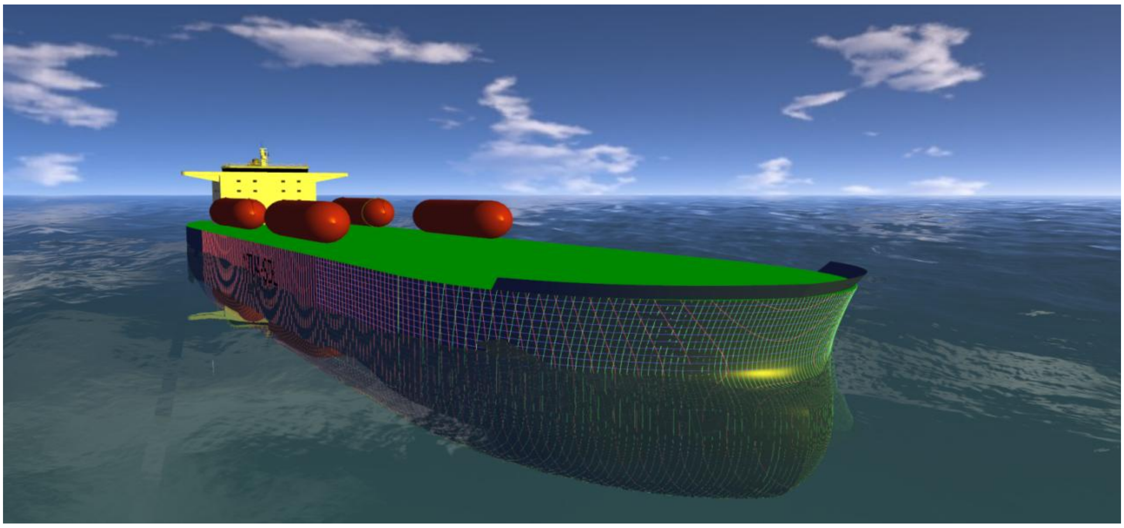
NATIONAL TECHNICAL UNIVERSITY OF ATHENS
SCHOOL OF NAVAL ARCHITECTURE AND MARINE ENGINEERING
SHIP DESIGN LABORATORY

“A Holistic Methodology For The Optimization of Tanker Design and Operation and Its Applications”

DIPLOMA THESIS

LAMPROS G. NIKOLOPOULOS



<u>Supervisor:</u>
Professor Apostolos D. Papanikolaou

<u>Supervising Committee:</u>

Professor	Apostolos D. Papanikolaou
Professor	Kostas J. Spyrou
Associate Professor	George Zaraphonitis

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Dedicated to the memory of my Grandfather who taught me the sea and ships inspiring me to become a Naval Architect and to my Father who taught me everything else.

FOREWORD AND ACKNOWLEDGEMENTS

The present document is the obligatory Diploma Thesis for acquiring the Diploma of Naval Architecture and Marine Engineering from the National Technical University of Athens (NTUA). The title of the Thesis is "A Holistic Methodology for the Optimization of Tanker Design and Operation and its Applications" and was done within the Ship Design Laboratory of the School of Naval Architecture and Marine Engineering at NTUA, having as supervisor the director of the laboratory Prof. Dr. Ing. Habil. Apostolos D. Papanikolaou.As this Thesis is a product of international collaboration and since the unofficial language of shipping is English it was chosen to write it in English. However there is an abstract in Greek were one can have a brief description of the work done.

This work couldn't have been made without the contribution and support of a number of people that worth mentioning.

First, my Professor, advisor and guide Professor Apostolos Papanikolaou who apart from always providing me with the most valuable guidelines throughout this quest in tanker design, actively supported my work and ensured that it could be done under proper infrastructure and state of the art capabilities. His lesson, discussions, mentality and academic excellence always inspire me for the future and for achieving professional, academic excellence and ethos (ήθος) in Naval Architecture. I will always be deeply grateful to him.
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Lampros G. Nikolopoulos
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ABSTRACT

Over the last decade the regulatory framework in shipping has put big pressure on ship designers, owners and operators for an improvement of the safety onboard and a drastic reduction of the environmental footprint of shipping. This new status of the regulatory constraints in combination with harsh economic conditions, charter rates volatility, high uncertainty and rising fuel and insurance costs challenge the future ship designs to change. This Thesis presents a holistic methodology that was developed for the systematic variation and subsequent optimization of innovative tanker designs using principles of simulation driven design in the Friendship Framework.

In the primary case study, the design concept is by definition a safer tanker in the AFRAMAX class, having two longitudinal bulkheads and twin screw/engine/skeg arrangement. A systematic and multi-staged optimization took place producing up to 6000 variants (with a total of 20000 working variants) having as an objective the reduction of the Required Freight Rate (indicative of transportation costs and including building,, operational and crewing costs), the Accidental Oil Outflow Index (as defined by MARPOL Reg.23) and the Energy Efficiency Design Index (as adopted by IMO MEPC 62). The results show a significant improvement in both three objectives, with the dominant variants being more competitive and efficient than existing conventional designs. A post analysis is made examining the use of LNG as a fuel and new and innovative propulsion systems.

In addition to the AFRAMAX case study, an applicability study has been made for the VLCC segment were the current results show a great potential for additional optimization. The sensitivities of both cases have been recorded and assessed.

Keywords: Multi Objective Ship Design Optimization, Tanker Design, Computer Aided Ship Design, Simulation Driven Design, Risk Based Design, Tanker Operations, Accidental Oil Outflow, Design for competitiveness.

ABSTRACT IN GREEK

Το παρόν έγγραφο αποτελεί την Διπλωματική Εργασία του γράφοντος, Λάμπρου Γ. Νικολόπουλου, στα πλαίσια ολοκλήρωσης των προπτυχιακών σπουδών του στο Εθνικό Μετσόβιο Πολυτεχνείο για την απόκτηση του Διπλώματος Ναυπηγού Μηχανολόγου Μηχανικού. Ο τίτλος της εργασίας στα ελληνικά μπορεί να μεταφραστεί ως «Ανάπτυξη μιας Ολιστικής Μεθόδου Βελτιστοποίησης Σχεδίασης και Λειτουργίας Δεξαμενοπλοίων και Εφαρμογές της», έχοντας ως επιβλέποντα τον Καθηγητή Απόστολο Παπανικολάου, Διευθυντή του Εργαστηρίου Μελέτης Πλοίου, της Σχολής Ναυπηγών Μηχανολόγων Μηχανικών του ΕΜΠ.
Το αντικείμενο της Διπλωματικής είναι η ανάπτυξη μιας ολιστικής μεθόδου, με αρχές προσομοίωσης, πάνω στην οποία γίνεται συστηματική διερεύνηση και κατόπιν βελτιστοποίηση της σχεδίασης και λειτουργίας δεξαμενοπλοίων. Τα κριτήρια της βελτιστοποίησης μπορούν να συνοψισθούν στην ελαχιστοποίηση του ρίσκου και την μεγιστοποίηση της αποδοτικότητας και οικονομικής επίδοσης του πλοίου, έχοντας ως παραμέτρους τόσο τις κύριες διαστάσεις όσο και παραμέτρους των δεξαμενών φορτίου αλλά και τοπικές γεωμετρικές παραμέτρους. Η μεθοδολογία αναπτύχθηκε στο πρόγραμμα παραμετρικής σχεδίασης και προσομοίωσης πλοίων Friendship Framework στα πλαίσια της συνεργασίας της εταιρίας με το Εργαστήριο Μελέτης Πλοίου και τον Γερμανικό Νηογνώμονα για το ερευνητικό πρόγραμμα BEST++ (Better Economics with a Safer Tanker).
Οι εφαρμογές της Μεθοδολογίας εντάσσονται στην προκαταρκτική μελέτη εφικτότητας και έως ένα βαθμό στον πιο λεπτομερή σχεδιασμό και είναι για δύο τύπου δεξαμενοπλοίων. Ένα διπλέλικο δεξαμενόπλοιο τύπου AFRAMAX, με διάταξη δεξαμενών 5X3 και καινοτόμο γάστρα καθώς και ένα συμβατικό μονέλικο δεξαμενόπλοιο πολύ μεγάλου μεγέθους (VLCC).

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INTRODUCTION

«Μέγα το της Θαλάσσης Κράτος»

Περικλής

«Great is the Nation of the Sea»

Pericles

INTRODUCTION

Shipping has been one of the earliest activities of the human race, as a result of the continuous struggle to survive, thrive, expand and explore. Throughout, the known history kingdoms, empires and economies have heavily depended on the sea and maritime transportation not only in the mean of conflict but more important in the means of communication, cooperation in the forms of trade and commerce. In the meantime, during the evolution of the scientific thinking and technology, shipping has been affected with several technological breakthroughs such as the introduction of sail, steam, iron and steel, welding procedures, diesel engines and many more.
While the ship technology advanced so did the operations and the support from a vast regulatory framework which initially depended solely on experience and mutual agreements but then was rationalized with the introduction of engineering and Naval Architectural principles.
Today, shipping is a very complex and volatile organism which is triggered and influenced by several exogenous organisms such as supply and demand functions, global conflicts and economy as well as ever increasing and sensitive oil prices. The ship designer, shipwright, owner, operator and charterer of today are challenged more than ever to survive not only due to the globalization and the increased level of competence but also due to the ever increasing order of volatility and uncertainty in global economic markets.
For this particular reason, when looking from a technical point of view, the Naval Architect of today is responsible not only for designing , delivering and operating a superior product but for making that product optimum in terms of efficiency, safety and more recently in terms of environmental friendliness. This term characterizes the 21st century, as it is a result of an excessive pressure from the society towards the policy makers to make steps towards a more sustainable and green profile in all levels of human activities including shipping.
When responsible for such a complex and difficult procedure the Naval Architect must be analytical and follow the principles of holism which is reflected in Holistic Ship design and Operation. Holistic Ship Design uses principles of Multi-Objective Optimization in order to solve conflicting arguments towards the best solution which satisfies the user requirements while it complies with the constraints set by society in form of Rules and Regulations.

This present Thesis aims at giving a solution and a tool to the Naval Architect of today, and in particular those interested in Tanker Design. Tankers are ideal for optimization since as ship systems usually they include a lot of contradicting requirements while the consequences of a potential accident can be catastrophic. In addition to the methodology two case studies are made in order to provide with solutions for two ship types: an AFRAMAX tanker and a VLCC. The first is a very detailed, multi staged and exhaustive application, while the second is a global and simple approach that aims in proving the applicability of the method and provide some food for thought for new research areas, ideas and projects.

In Chapter One, the background of the tanker industry is described, the evolution of a giant, and what the modern market and societal requirements are for oil and product shipping.

In Chapter Two, the reader can find a detailed analysis of some safety aspects of tankers as described and undertaken in the Formal Safety Assessment (FSA) for tankers. Afterwards some innovative and very characteristic tanker design concepts of the last decades are presented. In addition to that there is information about optimization principles in Ship and thus Tanker design and in the last part of the chapter there are some literature examples of tanker optimization, all based on the experience of the Ship Design Laboratory at NTUA on that area.

In Chapter Three there is a brief description of the developed methodology as well as a sensitivity analysis of the latter based on the optimization results. The sensitivity analysis aims at proving the robustness of the model and the methodology as well as some design directives for the preliminary and dimensioning stage.

In Chapter four the Case Study on AFRAMAX tankers is presented which is the core of the Thesis. The AFRAMAX case study was inspired as an applicable, viable and economically sustainable solution that meets the challenges of the future shipping industry. Volatile market conditions, cyclic charter periods and increased complexities of enlisted companies create a quest for increased efficiency and above all reliability. The changing profile of shipping into a greener and more reliable, and socially responsible transport sector is pushing for a leap of innovation and technology. However, the traditional shipping company is a very conservative organization, often impenetrable to innovation. This conservative approach though is to be changed as the exogenous factors that shape the industry's attitude and approach evolved over the years to include very strict safety and environmental demands. Following the global concern on the greenhouse gases and climate change in conjunction with the emission and air footprint of mankind's activities, a framework was set to regulate the footprint of several industries including shipping. The driving force behind the regulatory development in maritime emissions has been the International Maritime Organization (IMO) with the creation and continuous development of the MARPOL Annex VI. The threat of invasive species that can contaminate different marine ecosystems and is transported by deep sea vessels in their ballast tanks, triggered the creation of the Ballast Water Management convention. All of these developments create a new (almost chaotic) patch that both the existing and new built ships have to respond to. It is generally admitted that these requirements change entirely the way we think about shipping in general and the challenge is big and often a handicap and burden for the operability and profitability of the owning and managing company. This creates a new need for innovative, safer and more efficient designs that will not mitigate the economic performance, sustainability and competitiveness of each concept. Initially though these designs are not easily acceptable by shipyards and need additional capital expenditure. They key in making them a sustainable option is reduce the Operating Expenditures (OPEX) and maintenance costs, as well increase the availability and reliability of the product in order to achieve a balance. This balance will subsequently trigger new orders and investments towards this direction and in a long run a two Tier market, of upscale innovative ships and more conventional ones, with the last struggling to face the competition both in commercial and operating terms. It is the technology leap that will illustrate the potential of the new designs and establish them as actual and realistic solutions. One can see at this Chapter the evolution of the design and three generations with the last being the most innovative and mature.

In Chapter Five the Thesis concludes with a brief summary and outline of the work undertaken, providing some design directives for future, tender concepts as well as an outline of the VLCC optimization (global and less detailed one) that can also be found in Appendix II. The contribution of the Thesis in Tanker design is outlined and some perspectives for future work are underlined.

CHAPTER ONE:

BACKGROUND OF THE TANKER SHIPPING INDUSTRY

CHAPTER ONE: BACKGROUND OF THE TANKER SHIPPING INDUSTRY

1. HISTORY OF CARRIAGE OF OIL BY SEA: THE EVOLUTION OF A GIANT

The Race for Tonnage and the Tanker Market Characteristics

The carriage large quantities of oil by sea can be dated back to the late 19th and early 20th century, when the world was in the middle of an industrial revolution and hungry for raw materials and energy sources. At its Genesis and prior to the First World War, the tanker industry was dominated by oil companies, who built tankers to move their own oil. The first successful seagoing, purpose built tanker was the Glucklauf, built in Newcastle and was able to carry up to 3000 tons of kerosene in 16 tanks arranged in two columns. Her propulsion plant was located at the aft and was based on a steam cycle with coal boilers. The quality of the ships built back then was surprising and can be attributed to the investment of the oil companies that expected an economic and efficient transportation of their product that was most of all reliable and safe.

The period between the two wars saw the birth and the emergence of the independent tanker owner, meaning the individual company that has no oil of its own to transport and provides the transportation itself as a service, relying on the chartering of the vessel to the cargo owner, namely the oil company. The emergence of this market structure was largely attributed to the Great War. The naval battlefields and German U-boats prevented the supply of fuel oil to continental Europe, which lead to an ambitious shipbuilding program lead by the US totaling at approx. 600 ships or 3.3 million tons of tonnage. The demand that triggered this fleet expansion continued to the first couple of year following the end of the war until a massive surplus developed. In 1923 almost 800 000 tons of tankers were laid up. This surplus tonnage ended up to the hands of independent tanker owners thanks to a relaxed structure for the acquisition as well as the financing (all through the US Shipping Board). This trend was also triggered by the economies of scale experienced by independent tanker owners and the fact that the oil majors wanted to reduce their capital expenditure in shipping in order to finance new exploration and production projects. By the outbreak of WWII the independent ship owners controlled 39% of the tanker fleet. Concurrently the use of Flags of Convenience started taking place as a means to bypass the Shipping Neutrality Act in the first days of the Second World War, when the US needed to supply the allies and the war in Europe.

After the Second World War the tanker industry was deeply affected. Massive changes took place, starting by the shift of power to independent tanker owners due to the decimation of the Oil companies' fleets. Immediately after the war, a big over-supply was created just as a few years earlier. This was a perfect window of opportunity for the the Golden Greeks of this era such as Aristotle Onassis, Stavros Niarchos and Stavros Livanos who were able to acquire a large number of ships, They did not wait long , as the Marshall Plan act aimed into rebuilding Europe, which triggered a need for oil mainly originated from Texas and Venezuela. Tanker rates tripled almost overnight and these independent tanker owner were those that dominated this continuous competition for serving the need for oil transportation leading to a shipping boom. At the same time the vessel size changed dramatically. The workhorse tankers of WWII were the T-2 and T-3 tankers that had a deadweight of 16000 and 18000 tons. In 1948, Daniel Ludwig ordered a series of ten 30000 ton Bulkpetrol class, while Onassis followed with a 45000 tonner in the same year. This was only the beginning of a tanker arms race, between Ludwig, Onassis and Niarchos. In 1958 the 100 000 ton barrier was breached and in 1966 Idemitzu Maru was delivered; she had a deadweight of 206000. In ten years the size of tankers was increased by a number of ten. The independent tanker owners brought more than a willingness to take risks, both market and technical, having an ability to think outside the box. They were smarter than the oil companies, quicker and nimbler. They didn't have to follow the same rules and guidelines which made them very successful.

By the early 70s the tanker industry had the basic structure it has today. It is extremely cyclic. The basic pattern is long periods of low rates interspersed with short lived peaks during which spot tanker rates can go at historic highs.

The Big Accidents: Safety becomes more critical

The supply and demand balance and scale economies were not the only the exogenous factors influencing ship design and shipping then. Some series of catastrophic tanker accidents brought to light a new threat for the environment: the oil spill. The first incident that caused global attention was at the morning of March 18th, 1967. It was the grounding of the lengthened tanker TORREY CANYON. The ship was fully loaded with 120.000 tons of oil bound for Milford Haven in Wales, and the captain needed to make it to the tide at Milford Haven due to commercial implications. To save time, he decided to through the gap between the Scilly islands and Seven Stones Reef. By the time the captain realized he was too close to the reed it was too late given the inferior maneuverability characteristics of the vessel. The ship and cargo were lost and the resulted oil spill was by then the biggest one occurred. The most important and influential reaction to the Torrey Canyon accident was the MARPOL/73 convention, that limited tank size. It was the first regulation specifically for tankers that handled the issues of environmental protection against oil spills.

Picture [1]: The first major oil spill: The Torrey Canyon split in two off the coast of Wales

In the same era a critical problem of the jumboized vessels emerged. The larger tank sizes in combination with the need for cargo tank washing lead to massive explosions during these operations. The high speed jets of water impinging on the steel surface of the tank were creating static electricity that produced a spark in an environment with high hydrocarbon concentration. The solution to this phenomenon was tank inerting. The exhaust or stack gas from a properly operated boiler contains 1 to 5% oxygen. As opposed to about 21% of normal air. If the tank atmosphere contains less than about 11% O2, then the mixture will not support combustion regardless of the hydrocarbon content. The idea was to take the boiler stack gas, run it through a scrubber and pipe this inert gas into the tanks. This eliminated tank explosions while the internal tank corrosion rates were also reduced substantially.

Picture [2]: M/T Mactra after an oil tank explosion. Afterwards Shell introduced tank inerting

Almost a decade after the Torrey Canyon accident and the creation of MARPOL/73 the world was awakened for a second time after the accident of the VLCC Amoco Cadiz. At March 16th 1978, this vessel was proceeding north of the coast of Brittany in heavy weather, the under designed rudder (which was a systematic failure for the entire class of ships) failed. At this point a single screw, rudder vessel that is also fully loaded is at the sea's mercy, that proved a few hours later after the ship drifted ashore, broke in two and generated an oil spill of 267 mil liters.

Picture [3]: The Amoco Cadiz accident

The public outrage was evident and the discussions at IMO lead to the adoption of the MARPOL/78. In this new piece of regulation, an auxiliary steering gear has been introduced as mandatory in order to avoid such losses of control. Furthermore, a new regulation that was irrelevant to the Amoco Cadiz was introduced that was critical and most influential for tanker design. For the first time since the Glucklauf the tank arrangement was to be re-examined, and was subject to regulation in terms of the location and the segregation of the ballast tanks. Prior to MARPOL/78, almost all tankers employed a system in which about a third of the cargo tanks were also used as ballast tanks. This meant that every time the ship deballasted was also pumping some of the residual oil into the sea. By careful tank cleaning and decanting, the amount of oil in the discharged ballast water can be limited to a few hundred liters a trip. MARPOL/78 introduced three major new requirements:

a. Protectively located, segregated ballast tanks on all ships built after 1980.
b. A limit of 15 ppm oil in any ballast water discharged from existing ships and measures to attempt to enforce this.
c. No discharge of any oily ballast in certain areas such as the Mediterranean combined with a requirement that tanker load ports in these areas provide ballast reception facilities.

In a tanker employing segregated ballast a tank is either cargo or ballast but not both. Also the ballast piping and the cargo piping system are completely separate. Segregated ballast eliminates the great bulk of tanker oily ballast water discharges. MARPOL/78 also required that the pure ballast tanks to be located along the side of the ship where a kind of protection of the cargo tanks could be offered. These vessels with these characteristics are commonly referred to as MARPOL tankers.
It is thus evident that the new ballast tank requirements had a strong impact on tank arrangement and tanker design. The Naval Architect had to find more tank volume to make up for the fact they could not use the same volume for both ballast and cargo. This was achieved by increasing the height of the tanks up to 10 or even 20%. This affects directly the oil outflow in a grounding scenario, increasing the amount of oil spilled dramatically.

Wing tanks became narrower and longer, as it was a simple way to meet the 30% rule for the segregated ballast tanks. Centre tanks however grew significantly, while the number of cargo tanks decreased. This combination can lead to potentially higher outflow rates in case of an accident. In addition to that the ballast tanks on a MAPPOL tanker are not protected by tank inerting, which meant that the corrosion rate in these areas is higher. This characteristic lead to a very big number of structural failures and subsequent accidents like the Erika (1998) and the Prestige (2002). The amount of segregated ballast painted area increased by a factor of more than three. A 250.000 ton pre-MARPOL tanker had approximately 25.000 square meters of segregated ballast tank coated area, while the MARPOL equivalent has about 80.000 square meters.

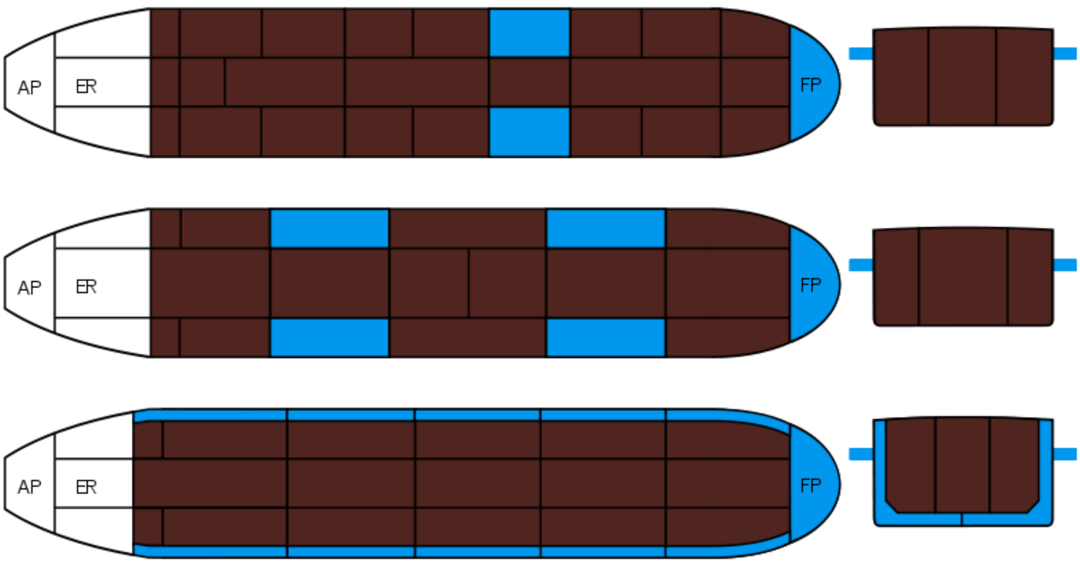

Figure [1]: Comparison of tank arrangement of a pre-MARPOL, MARPOL and double hull oil tanker.

The next accident that had an influence on the tanker industry was the final blow against the single hull arrangement: The Exxon Valdez. This notable oil spill occurred in the sensitive area of Alaska. The ship ran aground as a result of a navigation error by a tired third mate. Eight of the eleven tall cargo tanks were breached and the ship stranded on high tide. The 3 meter loss in external sea water pressure when the tide went out drastically increased the oil outflow. In all about 20% of the 200.000 ton cargo were lost, which was less compared to other spills. Nevertheless, the oil spill occurred in

Alaska, and the ship-owner was Exxon, one of the biggest and richest oil companies in the world. The beaches were spilled and the ecosystem in terms of birds and fish was affected. The clean-up costs were 2.5 billion dollars and the state of Alaska received 900 million. This is the biggest fine imposed to a shipping company, and by doing the calculation one can see that the equivalent Cost to Avert a Tonne of oil Spill (CATS) is at about 100 000$ per ton, way beyond the 25 000$/t calculated nowadays.
The US congress reacted immediately and passed the Oil Pollution Act of 1990. The single and most important aspect of this regulatory act was the phase out of single hull oil tankers operating in the US between 1997 and 2000 in favor of new double hull ships.
In a double hull tanker, the segregated ballast volume is in a U-shaped arrangement around the cargo spaces, define by the double bottom height and double hull width. These two parameters are influencing directly the oil outflow and available cargo spaces. The double hull concept is an effective way of turning a small spill into a zero spill. The double sides can also be very effective in terms of oil containment as long as the damage is entirely below the waterline. The disadvantages of this concept is that there is a risk of explosion for the double hull ballast tanks, in case of the dissipation of small amount of oil into that space. Combined with moisture this can be a flammable mixture. On the other hand he coated area of these tanks is now eight times that of a pre-MARPOL tanker of the same carrying capacity. Ballast tank maintenance has become an order of magnitude bigger job, while the improper maintenance can lead to big structural failures and losses.
The Exxon Valdez oil spill did not only rocked the boat of the regulators but that of the oil companies too. The fines required to be paid by the owner of the cargo (in that case the oil company) proved to be excessive, leading BP to introduce the vetting system, with all the other companies soon to follow. Vetting inspections are conducted by experienced inspectors hired by the Oil companies via the SIRE program of OCIMF. OCIMF is the Oil Companies International Marine Forum that handles pollution, quality assurance and liability issues. These inspections determine whether the ship is suitable for the charterer in terms of safety management and condition and can be considered as one of the most effective ways of mitigating the risk of oil spills, mainly due to the depth of the inspection itself and the commercial implications that can derive from the lower performance of a vessel.
The last accidents that caused international attention were those of the Erika and Prestige. They were almost the same kind of situation, were the degraded ship structure failed resulting into breaking the ship in two. Both cases are indicative of the poor structural design, maintenance and classification. They were both MARPOL ships with the cause of failure being the corrosion of the ballast tanks. The fact that both accidents occurred in European waters, lead to the acceleration of the phase out of existing single hull tankers, and the tightening of the Ship Management Systems provisioned by the International Safety Management Code (ISM).

The Modern Tanker: Design Aspects, Operation and Trades.

The tanker of the 21st century is the product of the evolutionary process we described. The commercial needs constrained by the regulatory development in a risk averse approach which is re-active rather than proactive, in other words regulation comes in force after serious accidents. The market of the tanker shipping sector is consisted by a big number of relatively small ship owners and can be characterized by a lack of concentration in contrast with the containership market which has the characteristics of the liner market. Most f the tanker owner nowadays are independent, meaning that they are not the owners of the cargo but providers of the transport service.
The size of a modern tanker can vary from less than 5000to more than 350000 tons DWT. The typical sizes are most of the times a function of the navigational constraints a ship has to comply with. The most common categories are the following:

- Handymax tankers: They have a deadweight of less than 50000 tons and are used primarily as crude as well as product carriers several trades.
- Panamax tankers: They are characterized as the biggest ships that can transit through the Panama Canal. The deadweight tonnage of these ships ranges from 50000 to 75000 tons. A typical 60000 DWT Panamax ship has the following principal dimensions L=228.6m, B=32.2m, T=12.6m, Lightship Weight 11000 tons, L/B=7, B/T=2.55.
- AFRAMAX tankers: They range from 80000 to 120000 metric tons deadweight (DWT) and have a breadth greater than 32.31 m. The term is based on the *Average Freight Rate Assessment* (AFRA) tanker rate system. Aframax class tankers are largely used in the basins of the Black Sea, the North Sea, the Caribbean Sea, the China Sea and the Mediterranean. A typical 100000 DWT AFRAMAX ship has the following principal dimensions: L=253m, B=44.2, T=11.6, LS=14850 tons, L/B=6, B/T=3.8.
- Suezmax tankers: They are the biggest ships that can transit through the Suez Canal at their full load condition[1] and range from 120000 to 200000 tons DWT, or 1 million barrels of oil. A typical 150000 DWT Suezmax has the following principal dimensions: L=274m, B=50m, T=14.5m, LS=20000 tons, L/B=5.5, B/T=3.4.
- Very Large Crude Carriers (VLCC): They have no navigational constraints as they are not able to pass through several canals and visit ports. They range from 200000 to 350000 DWT, with a typical 300000 DWT VLCC having the following dimensions: L=335m, B=57m, T=21m, LS=35000 tons, L/B=5.87, B/T=2.7.
- Ultra Large Crude Carriers (ULCC): They are almost extinct (only 4 active) and have a deadweight tonnage greater than 380000 tons.

The above mentioned sizes predominantly synthesize the world tanker fleet with the AFRAMAX having the biggest share as we can see on the following graph.

Depending on the mission of a vessel an oil tanker can be divided in Crude Carriers, Crude/Product carriers that can also carry by-products of oil like diesel, paraffin, vegetable and lube oils. Furthermore, shuttle tankers are Crude Carriers that load crude oil offshore, from storage and production vessels known as FPSO's (Floating Production and Storage). These vessels are characterized by the need for independent propulsion and dynamic positioning that can be achieved with the use of either podded propulsion or more commonly bow and stern thrusters (depending on the class notation).

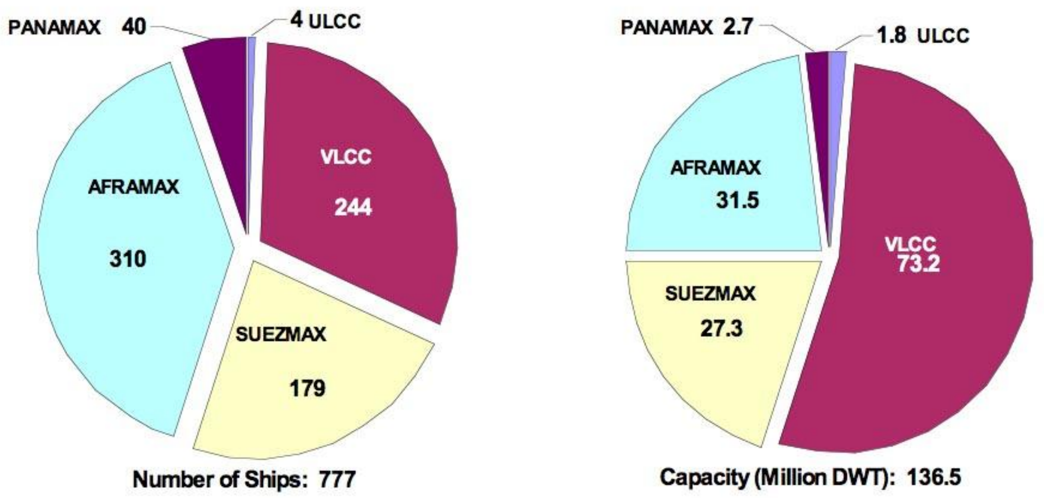

Figure [2]: Composition of World Tanker Fleet

The propulsion systems on board modern tankers are in most of the cases single screw, direct shaft drive. The propulsion motor in most cases is a 2stroke Low Speed Diesel Engine and the propulsor is a fixed pitch propeller rotating at about 80 RPM. Exceptions are the very small tankers were 4stroke engines may be used as well as some shallow draft designs (Stena Fleet) that are twin screw vessels. Recently, 4 Ice Class Shuttle tankers were built for Russian owner Sovocomflot that are Diesel Electric with Podded Propulsion.

The cargo handling on board a modern tanker is done by the cargo pumps. There are two different technologies that are compared in depth within this Thesis. The first is the conventional system that employs usually three pumps of big capacity, driven by steam and located aft of the (fore) Engine Room Bulkhead in the Pump Room. An alternative, recently developed is the independent deep well pump systems. In this case each tank has a submerged pump that is driven by high pressure hydraulics. In this case the pump room is eliminated, while the hydraulic pressure is generated by “Power Packs” consisted by small electric motors and small diesel engines. There are certain advantages of this system that are extensively presented in a comparative study made by the author within the context of this Thesis and the BEST+ research program and are presented in Chapter []. The main reason for the existence of this concept is the need for the segregation of cargoes that can be found in Product Carriers.

Auxiliary boilers are commonly found on board and in sets of two. They are necessary for the steam plant of the vessel that handles the cargo pumps (steam driven pumps) as well as the cargo heating. Crude Oil needs to have a certain kinematic viscosity during the transport operations that is achieved by the use of heating coils. In the case of a ship employing deep well pumps, the cargo heating is ensured by the power pack itself and the re-circulating of the cargo via a thermal resistance. This can reduce the boiler number to one only.

All of the modern tankers have inert gas systems for the protection of the cargo tanks against explosions. This system uses the flute gas from the auxiliary boilers, or the gas from an inert gas generator in the case of the Deep Well Pump concept. The inert gas passes through a scrubber in order to be clean from Sulphur oxides and is directed in the tanks in order to sustain the oxygen levels depending on a flammability diagram of the hydrogen carbon content and oxygen levels.

Leaving the technical aspect of tankers behind, the trade routes these ships are nowadays occupied can be seen in the following map (from Intertanko). The intercontinental trades are primarily served by VLCC and SUEZMAX vessels due to their long haul capabilities and the economies of scale. The PANAMAX ships serve special routes that the transit from the Panama canal is necessary while the AFRAMAX class focuses on medium to long range voyages, like those that can be found in the Caribbean market and the US to Europe or Intra-European trades. The Middle East to Europe trade is served by AFRAMAX tankers too. This versatility of the AFRAMAX tanker makes it a very popular choice from ship owners. It is also the largest Product Tanker size and a very popular size for shuttle tankers.

One can easily see, that one of the busiest routes is the Caribbean Trade Route, primarily focused on AFRAMAX Tankers. This route was chosen for study in the first Case Study produced, that of the AFRAMAX class Twin Screw Tanker.

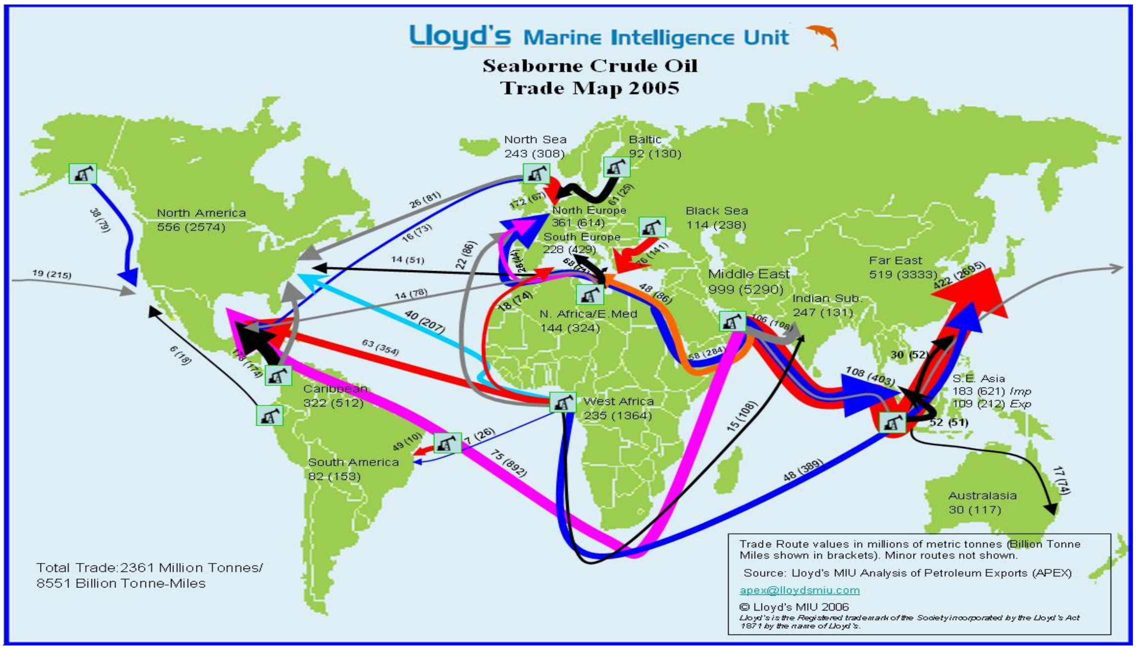

Figure [3]: Seaborne Crude Oil (Source: INTERTANKO)

It is also very interesting to see the global oil spills as a function of the trade routes:

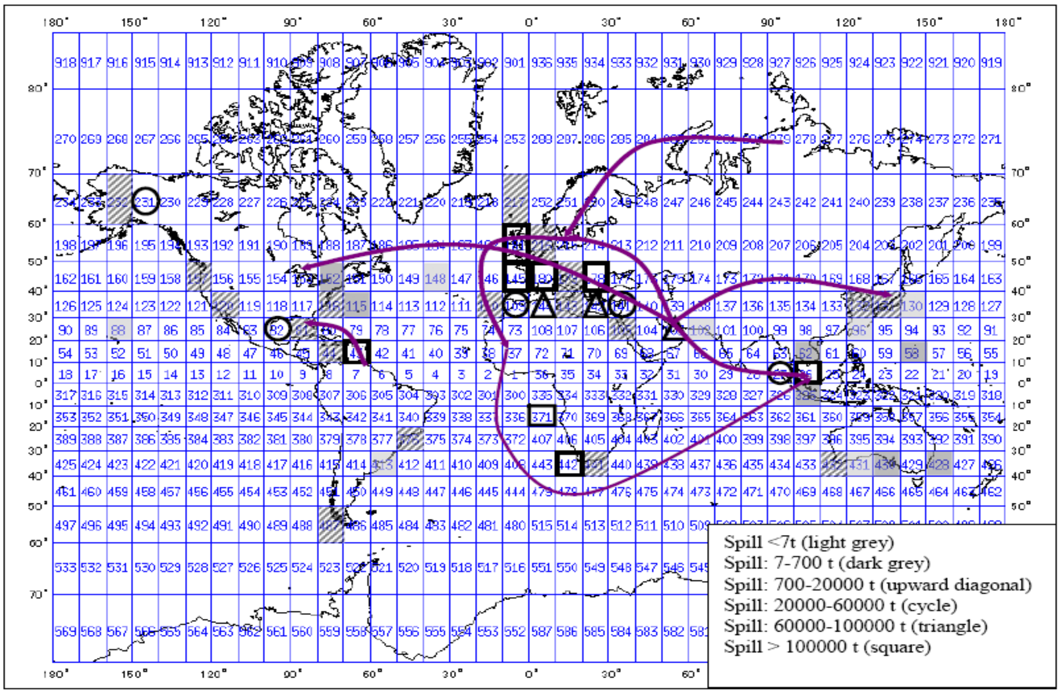

Figure [4]: Accidental Oil Outflow Distribution

<u>*References:*</u>

1. *Devanney J. , "The Tankship Tromedy", Chapter 2: A Brief History of Tanker Regulation.*
2. *INTERTANKO, Tanker Facts*
3. *Papanikolaou A., "Ship Design I: Preliminary Ship Design ", Athens 2009*
4. *Spyrou K., "Ship Design II: Detailed Design and Construction, Part B", Lecture Notes in Greek*

2. Modern Challenges for the Shipping Industry

Market Condition: Supply, Demand and Orderbook

Over the last decade, there has been an important fluctuation in the freight rate of several types of tankers. More precisely, in 2003 and 2008 FR rose dramatically especially in the market of VLCCs. A sudden drop occurred after 2009 which resulted in 2010 to the lowest level of the freight rate for the past ten years for VLCCs, Suezmax Tankers and Aframax tankers. The only exception have been Products Carries which had a slight fluctuation since 2001 compared with the rest types of tanker ship ending the decade with a slight upward trend.

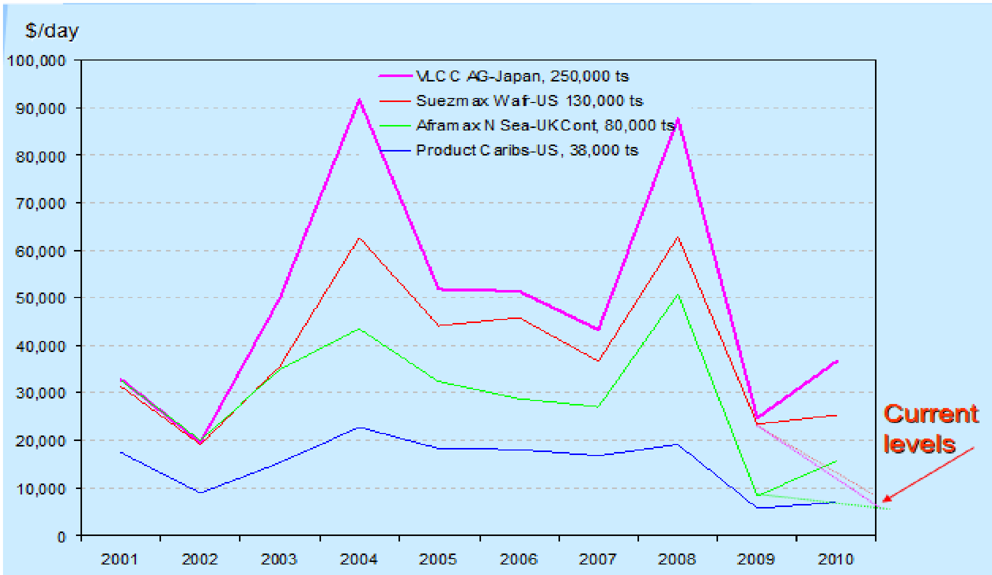

Figure [5]: Charter Rates (Source: Baltic Exchange/INTERTANKO)

Concerning the tanker fleet development, the fleet number had a minimal decrease between 1992 and 2001 but generally it remained stable around 260 ships. From 2002 to2011 including estimation for the next two years as well tankers fleet numbers rocketed at 550 ships which is really impressive.

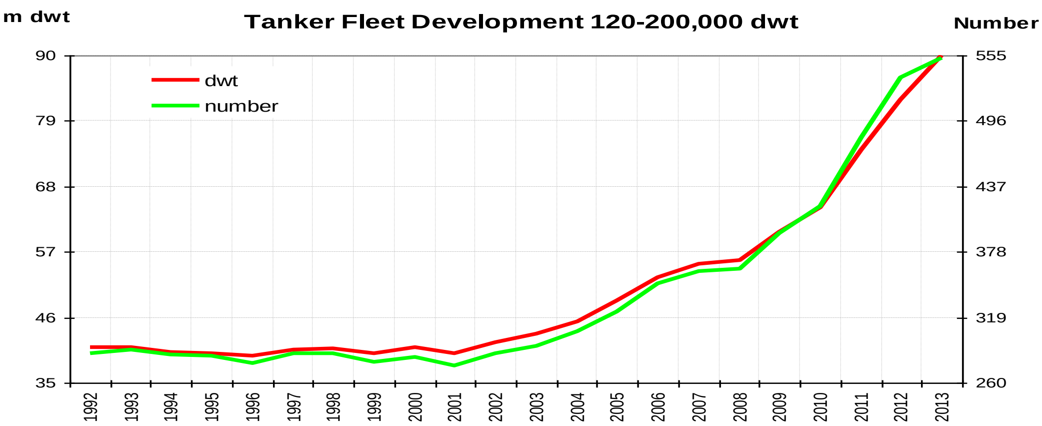

Figure [6]: Tanker Fleet Development (Source: INTERTANKO)

About the orders of new tankers, it is clear from the chart below that VLCCs and most of the other types of tankers, increased sharply between 2006 and2008 but in the years following orders plummeted again in the some levels there used to be from 1988 to 2000.

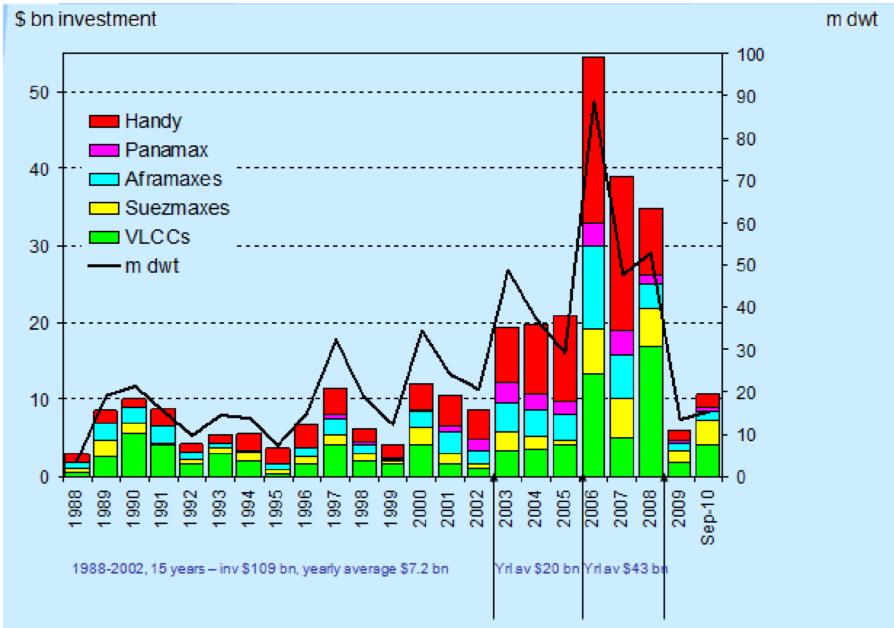

Figure [7]: Orders for new tankers - bn $ (Source: Clarkson Shipyard Monitor/INTERTANKO)

The increase from 2006 to 2008 was very significant but it was followed by a sharp fall in 2009 as we can verify again from the next graph. Despite the sudden drop, from 2010 the market has a slight recovery that was for a brief period. After 2011, the new building price is considerably down due to the big slump in charter rates and the tanker market as a hole.

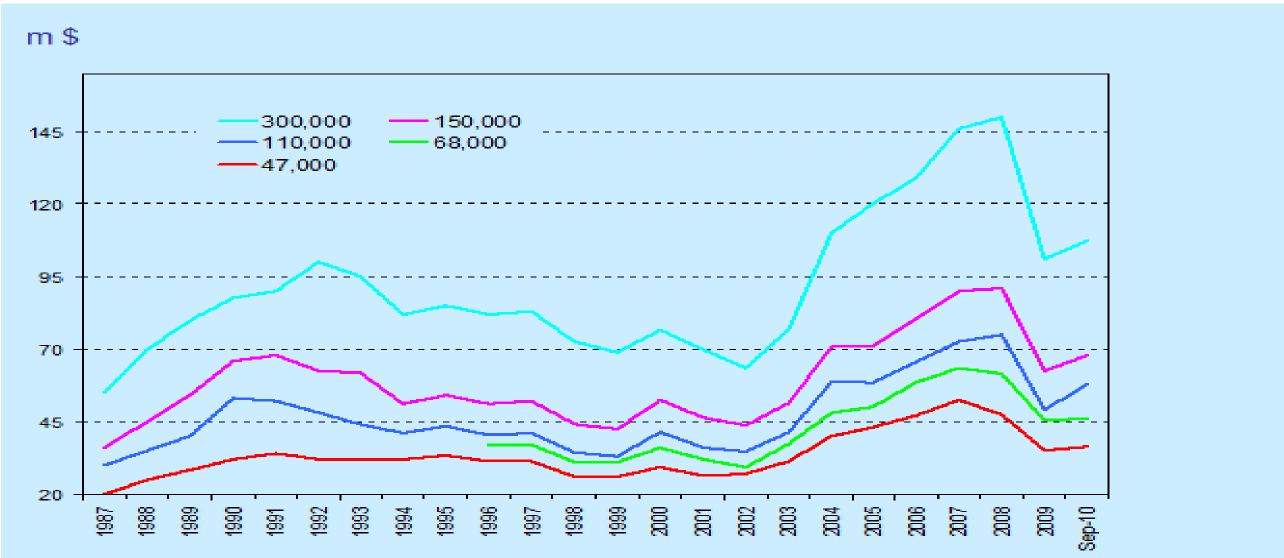

Figure [8]: Tanker newbuilding prices (Source: Clarksons)

The current (2012) situation of the industry can be described by very low charter rates (especially for larger vessels like Suezmax and VLCCs), an orderbook that will by 2013 be zero and an increased scrapping scheme that is not sufficiently high nevertheless to trigger the supply-demand equilibrium. This situation is putting more pressure to ship owners that experience big losses. The stock market listed companies that flourished over the last decade have an even bigger problem as they are liable to their investors and their assets and fortune is also subject to the stock market rules, that respond to this crisis by decreasing consistently the stock price. This can even lead to delisting of major companies, while bigger losses can be recorded due to this drop of the stock market price.

Environmental Regulations: Emission Control and Ballast Water Management for the Future

The raising concern on the impact of the human activities in the environment has brought into the spotlight a new set of regulations that aim into reducing the environmental footprint of shipping. The regulatory framework can be divided in "two streams" at this point:

a. The regulations for the emissions generated by shipping, the creation of Special Emission Control Areas (SECAs) and the creation of Key Performance Indicators (KPIs) for the efficiency performance of ships that are the EEDI (Energy Efficiency Design Index) and the EEOI (Energy Efficiency Operating Index) as well as the SEEMP (Ship Efficiency Management Plan).
b. The regulations for the handling and management of ballast water in order to eliminate the microorganisms that are contained in it and sometimes act as invasive species from one ecosystem to another.

These two are the main directions of the new environmental policies of the International Maritime Organization (IMO). The validity and effect of these is not to be assessed and examined in this Thesis. However, it is important for the readers understanding to describe some of the regulations of the first stream, in order for him to understand the new focus that is put for the design and construction of new ships.

Ship Emissions Control

IMO ship pollution rules are contained in the "International Convention on the Prevention of Pollution from Ships", known as MARPOL 73/78. On 27 September 1997, the MARPOL Convention has been amended by the "1997 Protocol";, which includes Annex VI titled "Regulations for the Prevention of Air Pollution from Ships". MARPOL Annex VI sets limits on NOx and SOx emissions from ship exhausts, and prohibits deliberate emissions of ozone depleting substances.
The IMO emission standards are commonly referred to as Tier I...III standards. The Tier I standards were defined in the 1997 version of Annex VI, while the Tier II/III standards were introduced by Annex VI amendments adopted in 2008, as follows:
1997 Protocol (Tier I)—The "1997 Protocol" to MARPOL, which includes Annex VI, becomes effective 12 months after being accepted by 15 States with not less than 50% of world merchant shipping tonnage. On 18 May 2004, Samoa deposited its ratification as the 15th State (joining Bahamas, Bangladesh, Barbados, Denmark, Germany, Greece, Liberia, Marshal Islands, Norway, Panama, Singapore, Spain, Sweden, and Vanuatu). At that date, Annex VI was ratified by States with 54.57% of world merchant shipping tonnage.
Accordingly, Annex VI entered into force on 19 May 2005. It applies retroactively to new engines greater than 130 kW *installed on vessels constructed on or after January 1, 2000*, or which undergo a major conversion after that date. The regulation also applies to fixed and floating rigs and to drilling platforms (except for emissions associated directly with exploration and/or handling of sea-bed minerals). In anticipation of the Annex VI ratification, most marine engine manufacturers have been building engines compliant with the above standards since 2000.
2008 Amendments (Tier II/III)—Annex VI amendments adopted in October 2008 introduced (1) new fuel quality requirements beginning from July 2010, (2) Tier II and III NOx emission standards for new engines, and (3) Tier I NOx requirements for existing pre-2000 engines.
The revised Annex VI enters into force on 1 July 2010. By October 2008, Annex VI was ratified by 53 countries (including the Unites States), representing 81.88% of tonnage.

Emission Control Areas.

Two sets of emission and fuel quality requirements are defined by Annex VI: (1) global requirements, and (2) more stringent requirements applicable to ships in Emission Control Areas (ECA). An Emission Control Area can be designated for SOx and PM, or NOx, or all three types of emissions from ships, subject to a proposal from a Party to Annex VI.
Existing Emission Control Areas include:

- Baltic Sea (SOx, adopted: 1997 / entered into force: 2005)
- North Sea (SOx, 2005/2006)
- North American ECA, including most of US and Canadian coast (NOx & SOx, 2010/2012).
- US Caribbean ECA, including Puerto Rico and the US Virgin Islands (NOx & SOx, 2011/2014).

Greenhouse Gas Emissions

2011 Amendments to MARPOL Annex VI introduced mandatory measures to reduce emissions of greenhouse gases (GHG). The Amendments added a new Chapter 4 to Annex VI on “Regulations on energy efficiency for ships”.

NOx Emission Standards

NOx emission limits are set for diesel engines depending on the engine maximum operating speed (n, rpm), as shown in Table 1 and presented graphically in Figure 9. Tier I and Tier II limits are global, while the Tier III standards apply only in NOx Emission Control Areas.

Tier	**Date**	**NOx Limit, g/kWh**		
		n < 130	**130 ≤ n < 2000**	**n ≥ 2000**
Tier I	2000	17.0	$45 \cdot n^{-0.2}$	9.8
Tier II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III	2016†	3.4	$9 \cdot n^{-0.2}$	1.96

In NOx Emission Control Areas (Tier II standards apply outside ECAs).

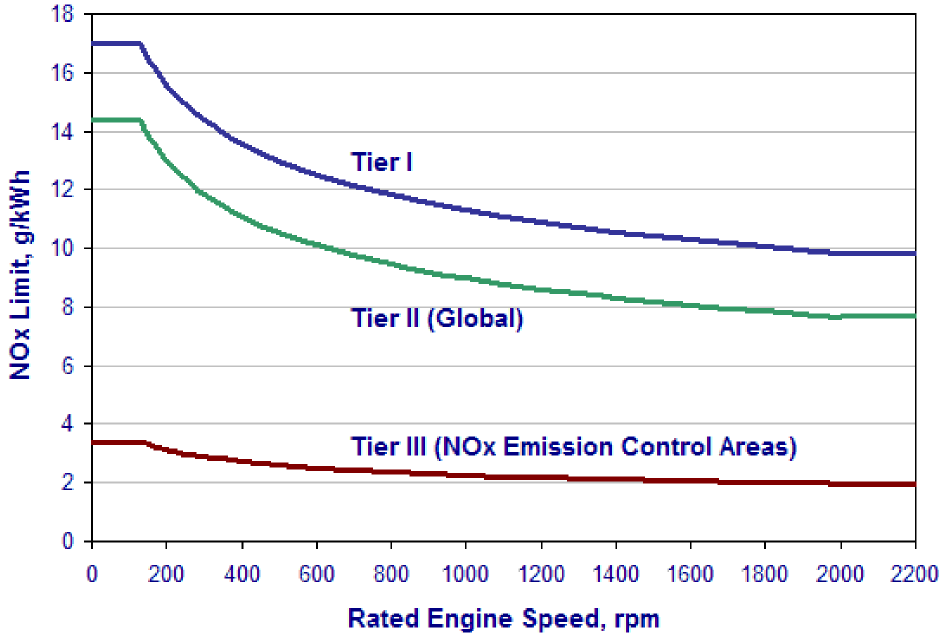

Figure [9]: MARPOL Annex VI NOx Emission Limits

- Tier II standards are expected to be met by combustion process optimization. The parameters examined by engine manufacturers include fuel injection timing, pressure, and rate (rate shaping), fuel nozzle flow area, exhaust valve timing, and cylinder compression volume.
- Tier III standards are expected to require dedicated NOx emission control technologies such as various forms of water induction into the combustion process (with fuel, scavenging air, or in-cylinder), exhaust gas recirculation, or selective catalytic reduction.

Sulfur Content of Fuel

Annex VI regulations include caps on sulfur content of fuel oil as a measure to control SOx emissions and, indirectly, PM emissions (there are no explicit PM emission limits). Special fuel quality provisions exist for SOx Emission Control Areas (SOx ECA or SECA). The sulfur limits and implementation dates are listed in Table 2 and illustrated in Figure 10.

Date	**Sulfur Limit in Fuel (% m/m)**	
	SOx ECA	**Global**
2000	1.5%	4.5%
2010.07	1.0%	
2012		3.5%
2015	0.1%	
2020[a]		0.5%

a - alternative date is 2025, to be decided by a review in 2018

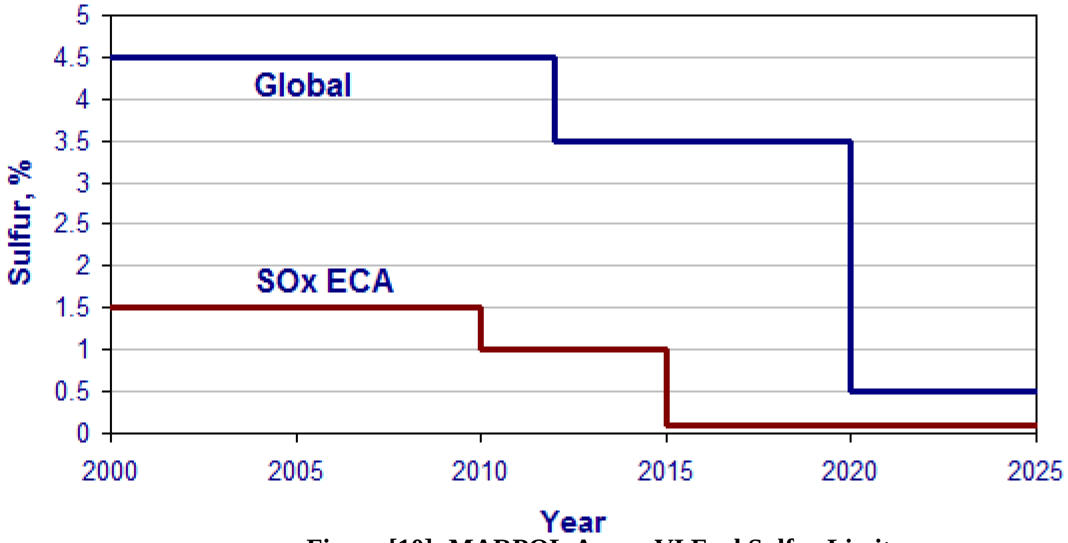

Figure [10]: MARPOL Annex VI Fuel Sulfur Limits

Heavy fuel oil (HFO) is allowed provided it meets the applicable sulfur limit (i.e., there is no mandate to use distillate fuels).
Alternative measures are also allowed (in the SOx ECAs and globally) to reduce sulfur emissions, such as through the use of scrubbers. For example, in lieu of using the 1.5% S fuel in SOx ECAs, ships can fit an exhaust gas cleaning system or use any other technological method to limit SOx emissions to ≤ 6 g/kWh (as SO_2).

Greenhouse Gas Emissions

MARPOL Annex VI, Chapter 4 introduces two mandatory mechanisms intended to ensure an energy efficiency standard for ships: (1) the Energy Efficiency Design Index (EEDI), for new ships, and (2) the Ship Energy Efficiency Management Plan (SEEMP) for all ships.

