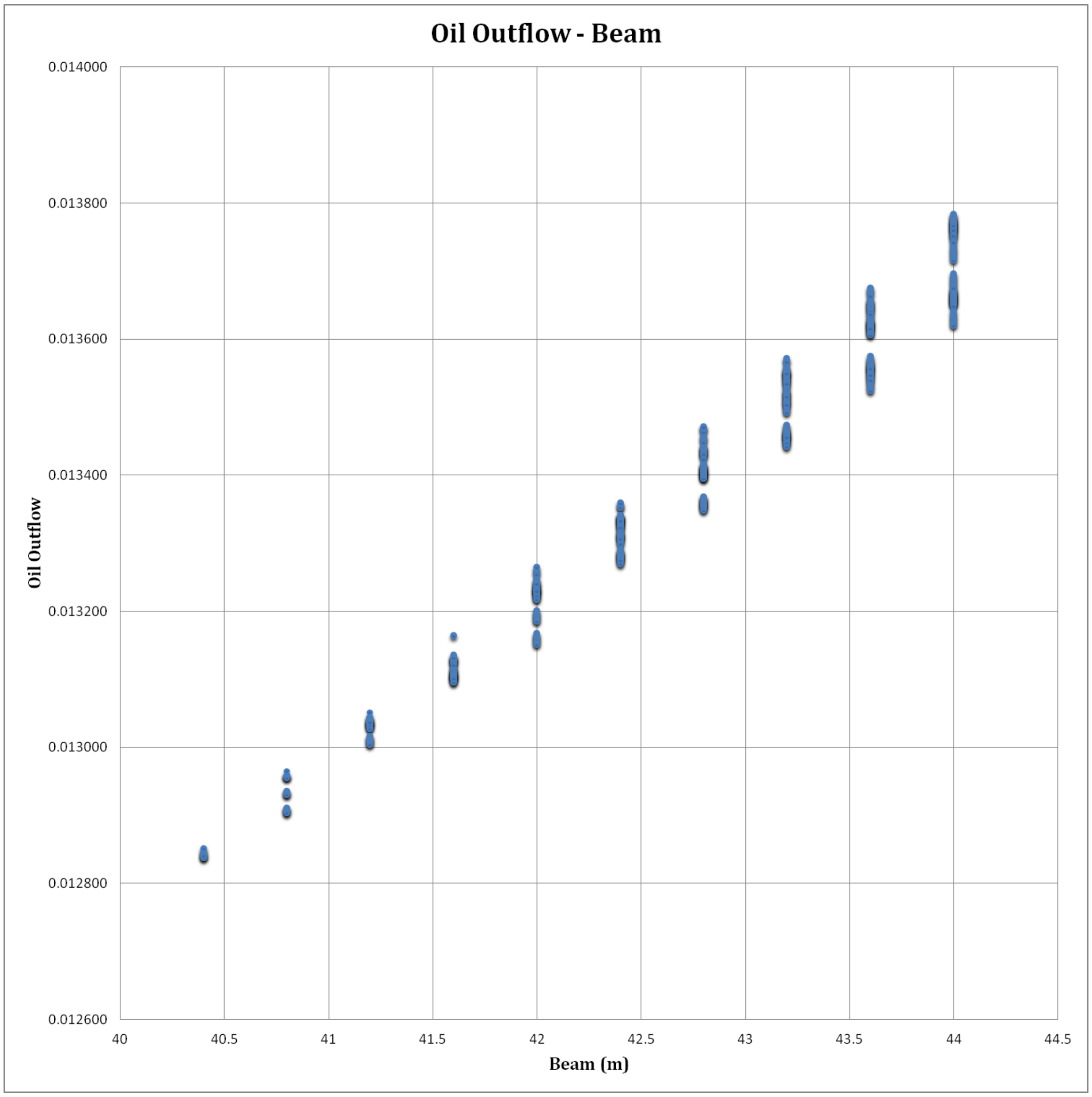

Diagram 4-12: *Oil Outflow - Beam*

In Chapter 3, it was explained that the oil outflow parameter depends on the mean outflow for side and bottom damage. Therefore, additional diagrams have been created, presenting the impact of the dimensions to the side damage outflow and to the bottom damage outflow for 0 and 2.5 m tide condition.

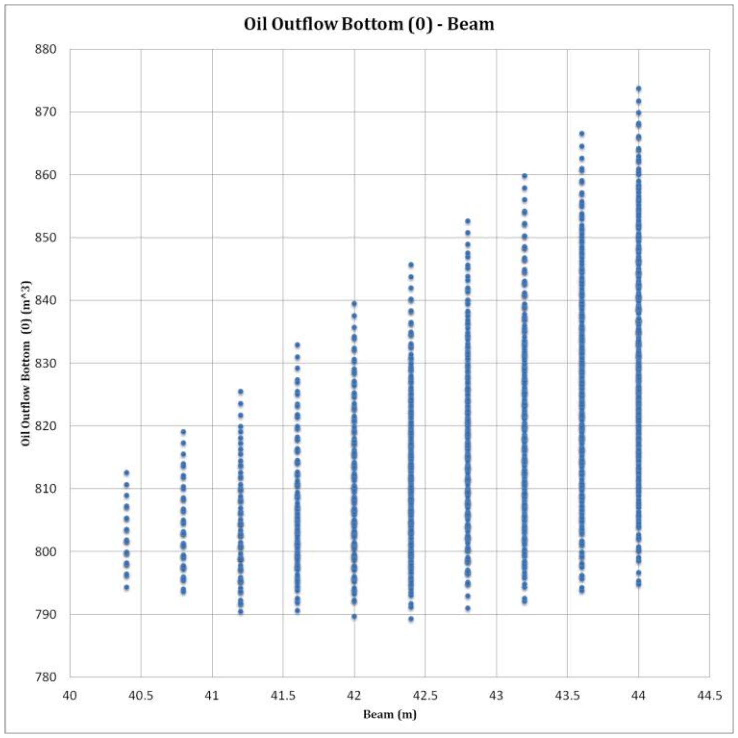

Diagram 4-13: *Oil Outflow Bottom 0 m tide vs. Beam*

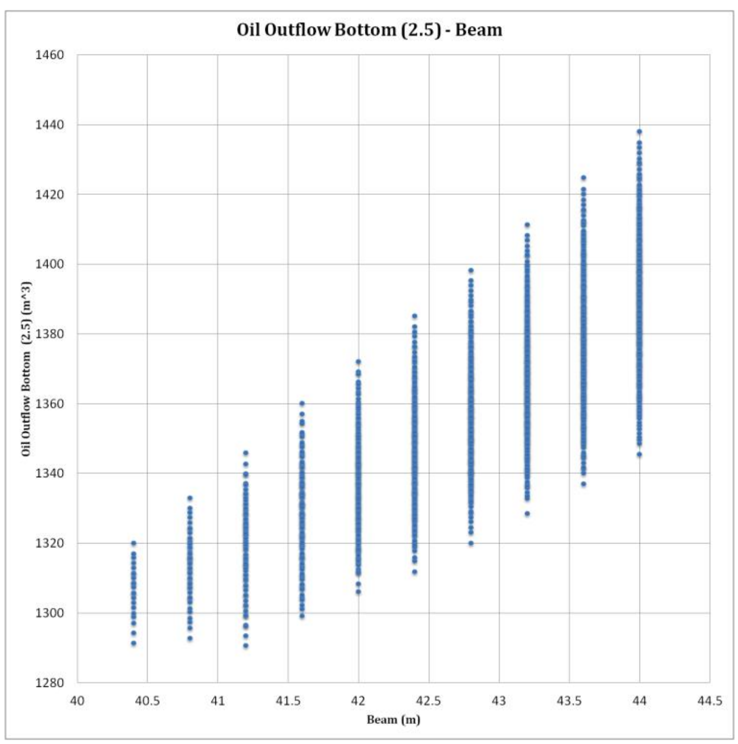

Diagram 4-14: *Oil Outflow Bottom 2.5 m tide vs. Beam*

In *Diagram 4-15*, it is shown that the value of the mean outflow for side damage is very high, compared to the outflow of the bottom damage. The probability of penetrating a cargo from side damage depends on the component y/B, where y=the minimum horizontal distance between the compartment and the side shell and B is the beam. As the beam increases, the y/B ratio is reduced and the probability of breaching the inner hull is increased, while the amount of cargo spilled into the sea is increased.

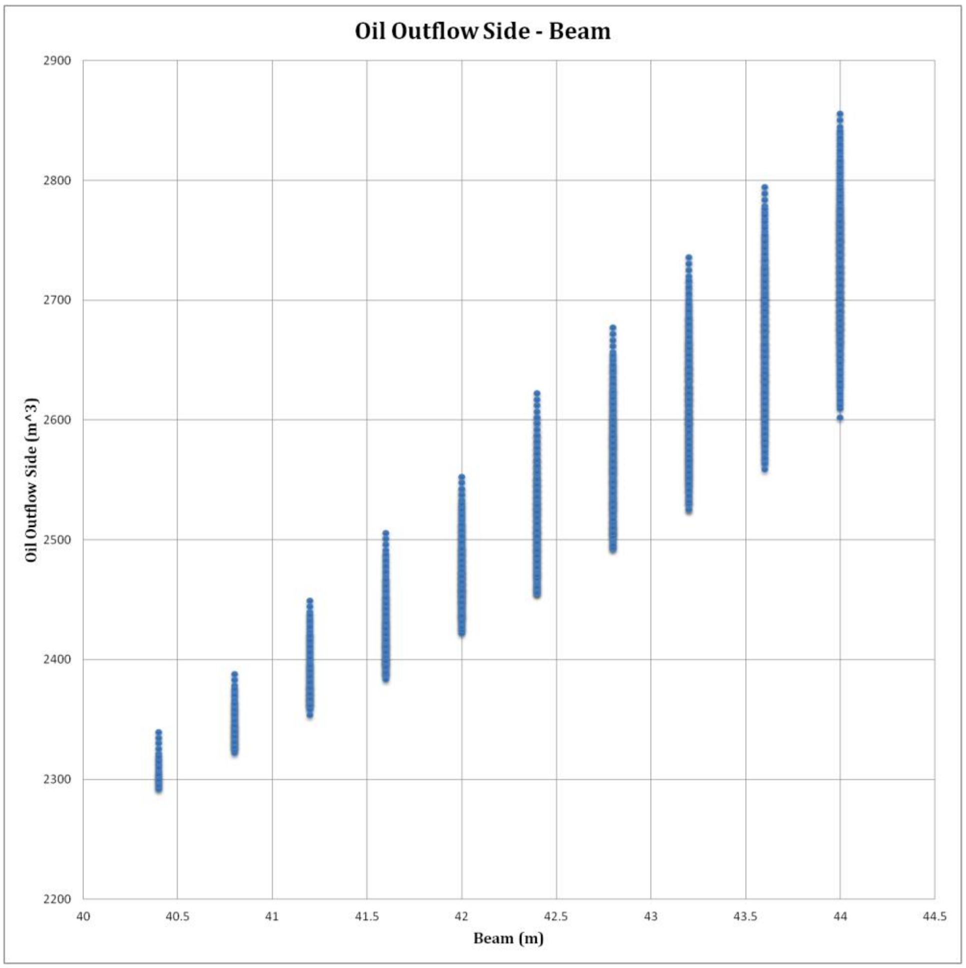

Diagram 4-15: *Oil Outflow Side vs. Beam*

Diagram 4-16 shows that as the ship's draught increases, the oil outflow is reduced. In the following three diagrams, the effect of the draught change on each component of the oil outflow is shown.

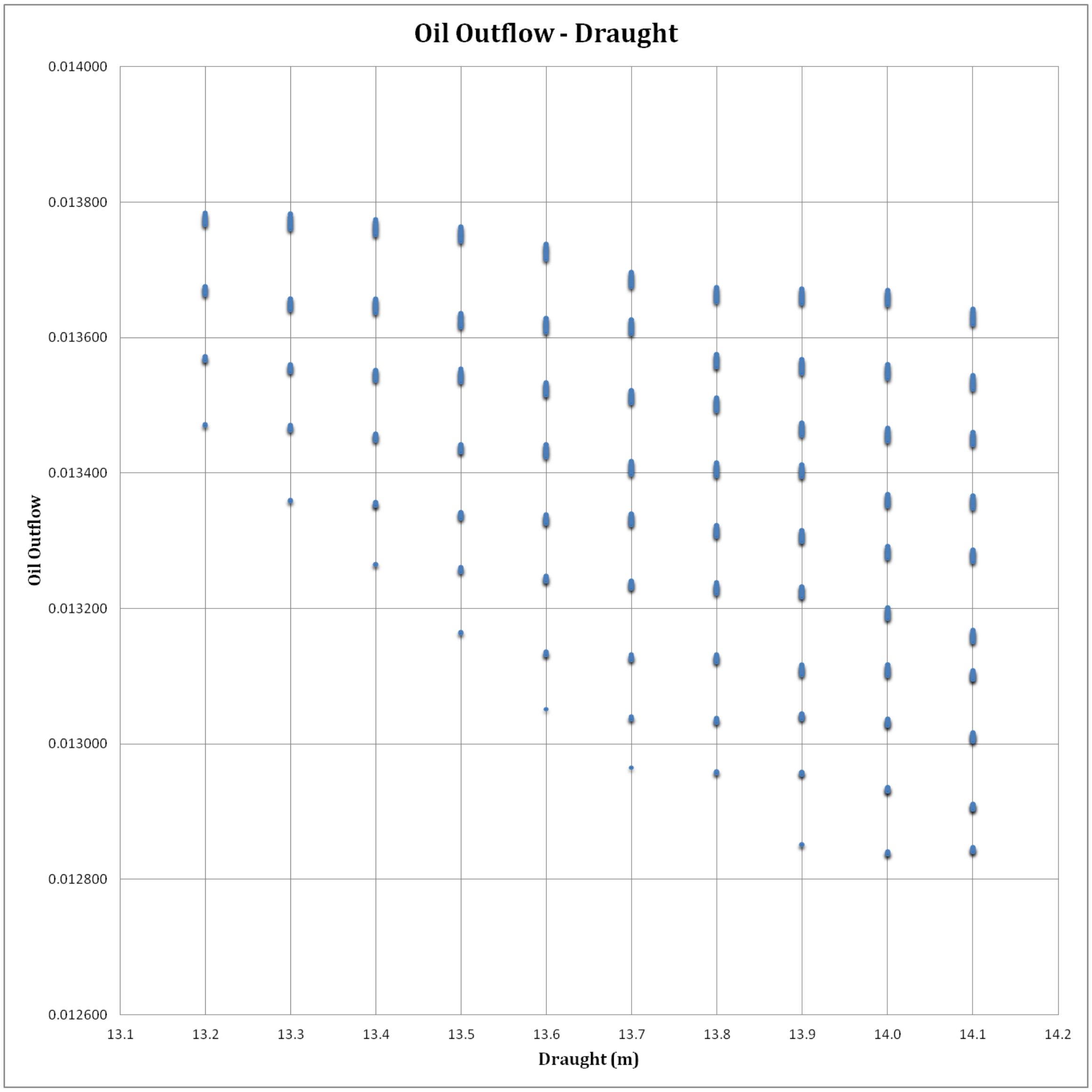

Diagram 4-16: *Oil Outflow vs. Draught*

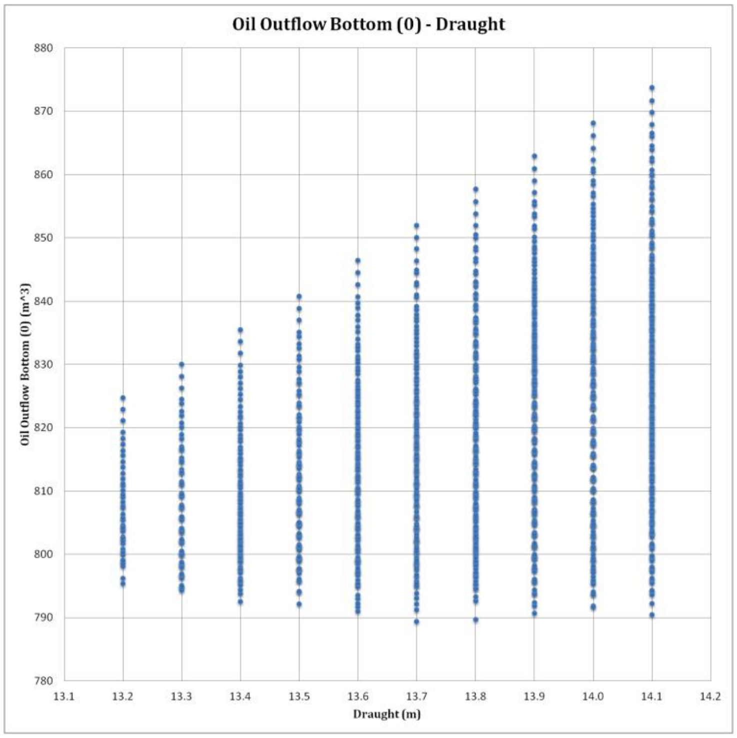

Diagram 4-17: *Oil Outflow Bottom 0 m tide vs. Draught*

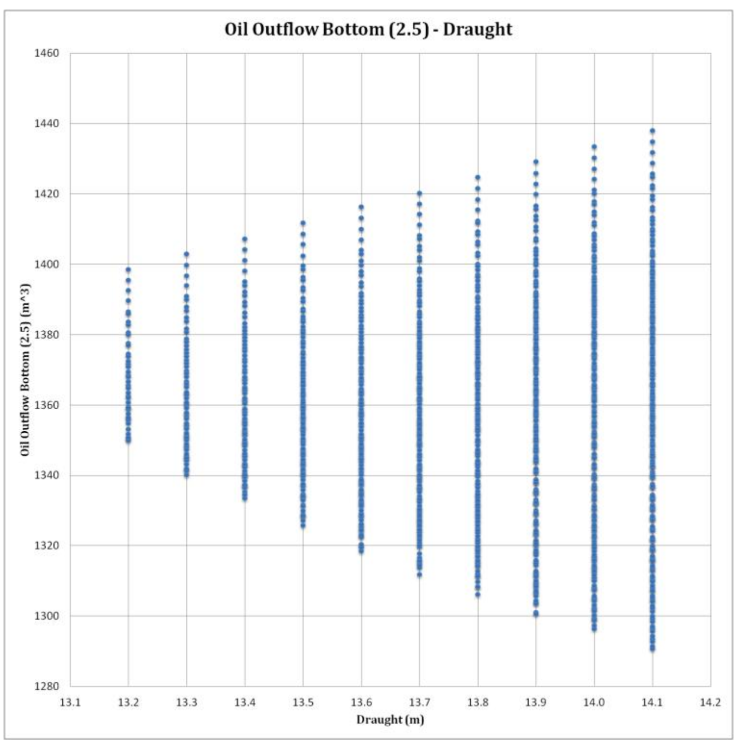

Diagram 4-18: *Oil Outflow Bottom 2.5 m tide vs. Draught*

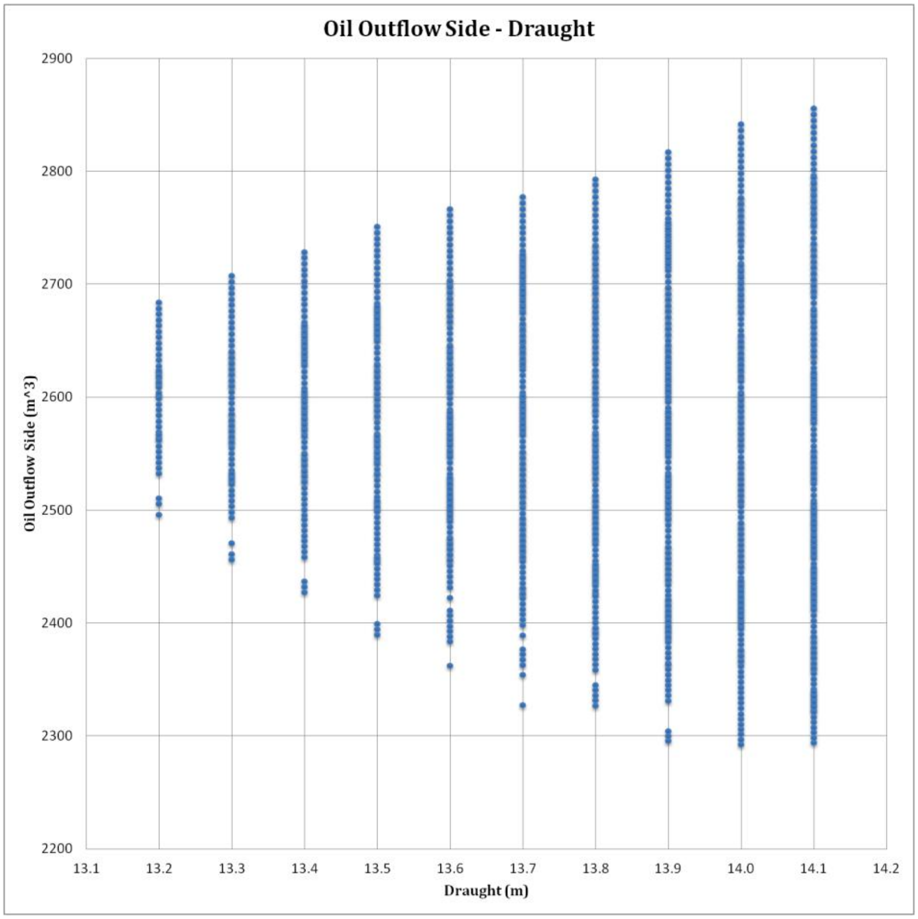

Diagram 4-19: *Oil Outflow Side vs. Draught*

The three diagrams (*Diagram 4-17*, *Diagram 4-18* and *Diagram 4-19*) show that by increasing the ship's draught, there is a significant impact on the mean oil outflow as well. The probability of penetrating a cargo from bottom damage depends on the component z/Ds, where z=the minimum vertical distance between the bottom shell and the lower point of the compartment and Ds is the ship's moulded depth. As the draught increases, the z/Ds ratio is reduced and the probability of breaching the double bottom is increased, while the amount of cargo spilled into the sea is also increased. However, as previously mentioned in *Diagram 4-16*, the oil outflow parameter is decreased when increasing the draught, at least for the designs with the best performance in terms of oil outflow. The oil outflow parameter is given by the formula $O_M=(0.4\ O_{MS} + 0.6\ O_{MB})/C$. When increasing the draught, the total oil volume of cargo oil is increased and subsequently the value of the oil outflow parameter is reduced. It seems that for the best designs in terms of oil outflow, the impact of the cargo oil increase is greater than that of the probability of breaching the tank's bottom. Therefore, according to the presented results, the oil outflow parameter can be reduced by choosing designs with high values of draught and low values of beam.

In *Diagram 4-20*, it is shown than when intact and damage stability are increased, as expressed by the KG Margin, the oil outflow also increases. Although the oil outflow parameter is not supposed to depend on stability margin, the above diagram provides an indication of the penalty that one needs to pay in terms of stability in order to reduce the oil outflow parameter and vice versa, based on the obtained designs.

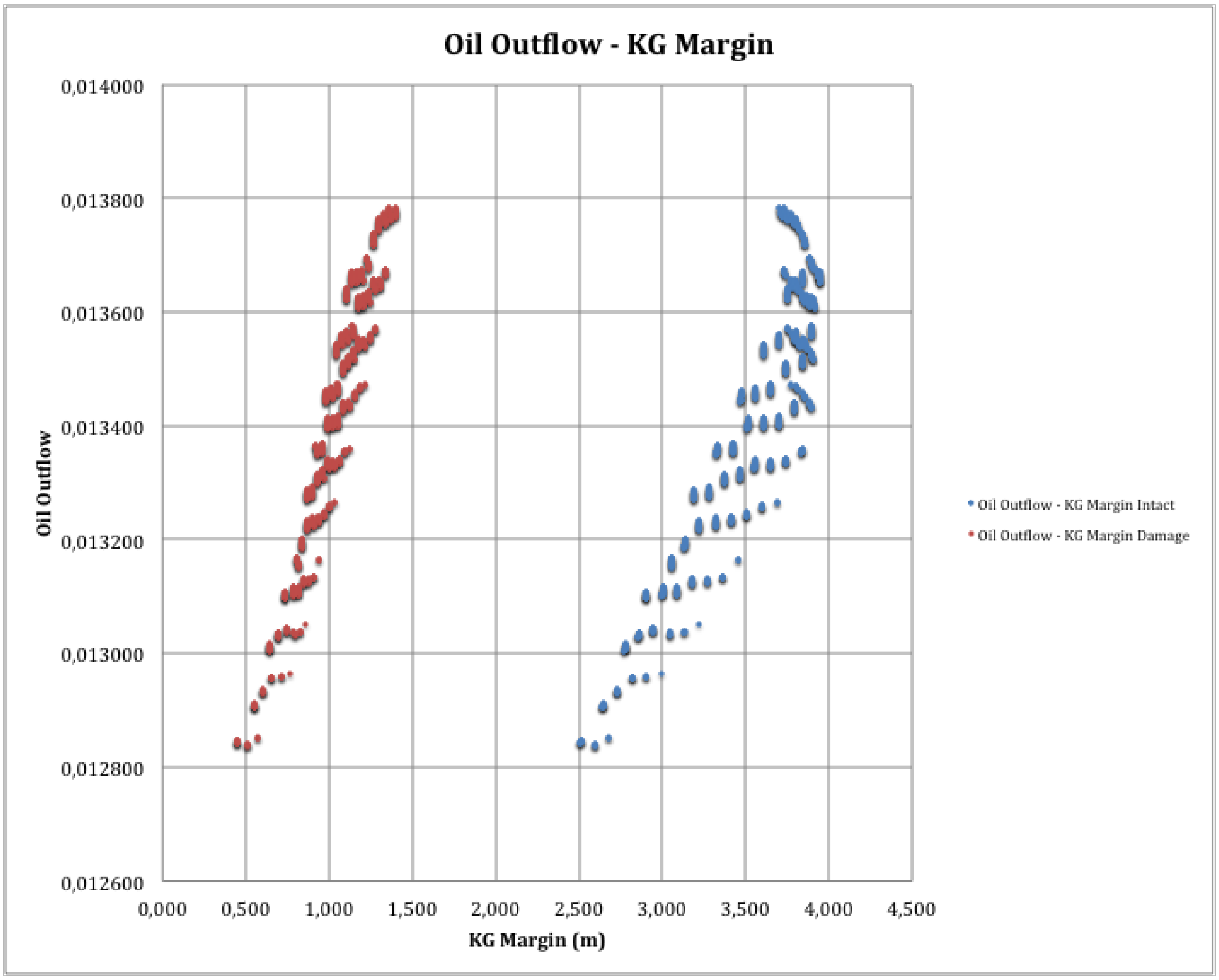

Diagram 4-20: *Oil Outflow vs. KG Margin (Intact & Damage Stability)*

As expected, NPV increases with the size of the ship, therefore with increased building cost. *Diagram 4-21* is composed of parallel, inclined lines. The points of each line have the same pair of beam and draught. Ships with lower length are generally located at the lower end of the group.