Energy Efficiency Design Index (EEDI)

The EEDI is a performance-based mechanism that requires a certain minimum energy efficiency in new ships. Ship designers and builders are free to choose the technologies to satisfy the EEDI requirements in a specific ship design. What EEDI measures is the CO2 emitted, as function of the fuel consumption with the use of a conversion factor ("emission factor"), divided by the so called "benefit to the society", namely the transport work which is determined by the deadweight tonnage multiplied by the design speed of the vessel.
One of the disadvantages of the EEDI is the involuntary mandate of speed limits to operation and slow steaming, that in certain cases can improve the operational profile of the vessel (in low charter periods) but it can mitigate the safety and security onboard. As it measures deadweight though, and is internationally known, EEDI was chosen during the optimization studies as a measure and objective function for the generation and selection of the design variants.

Ship Energy Efficiency Management Plan (SEEMP)

The SEEMP establishes a mechanism for operators to improve the energy efficiency of ships.
The regulations apply to all ships of and above 400 gross tonnage and enter into force from 1 January 2013. Flexibilities exist in the initial period of up to six and a half years after the entry into force, when the IMO may waive the requirement to comply with the EEDI for certain new ships, such as those that are already under construction.

Ballast Water Management Convention

The Ballast Water Management convention is another hot issue for the marine industry. It was voted in the MEPC 125 (53) as "Guidelines for Approval of Ballast Water Management Systems" that originally set the specifications for the concentration of plankton and microorganisms in ballast tanks. It is estimated that nowadays 3-120 billion tons of water ballast are transported each year, from which 5.5 million litres per hour are exchanged everyday and approx. 7000 different species are transported (Globallast Publication 2011). The IMO response to that came first in 2004, where the original orientation and rules were issued during the MEPC conference and it was expanded in 2005 during MEPC 53 with 14 directives. In October 2008 the convention was finalized (MEPC 58). The convention is set to be applicable from 2016. The requirements of the BWMC are subject to the concentration of invasive species and microorganisms depending on their size.

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2. *INTERTANKO, "Annual Tanker Report", 2011*
3. *Spyrou K., "Design for Safety and Environmental Protection", Lecture Notes in Greek, 2011*

CHAPTER TWO:

TANKER DESIGN ASPECTS, INNOVATIONS AND OPTIMIZATION

"Όσο φαρδύ τορνεύει μάστορης που κατέχει την τέχνη του άριστα
τον πάτο καραβιού για φόρτωμα,
τόσο φαρδιά κι ο Οδυσσέας την έφτιαξε την πλάβα,
στεριώνοντας τα ίκρια με πολλά στραβόξυλα,
ώσπου απλώνοντας μακριές σανίδες τέλειωσε την κουβέρτα.
Τότε και το κατάρτι το έμπηξε στη μέση μ' αντένα ταιριασμένη,
και το τιμόνι το μαστόρεψε, να 'ναι ο κυβερνήτης του.
Ύστερα τη σχεδία περίφραξε, στο κύμα για ν' αντέχει,
με κλωνάρια ιτιάς, ρίχνοντας από πάνω φύλλα.
Και ξαναφτάνει η Καλυψώ θεόμορφη με το λινό για τα πανιά·
καλά κι αυτά τα μαστορεύει.
Τα ξάρτια και τα κάτω καραβόσχοινα της έδεσε,
και με φαλάγγια τη σχεδία τη σέρνει και τη ρίχνει
στο θείο κύμα της θαλάσσης"

Ομήρου Οδύσσεια

(Excerpt from the Odyssey (how Ulysses built his raft))

CHAPTER 2: TANKER DESIGN ASPECTS AND OPTIMIZATION

1. TANKER SAFETY ASSESSMENT

In this chapter we present the main challenges the tanker designer faces nowadays with an emphasis on Tanker Safety. For this particular reason we use the results and discussions made in IMO during the creation of the Formal Safety Assessment (FSA) of Tankers.

At a first stage we present the Hazard Identification as written in the FSA. The last was done in several sessions during the SAFEDOR Project in which the Ship Design Laboratory participated actively.

A brief presentation of the Risk Control Options proposed in the FSA during a brainstorming session in NTUA follows.

Formal Safety Assessment (FSA) of Tankers: Hazard Identification

The current regulatory framework in the shipping industry is always re-active, following great maritime disasters. For this [particular reason, when thinking of new ways to enhance maritime safety in new rules and regulations a historical data must be available in order to be able to identify trends, threats, strengths and weaknesses. In the following figure one can see the evolution of the modern regulatory framework as a function of the navigational accidents per year for AFRAMAX tankers:

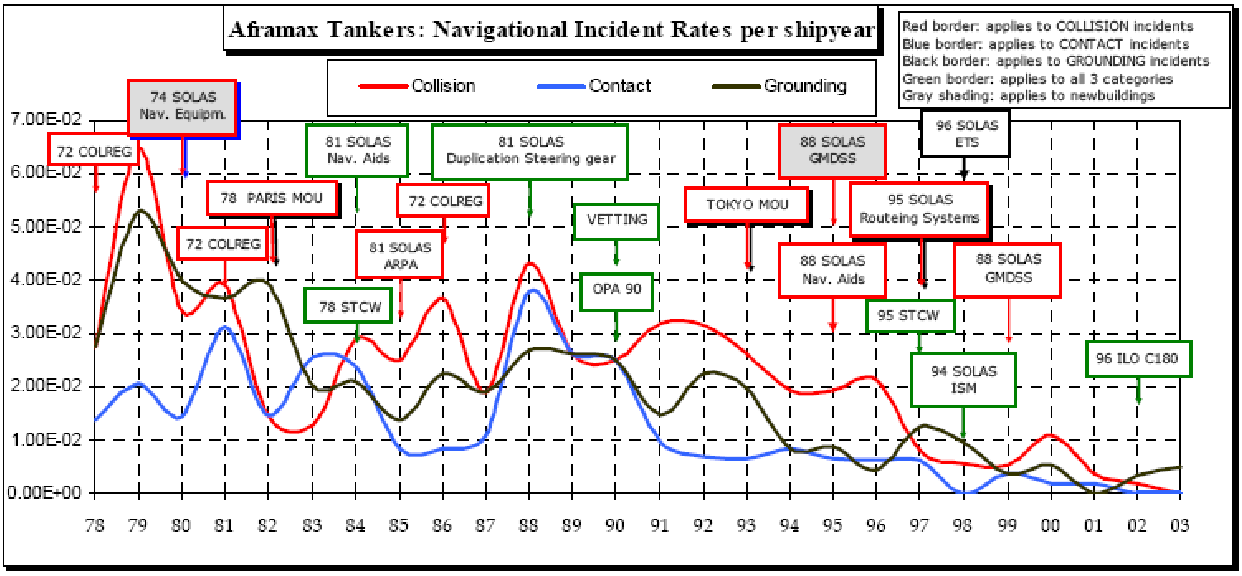


Figure [11]: Navigational Incident Rates per ship year for AFRAMAX Tankers (FSA, 2008)

The Hazard Identification process in the FSA comprised two stages: an analysis of statistical data aiming to identify the main hazardous processes followed by a hazard identification expert sessions in which hazards relating to the mentioned processes/operations were identified and prioritized.

The first stage is done with the help of casualty databases. They can be used to study and analyze the historic accident scenarios and to find the vulnerable operational or design problems. There are several casualty databases, most well known the Lloyd's Register Fairplay and Lloyd's Maritime Intelligent Unit. The FSA study we used uses the latest version of NTUA-SDL casualty database for the statistical analysis of historical data, which derives from the POP&C database (created from an EU funded research project).

During the second stage the following processes/operations were considered:

i. Loading/Unloading operations' including tank cleaning and crude oil washing.
ii. Ship-to-ship transfer (STS) at open sea
iii. Operations in coastal and restricted waters, including navigation under pilotage
iv. Maintenance tasks

The process identified in total 81 hazards which are distributed among the defined operational phases of a tanker. The navigational hazards were 36, the loading and unloading 30, the STS 8 and the maintenance 7.

Based on the top ranked hazards with respect to human life and to environmental damage the following scenarios were formulated:

Collision
The collision scenarios represent 30% of all registered initial causes in the historical accidents database.
Contact
Contact scenarios represent 13% of all registered initial causes in the set-up database.
Grounding
Grounding scenarios represent 21% of all registered initial causes in the set-up database.
Fire
Fire scenarios represent 11% of all registered initial causes in the set-up database.
Explosion
Explosion scenarios represent 6% of all registered initial causes in the set-up database.
Non-accidental Structural Failure
Non-accidental structural failures represent 19% of all registered initial causes in the set-up database.

Over the years the tanker casualties have evolved according to the following graph. One can notice that they used to be in relatively high levels during the 80s but after the peak in 1989-1990 (mainly due to the Exxon Valdez incident) and the subsequent regulation (OPA 90 and the introduction of the double hull arrangement) the casualties have significantly dropped, with an all time low in 2001 and a small increase in the years to follow.

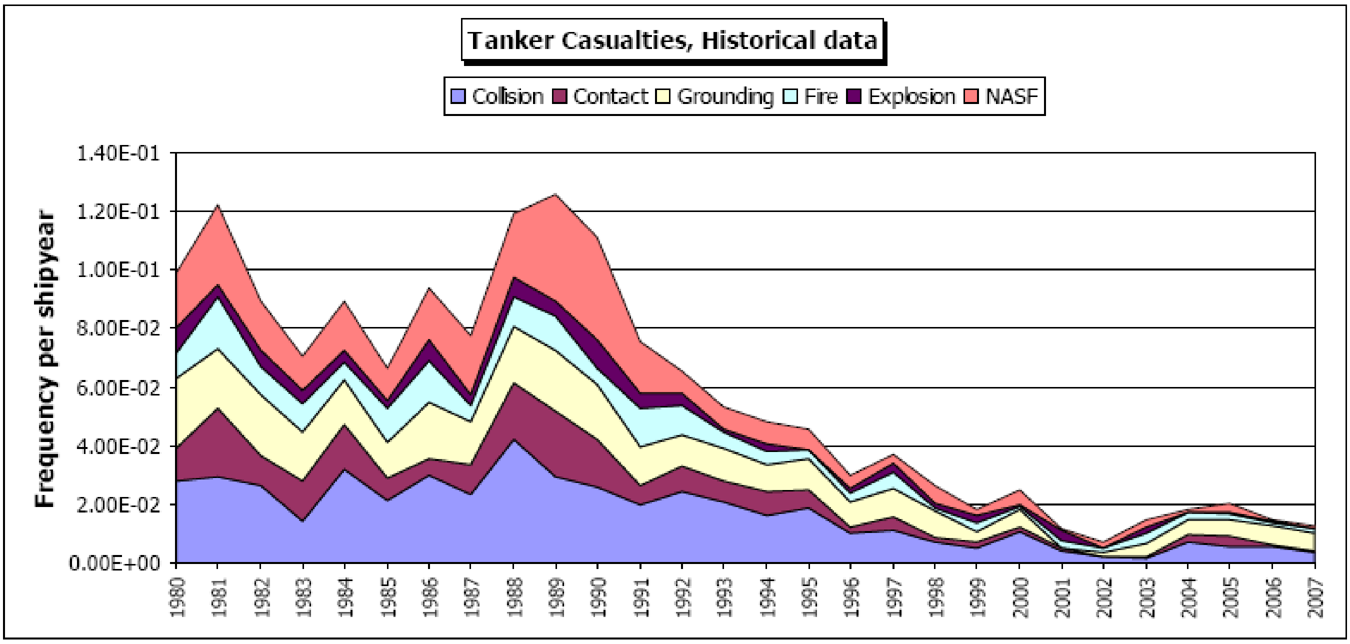


Figure [12]: Historical data of tanker casualties (FSA,2008)

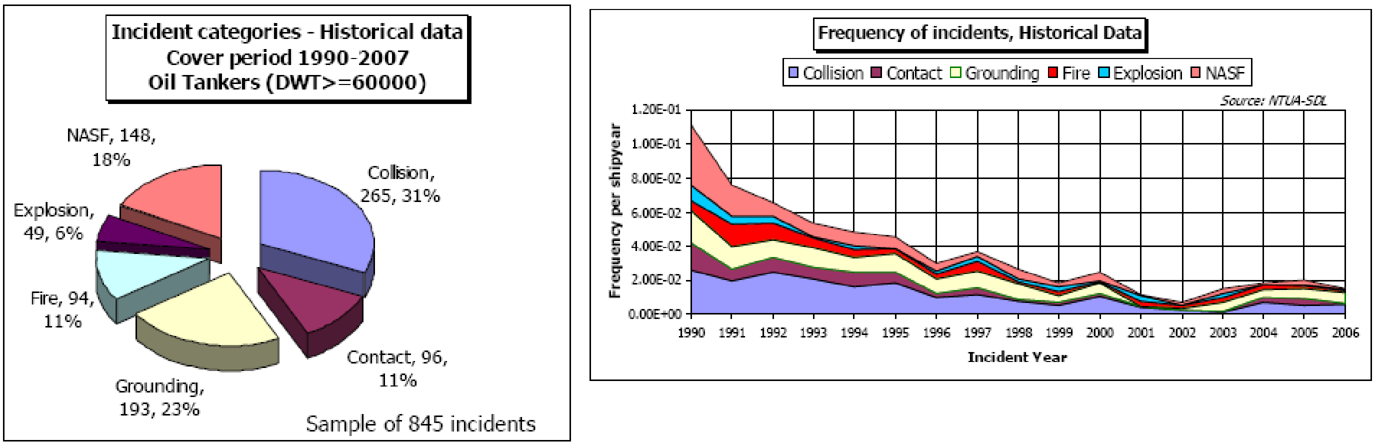
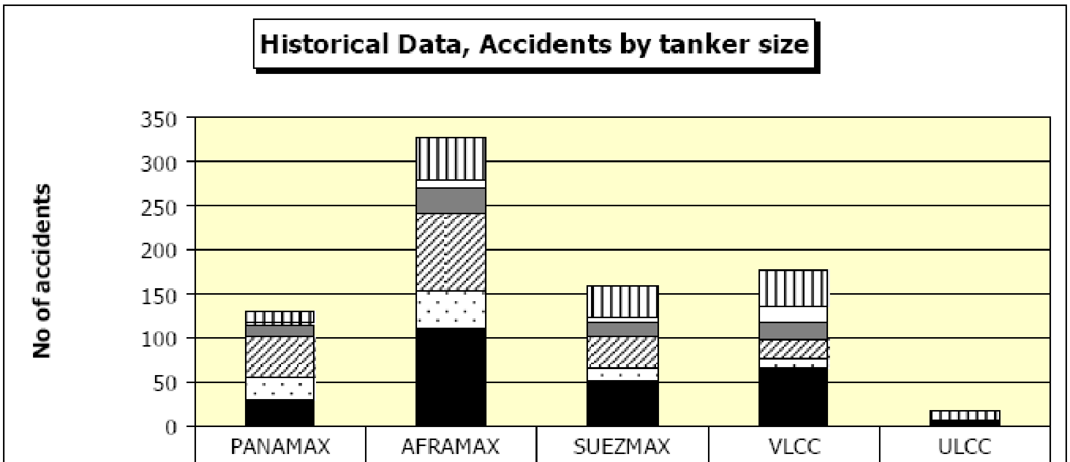


Figure [13]: Incident Categories and distribution (FSA, 2008)

Another interesting graph from the FSA studies is the following one. We can see the accident type (risk model) scenario distributed over the different tanker types (regarding their sizes).
For the AFRAMAX size we investigate (which holds besides the biggest number of ships currently afloat) the most common accidents are collision. In fact the collisions in AFRAMAX vessels are more frequent than in any other tanker type. AFRAMAX tankers are also very likely to sustain grounding accidents.



	PANAMAX	AFRAMAX	SUEZMAX	VLCC	ULCC
NASF	13	48	34	42	11
Explosion	5	9	6	19	0
Fire	12	29	16	18	1
Grounding	46	88	35	22	1
Contact	24	43	15	9	2
Collision	31	111	52	68	3

Figure [14]: Accidents by tanker size (FSA, 2008)

Based on the appeared frequency we can see that the biggest risks for the AFRAMAX tankers are the following in list of decreasing importance:

a. **Grounding**
b. **Collision**
c. **NASF**
d. **Contact**
e. **Fire**
f. **Explosion**

The order of importance we choose is such based on the frequency of the accidents.

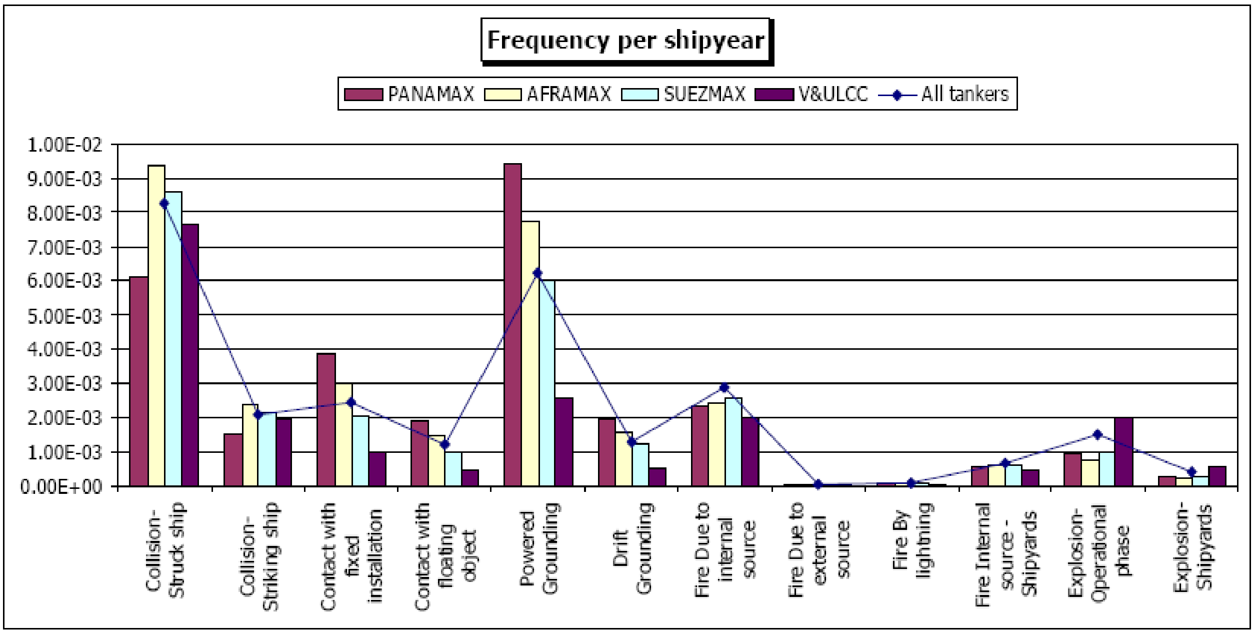


Figure [15]: Frequency of Accidents per Shipyear (FSA,2008)

Having these risks in mind, and after the FSA analysis of the possible and available Risk Control Options, we will be able to decide the type of design we will implement in order to reach our objective of increased safety for the tanker, which in the meantime is coincident with an increased environmental protection in terms of reduced oil outflow.

<u>Formal Safety Assessment (FSA) of Tankers: Risk Control Options</u>

The process of proposing Risk Control Options in the FSA is structured in the following stages:

1. Focusing on risk areas needing control
2. Identifying potential RCOs
3. Evaluating the effectiveness of the RCOs in reducing risk by re-evaluating Step 2
4. Grouping the RCOs into practical regulatory options

In general the RCOs should be aimed at one or more of the following:

1. Reducing the frequency of failures through better design, procedures, organizational policies, training etc,
2. Mitigating the effect of failures, in order to prevent accidents,
3. Alleviating the circumstances in which failures may occur and
4. Mitigating the consequences f the accidents.

For example, when improving the steering gear redundancy we are reducing the frequency of groundings/collisions (1) while when having smaller tanks in the tank arrangement, we reduce the oil outflow during an accident (4).

The procedure under which the FSA suggested Risk Control Options for the tankers was the following:

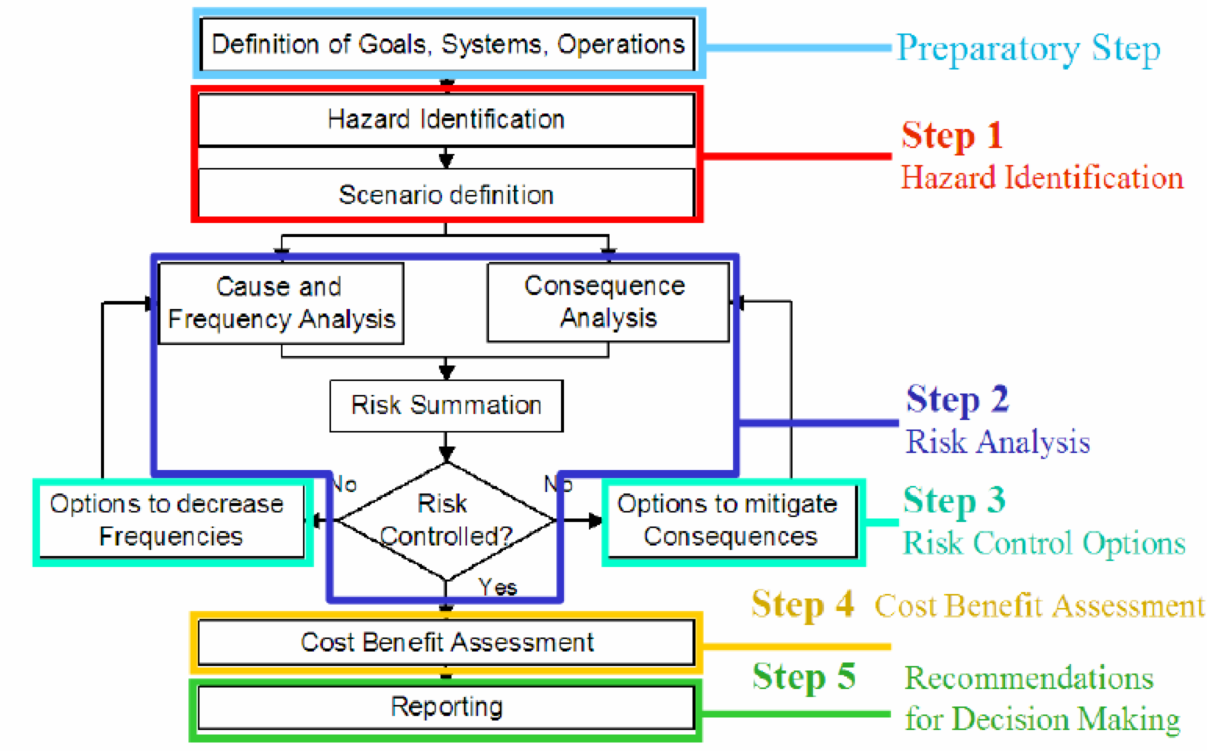


Figure [16]: Procedure for the Decision Making on Risk Control Options (FSA, 2008)

The above mentioned procedure in the FSA resulted in this list of recommended RCOs:

- Active Steering Gear Redundancy
- Electronic Chart Display and Information System (ECDIS)
- Terminal Proximity and Speed Sensors (Docking Aid)
- Navigational Sonar
- Design Modifications to reduce collision contact, grounding and oil pollution risks
- Better Implementation of Hot Work Procedures
- Double Sheathed Fuel oil pipes within the engine room
- Engine control room additional emergency exit
- Hull stress and fatigue monitoring system

In the present study, we will examine from the above recommended RCOs the Design Modifications to reduce collision, contact, grounding and oil pollution risks in the form of an improved cargo tank arrangement (see next paragraph on tanker design optimization) and improved propulsive redundancy (use of Diesel Electric systems, twin screw etc).

References

1. Formal Safety Assessment of Tankers for Oil, IMO 2008
2. Apostolos Papanikolaou, «RBD Application: AFRAMAX Tanker Design», Risk Based Ship Design, Chapter 6.2

2. INNOVATIVE TANKER DESIGNS

In this chapter we present some of the existing proposed concepts for the tanker industry. Some of them are focusing primarily on the accidental oil outflow performance of the vessel, while other designs try to confront multiple objectives.

Vossnack Cylinder Tanker

The first reference is the Vossnack cylinder tanker. The latter was developed by her namesake, the late Ernst Vossnack who was chief designer for Rotterdam Lloyd and Nedlloyd for more than thirty years. One of his many ideas was the concept of a triple –hull tanker with large membrane type crude oil tank cylinders with a smooth inner surface arranged in a conventional double shell hull, resembling in many ways with the LNG carriers of today (both spherical and membrane type).

Recently, such a concept was further developed by Bremen Naval Architect Helge Kringel and published in The Naval Architect magazine of RINA (Helge Kringel [2]). The proposed concept is a VLCC that incorporates, apart from the original idea of the cylinder tanks, several innovations such as twin skeg propulsion and a new way of inerting gas in the cargo spaces. According to Kringel ([2]) advantages of this design are:

1. High safety against oil spillage in case of grounding or a collision using a triple hull structure. Low oil spillage, if at all may be expected in case of a collision due to wide-side tank structure and the use of ductile TM-rolled material for the cylinder shells. No bottom spillage occurs in case of groundings due to the high double bottom and the cofferdam above.
2. No direct contact between the shell and oily media due to the arrangement of cofferdams. The HFO bunker is located at the centerline between two entirely independent main engine rooms and steering gear.
3. No direct contact occurs between the warm cargo oil and water ballast tanks and void spaces this there is less corrosion of the double hull structure.
4. Long service life of the vessel is expected due to the smooth internal surface of the cylinders which can be cleaned easily. Thus, significantly reduced corrosion and hence less maintenance cost of the cargo tanks will result.
5. Substantially-less corrosion by N2 inertization and high quality coating.

When reviewing the overall lifecycle of such a vessel, the initial cost is substantially higher (due to the increased steel weight and machinery) but it can be compensated according to H. Kringel by the lower maintenance cost, primarily for less preservation during the vessel’s long service. It is the author’s opinion, that mainly due to the major shipyard’s unwillingness to deviate much from their standard designs this particular one would be extremely expensive to be built and thus preventing most of independent tanker owners from building it.

<u>*SDL Zero Spill Tanker*</u>

Another innovative tanker design is proposed by NTUA SDL in the book «Risk Based Ship Design», as written by Professor Apostolos Papanikolaou. This particular concept aims on a zero spill behavior through the increase of the both the double bottom and double hull. When doing that in an extreme magnitude, a zero spill tanker can be achieved that has the same hull form but the cargo space is much different: the double bottom height is at about 6.3 meters from the bottom shell while the inner bulkhead is positioned in 13.2m from the side shell, resulting into a zero probability of outflow tanker with a significantly reduced cargo capacity (only 46000m^3 for an AFRAMAX which typically has 130000m^3). That reduction will make the ship to be significantly less competitive than the standard AFRAMAX design. However, at a price of crude oil close to 900 USD per tonne which is likely to further increase, an increase of the Required Freight Rate (RFR), namely the charter rate needed to even the expenses and the income of the vessel, from about 20$ to 40$ per tonne, thus by about 2% of the raw material cost, appears realistic, even for this extreme design scenario. Also, current discussions about the Formal safety Assessment of tankers at IMO and the Cost to Avert one Tonne of oil Spillage (CATS) suggest figures of up to 100,000USD/tonne, thus designing a risk free tanker ship may be a request in the future.
At the bottom line, the implementation of such a design clearly depends on the willingness of the society and maritime regulators to eliminate the risk of oil pollution. If so, which in other words means that the risk aversion of the society towards oil spill is very high, then the regulators should also find a way of supporting the external cost of this choice by allowing the transportation of oil by sea to be in general more expensive, which can affect the oil prices but not at an extreme level.

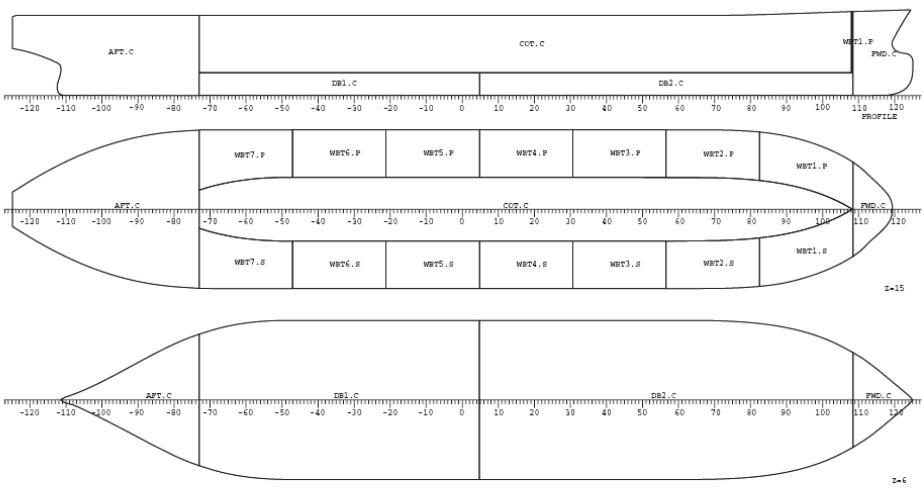
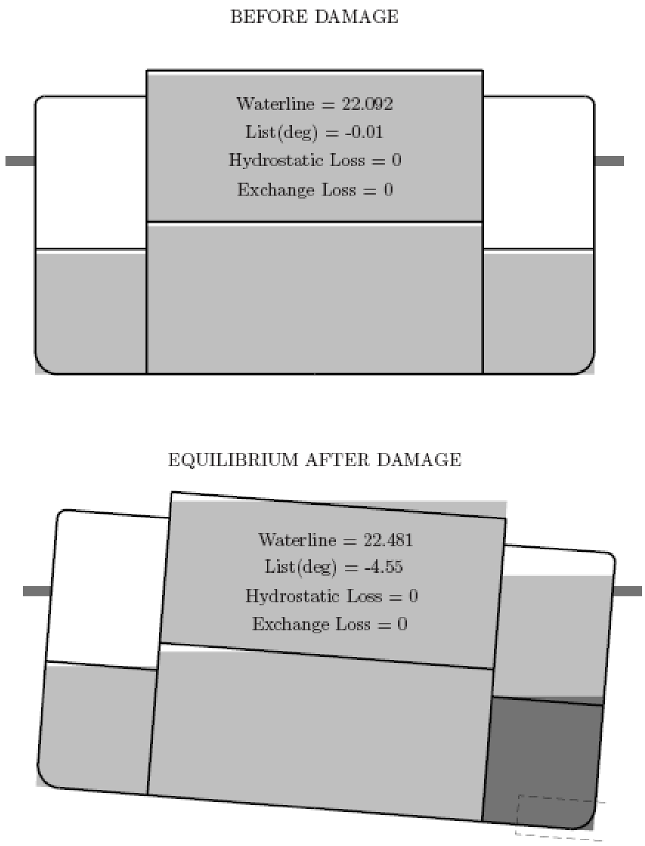


Figure [17]: Cargo Tank Sketch of the Zero Spill Tanker (Papanikolaou [3])

In both cases we can see that in order to achieve a zero spill tanker a sacrifice in cargo capacity and thus competitiveness must be made. However, when there is a high level of risk aversion for the transportation of crude oil by sea in a society the external cost of implementing such a measure can be justified with higher charter rates. It all comes to the question: «How much is society is willing to pay in order to reduce the risk of carrying crude oil by sea?».

Coulombi Egg Tanker

The Coulombi Egg is a mid deck tanker design, but the ballast tanks are set above the outboard cargo tanks. The lower tanks are connected to these ballast tanks by non-return valves. When a lower tank is damaged, the incoming sea water pushes the oil in the damaged tank up into the ballast tank. The Coulombi Egg Tanker is a design that is aimed at reducing oil spills. It was designed by Anders Björkman. It was approved by IMO as an alternative to the double hull concept. The United States Coast Guard does not allow this design to enter US waters, effectively preventing it from being built.
The design is an enhanced Mid-Deck Tanker and consists of a series of centre and wing tanks that are divided by horizontal bulkheads. The upper wing tanks form ballast tanks and act as emergency receiver tanks for cargo should the lower tanks be fractured. The lower tanks are connected to these ballast tanks by non-return valves.
When a lower tank is damaged, the incoming sea water pushes the oil in the damaged tank up into the ballast tank. Because of the hydrostatic pressure, there is an automatic transfer out of the damaged tank.
The double-hull design is aimed at the probability of zero outflow. There is an automatic transfer out of the damaged tank much like the active full vacuum ship. If the damage is near the bottom of a lower cargo tank, the Live Bottom will end up about 9m above the ship bottom well protected from the current wave action and ship motion.
In low energy casualties where only the outside hull is penetrated, this will be the case. However, in high energy casualties both hulls are penetrated. As the tanks of a double hull tanker are larger than those of MARPOL-tankers and preMARPOL-tankers and the height of the cargo above the water line is higher, the resulting spill can be much larger than these single hull designs. In the Coulombi Egg design spillage is greatly reduced, possibly to zero.
Where a double hull VLCC has a ballast tank coated area of about 225,000 m^3, in a Coulombi Egg tanker this area is reduced to 66,000 m^3. This reduces maintenance and corrosion risks, which otherwise may result in structural failure, as was the case with the Erika and Prestige. Ballast tanks properly inerted, this tanker is about as good as it gets in terms of minimizing ballast tank explosions on a segregated ballast tanker. Notice also that you can use air to blow out the damaged tank without putting any oil in the water. This can be a big help in refloating the ship. The Coulombi Egg in its current form has some faults. The tanks are too long and for a VLCC the centre tanks are too wide. More subdivision is needed and the roll behavior in ballast is quite unattractive. This issue however can be solved with the introduction of beamy, shallow draft twin screw hulls.



Picture [4]: Coulombi Egg Tanker behavior in a damage condition (Devanney, [4]

Triality VLCC

The Triality is a VLCC concept design and the most up to date of the innovative designs we present. It is developed by the Norwegian Classification Society (Det Norske Veritas, DNV) and was developed to demonstrate how the maritime industry may go forward in solving some of the environmental challenges lying ahead. The vessel had three objectives: it needed to be technically feasible, have significantly fewer emissions to the air and sea and be as financially competitive as a conventional VLCC. The Triality's three main features are LNG as a fuel, no use of ballast water and capture and use of volatile organic compounds of the cargo (VOC).

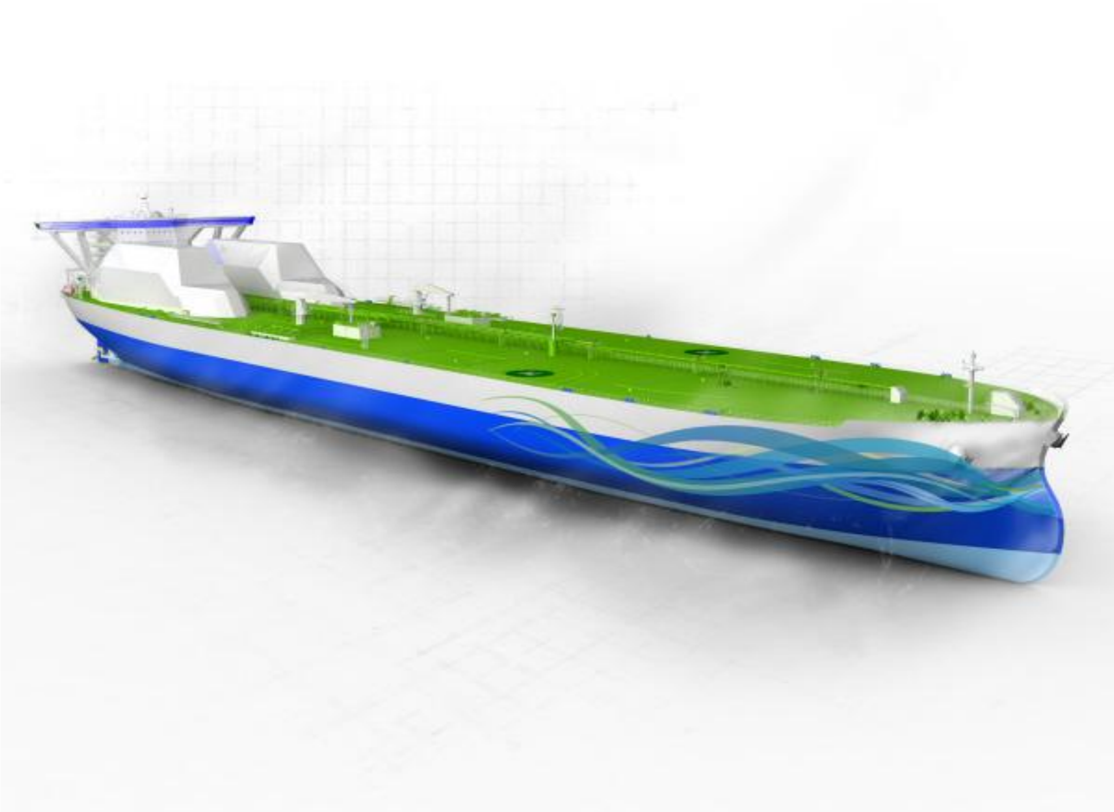
LNG is used for propulsion, power and steam production (instead of HFO). The Triality concept will have two high pressure dual fuel 2-stroke main engines with MGO as a pilot fuel, low pressure dual fuel generator engines with MGO as a pilot fuel, triple fuel boiler that can burn natural gas, MGO and VOC. Two type C pressure tanks each of 6750 m3 volume, located in a deck house. The main engines are dual fuel from MAN B&W and where chosen in cooperation with MAN, based on the operational profile of the vessel and are 2X 5S65ME-C8-GI-TII.

As we know, ballast water is needed (especially in tankers and bulk carriers, namely ships in charter trades) in order to obtain full propeller submerge and at the same time sink the bow enough to avoid slamming damage in head seas. The two unwanted effects from the ballast operation on a tanker are the biological pollution due to the organisms and invasive species developed inside the ballast tanks and the additional fuel needed to carry the ballast water, which in case of a VLCC is 80000 to 100000 m3 of seawater. The Triality is a ballast free ship with new cargo tank divisions making loading of the vessel possible without the need for ballast for strength or ballasting, new flared hull shape giving sufficient submersion without cargo without ballast while giving 16% less wetted surface, lower block coefficient and a more energy efficient hull (4%). The main dimensions of the project are characterized by a big variation of the beam along the waterlines as a result of the V-Shaped hull, an increased length, a small flat bottom beam and small block coefficients.

The low temperature from the LNG vaporizing is used to re-condence cargo vapors (VOC) normally released to air during cargo voyage. Up to 500 to 600 tones cargo vapors are assumed possible to collect for each cargo voyage. The collected VOC is stored in deck tanks, and replaces gas/MGO in the boilers during cargo discharge when large amounts of steam are needed for running cargo pumps. This is hence giving a direct fuel saving in addition to the saving of emissions from the release of the OVC. Based on the trading pattern the ice of VOC instead of LNG as boiler fuel during discharge gives an annual reduction in energy, which is supplied through LNG or MDO, consumption will be approximately 9%.

Overall the Triality Concept is a very promising one, however the authors have a few concerns:

1. The V-shape of the hull, combined with the increased length (30 meters), the very low Cb and the geometric complexity of the hull are going to rocket the building cost, especially if we into account the shipyard's reluctive policy against design changes. Even in terms of conceptual ship design, where feasibility is a second order priority, the increased building cost is a very heavy burden of this ship which will affect the Required Freight Rate and the Net Present Value of the investment.
2. There are concerns regarding the sea keeping behavior of V-shaped hulls, especially in head seas, as seen in container ship operation.



Picture [5]: The Triality VLCC rendering (DNV [5])

The Case for the Twin Screw Tanker

Back in 2008, Jack Devanney a predominant tanker expert wrote a paper on the values and advantages of twin screw tanker propulsion.

According to the CTX tanker casualty database machinery failures are an important cause o tanker accident and subsequently spillage. More specifically, there have been 165 accident due to machinery failure out of a total 856 accidents resulting into 111 dead and 1,093,839,802 liters of oil spilled out of 2173 dead and 6,456,287,392 liters of oil spilled by the entire tanker fleet in one year. One can easily see that the machinery failures are a significant part of the total tanker fatalities. A way of reducing this accident rate would be with the introduction of twin screw tankers. But what is twin screw?

It is a tanker that will have twin engine rooms with twin engines and auxiliaries, twin propellers and twin rudders. The redundancy degree in such a case would be doubled and the tanker casualty analysis would show a significant drop.

Furthermore, Mr. Devanney suggests based on his own experience on operating upscale well built ULCCs that the crew would witness in a total of 3500 at sea days ten involuntary total losses of power including one catastrophic liner failure, 13 reductions/shut downs mostly from leaking high pressure fuel oil piping, 5 crankshaft and 1 camshaft bearing failures and many others. Digging deeper, the DNV Loss of Control Number is equivalent to 1 loss of power/steering every 1.7 ship years, which means that the entire tanker fleet suffers at about 6 losses of power/steering per year.

Having seen the casualty analysis for machinery failure, it is suggested that based on the existing database and the incident descriptions, propulsion redundancy, properly implemented, can reduce the tanker total loss of power incidents dramatically (more than 100%).

The cost of implementing twin screw propulsion is also examined. The M/V Nanny a twin skeg ULCC is mentioned for its infamous maneuverability and the economies of scale it facilitated. According to Korean yards and the author the price increase for implementing twin screw for a tanker of the VLCC size would be at about 10% of the equivalent single screw price without bargaining. This cost, is an external cost that can be as a premium by the policy makers in order to dramatically reduce the risk of tanker casualty. As Mr. Devanney highlights the only way to make sure that twin screw is adopted is by regulation as it happened with the double hull arrangement two decades ago.

In the present market, the most notable example of the use of twin screw propulsion in tankers is the fleet owned by STENA Bulk, a well known Swedish shipping company, member of the Stena Sphere. The fleet is comprised by primarily Crude/Product carriers of PANAMAX size (~75000 DWT) and smaller product carriers. In addition to that, two sister ship VLCC’s that were shallow draft and twin skeg were designed and constructed in Hyundai Heavy Industries for STENA back in 2002 and set the example for the safe economic and efficient transportation at this size. Having such a background and experience, STENA has evolved the MAX concept for a range of sizes including the BMAX vessel which is suitable for the Baltic sea trade with a deadweight between a Suezmax and a VLCC (200.000 DWT). The MAX concept is the use of twin screw propulsion combined with a beamy and shallow draft hull.

A more common application for twin screw propulsion is that of shuttle tankers were propulsion redundancy and dynamic positioning is the most critical design aspect in order to be able to fulfill the mission requirements for offshore loading from FPSO’s (Floating, Production and Storage Onboard).

Having the mentioned work as inspiration, it was chosen to address the issue of propulsion redundancy by adopting a twin screw propulsion system realized by a Twin Skeg hull in the AFRAMAX segment. The reference ship used was also of twin skeg arrangement and is a shuttle tanker serving the Tee Kay fleet. The twin screw propulsion was combined with a beamy and shallow draft hull of a high block coefficient and elliptic bilge.

References

3. Formal Safety Assessment of Tankers for Oil, IMO 2008
4. Apostolos Papanikolaou, «RBD Application: AFRAMAX Tanker Design», Risk Based Ship Design, Chapter 6.2
5. Helge Kringel, «The Vossnack Cylinder Tanker», The Naval Architect, March & April 2011, The Royal Institution of Naval Architects (RINA)
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7. Jack Devanney, «2008 Tanker Loss of Power Casualties», Center for Tankship Excellence, USA, 2008

3. GENERAL PRINCIPLES OF SHIP DESIGN AND OPTIMIZATION

In this sub-chapter, the process of ship design is described as well as the evolution of traditional ship design in parametric hull modeling and simulation driven design. Furthermore, FRIENDSHIP Framework, the software employed for the design and optimization case studies is described as a representative simulation driven design software.

From the Shipwrights to Simulation Driven Design

Ship Design can be defined as the effort to produce a hull shape with certain properties, dimensioned, outfitted and with weight such in order to be able to fulfill specific criteria, commonly known as Mission Requirements. The mission or owner requirements, typically include the deadweight (and sometimes tank/hold capacity) of the vessel, it's speed, range and principal particulars. The latter are usually driven by navigational constraints of the trade route which the future vessel is going to be deployed in.
If we want to categorize the tasks the ship designer has to do, by looking to the references, typically we will find the Design Spiral. This is the epitome of what traditionally is called Ship Theory; the preliminary design, analysis and study of a vessel based on a reference ship with similar characteristics (mother vessel).

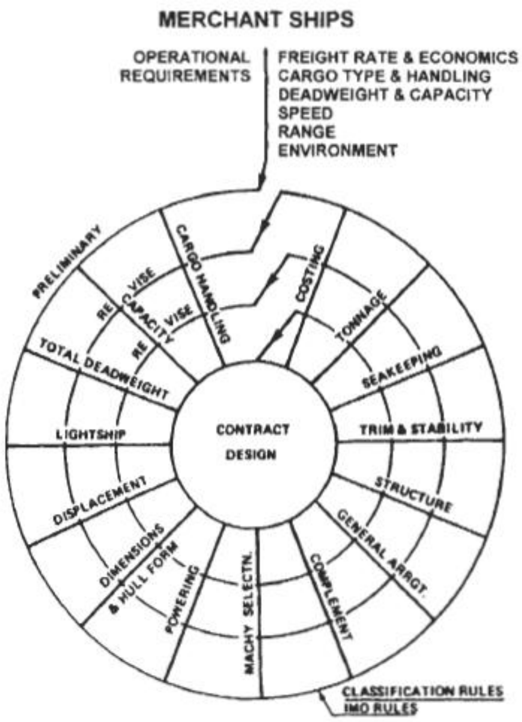

Figure [18] Design Spiral of Merchant Vessels (Practical Ship Design)

As we can see from the above spiral, one of the most important stages of the procedure throughout the process up to the contract design is the hullform and lines development (as it is used to be called by Naval Architects). This stage originally was done by hand by draughts men using splines and weights to create fair shapes that are easy to construct and seem to have good hydrodynamic properties, due to their fairness. This used to be the art of Naval Architecture. With the introduction and evolution of computational methods such as Computer Aided Design (CAD) and Computational Fluid Dynamics, there has been a shift towards computerized ship design which nowadays is dominant.

Parametric Ship Design

The design of ship hull forms usually takes a longitudinal perspective in which the modeling of sections dominates. Here the design information an flow direction are mostly in alignment. One can see that an intelligent formulation is needed since the effort to solve a (design) problem scales up rapidly with the freedom of the system.

Parametric models have been introduced and developed developed to capture the essence of functional surfaces while allowing the necessary freedom for individual design. The art of parametric modeling according to Harries (2008) is to provide the right balance between this freedom to what is described and the unavoidable predicament of having to reduce the definition to as few parameters as possible. In general, parametric approaches can be subdivided into:

a. Partially parametric and
b. Fully parametric

Partially parametric models build on existing shapes. Changes are described via parameters which act as the controls to create variants. Fully parametric modeling on the other hand, tries to generate geometry purely from parameters, each variant being an instance of actual values in the parameter set. As opposed to this, in conventional modeling shapes are defined by data items which are truly independent of each other and do not bear any task related information.

In the field of hull form definition important milestones are associated with scientists such as Taylor (1915), Weinblum (1953), Lackenby (1950), Thieme (1952), Buczkowski (1969), Granwille (1969), Nowacki (1977), Soding and Rabien (1979) and others. A prominent example of partially parametric modeling is the longitudinal shift of sections as presented by Lackenby (1950). Hull variants are realized by taking a parent hull and modifying it according to changes in the prismatic coefficient, the centre of buoyancy and the extend and position of the parallel midbody.

As highlighted by Harries and Nowacki (1999), in computer aided ship hull design (CASHD) the modeling of a hull's geometry is an undertaking which requires know-how and experience in both naval architecture and geometric modeling – the mathematical representations having largely replaced lines plans drawn with splines and ducks. The prime objective of the hull definition process is to develop a geometric description of the hull form such that:

1. all relevant physical and geometrical characteristics – i.e., form parameters like displacement, center of buoyancy, waterplane area, center of flotation, angle of entrance of the design waterline etc. – are met and
2. an acceptable shape quality – often expressed by fairness – is achieved.

Primarily driven by the underlying mathematics, the current methodology of most CASHD Systems is based on interactive shape generation. Typically points – e.g. the vertices of a B-spline's defining polygon or polyhedron – need to be manually positioned in three-dimensional space in a highly concerted manner. Conventionally, a naval architect produces an initial shape. He or she then evaluates the hull form in terms of its various derived properties. This means that the current design's actual form parameters are analyzed and compared to desired values and the fairness is judged from curvature plots or simply from a sharp (but subjective) look at the ship lines. The designer then has to modify and assess the geometry repeatedly. Once finished, further changing the geometry either to accommodate new form requirements or to systematically improve the shape to the benefit of, for instance, hydrodynamic performance is a tedious task since fairness has to be brought about by hand, and interactively introduced modifications usually propagate into considerable parts of the hull.
In parametric hull design the prime features of the hull shape are defined via geometric descriptors called form parameters. A ship's geometry is described in terms of longitudinal curves – so-called basic curves like the sectional area curve and the design waterline.

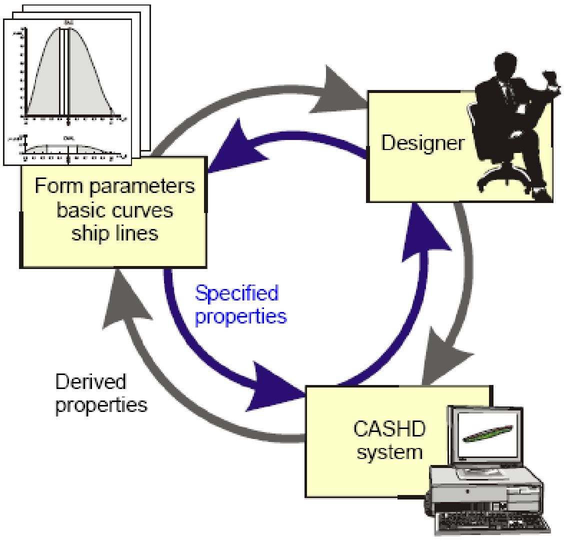

Figure [19]: Workflow in Computer Aided Ship Design Software

The basic curves are modelled from form parameter input, ideally containing all information needed to produce a hull's shape.
Instead of conventionally generating a shape and deriving its properties afterwards as illustrated by the clockwise process in figure 2, in form parameter design the object's required properties are specified first – i.e., quantified numerically – and then its shape is computed according to these specifications, see counterclockwise process in figure 1. In this way, rather than coping with the underlying mathematics, the naval architect is free to think lines and hull form as expressed by their form parameters. Form parameters can thus be regarded as high-level design elements; they are the vocabulary with which to formulate design ideas.

Focusing on bare hulls without appendages as depicted in figure 2, the modeling process is subdivided into three consecutive steps as shown in figure 3, see (Harries, 1998):

1. Parametric design of a suitable set of longitudinal *basic curves*.
2. Parametric modeling of a sufficient set of *design sections* derived from the basic curves.
3. Generation of a small set of *surfaces* which interpolate the design sections.

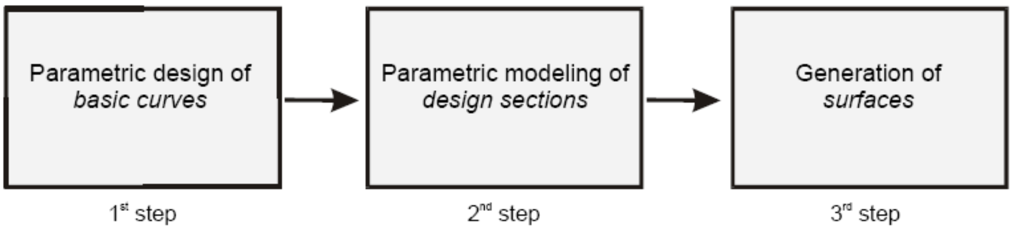

Figure [20]: Steps in the generation of parametric surfaces

Basic curves generally comprise three segments: a curved portion for the run, a straight part in the middle and again a curved portion for the entrance – though the straight part might vanish.
From the mathematical point of view, the curve generation problem is the same for basic curves and design sections, i.e., planar curves need to be found which simultaneously satisfy a set of chosen form parameters. However, there is a decisive semantic difference between the modeling of the two types

of curves: Laying out the basic curves essentially means *preparing the mental plan* for the hull while creating the design sections means *realizing the design idea*.
This is the base core and mentality of the Friendship Framework. The basic curves, such as Sectional Area Curve (SAC), the FOB and FOS curves, the deck and design waterline and many more are used to generate smooth surfaces and sections with the extensive use of features. Feature modeling and use is one of the basic specifications of the Friendship Framework.

Computer Aided Engineering and Simulation Driven Design

The close coupling of modeling and simulation is often referred to as Computer Aided Engineering (CAE). A newer term that is more appealing is simulation driven design. Instead while in the past modeling was the driver of the process, simulation is beginning to take over. This means that simulation is increasingly utilized in order to produce shapes (or series of shapes) rather than just to evaluate a handful of interactively created alternatives. Instead of checking and comparing the performance of a few manually created variants the idea is to let the simulation tell what the optimal shape should look like, making it the new driver of the design process. Important prerequisites of a software platform for simulation driven design are:

1. Modeling on functional basis. The shape has to be described and generated from meaningful parameters. The parameters should be more or less independent of each other and changing parameters should affect the functionality of the shape while staying feasible.
2. Tight coupling of simulation codes and modeling. The evaluation of design variants with numerical simulation tools should be readily accessible from within the modeling environment without the need for manual interaction. Results should be made available within the integration platform in order to asses and rank the created variants and to serve as a feedback to optimization algorithms.
3. High level support for the management of updates, variants and constraints. Changes in shape should trigger the update of performance characteristics. The multitude of variants and their corresponding results have to be organized and treated for comparison. Constraints have to be taken into account and observed, infeasible variants have to be labeled.

The Friendship Framework

Outline of the System

The CAE system Friendship Framework is a CAD-CFD integration platform which was developed for the simulation driven design of functional surfaces like ship hulls, propeller and appendages, but also for other applications like turbine blades and pump casings. It supplies a wide range of functionalities or simulation driven design like parametric modeling, integration of simulation codes, algorithms for systematic variation and formal optimization. The offered technologies are:

1. Complex fully parameterized models can be generated. Additionally, (non-parametric) imported shapes can be manipulated with parameterized transformations. Feature modeling, special parametric curve and surface types, as well as transformation techniques support those tasks.
2. External simulation codes, be it in-house codes or commercial codes can be conveniently coupled in a multitude of ways: tool-specific coupling, coupling via a common data interface on XML basis, project based coupling with template files and communication via the Component Object Mode (COM) interface. Except for the first one, all interfaces can be set up by the user.
3. A range of different algorithms for systematic variation, single- or multi- objective optimization is offered from the so-called Design Engines.

Feature Modeling

According to the common definition, feature modeling can be regarded as an extension to geometric modeling where in addition to geometric information; associated functional information is also stored in one object. Features are high level entities that can offer ready shaped and parameterized elements as opposed to primitive elements like points, lines and «normal» curves and surfaces, say a Bezier curve or a Coons patch. Apart from geometric form elements, features can also represent specific work processes. The properties of a feature type are defined in a feature class that constitutes the template for all instances. An instance of a feature is then created by specifying values for the input parameters and adding it to a model.

By using features in the context of a modeling environment, complex design tasks and recurring work steps can be encapsulated in a single object. Firstly, this leads to a clearer and more comprehensible structure, avoiding cluttering up the model. Secondly, a library of previously defined features can be employed whenever similar tasks are encountered. This supports the user in the design process and allows for a higher level of communication between the user and the modeling system. Finally, the reusability is a key for substantial time savings in the design process.

Because it is difficult to foresee all features a user would typically require, it is important to be able to introduce new features in the system. The users should be given the possibility to define, store and organize their own features.

Apart from supplying a set of predefined features, the Friendship Framework allows the user to setup his own feature definitions with a special feature definition editor. In this editor the necessary input parameters and types are specified as arguments of the feature. In the next step the process description is set up using the commands provided by the system. This script is evaluated and the produced output then makes up the feature’s attributes. Features can be combined, allowing a nesting of feature definitions.

For users that are not familiar with the commands needed for the process description, complementing this coding technique, a feature definition can also be automatically generated by selecting entities in the model. The selection set is transformed into a feature definition and supplying arguments are rapidly treated as input argument for the feature. The object that shall be encapsulated in a feature can be freely modeled and transformed into a feature definition afterwards. The feature definitions created by the user can be stored and organized, so that they can be reused in every following project. Text and images can be added for documentation purposes.

The Friendship Framework distinguishes between the persistent creation and the transient execution of a feature. Persistent creation means that an instance of that feature class is created as an object, which is stored in the model and which maintains the process description. The input parameters can be changed at any time, modifying the resulting output. This is particularly well suited for parameterized geometry elements. Transient execution means that the process described in the feature definition is executed only once, storing only the results in the model. The input can also be supplied only once and the procedure is quite comparable to a macro. This is particularly suited for the execution of work processes, where only the result is of interest and there is no new object, which should be modified to a later point in time.

Surface Generation with Features: The Friendship Meta-Surfaces

In the Friendship Framework features also serve as a basis for a special surface type called Meta-Surface. An arbitrarily oriented cross section of the surface is topologically described in a feature definition. Parameterized curves for the distribution of the section's input parameters along the surface can be created and linked to the feature definition through an entity called Curve Engine.
Via the Curve Engine sections are generated at arbitrary positions within the range of basic curves, based on the template stored in the feature. The Metasurface then uses this Curve Engine in a specified range. Since the shape of each surface cross section is known, a complete mathematical description of the surface is obtained without the need for interpolation. Smooth basic curves and sections yield a smooth surface without any further manual fairing. What is more, this surface description is then completely dependent on parameters, making it well suited for systematic variation.