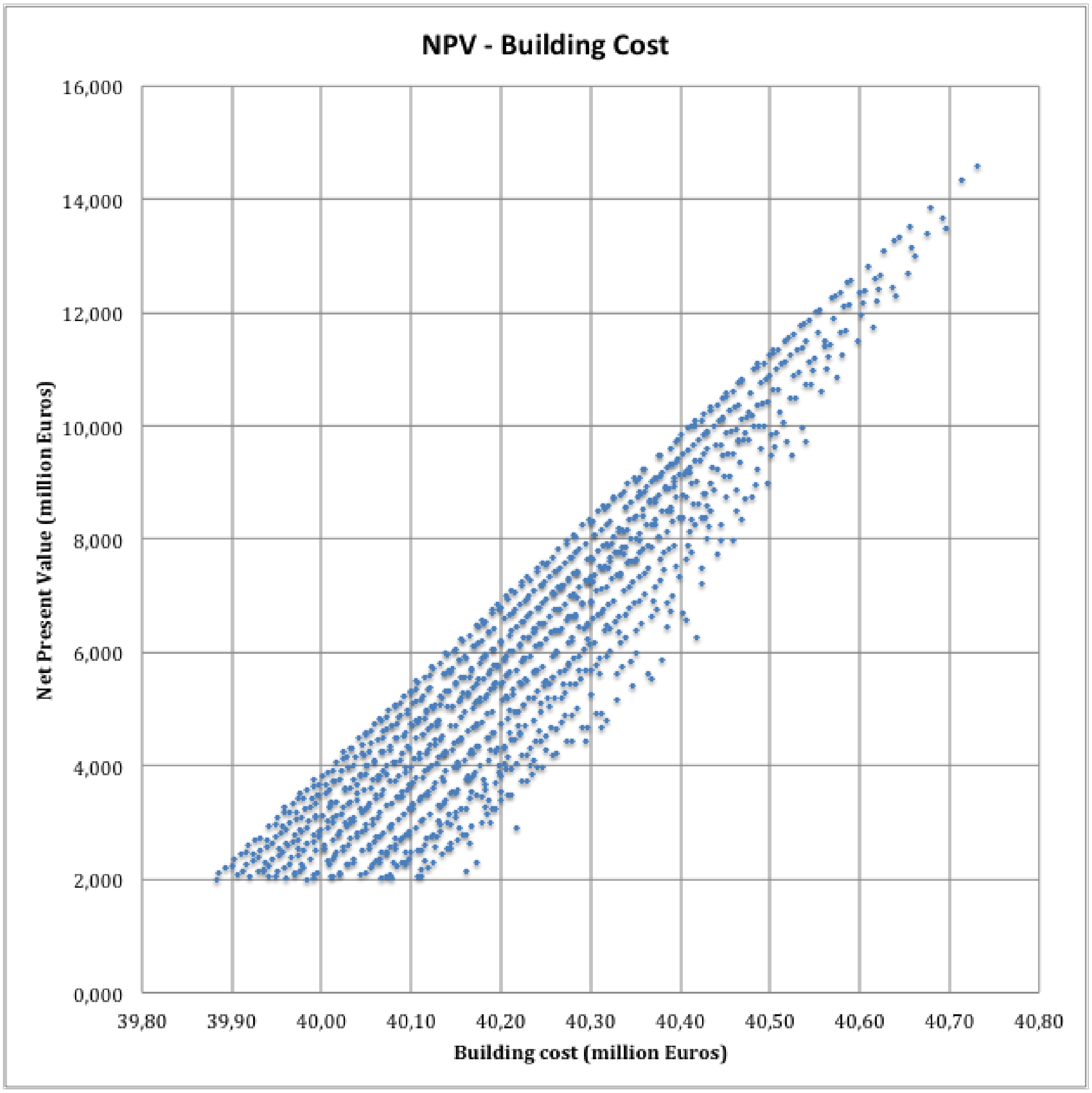

Diagram 4-21: *NPV vs. Building Cost*

During the development of the parametric model, the cargo oil's specific gravity was kept constant for all the designs. Therefore, there is a difference in most designs between the design draught and the actual draught at the Full Load Departure condition. This difference, denoted as dT is shown in *Diagram 4-22* in correlation with NPV. It is shown, that the designs with the highest dT tend to have the lowest net present value. The diagram is composed of parallel lines with their points having the same pairs of beam and draught.

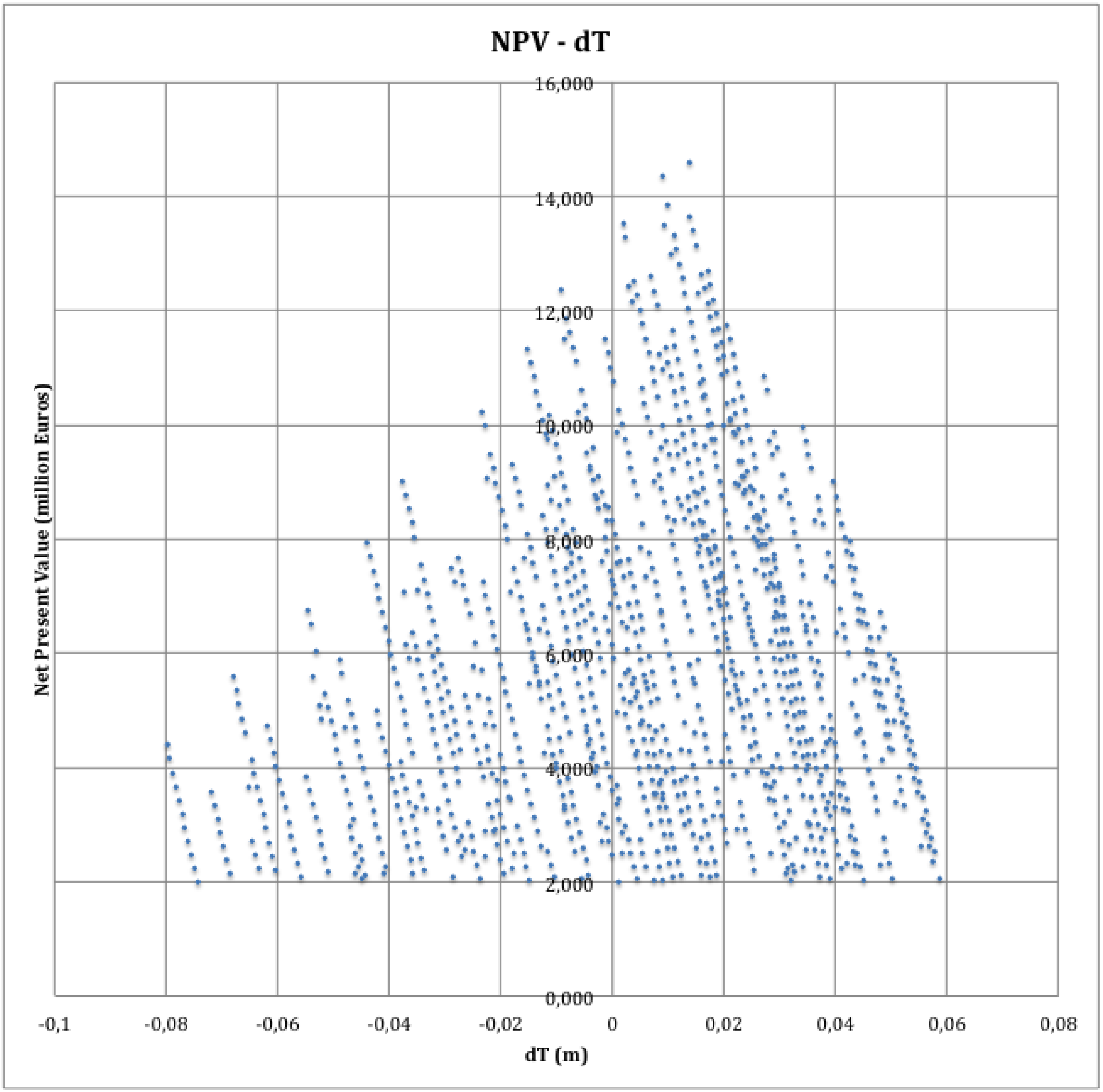

Diagram 4-22: *NPV vs. dT*

NPVI is calculated by the formula NPVI=NPV/Building Cost. The building cost values vary between 39.88 and 40.73 million Euros, whereas the NPV values vary between 2 and 14.59 million Euros. Thus, the building cost can be considered relatively stable and the correlation between NPVI and NPV is almost linear, as shown in *Diagram 4-23*.

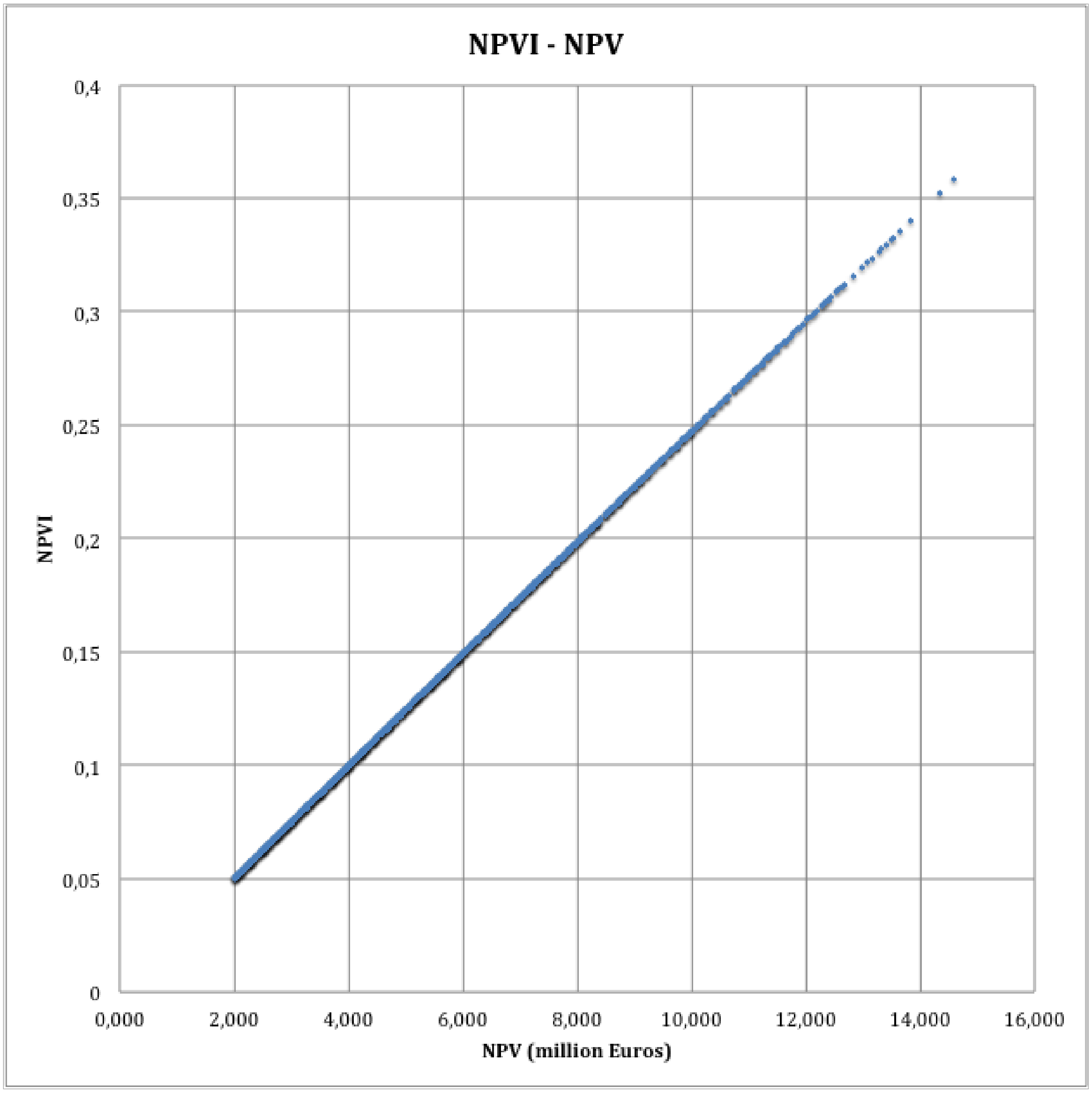

Diagram 4-23: *NPVI vs. NPV*

As shown in *Diagram 4-24*, the highest NPV values are connected to designs with generally improved energy efficiency.

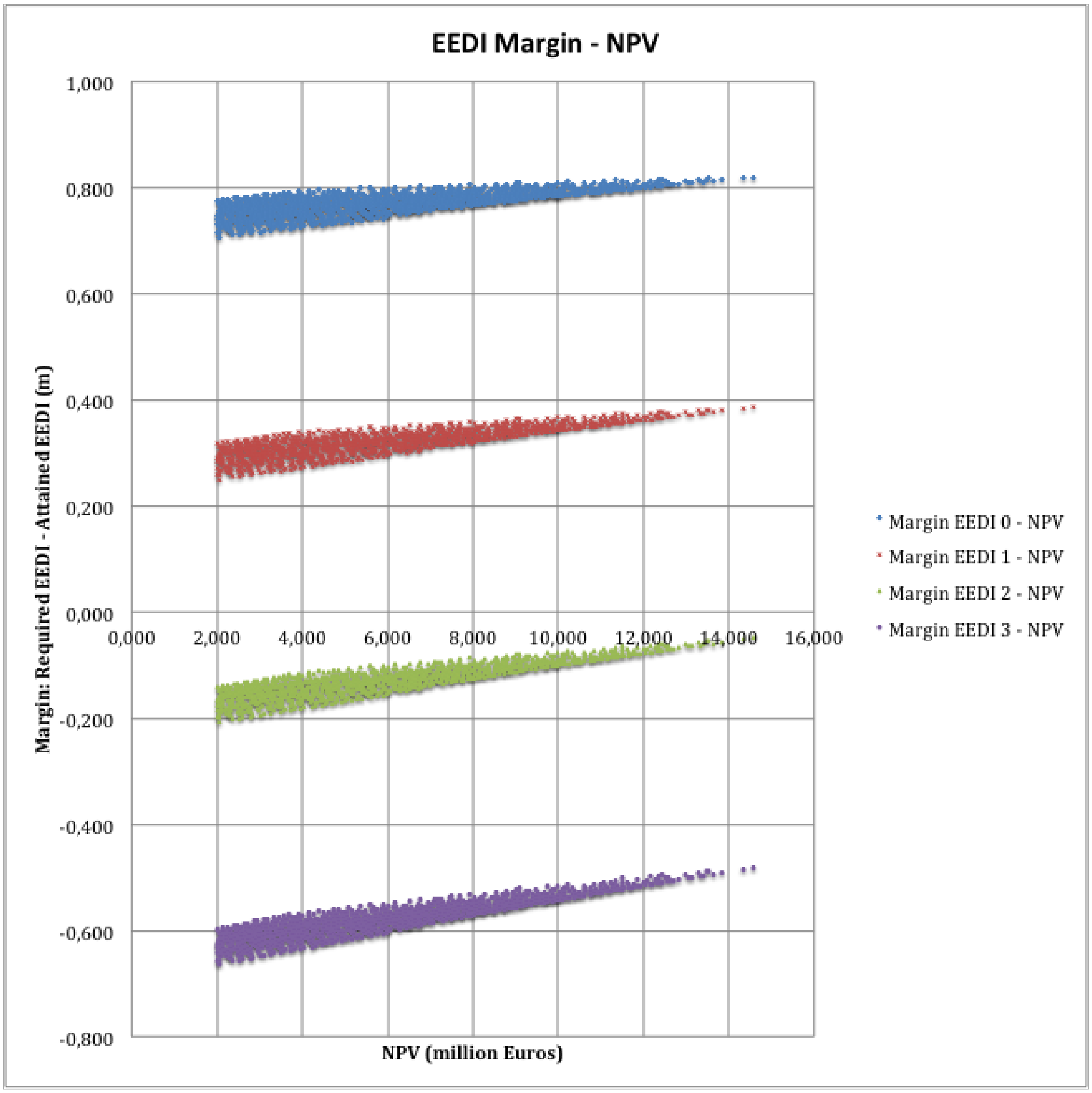

Diagram 4-24: *EEDI Margin vs. NPV*

The obtained results indicated that compliance with EEDI Phase 1 requirements was easily achieved, while at the same time no one of the alternative designs was able to fulfil the Phase 2 requirement (*Diagram 4-8* and *Diagram 4-9*). In an attempt to identify solutions fulfilling the requirement Phase 2 of the EEDI coming into force from January 1st 2020 until December 31st 2024, it was decided to investigate the impact of reduced speed. In this respect, a main engine of reduced power was selected, i.e. MAN B&W 5S60MC with an M.C.R. of 10200 kW at 105 rpm. This is actually the same engine as before, but with five cylinders instead of six. With this engine, in total 2000 designs were derived, 1028 of which were feasible. The remaining 606 designs were rejected, because their NPV was negative and additionally 366 designs were also rejected because their index NPVI was very low. The evaluation of the design alternatives was carried out by taking into consideration the same criteria, as in the designs with the previous main engine. In the following diagrams, a comparison between the various quantities of the feasible designs derived by the above studies with the two main engines is presented.

As depicted from *Diagram 4-25*, the main disadvantage of the engine with the 5 cylinders is that there is an approximately 1kn speed reduction from the engine with the 6 cylinders.

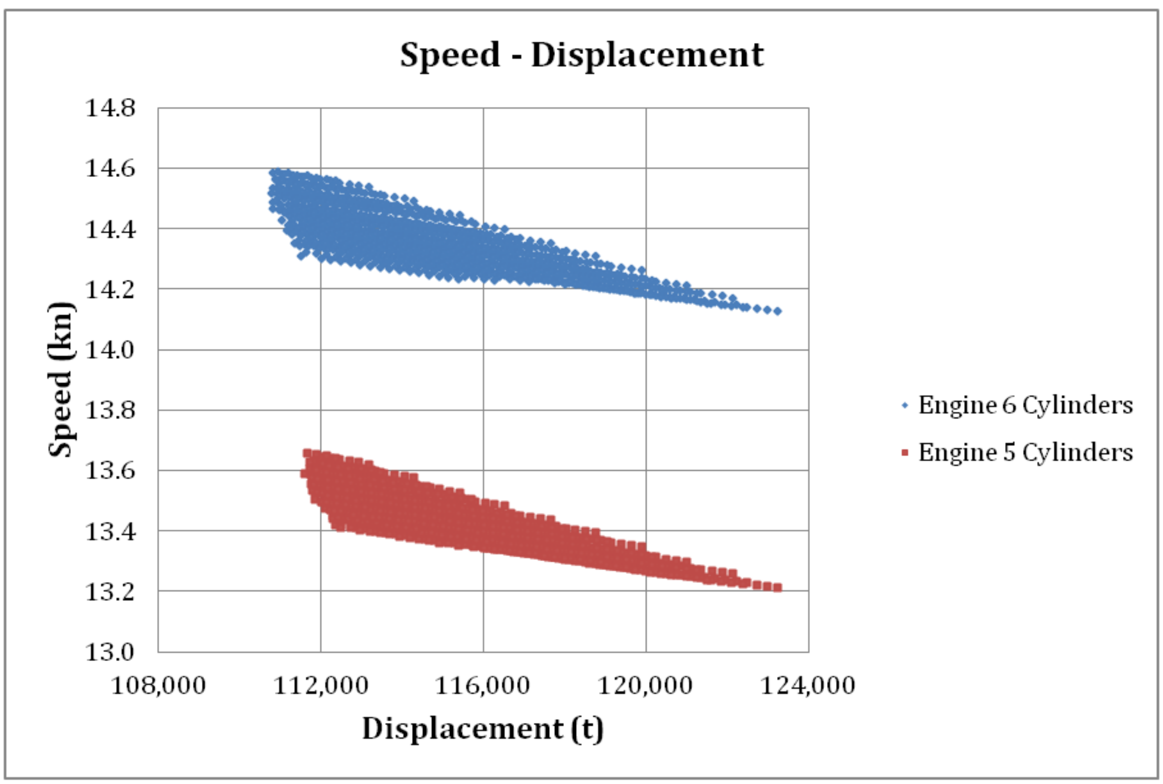

Diagram 4-25: *Speed vs. Displacement*

It is shown in *Diagram 4-26* that the designs with the 5-cylinder main engine achieve Phase 2 of the EEDI. The values of the required EEDI remain the same, as the required EEDI depends on the deadweight and some constant parameters. The difference between the EEDI margins obtained by using the two engines results from the difference of the values of the attained EEDI. More specifically the attained EEDI is given by the formula:

$$\text{Attained EEDI} = (\text{Engine Power} \times SFC \times C_F)/(DWT \times \text{speed})$$

Although the ship's speed, resulting from the 5-cylinder main engine, is lower, the impact of the Engine Power reduction on the attained EEDI is higher and phase 2 is achieved.

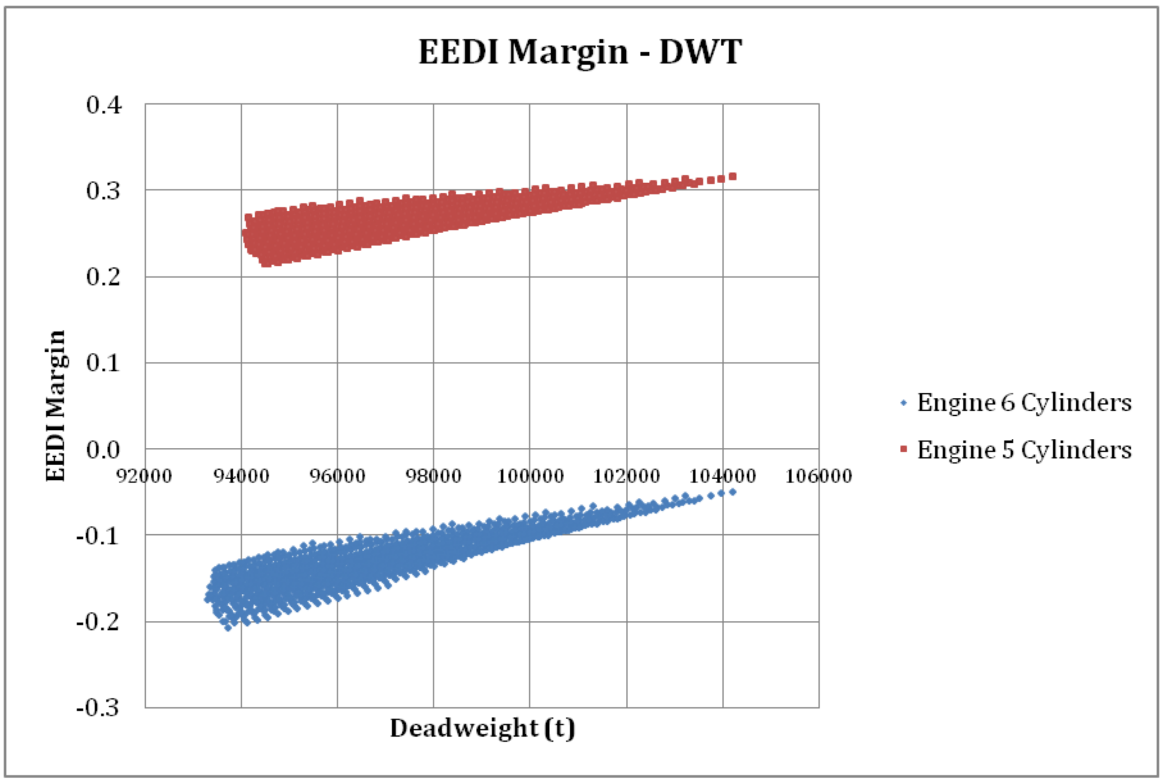

Diagram 4-26: *EEDI Margin vs. Deadweight*

In this diagram, the feasible designs, obtained with the 5-cylinders and the 6-cylinders engines are presented with their corresponding values of the NPVI. It is observed that the larger NPVI values are obtained with the 6-cylinder main engine, as a result of the increased number of round trips per year, due to the higher service speed.