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4. TANKER DESIGN OPTIMIZATION STUDIES

One of the research areas of the Ship Design Laboratory in NTUA is the holistic optimization of ships and especially tankers, containerships and RoRo vessels. In the lines that follow one can find a brief description of the procedures and tools used during these studies as well as some interesting results.
But what is ship design optimization? According to A.D. Papanikolaou et al (2009) it is the *selection of the best solution out of many feasible ones on the basis of a criterion, or rather a set of criteria*. As the same author states «It is evident that the optimal ship with respect to her whole life-cycle is the outcome of a holistic optimization of the entire ship system for its life-cycle». Inherent to the ship design process is the existence of conflicting arguments, even from the first stages of the process (conceptual stage). These conflicts quite often reflect the interests of the various stake holders such as the ship owner, shipbuilders, regulators, charters etc. The ship functions that need to be optimized may be divided according to Levander into two categories: Ship and Payload Functions as seen below:

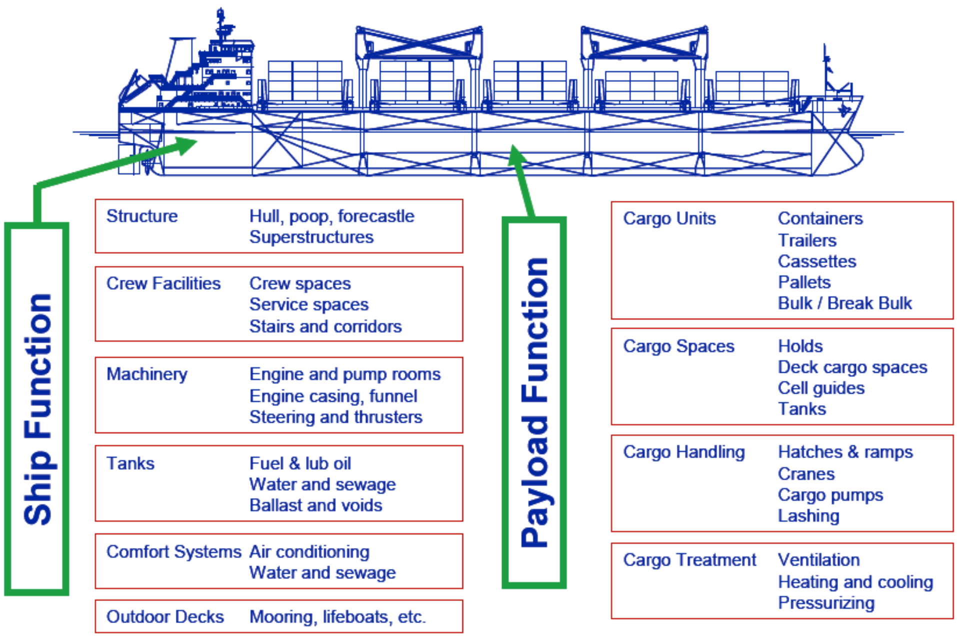


Figure [21]: Ship Functions (Levander 2003)

The «driver» and input for the ship design and optimization processes is in most of the cases (except naval vessels) the ship owners requirements regarding the economic performance, competitiveness and efficiency of the future vessel. Having these requirements in mind, the optimization process should result into a favorable result for these, which usually can be expressed with several indexes such as a low Required Freight Rate (RFR, the freight rate which balances the ship owner's costs, the break-even rate) , the highest level of safety for the crew, passengers and the cargo which in our case of the oil tankers can be reduced in the minimum environmental impact, or in other words the minimal accidental oil outflow. The above decisions can be conflicting as for example, a ship which can have an excellent performance in terms of oil outflow can be less competitive and economical due to a reduced cargo volume and payload (increased steel weight and thus lightship weight).

a. Tanker Design Optimization-TANKOPT

The TANKOPT research program was the first out of a generation that aimed at the systematic, Risk Based Optimization of AFRAMAX tankers, with emphasis on the cargo carrying capacity, steel weight and accidental oil outflow. This research was the base and inspiration for the development of the case studies that are presented in Chapter 3, which present a new approach for an alternative AFRAMAX tanker using however the same principles.

i. Design Optimization Procedure

In order to be able to get past these conflicting arguments a multi-objective methodology is required, leading to a set of «best designs», i.e. designs for which no objective can be improved without sacrificing the performance of another, known as a Pareto set and more generally, a Pareto frontier. The generation of such frontiers requires well established computational capability as well as a software tool that is able to produce a big number of different designs. This software is developed by NTUA-SDL and integrates the following packages:

- NAPA™, a naval architectural software
- POSEIDON™, a structural design and analysis software developed by GL
- modeFronter™, a general optimization program.

The work flow and procedure of the optimization can be seen in the following figure:

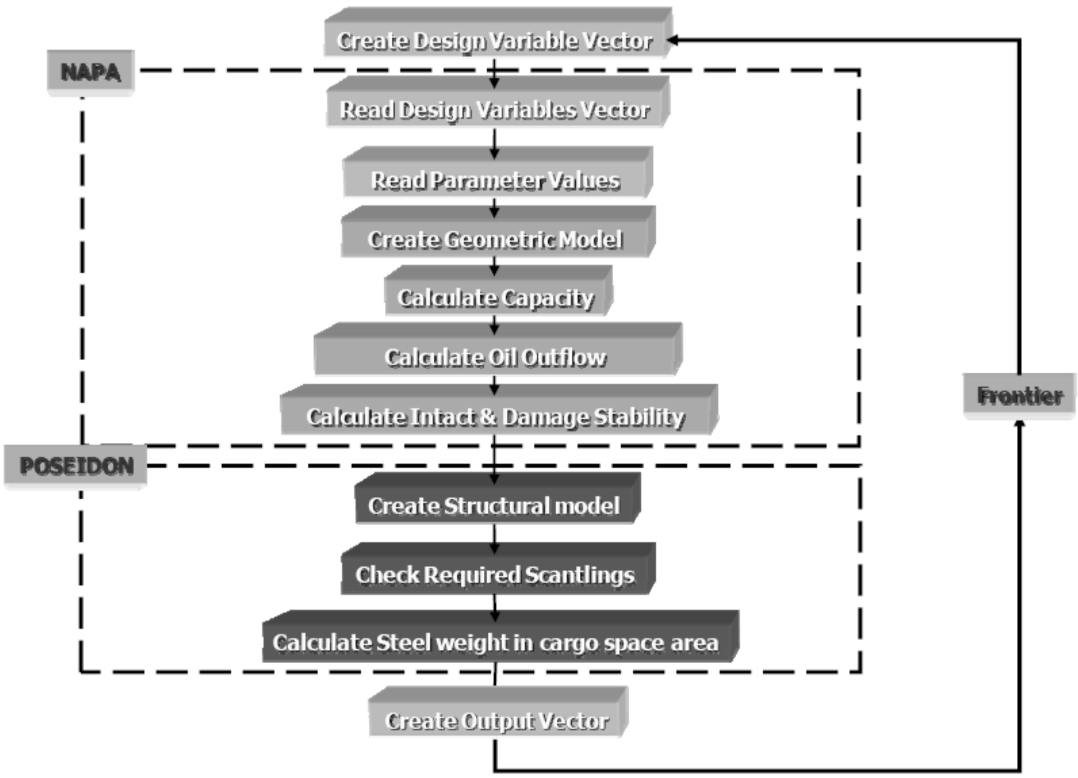


Figure [22]: Optimization Procedure implemented by SDL (Papanikolaou et al 2010)

ii. ***Overview of Design Problem***

The design problem can be expressed as the need to achieve the objectives of the study while satisfying the constraints. In the case of the tanker design, the objectives as conceived by SDL are the maximization of the cargo capacity, the minimization of the accidental oil outflow parameter (MARPOL Annex I Regulation 23) and the minimization of the structural steel weight in the cargo area while maintaining the IACS Common Structural Rules requirements. The constraints are the following MARPOL Regulations:

- Regulation 18 for mean draft, trim, propeller immersion etc
- Regulation 23
- Regulation 27, requirements for intact stability
- Regulation 28, requirements for damaged stability

iii. ***Resulting Design Alternatives***

The studies at SDL have considered five different configurations, with 6 or 7 tanks in the longitudinal direction, 2 or 3 tanks in the transverse and flat or corrugated bulkheads. A population of a total of 21500 was examined with the following distribution:

	Arrangement of cargo tanks	Bulkhead type	Number of designs
Configuration 1	6x2	flat	7287
Configuration 2	6x2	corrugated	1738
Configuration 3	6x3	flat	6147
Configuration 4	6x3	corrugated	3270
Configuration 5	7x2	flat	3043

Table [1]: Alternative Configurations examined by SDL (Papanikolaou et al, 2010)

The generated designs afterwards are compared and the Pareto fronts are created with the help of the generic optimization software.

One can easily see from Figure 6 that the «6X3 flat» Pareto designs dominate all the other, while there are several Pareto fronts with significantly better oil outflow and cargo volume performance than the reference design used.

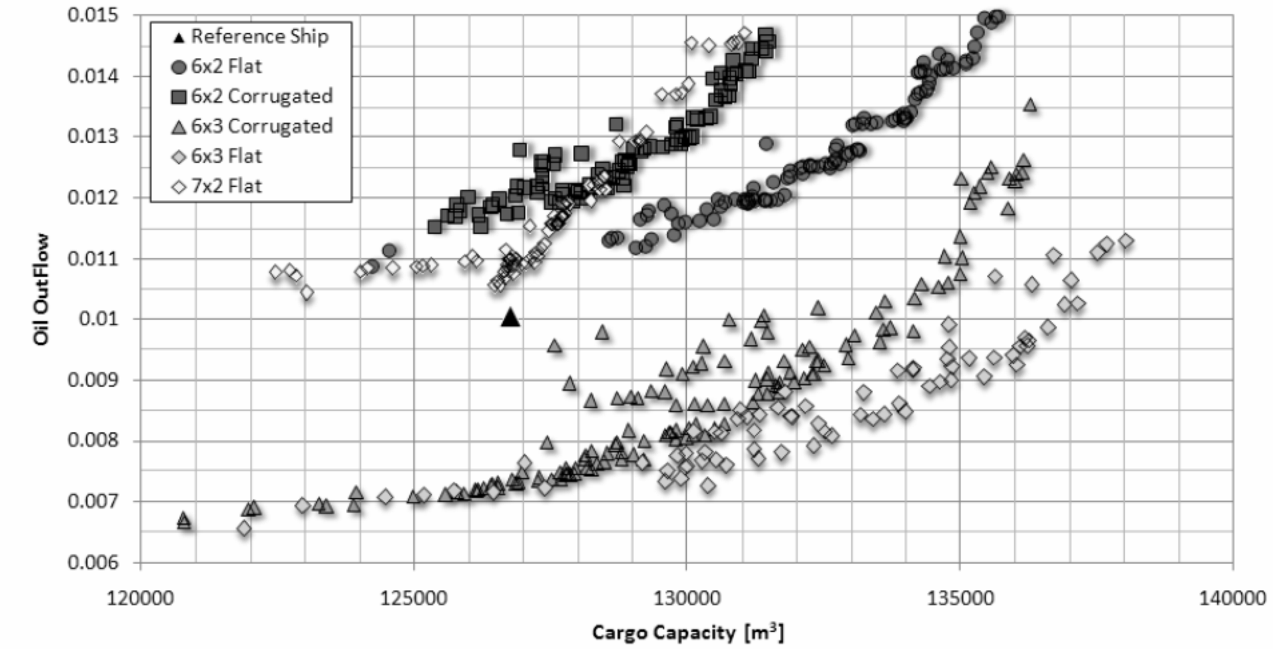


Figure [23]: Oil Outflow vs. Cargo Capacity-Pareto Designs from different configurations (Papanikolaou et al, 2010)

Regarding the relationship of the cargo capacity and lightship weight, the «6X2 flat» Pareto designs have the lowest lightship weight, while the 6X3 offer the biggest cargo volume with a slight increase of the lightship weight as we can see in figure 24:

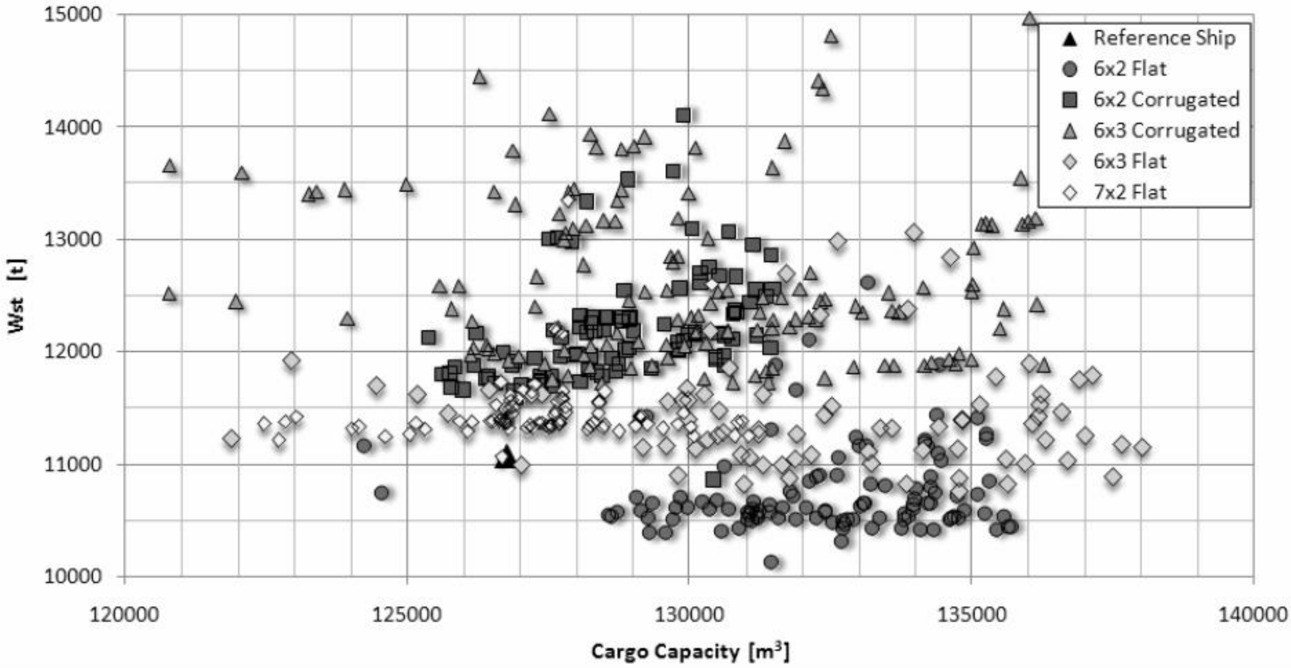


Figure [24]: Cargo Capacity vs. Steel Weight-Pareto Designs from different configurations (Papanikolaou et al, 2010)

The relationship of oil outflow and steel weight can be seen in figure 25. The Pareto front indicates that 6X3 and 6X2 designs dominate the region. In the bottom line, the 6X3 design can be considered to be the best comprise in terms of Wst and Oil outflow.

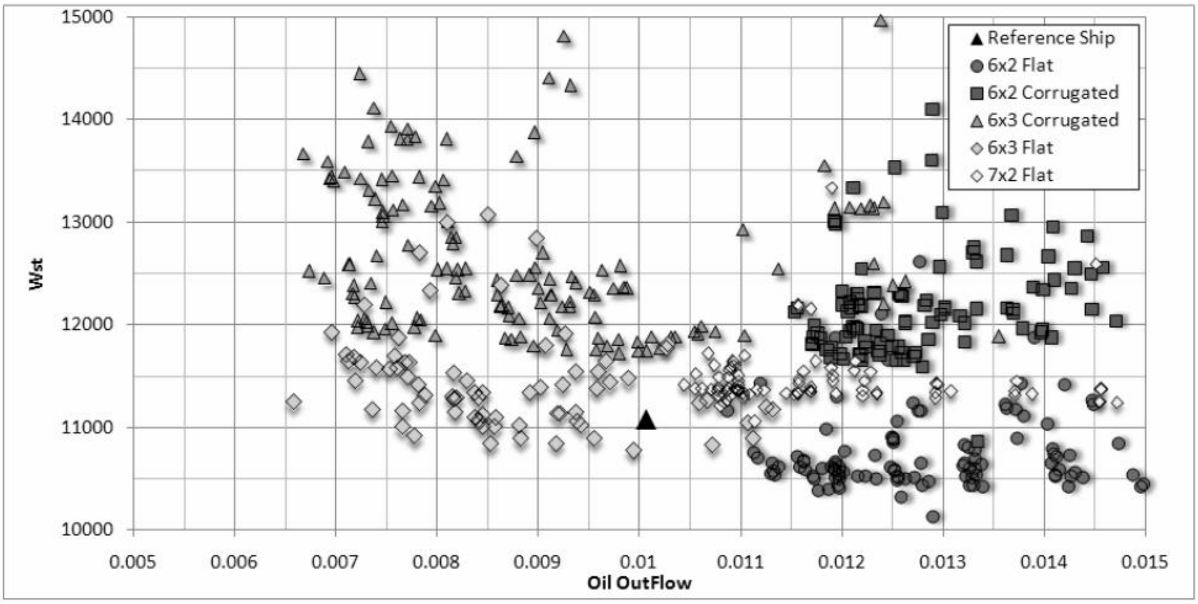


Figure [25]: Oil Outflow vs. Steel Weight-Pareto Designs from different configurations (Papanikolaou et al, 2010)

Other observations from the research results are that none of the corrugated arrangements proves to be better than the flat bulkhead and furthermore the 7X2 design has a very poor performance due to the increased steel weight (since there is one more transverse bulkhead) and the reduced cargo capacity.

iv. *Conclusions*

The conclusions regarding the optimal ship according to the SDL research can be seen in the following tables.
The choice of the optimal design is one using utility functions for solving this multi-criteria decision making problem. The utility functions used represent the objectives: Steel Weight, Oil Outflow, Cargo Capacity. At a first stage they are considered as equals for decision maker, namely each of the functions has a value of 1/3. The optimal designs are represented for that case in Table 2:

	Ref. Design	6x3 Flat		6x3 Flat	
ID		1710		2122	
Rank		1		2	
Cargo.Vol	126765	129804	+2%	135950	+7%
Oil.Outflow	0.01006	0.00777	-23%	0.00942	-6%
Wst.cargo.area	11077	10908	-2%	11013	-1%

Table [2]: Comparison of optimum and reference design for equal utility functions (Papanikolaou et al, 2010)

Another case is to consider the cargo volume more important than the steel weight (initial cost) and the oil outflow (environmental impact). For such a case the results are represented in Table 3:

	Ref. Design	6x3 Flat		6x3 Flat	
ID		2069		2122	
Rank		1		2	
Cargo.Vol	126765	137494	+8%	135950	+7%
Oil.Outflow	0.01006	0.0111	+10%	0.00942	-6%
Wst.cargo.area	11077	10894	-2%	11013	-1%

Table [3]: Comparison of optimum and reference designs when payload is more important (Papanikolaou et al, 2010)

In both cases, according to the research of SDL NTUA, the 6X3 configurations prove to be the most successful. However, the expected reduction in steel weight can be seen under some skepticism. The midship section sizing which directly influences the lightship weight, is done according to the loads as prescribed in the regulatory framework (class societies). If the loads calculated are based on the tank pressure then the weight of the structure should be increased. Else, if the loads are based on the bending moments as calculated by IACS URS 11 then we can expect the same or even lower steel weight.

The results we described above give us a picture of the potentials in cargo compartmentation which influences the tank arrangement of the solution we propose.

b. Better Economics with a Safer Tanker: BEST+

Overview
Germanischer Lloyd (GL) teamed up with the National Technical University of Athens (NTUA) in 2009 to continue research towards novel oil tanker design concepts. The first version of a highly optimized AFRAMAX oil tanker design concept was presented in 2009 and it won the Lloyd's List Greek Shipping Award for technical achievement. This first design optimized cargo capacity, hull structure and oil outflow in accidental conditions and it was documented that both safety and economics could be improved at the same time (Papanikolaou et al [6RINA]). Based on the feedback to the 2009 design concept received by ship owners, operators and yards GL and NTUA continued refining the design and integrated hull form optimization in the overall framework, taking in Friendship systems as an additional partner for Computer Aided Engineering. The design tool, which is generic in its nature yielded an AFRAMAX oil tanker design concept with a lower oil outflow index than required by MARPOL regulations, a lower EEDI compared to the current reference line and a higher speed (or lower fuel consumption at comparable speed) than all similar existing tankers while having a higher cargo capacity.

Design Focus
The design of the vessel focused on the following boundary conditions as design targets and constraints:

1. US ports on the Mexican Gulf coast have limited berth lengths and access routes. The related maximum vessel dimensions were used as constraints in the design optimization.
2. A high cargo capacity and a high speed were taken as requirements from tanker operators to enable taking a particular large cargo volume and to capitalize on the one extra voyage per year, with both delivering additional revenue compared to a standard AFRAMAX oil tanker design. The maximum installed engine power was fixed as input.
3. With the EEDI expected to be implemented at IMO before 2015, vessels with too high EEDI values will potentially struggle to find charters. Therefore, the aim was to have an attained EEDI value which will still be competitive in the years after 2015.
4. With the US coastal waters becoming an Emission Control Area (ECA), and with strict regulations demanding to use fuels with 0.1% Sulphur from January 2015, an AFRAMAX oil tanker for Caribbean trades needs to be equipped to have large MGO tank capacities, or exhaust gas scrubbing systems or prepared to be using alternative fuels like for instance LNG. For this design, however only large liquid fuel tank capacities were considered.

The design environment
Due to the contradicting nature of ship design, a multi-objective methodology is required, leading to a set of best designs also known as the Pareto Set. With the Pareto set on hand the designer can select an optimal solution according to the preferences which can be done in a number of ways. A genetic algorithm was employed during the first design activity, with creating and assessing about 1700 design variants. For the purpose of the current design optimization, a two-stage optimization approach was adopted comprising as first step a Design of Experiments (DoE) procedure, followed by a Tangent Search approach to refine the identified better design variants. A general flow chart of the design optimization is presented in the following figure.

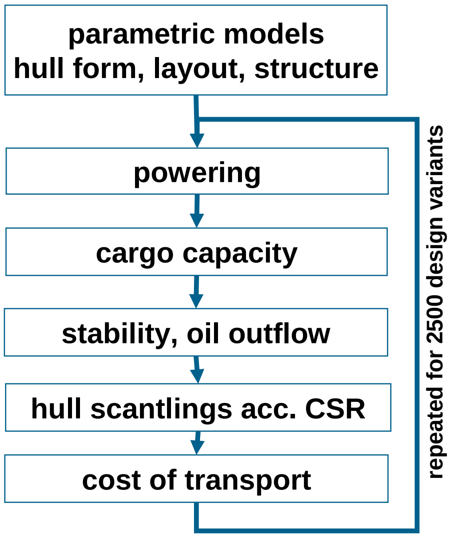


Figure [26]: The generic flow chart of the optimization process (Papanikolaou, Sames et al [6])

The optimization is based on developed parametric models for the hull form, hull layout and hull structure. The Cost of Transport, namely the ration of the annual total costs to annual cargo transported, was used to guide the optimization in the final stages. The Pareto front of optimum designs is clearly visible and the best designs in terms of oil outflow index, EEDI and cost of transportation are labeled explicitly. The optimum design with respect to cost of transport was used as a starting point for the final hydrodynamic optimization of the aftbody, addressing the quality of the wake field and propulsive efficiency as objectives

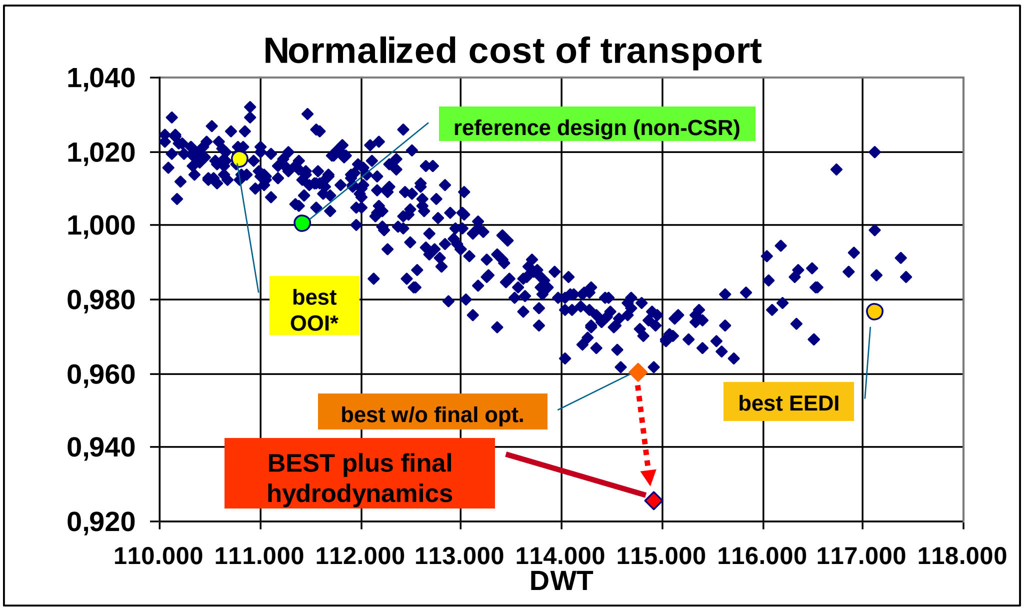


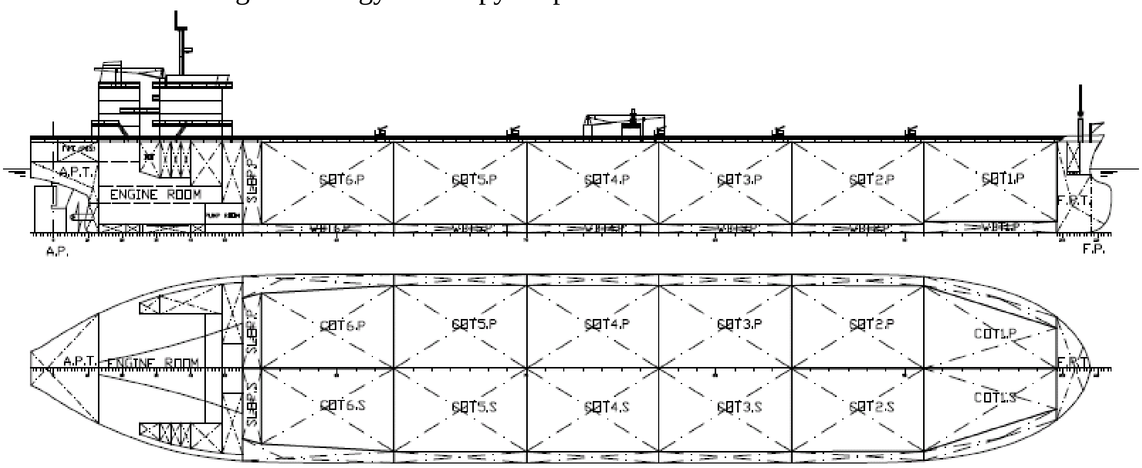
Figure [27]: Pareto Set of the optimization process (Papanikolaou, Sames et al [6])

<u>The Resulting Design</u>

The resulting design and its particulars is characterized by the following:

1. The hull and cargo oil tank layout is standard with a uniform tank length distribution and constant double hull width and double bottom height over most of the cargo hold.
2. The double hull width is larger than compared to similar designs (and to formal requirements of MARPOL) to facilitate low oil outflow in accidental conditions. A raised double bottom height in the cargo oil tank No. 1 area also reduces oil outflow in grounding accidents. To ensure structural continuity, an inclined inner bottom is located over two frames in cargo oil tank N.2 aft of the transverse bulkhead.
3. Slop, fuel and ballast tanks capacities have been kept similar to existing designs. MGO tank capacity was increased to 700 tones to enable longer voyages inside ECA areas.
4. The large cargo volume was realized, with main dimensions being constrained due to port facilities, by a larger depth than similar designs. The relatively large block coefficient also contributes to the high cargo capacity of this design.
5. The installed power was limited to the power available from a typical AFRAMAX engine (6S60MC-C) and the speed performance of the hull was optimized for scantling draft, design draft and ballast draft. This 58resulted into an increased speed which when fully loaded is 15.6 knots and 16.8 when ballasted.
6. The resulting design also features a 16% lower EEDI than required by the reference line. With the first reduction expected to be 10% after January 2015 the BEST+ appears to be the best prepared for the competition.

In conclusion we can see that with some advanced software and optimization skills, a safer greener and smarter vessel was designed. The oil outflow index is 9% lower than required by MARPOL, the EEDI is 16% lower than the current reference line and the cost of transport is 7% lower compared to a reference design. Taken together the new design concept demonstrates that better economics and higher safety can be realized in one design. Another key issue is that the BEST+ concept is 100% feasible with existing technology and shipyard policies.



Picture [6]: The General Arrangement of the BEST+ Tanker (Papanikolaou, Sames et al [6])

DWT	114.923	t	DB height	2,1	m
Cargo Volume	129.644	m3	DB height COT1	2,75	m
Loa	250,0	m	DH width	2,65	m
Beam	44,0	m	Oil outflow index	0,0142	
Depth	21,5	m	Speed at Td	15,6	kn
Design draft	13,7	m	Speed at Tb	16,8	kn
Cb	0,85		EEDI	3,281	g CO2/(t*nm)

Table [4]: main parameters of resultant optimum design (Papanikolaou, Sames et al [6])

c. ***Optimization of Twin Skeg Tankers***

A notable work on the optimization and analysis of twin skeg tankers has been the Diploma Thesis of Mr. Fabian Tillig at TU Berlin. The thesis was realized in the Friendship Framework were two types of skeg bossing have been development and parametrically modeled and analyzed using hydrodynamic principles and the tight integration with the SHIPFLOW package, which is a very popular CFD tool. The first model has skegs fully integrated with the lines of the hull without any discontinuities. The second model represents a gondola type, were the skegs are added to a bare hull, without ensured continuity between the shape of the bare hull and the skegs.

The integrated type model is controlled by a number of global characteristic parameters, such as the breadth, draft and length and also a set of more specific aftbody parameters such as the aftbody length, x position of the merge of the flat of side curve in to the deck curve, x position of the aft base and the position of the propeller. In addition some parameters describing the general arrangement of the skegs are needed, such as the distance of the skegs and the vertical and horizontal angle. The shape of the skegs is defined by three diagonals on each side (inner and outer side). It is also important to see that the model is divided into an inner and outer part, which is imperative for the computational fluid solver to understand the symmetry and asymmetry of the hull.

Within the parametric model of the gondola type the shape of the skegs is modeled almost independent of the aftbody hull. As input some objects from the bare hull model are needed to create suitable skeg geometry. These objects are the bare hull surface (one entity), the FOB curve of the bare hull and the keel curve of the bare hull. The skegs themselves are modeled almost analogously to the integrated model, but there are some differences while considering the upper diagonals.

The optimization was done with hydrodynamic principles with the objectives being the total resistance, the wake variation, the SVA wake quality criterion, the improved SVA wake quality criterion, the normalized pre-swirl moment, the ship merit factor and the difference between the required and the attained EEDI.

After an extensive design of experience and several automated optimizations using response surface methodology an optimized twin skeg design was found featuring an 11% lower total resistance than the baseline twin skeg design.

d. ***Other Studies on Tanker Optimization***

There are several studies in Tanker design, while in tanker design optimization are fewer. An interesting and recent study has been the Diploma Thesis of Dimitris Chotzopoulos who has developed an optimization tool for the principal dimensions of vessels based on the Formdata series. On the same direction Timoleon Plessas has built a similar tool but the optimization takes place under uncertainty, which means that several exogenous parameters, such as fuel prices and market condition, follow a statistical distribution and are not taken as a constant.

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CHAPTER THREE:

DESCRIPTION OF THE DEVELOPED HOLISTIC METHODOLOGY FOR TANKER OPTIMIZATION

"And may the sea grant each man hope, such as the sleep brings dreams"
Christopher Colombus

CHAPTER THREE: DEVELOPED METHODOLOGY FOR THE HOLISTIC OPTIMIZATION OF TANKERS

1. Introduction

Holism (from ὅλος holos, a Greek word meaning all, whole, entire, total), is the idea that natural systems (physical, biological, chemical, social, economic, mental, linguistic, etc.) and their properties, should be viewed as wholes, not as collections of parts. This often includes the view that systems somehow function as wholes and that their functioning cannot be fully understood solely in terms of their component parts.

In this chapter the developed and applied methodology is described. The methodology is holistic, meaning that all of the critical aspects of the design are addressed under a common framework that takes into account the lifecycle performance of the ship in terms of safety efficiency and economic performance, the internal system interactions as well as the trade-offs and sensitivities. The workflow of the methodology has the same tasks as the traditional design spiral with the difference that the approach is not sequential but concurrent.

2. General Objectives for Optimization

From the analysis of the tanker industry background and the current condition in chapters one and two, it can be interpreted that the main areas that require attention during any ship type, design optimization are the Safety, Efficiency, Competitiveness and Environmental Friendliness given the new circumstances in the industry. In the holistic nature we try to adopt our approach we consider that these objectives adequately fit within this context. The Accidental Oil Outflow is the first objective and expresses both the Safety and Environmental Friendliness, the Required Freight Rate is an indicator of the competitiveness while the IMO EEDI of the efficiency. Concurrently, the required ballast water amount according to the MARPOL requirements is recorded and acts as a secondary objective which in the AFRAMAX case study is satisfied by all the design variants due to the innovative hull shape.

3. Brief Description

We can see the workflow at the figure that follows. The geometrical modeling takes place in the Friendship Framework that also imposes the Lackenby shift and subsequent variation which is the driver behind the hullform development, variation and optimization. The result of the Lackenby transformation is a new hull surface with the desired hydrostatic properties that are also subject of the optimization.
On that surface the tank arrangement is generated with a feature of the Friendship Framework and its capacity is calculated. For this particular reason, and due to the tested accuracy and robustness of the Holtrop and Mennen statistical and empirical method it was chosen to implement this for the holistic methodology and perform some benchmarking for the twin screw model in order to ensure that the wave making resistance has no major deviations due to the innovative stern hull shape.

The Lightship weight is calculated using a mixture of traditional methods as well as a hybrid method developed within this Thesis (Appendix IV) that is responsible for the calculation of the steel weight of the cargo block based on the results of calculations of a structural program (POSEIDON) made during an independent study. The machinery and outfitting weights are well approximated with empirical methods such as the Watson and Gilfillan formulas and the Schneekluth methods.

The main engine is dimensioned from the MAN B&W marine engine program and based on their Specific Fuel Oil Consumption the consumables for a range of 15000 nautical miles are calculated. Given the consumables and the deadweight the payload weight is determined, which is used for checking the special gravity of the cargo given the cargo volume.

The initial intact stability is assessed by means of the metacentric height of the vessel (GM). The centre of gravity of the cargo is determined from the capacity calculation within the framework while the centre of gravity for the lightship and consumables is determined from non-dimensioned coeffiecnts (functions of the deck height) that derive from the information found in the trim and stability booklet of the reference ship. The maximum scantling draft (or in other words the minimum freeboard) is determined from the International Loadline Line Convention (ILLC 1966) guidelines programmed in a FFW feature.

Another, most critical item, for calculation during this simulation is the Accidental Oil Outflow Index in accordance with the guidelines of the Regulation 23 of the MARPOL convention. This was programmed in the NAPA software in previous studies (TANKOPT and BEST+) but in our case it was chosen to use a code provided by NTUA student Panagiotis Sotiralis. This code, programmed in Excel, was integrated with a COM type integration in the FFW and was calibrated using the MARPOL examples for the calculation of Regulation 23. This index, being the most indicative of the safety of the vessel since it is calculated with probabilistic principles has been one of the objectives for the optimization.
The Required Freight Rate, which is the second objective of the optimization and is indicative of the economic performance and competitiveness of the vessel. It is calculated by a feature of the FFW which takes into account the tank capacities, fuel consumption and subsequent cost as well as the operational profile for the entire lifecycle of the vessel (port operations, off hire days etc).
The Energy Efficiency Index (EEDI) is calculated based on the IMO MEPC 62 guidelines and is the third optimization objective as an indicative of the efficiency of each design.

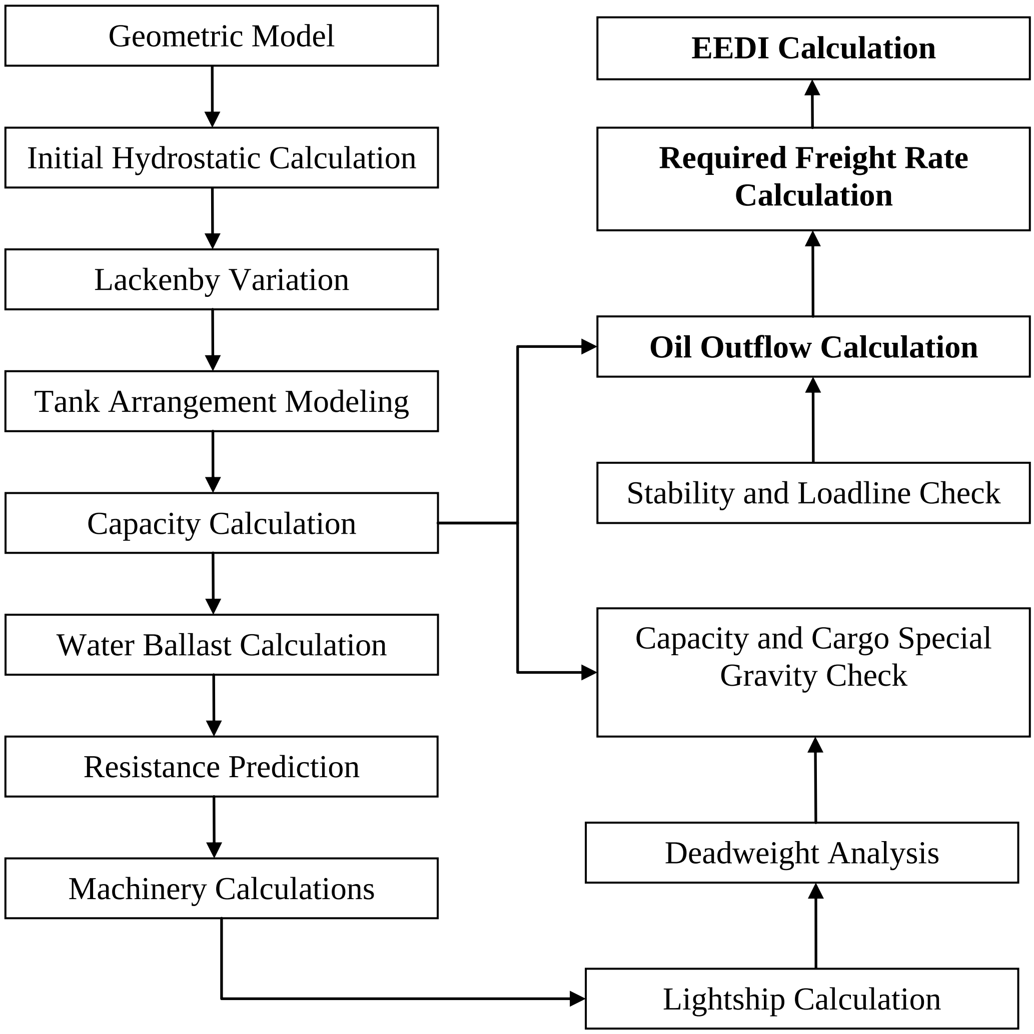


Figure [28]: Workflow in the developed Optimization methodology

4. Sensitivity Analysis

Within the context of the development of this holistic methodology it is imperative to know the sensitivities of the model and if there are any unwanted manipulations of the results in an extensive magnitude. For this particular reason, based on the results of the optimization algorithms (NSGA II for AFRAMAX and MOSA for the VLCC) a sensitivity analysis took place using the integrated tools of the FFW. The detailed graphs and analysis can be found in Appendix I.

1. Required Freight Rate (RFR) sensitivity

The RFR is used as a Key Performance Indicator for the operational efficiency and the market competitiveness. Namely it represents how economical the ship is to build, operate and how profitable its operation is (in terms of cargo capacity). A general impression is that the larger vessel sizes have a positive influence to the RFR thanks to the strong correlation to the tank capacity. This phenomenon is very common in ship design, as scale economies have been the primary driver of the evolution of tanker design up until recently, that there is an upper unofficial limit of tank sizes due to the risk of pollution. Other variables than the main dimensions that have a strong (the strongest) influnce are the tank variables while the local hullform shape has a less important but existing correlation.

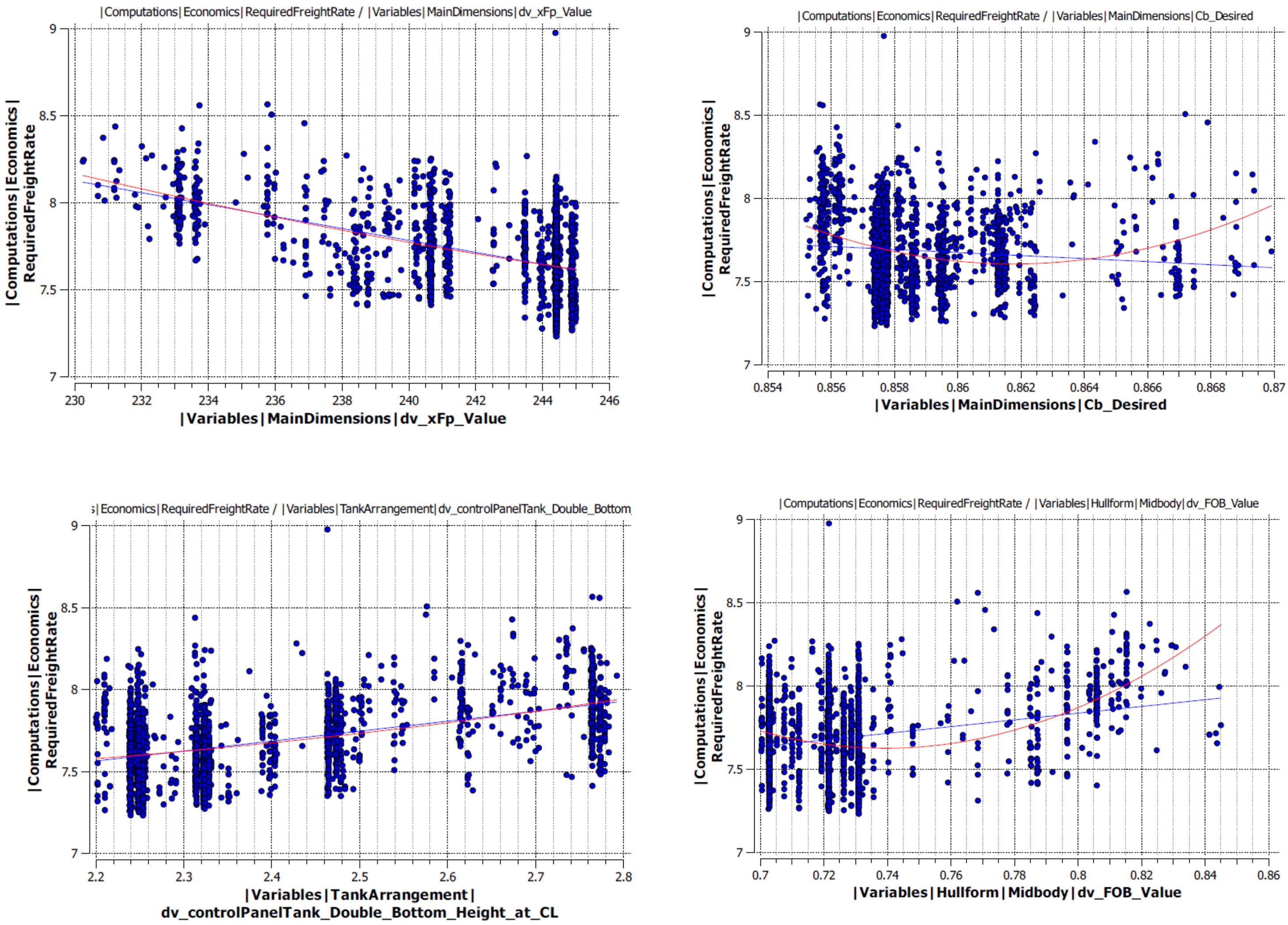


Figure [29]: Sensitivity analysis diagrams for the RFR (Lbp. Cb, h_{DB}, FOB-Appendix I)

2. IMO Energy Efficiency Design Index (EEDI) sensitivity

The EEDI is used as a Key Performance Indicator for the efficiency of each design and is calculated according to the guidelines decided on IMO MEPC 62. A general impression is that the larger vessel sizes have a positive influence to the EEDI thanks to the strong correlation to the deadweight and the smaller increase of the installed power. Since speed was not decided to be used in the optimization as a design variable the installed power was not varied significantly and it is also now clearer which designs have a better hydrodynamic performance. The local hullform parameters influnce the EEDI via the wetted surface and thus the installed power. It is also very interesting to see that the sensitivities found for the RFR objective are qualitive the same as in the EEDI which illustrated the "win-win" situation for the decision maker with the increase of the fuel and transport efficiency in conjunction with the economic performance.

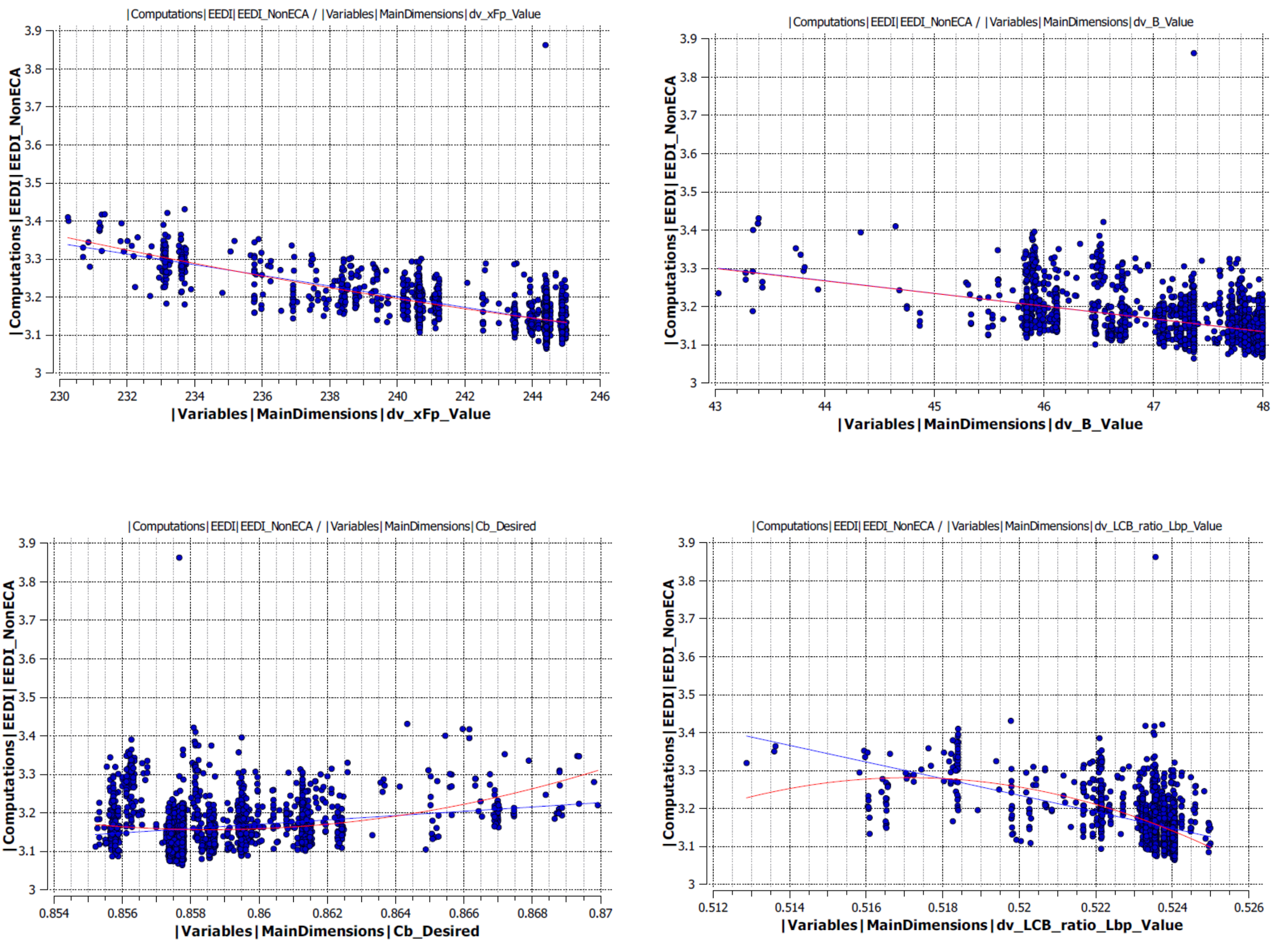


Figure [30]: Sensitivity analysis diagrams for the EEDI (Lbp. B, Cb, LCB-Appendix I)

3. Accidental Oil Outflow Index (OOI-according to MARPOL Reg. 23)

The Accidental Oil Outflow Index is a Key Performance Indicator for the safety of each design and follows the MARPOL probabilistic calculation. Two accidents and their respective probabilities are considered; grounding and collision. The parameters whose sensitivity is assessed in terms of the OOI are the tank variables and some of the main dimensions, as local hullform parameters have no influence on the Index (negligible changes of displacement only). The tank variables are directly correlated to the Oil Outflow Index as it is entirely dependent on the tank size, position and geometry. However it is interesting to see that the double bottom height is much less influencing the OOI than the side tank width, which can be attributed to the origins of Regulation 23, as collision accidents are more frequent and have bigger consequences than grounding accidents. This was done in order to illustrate the good oil outflow performance of the mid-deck tanker which was introduced in the early 90s as an alternative to the double hull arrangement (the mid deck tanker had a very small double bottom but a large wing ballast tank and a mid deck with a total performance better than a double hull tanker).
The main dimensions also affect the performance in terms of OOI as the larger vessel sizes come with larger tanks that correspond to a bigger probabilistic outflow

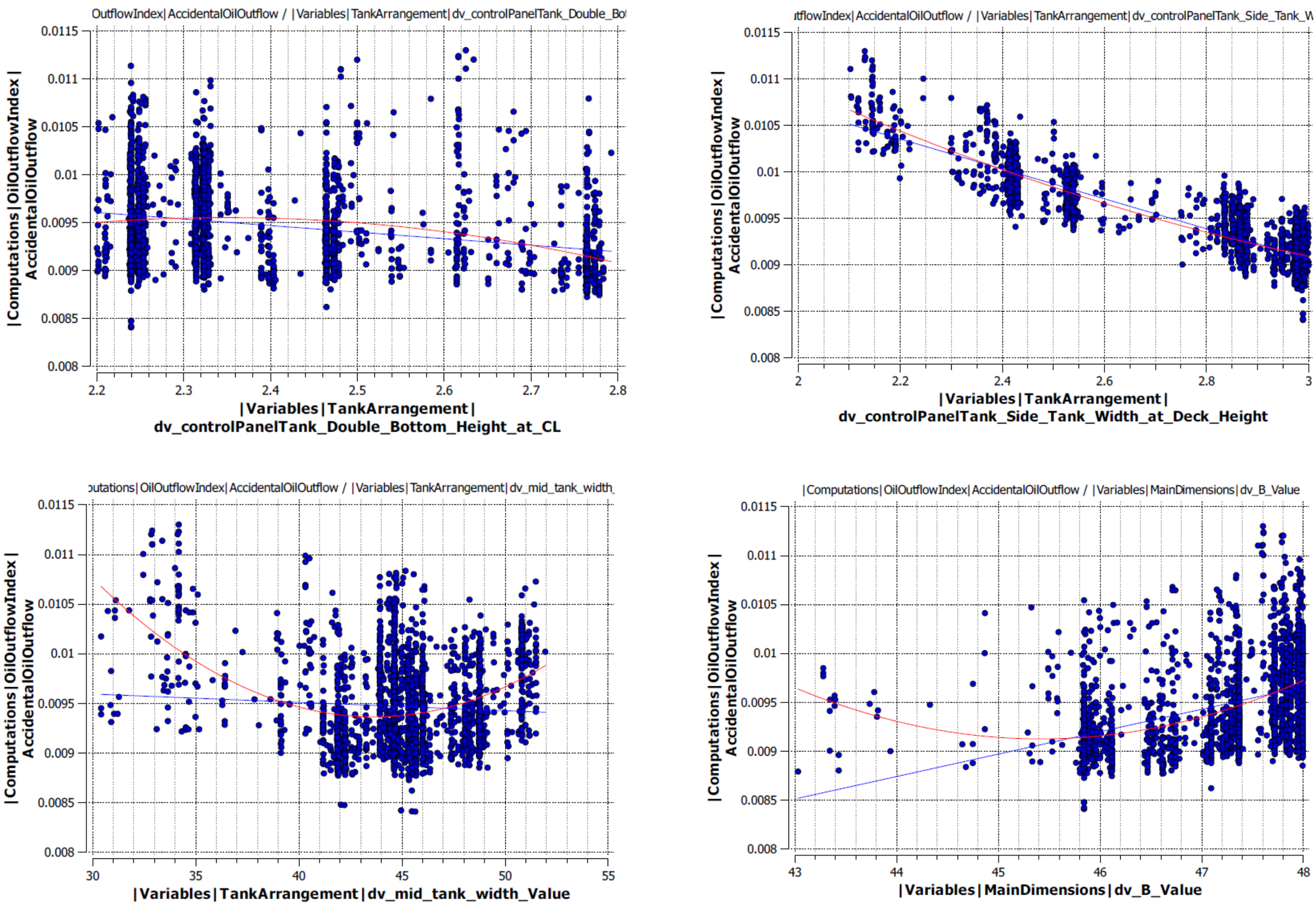


Figure [31]: Sensitivity analysis diagrams for the OOI (h_{DB}, w, mid tank width, B-Appendix I)

CHAPTER FOUR:

CASE STUDIES ON THE HOLISTIC OPTIMIZATION OF AFRAMAX TANKERS

"If you want to build a ship, don't drum up people to collect wood and don't assign them tasks and work, but rather teach them to long for the endless immensity of the sea."

Antoine de Saint-Exupery

CHAPTER FOUR: CASE STUDY ON THE OPTIMIZATION OF AFRAMAX TANKERS

This Chapter is the application of the developed methodology and illustrates the continuous approach of the author to deliver a new AFRAMAX design concept that trough groundbreaking innovation and systematic optimization can respond to all of the present and future requirements. Under this scope it can be considered as the core and main purpose of this Thesis. From figure [32] one can see the different stages of the work on this vessel type that has been the main object of the author's Thesis.

It has been a multi staged approach that started from a tender design (G5 Tanker) that was sort listed (4th place out of 20 contestants) in the VISIONS 2011 competition and other two parallel studies on some specific aspects of the AFRAMAX vessels.

Afterwards, in the second part (can be considered as a spiral) the tender concept along with the independent studies was combined under a holistic context with some new smart ideas (such as main engine derating) in a fully parametric model in the Friendship Framework that was subject to an exhaustive and systematic variation and optimization. The optimization can be considered global rather than local as the main dimensions, tank arrangement and only some local variables are used.

The result of this global optimization approach was exported and analyzed at a more advanced and detailed stage within the context of the VISIONS 2012 competition of WEGEMT. This created an entirely new design concept, Multi Venture, which features an improved bulb (product of CFD principles optimization), All Electric Propulsion with a use of LNG as a ship fuel and some hybrid components (fuel cells and steam turbine generator). In the meantime thanks to the innovative hull shape and the shallow draft characteristic as well as the smaller propeller diameter, the required ballast water in order to meet the MARPOL required drafts is almost half in comparison with a conventional ship. This new design concept can be considered as the epitome of the work done and the finished product that through innovation offers a very attractive solution for the future shipping industry.

The result is impressive as it offers increased safety together with an improved competitiveness and economic performance as well as a new standard for efficiency and environmental friendliness.

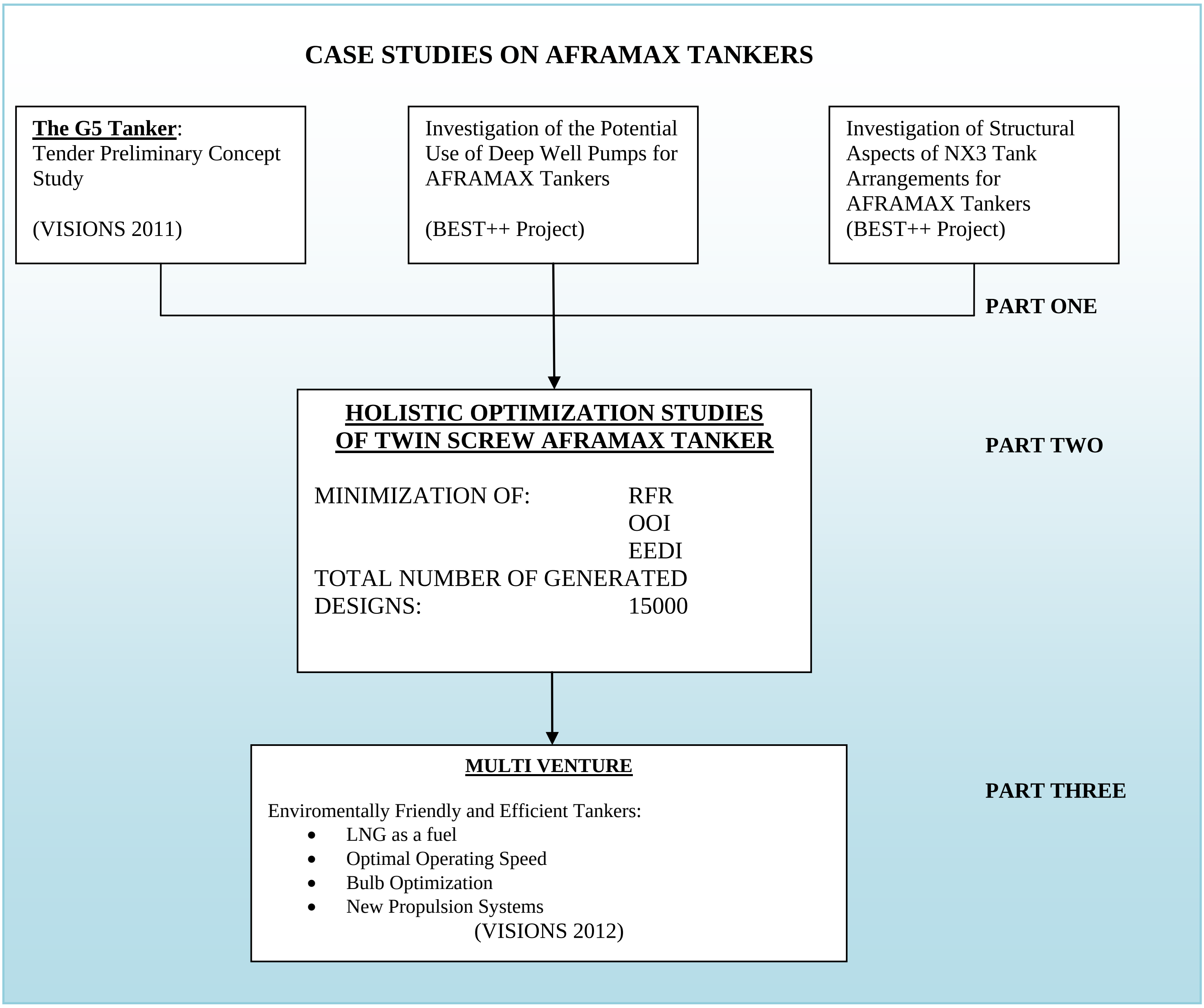
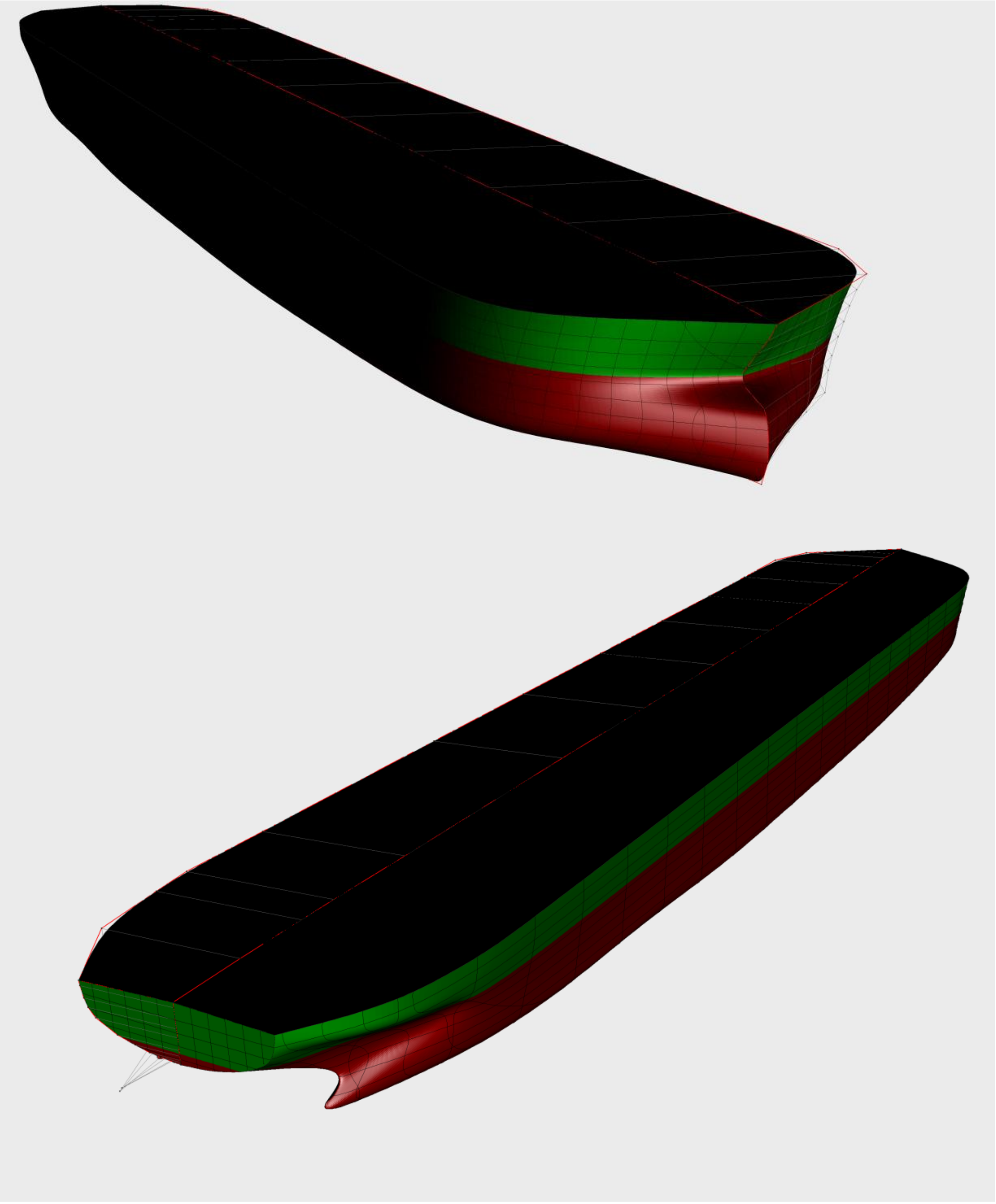


Figure [32]: The stages of the case study on AFRAMAX Tankers

PART ONE: INITIAL DESIGN CONCEPT AND ANALYSIS

1. THE G^5 TANKER

Having seen the existing innovative tanker designs and always having in mind the status of the tanker market and regulatory framework, we move a step forward by proposing a new concept of Crude Oil Tanker that can also be used as a platform for Product Carriers and Shuttle Tankers. This concept was developed for the VISIONS academic competition organized by WEGEMT (Association of Western European Universities of Maritime Technology). The scope of the competition was to promote the visionary concepts of the future with this year's theme being Green Transport. The team responded with an AFRAMAX tanker that is Green in 5 different stages.