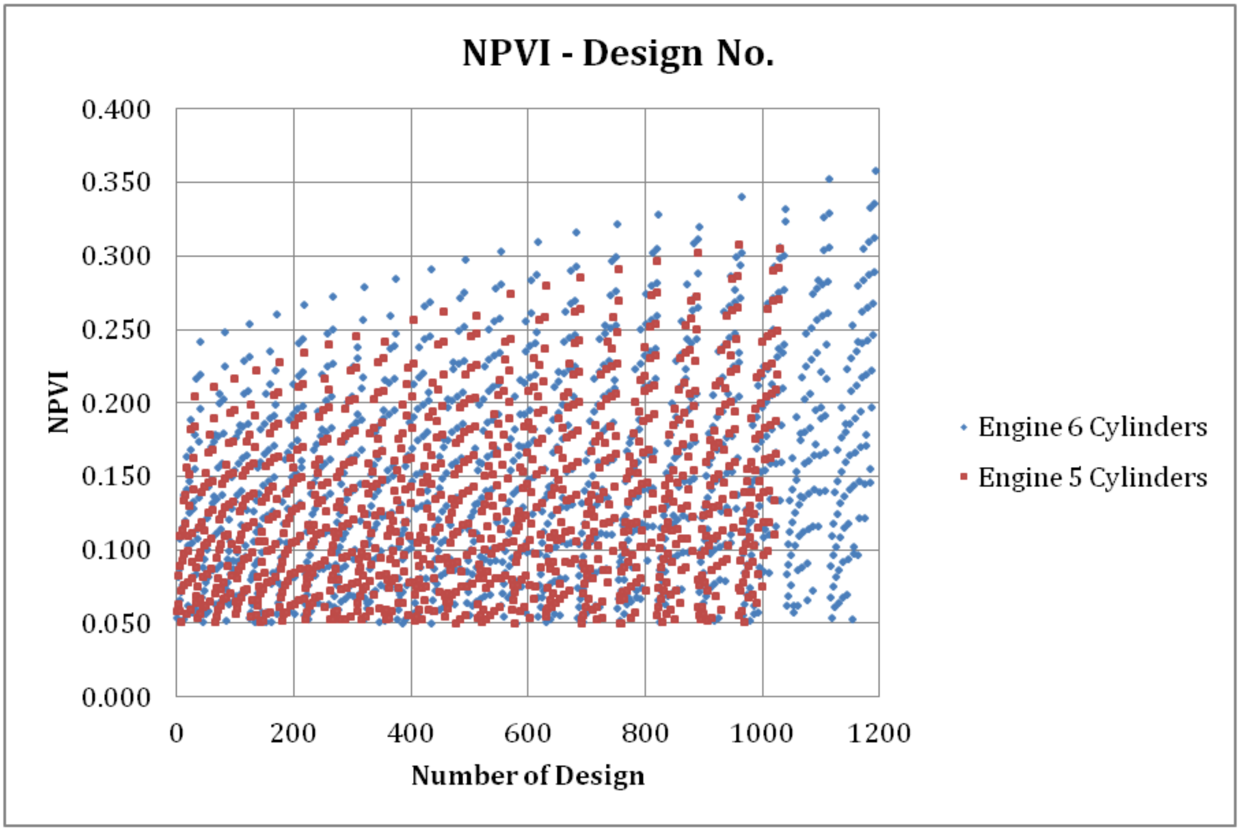

Diagram 4-27: *NPVI vs. Design Number*

5 Conclusion

The present thesis explored a non-traditional ship design approach, focusing on parametric modelling and optimisation of oil tankers. The case study of an AFRAMAX tanker was selected, and the work was carried out in two stages; the development of the parametric model, along with the required software tools carrying out the necessary calculations, and the application of the developed procedure and tools to perform the design optimisation. An investigation of the design space was carried out, in order to select the optimal design, which achieved specific objectives and was within the limits of the constraints.

The parametric model was set up in Napa and the Napa Basic programming language was used extensively. Due to the need for extensive programming for the development of the design alternatives, parametric modelling was proved a highly demanding task. However, when the parametric model was developed, it was possible to repeat the design process for a high multitude of variables in almost zero time (i.e. less than 50 sec).

The objective that was used for the selected case study was the maximisation of the NPVI. Thus, the optimal design achieved the maximum NPVI, but it also offered increased service speed, improved energy efficiency and enhanced environmental protection in case of accidents.

The obtained results indicated that intact and damaged stability requirements and oil outflow constraints were easily fulfilled. Regarding EEDI, all designs were in compliance with Phase 1 requirements, while no one of the initially obtained designs was able to comply with Phase 2. A second round of optimisation study was performed with a reduced engine power (same engine model but with 5 cylinders instead of 6), and the results indicated that in order to comply with Phase 2, a 1kn speed reduction was required.

Some suggestions for further work are presented below:

- ❖ Development of a more accurate method for the resistance assessment, to replace the Holtrop-84 method used in this study. CFD is a very time-consuming tool, for the development of a high multitude of design alternatives. A possible solution might be to perform CFD calculations for a large number of designs in order to develop a fast prediction method based on the obtained results, for example by the use of artificial neural networks.
- ❖ Development of a more accurate and detailed method for the calculation of the lightship weight and building cost, with particular emphasis on the analytic calculation of steel weight.
- ❖ Development of a more generic and flexible geometric model. This would give the user the possibility to choose the number of the longitudinal and the transverse

bulkheads, decide whether the bulkheads should be corrugated or plane, choose the hopper plate's inclination etc.

- ❖ Development or integration of additional software tools for a more comprehensive assessment of each design alternative. For example it would be very useful to be able to assess the manoeuvring characteristics of each design.
- ❖ Finally, a general-purpose optimisation software could be used, offering more efficient optimisation, instead of the exhaustive search method that was applied for this study.

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Appendix

The objective, based on which the optimal design was selected, is the maximisation of the NPVI. The selected design is within the limits of the constraints, defined during the development of the parametric model; it complies with the pre-mentioned regulations, meets the intact and damage stability criteria, achieves the suitable oil outflow parameter and EEDI and finally offers a positive NPV.

Optimal Design Characteristics

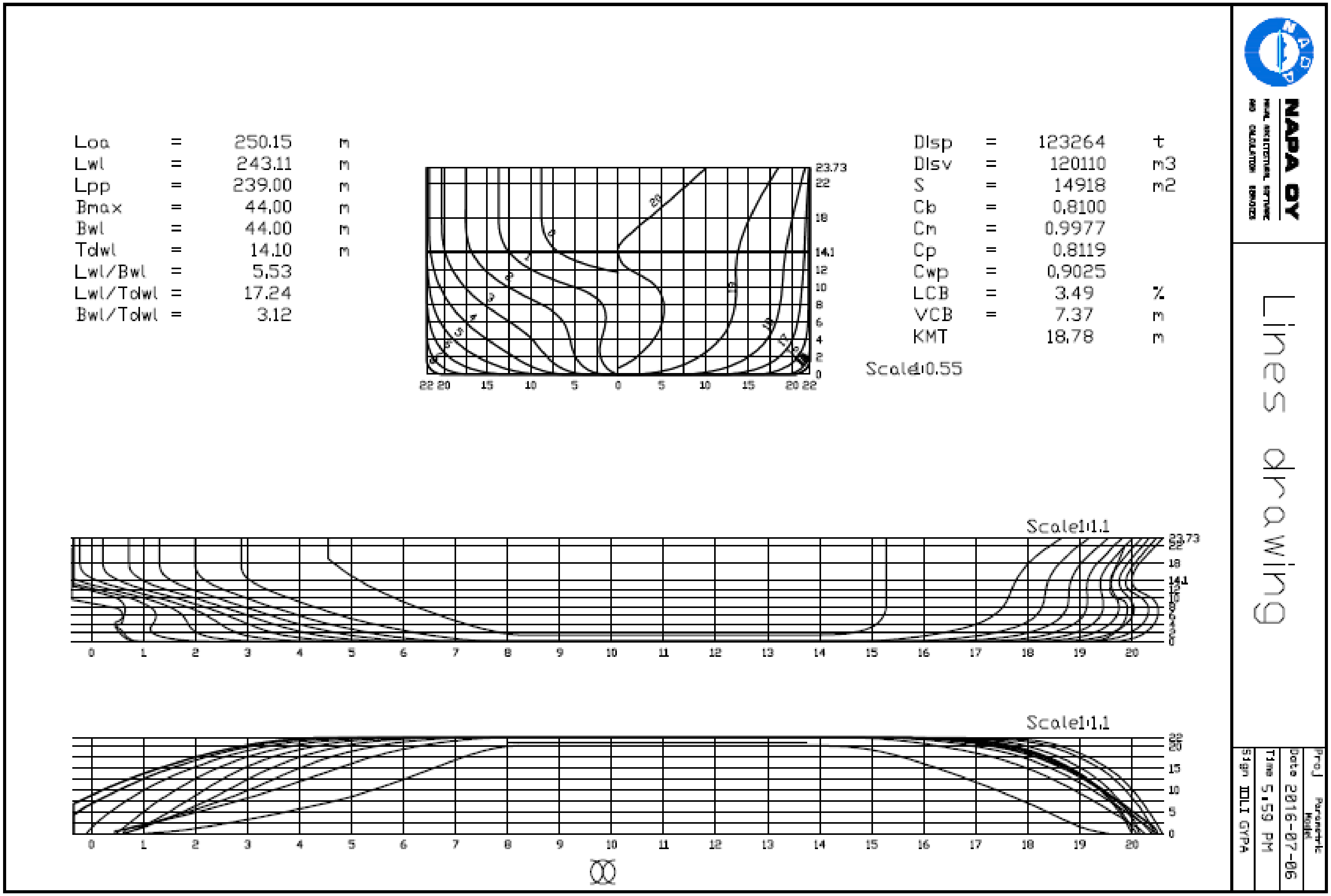
Optimal Design Characteristics		
L_{BP}	m	239
Beam	m	44
Draught	m	14.1
Depth	m	21.5
Speed	kn	14.124
C_B		0.81
Displacement	t	123264
Lightship	t	19078
Deadweight	t	104187
Cargo Capacity	m^3	129819
Water Ballast Capacity	m^3	40701.1
Propeller Diameter	m	7.293
KG Margin Intact Stability	m	3.755
KG Margin Damage Stability	m	1.105
Required Mean Oil Outflow Parameter		0.015
Real Mean Oil Outflow Parameter		0.01362
Required EEDI Phase 1		3.904
Attained EEDI		3.519
Building Cost	million Euros	40.73
Net Present Value	million Euros	14.59
NPVI		0.35822

Hydrostatic Table

T	DISP	VOLM	TPC	MCT	LCB	LCA
m	t	m^3	t/cm	tm/cm	m	m
2.0	14861	14417.6	79.58	982.71	131.91	131.74
2.5	18879	18334.3	81.06	1026.04	131.87	131.71
3.0	22965	22317.4	82.31	1062.61	131.83	131.68
3.5	27108	26357.0	83.37	1093.98	131.81	131.64
4.0	31302	30445.3	84.31	1121.55	131.78	131.56
4.5	35539	34576.5	85.13	1146.23	131.74	131.45
5.0	39814	38745.2	85.88	1168.86	131.70	131.30
5.5	44126	42948.9	86.57	1190.55	131.65	131.08
6.0	48471	47185.5	87.22	1211.93	131.59	130.80
6.5	52848	51453.4	87.85	1233.19	131.51	130.46
7.0	57257	55751.7	88.47	1255.02	131.41	130.05
7.5	61696	60080.2	89.09	1277.93	131.30	129.57
8.0	66167	64438.9	89.71	1301.59	131.16	129.01
8.5	70668	68827.8	90.33	1325.95	131.00	128.37
9.0	75201	73247.1	90.96	1351.22	130.82	127.67
9.5	79764	77696.9	91.59	1377.48	130.62	126.88
10.0	84360	82177.9	92.23	1405.08	130.39	126.02
10.5	88989	86690.6	92.88	1433.44	130.14	125.11
11.0	93649	91234.8	93.53	1462.98	129.86	124.13
11.5	98340	95807.8	94.16	1491.79	129.56	123.17
12.0	103067	100417.0	94.85	1524.43	129.25	122.26
12.5	107828	105059.0	95.54	1558.20	128.93	121.39
13.0	112621	109732.0	96.19	1590.61	128.59	120.61
13.5	117444	114435.0	96.74	1617.34	128.25	120.03
14.0	122292	119162.0	97.20	1639.27	127.91	119.61
14.1	123264	120110.0	97.28	1643.21	127.85	119.54
14.5	127164	123913.0	97.59	1658.10	127.59	119.33
15.0	132052	128679.0	97.92	1673.62	127.28	119.15
15.5	136956	133461.0	98.20	1687.28	126.99	119.07
16.0	141874	138257.0	98.46	1699.64	126.71	119.07
16.5	146804	143064.0	98.69	1710.89	126.46	119.13
17.0	151745	147882.0	98.89	1721.08	126.22	119.25

T	VCB	KMT	KML	WLA	WSA	CB	CM	CP	CW
m	m	m	m	m^2	m^2				
2.0	1.029	71.32	1581.42	7763.89	8132.55	0.6855	0.9840	0.6967	0.7377
2.5	1.289	58.30	1300.21	7908.53	8435.00	0.6974	0.9872	0.7064	0.7515
3.0	1.549	49.63	1107.44	8029.98	8723.67	0.7074	0.9893	0.7150	0.7631
3.5	1.809	43.46	966.32	8134.00	9003.18	0.7161	0.9909	0.7227	0.7730
4.0	2.069	38.85	858.43	8224.95	9276.76	0.7238	0.9920	0.7296	0.7816
4.5	2.329	35.29	773.18	8305.56	9546.18	0.7307	0.9929	0.7359	0.7893
5.0	2.589	32.47	704.24	8378.18	9811.69	0.7369	0.9936	0.7416	0.7962
5.5	2.849	30.19	647.69	8445.41	10074.60	0.7426	0.9942	0.7469	0.8026
6.0	3.109	28.33	600.69	8509.46	10336.50	0.7478	0.9947	0.7518	0.8087
6.5	3.369	26.78	561.07	8570.72	10597.80	0.7527	0.9951	0.7565	0.8145
7.0	3.630	25.48	527.50	8631.02	10859.40	0.7574	0.9954	0.7608	0.8203
7.5	3.890	24.38	498.94	8691.70	11122.50	0.7618	0.9957	0.7650	0.8260
8.0	4.151	23.45	474.30	8752.29	11387.70	0.7660	0.9960	0.7690	0.8318
8.5	4.412	22.66	452.85	8812.86	11655.80	0.7700	0.9962	0.7729	0.8375
9.0	4.673	21.98	434.12	8873.84	11927.10	0.7739	0.9964	0.7767	0.8433
9.5	4.935	21.40	417.68	8935.34	12201.90	0.7777	0.9966	0.7804	0.8492
10.0	5.198	20.90	403.27	8998.11	12481.60	0.7815	0.9968	0.7840	0.8551
10.5	5.460	20.47	390.45	9061.29	12764.50	0.7851	0.9970	0.7875	0.8611
11.0	5.724	20.11	379.09	9125.15	13051.60	0.7887	0.9971	0.7910	0.8672
11.5	5.987	19.79	368.55	9186.72	13337.90	0.7922	0.9972	0.7944	0.8731
12.0	6.251	19.53	359.75	9253.43	13623.20	0.7957	0.9973	0.7979	0.8794
12.5	6.516	19.30	351.89	9320.71	13908.20	0.7992	0.9974	0.8013	0.8858
13.0	6.782	19.11	344.34	9384.29	14187.70	0.8027	0.9975	0.8047	0.8919
13.5	7.047	18.94	336.18	9437.88	14456.10	0.8061	0.9976	0.8080	0.8970
14.0	7.313	18.80	327.68	9482.55	14715.80	0.8094	0.9977	0.8112	0.9012
14.1	7.366	18.78	325.97	9490.62	14766.90	0.8100	0.9977	0.8119	0.9020
14.5	7.579	18.68	319.21	9521.07	14969.60	0.8126	0.9978	0.8144	0.9049
15.0	7.844	18.59	310.75	9553.03	15220.00	0.8158	0.9979	0.8175	0.9080
15.5	8.109	18.51	302.56	9580.95	15468.40	0.8188	0.9979	0.8205	0.9106
16.0	8.374	18.45	294.70	9605.79	15716.00	0.8217	0.9980	0.8233	0.9130
16.5	8.639	18.40	287.18	9627.98	15964.40	0.8245	0.9981	0.8261	0.9151
17.0	8.903	18.37	279.98	9647.84	16213.30	0.8272	0.9981	0.8288	0.9170

Lines Drawing



Loading Conditions

Full Load Departure

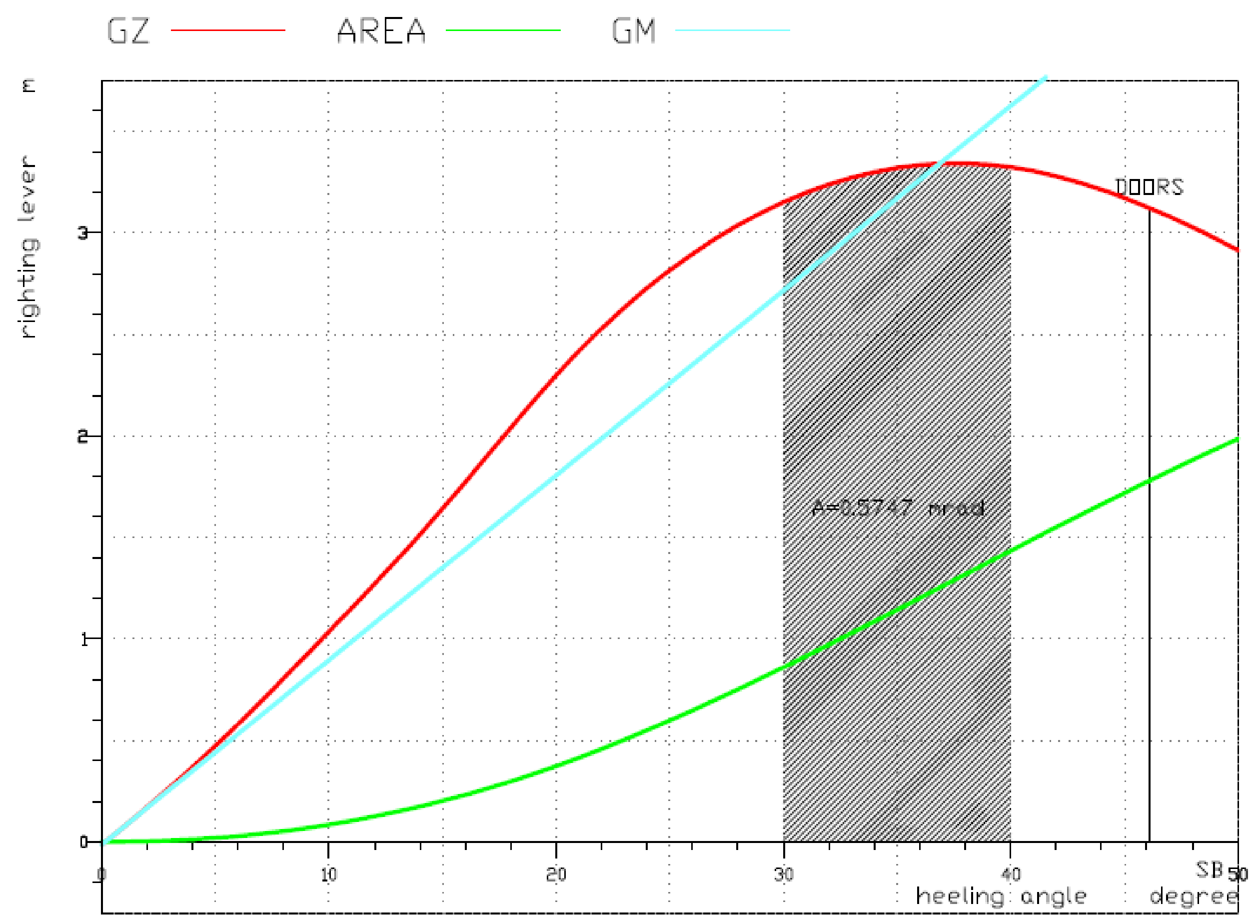
Name	Max. weight	Mass	Center of gravity cgx	cgy	cgz	Free s. moment
Liquid Cargo, RHO=0.790						
RCH6P	8108.1	7946.0	62.18	8.99	12.60	13424.14
RCH6S	8108.1	7946.0	62.18	-8.99	12.60	13424.14
RCH5P	8850.3	8673.3	91.96	9.63	12.13	14453.52
RCH5S	8850.3	8673.3	91.96	-9.63	12.13	14453.52
RCH4P	8893.8	8715.9	122.16	9.67	12.10	14521.15
RCH4S	8893.8	8715.9	122.16	-9.67	12.10	14521.15
RCH3P	8893.5	8715.6	152.39	9.67	12.10	14520.67
RCH3S	8893.5	8715.6	152.39	-9.67	12.10	14520.67
RCH2P	8679.6	8506.0	182.49	9.45	12.15	13719.66
RCH2S	8679.6	8506.0	182.49	-9.45	12.15	13719.66
RCH1P	6827.3	6690.7	211.26	7.72	12.41	8385.12
RCH1S	6827.3	6690.7	211.26	-7.72	12.41	8385.12
RSLOPP	1058.3	1037.1	44.20	8.75	13.72	1764.84
RSLOPS	1058.3	1037.1	44.20	-8.75	13.72	1764.84
Total of CAL	102622	100569.2	133.17	0.00	12.27	161578.17
Fresh Water, RHO=1.000						
RFWP	136.6	136.6	8.31	9.63	19.41	0.00
RFWS	46.2	46.2	8.59	-11.48	19.39	0.00
RDWS	90.3	90.3	8.17	-8.68	19.42	0.00
Total of FW	273.2	273.2	8.31	0.00	19.41	0.00
Heavy Fuel Oil, RHO=0.990						
RHFO1P	457.8	448.7	39.35	11.82	15.39	0.00
RHFO1S	457.8	448.7	39.35	-11.82	15.39	0.00
RHFO2P	966.9	947.6	31.27	15.81	15.94	0.00
RHFO2S	731.9	717.3	30.21	-16.29	15.66	0.00
RHFOSERV	92.3	90.4	29.42	-14.34	16.51	0.00
RHFOSET.	92.3	90.4	35.95	-14.34	16.51	0.00
RHFOSET.	92.3	90.4	32.68	-14.34	16.51	0.00
Total of HFO	2891.2	2833.4	33.69	-0.21	15.75	0.00
Diesel Oil, RHO=0.900						
RMDOS	55.9	54.8	25.73	-3.62	1.61	0.00
RMDOP	101.3	99.3	28.50	3.34	1.52	0.00
RMDOSERV	39.5	38.7	21.65	-14.76	19.29	0.00
Total of DO	196.7	192.7	26.34	-2.27	5.11	0.00

Name	Max. weight	Mass	Center of gravity cgx	cgy	cgz	Free s. moment
Lubricating Oil, RHO=0.900						
RMAINLO.	34.9	34.2	35.54	-0.88	19.47	0.00
RMAINLO.	33.7	33.0	35.54	-2.62	19.45	0.00
RMLOSUMP	23.7	23.2	23.09	0.00	1.62	0.00
RGELOST2	13.7	13.4	35.14	-4.36	19.43	0.00
RGELOST1	13.7	13.4	36.77	-4.36	19.43	0.00
RTURBLO.	6.9	6.7	33.91	-4.36	19.43	0.00
RCYLOIL1	51.1	50.1	35.54	1.30	19.46	0.00
Total of LO	177.7	174.1	33.89	-1.14	17.08	0.00
Miscellaneous, RHO=1.000						
RBHS	39.4	39.4	14.72	-1.16	1.56	0.00
ROILYBP	25.3	12.6	16.07	1.09	0.95	0.00
RFOOVERS	51.1	25.5	31.91	-2.77	0.81	0.00
RSLUDGE	97.6	48.8	31.05	-10.43	12.65	0.00
RCW	46.3	46.3	9.00	0.00	3.46	0.00
Total of MIS	259.7	172.7	20.45	-3.54	5.05	0.00
CONST						
(CONST)	0.0	65.1	89.70	0.00	20.56	0.00
Deadweight		104280.4	129.56	-0.02	12.37	161578.2
Lightweight		19077.7	110.06	0.00	11.79	
Displacement (rho=1.025)		123358.1	126.54	-0.01	12.28	161578.2

F L O A T I N G   P O S I T I O N

Draught moulded	14.108	m	KM	18.80	m
Trim	-0.987	m	KG	12.28	m
Heel, PS=+	-0.2	deg			
TA	14.602	m	GM0	6.53	m
TF	13.615	m	GMCORR	-1.31	m
Trimming moment	-161070	tonm	GM	5.22	m

RCR TEXT	REQ	ATTV	UNIT	STAT	SIDE
LR.AREA.Area under GZ curve .	0.055	0.860	mrad	OK	SB
LR.AREA.Area under GZ curve .	0.090	1.434	mrad	OK	SB
LR.AREA.Area under GZ curve .	0.030	0.575	mrad	OK	SB
LR.GZ0.2Min. GZ > 0.2	0.200	3.343	m	OK	SB
LR.MAXG.Max. GZ at an angle .	25.000	37.617	deg	OK	SB
LR.GM0..GM > 0.15 m	0.150	5.216	m	OK	SB
LR.IMOW.IMO weather criterion	1.000	5.372		OK	SB
LR.IMOW.HEEL < 16 deg	16.000	0.387	deg	OK	SB
LR.IMOW.HEEL < 80% of FRB im.	15.047	0.387	deg	OK	SB



Righting lever vs. heeling angle: Evaluation of criterion "Area 30-40°" in Full Load Departure