Picture [7]: Renderings of the bow and stern of the G^5 Tanker (Nikolopoulos et al [7])

The Objectives and the G^5 Concept

Safety-Efficiency-Competitiveness:

Although contradicting arguments, the above mentioned goals can be accomplished through the implementation of multi objective optimization and holistic ship theory.

More specifically, regarding Safety, the results of Risk Based Design in terms of cargo tank compartmentation are used. Other Risk Control Options (RCOs) are used such as the implementation of twin skeg propulsion configuration for improved redundancy in case of loss of power or steering.

Regarding Efficiency a major power reduction is the primary goal in the Project. The power reduction using basic principles of fluid mechanics and Hydrodynamics is mainly a function of the ship's speed, thus the design speed of the vessel is significantly reduced in comparison with the competition. In order to remain competitive, the time lost at sea due to reduced speeds is aimed to be compensated by efficient and faster port operations thanks to a new developed cargo handling system inspired by the Product Carriers of today.

Last but not least, the Competitiveness of the vessel is increased due to the higher efficiency in terms of a lower Required Freight Rate and the increased cargo tank capacity of the vessel.

We can see that in order to optimize an AFRAMAX tanker for Safety-Efficiency-Competitiveness while the ship is enhancing environmental sensitiveness issues the following areas have to be addressed:

1. Cargo Tank Arrangement and cargo handling
2. Power Redundancy (Main Engine redundancy)
3. Machinery Efficiency.
4. Ballast Water Management.

The main dimensions of the developed dimensions were the following:

G^5 Tanker NTUA-Main Particulars	
L (m)	260
B (m)	52
T (m)	11.6
D (m)	19
Cb	0.85
Cwl	0.9
Cp	0.857
CM	0.992
Δ (tonnes)	137118
Lightship Weight (t)	24497
DWT (t)	112621
Payload (t)	109241
Capacity (m^3)	128821.3
Vs (knots)	13.5
Cad	408
Pb (kW)	11251
Main Engines	2 X MAN 5S46 ME-C8
Gensets	3X Wartsila 4L20
Shaft Generators (kW)	2 X 500
Number of Cargo Pumps	15
Pump Capacity (m^3/h)	200

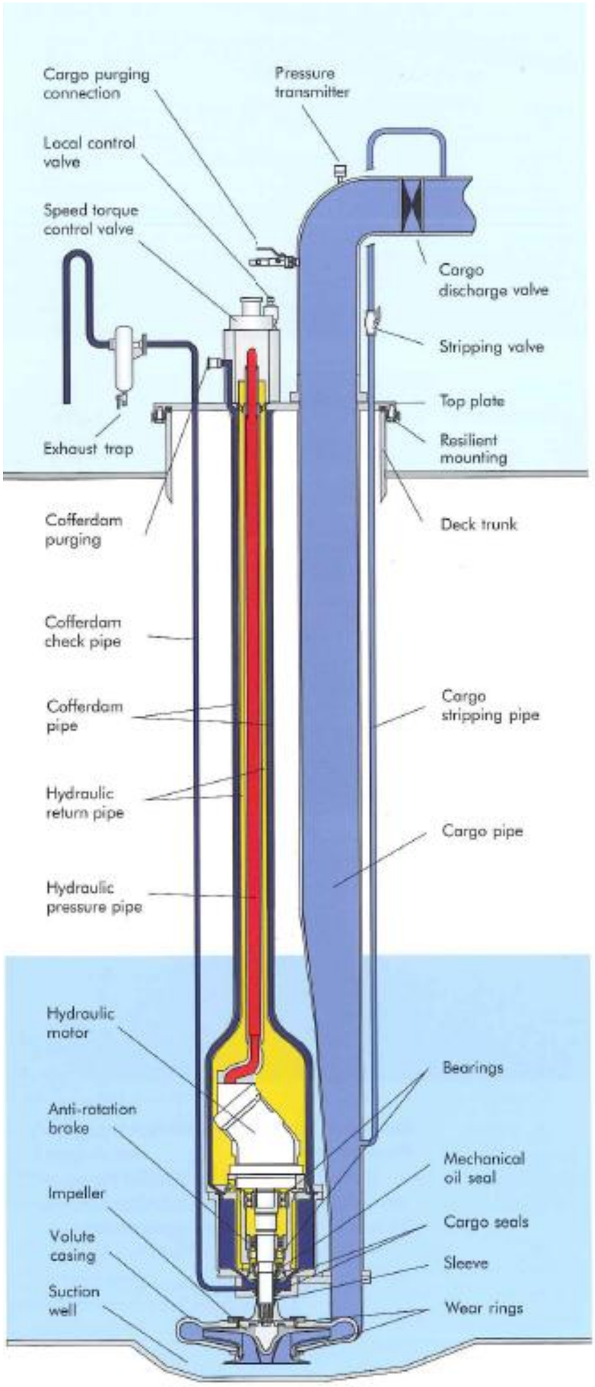
Table [5]: The G^5 Principal Particulars (Nikolopoulos et al [7])

2. THE POTENTIAL USE OF DEEP WELL PUMPS FOR TANKERS

With energy efficiency being a pressing issue it is imperative to illustrate a few tender technologies that applied on a tanker can reduce the consumption of energy onboard. The first study was made by the Author, within the context of the BEST++ research project, aiming at investigating the potential use of deep well pumps for AFRAMAX class ships. The second part includes a demonstration of existing power train technologies that can reduce the energy consumption and the emissions improving the environmental footprint of the vessel.

5. *Investigation of the Potential Use of Deep Well Pumps for AFRAMAX tankers*

The term Deep Well Pump refers to an alternative pumping system for crude oil and product carriers. Traditionally the pumping of the cargo during discharge is performed by the onboard pumping system. The latter is situated in the pump room (fore of the engine room and beneath the HFO tanks) and is in general comprised of 3 large pumps (depending on the tanker size, their discharge rate can be up to 8000 m^3/h). Each pump is driven by a steam turbine which uses the steam produced by the auxiliary boilers of the vessel. The rate of discharge does not depend solely on the tank capacity but also on the inerting system of the vessel, as well as the stability and trimming of the vessel.

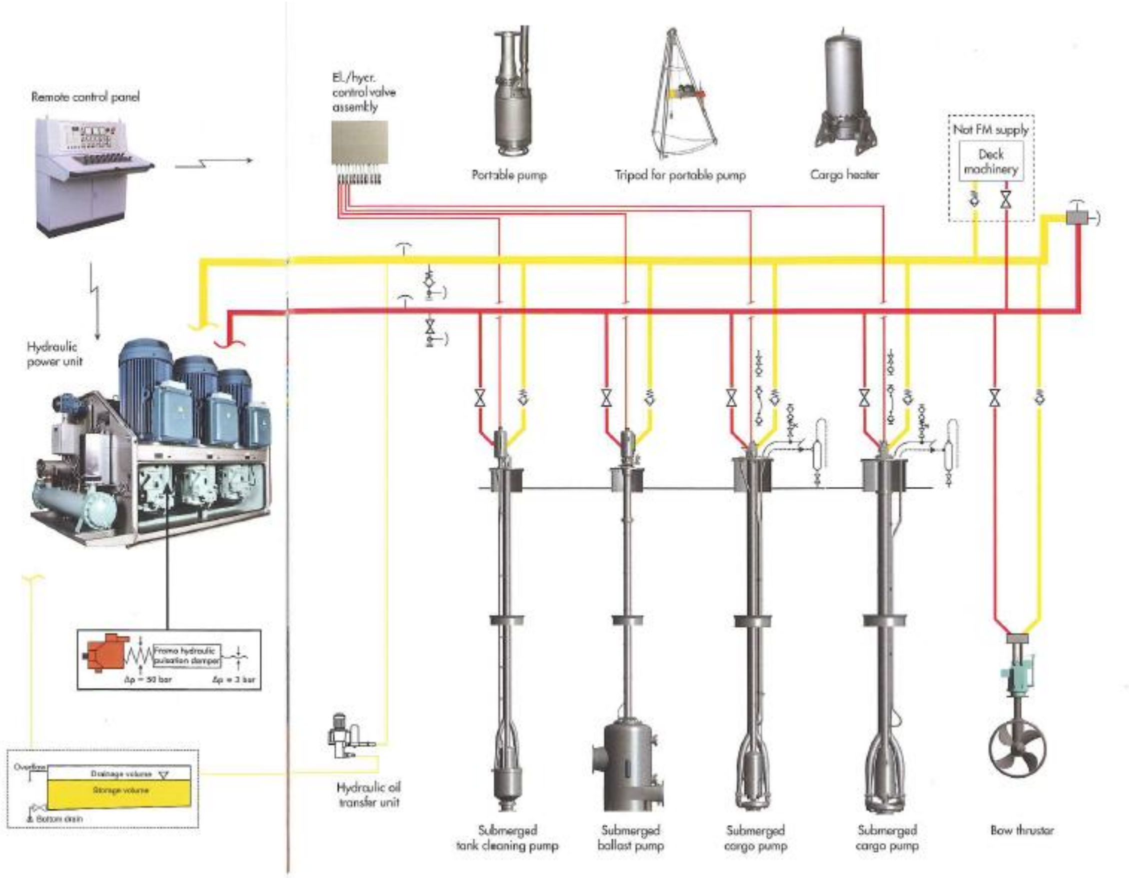


The Deep Well Pumping System was originally developed for the product carrier and OBO tanker ship segment where segregation of cargoes is necessary in order to be able to switch effectively between clean and dirty cargo and thus achieve a higher vessel utilization. The general principle of the system is the use of independent submerged pumps, one for each cargo hold driven by a high pressure hydraulic system. The leader in manufacturing, engineering and supplying of such systems is the Norwegian company Frank Mohn SA, the developer of the FRAMO pumping system.

The application of such hydraulically driven submerged cargo pumps provide safe, efficient and flexible cargo handling of any type of liquid cargo. Improved cargo handling performance gives quicker turnaround time, more ton-miles and fewer voyages in ballast. The cargo pump is a vertical stage centrifugal pump (single suction impeller, vertically balanced) powered by a hydraulic motor for safe and efficient operation. The construction material is stainless steel and the pumps are designed with a smooth and easy-to-clean surface with a limited number of flanges which enables them to pump any kind of fluid.

The pumps, unlike the conventional system are driven by a *hydraulic system*. A hydraulic power unit, driven by a combination of diesel engines and electric motors, is producing the high pressure hydraulic oil which runs through a *common line for all the cargo pumps and the ballast water pumps as well*. Potentially, even a small hydraulic bow thruster can be fitted to the system, improving the port operational behavior of the vessel. The combination of the electric motor and diesel engine prime movers allows the ship's generators to be designed for the relatively low power requirement in sea-going mode rather than the considerably higher requirement during cargo unloading. The ship's auxiliary engines can therefore operate with an economic load while at sea where the majority of the running hours will be. The diesel hydraulic power packs will provide any additional power needed for a high capacity discharge. A power saving device incorporated into the control system automatically regulates and shares the load between each power pack in operation.

The deep well system can also integrate cargo heaters that are much more efficient than the traditional heating coils and are mounted on deck.



Picture [8]: Schematic of the Hydraulic Powering system, developed by FRAMO

i. Comparison of Conventional vs. Deep Well Pumps

Having described the origins and the main characteristics of the deep well pumps we move on, in comparing them with the conventional pumping system. The figures and data of this comparison are provided by FRAMO and a study they did on an PANAMAX and AFRAMAX tanker design and are considered confidential and only for the purpose of the proposal within the BEST+ Research Project.

1. Building Cost Comparison

One of the major orders for FRAMO pumping systems came from SKS OBO Limited, a Norwegian owner of Product carriers, who ordered 10 Product Carriers to be built in Hyundai Samho Heavy Industries from 2010 to 2012 (SKS D-Class Vessels). According to FRAMO, the yard charged an extra of 3mil. $ to the owner at a ship of 80mil.$ value when the contract was signed. That is considered a big amount as extra and cannot be justified since the yard is able to make significant savings due to the reduced piping arrangements. More specifically, if we look at a study made for a 95000 DWT PANAMAX tanker, we can see the cost comparison:

- The cost of pumps is 700k. $ for the conventional compared to 2.5mil. $ for the FRAMO package, while the man hours are 4000, for the conventional and 6000 for the FRAMO system.
- The cargo piping on the other hand, costs 450k $ for the conventional and requires 27500 man hours while the FRAMO system piping costs 144k $ and requires 8800 man hours.
- The cargo valves for the conventional system cost 400k. $ and require 9000 man hours while for FRAMO they cost 200k.$ and require 4500 man hours.
- The cargo heating for the conventional system (mild steel heating coils ND50) costs 200k. $ and requires 10400 man hours while the FRAMO system has its own integrated heaters (included in FRAMO package price) and requires 2500 man hours.
- The boiler (cargo heating) for conventional system is 2X 25 ton/h at a cost of 600k. $ and 700 man hours while the FRAMO system requires only one auxiliary boiler at a cost of 300k. $ and 350 man hours.
- The Diesel Generators are for both systems the base.
- The pump room construction for the conventional system costs 100k. $ and 5500 man hours while the FRAMO system requires no pump room whatsoever.
- The Inert Gas System for the conventional system (Fuel Gas System from boilers system) costs 140k.$ while for the FRAMO system an inert gas generator is needed at a cost of 200k.$

Summing up the above we can see that the total installation cost for a conventional system is 2.590.000 $ while the FRAMO system has a total installation cost of 3.444.000 $. However, the conventional system requires 42350 extra man hours, which at a cost of 30$/man.hr (Korean price) is 1.270.500. The grand total thus is 3.860.500 for the conventional system and 3.444.000 for the FRAMO one.

From the comparison above one can easily see that a shipyard can have a profit by installing FRAMO pumping systems by reducing the total man hours needed for the construction. On the contrary, this system is charged as an extra which means that the shipyard has a triple benefit, from the reduced man hours, the improved productivity and the increased contract price with the owner. That, according to a FRAMO representative, may change in a few years if the shipyards adopt FRAMO system as the base system and charge extras for the pump room system.

ii. ***<u>Design Implications of the Deep Well Pumps</u>***

Moving on, we shall now examine the concept design (and operational) differences of the use of deep well pumps for AFRAMAX tankers.

From the design stand point, as one may have seen earlier, the deep well pumps eliminate the need of a traditional pump room. The power packs are situated within the engine room so the space left for the pump room can either be used for the slop tanks or for some extended fuel tanks. By re-arranging the spaces of that area, a 2-3% of increase is expected for the cargo capacity (that is the increase seen at the SKS D-Class Vessels, a series of 10 AFRAMAX product carriers ordered by a Norwegian owner). At an already optimized design, like BEST+, this can be an additional benefit that will make the concept even more competitive and able to perform more tonne-miles per year in conjunction with the increased speed of the BEST+ concept.

Picture [9]: The SKS D-Class vessels that achieved a 2-3% cargo capacity increase thanks to deep well pumps

Another design feature of the deep well pumps is that the discharge rate is much higher than the conventional system and thus the port operations can be more efficient, although the time reduction is not significant. One pump per tank and deck mounted cargo heaters eliminate the need for in-tank suction lines/heating coils that are required for a tanker with a conventional centralized cargo pump room system. Without these in-tank restrictions the time required for tank cleaning is significantly reduced and allows the vessel to obtain clean status directly after a dirty cargo. In other words improved potential to pick up return cargos and avoiding ballast voyages, thus improving the vessel utilization.

From the efficiency stand point, deep well pumps operated by hydraulic power packs are much more efficient due to the use of diesel engines and electric motors. Furthermore, it is more environmentally friendly as the fuel used by the diesel engines is low-sulphur MDO which produces much less SOx and NOx emissions compared to the HFO burnt in auxiliary boilers. The savings in fuel cost with FRAMO vs. pump room system during a complete discharge operation are significant, however small compared to the increased revenues that are generated by being able to pick up more return cargo rather than performing ballast voyages.

iii. Operational Comparison – Efficiency and Economy

Below we can see the results of a comparative study of the traditional pump room system versus the independent submerged pumps as conducted by FRAMO for a 115000 DWT Crude Oil/Product Carrier. The tanks capacity of the vessel in question is 132000 m^3 and is distributed in 12 tanks (6X2 arrangement) with 10 tanks (5 pairs) having 11000 m^3 and 2 tanks (1 pair) having 9000 m^3.

1. Operational Profile

Traditional pumping systems are based on a centralized pumping system with separate stripping pumps with stripping lines and vacuum draining pump. The total discharge time for a system installed in the vessel in question (3 pumps of 3000 m^3/h each, 9000 m^3/h grand total) is 20 hours which are consisted by 15 hours of pumping time and 5 hours of stripping and draining time.

On the other hand the FRAMO system needs much less time for stripping due to in-tank pump with efficient built-in stripping capabilities and thus same or less total discharge time can be achieved with less cargo pump capacity. The FRAMO system for the same study vessel is consisted by 12 independent pumps of 1250 m^3/h each (15000 m^3/h grand total) and it takes 18 hours of discharging, consisted by 17.5 hours of pumping and 0.5 hours of stripping.

2. Energy Considerations and Cost Comparison

In order to be able to assess the operational profile of the pumping system in terms of a cost benefit analysis, we need to have a common denominator which in that case will be the cost for a single discharge. Furthermore, the assumptions of fuel prices are 655 USD for HFO380 and USD 1040 for MDO.

- ***Conventional Pump Room System***

For the conventional pump room system arranged with steam turbine driven pumps, the required power is about 3750 kW. The auxiliary steam boilers are assumed to be working also during stripping. The steam plant/pumping system is assumed to be normally running at full capacity, as cargo discharge capacity will be regulated by throttling of the cargo valves. When running with HFO the consumption is expected to be:

3750 kW * 13.5 kg/kW=50625 kg/h

50625 kg/h * 20 h*0.076 kg HFO/kg steam=<u>77 ton HFO</u>

And the cost for that is **50 000 USD/discharge**

For the ECA's however the boiler fuel must be either MDO or low sulphur diesel, and by assuming the same boiler consumption for MDO, the cost is **80 000 USD/discharge**

- ***Deep Well Pump System***

On the other hand, the FRAMO system needs less discharge head as the pumps are discharging directly to deck, with no suction lines through cargo tanks and pump room. The fuel consumption is calculated as followed:

a) 4 electric hydraulic power packs 450 kW each, a total of 1800 kW. On the auxiliary engine side this will be equal to 4X510 kW, totally 2040 kW, due to the losses in electric motors, generators and cabling. The fuel required in order to produce this power is 2040 kW*17.5h*0.220kg HFO/kWh= <u>7.9 ton HFO</u>.
b) 4 Diesel Engine power packs each 450 kW which have a fuel consumption of 1800 kW*17.5h*0.205 kg MDO/h=<u>6.5 ton MDO</u>.
c) Inert Gas Production from IG Generator is 9400 Nm^3/h for a duration of 17.5 hours, which has a fuel consumption of
9400 m^3/h*0.074kg HFO/m^3*17.5h=<u>12.2 ton HFO</u>.

The total fuel consumption is 20.1 tons of HFO and 6.5 tons of MDO. The cost per discharge in that case is 655*20.1+1040*6.5=13000 + 7000= **20 000 USD/discharge**.

In case cleaner fuel is required due to environmental regulations, the cost per discharge for running only with MDO is **27 000 USD/discharge**.

We can clearly see that the cost for a discharge with a Deep Well Pump system is 30 000 USD lower than the conventional (*60% saving*). If we assume 20 discharges per year the fuel savings are expected to be 600 000 USD/year. *This means that when the yard charges a 3mil. USD extra for the FRAMO pumping system (acc. to FRAMO) the payback time is expected to be merely 5 years*. From experience, both from shipping companies and FRAMO, the payback time is expected to be less than two years, especially due to the imposition of stricter new regulations for the use of cleaner fuel.

iv. Discussion of the results and conclusions

Having seen all the aspects of the potential use of deep well pumps for AFRAMAX tankers, and in the context of the BEST+ Research Project, we believe that it is highly recommended to carefully look into this technology. The primary reasons for installing these pumps on board a BEST+ ship, which is an already competitive vessel, are:

1. The elimination of the pump room and the installation of the power packs inside the engine room will further increase the capacity of the vessel by 2-3%, meaning it can perform better in terms of competitiveness.
2. The reduced overall discharge time combined with the use of a hydraulic bow thruster (parallel to the power pack system) can lead to optimized port operations which can also compensate any time lost at sea (due to slow steaming).
3. The energy efficiency of the system is much higher compared to the conventional due to the use of diesel instead of steam. The savings are significant and up to 60% per discharge. The environmental aspect is also important as the system uses cleaner fuel and much less fuel is needed (thus there is a reduction of the $CO2$ emissions).
4. By adopting a new operational edge and with combination of epoxy coated tank, the BEST+ design can operate as a Crude/Product Carrier, taking the advantage of the increased vessel utilization and the minimization of the ballast leg voyages.

On the other hand, the greatest bottleneck regarding the implementation of such a technology as a standard design is the shipyard policy of charging the system as an extra and thus penalizing the owner. Another disadvantage of the system is the need for specialized personnel in order to perform maintenance of the equipment, though overall maintenance costs may be comparable acc. to FRAMO.

3. INVESTIGATING STRUCTURAL ASPECTS OF NX3 AFRAMAX TANKERS

Due to assumptions made for the steel weight calculations based on a 6X2 reference during earlier projects as there was a lack of references for a NX3 design, the steel weight calculation had to be validated. This became a priority since such a vessel in AFRAMAX size was found, a shuttle tanker owned by Teekay Shipping, built in 1997 in a Spanish shipyard.

The structure of the reference vessel was modeled in the GL software POSEIDON and afterwards analyzed and compared to some standard designs. Except that, a new platform with the BEST+ dimensions was made in order to bring the results under a common denominator. The breakdown of the structural steel components was also used in the optimization studies that followed in order to determine the structural steel weight for each variant.

More Details can be found in the optimization studies (Part Two of this chapter) and in the presentation in the attached CD.

PART TWO: HULL OPTIMIZATION AND DESIGN

1. THE BASELINE MODEL

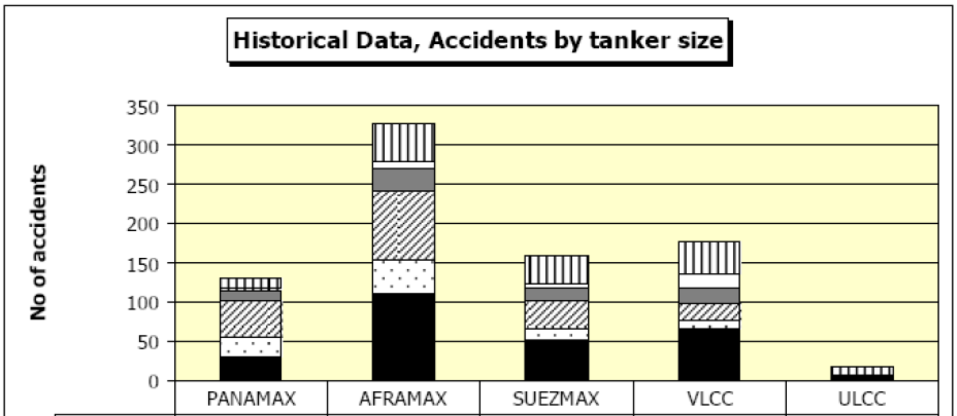
1.1. Introduction to the Design Concept, Description and Assumptions

In part two, this model has been the core of one of the Case Studies in the AFRAMAX class and was developed during his stay at Friendship Systems Gmbh and was the basis on which he developed his skills in this software. In addition to that it is a product of the joint collaboration of the Ship Design Laboratory at NTUA with Germanischer Lloyd and Friendship Systems for the BEST++ research project which is its part.
This AFRAMAX tanker is an evolution and a parametric version of an earlier tender design, made for the 2011 VISIONS Olympics organized by WEGEMT combined with a detailed study on the pumping systems and the structural aspects of the design. More specifically, the basic design characteristic of this vessel is its twin screw, twin skeg configuration, chosen to maximize the propulsive redundancy thus making the vessel much safer. Previous work on twin skeg tankers was very helpful, especially that of Fabian Tillig, a student assistant at Friendship too, whose Thesis worked as a very useful guide during the modeling process.
Another innovative characteristic of this design is its bilge arrangement. It is not a circular, rather an elliptic shaped bilge of a much greater extent than in conventional designs. The reason for such a choice is the geometric property of the ellipse to have the minimum surface while maintaining the desired volume. Thus it is a measure to reduce actively the wetted surface of the model while maintaining most of the equivalent displacement. In the meantime the extension of the bilge is such as to minimize the block coefficient in the ballast draft and thus achieve an almost ballast free design, although this works as a secondary object having in mind the validation of the Ballast Water Management Convention.

1.2. Twin Skeg Configuration: An issue of Safety and Potential Efficiency

The twin skeg configuration is the major design feature of the hull form model for this project. It is also one of the core concepts aimed to be explored by this present report. The reason for this is very simple: redundancy.
Propulsive redundancy is a matter already settled in more elaborate and fast ships, like passenger ships but not particular attention has been paid for commercial merchant vessels. The reason for this is the increased capital cost and design as well as construction difficulties for the size of a tanker from the shipyards point of view. Furthermore, up until recently, due to the lack of hydrodynamic optimization and proper understanding of the concept the engines in such designs were oversized leading to increased fuel consumption and thus operating costs.

The need for propulsive redundancy in tankers is also important, especially since the regulations tend to be striker and the societal risk perception of the oil transportation industry is high. Due to this risk averse attitude and due to the big size of the cargo tanks and the ships themselves the potential loss of cargo (PLC) and the potential loss of life (PLL) are continuously rising. The best way to address this issue, within the context of a “green” shipping attitude, is to examine some Risk Control Options (RCO) in order to minimize either the probability of an oil spill, the consequences of an oil spill or both. Some RCOs can be operational in the form of best practices while others can be design RCOs for future newbuildings. In order to choose an adequate RCO the decision maker should before that perform a risk assessment and analysis. The IMO has addressed this in tankers and bulk carriers by using the Formal Safety Assessment (FSA). The results of the FSA for tankers suggested a structured way in order to decide for an RCO. Some interesting results from damage statistics for large tankers indicate that according to historical data, the main accident types for the AFRAMAX size we examine are grounding and collisions followed by non accidental structural failures.



	PANAMAX	AFRAMAX	SUEZMAX	VLCC	ULCC
NASF	13	48	34	42	11
Explosion	5	9	6	19	0
Fire	12	29	16	18	1
Grounding	46	88	35	22	1
Contact	24	43	15	9	2
Collision	31	111	52	68	3

Figure [33]: Historical Data of Tanker Accidents (FSA 2008)

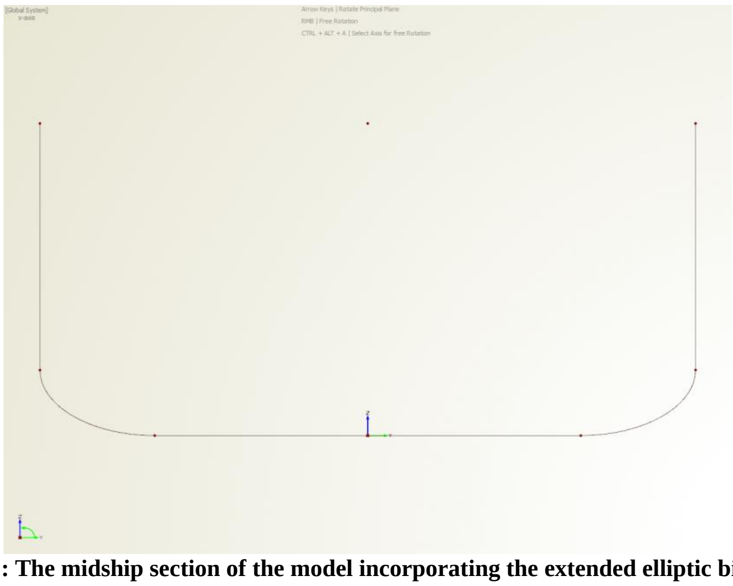
This data is very helpful for the decision of which RCO to use. However, when one also takes into account the database that was used to generate this it is possible to see that accidents that the primary cause was loss of power were labeled as groundings or collisions. This can be explained in terms of risk analysis by the use of event trees. The aim is to start from an initiating event and find the consequences of this event along with a respective quantitive assessment, mainly in terms of probability. According to Jack Devanney, in the database he developed (CTX database) there are 165 accidents due to machinery failure out of total of 856 accidents, resulting in to 111 dead and 1.093.839.802 liters of oil spilled out of 2173 dead and 6.456.287.392 liters of oil spilled by the entire tanker fleet in one year. This indicates that the root cause for many accidents recorded as groundings and collisions is the loss of control, either in terms of propulsion power or steering. Some notable accidents include the Torrey Canyon, the Amoco Cadiz and the Braer.

The reason mentioned above, for tankers alone is very supporting for the implementation of twin engine, twin screw, twin rudder tankers which can be realized as a whole by the concept of the twin skeg arrangement. This philosophy has been implemented already by Swedish ship owner STENA, who has built and operated twin skeg tankers of VLCC and PANAMAX size.

The twin skeg concept is a hull with a stern featuring two independent skegs, with stern bulb and stern tubes that incorporate the shafts of the two engines (usually smaller two stroke slow speed engines) of the vessel. The first design implication that arises is the potential to incorporate a larger block

coefficient as a method to compensate from increased initial costs by boosting the profitability. As each propeller disk is located towards the free flow has a better wake field and more importantly the deck line and beam of the transom do not change rapidly as in the case of a single screw design were the flow and wake has to reach a propeller disk situated at the centerline of the ship. However, the total resistance of these vessels can be higher due to the increased wetted surface. Another drawback of these designs is the increasing maintenance costs due to the double machinery installations not only in terms of main engine but also in other equipment such as fuel pumps etc.
Overall the hydrodynamic performance of these designs can be more efficient and thus the total efficiency of the ship is better, which is very encouraging when having in mind the new regulatory framework for efficiency in maritime transport (IMO EEDI etc). However, there is a big lack of references for these designs. The most recent study was done by Fabian Tillig in his Master Thesis in collaboration with Friendship Systems and FLOWTECH, were two different twin skeg arrangements were assessed and optimized. The two arrangements were a gondola type and integrated type, both of which for an AFRAMAX size tanker featured a slightly increased displacement and increased wetted surface in the re-modeling procedure. The optimization studies undertaken focused on the hydrodynamic aspects of the design using the integrated SHIPFLOW codes in the Friendship Framework (FFW). It was found that an overall 11% lower resistance than the conventional reference was achieved, making the twin skeg a very attractive option in terms of efficiency especially as the fuel costs continuously rise.

Another design feature of the model investigated in this report is an extended elliptic bilge. This extended bilge using the geometrical properties of the ellipse allows us to decrease the wetted surface of the ship while the displacement volume is not equally decreased and almost kept constant. The parameters used to control this surface are the Flat of Bottom (FOB) extent and the Flat of Side (FOS) extent. The generated midship section shows that the cargo carrying capacity can be met, while there are no implications with the tank arrangement, with the hopper angle being the same as in the optimized BEST+ project. Meanwhile the ballast water required according to the MARPOL criteria is much less because the displacement in the ballast draft is smaller due to decrease of the respective block coefficient. This reduction is very impressive and can be linked with savings from ballast water treatment processing units which are big consumers of ship board energy. Furthermore, segregated ballast spaces can be used as cofferdams further increasing the protection of the cargo while coatings can be saved due to the smaller number of ballast tanks which require special coatings and paints according to the IMO PSPC convention.
A typical midship section can be seen at the snapshot below:



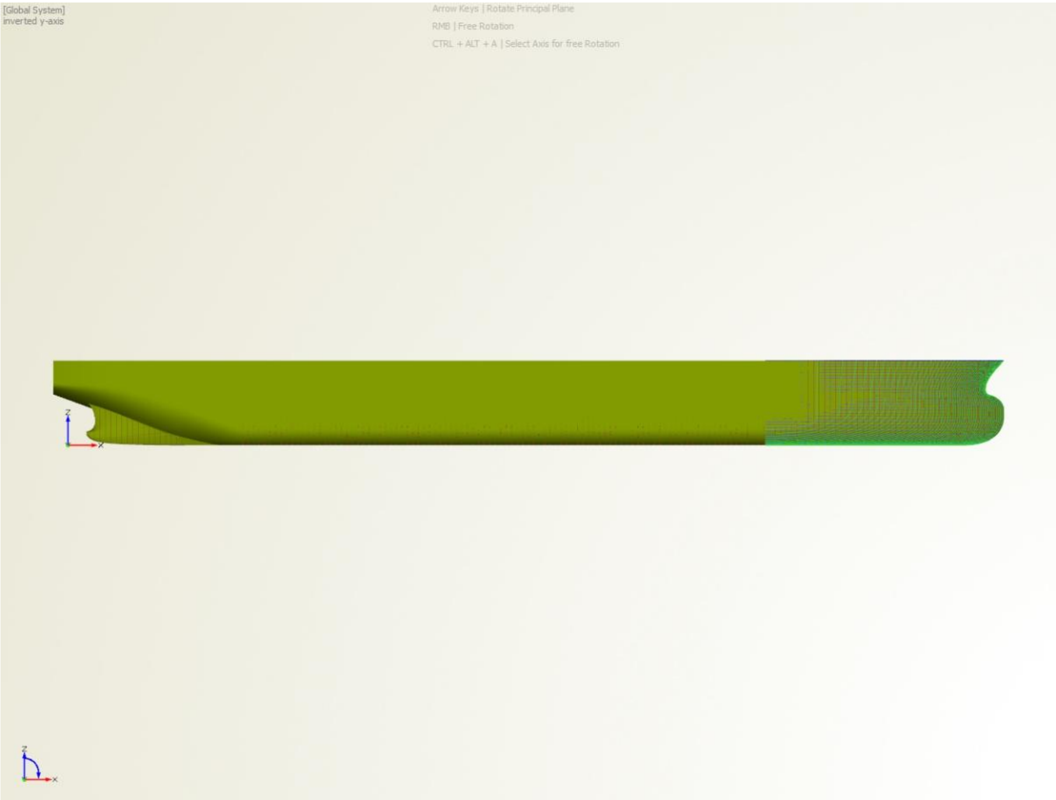
Picture [10]: The midship section of the model incorporating the extended elliptic bilge concept

Hull Generation and Modeling

The above mentioned concept was realized in the Friendship Framework environment during a stay of the author in Potsdam from October to November 2011. It has been done in collaboration with Mr. Daehwan Park, Naval Architect working at F.S. The main focus was in producing a twin skeg blended with elliptic features that aims at minimizing the wetted surface. For this particular reason a new project had to be generated from the beginning using features of the framework such as curve engines and Metasurfaces that are enabling a complete control of the surface. As the optimization studies are global, it is evident that a fully parametric model was necessary in order to be able to generate a great number of variants. The detailed description of the strategy for the hull geometry, as conceived by Daehwan Park, can be found in Appendix I of the report.

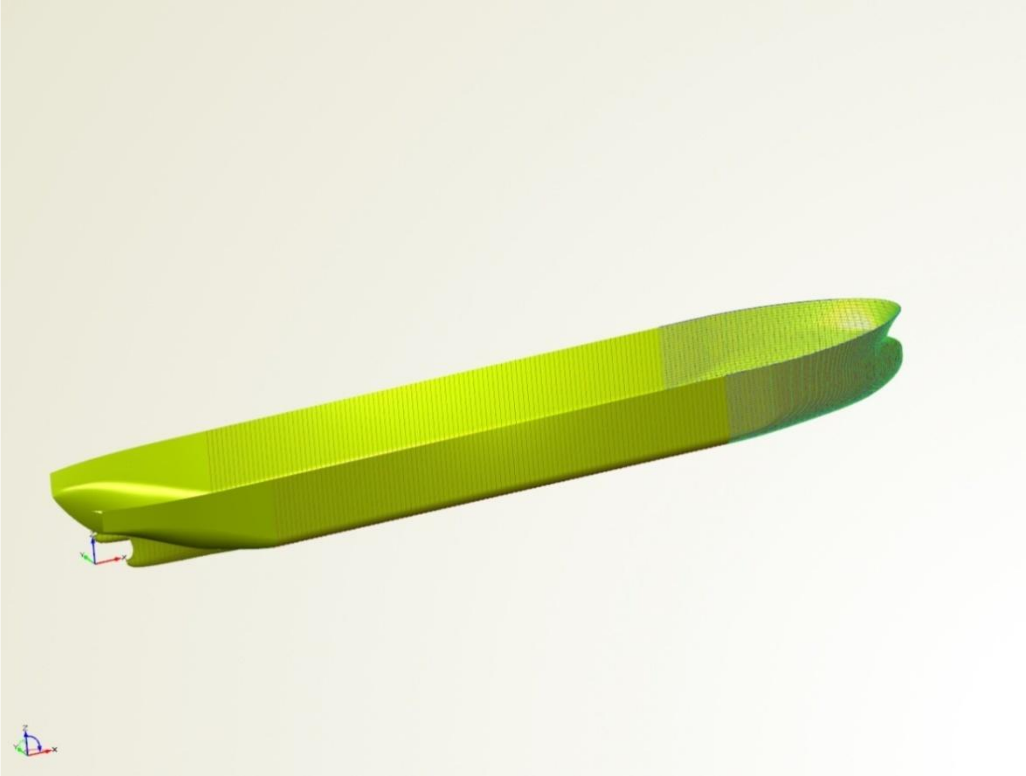
- ***Final Ship Surface***

Below we can see the finished surface with the desired characteristics, such as the twin skeg configuration, the bulbous bow and the elliptic shaped bilge. It is obvious that it is a high blockage slow speed ship that aims in maximizing the transport work for a given trip.

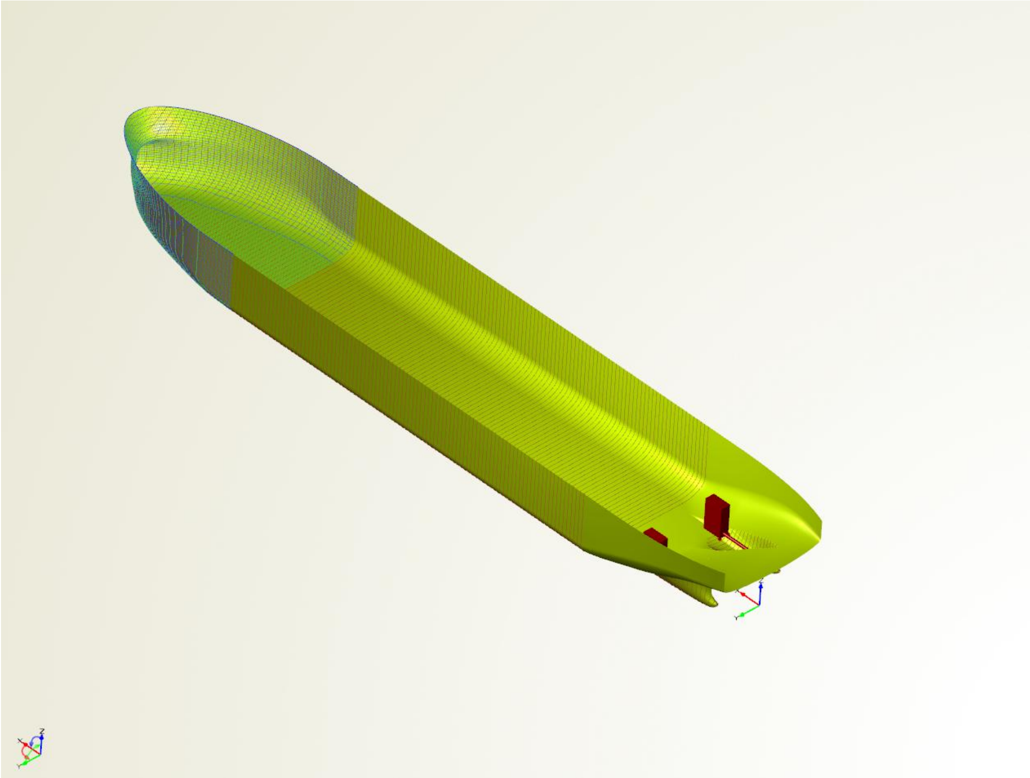


Picture [11]: Profile view of the vessel in question

One of the considerations during the design process was to make sure that the engines would fit to the more restricted engine room area and that the skegs generated are not too slim. This led to the perception of an engine box with the designated engine dimensions (MAN B&W 6S50ME). This acted as a constraint and was also a concept around which the entire skeg geometry was built.



Picture [12]: 3D view of the vessel



Picture [13]: 3D view of the vessel together with its engines

1.3. Tank Arrangement, Modeling and Geometry

The tank arrangement modeling is the second item of core importance of this project. Since we mentioned that the optimization is holistic, the cargo tank arrangement bears particular attention, and acts as the second core objective of our study: maximize the safety and the competitiveness of the design.

The concept for the tank arrangement is based entirely on the previous work of GL and the Ship Design Laboratory (SDL) at NTUA, on the Risk Based Optimization of AFRAMAX tankers. The results of the research project SAFEDOR and the following research projects TANKOPT and BEST indicate that by adopting a tank configuration with 3 instead of 2 tanks across, namely incorporating two longitudinal bulkheads for the cargo area, can minimize the accidental oil outflow index while the capacity is increased and sometimes the steel weight is reduced.

	Ref. Design	6x3 Flat		6x3 Flat	
ID		1710		2122	
Rank		1		2	
Cargo.Vol	126765	129804	+2%	135950	+7%
Oil.Outflow	0.01006	0.00777	-23%	0.00942	-6%
Wst.cargo.area	11077	10908	-2%	11013	-1%

Table [6]: Results of TANKOPT study

The table [6] above illustrates this advantages of 6X3 arrangements that incorporate a reduction of the accidental oil outflow up to 23% which is a very impressive results. Meanwhile the cargo capacity is increased and the steel weight for the cargo area is decreased. However, the lack of steel structures for 6X3 tankers in the AFRAMAX size led to several assumptions for the structure that fired several uncertainties for the result in structural weight terms. Thus it was evident that a more careful investigation had to take place.

Investigating Structural Aspects of NX3 AFRAMAX Tankers

Since the assumptions made for the steel weight calculations are based on a 6X2 reference due to the lack of references for a NX3 design, the steel weight calculation had to be validated. This became a priority since such a vessel in AFRAMAX size was found, a shuttle tanker owned by Teekay Shipping, built in 1997 in a Spanish shipyard.
The first step was to model the cargo block area in POSEIDON in order to find a more accurate weight estimation for the cargo block weight and then afterwards to derive with a coefficient in order to be able to compare it with a 6X2 equivalent.
Due to the shuttle tanker entity of the reference ship and the increased length (260 meters instead of 240m) the weight was considerably larger as seen in the following table [7], which is for only one block corresponding to one tank of the entire cargo area.

Design ID	Weight of Long.Members	Weight of Trans. Members	Bulkhead Weight	Total
6X2 template	1845,56 tonnes	392,5 tonnes	167,8 tonnes	**2406 t**
BEST+	1773,2 tonnes	329,5 tonnes	154,8 tonnes	**2258 t**
Navion Britannia	1983,6 tonnes	466,5 tonnes	150 tonnes	**2600 t**
NX3 CSR Design	2002,4 tonnes	477,3 tonnes	55,8 tonnes	**2537 t**

Table [7]: Steel Weight Comparison of NX3 with 6X2 designs

If we adapt the above results using a cubic coefficient $\lambda_{Wst} = \frac{Wst}{L*B*D}$ and expand the results for the entire cargo block the same conclusion can be met (table [8]).

Design ID	Wst*/LBD	Wst Corrected
Navion Britannia	0,0869	15192 t
NX3 CSR Design	0,08474	14815 t
6X2 template	0,08257	14435 t
BEST+	0,07748	13545 t

Table [8]: Weight of the adapted structure using a cubic coefficient

It is obvious that the reference ship is heavier by 747 tones (namely 5%) even for the adapted dimensions. This is due to the relatively low percentage of high tensile steel use and the older technology as well as the shuttle tanker requirements and the higher bending moment required due to the increased length which was not able not to dimensionalize. By reducing the number of longitudinal tanks from 6 to 5 it was possible to reduce this difference to 4%. Taking into account that a structural optimization would lead in a reduction of maximum 3% it is obvious that the designs with two longitudinal bulkheads will always have a disadvantage in comparison with a 6X2 equivalent. This disadvantage can be interpreted due to the increased surfaces of the bulkheads, exposed to the tank load which according to the CSR mentality, (not doing calculations according to the Section Modulii but according to the tank loads) is penalizing the two longitudinal bulkheads arrangement.

However it was interesting to see how a structure built in the BEST+ dimension template but with two longitudinal bulkheads and respective structural arrangements would perform. For this particular reason an adapted model was built, again for the tank No.3 module (midship tank) and assessed with POSEIDON. The results showed that as we head to shorter and beamier designs (in comparison with the original shuttle tanker) a reduction of the weight coefficients can be realized as seen in table [9].

Design I.D	Longitudinal Members (t/m)	Longitudinal Members (tonnes)	Trans. Members (tonnes)	Trans. BHD (tonnes)	Total (tonnes)
Template_6X3	54,8	1932,92	383,7	230,1	**2546,72**
Template_5X3	54	1905,2	252,4	233,5	**2391,1**
Template_6X2	53,1	1888,48	392,5	167,8	**2448,78**
BEST_Optimized	50	1773,2	251	154,8	**2179**

Table [9]: Weight of the structures made for the BEST+ template

It is now obvious that the difference of the structural weight between the 5X3 template and the 6X2 reference vessel template is reduced for the longitudinal members alone to 0.8% which is very satisfying, since the longitudinal members seem to be the critical in terms of structural weight.
It is thus possible to be able to reduce the steel weight of the structure of 5X3 design and using a potential structural optimization the weight can be reduced and be even competitive with a 6X2

equivalent. However due to time and resources limitations it was chosen not to take that path and perform a global optimization instead within the context of holistic ship theory.

Tank Arrangement Assumptions

From the analysis made above and the previous literature and work on the optimization of the AFRAMAX tank arrangement it was chosen as a default to use a 5X3 arrangement that incorporates both the excellent accidental oil outflow performance and the reduced steel weight in comparison with the 6X3 arrangement.
The tank dimensioning was partially subject of the optimization procedure, as the main dimensions of the tank space such as the double bottom height and the double side width were used as design variables for the optimization procedure. The modeling of the tanks was realized in the Friendship Framework as later described.
Some of the parameters however were kept as constant with values taken from the BEST+ tanks which are also a product of extensive optimization. More specifically, the hopper angle and length were taken the same as with the BEST+, having a 37.5 degree angle of hopper with a length of 5 m.

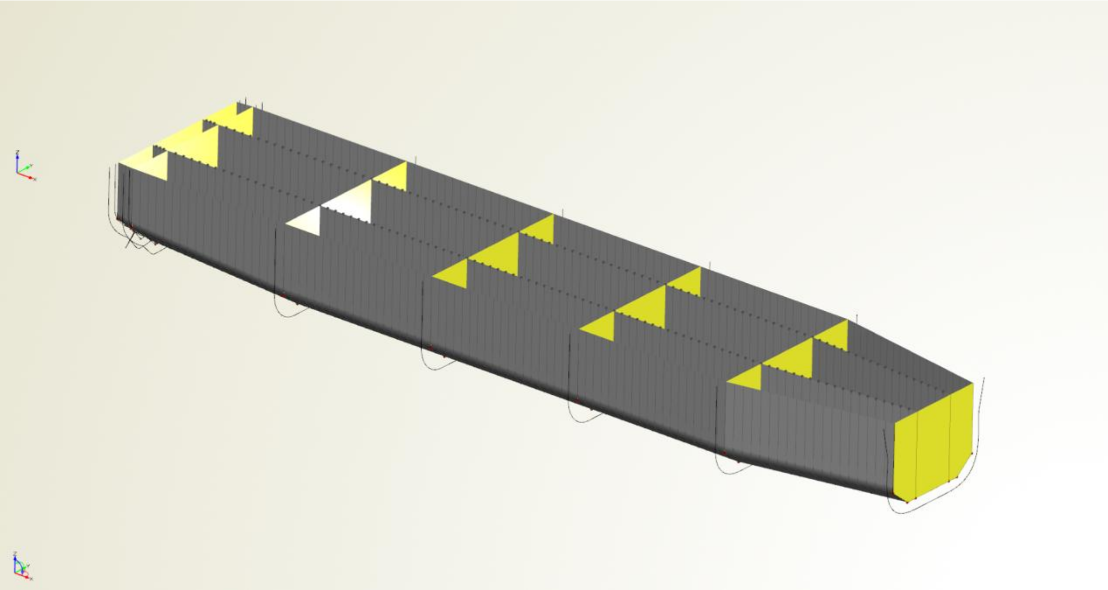
Tank Design Implications from the Use of Deep Well Pumps

The incorporation of deep well pumps was decided following the investigation of the potential use of this technology onboard a tanker, which indicated several advantages against a conventional pump room system. The decision was based on the previous report sent to the BEST+ project and the outcome of the VISIONS 2011 competition.
This decision, along with the fuel cost savings for the unloading procedures, came with two major implications, one of the tank design and one of the operational profile. The operational implication is the reduction of the unloading time which affects the required freight rate due to an increased number of trip per year.
From the other hand, the most important implication would be the elimination of the pump room. This enables the designer to change the location of the engine room bulkhead which separates the engine room from the cargo area. By doing so, and by also considering the required spaces for fuel and machinery spaces, it was possible to move this bulkhead towards the aft region corresponding to an increase of the cargo tank capacity. According to FRAMO, a leading deep well pump system manufacturer, this increase for an equivalent 6X2 AFRAMAX was 2 to 3% but for this particular case, the increase is bigger up to a 5%. That alone, without the optimization procedure can compensate from the increased initial building cost and the increased steel weight. The global optimization including both tank arrangement and hullform is expected to deliver even more impressive results.

Tank Modeling in the Friendship Framework

The tank surfaces and their respective parametric entity were realized within the FFW. More specifically, for continuation and robustness purposes, the feature definition and control panel used in the BEST+ model was used, with a few modifications in order to incorporate the two tanks across concept. Furthermore, the hydrostatic calculations within the FFW were used to calculate the capacity of the tanks, which is necessary for most of the computations. Some of the definitions, like the engine room bulkhead positions had to be refined in order to increase the robustness of the procedure as for certain values it was not possible to generate a feasible geometry (the slop tanks were crashed). This happened due to compatibility complexity with the position of the aft end of the parallel mid body.

The tank arrangement can be seen at the pictures that follow:



Picture [14]: Snapshot of the tank arrangement

2. DESIGN APPROACH AND METHODOLOGY

2.1. Calculations Workflow

As we mentioned earlier, in the chapter two, the main characteristic of the Friendship Framework is the Simulation driven design principle. The simulation of several design variants and the use of optimization algorithms is the objective and the main purpose of this model and the author's Thesis. In order to achieve this, several integrations have to be made that will perform all of the fundamental calculations needed through the preliminary (and sometimes detailed) design of a ship.
The work flow was inspired from the work of the Ship Design Laboratory NTUA together with F.S and GL (Harries, Tillig, Wilken, Zaraphonitis 2011) on the BEST+ research project. After working closely with the project coordinators both in Athens and in Germany, consultancy from Professor Papanikolaou (principal investigator for the project at NTUA) and a preliminary study on the comparison of NX3 and NX2 structural tank configurations, the following work flow was decided:

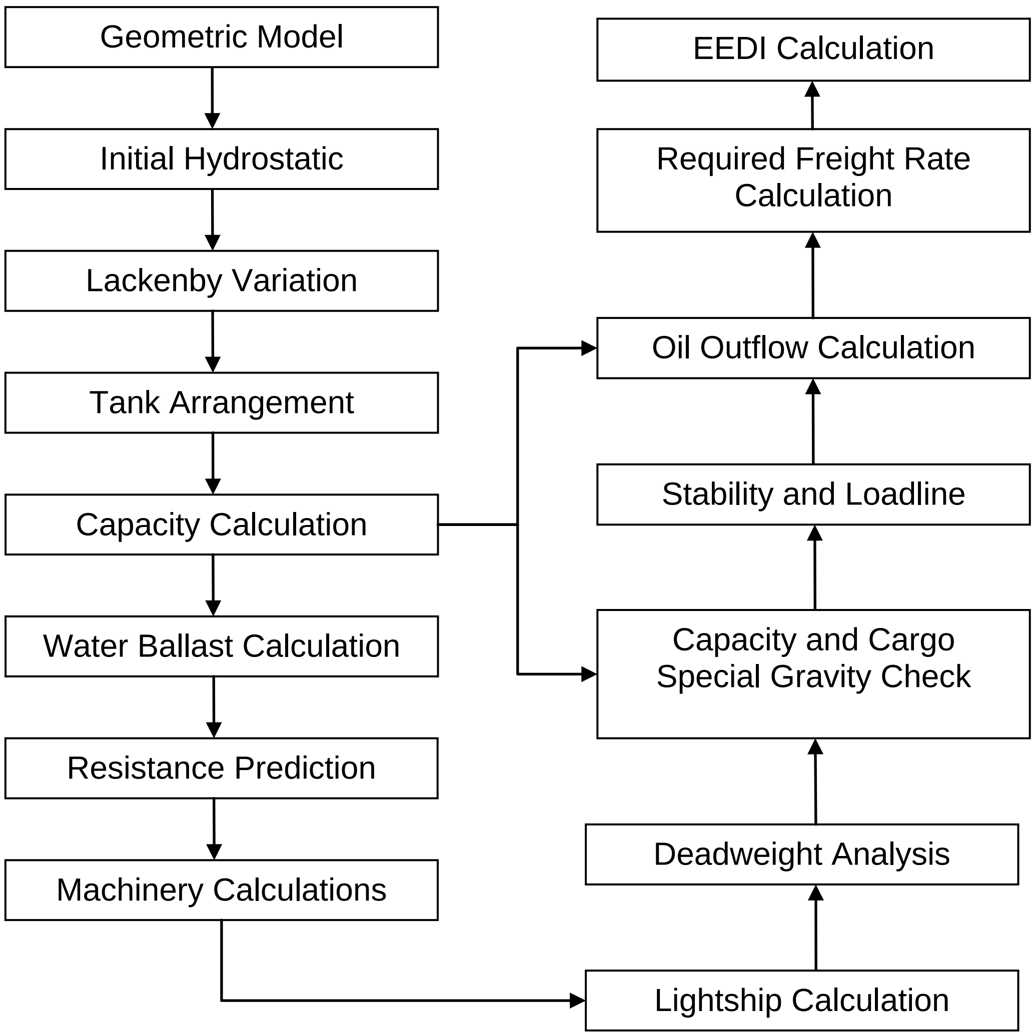


Figure [34]: The integration and calculations workflow

In the lines that follow there is a brief description of each calculation and the methods and assumptions followed.

2.2. Hydrostatic Calculation and Lackenby Variation

The hydrostatic calculation aims on checking the displacement volume, block coefficient and centre of buoyancy of the design. It is performed by an internal computation of friendship and for its execution a dense set of offsets (sections) is required as well as a plane and a mirror plane.
Having obtained the volume we can easily produce the block coefficient of the design. In order to be able to control the desired geometrical properties of the lines, namely the Cb and the longitudinal centre of buoyancy the Lackenby variation is applied. As explained earlier, this variation is a shift transformation that is able to shift sections aft and fore accordingly. Instead of applying quadratic polynomials as shift functions, fairness optimized B-Splines are used allowing the selection of the region of influence and the smooth transition as well. The required input for the transformation is the extent of the transformation which in this case is from the propeller position to the fore peak and the difference of the existing and desired Cb and LCB as well.

2.3. Resistance Prediction

The resistance prediction of this model uses a hybrid method and two different approaches, depending on the optimization stage.
During the design of experiment and the global optimization, where a great number of variants is created there is a need for high processing speed and need for computational power. For this particular reason the Approximate Powering Method of Holtrop is used that derives from editing statistical data and is a very fast method. Especially in tankers it is very accurate too, since the wave making resistance is a small fraction of the total resistance of these ships.
The Holtrop methodology uses the ITTC principle of segregating the different categories and types of resistance, and particularly the frictional (calculated by the ITTC 1957 formula) and the wave resistance (derived from formulas as a function of main dimension ratios, the prismatic coefficient, the entrance angle and the bulbous bow shape). The appendage resistance, transom immersion resistance and model ship correlation are also calculated either using physical principles or results of statistical analysis.
The Holtrop method is programmed within the Framework and is also generated as a feature for later use (e.g. in the VLCC case study). The assumptions made are for some dimension ratios (L/T, B/T) that are the same approximately for every tanker or bulk carrier. Actual data from the geometric model is also used, such as the entrance angle, prismatic coefficients etc.

Although this method is among the most precise for ships of that type and size there are several uncertainties regarding the results due to the statistical nature of the method and the lack of the particular details of local hullform shape that might trigger irregularities and problems at the viscous pressure resistance and the wave field. At a later stage, the CFD code package SHIPFLOW is used, in order to validate the trends in terms of propulsion efficiency for the Pareto front designs. However, the results of Holtrop are generally conservative and at the safe side compared with CFD analysis. In addition to that, following extensive runs in several CFD packages, due to the complexity of the stern, there were serious robustness issues as well as the results seem to be not only unrealistic but also violating basic principles of hydrodynamics. The CFD analysis is robust only for the wave making part which is very small for these vessels. Thus it can be considered a correct choice to use Holtrop instead since it is very fast and accurate for a global application.

2.4. Lightship Calculation and Deadweight Analysis

- ***Lightship Weight Teams***

The lightship calculation follows the traditional categorization in three weight groups, the machinery weight, the outfitting weight and the steel weight.
The machinery weight calculation is based on the average of two methods: the Watson-Gilfillan formula and the calculation based on the Main Engines weight respectively. The average is used to balance out any extreme differences, and the coefficients of the Watson-Gilfillan formula are calibrated for low speed, two stroke engines.
The outfitting weight is a also based on the average of two independent calculations. The Schneekluth method is one and the use of empirical coefficients for sub-groups of that particular weight group is the other one.

- ***Steel Weight***

Last, the most important weight group (and the one with the biggest share of the lightship), the steel weight is calculated by a hybrid method. The steel weight for the cargo block are is split in three teams, one representing the longitudinal members of the structure (plates, stiffeners etc) , one representing the transverse members (girders, web frames etc) and the transverse bulkheads. The information for the weight of each team, derives from a previous analysis on the weight of 5X3 tank structures made for the BEST+ project. In this analysis, a POSEIDON model is made for the dimensions of an equivalent 6X2 design. On this template model, eight variations took place taking into account the position of the longitudinal bulkheads, the breadth and the deck height of the ship. The results were compliant with the IACS CSR Rules for Tankers and gave also a weight for each of the steel weight teams. As a result, an average weight distribution coefficient was derived for each team, depending on the length of each cargo hold. The latter is expressed in frames instead of meters. The weight of the cargo hold thus can be very well approximated. However there is a need for the weight of the remaining engine room and peaks, namely of the entire structure without the cargo block. Due to the peculiarity of using a twin skeg arrangement, the reference vessel NAVION BRITANNIA was used. A Schneekluth calculation is performed for the entire ship structure as well as a POSEIDON calculation for the cargo block. The difference of the two is thus derived and expresses the weight of the aft and fore peaks and of the engine room as well. A cubic coefficient is subsequently created in order to identify the weight changes per model and have in this way a greater sensitivity in main dimension changes in relation to steel weight. The weight of the superstructures is approximated using the Muller-Kostner method for NAVION BRITANNIA and is taken the same.

After the lightship calculation is complete a calibration is performed, taking account the divergence of the reference design with the methods used. This benchmarking dictates us to use a correction factor of 1.1 in order to be “on the safe side”, although this can be considered as a conservative view.

- ***Deadweight Analysis***

The deadweight of the vessel is comprised by subgroups such as the consumables, the crew weight and the deadweight constant. The Deadweight analysis is the prediction of the payload of the vessel based on the calculation of the consumables.
As mentioned before, the consumables for the machinery is calculated, namely the Heavy Fuel Oil for the main engines, the Diesel Oil for the generators, the Lubricating Oils of the engines and generators. Furthermore, based on the number of the crew members (30), the fresh water onboard is calculated as well as the supplies and the stores of the vessel.

2.5. Tank Arrangement Modeling and Capacity Calculation

The Crude Oil tanks are modeled geometrically, within the Framework using a feature of the BEST+ model in FFW. This feature uses as an input the tank variables such as the hopper length and angle, the double bottom and double side, the number of tanks, the position of the longitudinal bulkheads, the engine room bulkhead position etc.
The capacity of each tank is calculating by creating offsets for each one of the tank surfaces and joining them together. Afterwards, a hydrostatic calculation of the tanks takes place and the total capacity can be checked.
Since the total capacity is known as well as the payload weight, we can calculate the Specific Gravity of the cargo, that should be at about 0.86 tonnes/m^3. A constraint is set for this value, as well as for the double bottom and double side values (by MARPOL limits) and the GM of the design.

2.6. Oil Outflow Calculation

The Accidental oil Outflow Parameter is calculated according to the MARPOL Regulation 13. The index is calculated for each design variant by integrating an Excel Spreadsheet. The Excel is integrated within the Framework by using a COM interface and is something that is relatively easy.
The Excel spreadsheet was developed by Assistant Professor Nikolaos Ventikos of NTUA and Mr. Panagiotis Sotiralis, alumnus of NTUA. The input used for the Excel is the main dimensions, the tank capacities, the bulkhead positions and the tank distances from the side shell. The output gives the absolute value of cubic meters , which is then divided by the capacity according to the MARPOL regulation. The integration and the calculation are calibrated according to the VLCC example given by MARPOL. At this point, we should note that the MARPOL calculation according to a study of N.Ventikos and P. Sotiralis are conservative and according to real damage statistics a better performance is expected.

2.7. Stability Check

The stability check is not the most critical issue for this design due to its beamy characteristics and tanker nature, as it would be for a containership or a passenger ship.
However it is an important check and cannot be neglected. For this reason, the centers of gravity of the ship at a fully loaded condition are calculated and the hydrostatics properties are calculated by the integrations of Friendship. Thus it is possible to calculate the GM of each design, which is at the region of 3.5 to 4.5 meters, a value more than adequate.

2.8. EEDI Calculation

The Energy Efficiency Design Index (EEDI) is calculated according to the proposed at IMO MEPC 62 formula, using the payload, 75% of the MCR of the engines and some corrections factors for the fuels. Two versions are made, one for HFO fuel use and one for the case of LNG fuel use:

$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \, C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE} *\right) + \left(\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}{f_i \cdot Capacity \cdot V_{ref} \cdot f_w}$$

The minimization of this index is one of the primary aims of the optimization, which is correlated both with the deadweight of the design as well as the design speed and subsequently the engine power. The engine power is directly connected to the resistance of the hullform and the deadweight is also connected both to the hullform in terms of displacement and to the lightship weight.

2.9. RFR Calculation

The required Freight Rate serves along with the EEDI as an objective function in order to access the economic viability and the competitiveness of each design.
It is calculated within the Framework and takes into account the operating and maintenance costs and the building cost (increased by 15% for the twin skeg configuration). The feature created for the BEST+ project is used for the calculation of the RFR, making the same assumptions for the operational profile in terms of the route. The unloading time for this design is shorter due to the use of deep well pumps. This will enable all of the designs to have a better performance in comparison with a conventional one from the starting point. The HFO and MDO rates are taken constant, however at a later stage a comparison of the Speed-RFR curve is made for different fuel prices.
Furthermore, in order to avoid excessive economies of scale that might distort and manipulate the results, a penalization for big lightship weights takes place as a further extra. This extra is modeled as in the BEST+ project, were the difference from a reference steel weight is found and charged by actual Korean labor prices. This however is a conservative way in order to make sure that the results are not unrealistic and optimistic which also subject to the owner's negotiations with the yard. An adaptation at a later stage is possible nevertheless.

3. OPTIMIZATION STUDIES

3.1. Introduction and Approach

This is the second stage of the report and the most interesting one. It contains the design exploration, simulation and optimization for the AFRAMAX tanker. As mentioned before, the approach is holistic and addresses the ship design problem in its hole as we can see from the workflow above. The aim of this optimization study is to identify at a preliminary design stage possible trade-offs and areas of improvement for a twin skeg tanker. This ship is by definition safer, both in terms of propulsive redundancy and tank arrangement (accidental oil outflow). However, it is not as competitive as a conventional equivalent, either single screw or 6X2. In other words, at a first stage effort is given in order to make a safer ship equally competitive and at a later stage even more. We must point out nevertheless that if we use the same methodology for a conventional ship more impressive results could have been achieved.

Having in mind the framework and boundaries we mentioned above, it has been decided to set the following design goals and objectives:

- Increase the **Safety**
- Increase the **Competitiveness**
- Increase the **Efficiency**

Or in other words:

- Reduce the Required Freight Rate at a minimum
- Record and reduce the Accidental Oil Outflow
- Reduce the IMO Energy Efficiency Design Index

In order to be effective and produce adequate and at the same time realistic results, we must define an approach strategy. This was decided to be at three milestone stages, briefly described below:

Stage 1: Explore the Design Space by Designs of Experiment (DoE)

Before launching an optimization routine one should be aware of the design space boundaries and the capabilities of the code. For this particular reason, a two stage DoE was performed. At first the debugging and sorting out of the design variables took place. With the variables refined and the code robust and sustainable the Design of Experiment was formally launched at two subsequent stages. First a global search using the Sobol algorithm with a constant design speed of 15 knots and then using the same principles but at a speed range of 13 to 16 knots. The design speed was chosen as a variable in order to identify and verify the trends of the algorithm and also to see that the dominant designs were still dominant for a number of speeds, allowing the operational practice of slow steaming.

Stage 2: Global Optimization using Genetic Algorithms

The dominant variant of the DoE stage was exported. The feasibility of the design was assessed and proved to be realistic. Based on this design, the second stage was launched, namely the formal global optimization process. The design variables did not change and were kept constant with a few minor refinements. Initially the population was set to 2700, as a result of 100 generations of 25 designs population each. Since the results in a scatter diagram were satisfying and the dominant variant of the pareto front was calculated with the use of an utility function. This was then subject to the final optimization procedure, that of 150 generations of 20 population each. Following this the choice was made for several scenarios either by use of graphic scatter diagrams or by utility functions (instead of objective).

Stage 3: Local Hydrodynamic Optimization, Validation and Operational Analysis

With the results of the extensive global optimization in hand, the validation of the results and the analysis of the operational profile of the dominant vessel had to be made.
First the trend in terms of propulsion calculation was verified using the CFD code Shipflow to verify the relationship between the Pareto designs. Second, the cargo block weight was verified by creating a new structural model in POSEIDON. Third a separate study was done for the dominant variant in order to determine the optimum operational speed in order to achieve the lowest Required Freight Rate for a number of different scenarios depending on the fuel price alone.

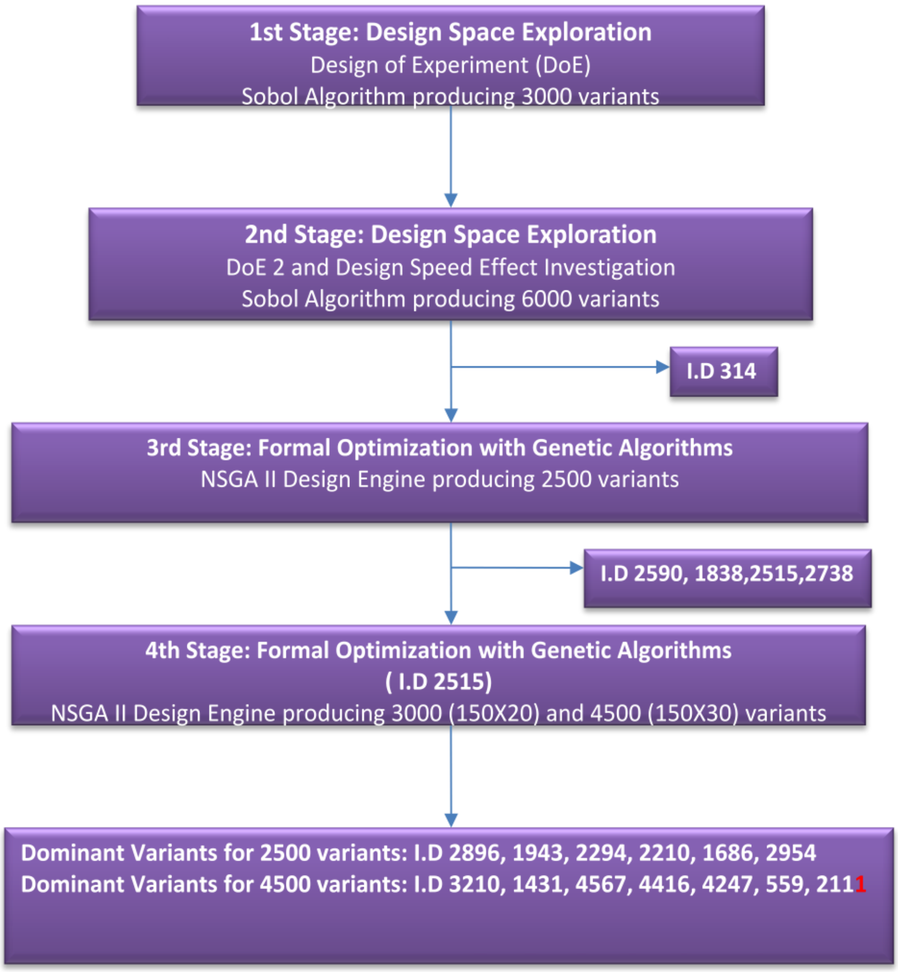


Figure [35]: The optimization stages

3.2. Design Variables Chosen

After the debugging process we mentioned earlier the final choice of the refined design variables can be seen on Table [10]. As we can see it spans all over the design process either in terms of main dimensions, hullform or tank arrangement.

Design Variable	Lower Bound	Upper Bound
Length Between Perpendiculars (m)	235	245
Beam (m)	44	48
Deck Height (m)	21.5	22.5
Draft (m)	14.2	14.7
Cb	0.855	0.87
LCB (% Lbp)	0.515	0.525
FOB (% B)	0.7	0.85
FOS (%D)	0.65	0.85
End of Parallel Midbody (% Lbp)	0.2	0.22
Beggining of Parallel Midbody (% Lbp)	0.7	0.75
Bulb Length (% Lbp)	0.025	0.03
Double Bottom Height (Tanks 2-5, m)	2.1	2.8
Double Hull Width (m)	2.1	3
Mid Tank Width (% Bcargo)	30	52
Design Speed (DoE 2 only, knots)	13	16

Table [10]: Design Variables chosen

Furthermore, regarding the tank arrangement, other design variables were taken constant such as the hopper length an angle as well as the Engine Room Bulkhead. The first were taken the same as the values following the optimization studies of the BEST+ concept and the second were taken at a minimum value, having in mind space requirements for the fuel tanks and engine room but not the pump room (it is chosen as a deep well pump design).

3.3. Design Objectives

The design objectives were different in the DoE and the genetic algorithms. First, as it is a quasi-random design space exploration the objectives are only monitored and are not objectives. Therefore, the objectives were the parameters we wanted to monitor:

- Lightship Weight
- Cargo Volume
- Deadweight
- Installed Power
- Ballast Water Required
- EEDI Index
- Accidental Oil Outflow Parameter
- Required Freight Rate

In contrast to that, the objectives chosen for the genetic algorithms were the following:

- EEDI Index
- Required Freight Rate
- Accidental Oil Outflow

The reason for this choice was that these objectives are the most representing and contain directly the other objectives. After all these three are the ones that we defined earlier.

3.4. Design Constraints, Sensibility and Feasibility

In order to be sure that the designs that are not feasible are properly identified a series of constraints was used in order to sort out the produced variables as we can see in table [11]. This particular model due to the transitional geometry of the stern and the 5X3 tank geometry had a high degree of sensitiveness in terms of tank arrangement. For rapid changes at the tank geometry and the stern hullform the tank configuration for the slop tank and the last cargo tank crashed resulting in variants with a very small cubic cargo capacity.

Constraint	**Limit**
Upper Special Cargo Gravity	<0.92
Lower Special Cargo Gravity	>0.82
Deadweight	<125000 tonnes
Double Bottom Height (MARPOL limit)	>2.0m
Double Hull Width (MARPOL limit	>2.0m
Accidental Oil Outflow Parameter (MARPOL limit)	<0.015
Draft (Port Restrictions)	<14.8m

Table [11]: Design constraints

By introducing these constraints and further refining the boundaries of the design variables , that in fact act as constraints themselves too, the feasibility of the design engine was at a very satisfactory level of about 75% for the DoE and at a 93% for the genetic algorithms. During the selection process, the dominant variants proved to be feasible and when exported and carefully examined did not have irregularities of any kind.

3.5. First Design of Experiment-Design Space Exploration and Initial Solution

The first design of experiment aimed to identify our initial design space and enable us to see the potential for improvement. The variant generation was done in a stepped way using exactly the same variables and constraints in order to avoid memory overload and to have a better control.
The experiment used the Design Engine Sobol of FFW as it is a quasi-random algorithm that can avoid local design concentrations and thus is aware of the majority of the design space. This algorithm also has the capability of starting from the last design it stopped, which proves to be extremely useful for the steped procedure we mentioned earlier. The variables that the algorithm used are the ones in Table [10], without the design speed however which was taken constant at 15 knots. The results table was exported as Comma Separated Values (CSV) format in order to be able to discuss and edit the results in the Microsoft Excel suite.

The scatter diagram represents the relationship of two of the three objectives, the RFR and the accidental oil outflow.

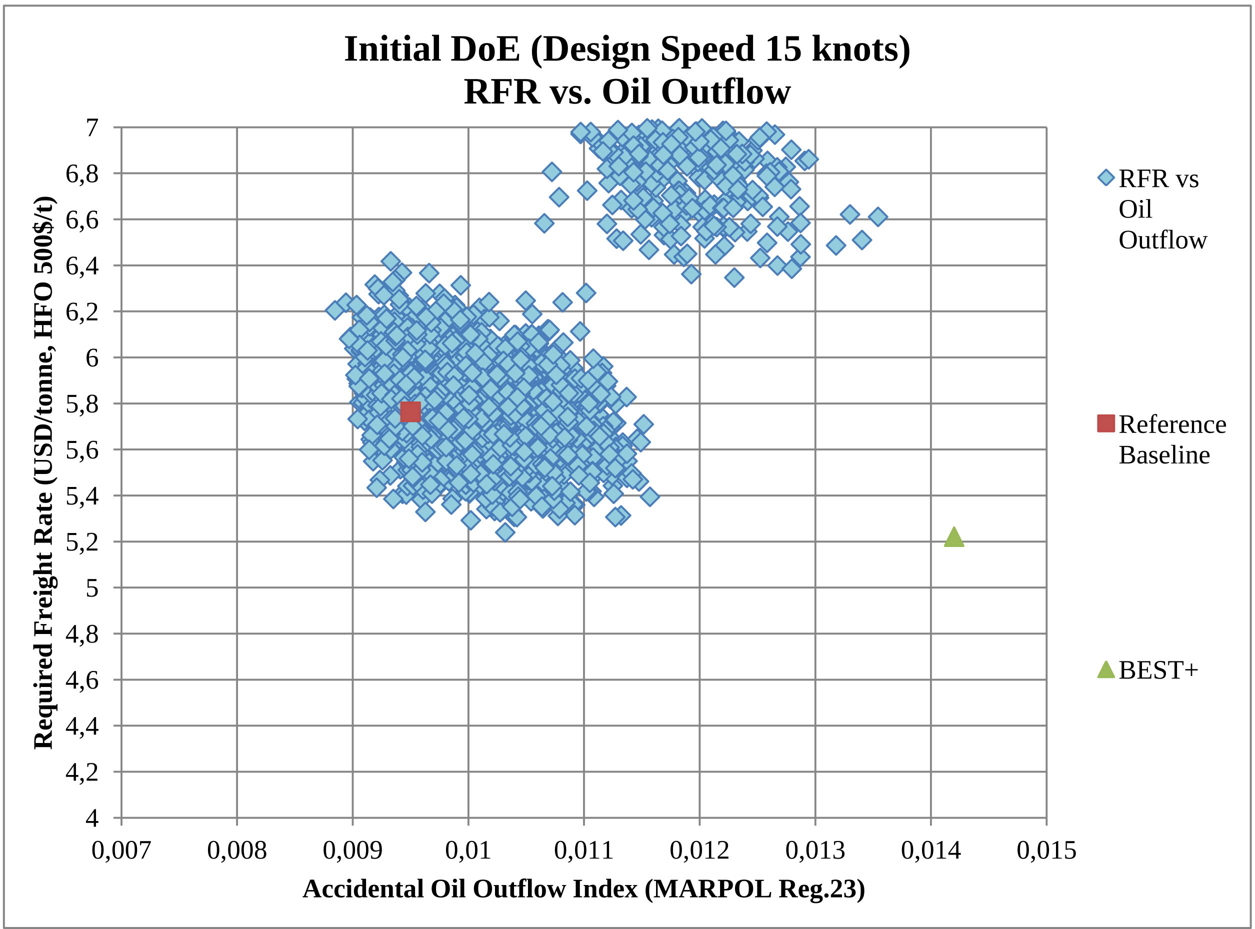


Figure [36]: First DoE RFR-Oil Outflow Relationship

Two scatter design clouds can be identified with the lower one being more dense. After analysis it was realized that the upper cloud represents at its majority the unfeasible designs. Furthermore, it is evident that all of the feasible designs have a superior behavior in terms of accidental oil outflow in comparison with any 6X2 design including BEST+. Furthermore, we can see an very small number of designs that have a better performance in terms of RFR ion comparison both with the baseline model and BEST+. However, there is a degree of uncertainty for that as the installed horsepower for the twin skeg design was calculated using Holtrop method in contrast to the CFD prediction.

Nevertheless, a 20% weather margin was given and an additional 5% for fouling, uncertainty and derating purposes.

Similar trends can be seen at the relationship between the IMO EEDI and the Required Freight Rate. Both of them are strongly correlated to the Cargo Volume Capacity which is greatly increased as a bulkier hullform is achieved. This can be also seen by the bigger improvement margins seen here. We can also identify the very good performance of the BEST+ design, which loses ground to other dominant variants due to the bigger capacities and deadweights of the latter (about 7000 m^3 more).

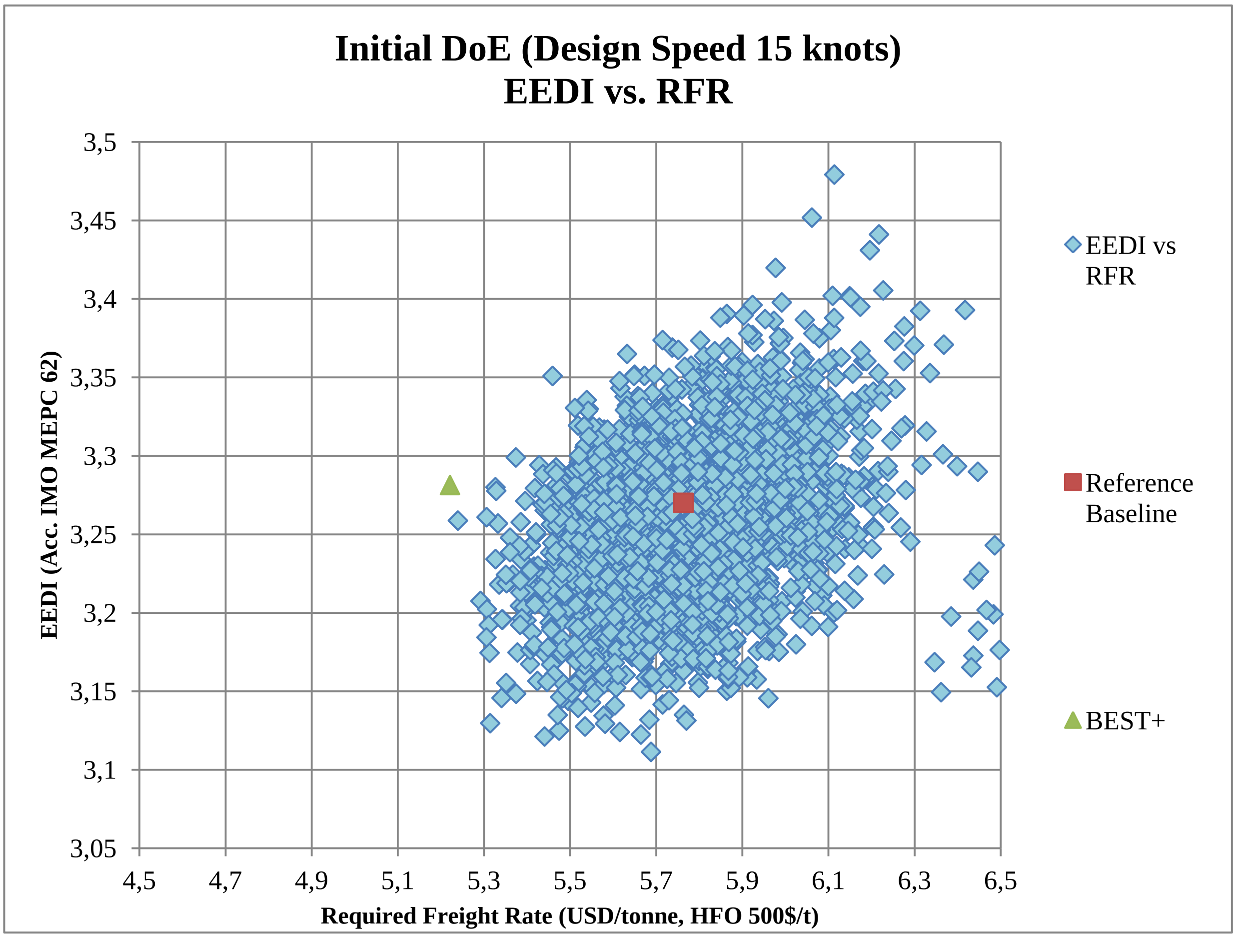


Figure [37]: First DoE EEDI-RFR Relationship

Another important note is that for both cases where we have regulatory constraints, namely the MARPOL Reg. 23 for the accidental oil outflow performance and the EEDI limits as set at the IMO MEPC 62 all of the designs are well below both the present and the future, striker limits.

3.6. Second Design of Experiment-The effect of design speed

The second DoE aimed at a bigger design exploration by stretching the main dimension boundaries and by introducing the design speed as a variable. Having in mind some commercial considerations in either high or low market conditions we set the range from 13 to 16 knots in order to have a sustainable transport chain and not mitigate the safety or the commercial competitiveness. Furthermore, at the lower the barrier of the 13 knot design speed we can compensate with the use of deep well pumping arrangements the time lost at sea, as indicated by the analysis of the deep well pumps (Part One), in comparison with a 15 knot ship.
Except from the extra design variable the procedure was kept the same. The resulting variants were at a population of 6000 and had a feasibility of about 80%. As before, the variant generation was in two stages with 3000 population for each subset.

At a first glance we can see that the absolute numbers for the required freight rate are significantly lower, which can be attributed to the lower design speeds. This is evident as the majority of the pseudo Pareto designs have the lowest bound for the design speed. This verifies our initial guess and also shows the robustness of the solutions as they are valid for a range of design speeds. It also enables us to see that there is room for improvement of the RFR for a significantly lower Oil Outflow Index.

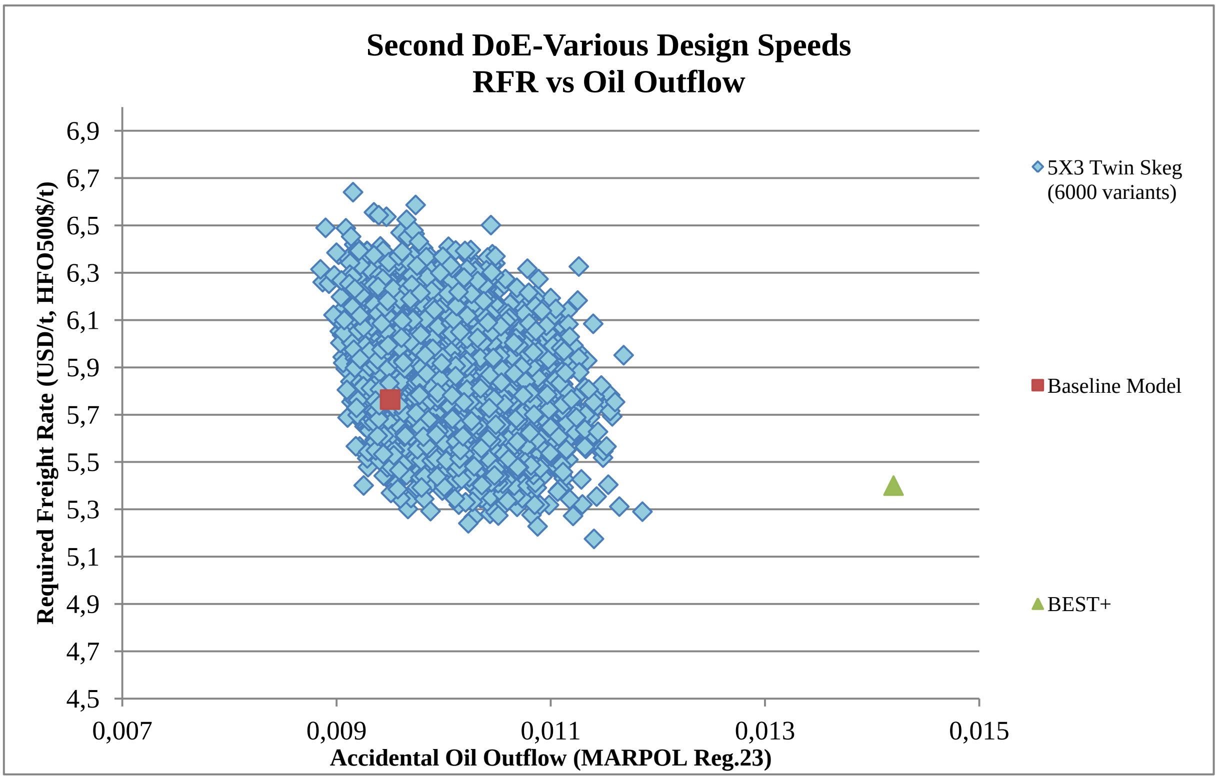


Figure [38]: Second DoE RFR-Oil Outflow Relationship

Another note would be on the ratio of the competitive designs to whole number of variants. It is evident that approximately 10% have lower freight rates than the baseline and the BEST+ concept, in contrast to the 5% ratio of the previous stage. This can explained due to the introduction of the speed as a design variable.
This kind of trend can be clearly identified when looking at the relationship of the IMO EEDI index with the Required Freight Rate (Figure [39]). The number of designs with lower EEDI is the majority of the produced alternatives, which is attributed to the direct correlation of the EEDI to the vessel's speed. Under its current formulation, this kind of results is expected for future designs and many researchers express worries about the safety levels of these in terms of maneuverability and added

wave resistance adequacy. However, as the minimum design speed at the present study is 13 knots and the derated engine can be tuned for a bigger output we can consider the safety level equal to a conventional 15 knot tanker. In terms of market competitiveness, the greater tank capacity combined with a bigger Cb can boost the profitability of each voyage as an effect of the economy of scale. This means that the RFR will remain at a lower level regardless of the concurrent increase of lightship (due to 5X3 and twin skeg arrangement), required power and initial building cost.

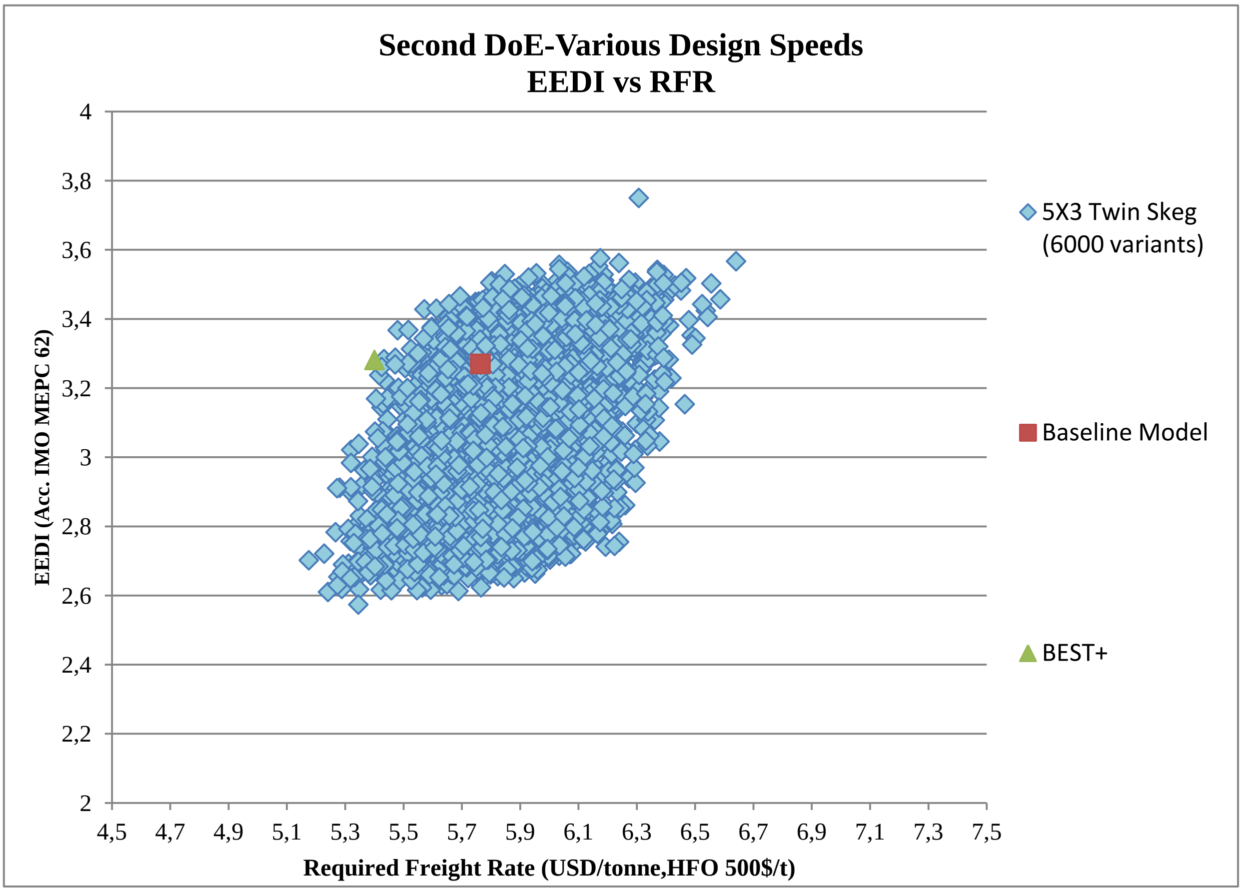


Figure [39]: Second DoE Relationship of EEDI and RFR

This DoE verified our initial assumption, that under current market conditions (in terms of emission control and fuel prices) lower speeds are favored and the optimum designs in regard to other parameters remain to be optimum at a lower speed. For this particular reason and after making a trial run on NSGA II which showed that the genetic algorithm leads to lower speeds after a number of generations it was decided to keep the design speed fixed at a competitive 15 knots. Since the effect of speed is universal for all designs, it is considered a better practice to study the actual service (and not design) speed for the dominant variants at a range of fuel prices and determine the optimum value of the service speed with regard to the lowest RFR. Apart from that, it is still under consideration a local hydrodynamic hullform optimization using CFD tools of the dominant designs in order to increase the design speed for a constant installed horsepower (same principle of BEST+ concept).

3.7. First Genetic Algorithm Run (NSGA II Design Engine)

3.7.1. Introduction, Design Variables and Objectives

The design exploration undertaken in the Design of Experiment stage aimed at verifying the potential for improvement and its margin and also to refine the number of design variables and their respective boundaries.
Following this procedure the dominant variant (I.D DoE 0314) was selected and exported for further optimization. This was preferred instead of the baseline model as it demonstrates a superior behavior in both three objectives and thus it can serve as a better initial solution as the baseline model. With this choice therefore, the speed of convergence and the improvement margin increase and the robustness and feasibility of the produced design is ensured. Indeed, the feasibility index increased from 75% to85%, meaning that only 15% of the solutions did not comply with the imposed constraints.

The design variables were kept the same with the first DoE (Table [12]), however the main dimensions boundaries changed as effects of economies of scale were identified and a relaxation in the dimension boundaries means that the margins of improvement can b additionally increased.

Design Variable	Lower Bound	Upper Bound
Length Between Perpendiculars (m)	230	245
Beam (m)	43	48
Deck Height (m)	21.5	22.5
Draft (m)	14.2	14.7
Cb	0.855	0.87
LCB (% Lbp)	0.515	0.525
FOB (% B)	0.7	0.85
FOS (%D)	0.65	0.85
End of Parallel Midbody (% Lbp)	0.2	0.22
Beggining of Parallel Midbody (% Lbp)	0.7	0.75
Bulb Length (% Lbp)	0.025	0.03
Double Bottom Height (Tanks 2-5, m)	2.2	2.8
Double Hull Width (m)	2.1	3
Mid Tank Width (% Bcargo)	30	52

Table [12]: The design variables chosen for the NSGA II runs

The objectives of the routine were the RFR, EEDI and Oil Outflow Index. These were kept only as several other objectives are correlated with their calculation and thus they can be considered as more global and representative. Furthermore, by using such global indexes possible conflicting arguments of several objectives can be resolved without user interference.

The design engine that was used for the generation of variants was the NSGA II, which is built in the FFW. As it is an application of genetic algorithms for optimization the number of variants can be determined by the number of generation and the population of each generation. A population of 15 to 25 individuals can be considered adequate and takes into account the majority of the design space. The number of different generations is very important, as it defines the solution vector and thus the extent of the optimization process. In order to achieve a number of approximately 3000 variants (comparable to the BEST+ population) a number of 100 generations was considered for the first run.

The produced results were exported using the CSV (comma separated values) format available at the FFW and edited in Microsoft Excel. When looking at the relationship of the accidental oil outflow parameter to the required freight rate, a pareto front is created. The pareto front or frontier by definition is the set of choices that are pareto efficient. By restricting attention to the set of choices that are Pareto-efficient, a designer can make tradeoffs within this set, rather than considering the full range of each parameter. If we assume that the preferable values of each criterion parameter of a system (eg. EEDI or RFR) are the lesser ones, the aim is to minimize the dimension of each criterion vector.

One criterion vector **y** *strictly dominates* (or "is preferred to") a vector **y*** if each parameter of **y** is not strictly greater than the corresponding parameter of **y*** and at least one parameter is strictly less: that is, $\mathbf{y}_i \leq \mathbf{y}^*_i$ for each *i* and $\mathbf{y}_i < \mathbf{y}^*_i$ for some *i*. This is written as $\mathbf{y} \prec \mathbf{y}^*$ to mean that **y** strictly dominates **y***. Then the Pareto frontier is the set of points from *Y* that are not strictly dominated by another point in *Y* [].

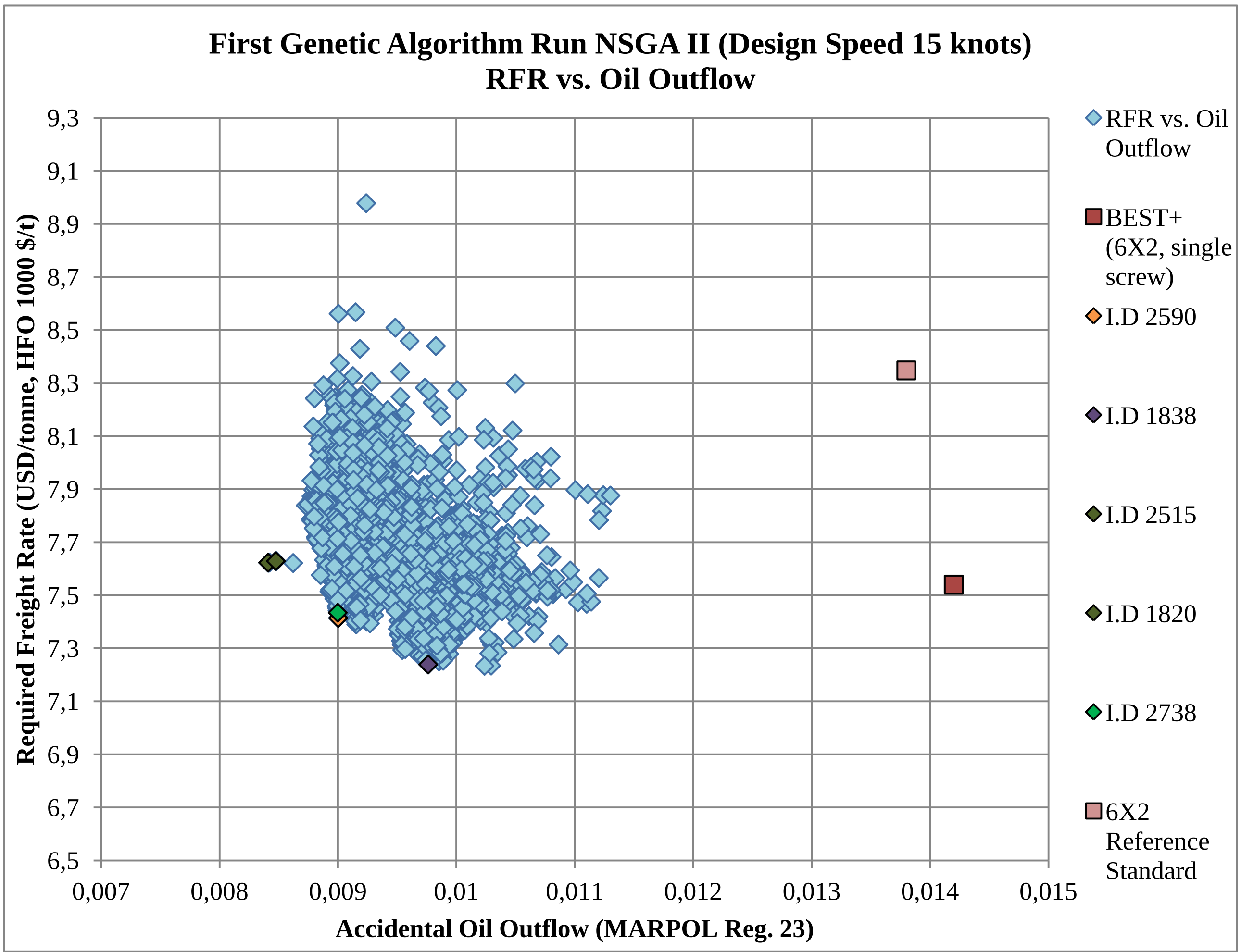


Figure [40]: The RFR-OOI relationship for the first G.A optimization run

This kind of Pareto behaviour can be identified in the scatter plot of the produced feasible designs by the genetic algorithm. In figure [40] two distinctive areas can be identified for the Pareto frontier. First there is a steep front for lower OOI values that ends at a peak. The peak is followed by a small gap and a second peak of variants with a particularly low RFR and a higher OOI value.

So in general the results can be grouped under two categories of dominant variants. The first includes lower oil outflow ships, were the decision maker can decide the trade-off in terms of RFR he wants to make in order to achieve an even lower OOI. The second area is in fact a peak of Pareto designs with a relatively small breadth but high concentration that includes designs that incorporate the lowest freight rates for a relatively higher oil outflow. This area includes the dominant designs (I.D 2590 etc)

sorted by the utility functions of 3 from 5 scenarios examined, which suggests that the "best compromise" can be achieved in this area.
Regarding the efficiency of the run, it should be noted that about 30% of the designs are better both in terms of OOI and RFR than the BEST+ concept and the baseline model. Furthermore, the shape of the design cloud has changed, with the designs now being "pushed" towards the pareto frontier. This ensures that the frontier has a greater population and thus there are more optimal solutions for a range of scenarios. Besides, the decision maker (in this case the designer) will make a choice on the basis of the distance from the pareto front. Another interesting observation is that the maximum value of the OOI is approximately at 0.012, which is an improvement of 20% in comparison to the limit of the regulations of 0.012 and a 16% improvement in comparison to the performance of BEST+, which is a 6X2 design.
From the other hand, the minimum OOI has a value of 0.0085, indicating a 43% improvement of the accidental performance of the ship based on the MARPOL regulation alone It is also interesting to see that there are two designs that are feasible and incorporate the lowest OOI for a medium to small freight rate. These can be a basis for the next optimization step, provided that their EEDI performance is adequate. The reason for a small number of designs with such characteristics is the number of generations (100) which is going to be increased in the next run. It is also interesting to see that these designs (I.D 2515 and I.D 1820) are sorted in the dominant variants (in the top position for one scenario with more weight to the OOI) by the utility functions used. This indicates that this area has a potential for results for low OOI levels the RFR performance is better.

Significant improvements can also be seen from the EEDI perspective. The trends first experienced at the Design of Experiment are verified here. The Pareto frontier is obvious and very distinctive and has a linear trend to lower values. This is a very good sign and shows the strong correlation between the EEDI and the transport cost as both objectives are heavily depended both on the installed horsepower (hull performance) and the cargo carrying capacity expressed either as cargo volume or deadweight. This property is very convenient for the optimization studies, since both the EEDI and the RFR are objectives for the optimization routine. This means that there are cases where both objectives can be satisfied by a single design. In the meantime, some effects of scale economies may influence the EEDI performance as the formula is by definition favouring bigger ships. This is the reason why the majority of the variants generated have lower values of the EEDI than the BEST+ concept which is smaller, especially in terms of breadth (thus displacement), deadweight and cargo volume.
Regarding the results themselves, the minimum EEDI recorded was at about 3.09, which corresponds to a regulation margin of 23.7% in comparison to the 4.05 limit set by the IMO for tankers at the region of 120000 DWT. The maximum value of the EEDI is coincident to the maximum value of the RFR, and thus we do not need to further investigate them. In comparison to the BEST+ ship, the EEDI is decreased by 6%, a percentage that is adequate but can be changed due to model and method uncertainties.

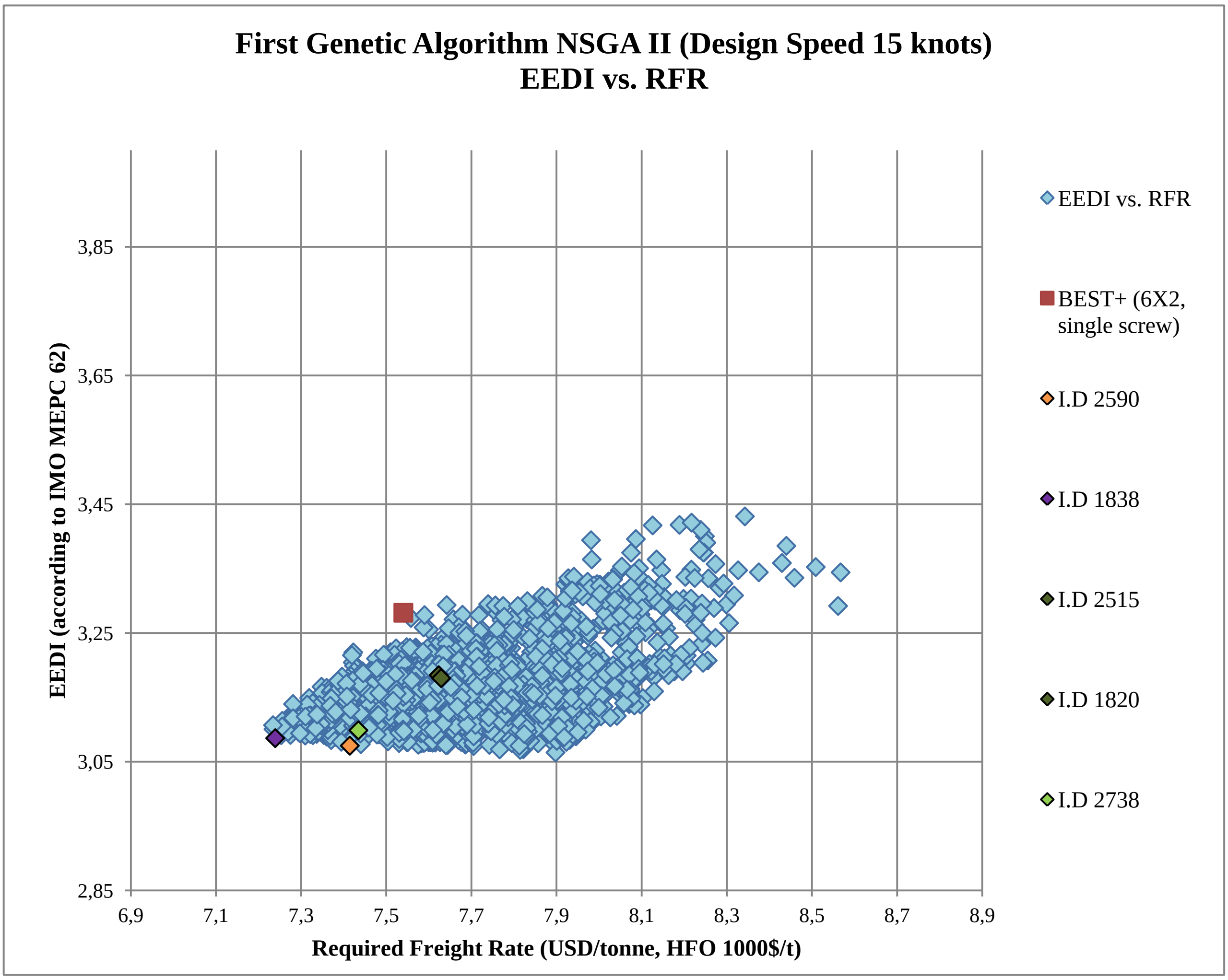


Figure [41]: The relationship between EEDI and RFR for the first G.A optimization run

However the change cannot be dramatic since the EEDI depends on the deadweight of the vessel too, which for the case of the twin skeg is greater due to bigger dimensions and bulkier hullform. For the baseline model the difference is at 4.2% indicating that the starting point was very good. It is also an indicative of the performance of the method, as in this case the optimization is only global and does not include local hullform parameters and refinements that can further improve the ship efficiency. In any case this study alone indicates that the limit and criteria set by the IMO both for the present (phase 0) and future limits (phase 1 and 2) are satisfied. In timeline these limits cover a big portion of the vessel's design life supposing that it is built now and for a 25 year service.
Interestingly, the designs discussed earlier that incorporate lower OOI values have a lower EEDI than BEST+ and generally have an average EEDI performance.

3.7.2. Choice of dominant Variant with the use of an Objective Function

The choice and the sorting of the dominant variants is not a trivial task. For this particular reason we need a rational approach in order to consider all of the tradeoffs that exist. The approach followed earlier, with the use of an objective function is functional but not the ideal one. The reason for that is that it does not take into account the distance of each variant from the optimal ones, in other words the Pareto frontier. This kind of distance can be found by using a utility instead of an objective function.