Full Load Arrival

Name	Max. weight	Mass	Center of gravity cgx	cgy	cgz	Free s. moment
Water Ballast, RHO=1.025						
RAPT	1253.9	1253.9	4.60	-0.06	14.27	0.00
Liquid Cargo, RHO=0.790						
RCH6P	8108.1	7946.0	62.18	8.99	12.60	0.00
RCH6S	8108.1	7946.0	62.18	-8.99	12.60	0.00
RCH5P	8850.3	8673.3	91.96	9.63	12.13	0.00
RCH5S	8850.3	8673.3	91.96	-9.63	12.13	0.00
RCH4P	8893.8	8715.9	122.16	9.67	12.10	0.00
RCH4S	8893.8	8715.9	122.16	-9.67	12.10	0.00
RCH3P	8893.5	8715.6	152.39	9.67	12.10	0.00
RCH3S	8893.5	8715.6	152.39	-9.67	12.10	0.00
RCH2P	8679.6	8506.0	182.49	9.45	12.15	0.00
RCH2S	8679.6	8506.0	182.49	-9.45	12.15	0.00
RCH1P	6827.3	6690.7	211.26	7.72	12.41	0.00
RCH1S	6827.3	6690.7	211.26	-7.72	12.41	0.00
RSLOPP	1058.3	1037.1	44.20	8.75	13.72	0.00
RSLOPS	1058.3	1037.1	44.20	-8.75	13.72	0.00
Total of CAL	102622	100569.2	133.17	0.00	12.27	0.00
Fresh Water, RHO=1.000						
RFWP	136.6	13.7	8.32	9.62	17.04	0.00
RFWS	46.2	4.6	8.61	-11.46	17.05	0.00
RDWS	90.3	9.0	8.17	-8.69	17.04	0.00
Total of FW	273.2	27.3	8.32	0.00	17.04	0.00
Heavy Fuel Oil, RHO=0.990						
RHFO1P	457.8	44.9	39.40	9.24	8.52	0.00
RHFO1S	457.8	44.9	39.40	-9.24	8.52	0.00
RHFO2P	966.9	94.8	33.45	14.65	9.68	0.00
RHFO2S	731.9	71.7	33.85	-14.55	9.33	0.00
RHFOSERV	92.3	9.0	29.42	-14.34	11.80	0.00
RHFOSET.	92.3	9.0	35.95	-14.34	11.80	0.00
RHFOSET.	92.3	9.0	32.68	-14.34	11.80	0.00
Total of HFO	2891.2	283.3	35.36	-0.16	9.43	0.00
Diesel Oil, RHO=0.900						
RMDOS	55.9	5.5	26.66	-3.03	0.42	0.00
RMDOP	101.3	9.9	30.16	2.49	0.29	0.00
RMDOSERV	39.5	3.9	21.65	-14.76	17.03	0.00
Total of DO	196.7	19.3	27.46	-2.54	3.69	0.00

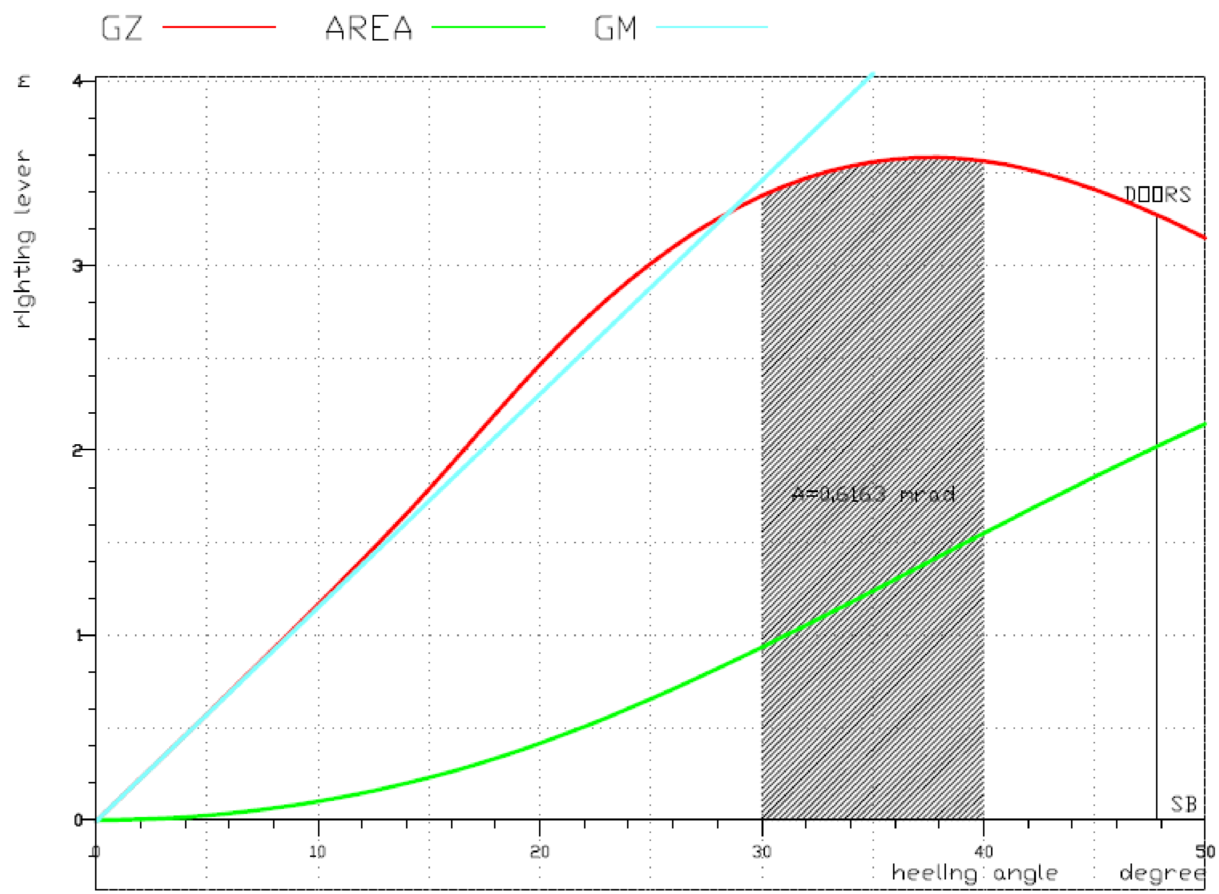
Name	Max. weight	Mass	Center of gravity cgx	cgy	cgz	Free s. moment
Lubricating Oil, RHO=0.900						
RMAINLO.	34.9	27.3	35.54	-0.88	18.93	0.00
RMAINLO.	33.7	26.4	35.54	-2.62	18.92	0.00
RMLOSUMP	23.7	18.5	23.14	0.00	1.50	0.00
RGELOST2	13.7	10.8	35.14	-4.36	18.90	0.00
RGELOST1	13.7	10.8	36.77	-4.36	18.90	0.00
RTURBLO.	6.9	5.4	33.91	-4.36	18.90	0.00
RCYLOIL1	51.1	40.1	35.54	1.30	18.92	0.00
Total of LO	177.7	139.3	33.89	-1.14	16.60	0.00
Miscellaneous, RHO=1.000						
RBHS	39.4	19.7	14.76	-0.98	0.96	0.00
ROILYBP	25.3	12.6	16.07	1.09	0.95	0.00
RFOOVERS	51.1	25.5	31.91	-2.77	0.81	0.00
RSLUDGE	97.6	48.8	31.05	-10.43	12.65	0.00
RCW	46.3	46.3	9.00	0.00	3.46	0.00
Total of MIS	259.7	153.0	21.19	-3.83	5.42	0.00
CONST						
(CONST)	0.0	52.8	95.64	0.00	20.26	0.00
Deadweight		102498.2	130.95	-0.01	12.28	0.0
Lightweight		19077.7	110.06	0.00	11.79	
Displacement (rho=1.025)		121575.9	127.67	-0.01	12.21	0.0

F L O A T I N G   P O S I T I O N

Draught moulded	13.926	m	KM	18.83	m
Trim	-0.222	m	KG	12.21	m
Heel, PS=+	-0.1	deg			
TA	14.037	m	GM0	6.62	m
TF	13.815	m	GMCORR	0.00	m
Trimming moment	-35896	tonm	GM	6.62	m

LD?>

RCR TEXT	REQ	ATTV	UNIT	STAT
LR.AREA.Area under GZ curve .	0.055	0.935	mrad	OK
LR.AREA.Area under GZ curve .	0.090	1.551	mrad	OK
LR.AREA.Area under GZ curve .	0.030	0.616	mrad	OK
LR.GZ0.2Min. GZ > 0.2	0.200	3.586	m	OK
LR.MAXG.Max. GZ at an angle .	25.000	37.664	deg	OK
LR.GM0..GM > 0.15 m	0.150	6.623	m	OK
LR.IMOW.IMO weather criterion	1.000	4.802		OK
LR.IMOW.HEEL < 16 deg	16.000	0.249	deg	OK
LR.IMOW.HEEL < 80% of FRB im.	15.733	0.249	deg	OK



Righting lever vs. heeling angle: Evaluation of criterion "Area 30-40°" in Full Load Arrival

Normal Ballast Departure

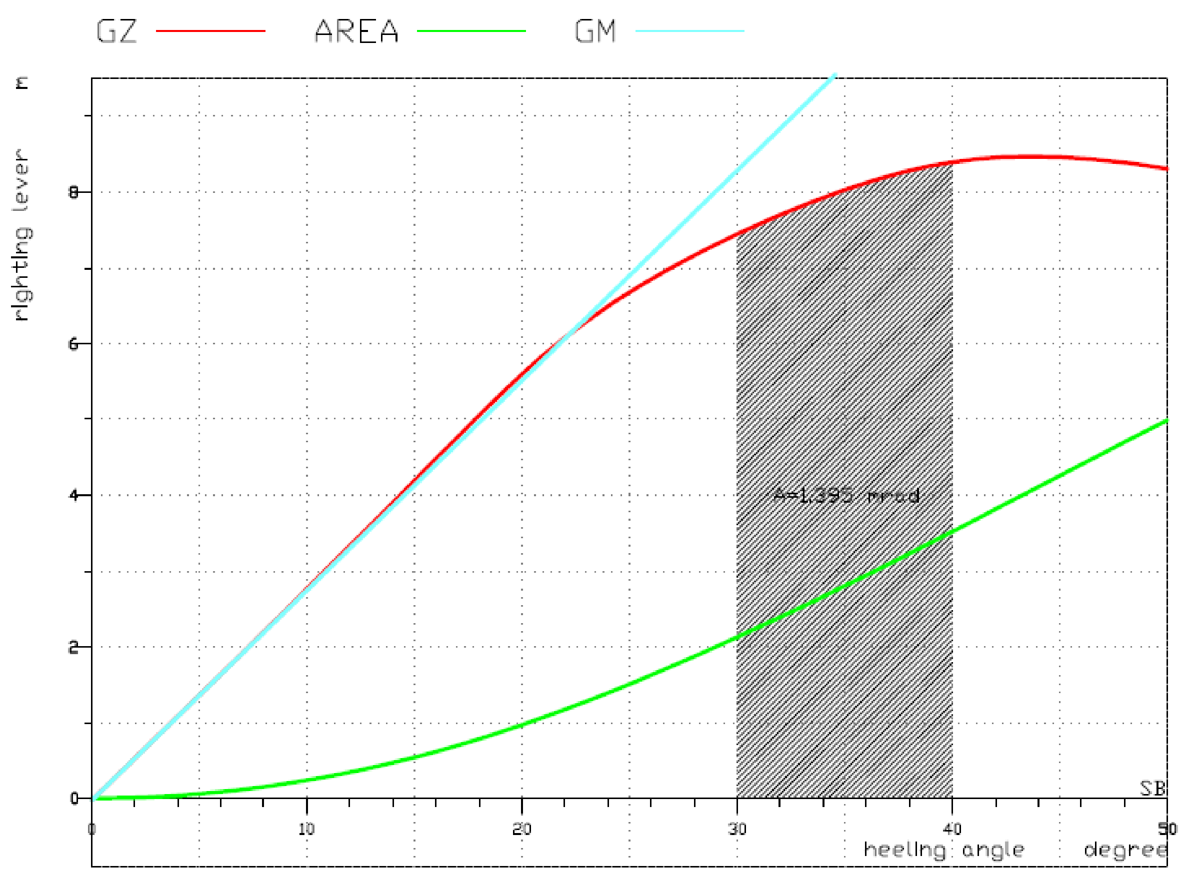
Name	Max. weight	Mass	Center of gravity cgx	cgy	cgz	Free s. moment
Water Ballast, RHO=1.025						
RWB6P	3852.7	2230.7	59.83	11.67	3.23	1082.18
RWB6S	3852.7	2230.7	59.83	-11.67	3.23	1082.18
RWB5P	3140.2	3140.2	91.96	15.69	6.41	0.00
RWB5S	3140.2	3140.2	91.96	-15.69	6.41	0.00
RWB4P	3140.9	3140.9	122.16	15.73	6.31	0.00
RWB4S	3140.9	3140.9	122.16	-15.73	6.31	0.00
RWB3P	3140.8	3140.8	152.39	15.73	6.31	0.00
RWB3S	3140.8	3140.8	152.39	-15.73	6.31	0.00
RWB2P	3276.0	3276.0	182.66	15.76	6.75	0.00
RWB2S	3276.0	3276.0	182.66	-15.76	6.75	0.00
RWB1P	3352.9	3352.9	212.93	13.79	9.00	0.00
RWB1S	3352.9	3352.9	212.93	-13.79	9.00	0.00
RFPTK	2077.1	2077.1	233.57	0.00	6.39	0.00
Total of WB	41884.3	38640.3	146.97	0.00	6.52	2164.37
Fresh Water, RHO=1.000						
RFWP	136.6	136.6	8.31	9.63	19.41	0.00
RFWS	46.2	46.2	8.59	-11.48	19.39	0.00
RDWS	90.3	90.3	8.17	-8.68	19.42	0.00
Total of FW	273.2	273.2	8.31	0.00	19.41	0.00
Heavy Fuel Oil, RHO=0.990						
RHFO1P	457.8	448.7	39.35	11.82	15.39	0.00
RHFO1S	457.8	448.7	39.35	-11.82	15.39	0.00
RHFO2P	966.9	947.6	31.27	15.81	15.94	0.00
RHFO2S	731.9	717.3	30.21	-16.29	15.66	0.00
RHFOSERV	92.3	90.4	29.42	-14.34	16.51	0.00
RHFOSET.	92.3	90.4	35.95	-14.34	16.51	0.00
RHFOSET.	92.3	90.4	32.68	-14.34	16.51	0.00
Total of HFO	2891.2	2833.4	33.69	-0.21	15.75	0.00
Diesel Oil, RHO=0.900						
RMDOS	55.9	54.8	25.73	-3.62	1.61	0.00
RMDOP	101.3	99.3	28.50	3.34	1.52	0.00
RMDOSERV	39.5	38.7	21.65	-14.76	19.29	0.00
Total of DO	196.7	192.7	26.34	-2.27	5.11	0.00