The utility function uses the user based optimum designs. The optimum solution in our case would be the minimum EEDI value, the minimum OOI value and the minimum RFR value. Instead now of using a fixed weight for each variant the weight has a distribution in our case, it was chosen a linear distribution, in other words a straight line described by the formula $y=ax+b$. The optimal values (for our case the minimum values) of the objectives have the maximum value of a weight which is set by the user, under the constraint that the sum of all the weights is equal to 1. The less optimum values, in our case the maximum values of the objectives, have a zero weight as they are far away from the optimum state, the pareto frontier. For all of the objective values between the maximum and the optimum the weight is set by the equation of the linear distribution mentioned earlier.
At this point is should be also noted that not the exact values of the objectives are assessed as they have different units and boundaries, but the normalized values, in other words the values divided by the maximum of each objective, thus defining the price range theoretically from 0 to 1.
Since the normalized values are derived the equation of the weight distribution is determined resulting into the corrected values for the weights. Given the weights now, the utility function for each variant is the following:

$$U = w_{EEDI} * u(EEDI) + w_{RFR} * u(RFR) + w_{OOI} * u(OOI)$$

The maximization of this utility function is the objective now, and the dominant variants are the ones that have the maximum value of this utility. The sorting of the variants now includes the 20 most favorable for 5 scenarios resulting into sorting and finding 100 designs with a better performance according to each scenario. Each scenario gives a bigger proportion of weight to a respective objective, with the exception of the first scenario that assumes equal weights. The weights for each scenario can be seen at the table below:

Objective	**1st Scenario**	**2nd Scenario**	**3rd Scenario**	**4th Scenario**	**5th Scenario**
RFR	1/3	0.8	0.3	0.2	0.4
EEDI	1/3	0.1	0.4	0.2	0.1
OOI	1/3	0.1	0.3	0.6	0.4

Table [13]: The weights for each scenario

As we can see from this table, the scenarios are corresponding to an equal weight decision, a decision based on a priority for economic performance, a decision based on accidental oil outflow performance, a decision based on the EEDI with a less weight however and last a decision giving more weight to the RFR and the EEDI. We must note that the weight given to the EEDI in any case is not very big as the EEDI is not yet finalized and can provide misleading results. Furthermore, the good EEDI performance can be coincident to the good RFR performance.
The scenarios and the respective sorting of dominant variants can be seen at the following figures:

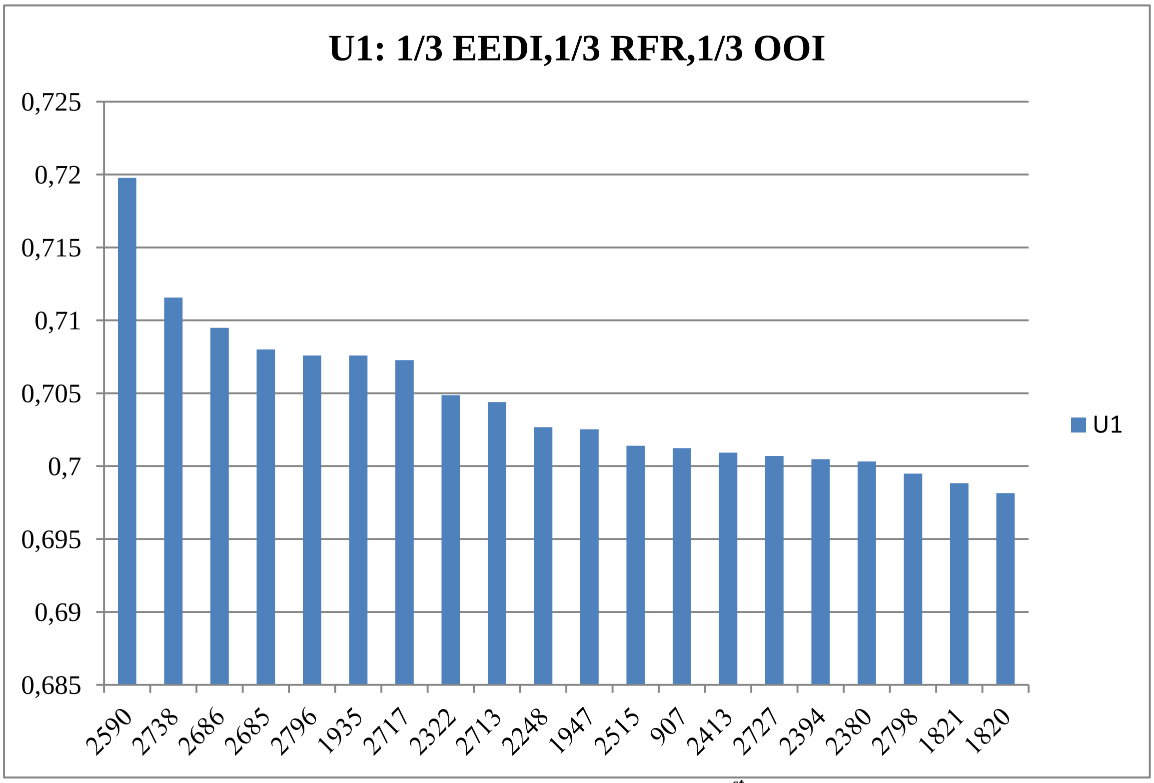


Figure [42]: Design Ranking according to the 1st Scenario

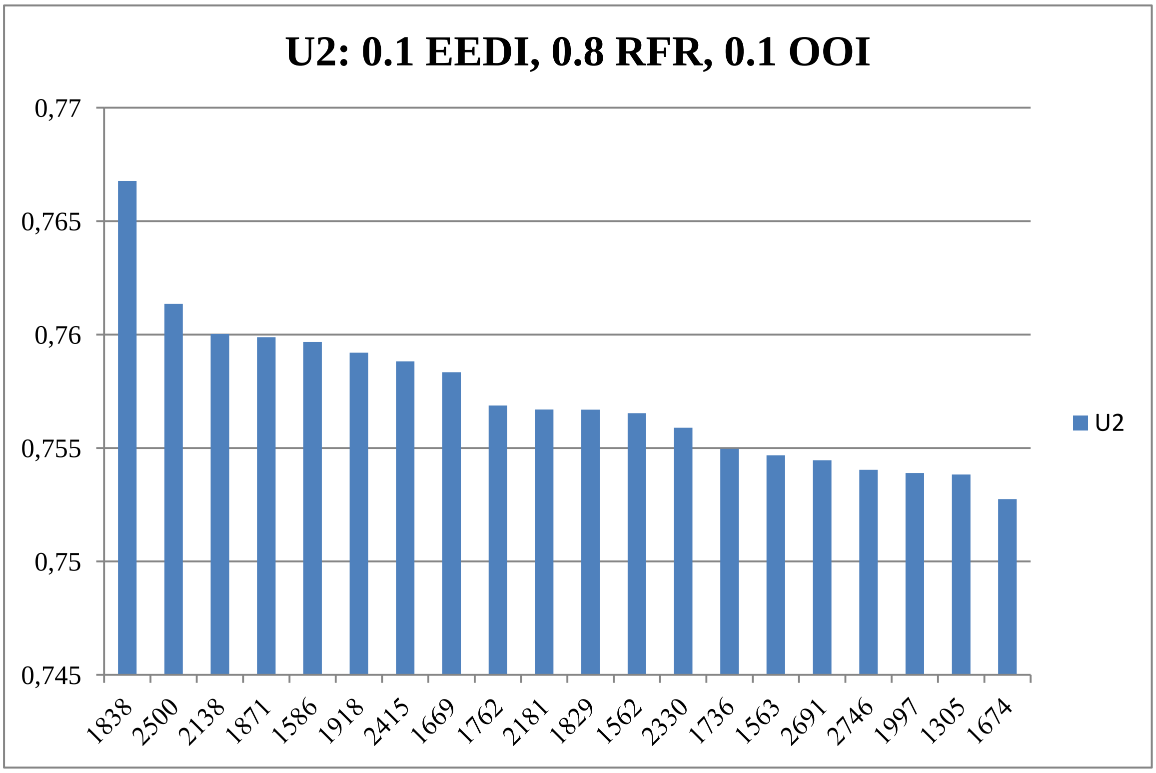


Figure [43]: Design Ranking according to the 2nd Scenario

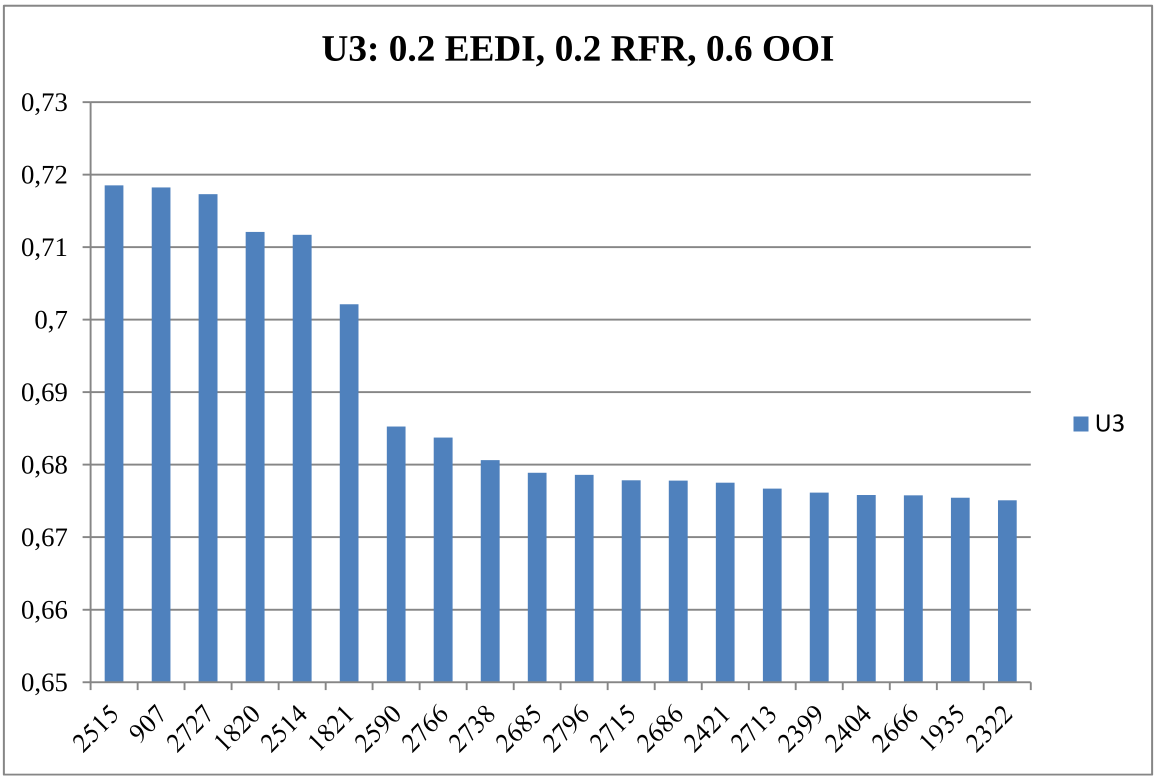


Figure [44]: Design Ranking according to the 3rd Scenario

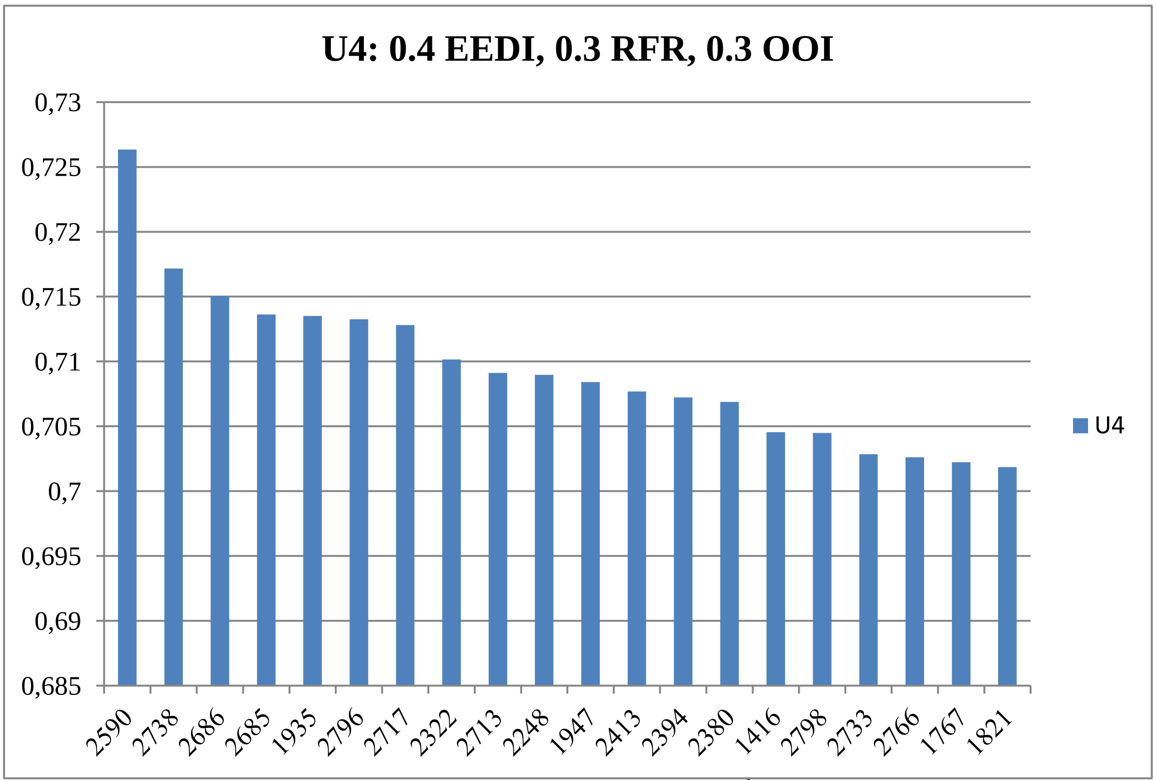


Figure [45]: Design Ranking according to the 4th Scenario

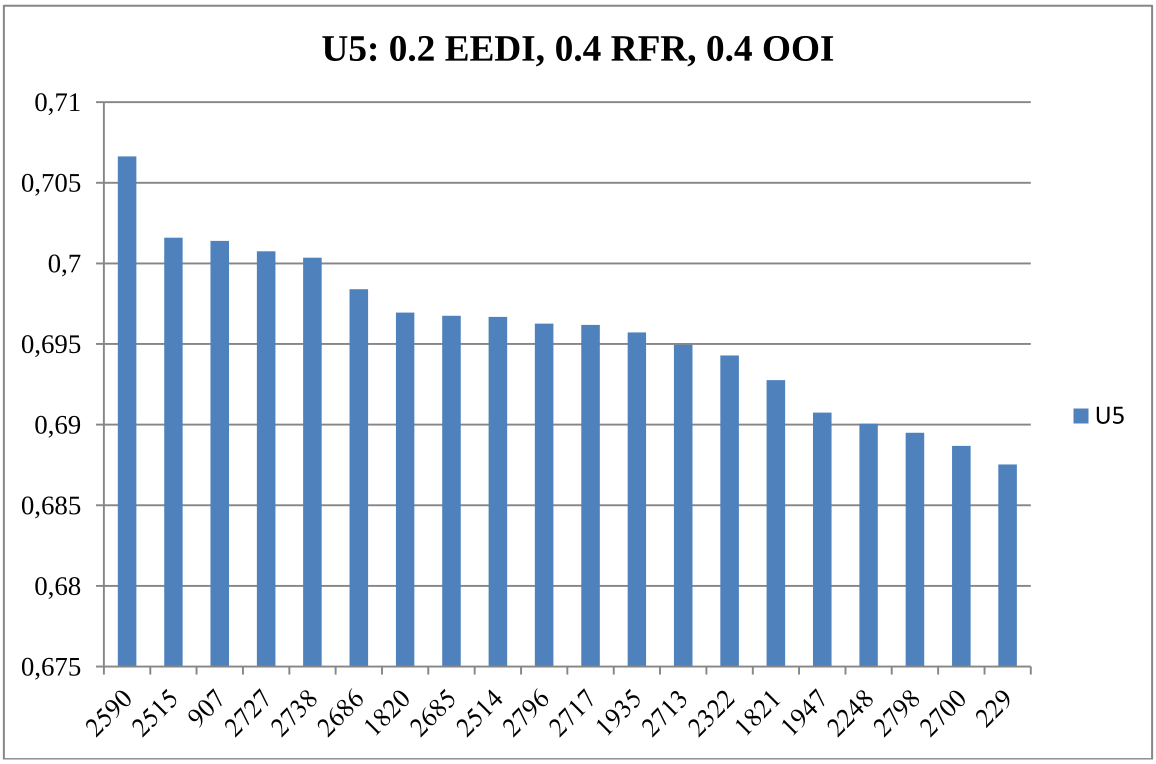


Figure [46]: Design Ranking according to the 5th Scenario

It is evident from the sorting in different scenarios that the optimal designs are in dominant positions (like design I.D 2590 and I.D 2515). In the meantime the top position varies depending on the scenario, although scenarios 1 and 4 seem to have identical results due to the close similarity of the nominal utility weights. The top two designs from each category can be seen at the following table:

Position	**1st Scenario**	**2nd Scenario**	**3rd Scenario**	**4th Scenario**	**5th Scenario**
1st Place	I.D 2590	I.D 1838	I.D 2515	I.D 2590	I.D 2590
2nd Place	I.D 2738	I.D 2500	I.D 907	I.D 2738	I.D 2515

Table [14]: Top two designs for each decision scenario

The I.D 2590 design appears very frequently. This can be explained by its position on the scatter diagram of the RFR vs. OOI (Figure [40]), which is at the bottom of a peak of the Pareto frontier at a lower OOI value. It is also interesting to see that the designs that were discussed and incorporate the lowest OOI for a very low RFR appear frequently appear too with the exception of the second scenario (0.8 weight to the RFR) which is peaking designs from the far left peak of the RFR-OOI scatter diagram Pareto front. For this particular reason and in order to better explore the potential for a combined reduction of the oil outflow index and the required freight rate design I.D 2515 was chosen to be exported for the next stage of multi-objective optimization using genetic algorithms.

3.8. Second G.A Optimization (NSGA II Design Engine-3000 Variants)

3.8.1. Introduction

The first optimization run highlighted the design I.D 2515 as a favorable variant, which was exported and used as a baseline model. This stage of optimization was in two subsequent versions in order to assess the design space exploration. The first version was consisted by 150 generations of a population of 20 each. However, performance in terms of RFR and OOI like the one experienced at the previous algorithm was not evident. For this particular reason the decision was taken to expand the procedure and have a second version of 6000 variants created by 200 generations of a population of 30 each. This ensures that the big population covers a bigger portion of the design space and the necessary generations force the algorithm to produce variants towards this direction.
The design variables were kept the same as the previous run with the exception of the beginning of the parallel midbody were the boundary was expanded due to a potential for efficiency improvements in terms of reduced resistance.

3.8.2. Results-150 Generations of 20 Population

As written before, the first version of this optimization stage is using 150 generations each having a population of 20 designs. In comparison to the previous stage some aspects of the design space may be neglected due to the smaller population of each generation. However, the Pareto frontier is very distinctive and some promising results can be identified.

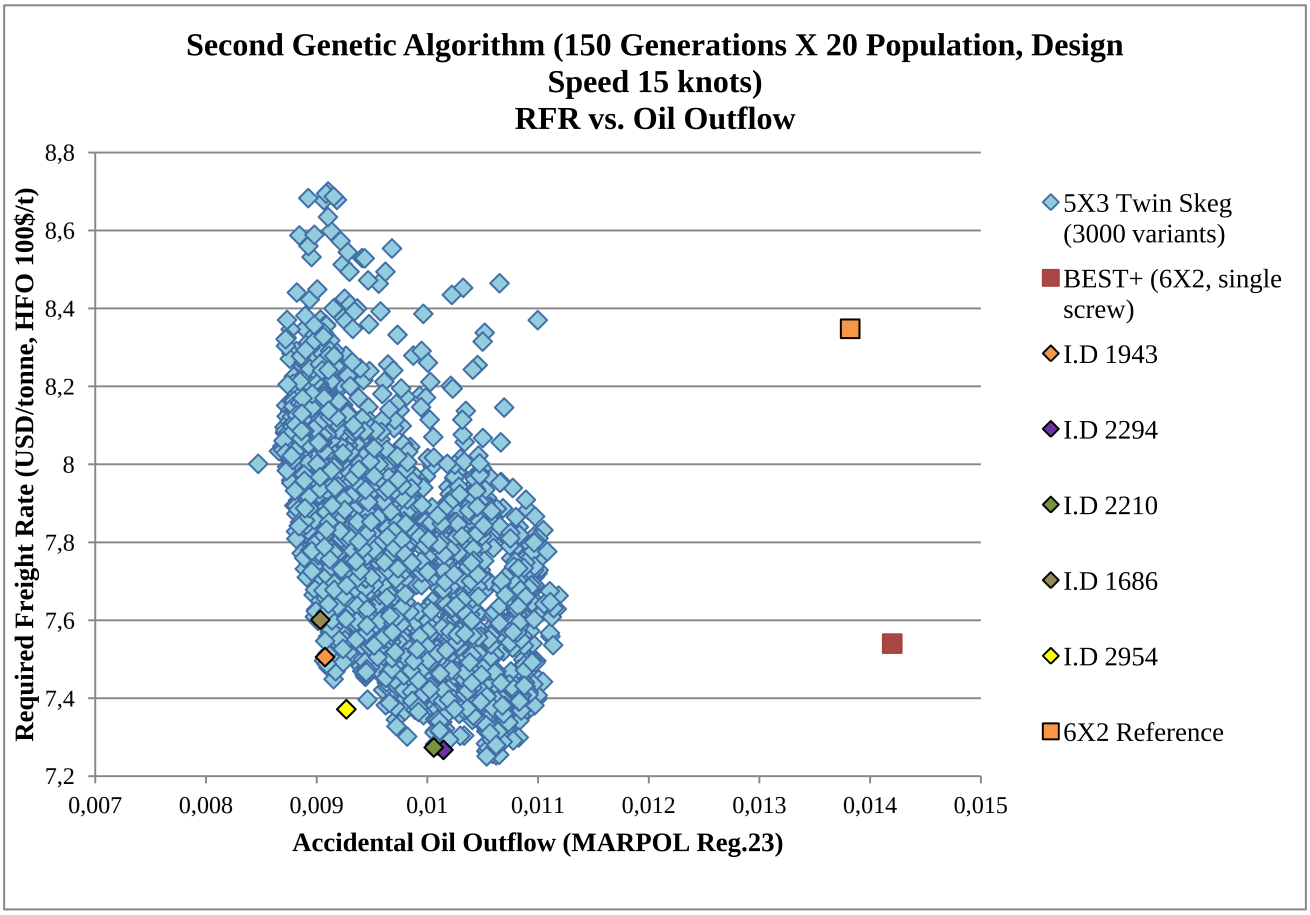


Figure [47]: RFR-OOI Scatter Diagram for the Second Stage Optimization

When looking at the relationship between the accidental oil outflow and the required freight rate (figure [47]), the frontier is very steep for low OOI levels and has two peaks of minimum freight rates for an almost same OOI. There are plenty designs (almost 30%) that have a better performance in terms of freight rate in comparison to the BEST+ values, and can be found at the right peak, which is also the area of the minimum oil outflow for this frontier. In contrast to the previous optimization the drop of freight rate for low OOI is steeper, however there are no designs that incorporate the minimum OOI in combination with a smaller RFR level. This can be attributed to the smaller population of each generation.

It is also indicated that small values of accidental oil outflow are coincident with smaller tanks which leads to a lower usability and profitability and thus increased freight rate. However if we compare with a 6X2 equivalent, we can see that the majority of the designs have a lower freight rate and a design with the same freight rate has an OOI of about 0,009 or a 38% improvement. This leads to the conclusion that in any case each of the generated designs is superior in terms of accidental performance in comparison with any existing AFRAMAX which has by definition a 6X2 arrangement. Furthermore, we can consider that the tank arrangement as a risk control option for this case is very cost effective and in limited cases, more competitive than an equivalent 6X2. After all, the scope of this study is not only to find a better alternative in absolute numbers but to highlight the trends and relationships between the variants and provide the decision maker with the dominant variants as the final choice as mentioned earlier is always subject to the decision makers mentality.

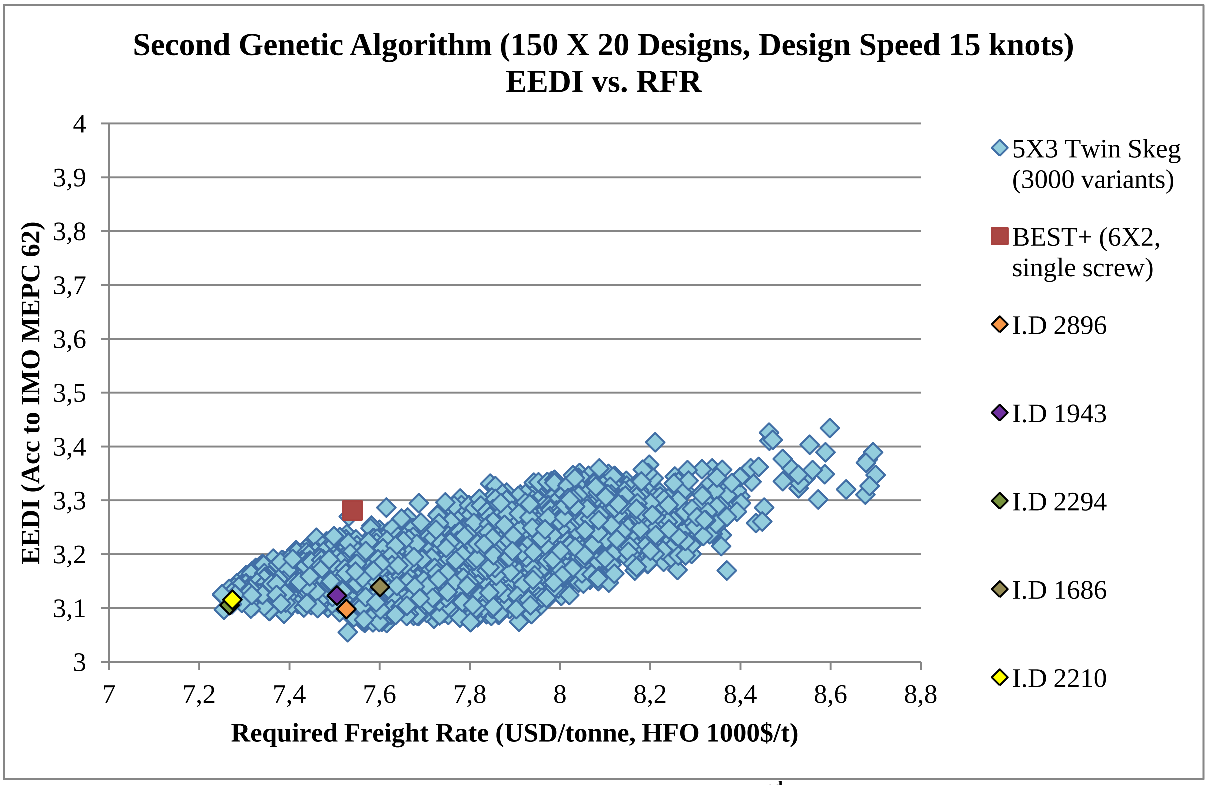
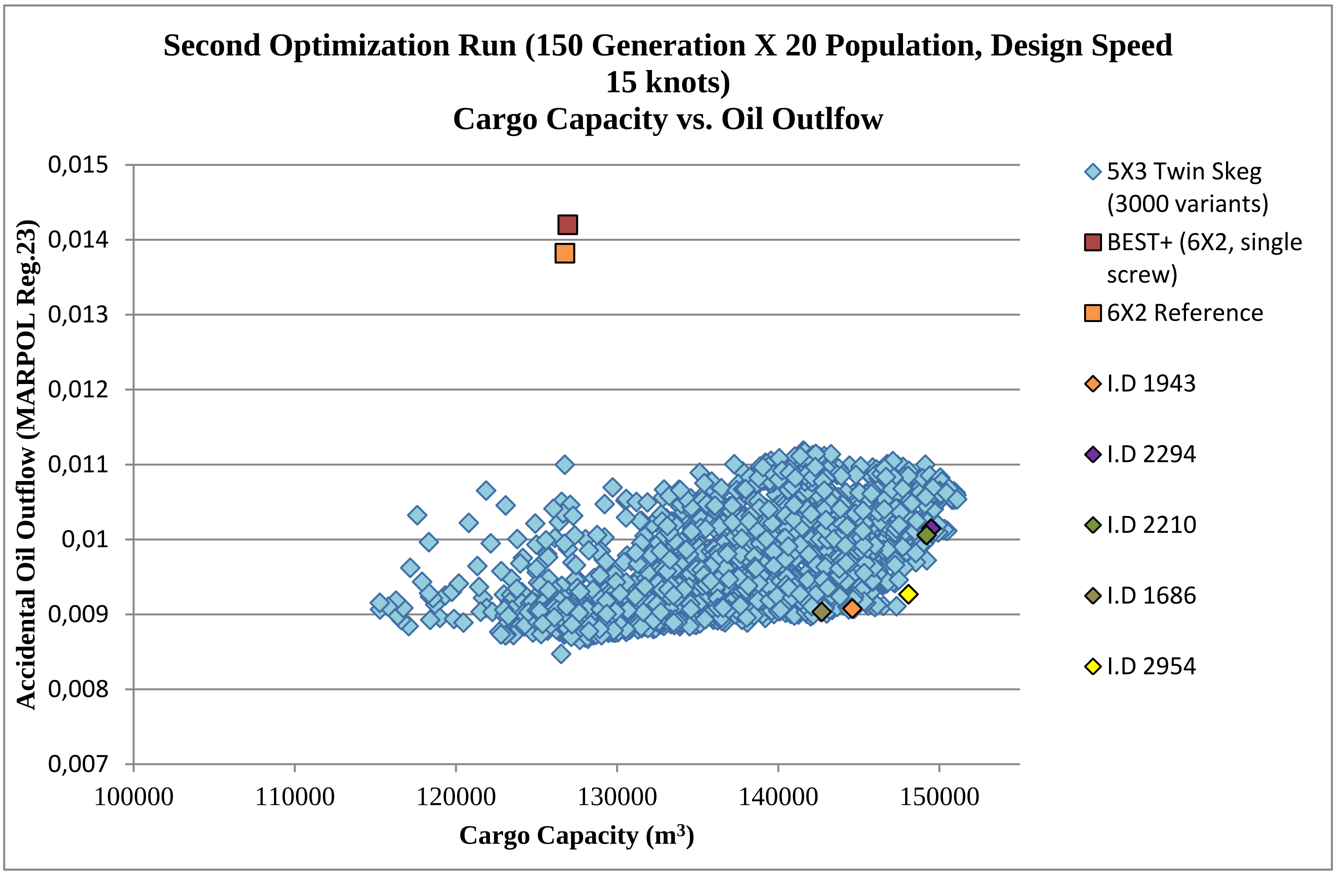


Figure [48]: The EEDI-RFR relationship for the 2nd Optimization Run

When looking now at the EEDI-RFR performance, the results are the same as the previous optimization and are no surprise. The EEDI-RFR relationship is almost linear which reduces the complexity of the final decision and furthermore does not create any conflicting arguments. This is clear when looking back at figure [47] at the RFR-OOI relationship, where the ship with the best EEDI value is at the region of the low freight rate ships and very close to the ship with the lowest freight rate. The same cannot be said for the ship with the best accidental oil outflow performance as it can be spotted at a region were ships with bigger EEDI values can be found. This verifies that the smaller capacity is penalized in terms of RFR and EEDI but favored in terms of OOI. This tendency also acts as a filter for the effects of economies of scale, which as mentioned earlier, are very big. We can also see that the BEST+ concept has a better performance in terms of freight rate than the minimum spill ship but has a slightly bigger EEDI. The relationship of the OOI with the cargo capacity can be seen Figure [49].The effects of scale economies are clear in this diagram, as well as the strong correlation of the tank capacity with the Required Freight Rate as shown by the BEST RFR variant (minimum RFR) which has the biggest tank capacity.

Figure [49]: Cargo Capacity vs. Oil Outflow

From the above mentioned discussion we can consider that the outcome is a very basic question of ship design. Do we want to take benefit from the effects of scale economies. There are two ways in this case. The one way would be to prefer a ship with a better accidental performance which however has a limited tank capacity in comparison with other designs. This kind of mentality leads to choosing



a design from the first, steep frontier and peak of figure [47]. From the other hand, which is more common, more weight could be given for the economic performance which is coincident to the environmental performance of the design (according to the so far status quo of IMO regulations) as the benefit to the society (expressed as the deadweight of the vessel) is bigger. This would lead to choosing a design from the far right region of the frontier in figure [47].In the real, shipping world the second would be the choice as it satisfies MARPOL Regulation 23 with a great margin. In optimization terms however the choice would be somewhere in between the two regions considering the tradeoffs the decision maker has to make and the maximization of his utility as well. So one can understand that the next and possibly one of the most critical steps, is the sorting and the choice of the dominant variants.

3.8.3. Search, Ranking and Choice of the Dominant Variants using Utility Functions (150X20)

The search and ranking of the dominant variants was done using the same approach used in the previous stage, by linear utility functions. An interesting expansion to that would be to use exponential utility functions in order to decrease the elasticity of the decision maker's utility and thus be more demanding and penalize deviations from the optimum levels (Pareto frontier).

The scenarios and the respective weights for this process are the same as previously:

Objective	**1st Scenario**	**2nd Scenario**	**3rd Scenario**	**4th Scenario**	**5th Scenario**
RFR	1/3	0.8	0.3	0.2	0.4
EEDI	1/3	0.1	0.4	0.2	0.1
OOI	1/3	0.1	0.3	0.6	0.4

Table [15]: The weights for each scenario

As we can see from this table, the scenarios are corresponding to an equal weight decision, a decision based on a priority for economic performance, a decision based on accidental oil outflow performance, a decision based on the EEDI with a less weight however and last a decision giving more weight to the RFR and the EEDI. We must note that the weight given to the EEDI in any case is not very big as the EEDI is not yet finalized and can provide misleading results. Furthermore, the good EEDI performance can be coincident to the good RFR performance.

The sorting of the variants can be visualized in the following graphs that the utility and the respective design I.D.

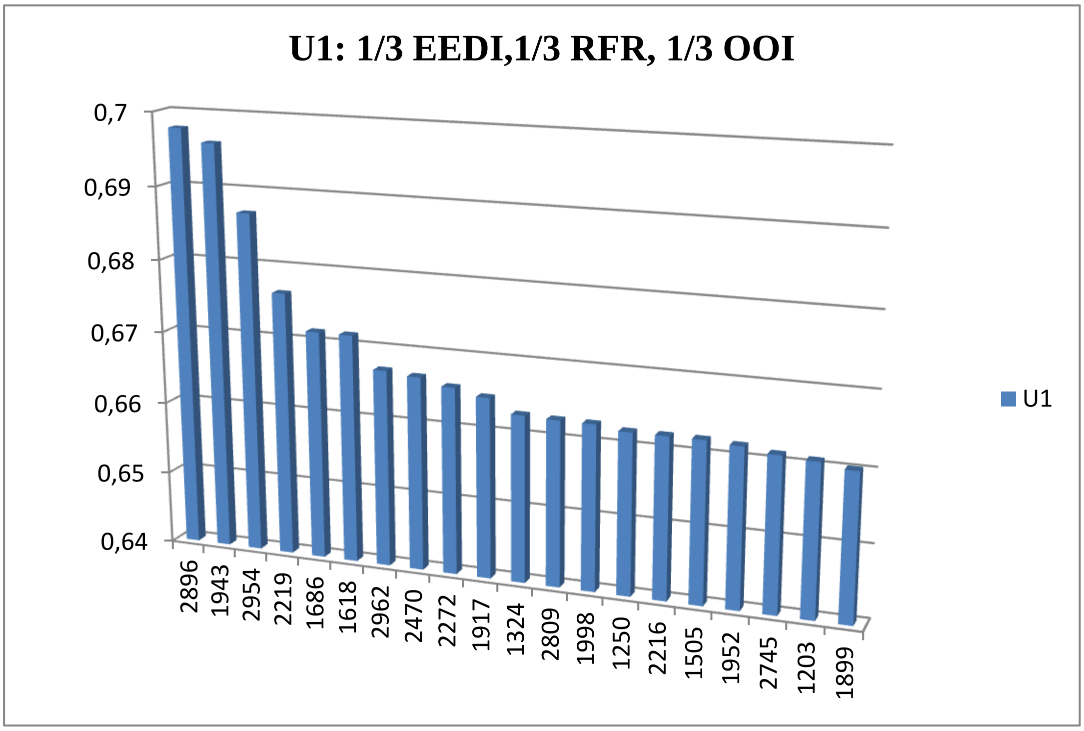


Figure [50]: Design Ranking according to the first scenario

Due to the big difference of the weights between the first and the second scenario (figures [49] and [50]), it is obvious that the ranking is quite different, with both 20 prevailing designs being different.

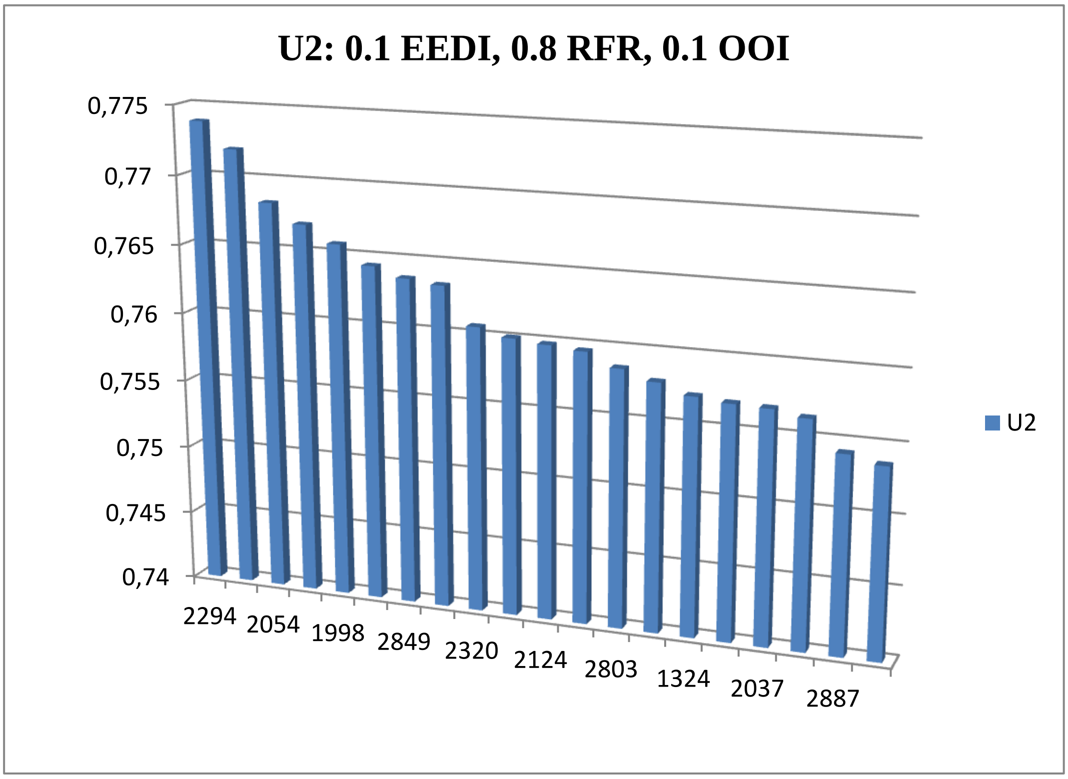


Figure [51]: Design Ranking according to the second scenario

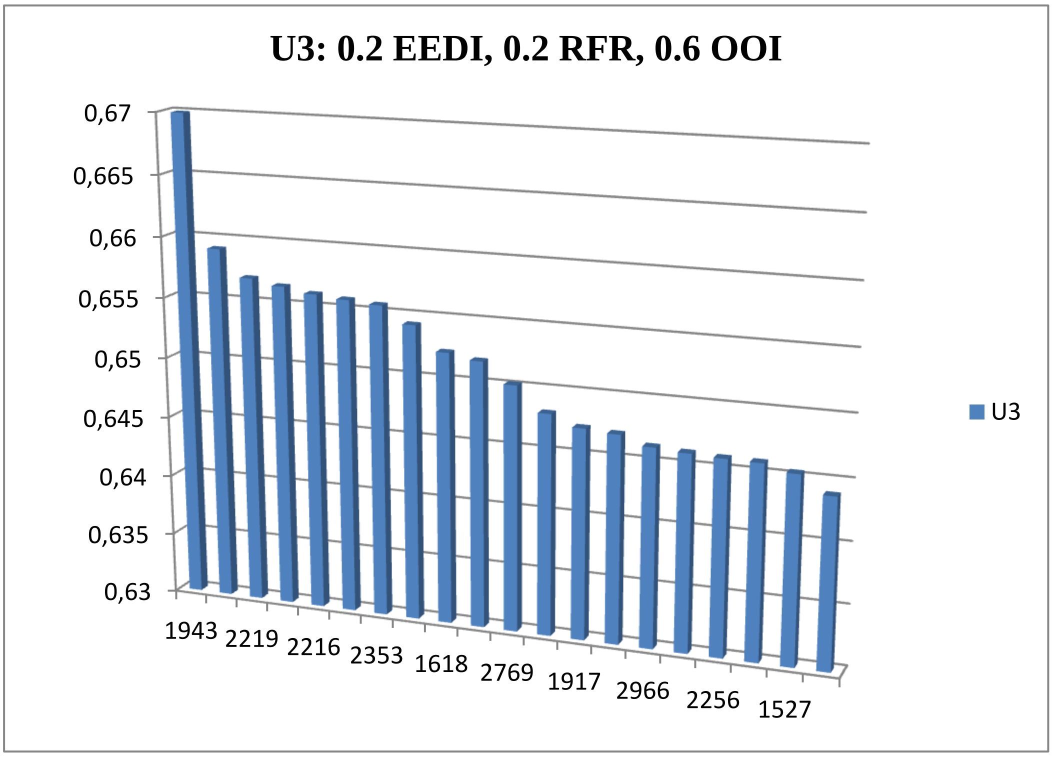


Figure [52]: Design Ranking according to the third scenario

However the 3rd scenario ranking indicates the same top 5 designs with a different order, due to the very close values of the weights.

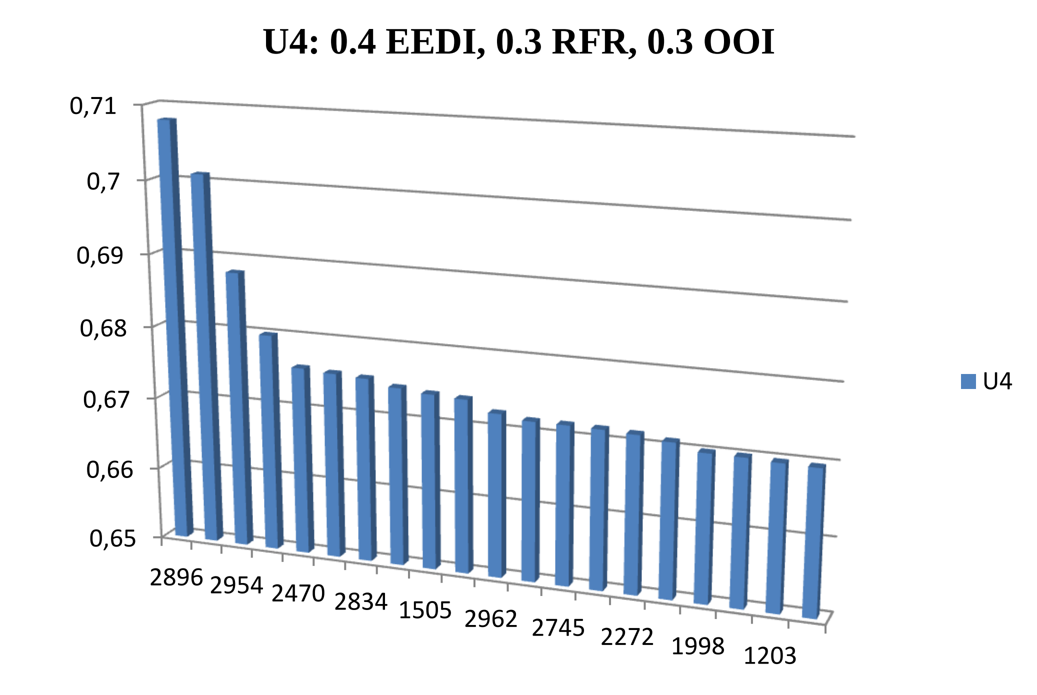


Figure [53]: Design Ranking according to the 4th scenario

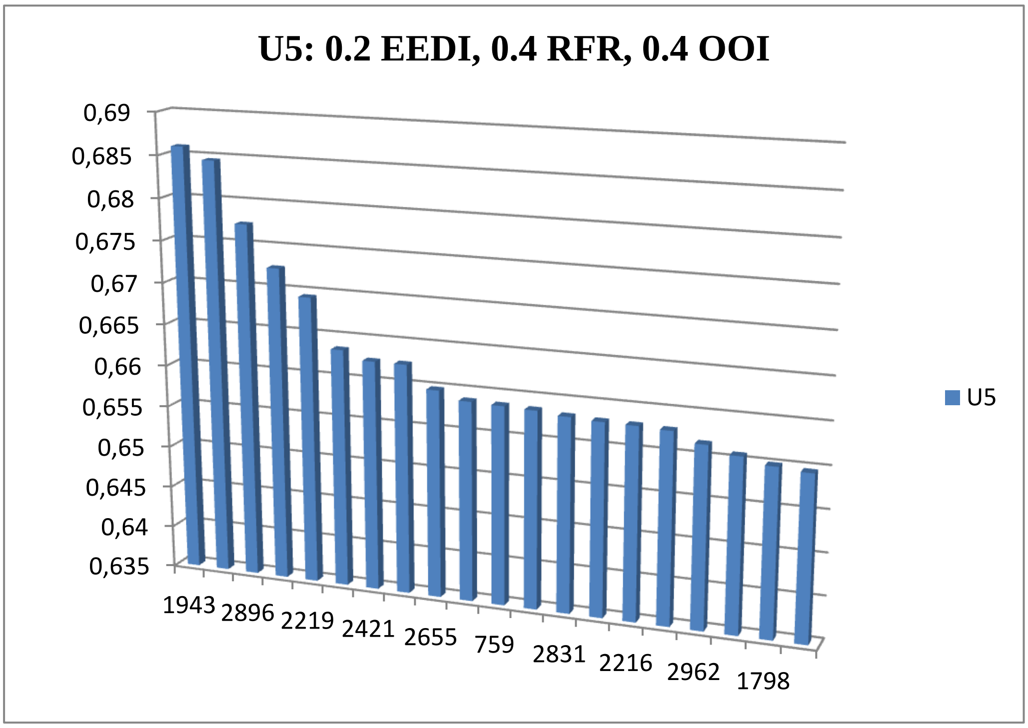


Figure [54]: Design Ranking according to the 5th scenario

The same cannot be said for the 4th scenario where the lower oil outflow designs prevail. However design I.D 715 maintains a good position. This can be explained by the RFR and OOI regions we mentioned earlier. The designs above are mostly the ones in the region of a lower oil outflow which is a very steep and thus subject to rapid and sensitive change.

The last scenario which combines, the so far contradicting objectives of the RFR and EEDI has a design ranking similar to the ones before. With the most preferred design being the same as in the first scenario.

The five best designs for each scenario can be summarized in the table below:

Ranking	**1st Scenario**	**2nd Scenario**	**3rd Scenario**	**4th Scenario**	**5th Scenario**
1	I.D 2896	I.D 2294	I.D 1943	I.D 2896	I.D 1943
2	I.D 1943	I.D 2210	I.D 1686	I.D 1943	I.D 2954
3	I.D 2954	I.D 2054	I.D 2219	I.D 2954	I.D 2896
4	I.D 2219	I.D 2701	I.D 2274	I.D 2219	I.D 1618
5	I.D 1686	I.D 1998	I.D 2216	I.D 2470	I.D 2219

Table [16]: The prevailing designs following the optimization procedure according to 5 scenarios

3.8.4. Results-150 Generations with 30 Population

Having seen the performance of the genetic algorithm in the first run and it's variance depending on the population size, given the fact that the performance of a bigger number of population is more impressive and can lead to more interesting results, it was decided to run the second optimization in another version using the same design variables with the same boundaries and the same constraints but in a more "exhaustive way" in order to explore the potential and applicability of the optimization methodology developed and applied. The population was increased to 30 designs per generation (1st G.A: 25 pop, 2nd G.A: 20 pop) and the generations were kept constant to 150 in order to force the algorithm to go even deeper towards better solutions. This leads to the generation of 4500 variants which is a big number and can illustrate the full potential of the method, if one can consider that the BEST+ optimization used 2500 variants.

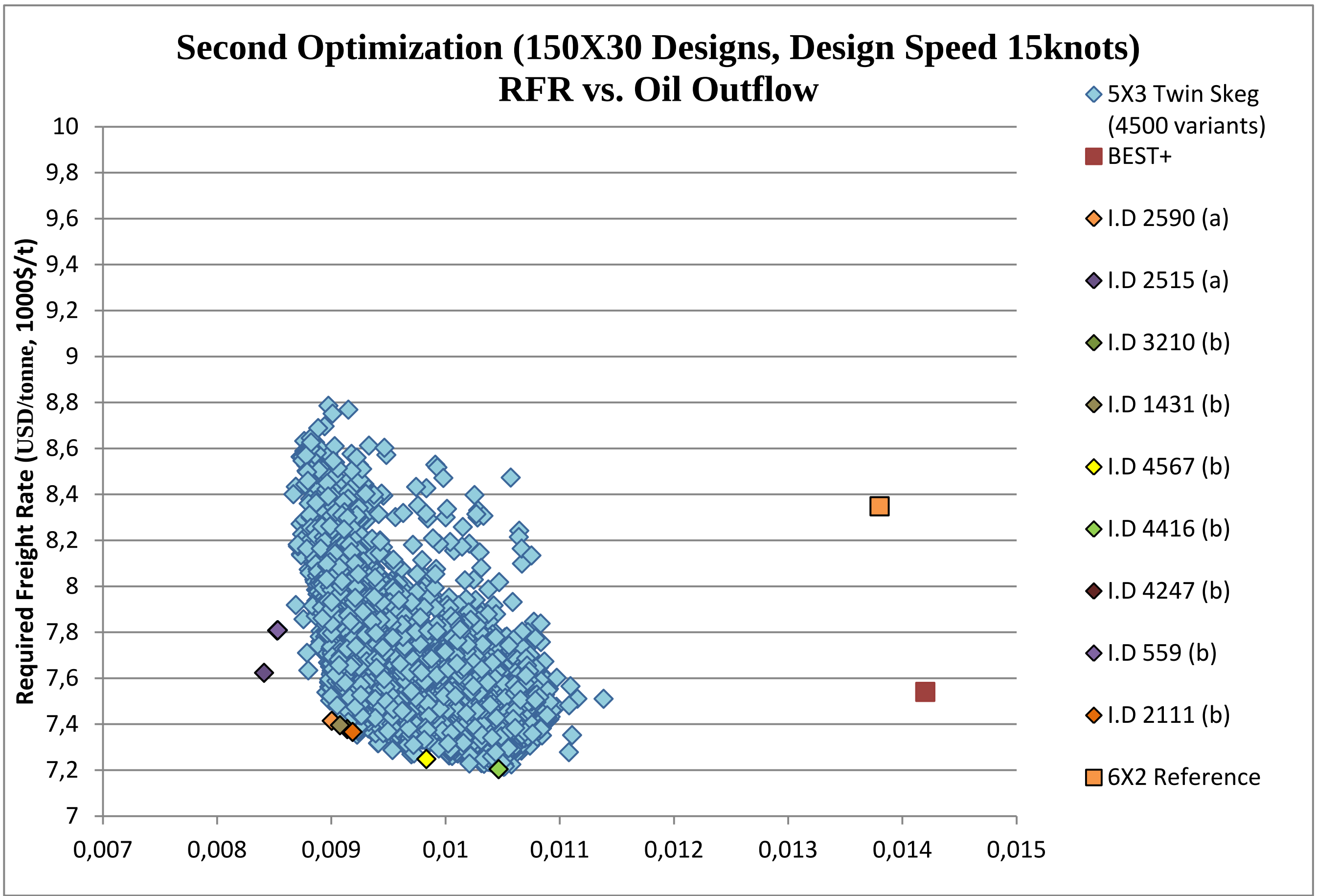


Figure [55]: RFR-OOI Relationship for the second optimization using 30 population

The effect of the change of the population size is noticeable as the scatter diagram is much more dense and the peaks are now less distinctive due to the coverage of these areas. Regarding the relationship of the RFR with the OOI the new scatter diagram illustrates two characteristic areas in an "V-shaped" Pareto frontier. The area on the right is characterized by designs with the lowest freight rates that have a generally low OOI but the latter changes rapidly as the freight rate is lower. These variants are obviously ships with a greater cargo capacity which is the reason for the relatively increased oil outflow. On the other hand there is a more steeped frontier at the left of the diagram that includes ships with a smaller cargo capacity and a greatly reduced oil outflow index. It is interesting to see that all of these variants appear to be equally or, in most of the cases, more competitive than conventional designs, like the BEST+. The optimum solution, according to optimization theory and not depending entirely on the decision makers mentality, is the best compromise between these two areas. One of the designs belonging in this area is I.D 2590 which according to the ranking using a utility function appears to be the best solution for a range of scenarios.

The other objective, the EEDI according to the IMO MPEC 62, appears to have the same behavior as in the previous studies (figure [27]) due to the big correlation of the EEDI and the RFR with the deadweight and the cargo carrying capacity. The scatter diagram now is more dense and has a local minimum but in general outlook it remains the same.

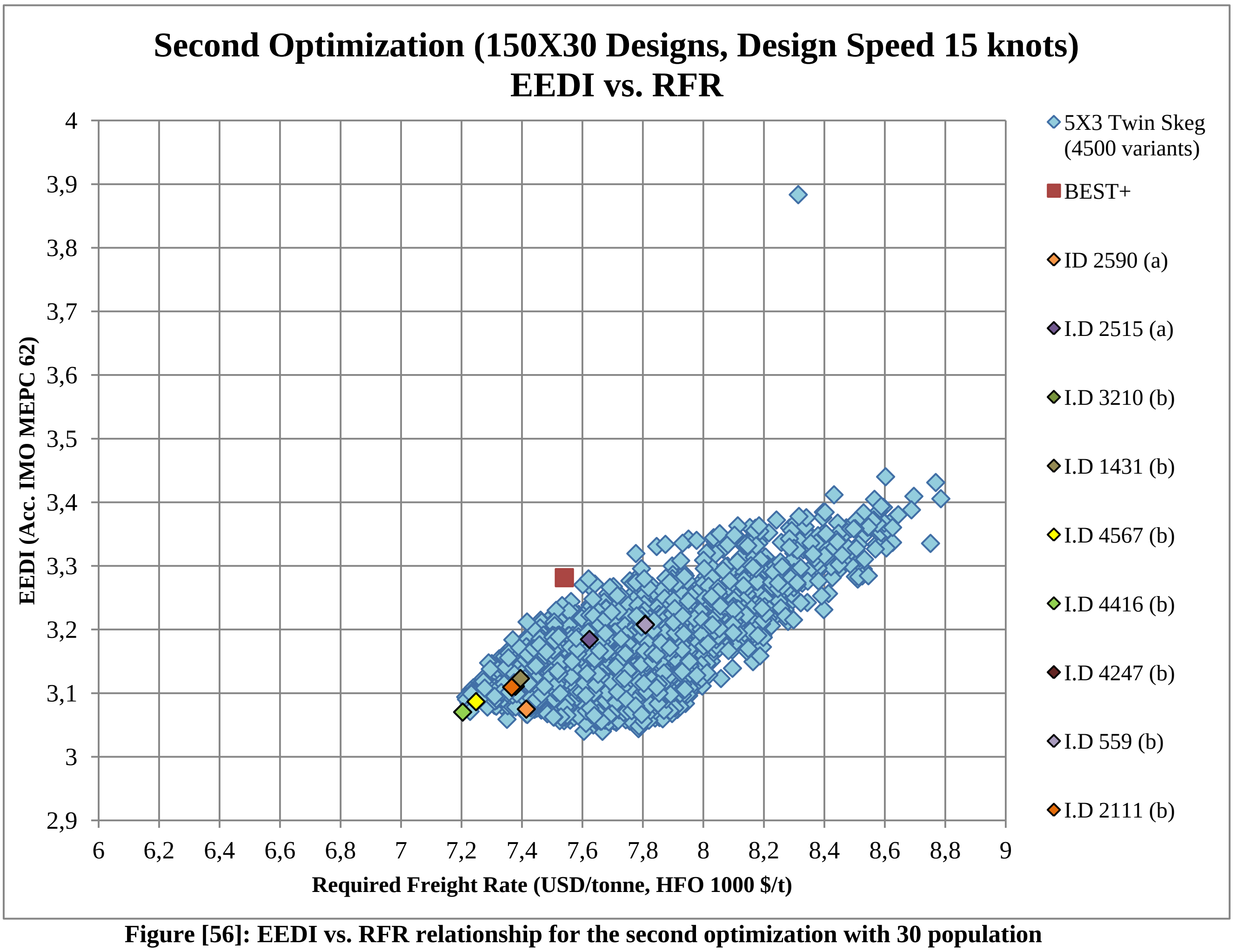


Figure [56]: EEDI vs. RFR relationship for the second optimization with 30 population

It is also interesting to see that the dominant variants have an EEDI value of approximately 3.09, which is 22.8% lower than the IMO limit for this deadweight size tankers. This means that even after phase 2 (10 year after the implementation of the EEDI), these ships are going to be within a respectable margin of the reference line set by the regulation. Only at the end of this ship's lifespan (assuming that it is built now) it will have to face a sticker 30% reduction of the EEDI reference line. That however will be for the newbuilds of that respective era. Furthermore, one can notice that the BEST+ has a slightly worse performance than the 5X3 equivalent designs. However this is not entirely accurate as it is a smaller deadweight ship so it loses in terms of scale economies.
The scale economies can also be seen at the relationship of the accidental oil outflow with the cargo carrying capacity. The first is a function of the second as the greater the cargo oil tanks are the bigger the consequences from a potential collision or grounding.

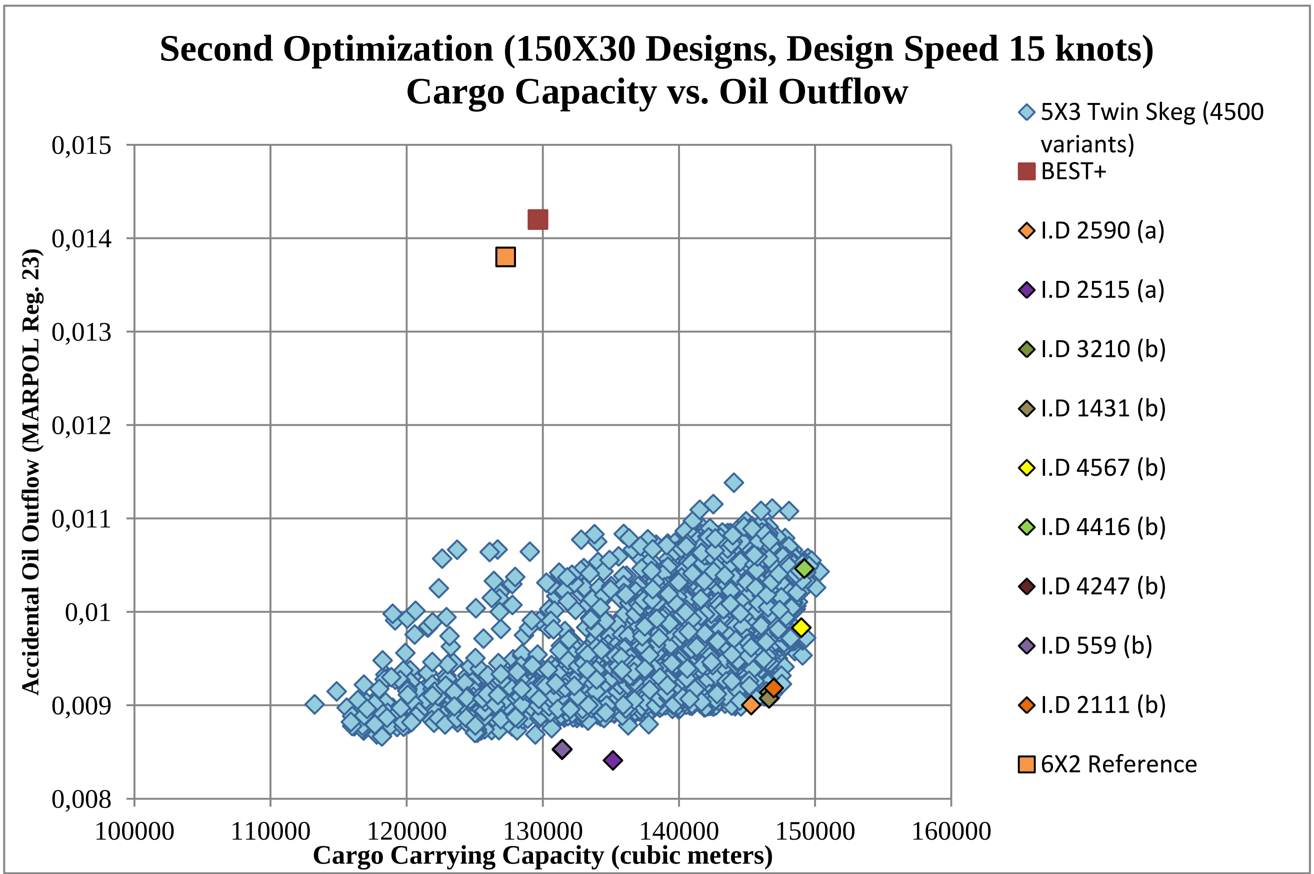


Figure [57]: Cargo capacity vs. Oil Outflow Relationship

From figure [57], it is noticed that there is a steep increase in the OOI for the increase of the capacity beyond 145k cubic meters which can set the limit for the tank size. The designs that are favourable according to the utility function ranking can be concentrated around this area of 145000 cubic meters which is very competitive in comparison with industry standards for the AFRAMAX class which sets the capacity at about 130000 cubic meters.