Name	Max. weight	Mass	Center of gravity cgx	cgy	cgz	Free s. moment
Lubricating Oil, RHO=0.900						
RMAINLO.	34.9	34.2	35.54	-0.88	19.47	0.00
RMAINLO.	33.7	33.0	35.54	-2.62	19.45	0.00
RMLOSUMP	23.7	23.2	23.09	0.00	1.62	0.00
RGELOST2	13.7	13.4	35.14	-4.36	19.43	0.00
RGELOST1	13.7	13.4	36.77	-4.36	19.43	0.00
RTURBLO.	6.9	6.7	33.91	-4.36	19.43	0.00
RCYLOIL1	51.1	50.1	35.54	1.30	19.46	0.00
Total of LO	177.7	174.1	33.89	-1.14	17.08	0.00
Miscellaneous, RHO=1.000						
RBHS	39.4	39.4	14.72	-1.16	1.56	0.00
ROILYBP	25.3	12.6	16.07	1.09	0.95	0.00
RFOOVERS	51.1	25.5	31.91	-2.77	0.81	0.00
RSLUDGE	97.6	48.8	31.05	-10.43	12.65	0.00
RCW	46.3	46.3	9.00	0.00	3.46	0.00
Total of MIS	259.7	172.7	20.45	-3.54	5.05	0.00
CONST						
(CONST)	0.0	65.1	89.70	0.00	20.56	0.00
Deadweight		42351.4	136.88	-0.04	7.27	2164.4
Lightweight		19077.7	110.06	0.00	11.79	
Displacement (rho=1.025)		61429.1	128.55	-0.03	8.67	2164.4

F L O A T I N G   P O S I T I O N

Draught moulded	7.524	m	KM	24.59	m
Trim	-1.327	m	KG	8.67	m
Heel, PS=+	-0.1	deg			
TA	8.187	m	GM0	15.91	m
TF	6.861	m	GMCORR	-0.04	m
Trimming moment	-170513	tonm	GM	15.88	m

RCR	TEXT	REQ	ATTV	UNIT	STAT
LR.AREA.	Area under GZ curve .	0.055	2.125	mrad	OK
LR.AREA.	Area under GZ curve .	0.090	3.520	mrad	OK
LR.AREA.	Area under GZ curve .	0.030	1.395	mrad	OK
LR.GZ0.2	Min. GZ > 0.2	0.200	8.471	m	OK
LR.MAXG.	Max. GZ at an angle .	25.000	43.716	deg	OK
LR.GM0..	GM > 0.15 m	0.150	15.878	m	OK
LR.IMOW.	IMO weather criterion	1.000	3.661		OK
LR.IMOW.	HEEL < 16 deg	16.000	0.357	deg	OK
LR.IMOW.	HEEL < 80% of FRB im.	29.191	0.357	deg	OK



Righting lever vs. heeling angle: Evaluation of criterion "Area 30-40°" in Water Ballast Departure

Normal Ballast Arrival

Name	Max. weight	Mass	Center of gravity cgx	cgy	cgz	Free s. moment
Water Ballast, RHO=1.025						
RWB6P	3852.7	3852.7	58.21	15.10	8.13	0.00
RWB6S	3852.7	3852.7	58.21	-15.10	8.13	0.00
RWB5P	3140.2	3140.2	91.96	15.69	6.41	0.00
RWB5S	3140.2	3140.2	91.96	-15.69	6.41	0.00
RWB4P	3140.9	3140.9	122.16	15.73	6.31	0.00
RWB4S	3140.9	3140.9	122.16	-15.73	6.31	0.00
RWB3P	3140.8	3140.8	152.39	15.73	6.31	0.00
RWB3S	3140.8	3140.8	152.39	-15.73	6.31	0.00
RWB2P	3276.0	3276.0	182.66	15.76	6.75	0.00
RWB2S	3276.0	3276.0	182.66	-15.76	6.75	0.00
RWB1P	3352.9	3352.9	212.93	13.79	9.00	0.00
RWB1S	3352.9	3352.9	212.93	-13.79	9.00	0.00
RFPTK	2077.1	2077.1	233.57	0.00	6.39	0.00
Total of WB	41884.3	41884.3	139.92	0.00	7.16	0.00
Fresh Water, RHO=1.000						
RFWP	136.6	13.7	8.32	9.62	17.04	0.00
RFWS	46.2	4.6	8.61	-11.46	17.05	0.00
RDWS	90.3	9.0	8.17	-8.69	17.04	0.00
Total of FW	273.2	27.3	8.32	0.00	17.04	0.00

Name	Max. weight	Mass	Center of gravity cgx	cgy	cgz	Free s. moment
Heavy Fuel Oil, RHO=0.990						
RHFO1P	457.8	44.9	39.40	9.24	8.52	0.00
RHFO1S	457.8	44.9	39.40	-9.24	8.52	0.00
RHFO2P	966.9	94.8	33.45	14.65	9.68	0.00
RHFO2S	731.9	71.7	33.85	-14.55	9.33	0.00
RHFOSERV	92.3	9.0	29.42	-14.34	11.80	0.00
RHFOSET.	92.3	9.0	35.95	-14.34	11.80	0.00
RHFOSET.	92.3	9.0	32.68	-14.34	11.80	0.00
Total of HFO	2891.2	283.3	35.36	-0.16	9.43	0.00
Diesel Oil, RHO=0.900						
RMDOS	55.9	5.5	26.66	-3.03	0.42	0.00
RMDOP	101.3	9.9	30.16	2.49	0.29	0.00
RMDOSERV	39.5	3.9	21.65	-14.76	17.03	0.00
Total of DO	196.7	19.3	27.46	-2.54	3.69	0.00

Lubricating Oil, RHO=0.900

RMAINLO.	34.9	27.3	35.54	-0.88	18.93	0.00
RMAINLO.	33.7	26.4	35.54	-2.62	18.92	0.00
RMLOSUMP	23.7	18.5	23.14	0.00	1.50	0.00
RGELOST2	13.7	10.8	35.14	-4.36	18.90	0.00
RGELOST1	13.7	10.8	36.77	-4.36	18.90	0.00
RTURBLO.	6.9	5.4	33.91	-4.36	18.90	0.00
RCYLOIL1	51.1	40.1	35.54	1.30	18.92	0.00
Total of LO	177.7	139.3	33.89	-1.14	16.60	0.00

Miscellaneous, RHO=1.000

RBHS	39.4	19.7	14.76	-0.98	0.96	0.00
ROILYBP	25.3	12.6	16.07	1.09	0.95	0.00
RFOOVERS	51.1	25.5	31.91	-2.77	0.81	0.00
RSLUDGE	97.6	48.8	31.05	-10.43	12.65	0.00
RCW	46.3	46.3	9.00	0.00	3.46	0.00
Total of MIS	259.7	153.0	21.19	-3.83	5.42	0.00

CONST

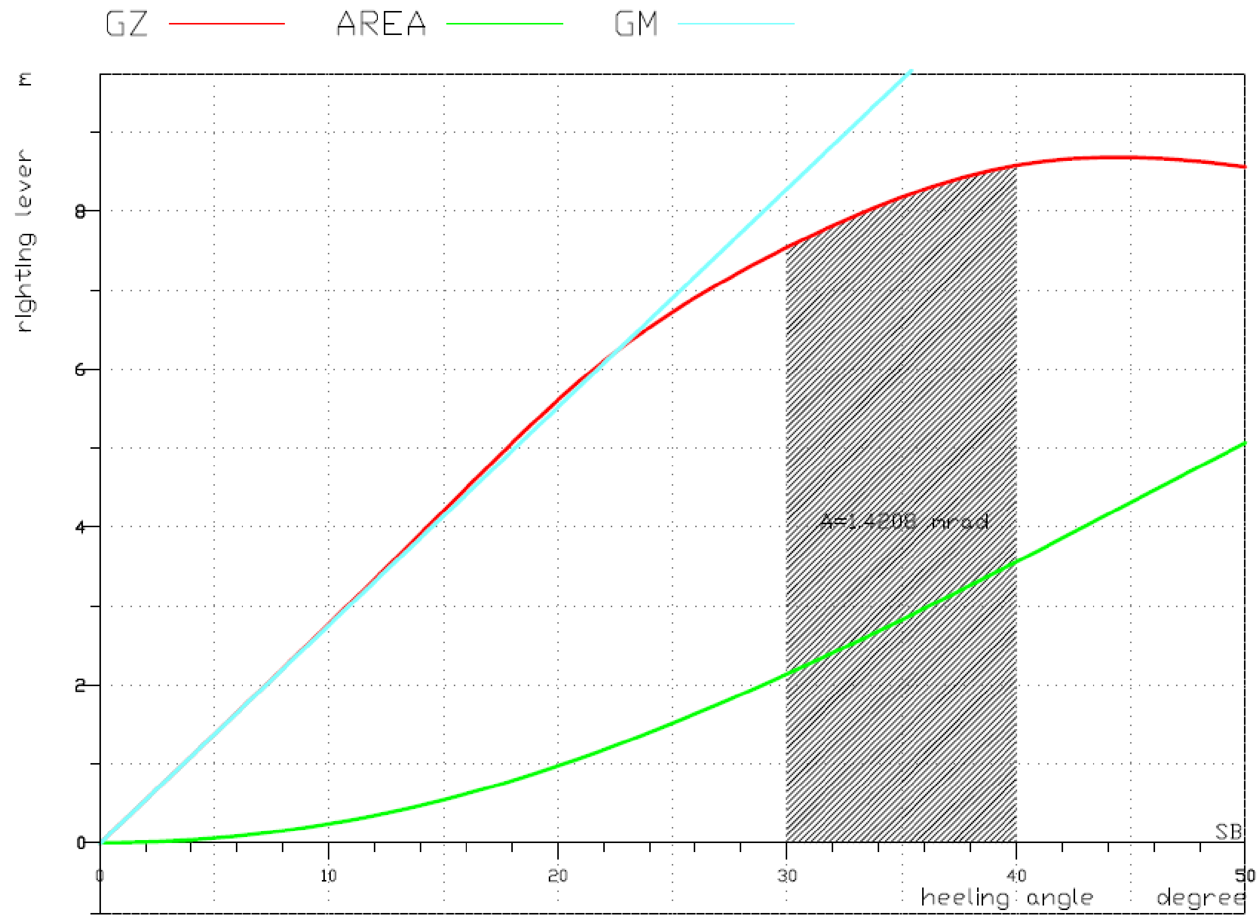
(CONST)	0.0	57.2	98.17	0.00	20.20	0.00

Deadweight	42563.7	138.26	-0.02	7.23	0.0
Lightweight	19077.7	110.06	0.00	11.79	
Displacement (rho=1.025)	61641.4	129.53	-0.01	8.64	0.0

F L O A T I N G   P O S I T I O N

Draught moulded	7.529	m	KM	24.49	m
Trim	-0.855	m	KG	8.64	m
Heel, PS=+	0.0	deg			
TA	7.956	m	GM0	15.85	m
TF	7.101	m	GMCORR	0.00	m
Trimming moment	-109335	tonm	GM	15.85	m

RCR	TEXT	REQ	ATTV	UNIT	STAT
LR.AREA.	Area under GZ curve .	0.055	2.138	mrad	OK
LR.AREA.	Area under GZ curve .	0.090	3.559	mrad	OK
LR.AREA.	Area under GZ curve .	0.030	1.421	mrad	OK
LR.GZ0.2	Min. GZ > 0.2	0.200	8.684	m	OK
LR.MAXG.	Max. GZ at an angle .	25.000	44.414	deg	OK
LR.GM0..	GM > 0.15 m	0.150	15.849	m	OK
LR.IMOW.	IMO weather criterion	1.000	3.745		OK
LR.IMOW.	HEEL < 16 deg	16.000	0.297	deg	OK
LR.IMOW.	HEEL < 80% of FRB im.	28.851	0.297	deg	OK



Righting lever vs. heeling angle: Evaluation of criterion "Area 30-40°" in Water Ballast Arrival