3.8.5 Search, Choice and Ranking of the Dominant Variants using Utility Functions (150X30)

As in the previous run, five scenarios are chosen to be used as weights for the utility functions that are assisting to rank the dominant variants and find a good solution.
The scenarios and the respective weights for this process are the same as previously:

Objective	1st Scenario	2nd Scenario	3rd Scenario	4th Scenario	5th Scenario
RFR	1/3	0.8	0.3	0.2	0.4
EEDI	1/3	0.1	0.4	0.2	0.1
OOI	1/3	0.1	0.3	0.6	0.4

Table [17]: The weights for each scenario

The ranking of each scenario can be seen at the graphs below:

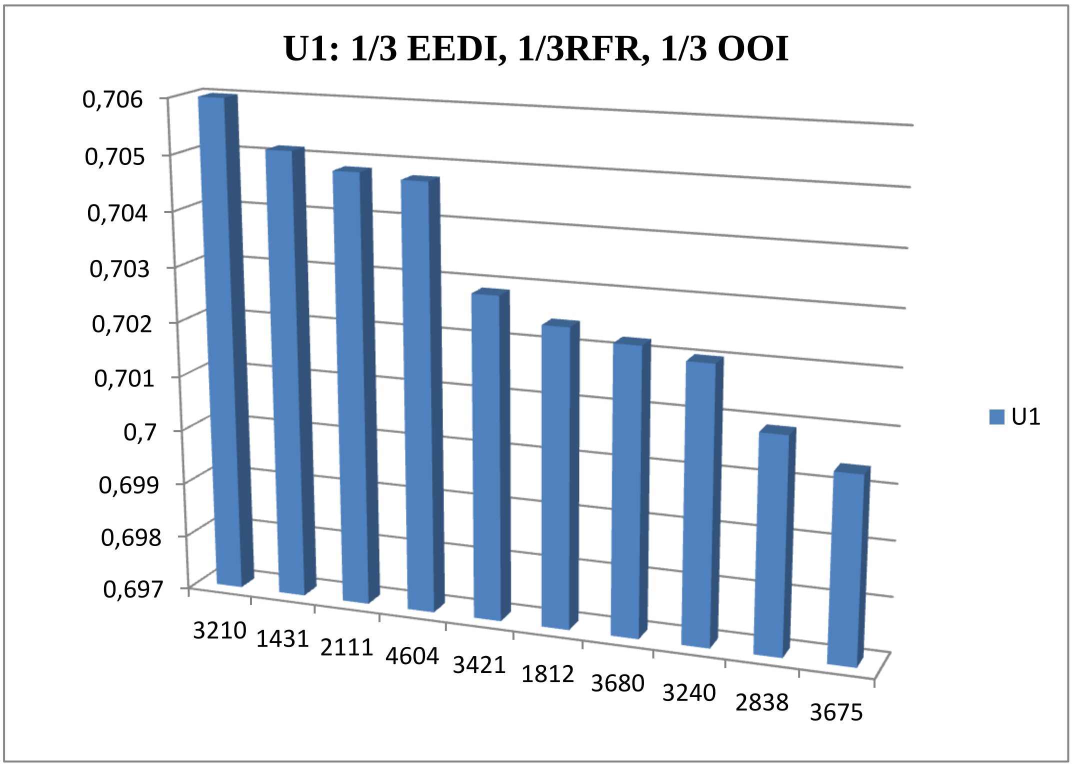


Figure [58]: Design Ranking according to the first scenario

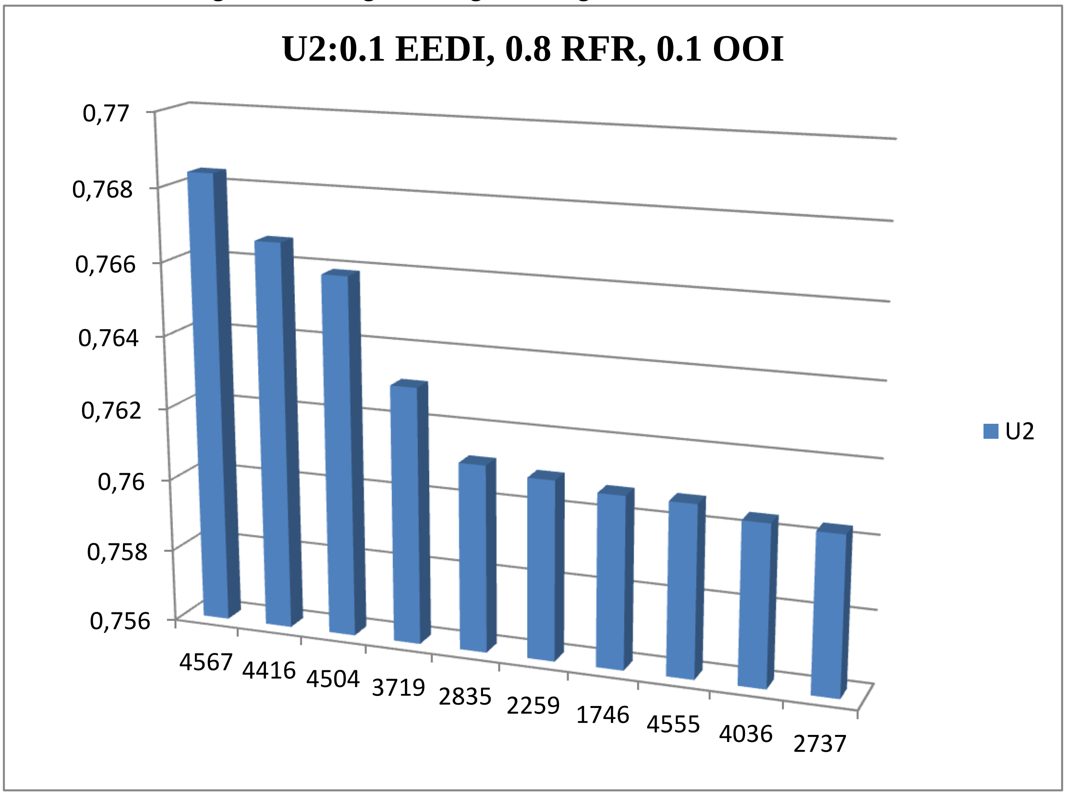


Figure [59]: Design Ranking according to the second scenario

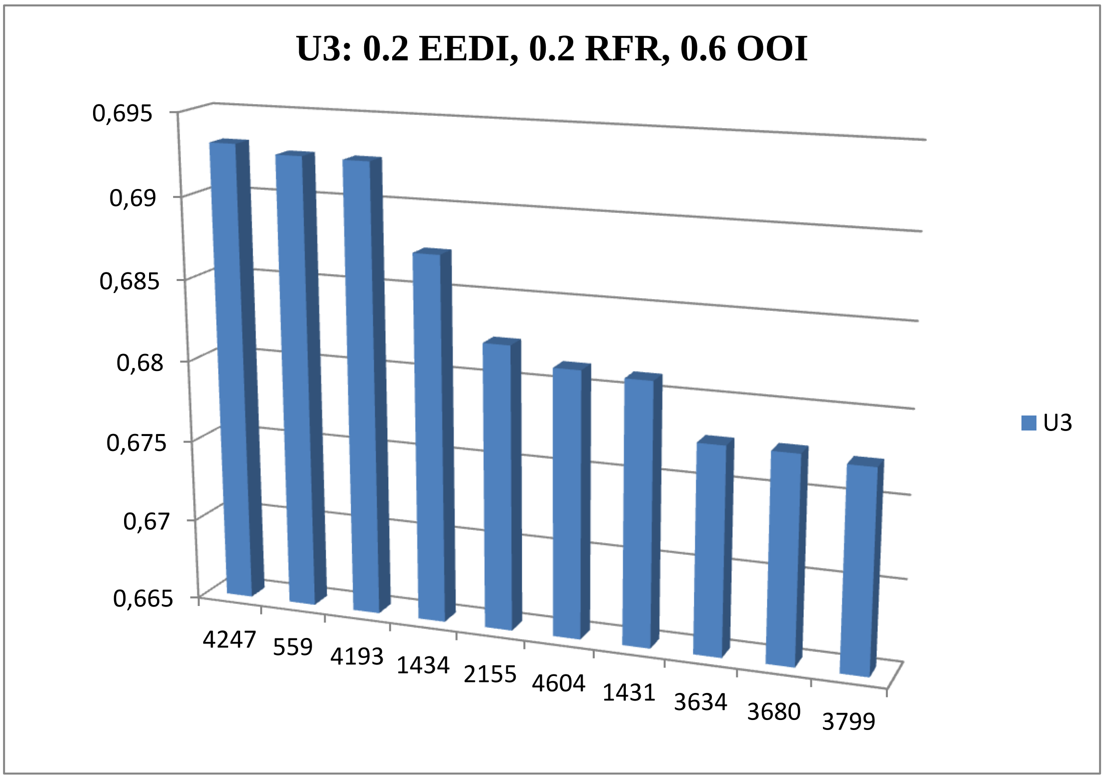


Figure [60]: Design Ranking according to the third scenario

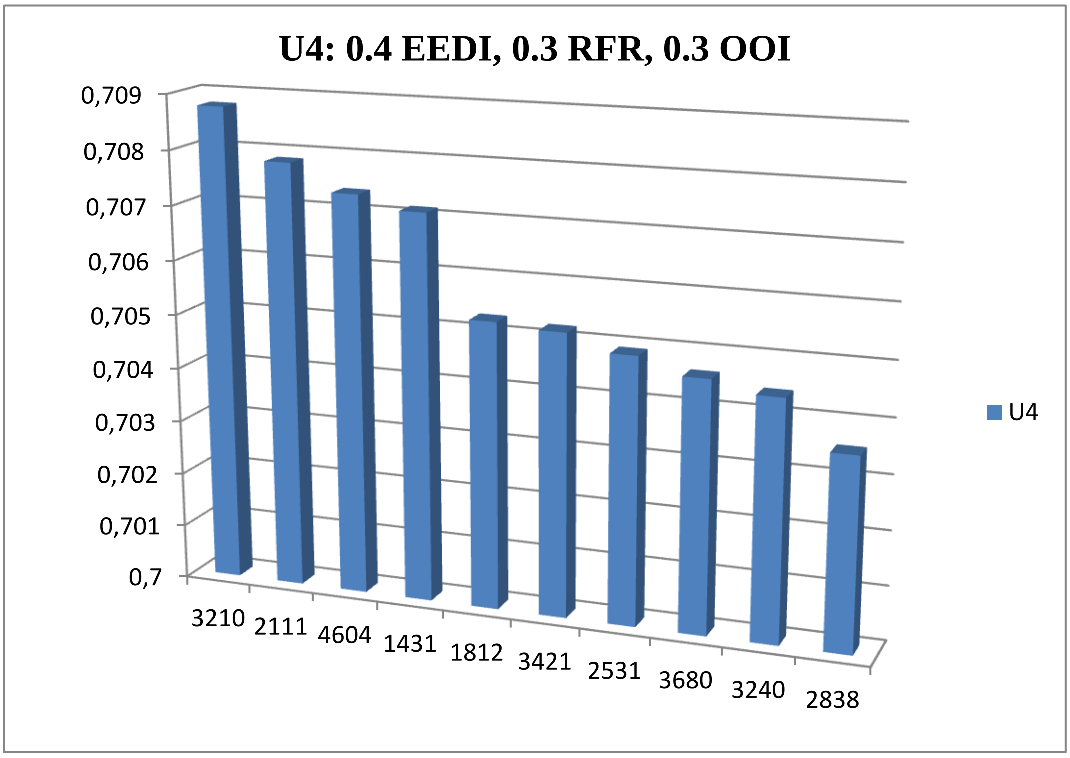


Figure [61]: Design Ranking according to the fourth scenario

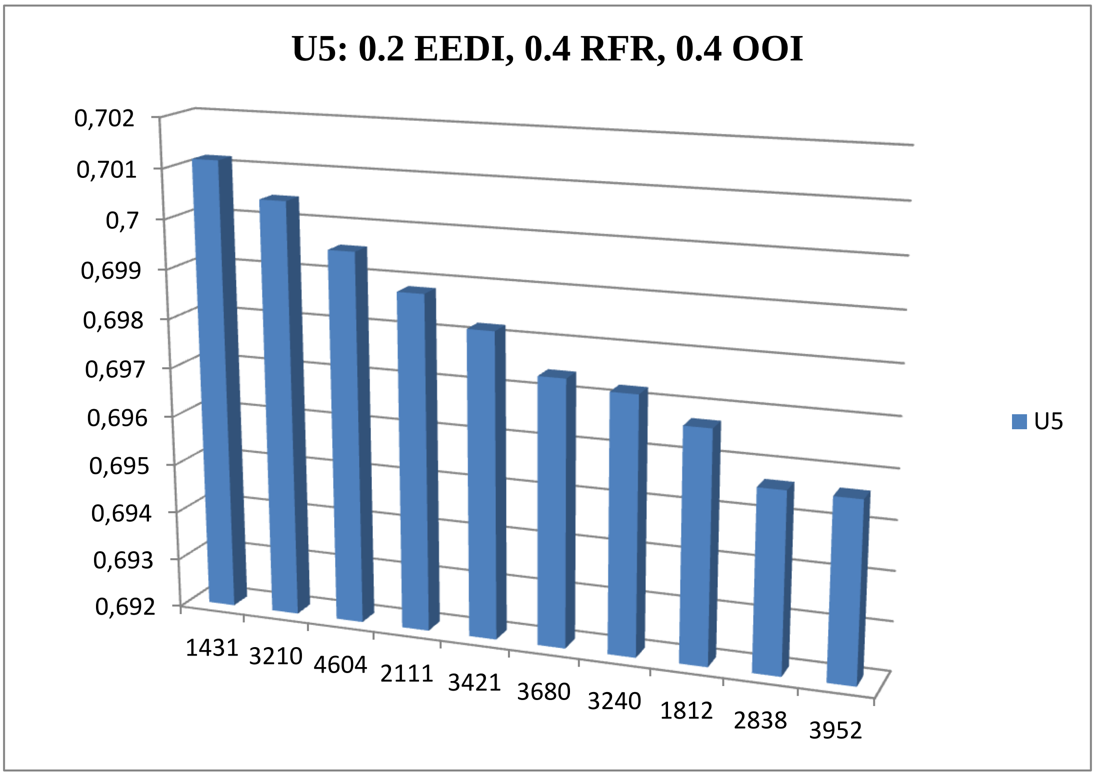


Figure [62]: Design Ranking according to the fifth scenario

As in previous rankings the results of the first and fourth scenario are very similar, with the top four designs being the same but with different order. Furthermore, the 5th scenario also maintains some of the dominant variants of the other four. For this last optimization study we can summarize the IDs of the dominant variants at the table below:

Ranking	1st Scenario	2nd Scenario	3rd Scenario	4th Scenario	5th Scenario
1	I.D 3210	I.D 4567	I.D 4247	I.D 3210	I.D 1431
2	I.D 1431	I.D 4416	I.D 559	I.D 2111	I.D 3210
3	I.D 2111	I.D 4504	I.D 4193	I.D 4604	I.D 4604
4	I.D 4604	I.D 3719	I.D 1434	I.D 1431	I.D 2111
5	I.D 3421	I.D 2835	I.D 2155	I.D 1812	I.D 3421

Table [18]: The 5 dominant variants of each scenario

This selection process concludes the optimization study on the twin skeg designs and the concept developed. It is of vital importance however, to see how these designs perform in comparison with results from previous optimization studies, apart from the BEST+. The scatter diagram that follows illustrates the top two variants for each scenario for the two optimization stages of this present study compared with the results of the TANKOPT research project. These results include single screw ships with 6X2, 6X3 and 7X2 tank arrangements, with or without corrugated bulkheads. It is natural that the 6X3 designs have a superior performance in terms of oil outflow in comparison with the 5X3, although we can see that some of the derived 5X3 have a better performance than a range of other 6X3. Nevertheless half of the 6X3 have a better performance than the 5X3 equivalent.

Another interesting observation is that the one longitudinal bulkhead produce designs that are in general inferior in terms of OOI than the two longitudinal bulkheads. The 5X3 serves as a trade-off, offering in this particular study a better cargo capacity than any other design.

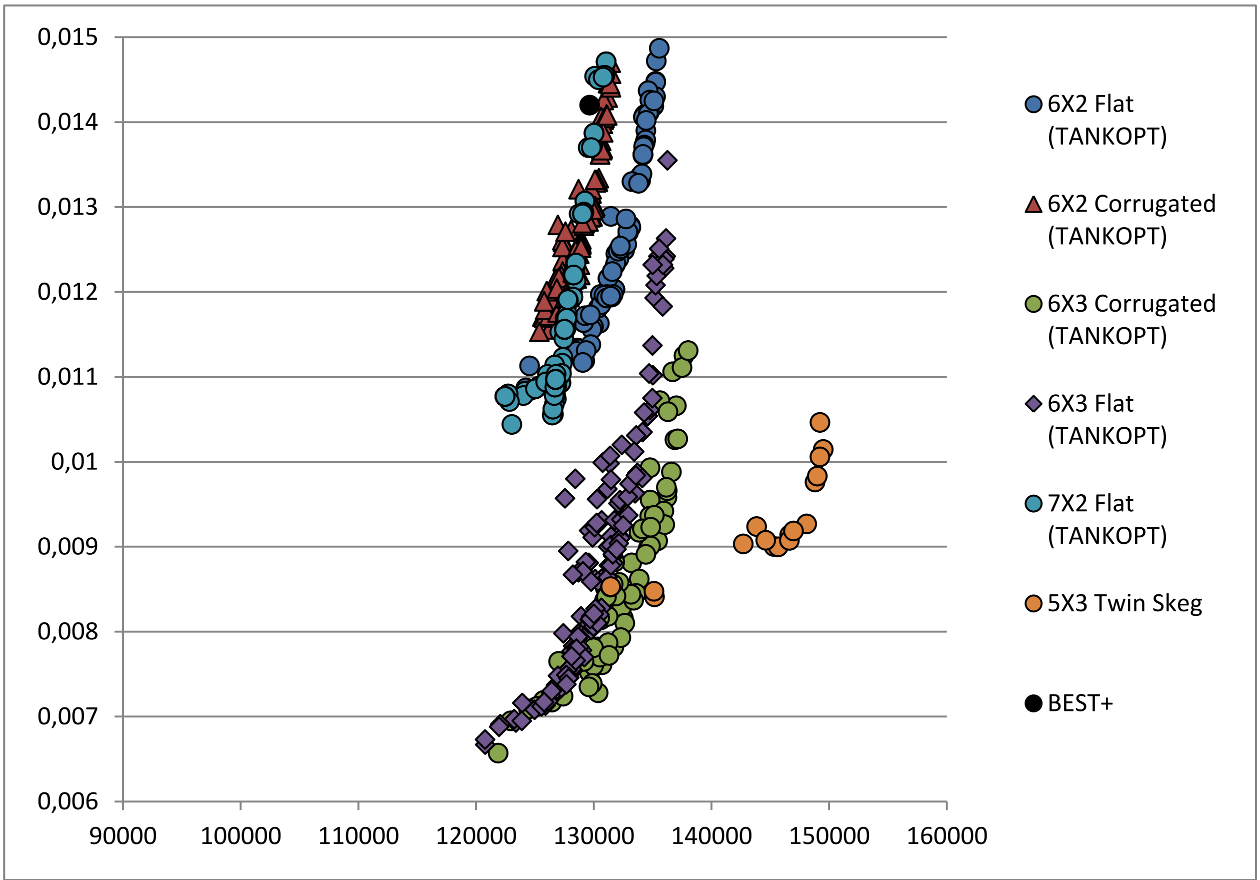


Figure [63]: Scatter Diagram of the results of various optimization projects

The reason of course for the big increase in the cargo tank capacity is the change and relaxation of the boundaries for the breadth of the ship (leading to a bigger ship), while the length and draft remain and decrease accordingly. The elimination of the pump room and the optimization of the double bottom and double side further increases the cargo tank capacity, leading to a final capacity of about 138000 m^3.

This type of arrangement, the 5X3 can thus provide an alternative arrangement considered as a trade-off between the 6X2 and the 6X3 arrangement. The OOI is increased but the steel weight is reduced due to the elimination of one transverse bulkhead.

At the tables that follow one can find the principal particulars of the dominant variants along with the reference 6X3 tanker, the reference 6X2 and the BEST+ concept.

	6X2 Reference	**I.D 2515**		**I.D 3210**	
OOI	0.0138	0.00841	**-39.057%**	0.009139	**-33.78%**
Wst cargo	11077 t	13590	+18.49%	14261 t	+22.32%
Cargo Capacity	126764.7 m^3	135154 m^3	**+6.21%**	146642.7 m^3	+15.68%
RFR	8.347 $/t	6.7209 $/t	**-19.38%**	6.513 $/t	**-21.97%**
Ballast Water	35378 m^3	18699 m^3	**-47%**	29287 m^3	-17.2%

Table [19]: Comparison table of 6X2 reference with dominant variants

It is also very interesting to see that the ballast water amount required by MARPOL is also greatly reduced, which means that the operation and maintenance of the design is going to be improved.

Principal Particular	I.D 2515 (a)	I.D 2896 (b-1)	I.D 1943 (b-1)	I.D 1686 (b-1)
L (m)	244.41	244.474	244.241	242.730
B (m)	45.843	47.998	47.588	47.921
D (m)	22.04	22.4727	22.370	22.47
T (m)	14.6516	14.656	14.654	14.688
Cb	0.85775	0.85708	0.8655	0.857
LCB (m)	0.52354	0.5248	0.5248	0.52434
FOB (%B)	0.7028	0.7568	0.7567	0.75666
FOS (%D)	0.6769	0.78859	0.6908	0.66666
Bulb Length (m)	0.03077	0.0318	0.0256	0.03433
Displacement (tonnes)	144332	151087	151106	150095
Height DB (m)	2.239	2.395	2.404	2.694
Width DH (m)	2.989	2.9776	2.985	2.975
No. Of Tanks	**15 (5X3)**	**15 (5X3)**	**15 (5X3)**	**15 (5X3)**
Mid Tank Width (% B)	45.643	46.203	45.547	46.202
Cargo Capacity 98%	135154	143831.4	144605.3	142699.6
Design Speed (knots)	15	15	15	15
Installed Power (kW)	13955	14508	14471	14558
Lightship Weight (tonnes)	22070	23234	22927	23086
Deadweight (tonnes)	122263	127853	128179	127010
Payload (tonnes)	118511	123974	124309	123120
EEDI (t CO2/tonne*mile)	3.184332	3.098214	3.123271	3.115593
RFR (USD/tonne)	7.623023	7.526236	7.505374	7.601012
Reg.23 Oil Outflow Index	0.008476	0.009237	0.009076	0.009033

Table [20]: Principal Particulars of favored designs

4. HYDRODYNAMIC,STRUCTURAL AND OPERATIONAL ANALYSIS

Following the optimization studies, the results, the search and the sorting of the dominant variants according to the decision maker's mentality a more detailed analysis of critical areas of the design concept took place.

The critical areas for this design concept are the following:

- Structural Weight, as the coefficients of the cargo block weight and correction factors assumed have to be re-examined by the use of POSEIDON for the new structural arrangement. The design implications of the new structural arrangement are in terms of the new, optimum values for the longitudinal bulkheads.
- Hydrodynamic Analysis, as the Holtrop method used in the methodology is a statistical method it appears to be conservative and does not take into account the local hullform shape. For this particular reason the SHIPFLOW CFD packet was used to validate the dominant variants of the 5 utility scenarios.
- Operational Analysis, which determines the optimum operational profile and speed for a range of scenarios for the fuel cost. Suggestions are given for the design speed in order to achieve the lowest required freight rate.

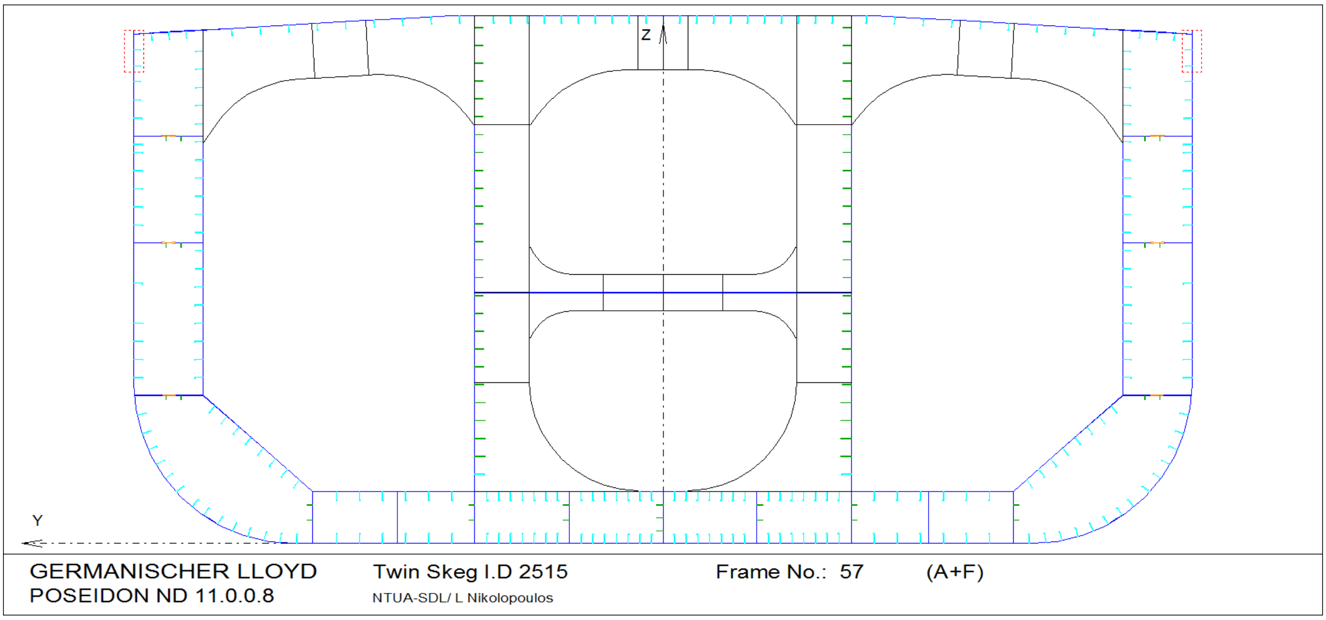
At any point the reader should understand that as this is a preliminary, in other words concept design, details in certain areas are negligible. This should a subject of a detailed, contract design which is out of the context of the present report. The scope of this section is to eliminate any uncertainties regarding the methodology itself and calibrate some of the results. Furthermore, it is the nature, innovation and peculiarity of this concept and its references that suggests that a conventional approach is at the boundaries of its application.

4.1. Structural Analysis of the Dominant Variants

Back in chapter 3, the lightship and steel weight calculation methodology was described, which is a hybrid one. For the peaks and the engine room the steel weight is calculated by an empirical factor derived from the detailed weight analysis of the reference ship, NAVION BRITANNIA.
The cargo block steel weight was calculated following the structural modeling of a prismatic cargo block initially for the reference ship and afterwards for a ship with the BEST+ dimensions. However, this design methodology takes into account the effects of ship size but not that of the changing bending moment and ship loads which are used for the classification and the determination of the required thicknesses. In the previous BEST+ project, the Friendship Framework was linked with POSEIDON providing the hullform and tank arrangement necessary information while POSEIDON calculated the scantlings according to the Common Structural Rules (CSR). This is the most detailed and exact procedure but it requires advanced programming skills in Python in order to achieve the link. The time frame for such a task would be of about 3 man months which was not plausible in order to make the time limit.
For the reasons mentioned above it was chosen to follow the empirical weight calculation techniques and then proceed to a formal weight calculation for the dominant variants to validate the results and correct the final particulars of the design. It should be mentioned that any errors produced and deviations from the empirical coefficients will be systematic for all of the design variants and thus the optimization as a procedure is not affected as the interest lies more on the relative improvement than the absolute figures (of course the latter are equally important).
In order to dimension and find the weight of the new structure, a new POSEIDON project had to be made. The stiffeners, plates and design philosophy was the same as the adapted 5X3 design to the BEST+ dimensions made for the comparison of the 6X2 and 5X3 concepts.

The dominant design initially selected for the POSEIDON estimation was I.D 2515 as it is a representative design and twice a dominant. Due to dimensional changes and the innovative features such as the extended bilge concept, several adaptations were made, while some of the parameters were kept constant. Such design parameters include the transverse girder, the cross tie arrangement (necessary for all NX3 arrangement designs). The spacing of floors and frames was kept as in the BEST+ concept. The stiffeners were adapted to the new dimensions which differ in terms of breadth from the narrower BEST+ dimensions, by using the same spacing but a different number of stiffeners.

The cross section results as generated by POSEIDON can be seen at the picture below:



Picture [15]: Midship Cross Section of I.D 2515 in POSEIDON

After defining the tanks the calculation of the sloshing values took place in order to be able to define the desired thicknesses according to the CSR. The thicknesses were calculated using the rules check command, by following the "determine" option which is the one that provides us with the required thickness instead of assessing a user defined value. The results of this procedure are seen in the following table:

Item	**I.D 2515 Calculated in FFW**	**I.D 2515 Calculated in POSEIDON**	**BEST+ NX3 Model in POSEIDON**
Longitudinal Members Weight	58.68 t/m	62.83 t/m	54 t/m
Transverse Members Weight	8.19 t/m	5.8 t/m	8.19 t/m

Table [21]: Results of the weight calculation for a dominant variant

From the results above, we can see that the longitudinal members weight, which is the most critical of the weight groups for the cargo block steel weight, is underestimated in the FFW analysis programmed. However, the sensitivity is correct and the deviation is due to the larger tank size in POSEIDON which does not take into account the different tank size for the first tank, thus resulting into bigger loads. The difference is at a level of 6.6% which can be absorved in the total correction factor imposed to the lightship weight which is 10%.

4.2. Hydrodynamic Analysis using Potential Flow Theory in SHIPFLOW

As mentioned in Chapter 3, the resistance prediction for each variant is done using the Holtrop and Mennen statistical method. The method is very successful and can be considered as very accurate and sometimes conservative regarding its results. The total resistance of the ship according to this methodology as commonly done and understood worldwide, breaks in the several parts:

- Frictional Resistance, which for a tanker with the Froude number we examine is the biggest and therefore most important part. It is predicted using the ITTC formula of 1957 for the calculation of the frictional resistance coefficient.
- Wave Resistance, which is a smaller part of the total resistance and is calculated using statistically derived formula: $R_W = c_1 c_2 c_5 * \nabla * \rho * g * \exp\left(m_1 * Fn^d + m_2 \cos\left(\lambda * Fn^{-2}\right)\right)$.

  The c numbered coefficients are functions of the main dimension ratios and the entrance anlge of the design waterline, while λ is a function of the prismatic coefficient and L/B ratio and m coefficients are functions of the prismatic coefficient, main dimension ratios and Froude number.
- Appendage Resistance, which depends on the number of rudders and other exposed surfaces like anodes, shafts and shaft brackets.
- Additional pressure resistance of bulbous bow, which takes into account the pressure increase (can also be seen in the potential flow results) due to the presence of the bulbous bow and it is a function of the transverse area of the bulb at the fore peak.
- Additional Pressure Resistance due to immersed transom stern. It takes into account the pressure increase and increase wave at the transom area as well as the flow separation there.
- Model Ship correlation resistance.

This kind of analysis is very detailed and serves well for optimization purposes in a preliminary stage. However due to the innovative and unconventional stern having a twin skeg configuration and due to the fact that there is generally a lack of references of twin skeg vessels the prediction for the model used has certain uncertainties. The biggest uncertainties for this kind of vessels are the wave resistance and wave patterns for the bow and stern areas. The bow due to the fore position of the LCB is of a bulky form and thus a closer examination of the bow wave had to be done.
For this particular reason, the XPAN code of the SHIPLFOW package was used for the dominant variants. The full run of viscous codes was considered but for a later stage and for only one variant due to the big computation power requirement and tight schedules.

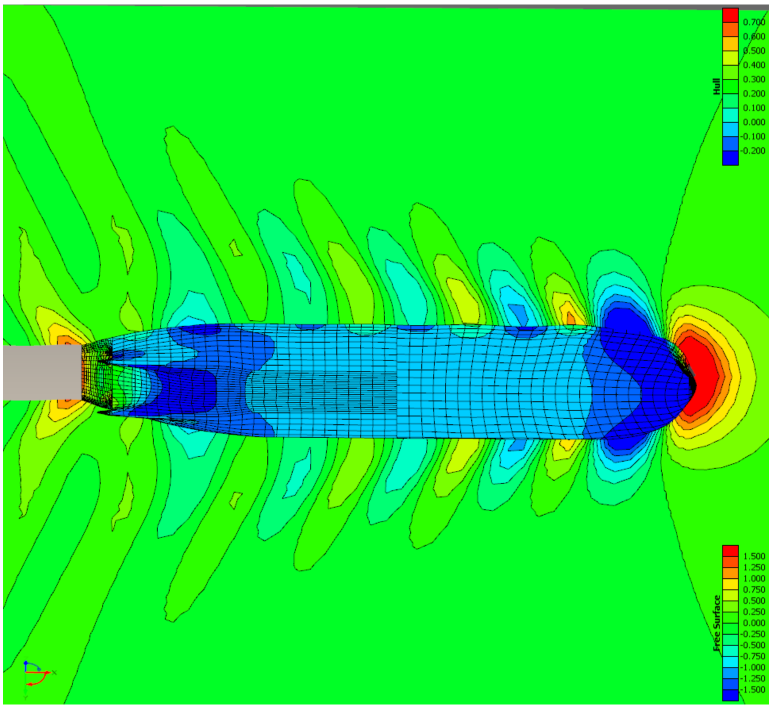
The offsets required for a twin skeg vessel by SHIPFLOW are the following 8 groups (instead of conventionally 4):
Bulb, Hull, Outer Hull, Inner Hull, Outer Stern, Inner Stern, Outer Boss, Inner Boss. The reason for outer and inner offsets is that the vessel is symmetrical both around the centerline of the keel but also around the shaft of each skeg. So a comprehensive information has to be provided for the offset geometry of the inside and outside parts of the shaft. This division for functional purposes is extended until the midship.
The runs were made in an older version of SHIPFLOW that was available at NTUA, the 4.1 version, with the offsets being exported from FFW as well as the configuration itself. The runs were made using the wavecut option too with the assessment is made based on Cw derived from these wavecuts. The reason for this choice is the scope that the wave resistance is examined. The purpose of this study is to identify any unexpected wave patterns with extreme wave heights that can lead in a big deviation of the wave resistance predicted by Holtrop's method.
The dominant variants were thus exported and the computations were performed in the SHIPFLOW 4.1 version and can be summarized at the table below

Design I.D	L_{bp}	B	T	F_n	Wetted Surface	Cw wavecut	Cw Holtrop
2515	244.41	45.8492	14.6516		15444.39	0.000018533	$2.96783*10^{-5}$
1838	244.411	47.8340	14.67552	0.15759	15779.25	2.00328E-05	$2.70299*10^{-5}$
2590	244.411	47.93	14.6989	0.15759	15677.6	0.00002074	$2.70934*10^{-5}$
2738	244.4117	47.992	14.69896	0.157592	15827.76	0.00002128	$2.67772*10^{-5}$
2896-2a	244.473	47.998	14.6563	0.157572	15879.56	2.00588E-05	$2.58295*10^{-5}$
1943-2a	244.24	47.588	14.65428	0.15764	15852.92	0.000024577	$2.76644*10^{-5}$
2294-2a	244.94	47.997	14.65856	0.15742	15954.25	1.70883E-05	$2.58859*10^{-5}$
2210-2a	244.758	47.919	14.65474	0.15748	15935.93	0.000018847	$2.6232*10^{-5}$
1686-2a	242.730	47.920	14.68798	0.158137	15827.07	0.000023244	$2.66271*10^{-5}$
2954-2a	244.963	47.607	14.64061	0.157414	16088.02	0.000018341	$2.66116*10^{-5}$

Table [22]: The Results of potential flow calculation for the dominant variants

It can be seen from the above analysis that the variance of the Cw wave resistance coefficients based on the wave cut calculation is not great compared with the equivalent coefficient produced by the analysis of Holtrop. That can be explained by the Froude number and the characteristics of the vessel, which is a slow speed, bulky form oil tanker. This means that the wave resistance is only a small portion of the total resistance and is less sensitive in main dimension changes. Both Holtrop's method and the wave cut analysis indicated that the wave resistance coefficient is of the same order (10^5) and are in absolute terms very small portions of the ship's resistance. Furthermore the resistance in Holtrop's method is overestimated in comparison with the potential flow theory, although the difference may slightly decrease as the panelization becomes more dense. This validates that the Holtrop method is very accurate and conservative for the resistance prediction of ships with a low Froude number.

Thus it can be considered that the assumptions made in the optimization routine are correct and any deviations are not significant as they are lost within the total resistance which greatly and more importantly depends on the frictional resistance. For this reason we assume that the effect of changes in the wave resistance can be considered negligible within the optimization routine.



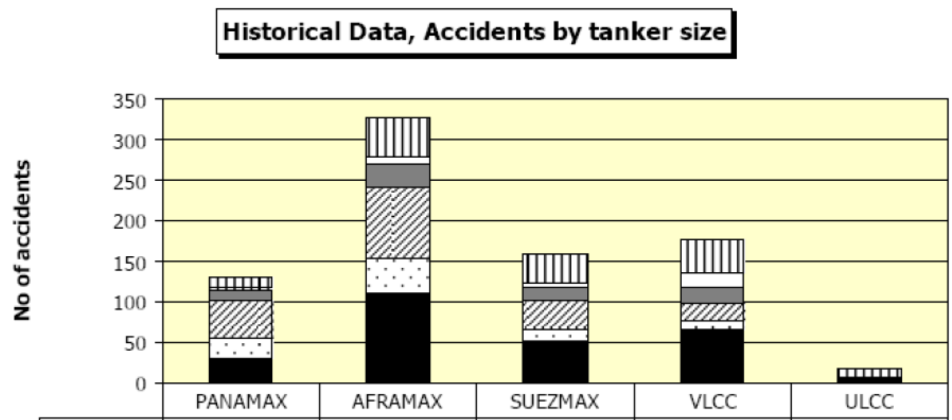
Picture [16]: Snapshot of the Wave Pattern as computed in SHIPFLOW

4.3. Risk Analysis of the Design Concept

As the design concept presented is by default a safer ship, it is necessary to present at this stage a means to quantify the safety level by means of a risk analysis following the principles of the Formal Risk Assessment (FSA) for tankers as adopted by IMO and developed in the research project SAFEDOR.
The risk analysis, as done in the SAFEDOR project can be separated in two parts, depending on the type of accident examined. Thus, the case of collision (as a struck ship which is the critical part) and the case of drift and powered grounding is examined. The aim is to demonstrate the improved safety level (as a Potential Loss of Cargo-PLC) compared to a single screw vessel and of conventional arrangement.

4.3.1. Grounding Accidents

As discussed at the beginning of the report, after the formal safety assessment for large tankers (FSA) by the IMO, the most frequent tanker size engaged in accidents is the AFRAMAX class.



	PANAMAX	AFRAMAX	SUEZMAX	VLCC	ULCC
NASF	13	48	34	42	11
Explosion	5	9	6	19	0
Fire	12	29	16	18	1
Grounding	46	88	35	22	1
Contact	24	43	15	9	2
Collision	31	111	52	68	3

Figure [64]: Accidents by tanker Size (Tanker FSA, 2008)

As seen in the figure above, the groundings are the second most frequent accidents after collision for the AFRAMAX class. A grounding can be either drifted or powered grounding, with the second being subject to navigational errors of the crew and the first depending on the total loss of power and steering. The drifted grounding account according to the SAFEDOR event tree for 17% of all groundings. This percentage however will change for the case fo a twin screw design, were all systems like propeller, steering, main engine and fuel lines and bunkers are independent and separated by fireproof bulkheads. This means that the both the probability of drifted grounding and the number of accidents due to grounding will rapidly decrease changing the initial frequency used at the event tree that FSA and thus decreasing the Potential Loss of Cargo (PLC) which is indicative of the safety level.

4.4. Operational Analysis of a dominant Variant.

This section is the last of the more detailed analysis of the dominant variants generated by the optimization process and aims at exploring operational ways to reduce te freight rate and demonstrate the versatility and the profit margin of the ship for a range of scenarios. First the optimum operational speed is determined in terms of minimizing the RFR for a number of scenarios regarding the fuel price. The implications of slow steaming for the main engine and the SFOC are also mentioned and some tuning methods and precautions are suggested.

At the second part a timeline of the Worldscale rates for the tanker Caribbean trade (and for the AFRAMAX segment) is analyzed and compared to the required freight rate, in other words the minimum rate in order to balance the income and the expenses (break even). The market condition also suggests that in certain periods of time it is sustainable to slow-steam especially when the demand is low.

5.4.1. Investigation of the Optimal Operating Speed

The selection of which pareto design should be investigated for the optimal speed at this preliminary stage is not critical and important as this is investigated within FFW and the only design variable is the speed while the evaluation is the RFR, which means that the changes are the same for all models regardless of their characteristics since there are no changes in the design itself. The investigation is made using the Sobol algorithm of FFW.
Three scenarios are examined regarding the fuel price (HFO). One is for a very low price of 200$/t the second is for a price of 500$/t (where the BEST+ is based on) and the third is for an HFO cost of 1000 $/t, which was used for the optimization series because it is more likely to be introduced especially with low sulphur fuels on the horizon and the expansion of Emission Control Areas (ECAs).
The results are visible at the following graph:

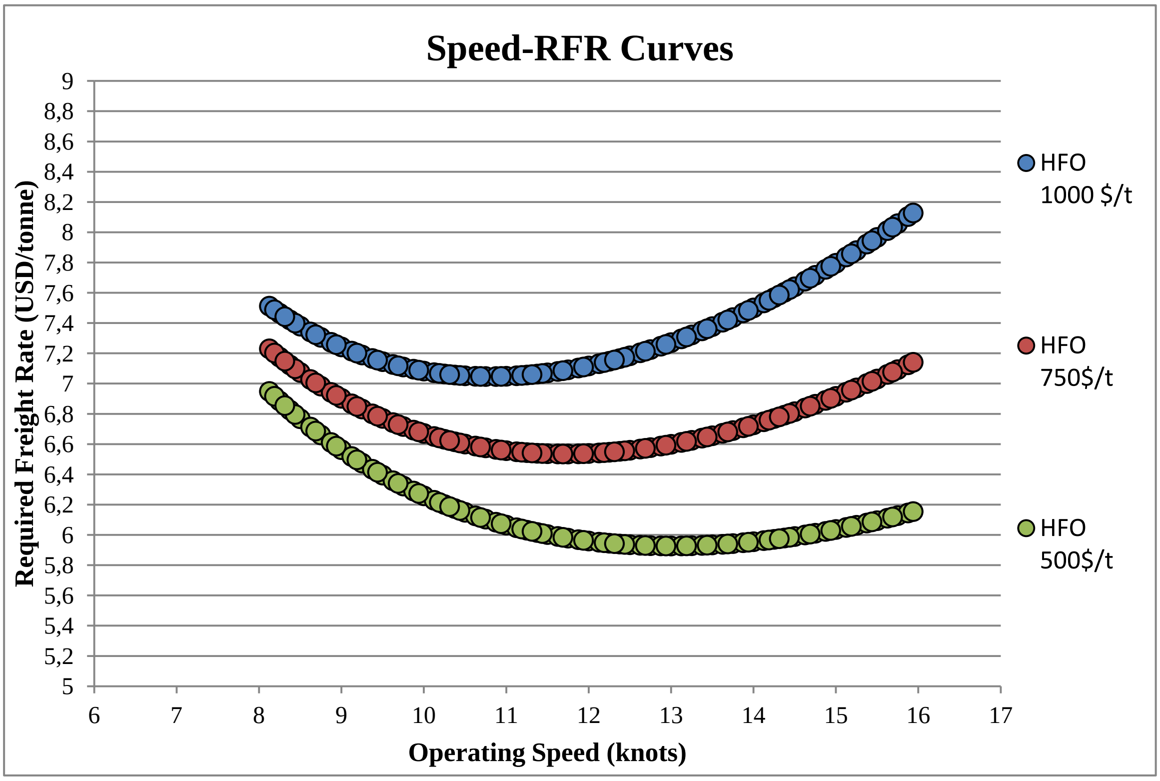


Figure [65]: Variation of the RFR as a function of the operating speed

From the speed curves above it is obvious that the operators are forced to slow steam in periods of increased fuel cost, especially if the latter is combined with a low market situation with little demand and increased supply of tonnage. This drives the operator to slow steam. The optimum operating

speed in the case investigated here would be the one that corresponds to the lowest freight rate, as the fuel costs and trips per year are taken into account. This means that the ship is in the spot market and not time chartered since in that case the charterer is the one responsible for this cost.
For a fuel cost of 1000 US dollars per tonne, the speed corresponding to the lowest freight rate is 10.75 knots, while the increase of speed leads to a rapid increase of the required freight rate.
Similarly, the optimum speed for the case of the fuel costing 750$/t is 11.7 knots, while the increase of RFR due to speed increase is more elastic. Last, for the case of 500$/t the optimal ship is higher at 13 knots, with the curve being more elastic to change of operational speed, while decreasing it will result in a far bigger freight rate. For these scenarios the engine load can vary from 38% up to 66% for the cheapest fuel case. That means that choosing to operate at the speeds investigated as minimum for the freight rate can be considered as slow steaming in machinery terms.
The choice of slow steaming is nowadays very popular, as in any period of low demand and increased fuel cost. However this practice has a direct effect on the machinery and propulsion systems onboard. Some precautions regarding the operation are the following, as recommended by Wartsila for the RT and RTA 2stroke diesel engines (Wartsila, 2010):

1.1.1. Ensure that the nozzle condition is correct. This standard practice should be more cautious than in normal operation.
1.1.2. Maintain higher fuel temperatures and aim to achieve lower viscosities.
1.1.3. Keep the LT cooling water temperature at 36^o in order to maintain the optimum scavenge air temperature, and the jacket cooling water temperature at the upper limit ($85\text{-}95^o$). A high cooling water temperature will reduce condensation and thermal stresses.
1.1.4. Normally the cylinder oil feed rate is load dependant, and no adjustment is needed. However, frequent piston underside inspections are recommended to monitor piston running conditions and signs of over or under lubrication. When symptoms of increased ring wear occur, a temporary increase of the cylinder lubricating feed rate will help stabilize the situation and recover the reliable piston-running performance.
1.1.5. It is important that the temperature of the exhaust gas after the cylinders is kept above 250^oC in order to reduce the risk of cold corrosion. In case the exhaust gas drops below this temperature the engine load has to be increased.
1.1.6. High exhaust temperatures, above 450^oC, after the cylinders should be avoided during the period following the auxiliary blower cut out or before cut in. This may cause hot corrosion and burning of the exhaust gas valves. As a countermeasure the auxiliary blower should be switched to continuous operation.
1.1.7. The engine load should be periodically (twice a week) increased to as high as possible (at least to 70%) for a minimum of one hour in order to blow through any accumulated carbon deposits. Whist operating at these loads, turbocharger washing and soot blowing of the soot should be undertaken in order to reduce fooling.

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PART THREE: MULTI-VENTURE CONCEPT

THE CASE OF THE ENERGY EFFICIENT TANKER

In the third part of the AFRAMAX case studies , or the post analysis of the results, it was decided to use the optimization results as a platform for a new design concept that incorporates LNG as a fuel and new propulsion systems.
Multi Venture is an additional study that takes place in order to maximize the efficiency of the design and implement alternative fuels. This effort is done following a holistic approach but by emphasizing two design aspects:

1. The local hullform optimization as a means to maximize the efficiency of the design and energy conservation by means of resistance reduction. This is done using principles of simulation driven design and coupling with state of the art design and CFD software. The efficiency of the propulsor is also addressed by designing a new propeller adapted to the wake field of the vessel.

2. The machinery arrangements are re-examined, considering LNG as main fuel. The use of hybrid power plants and applications within an all electric ship is taken into account as well as the optimization of the piping and machinery arrangements. The lifecycle performance is considered and the energy conservation is of primary importance.

The overall concept of Multi Venture can be summarized as:

- **Safe and Pollution free:** Reduction of the Accidental Oil Outflow Index is at the level of 40%.
- **Transport Efficient:** More cargo is transported with the same principal dimensions
- **Energy Efficient:** Innovative Propulsion System that utilizes waste heat and fuel cell technologies, within a smarter hybrid propulsion plant.
- **Alternative Fuel**: Use of LNG as primary ship fuel
- **Emission Free**: Increased Efficiency and LNG drastically reduce the environmental footprint
- **"Semi-Ballast Free" design:** 50% reduction of the required ballast water
- **Reliable:** Structural maintenance is reduced and machinery failures are ssutained by the increased redundancy
- **Competitive:** Increased cargo spaces combined with reduced overall fuel costs and reduced ballast voyage costs
- **Maintainability:** Reduced ballast spaces (side tanks) reduce significantly the structural maintenance costs while the modularized engine room concept
- **Economic**: Over the ship's lifecycle the Required Freight Rate is up to 12% lower in comparison with conventional designs.

The business scenario assumed for Multi Venture is that of an AFRAMAX tanker trading in the Caribbean and Gulf areas with a typical voyage of 2015 nautical miles. The Gulf ECA is soon to be implemented and force the ship to run on low sulphur fuels, while the ports of the area impose important draft restrictions.

Multi Venture can provide a new niche market for the European Shipbuilding Industry both in retrofitting of systems or in new built ships. This effort was done within the VISIONS 2012 competition and in collaboration with Mr. Nikos Mantakos (who provided also the lifecycle analysis tool) and Mr. Michalis Pytharoulis.

1. LNG AS A SHIP FUEL

Industrial emissions have increased substantially in the last 100 years, releasing undesirable byproducts in the atmosphere. Particularly detrimental byproducts including nitrogen oxides(NOX) , sulfur oxides(SOX), and carbon dioxide.
As discussed previously, the International Convention for the Prevention of Pollution from ships (MARPOL) was revised in 2008 to set stricter standards for emissions from ships. The proposed future regulations for controlling emissions and the pending ECA zones in the U.S will require that diesel-propelled vessels burn ultra low sulfur diesel oil. In this section the background and the aspects of LNG as a ship fuel are going to be briefly discussed, based on a literature survey.

Natural gas appeared for decades as a form of energy that was difficult to exploit, particularly due to high investment and transportation costs towards the end user. This resulted in a slow development throughout the world, and a lot of gas was flared as a bi-product of oil production. Today gas discoveries have been made at all continents, making natural gas more available. Six countries, Russia, Iran, Qatar, Saudi Arabia, USA and Abu Dhabi possess approximately two-thirds of the world's gas reserves, with 50% of the reserves located in Iran, Qatar and Russia. According to geological data, the world has 187.5 trillion cubic meters (tcm) of proven conventional reserves, which are sufficient to meet 58.6 years of global production. It is impossible to know exactly how much natural gas resources that are left in the ground, and estimates vary among different sources. In recent years advances in exploration and the discovery of unconventional resources, have increased the total reserves. It is estimated that the recoverable unconventional gas resources are over 400 tcm, and that half of them are shale. With the discovery of shale-gas, United States has almost doubled its proven resources, and now their total reserves amount to 7.7 tcm. The US shale gas revolution will influence the LNG-market. More LNG will be available for Europe and Asia, and it will change the investment pattern in the US from import to export. At the same time it is important to notice that the shale gas revolution in the US has not yet been quantified. There are uncertainties on how much of the gas that is actually recoverable, and if it the process is easily repeated elsewhere. Critical success factors have been ideal geology, interested companies, support 4 amongst politicians, environmental issues and the pricing of gas. Unconventional gas reservoirs are without a doubt a game changer, and cover the growing demand for natural gas.

Natural Gas Properties

The natural gas composition varies from field to field, but consists mainly of 80-90% methane (CH_4), and
more heavier hydrocarbons such as ethane (C_2H_6), propane (C_3H_8) and butane (C_4H_{10}). The value of natural gas is determined by the combustion properties of methane, which is a colorless, odorless, non-toxic and non-corrosive gas. Natural gas is the cleanest burning fossil fuel, producing mostly just water vapor and carbon dioxide. The primary use of natural gas is
to supply gas-fired power plants and residential use such as heating and stoves. It is also used as cleaner alternative to gasoil and diesel in the transportation industry, as compressed natural gas, CNG. Natural gas is an important available source of hydrocarbons for petrochemical feedstock and a major source of elemental sulfur.

LNG Production and Supply Chain

Production

In 2010 the global demand for natural gas increased by 7.4 per cent to 3284 bcm. The main drivers of the development of natural gas are lower emissions of greenhouse gases, as OECD is enforcing stricter regulations regarding energy sources. Natural gas offers half the carbon emissions for the same amount of energy produced as coal, which is the main alternative as a power feedstock in many regions. The global gas resources are also vast and widely dispersed geographically, making natural gas available and affordable for many countries. China's gas consumption in 2010 reached 107 bcm, more than any European or other Asian country. They are now investing in domestic shale and tight gas projects, as well as securing supply with new long-term LNG contracts and new pipelines from Turkmenistan. Japan's demand for LNG is expected to increase, to meet their energy demand after the Fukushima nuclear disaster. Only 13 out of Japan's existing 54 nuclear reactors are now operating. As a consequence of the disaster the German government announced a shutdown of their nuclear power plants within 2022. Germany had 140 TWh of nuclear power, representing 23% of their total supply, which will now be supplemented by other types of energy. Consequently, the demand for natural gas will increase, and by 2030 IEA predict it will have the same market share as coal and oil. Production of gas depends on both gas prices and development in exploration and production. An increased gas price will increase production even in economical marginal fields.
Natural gas fields are generally located far from residential and industrial consumers, so-called stranded areas. The most efficient way to transport natural gas in circumstances where the gas market is far from the reserves is in the form of Liquefied Natural Gas (LNG). It is estimated that approximately 60 per cent of the world's gas resources are considered stranded, and which makes LNG-technology attractive. LNG is natural gas that has been cooled and condensed to liquid. At atmospheric pressure LNG has a temperature of about -162 C, and only takes 1/600th-part of the volume natural gas has in gaseous state. The liquefaction process involves removal of oxygen, carbon dioxide, sulfur and water from the natural gas, and thus LNG is almost pure methane.

Trade and Supply Chain of LNG

In the early years of LNG-trading, the business was characterized by self-contained projects of large scale facilities. They required huge capital investments, and complex long-term contracts between suppliers and buyers to share the large up-front investment risk. A certain volume of LNG from a given production site was transported to a fixed market location at a known price. As gas price rose and production cost fell, LNG became more economically feasible, even in small-scale. The LNG-market has become more dynamic, flexible and adjustable in respect to demand fluctuations, delivering location and shipping arrangement. Today the LNG supply chain consists typically of an upstream sector that develops the natural gas resources and liquefies the gas, a midstream sector that transport and store the LNG, and a downstream sector that re-gasifies and distributes the gas to the end-user. A trend is that companies involved in the LNG-trade have opted to own more of the value chain from upstream production of gas, till downstream towards the market place.

Depending on where the natural gas is found, its composition, distance to the market and size of the field will determine if the gas is transported in its gaseous state in a pipeline, or if it shipped as LNG. The large investment in production facilities, ships and receiving terminals gives high initial cost for LNG, but when the transportation distances increase, transportation by LNG become beneficial. When building liquefaction and transport facilities one also need to consider the size of the reserves justifies the capital investment of a base load LNG-plant.

The LNG supply chain involves a number of steps:

1. First, energy companies do exploration and production. This stage involves the supply of gas and condensate from the well, either in offshore or onshore facilities, through a pipeline into the processing facilities.
2. The second step is production of LNG from the raw product. This involves gas treating, liquefaction, and removal of mercury, $CO2$, $H2S$ and heavy hydrocarbons. Liquefaction is done to increase the energy density of the gas for storage or transportation. At the plant heavy hydrocarbons are removed by purification and separation techniques for safety reasons, in compliance with environmental regulations and product specification.
3. After LNG is made, it can be transported. Shipping is the most profitable solution when distances increase, but also transport of LNG by rail or trucks are possible. Due to economies of scale the LNG carriers are increasing their capacity and the largest carriers in use hold 266 000 m3. The LNG is kept cooled during transportation by utilizing a fraction of the evaporated LNG.
4. The LNG is sent to receiving facilities, which include unloading, storage, regasification and distribution. The LNG is re-heated and vaporized to its original gaseous state.
5. At the last stage the LNG is sent to gas fired power plants, the domestic gas grid or the final customers.

<u>LNG Related Emissions</u>

Carbon Dioxide (CO2)

CO2 is associated with global warming. CO2 abatement is possible only by burning less fuel or by burning different fuel. A range of energy efficiency measures have been introduced for shipping, including the Energy Efficiency Design Index (EEDI) for vessel design and the Ship Energy Efficiency Management Plan (SEEMP) for operations. The use of LNG as a fuel has the greatest impact, reducing CO2 emissions by around 29% when compared with oil.

Sulphur Oxides (Sox)

SOx combine with water to form “acid rain”. Under Annex VI, North European nations were granted a Sulphur Emissions Control Area (SECA) in 2005 with the North Sea and English Channel following in 2007. This limited ships from burning fuels with a sulphur level greater than 1.5%. In 2010, the SECAs were re-designated Emission Control Areas (ECAs), sulphur maximum dropped to 0.5% and new limits on NOx and PM introduced. Concurrently, in 2011 a global fuel sulphur cap of 3.5% replaced the previous limit of 4.5%. This was not an arduous requirement for shipping or the bunker supply industry as 3.5% sulphur fuel was widely available.

Nitrogen Oxides (NOx)

NOx also combine with water to form damaging corrosive acids. This can damage the lungs and has been associated with asthma and heart disease. NOx is a major contributor to smog formation. NOx is reduced through the use of Selective Catalytic Reduction (SCR) technology, described previously. ECA NOx regulation in MARPOL Annex VI was applied retroactively by Tiers, based on functions of the age of build of the vessel and the engine speed. Tier I was for vessels built from 2000-2010, Tier II from 2011 and Tier III from 2016.

Particulate Matter (Pm)

PM is smoke or soot emanating from the ship’s exhaust. It is partially burned hydrocarbon material that includes condensed aromatic forms. These molecules include free radicals that can cause respiratory ailments and cancer. On ships, in addition to being a health hazard, PM causes stubborn oily acidic deposits causing corrosion to metal. Smaller particles (between 2μm and 10μm) can be caught by the wind and transported over great distances. Some deposit on and discolour glaciers and ice sheets and this has been associated with the promotion of accelerated ice melt.

In addition to meet the environmental regulations the fuel has to be technological feasible, commercially available and economically justified. Bio-fuels and hydrogen are not expected to be commercially available in the shipping industry in large scale until after 2030. The use of nuclear reactors on board is not anticipated to be an interesting option for international shipping, due to environmental, political and safety reasons (IMO, 2009). Substitution of HFO with MDO is a possible solution, but it is more expensive because the oil-gas differential is increasing. The refining industry would also struggle to supply an extra 4 mbd of gasoil because of limited production. Compressed natural gas (CNG) or LNG is less carbon intensive, but need new engine design, larger tank volumes and rely on better infrastructure. Since a LNG-tank will require only half the volume compared to CNG, it is the most likely alternative. This analysis gives us two plausible solutions that comply with the ECA-regulations, are technological feasible and economically justified: Installment of smoke scrubbers to clean HFO on existing machinery and LNG-fueled ships.

Economic Evaluation of LNG

The oil-gas differential is the single most important factor. Taxes, port fees and repairs are also significant. A modest estimate can give 10 % reduction OSVs and RO-ROs rely heavily on cargo space. At the same time, off-hire time is worst case related to ship revenues that can be talked by the higher operational reliability with LNG.

To do an objective economical analysis of LNG-engines is difficult, as many ships have been produced as highly customized ships, and an efficient LNG bunker market affecting the operation cost does not exist. The fuel cost is probably not directly comparable, the market relies on some agreements and developments of standards for bunkering are still to come. The interval on both capital expenditure and operational expenditure are huge. In Norway the NOX-fund has supported retrofit and new builds with LNG engines, as long as the operators cut the emissions of NOX, this support has made it profitable and an increased incentive for ship owners to shift.

Choice for Multi Venture

Liquefied natural gas (LNG) has been proposed as an alternative and less costly solution to the challenge of cleaner shipping fuels for scheduled trades in Northern Europe and particularly those in ECAs. The environmental qualities of LNG are superior to those of any liquid petroleum fuel.

The technical and operational viability of LNG as a fuel for ships is demonstrated by our design for the VISIONS 2012 competition.

The use of LNG effectively eliminates the need for exhaust treatment due to very low NOX formation in the engines as well as the absence of sulphur. Notably the LNG as a fuel emits no SOX , very little NOX and no particular matters. However it does emit CO2 20-25% less than all liquid fuels.
Table 23 depicts the differences in emissions, shown in grams per kilowatt hour(g/kwh) between LNG and other liquid petroleum fuels (Marine technology, SNAME, 2011)

FUEL TYPE	SOX(gr/kwh)	NOX(gr/kwh)	PM(gr/kwh)	CO2(gr/kwh)
RESIDUAL OIL 3.5 % sulphur	13	9--12	1,5	580-630
Marine diesel oil, 0.5%S	2	8--11	0.25--0.5	580-630
Gasoil, 0.1% sulphur	0.4	8--11	0.15--0.25	580-630
Liquefied natural gas(LNG)	0	2	0,075	430-480

Table [23] LNG Emission Comparison (Marine Technology 2011)

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LNG Storage and Bunkering

As described in the previous chapter the Multi Venture concept is using a Dual Fuel concept in order to enhance the use of alternative fuels in the marine industry. In all LNG fueled vessels, one of the most critical designs aspects is the storage of the LNG onboard. For LNG carriers this is not a problem since the boil-off gas from the cargo tanks is used as a fuel. In the case of any other commercial vessel though, and in our case a tanker, special attention must be paid to the technology used and the space and weight of the installed tanks.
Since the density of the liquefied gas is very small, the storage is very difficult and the range required for an AFRAMAX tanker (~15000 nm) cannot be met. So the designer has to specify the business scenario under which LNG can fuel the vessel and the range in hours and nautical miles accordingly for the operation. In the case of Multi-Venture, the Caribbean trade business scenario is examined, which corresponds to a round trip of 2015 nautical miles which is a valid target for LNG only propulsion.

The applicable LNG storage technologies for an AFRAMAX tanker are either prismatic, IMO B-Type tanks, that are the ones used by LNG carriers as cargo tanks or IMO C-Type tanks, that are of cylindrical shape and can be mounted on the large deck area since there are minor disruptions. There are several other types of containment systems for LNG available, but some are not feasible for the given conditions on ships using LNG as fuel following current designs. E. g. most of the membrane tank systems as used on the very large LNG carriers are sensitive to sloshing and could therefore not carry partial loads – thus any use as fuel tank is not possible. IMO type A (self-supporting tanks designed like ship structures) and type B (self supporting prismatic or spherical) tanks are generally feasible for fuel gas tanks, but their requirement for pressure maintenance and secondary barrier rise difficult problems that are not yet solved in a technically and commercially sound way. This will be a future solution for ships carrying large amounts of LNG as fuel. So IMO type C tanks (pressure vessels based on crack propagation design) turn out to be the preferred solution for today.

Those tanks are very safe and reliable, their high design pressures allow for high loading rates and pressure increase due to boil-off; finally they are easy to fabricate and install. The major disadvantage is the space consumption of this tank type that is restricted to cylindrical, conical and bilobe shape. In addition to the unfavorable LNG density these tank shapes lead to a total factor of 3 to 4 times the oil bunker tank volume to carry the same energy in LNG. On top of that, high design pressures reduce the allowable maximum filling limits, if following today’s status of regulation.

Tank insulation is required in order to reduce heat ingress and to protect the ship structures against the cryogenic temperatures of LNG. This may be done by vacuum or foam insulation depending on the operational and tank shape requirements. Vacuum tanks have an excellent insulation performance; however, they are restricted to cylindrical shape, limited in size and usually do not have a manhole for inspection or mounting of in-tank equipment. Foam insulated single shell IMO type “C” tanks are feasible in cylindrical, conical or bilobe shape in order to better fit to the available space. Either foam panels are glued to the tank and protected by vapour barrier and steel sheets, or foam is directly sprayed to the tank surface and covered by a polymeric layer. Both has been done for small LNG carriers with type C tanks. Even with special high-capacity panels the heat ingress is clearly higher than for vacuum insulated tanks. This technology has been applied for the gas propulsion of Bit Viking, a chemical tanker operating in the Baltic region.

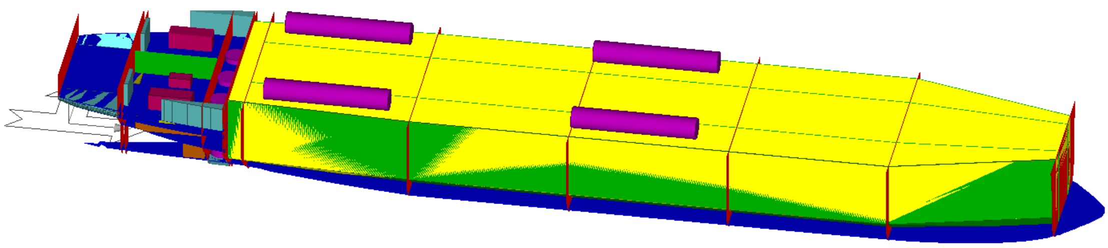
Picture [17]: Example of IMO C-Type tanks used in the Bit Viking Project

The chosen system for Multi-Venture is supplied by Wartsila and is called the LNGpac. A total of 7 C-Type tanks were used, 4 mounted on the deck and 3 installed in the engine room area with a vertical orientation.

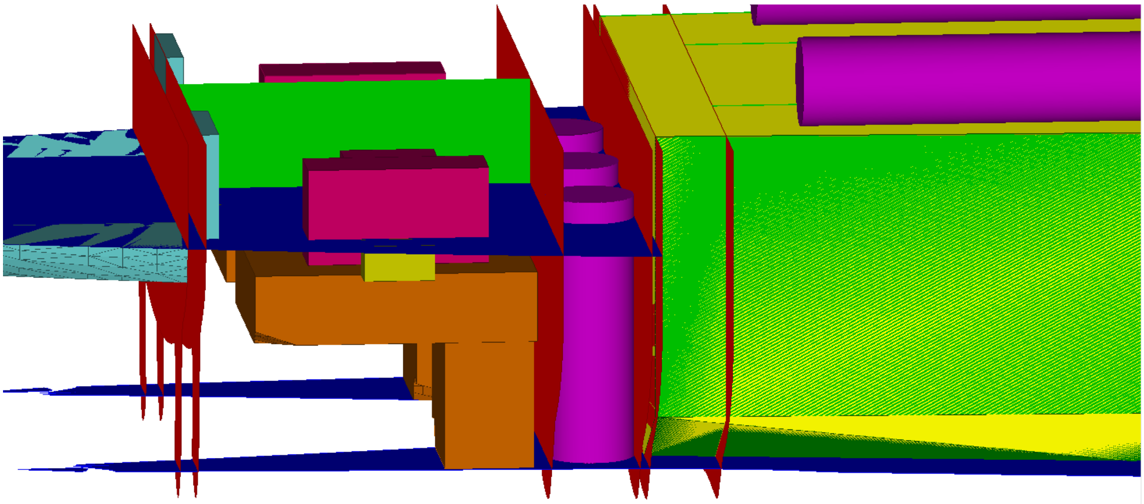
The deck tanks have a nominal capacity of 400 m^3 , a total length of 30m, a diameter of about 5m and a net weight of approximately 135 tons.

The vertical tanks installed in the engine room are protected by two void, cofferdam spaces aft and fore have a capacity of 200 m3 with a length of 15m and the same diameter of 5m.

The total weight of the LNG tanks is 1015 tons that are included in the amended lightship, in the outfitting weight category. The increase of the outfitting weight is sustained by the decrease of the machinery weight (thanks to diesel electric propulsion), so in terms of lightship a small reduction can occur.



Picture [18]: Snapshot from AVEVA illustrating the LNG tank arrangement on the deck



Picture [19]: Snapshot from AVEVA illustrating the vertical LNG tanks in the engine room

The LNG tanks were modeled together with the entire compartmentation study in AVEVA, in order to see the effect of the newly installed tanks on the trim and hydrostatics of the vessel.

A provision for a Gas preparation station was also made, during the engine room design phase, were both vertical and deck tanks can be serviced.

The total LNG capacity of the plan is estimated at 2000 m3 that corresponds to a range of 19.5 days of continuous operation, or 7000 nautical miles, which is approximately 5 round trips as seen at the table below:

Available capacity (m3)	2200
Range (d)	19.50960256
Working hours	468.2304614
Range (nm)	7023.456922

Table [24]: Range of ship running entirely on LNG

This surplus of fuel means that the ship operator can optimize the bunkering process in terms of purchase time and reduce the fuel purchasing costs by finding the optimal prices. Inconsistent bunkering issues can also be resolved thanks to this increased range with LNG.

2. BALLAST WATER REDUCTION AND ANALYSIS

As mentioned earlier in the results section the reduction of the required by the MARPOL convention ballast water, is greatly reduced. The required ballast water is specified by the requirement for a minimum aft, mid and fore draft. The aft draft must be bigger than the propeller diameter in order to avoid unwanted propeller racing phenomena, while the mid and fore draft ensure that the ship has a displacement that ensures an adequate controllability.

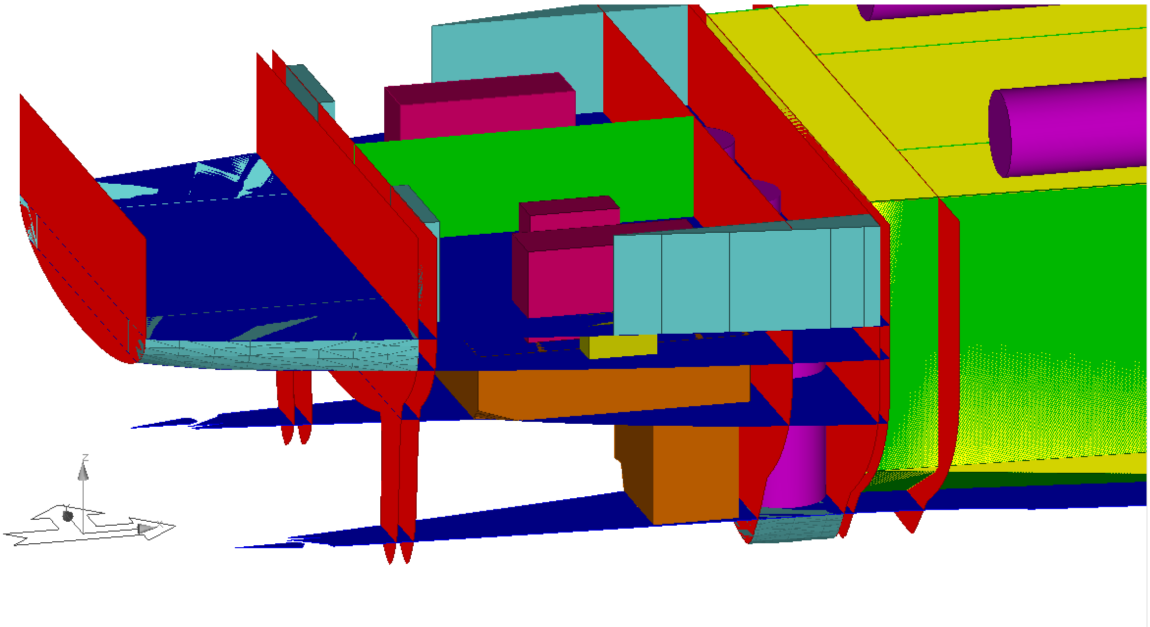
Detailed Hydrostatic and Trim Check

Initially, the ballast water was checked within the Friendship Framework as a rough approximation without taking into account the moments of smaller fuel and lube oil tanks but only the cargo oil tanks.

For Multi Venture however, it was chosen to undergo a more detailed hydrostatic analysis in order to investigate the optimal position of the LNG C-Type tanks that are installed on the main deck. The hydrostatic calculation took place for four loading conditions, the Full Load Arrival, Full Load Departure, and Water Ballast Arrival and Departure and was performed using the AVEVA package.

In order to be able to work within the AVEVA framework the hull geometry needed to be exported from the Friendship Framework via an SHF format and after editing was transformed to a Britfair file that the AVEVA program uses as an input. The cargo oil tanks were modeled in AVEVA using the same positions and parameters as specified by the dominant variant from the optimization procedure.

However the engine room arrangement changed as the Multi Venture concept features Dual Fuel Diesel Electric propulsion, which offers the flexibility to change the engine room position, shifting the generating sets to the upper decks close to the main deck area, since there is no two stroke engine that has specific space requirements
The location of the engine room was shifted to the upper parts, one level below the main deck. This feature (also found in Arctic Shuttle Tankers) can enable the easier maintenance of the engines along with quicker parts removal and dismantling. The engine platform deck is subdivided in the transverse direction by a fireproof longitudinal bulkhead in order to provide safety in case of explosion (e.g. crankshaft explosion) of one engines and not mitigate the safety of the other generators. Each subdivided engine room has a pair of engines arranged symmetrically (for heeling purposes) by having a large and medium genset together.
The engine room is constrained within the platform deck by two bulkheads. Aft of the engine room and on the same deck, the control rooms and main switchboards are located and aft of that the steering gear room. A control unit that collectively is responsible for the generator operation (with an additional class notation an unmanned engine room can be operated), steering and electronic control is such arranged. This can be regarded as a security measure, since this area is sealed by a transverse bulkhead at the fore end and the transom stern at the aft, creating in this way a “citadel” which is isolated and can have full control of the ship even when under attacked by pirates, without mitigating the safety of the crew and the ship.
Below the engine platform there is a small deck (2m high) that accodomodates the lube storage and sumpt tanks for the main engines and is easily accessible from the main platform. Furthermore, the settling and daily tanks were properly arranged. Below that a third deck accomodates the main HFO storage tanks that are in compliance with the SOLAS regulations for the void space between the side shell and the tank boundaries.



Picture [20] : Snapshot of the compartmentation mode of AVEVA, where the engine platform deck can be seen along with the control room and fuel tank decks.

Having modeled the tanks, a check of the hydrostatics takes place for the four specified loading conditions. Since the business scenario is for the Caribbean trade, the range with LNG is available for the entire laden leg, so the ballast conditions, use LNG as a fuel instead of HFO. The loading of the tanks that use ballast was done in a staged approach and using a trial and error mentality, each time monitoring the draft requirements set by MAPROL.
First the bottom tanks were loaded, were it was noted that the draft restrictions at the aft part were met. The fore draft however was not satisfied, which meant that ballast had to be used in the Fore Peak Tank for counter balance. The engine room water ballast tanks ensured that the propeller is immersed. The final loading condition particulars can be seen at the tables that follow:

WATER BALLAST DEPARTURE CONDITION

Heavy Fuel Oil

	Cargo	% full	SG	Weight	LCG	TCG	VCG	FSM
HFO (P	FO	98	0.9	733.5	27	-9.5	11.96	2636.4
HFO (S)	FO	98	0.9	733.5	27	9.5	11.96	2636.4
HFO2(P)	FO	98	0.9	286.5	32.52	-9.31	6.1	230.3
HFO2(S)	FO	98	0.9	286.5	32.52	9.31	6.1	230.3
H.F.O Sett.	FO	98	0.9	37.8	16.5	11.5	19	0
H.F.O Serv.	FO	98	0.9	37.8	16.5	-11.5	19	0
Total Heavy Fuel Oil				**2115.6**	**28.12**	**0**	**10.62**	**5733.4**

Lube Oil

	Cargo	% full	SG	Weight	LCG	TCG	VCG	FSM
Main L.O TNK	LO	100	0.9	36	17	0	15	0
SumptTNK	LO	100	0.9	10.8	27.5	0	15	0
SumptTNK2(P):	LO	100	0.9	14.4	27	17	15	0
SumptTNK2(S):	LO	100	0.9	14.4	27	-17	15	0
Total Lube Oil				**75.6**	**22.31**	**0**	**15**	**0**

LNG bunker

	Cargo	% full	SG	Weight	LCG	TCG	VCG	FSM
CLN1:	LNG	90	0.5	265.1	65	-15	24.27	59.2
CLN10:	LNG	90	0.5	265.1	139.1	15	24.27	59.2
CLN2:	LNG	90	0.5	265.1	65	15	24.27	59.2
CLN6:	LNG	90	0.5	265.1	139.1	-15	24.27	59.2
CLN7:	LNG	90	0.5	132.5	38.5	-10	8.99	15.2
CLN8:	LNG	90	0.5	132.5	38.5	10	8.99	15.2
CLN9:	LNG	90	0.5	132.5	38.5	0	8.99	15.2
Total LNG bunker				**1457.9**	**84.72**	**0**	**20.11**	**282.4**

Water Ballast

	Cargo	% full	SG	Weight	LCG	TCG	VCG	FSM
1WBI	WB	100	1.025	2887.3	218.89	0	1.18	0
2WBI	WB	100	1.025	3427.2	181.81	0	1.16	0
3WBI	WB	100	1.025	3450.2	143.36	0	1.16	0
5WBI	WB	100	1.025	2954.9	66.68	0	1.18	0
APTNK	WB	100	1.025	1355.8	8.89	0	12.31	0
ERBWT	WB	100	1.025	114.4	35.78	-20.79	19	0
ERBWT1	WB	100	1.025	114.4	35.78	20.79	19	0
ERBWT3	WB	100	1.025	200.4	38.69	0	1.43	0
FPTNK	WB	100	1.025	4194.8	243.66	0	11.74	0
Total Water Ballast				**18699.4**	**160.26**	**0**	**4.57**	**0**

Summary

Total Water Ballast	18699.4	160.26	0	4.57	0
Lightweight	22848.6	107.1	0	17.23	0
Deadweight	22694.6	140.32	0	6.32	6015.6
Total Displacement	45543.2	123.65	0	11.8	6015.6
Buoyancy	45553	123.51	0	2.91	1527019.5
Total Buoyancy	45553	123.51	0	2.91	1527019.5

Drafts at Equilibrium

Draft at LCF	5.302	metres
Draft aft at marks	7.379	metres
Draft fwd at marks	3.523	metres
Draft at AP	7.379	metres
Draft at FP	3.523	metres
Mean draft at midships	5.451	metres

Hydrostatics at Equilbirium

Density of water	1.025	144agni/cu.m
Heel	No heel	
Trim by the stern	3.857	metres
KG	11.797	metres
FSC	0.132	metres
KGf	11.929	metres
GMt	24.507	metres
BMt	33.522	metres
BMl	861.02	metres
Waterplane area	9668.51	sq.metres
LCG	123.654	metres
LCB	123.512	metres
TCB	0	metres
LCF	131.331	metres
TCF	0	metres
TPC	99.102	144agni/cm
MTC	1607.463	144agni-m/cm
Shell thickness	0	mm

It is evident from the analysis above that the loading condition is according to the requirements. It is also evident that the ballast water required in order to meet the regulatory constraints is 18699.4 tonnes which is a significant reduction. It is also significant to see from the loading condition output that only the bottom ballast tanks are used. This means that the side tanks can be characterized as void spaces and not segregated ballast areas with an important effect on the maintenance of the structural steel structure of the ballast tanks. Additionally the reduced ballast amount has a profound effect on the energy efficiency onboard both due to the reduction of the working time of the ballast pumps (which is also beneficial for the number of voyages) and the reduction of the energy required for ballast treatment.

Structural Maintenance Effects

As mentioned earlier in the Multi venture concept the side tanks for ballast storage are not used and instead characterized as void spaces. This has a profound effect on the maintenance of the steel structure of the vessel. The spaces are assumed to be painted with the same specification (IMO PSPC) with the ballast tanks, as in commercial shipyard terms the cost difference is negligible and subject to ship owner's negotiation.
In that case the exposure of the side tank spaces (which are bigger in comparison to bottom tanks) to salt water is avoided triggering a big reduction of the corrosion rate and subsequent wastage of the steel structure. According to AVEVA, the surface of the internal spaces in the side tanks is approximately 21710.92 m^2. These can be excluded from the maintenance part as the corrosion rates in void spaces are reduced drastically.

For Multi Venture, this means that despite its inherent increased capital cost, the maintenance costs and off-hire days are reduced.

Ballast Water Treatment Effects

The reduction of the usable ballast water is also very important in view of the upcoming Ballast Water Treatment convention which is going to be applicable to all ships having more than 5000 m3 ballast tanks. This has been after all one of the motivational triggers for the generation of an almost ballast free ship.

There is a big variety of systems that have IMO type approval and offer ballast treatment, using different technologies, such as electrolysis, chemical treatment, ozone treatment and nitrogen treatment. For this present study it is not of our interest to present an ideal solution for the ballast treatment system itself, as there are several commercial implications bound to that. The aim is to assess the efficiency gain from the reduced ballast tank.

The majority of the available ballast water treatment solutions depend on the ballast pump output and rate rather than the ballast capacity. However, since the pumping system is provided by FRAMO as a power pack and includes two submerged ballast pumps it was chosen not take into account the reduction of the ballast water capacity to the dimensioning of these components. Nevertheless, the pumping time will reduced by the same of order of magnitude as the ballast capacity, since the pumping rate will be the same (2 pumps of 1250 m3/h each). This can induce a twin way benefit:

- The operating time of the pumps is smaller, thus the induced fuel costs (via the FRAMO pumping system)
- The operating time of the ballast water treatment system is smaller.

The MARTOB research project calculated a few years ago the costs per cubic meter for BWT, for a variety of available technologies, with the inclusion of the capital, maintenance and operational costs (table [25]).

	Annual Cost per m3 of ballast (€/m^3)
Thermal Treatment	0.55
Biological Oxygen Treatment	0.10
UV	0.11
US	0.28
Ozone	0.22
Oxicide	2.34
BenRad	0.17-0.30

Table [25]: BWT costs per m3 for different technologies (MARTOB, 2004)

From table [22], since the costs are non-dimensionalize by the cubic capacity the cost reduction for BWT in Multi Venture is linear since it uses 47% less ballast or 16679 tons less (from the original 35378 tons) according to the worst case scenario (corresponds to the minimum ballast loaded by the conventional ship; in reality this difference is much bigger). More specifically the ship owner will be able to save during one operating year, depending on the system choice from 1668 to 39263 Euros. (Table [23]).

	Annual Cost per m3 of ballast (€/m^3)	Annual Cost Reduction for Multi Venture (€)
Thermal Treatment	0.55	9173.45
Biological Oxygen Treatment	0.10	1667.9
UV	0.11	1834.69
US	0.28	4670.12
Ozone	0.22	3669.38
Oxicide	2.34	39028.86
BenRad	0.17-0.30	2835.43-5003.7

Table [26]: Annual Cost Reduction for BWT in the case of Multi Venture

It is obvious that when energy intensive and expensive methods are preferred the advantage of the reduced ballast water amount is more obvious.

Operational and Voyage Effects

Another very important effect of the ballast leg is that on the operational profile of the vessel, since we are talking about tankers. In the tanker industry, with the exception of the product tankers, 50% of vessel's operational life it is expected to be at ballast leg given the existing trade patterns.
Multi Venture, which is based on the optimization results (I.D 2515) features a reduced C_b and displacement at the ballast draft thanks to the elliptic bilge concept explained earlier. The elliptic bilge, like the tumbled containerships designed by Blohm und Voss in the 70s, offers a reduction of the C_b at the ballast draft while sustaining the displacement loss at a minimum level. Since the resistance of the vessel depends on the displacement too ($\Delta^{2/3}$ rule in the British Admiralty number), it has to be re-examined. According to the Holtrop and Mennen empirical formula used in the optimization studies, the modified resistance for the ballast draft taking into account the change of the hydrostatic particulars (such as Cb, displacement, wetted surface and water plane area), is reduced and the propulsion factors such as wake and thrust deduction are reduced too. This results into an overall decrease of the required engine load of 35 to 40% or else operating at 60% load, for the same operating speed of 15 knots. This reduction of load is very important for the Required Freight Rate. The Specific Fuel Oil Consumption (SFOC) may increase for low load operations (since the engine is tuned for part load operation) but the overall fuel costs decrease since the required power is smaller. The decrease of the fuel costs can be estimated from the Friendship Framework calculations to be at a level of approximately 8% (834537 $). This is very important both for the efficiency and the emissions standpoint too, and it's importance will be even more obvious as the fuel costs continue to rise which is the expected trend.
Overall we can see that the use of a design that by default has a better ballast profile but also undergoes a systematic optimization is a sound strategy given the existing and future regulatory framework and IMO conventions, and given the portion of ballast condition over the ship's lifecycle. Multi Venture addresses this hot potato issue efficiently providing the potential user a flexibility and advantage that is going to be more obvious in the years to come, when a two tiered market is expected to be dominant, where efficient and regulation compliant ships are going to be subject to better commercial promotion and charter potential than conventional and low technology alternatives.

3. FINE TUNING OF BULBOUS BOW

The bulbous bow of the resulting dominant variant (I.D 2515) was chosen to be refined for the concept of Multi Venture. The reason for this refinement was to avoid any irregularities of the hull due to the extensive shifts made during the Global Optimization in the Lackenby shift, in order to achieve the desired LCB and Cb. During this operation the parameters were re-examined. The principles behind this fine tuning are hydrodynamic, namely the scope is the reduction of the resistance.

1. Resistance Components and Assessment

For a tanker of that size and speed the main component of the resistance is the frictional resistance and the viscous pressure resistance, while the wave resistance is of a second order magnitude. The accurate prediction of the viscous pressure resistance depends solely on the use of CFD software and viscous flow solvers in order to find where the onset flow separates from the boundary layer. This prediction, even when using very detailed meshes and models is very difficult and usually must be done in model scale. From the other hand, the frictional resistance, without the viscous pressure effects can be correlated directly to the Wetted Surface of the hull in the design draft.
In the case of the fine tuning we examine in this chapter, the viscous flow computations need a big preparation in order to produce a fine mesh and sufficient grid for a watertight body and the bounding box. Additionally, each run, depending on the resolution and detail of the grid can take up to 20 hours. For this reason, and in order to achieve a fast yet accurate result, we chose not to take into account during the refinement phase the viscous flow, leaving behind in such way the contribution and effect of the new bulb to the viscous pressure resistance.
The part of the frictional resistance in the model that was built for the Global Optimization, as mentioned is approximated by the ITTC 1957 formula, which is included in the Holtrop and Mennen methodology. Under this scope it was chosen to assess the wetted surface , in which the frictional resistance has the greater sensitivity, for each design.

2. Generation of Designs and Assessment

Design Creation

The designs are produced using a genetic algorithm (NSGA II) in order to be able to converge fast and with accuracy in new generations of designs that incorporate a smaller wetted surface, which is the single objective of this optimization run. After an exhaustive run, the algorithm did converge in such a way that 50 designs out of a population of 450 designs (150 generations of 30 population each) had almost the same wetted surface.

Design Constraints

During the phase of design generation the deadweight, displacement and Tank Volume were used as constraints, with a tolerance of approximately 1%. This can be evidenced by the reduction of the wetted surface which was at the level of 0.6-0.9% and is connected to the displacement. The reason for imposing such constraints was to reduce the risk of compromising deadweight and thus payload in order to reduce the bulb surface.

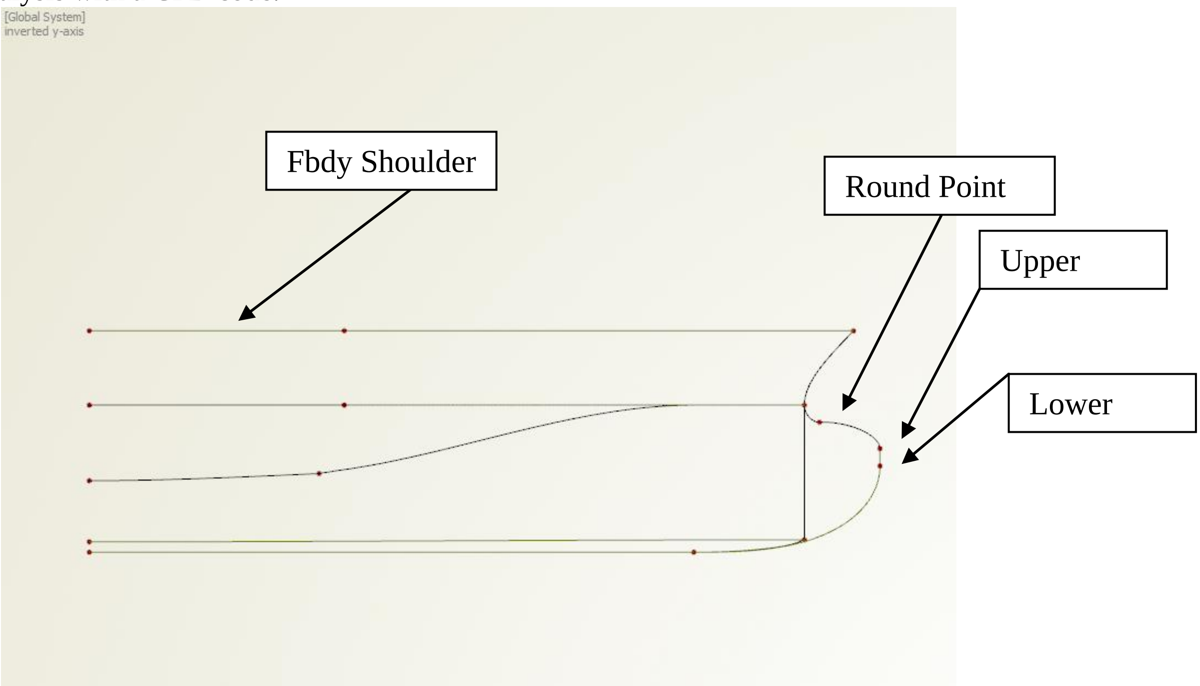
<u>*Design Variables*</u>

During the creation of the variants, as in every simulation or optimization the manipulation of certain design variables, chosen by the user, triggered the design variation, generation and assessment. For this case the design variables are geometrical properties of the bulb such as the position of the top and bottom point (influencing the vertical extent of the bulb), the design waterline angle, the bulb fullness in the transverse plane as controlled by the stem angle of the bulb and the tangent of the curve above the top bulb point (Table [27]).
At picture [21], one can see the points and curves that control the bulb geometry, as well as those geometrical variables that are used in the automated design generation.

Design Variable	Lower Bound	Upper Bound
Tangent at Round Point (Degrees)	80	110
Forebody Deck Shoulder (%Lbp)	0.81	0.83
Round Point Vertical Position (% Draft)	0.8	0.95
Design Waterline Entrance Angle (Degrees)	65	90
Stem Angle (Degrees)	40	70
Lower Point Vertical Position (% Draft)	0.2	0.6
Upper Point Vertical Position (% Draft)	0.6	0.8

Table [27]: Design Variables used for Bulb Fine Tuning

One can notice from the range and the boundaries of these variables that the bulb is allowed to take an almost free shape that will result in the objectives set. It is also interesting to see that for the 50 design with almost the same wetted surface, different bulb shapes were created. The final choice was made after an analysis with a CFD code.



Picture [21]: The functions and points that define the fore body

Assessment and Choice of Dominant Designs

In order to make the sorting and ranking of dominant variants an objective function had to be used, which in this case was the Wave Making Resistance of each design, as calculated in SHIPFLOW, using the Potential Flow Theory and the pressure integral Cw as well as the wave cut integral Cwtw. This choice can offer a double benefit to the designer as he can chose for an almost constant wetted surface, the best design in terms of performance in the wave making resistance. And that choice is made without mitigating the economic performance and cargo carrying capacity that was achieved during the initial optimization phase.

After an analysis of the designs with the least wetted surface, Design I.D 210 was chosen and exported as it illustrated a 42% reduction in the pressure integral Cw that can be interpreted as an equal reduction to the wave making resistance of the vessel. However, due to the second order effect of the wave making resistance to the total resistance of the vessel this reduction was not seen at the total resistance. Nevertheless, an improvement of approximately 0.8% (95 kW) to the total installed power was achieved. This improvement can also be reflected at the Required Freight Rate. The documented improvement for the cost of transport is also 1%.
Below renderings of the initial and the final geometry are available as well as a comparison of the bow wave pattern of the initial model (baseline-I.D 2515) and the improved result (I.D 2515-210).

Picture [22]: Comparison of the wave pattern of the baseline (down) and improved model

4. ALL ELECTRIC SHIP (AES) CONCEPT AND SYSTEM OVERVIEW

An alternative to a conventional two stroke propulsion plant, that is the dominate solution for a tanker, is to use diesel-electric propulsion. Within this study an effort was made to provide a propulsion plant configuration that is using LNG as a fuel and can also utilize alternative energy sources such as fuel cells, lithium batteries etc. This is achieved thanks to the All- Electric Ship (AES) concept that is adopted and aims at substituting partially the electrical energy produced by generators. This kind of applications is usual for cruise ships and ferries, while in the tanker industry there are some examples of shuttle tankers (with Ice Class notation). The reason for this is the need for dynamic positioning, power redundancy and a robust power transmission for a big load range. Within this concept, a Gas Hybrid Power Plant is considered. A previous study made on this subject was by Edward Eastlack [1] for his Thesis in the USCG academy. The Diesel Electric power plant can provide the ideal platform for this concept. The advantages of such a system that are based on the generation, management and distribution of electrical instead of mechanical energy are:

- Decreased weight, that means that the payload can be increased,
- A big variety of hybridization options that can shift loads from the main generators by means of alternative energy sources,
- Increased Efficiency,
- Less Engine Room Spaces that can increase the space utilization onboard
- Quicker response time when the load must change (increased manoeuvrability)
- Increased Power Redundancy, as now the ship can drift only if all generators (more than 2) and power sets fail,
- More Flexible operating profiles

  In the case of slow steaming some gensets can be cut off and thus maintain the operating engines at their optimal load. Furthermore, by using an advanced and optimized controller (part of the control system of the ship) it is able to have a power management plan, increasing the efficiency.
- Increased potential for future retrofit, as the engines are located close to the main deck and can be easily removed and replaced. This can also trigger a new kind of ship management with engine leasing systems that can help improve the logistics and the maintenance policy.
- Reduced lube oil consumption and easier maintenance for the 4 stroke generators.

On the other hand some disadvantages for such a system are:

- Increased initial building cost, that can be deduced by introducing engine leasing programs,
- The relative efficiency of each generator is lower compared to the efficiency of a 2 stroke reciprocating engine,
- Increased complexity for the crew to operate.

From the electrical stand point, the propulsion plant now is more complex. The loads that have to be handled are in two categories: the propulsion loads and the auxiliary service loads.

a. Propulsion Load

The propulsion load is the required electrical power to move the corresponding electric motors. From the preliminary design, following the optimization studies presented, the required power for the design speed of 15 knots is estimated at about 13900 kW, including the fouling and sea margin as well as a derating margin (in the original study the ship was equipped with 2 stroke engines with mechanical drives). This margin (5%) is deducted, thus the power required for propulsion is 13292 kW, or 6646 kW for each propeller. With an estimated propeller diameter of 6 meters, and given the wake and thrust deduction of the vessel, the RPM that correspond to the biggest propulsive coefficient is taken to 100. The motors are to be installed within the skegs and not to be installed as podded propulsion.

Based on these results, the electric motors to be installed need to produce a 6646 kW power at the 100 RPM. Using figure [66] provided by ABB it is evident that the Type 25 Azipods are suitable, although this vessel does not implement podded propulsion but the motors used in the pods can be used for a traditional configuration. The fact that these motors originate from pods is beneficial for the space requirements, since this issue is critical for the Azipod configuration.

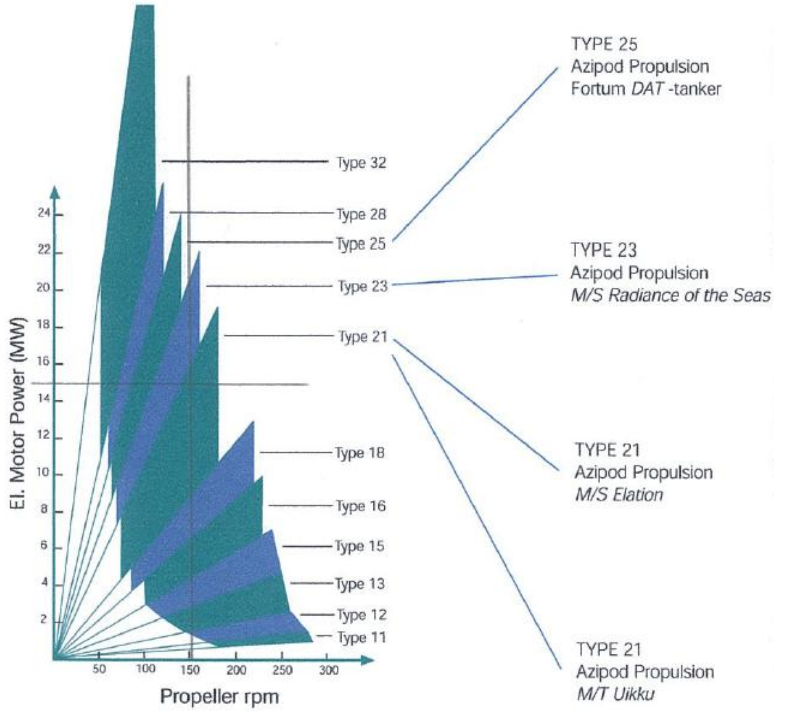


Figure [66]: Selection diagram for electric motors (source: ABB)

b. Auxiliary Service Loads

The auxiliary loads for a crude oil tanker in that size (AFRAMAX) can be categorized as the following:

- Main Engine Auxiliaries
- Engine Room Auxiliaries
- Cargo and Ballast Pumps
- Boiler Plant
- Deck Machinery

- Air Condition and Refrigeration
- Ventilation
- Galley/Laundry
- Lighting/Navigation
- Misc.

The cargo and ballast pumps are powered by the electric hydraulic power pack, provided by FRAMO, and are the biggest of the auxiliary loads (2048 kW). The rest of the requirements, were taken from an equivalent size (Capesize) bulk carrier following a benchmarking study.

c. ***Total Load***

The total load is calculated for 4 conditions: Normal Sea going, Manoeuvring, Cargo Handling and Harbour. Based on the maximum load calculated from the four conditions the generator sets are chosen.

	Normal Sea Going		**Manoeuvring**				**Cargo Handling**		**Harbour**	
			With Ballast		**Without Ballast**					
Consumer Group	**C.L**	**I.L**	**C.L**	**I.L**	**C.L**	**I.L**	**C.L**	**I.L**	**C.L**	**I.L**
Main Engine Aux	76.9	1.4	167.5	1.4	167.5	1.4	81.6	4.7	81.6	5.6
Engine Room Aux	86.3	296.6	360.1	73.1	134.3	73.1	302.8	255.2	79.9	202.5
Boiler Plant	4.3	0	6.4	0	6.4	0	6.4	0	6.4	0
Deck Machinery	12.2	0	184.2	0	184.2	0	62.2	159.7	0	30.5
Air Cond/Ref.	72.8	0	72.8	0	72.8	0	72.8	0	72.8	0
Vents	68.7	0	68.7	0	68.7	0	48.3	0	48.3	0
Galley/Laundry	0	62.4	0	62.4	0	62.4	0	62.4	0	62.4
Lighting/Navigation	81.5	0	81.5	0	81.5	0	81.5	0	81.5	0
Misc	0	2.7	0	14.9	0	14.9	0	25.4	0	25.4
Total	402.7	363.1	941.2	151.8	715.4	151.8	655.6	507.4	370.5	326.4
Total Continuous Load		402.7		941.2		715.4		655.6		370.5
Total Intermitent Load		363.1		151.8		151.8		507.4		326.4
Diversity Factor		33		33		33		33		33
Actual Load of IL		119.823		50.094		50.094		167.442		107.712
Total Auxilliary Load		522.523		991.294		765.494		2526.212		478.212
Propulsion Load		13292		3987.6				0		
Total Maximum Load		**13814.523**		**4978.894**		**4753.094**		**2526.212**		**478.212**

Table [28]: Electrical Load Analysis for dimensioning of the AES

d. Power Production in All Electric Gas Hybrid Plant

i. Outline of the system

In order to have the potential of a more flexible operation and an increased redundancy, four generating sets are chosen to produce the required electrical power, and a smaller generator is also installed for the harbour loads in order to avoid very small loading of the main gensets. As described in the introduction, the aim is to use alternative fuels, such as LNG and potentially biofuels. For this particular reason the generating sets chosen are moved by Dual Fuel engines that use the LNG stored onboard. Manufacturers of such units are MAN Diesel, Wartsila, Rolls Royce and Caterpillar. The Wartsila option was chosen based on available technical material and project guides.
The four main gensets are designed to be in pairs of two:

- Twin Wartsila 8L50DF, with an output of 7330 kWe (7600 engine kW)
- Twin Wartsila 6L34DF, with an output of 2510 kWe (2610 engine kW)

For each operational condition, including the case of slow-steaming, different combinations are used in order to supply the necessary power, having the loading of the generators as the criterion for the choice. The reason for this careful selection is that the performance of generators in low loads is very inefficient in terms of Specific Fuel Oil Consumption (SFOC), and thus a part to high load is always required (above 75%).
The generators used for electrical power generation are of medium voltage technology (6600 V, 60Hz) as usually applied in these installations, and are connected to the main bush which is taken symmetrically in order to ensure power redundancy.
Complementing the generators are the other elements of the Gas Hybrid Propulsion plant under consideration, such as Fuel Cells and solar panels. The specific information can be seen at the respective chapters. The overall installation can be seen at the simple wiring diagram that follows. The two groups of load producers and consumers can be seen segregated.

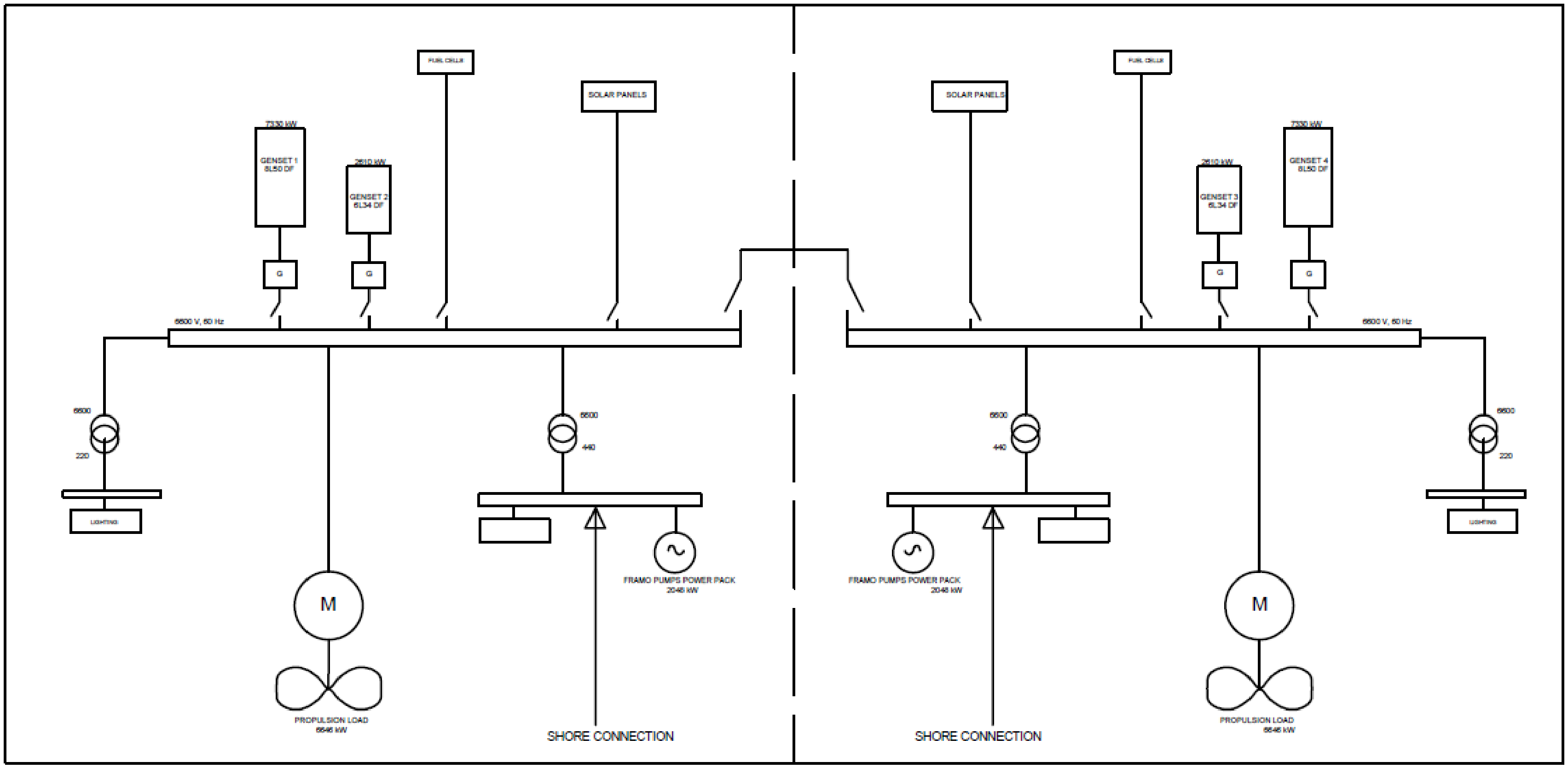


Figure [67]: Schematic of the Electrical Installation of the Hybrid Propulsion Plant

5. DUAL FUEL DIESEL ELECTRIC GENERATORS

The core of the All Electric Ship concept developed is the generator plant. Following the competition's theme for energy efficiency and alternative fuels, a dual fuel system using HFO and LNG. The primary reason for having this and not using LNG entirely as a fuel is that the required space for the bunkering onboard for LNG is too high and the required range for a ship of this size (15.000 nautical miles) is very difficult to be achieved. Furthermore, excessive spaces for LNG tanks will affect both the payload and the cargo carrying volumetric capacity decreasing the profitability and competitiveness of the ship.
Another advantage of the Dual Fuel concept is that a bigger flexibility is achieved, both in terms of bunker purchasing strategies (mostly timing) and in terms of operating in areas where LNG bunkering is not available.
The gensets are taken from the Wartsila marine program and meet the IMO Tier II requirements for emission standards.

Engine I.D	**Power (kW)**
50 DF	7330
50 DF	7330
34 DF	2610
34DF	2610
20DF	1056
Total Available	20936

Condition	**Aux**	**Total Power**	**Engines Operating**	**Power**	**Load**
Normal Sea Going	522.523	13814.523	2 X 50,1 X34	17270	0.799
Maneovring	991.294	4314.294	2X34	7330	0.826
Maneovring II	765.494	4088.494	2X34	7330	0.783
Cargo Unloading	2526.212	2526.212	1 X 34, 1 X 20	3666	0.689092199
Port	478.212	478.212	1X20	1056	0.452852273

Table [29]: Installed Generators and Usage depending on condition

e. *8L50 DF Gensets*

These are the primary gensets and are used for covering the propulsion load of the system. Their load is assured to be at about 75% by using a third generator of the smaller output (34DF). The Wärtsilä 50DF is a 4-stroke, non-reversible, turbocharged and inter-cooled dual fuel engine with direct injection of liquid fuel and indirect injection of gas fuel. The engine can be operated in gas mode or in diesel mode. The Wärtsilä 50DF engine operates on the lean-burn principle. Lean combustion enables a high compression ratio, which in turn increases engine efficiency, reduces peak temperatures, and therefore also reduces NOx emissions. Both the gas admission and pilot fuel injection are electronically controlled. The engine functions are controlled by an advanced automation system that allows optimal running conditions to be set, independent of the ambient conditions or fuel type. The engine is

fully compliant with the IMO Tier II exhaust emissions regulations set out in Annex VI of the MARPOL 73/78 convention. The main characteristics of the engine are the following:
Cylinder bore .... 500 mm
Stroke .... 580 mm
Piston displacement .... 113.9 l/cyl
Number of valves .... 2 inlet valves and 2 exhaust valves
Cylinder configuration .... 6, 8 and 9 in-line; 12, 16 and 18 in V-form
V-angle .... 45°
Direction of rotation .... clockwise
Speed .... 500, 514 rpm
Mean piston speed .... 9.7, 9.9 m/s

The 8L50 engine has 8 cylinders arranged in an inline (L) configuration. A cross section of the inline cylinder configuration can be seen below:

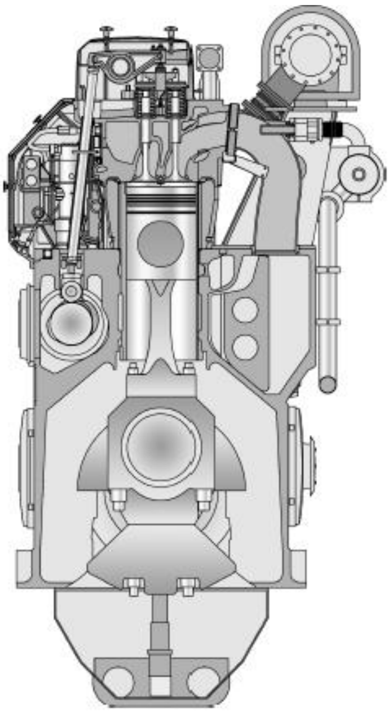


Figure [68]: Cross section of L50 DF engines (Wartsila)

The engine operates on the lean-burn principle: the mixture of air and gas in the cylinder has more air than is needed for complete combustion. Lean combustion reduces peak temperatures and therefore NOX emissions. Efficiency is increased and higher output is reached while avoiding knocking. Combustion of the lean air-fuel mixture is initiated by injecting a small amount of LFO (pilot fuel) into the cylinder. The pilot fuel is ignited in a conventional diesel process, providing a high-energy ignition source for the main charge. To obtain the best efficiency and lowest emissions, every cylinder is individually controlled to ensure operation at the correct air-fuel ratio and with the correct amount and timing of pilot fuel injection. Wartsila has developed a special electronic control system to cope with the demanding task of controlling the combustion in each cylinder, and to ensure optimal performance in terms of efficiency and emissions under all conditions by keeping each cylinder within the operating window. Stable and well controlled combustion also contributes to less mechanical and thermal load on the engine components.

The fuel system of the Wartsila 50DF trifuel has been divided into three: one for gas, one for liquid fuel and a separate pilot fuel system. The Wartsila 50DF is normally started in diesel mode using both main diesel and pilot fuel. Gas admission is activated when combustion is stable in all cylinders. When running the engine in gas mode, the pilot fuel amounts to less than 1% of full-load fuel consumption. The amount of pilot fuel is controlled by the engine control system. When running the engine in liquid fuel mode the pilot is also in use to ensure nozzle cooling.

Gas Supply

The natural gas is supplied to the engine through a valve station. The gas is first filtered to ensure clean supply. The gas pressure is controlled by a valve located in the valve station. The gas pressure is dependent on engine load. At full load the pressure before the engine is 3.9 bar (g) for LHV 36 MJ/m3. For lower LHV the pressure has to be increased. The system includes the necessary shut-off and venting valves to ensure safe and trouble-free gas supply. On the engine, the gas is supplied through large common-rail pipes running along the engine. Each cylinder then has an individual feed pipe to the gas admission valve on the cylinder head. Gas piping in marine installations is of double wall design as standard.

Diesel Oil Supply

The fuel oil supply on the engine is divided into two separate systems: one for the pilot fuel and the other for liquid fuel. The pilot fuel is elevated to the required pressure by a pump unit. This includes duplex filters, pressure regulator and an engine-driven radial piston-type pump. The high-pressure pilot fuel is then distributed through a common-rail pipe to the injection valves at each cylinder. Pilot fuel is injected at approximately 900 bar pressure and the timing and duration are electronically controlled. The pilot fuel system is separated from the liquid fuel system with separate connections on the engine. The liquid fuel is separated from the pilot fuel system and is fed to a normal camshaft-driven injection pump. From the injection pump, the high-pressure fuel goes to a spring-loaded injection valve of standard design for a diesel engine.

Injection Valve

The Wδrtsilδ 50DF has a twin-needle injection valve. The larger needle is used in diesel mode for LFO or HFO operation and the smaller for pilot fuel oil when the engine is running in gas mode and also in liquid fuel operation to ensure nozzle cooling. Pilot injection is electronically controlled and the main diesel injection is hydromechanically controlled. The individually controlled solenoid valve allows optimum timing and duration of pilot fuel injection into every cylinder when the engine is running in gas mode. Since NOX formation depends greatly on the pilot fuel amount, this design ensures very low NOX formation while still employing a stable and reliable ignition source for the lean air-gas mixture in the combustion chamber.

Gas Admission Valve

Gas is admitted to the cylinders just before the air inlet valve. The gas admission valves are electronically actuated and controlled by the engine control system to give exactly the correct amount of gas to each cylinder. This way the combustion in each cylinder can be fully and individually controlled. Since the valve can be timed independently of the inlet valves, the cylinder can be scavenged without risk of gas being fed directly to the exhaust system. Independent gas admission ensures the correct air-fuel ratio and optimal operating point with respect to efficiency and emissions. It also enables reliable performance without shutdowns, knocking or misfiring. The gas admission valves have a short stroke and specially selected materials, thus providing low wear and long maintenance intervals.

Injection Pump

The Wartsila 50DF utilizes the well-proven monoblock injection pump developed by Wδrtsilδ. This pump withstands the high pressures involved in fuel injection and has a constant-pressure relief valve to avoid cavitation. The fuel pump is ready for operation at all times and will switch over from gas to fuel oil if necessary. The plunger is equipped with a wear-resistant coating.

Pilot Pump
The pilot fuel pump is engine-driven. It receives the signal for correct outgoing fuel pressure from the engine control unit and independently sets and maintains the pressure at the required level. It transmits the prevailing fuel pressure to the engine control system. High-pressure fuel is delivered to each injection valve through a common-rail pipe, which acts as a pressure accumulator and damper against pressure pulses in the system. The fuel system has a double wall design with alarm for leakage. The engine can be switched automatically from fuel oil to gas operation at loads below 80% of the full load. Transfer takes place automatically after the operator's command without load changes. During switchover, which lasts about one minute, the fuel oil is gradually substituted by gas. In the event of for instance a gas supply interruption, the engine converts from gas to fuel oil operation at any load instantaneously and automatically. Furthermore, the separate correct air-fuel ratio under any operating conditions is essential to optimum performance and emissions. For this function, Wδrtsilδ 50DF is equipped with an exhaust gas waste-gate valve.

Engine Cooling System
The 50DF engine has a flexible cooling system design optimized for different cooling applications. The cooling system has two separate circuits: high-temperature (HT) and low-temperature (LT). The HT circuit controls the cylinder liner and the cylinder head temperatures while the LT circuit serves the lubricating oil cooler. The circuits are also connected to the respective parts of the two-stage charge air cooler. The LT pump is always in serial connection with second stage of CA cooler. The HT pump is always in serial connection with the jacket cooling circuit Both HT and LT water pumps are engine-driven.

Engine Lubrication System
The Wδrtsilδ 50DF has an engine-driven oil pump and can be provided with either a wet or dry sump oil system, where the oil is mainly treated outside the engine. Marine engines have a dry sump and power plant engines a wet sump. On the way to the engine, the oil passes through a full-flow automatic filter unit and a safety filter for final protection. Lubricating oil is filtered through a full flow paper cartridge filter. A separate centrifugal filter acts as an indicator of excessive dirt in the lubricating oil. A separate prelubricating system is used before the engine is started to avoid engine part wear. For running in, provision has been made for mounting special running-in filters in front of each main bearing.

Operation Mode Transfer Air-Fuel Ratio Control
Part of the exhaust gases bypasses the turbocharger through the waste-gate valve. The valve adjusts the air-fuel ratio to the correct value independent of the varying site conditions under high engine loads. The Wδrtsilδ 50DF is equipped with the modular-built Spex (single pipe exhaust) turbocharging system, which combines the advantages of both pulse and constant pressure charging. The interface between engine and turbocharger is streamlined with a minimum of flow resistance on both exhaust and air sides. High-efficiency turbochargers with inboard plain bearings are used, and the engine lubricating oil system is used for the turbocharger. The waste-gate is actuated electro-pneumatically.

Operation
The propulsion control and the power management system must not permit faster load reduction than 20s from 100% to 0% without automatic transfer to diesel first. In electric propulsion applications loading ramps are implemented both in the propulsion control and in the power management system, or in the engine speed control in case isochronous load sharing is applied. When the load sharing is based on speed droop, it must be taken into account that the load increase rate of a recently connected generator is the sum of the load transfer performed by the power management system and the load increase performed by the propulsion control. The electrical system must be designed so that tripping of breakers can be safely handled. This requires that the engines are protected from load steps exceeding their

maximum load acceptance capability. If fast load shedding is complicated to implement or undesired, the instant load step capacity can be increased with a fast acting signal that requests transfer to diesel mode. The engine can be started, stopped and operated on gas, heavy and light fuel oil under all operating conditions. Operation in gas mode below 10% load is restricted to 5 minutes. The engine automatically transfers into diesel mode if the load remains below 10% of the rated output for more than 5 minutes. This function will most likely be removed in the near future. Absolute idling (declutched main engine, disconnected generator):

- Maximum 10 minutes if the engine is to be stopped after the idling. 3-5 minutes idling before stop is recommended.
- Maximum 8 hours if the engine is to be loaded after the idling.

Operation below 20 % load on HFO or below 10 % load on MDF

- Maximum 100 hours continuous operation. At intervals of 100 operating hours the engine must be loaded to minimum 70 % of the rated output.

Operation above 20 % load on HFO or above 10 % load on MDF or gas:

- No restrictions.

f. *6L34 DF Gensets*

These gensets are complementing the twin 8L50 DF in the power generation especially in the most demanding conditions, like the full load normal sea going condition. The scope of using these engines is to optimize the load of each generator and furthermore have an active support and redundancy for the main generators in case of power loss or maintenance.
The Wärtsilä 34DF is a 4-stroke, non-reversible, turbocharged and inter-cooled dual fuel engine with direct injection of liquid fuel and indirect injection of gas fuel. The engine can be operated in gas mode or in diesel mode.

Cylinder bore .... 340 mm
Stroke .... 400 mm
Piston displacement .... 36.3 l/cyl
Number of valves .... 2 inlet valves and 2 exhaust valves
Cylinder configuration .... 6 and 9 in-line; 12 and 16 in V-form
Direction of rotation .... clockwise, counter clockwise on request
Speed .... 720, 750 rpm
Mean piston speed .... 9.6, 10.0 m/s

Furthermore, during low load operations (e.g slow steaming) or in the manoeuvring condition the twin 6L34 DF are used in lieu of the bigger gensets as they are operated in their optimum load point in terms of Specific Fuel Consumption. This flexibility after all is the main merit of the All Electric Ship principle we adopted for Multi Venture.
The lean burn technology is also used in this engine, while the different engine components are of the same technology of the L50 engines. A cross section of the inline cylinder configuration can be seen below:

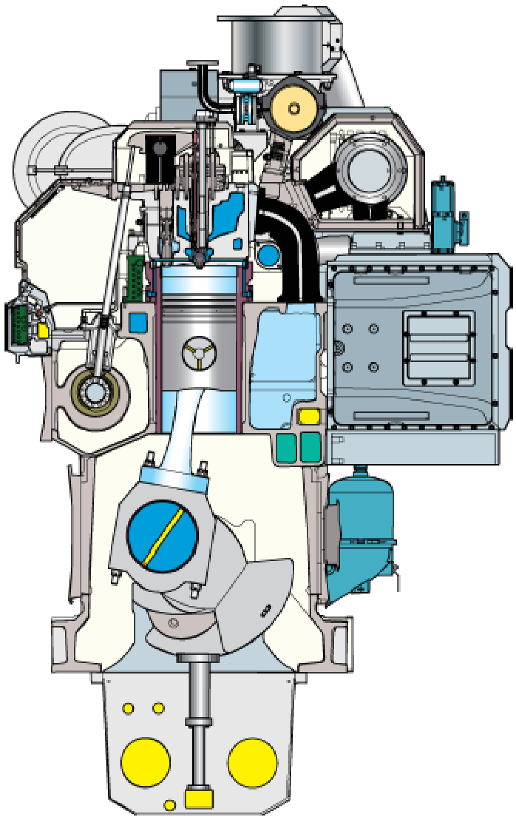


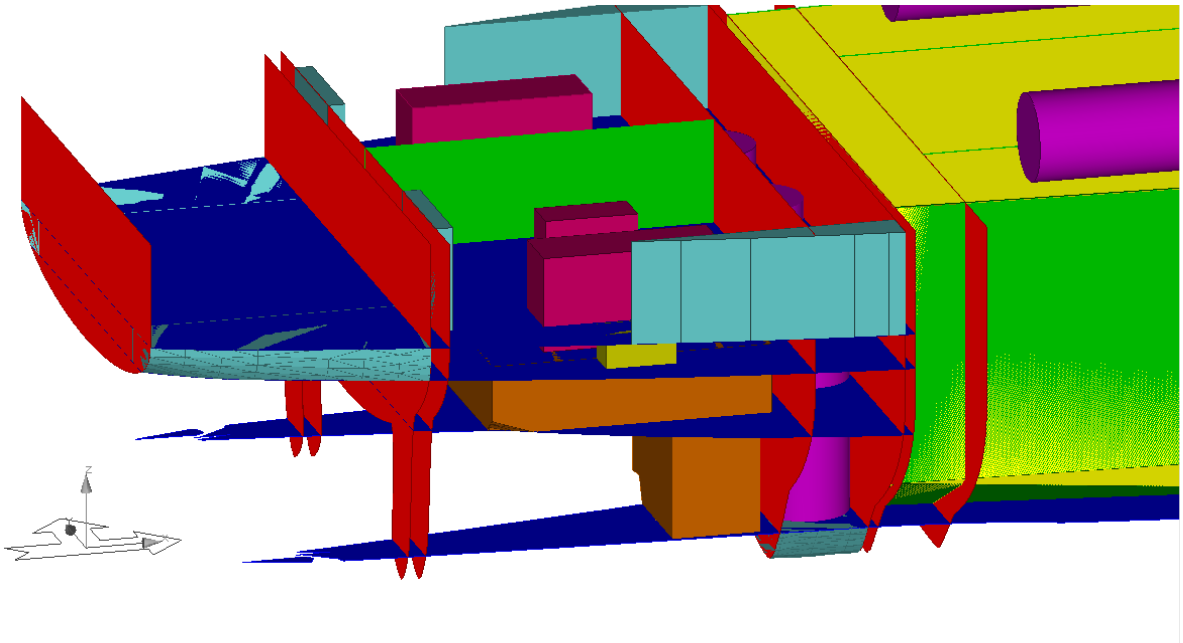
Figure [69]: Cross Section of 6L34 DF engine

g. *6L20DF Generator*

This smaller generator is used for the port loads in order to avoid having very small loads in the other components. In the harbour condition its use can be assisted also by the fuel cell system and the shore supply (cold ironing mode). The latter is subject to port infrastructure and the overall management can be optimized by the establishment of a proper Energy Management Plant.

6. ENGINE ROOM ARRANGEMENT

The arrangement of the engine room was modelled in AVEVA in order to be able to access in the meantime the loading, trim and stability of the vessel. The LNG tanks were also taken into consideration.
The location of the engine room was shifted to the upper parts, one level below the main deck. This feature (also found in Arctic Shuttle Tankers) can enable the easier maintenance of the engines along with quicker parts removal and dismantling. The engine platform deck is subdivided in the transverse direction by a fireproof longitudinal bulkhead in order to provide safety in case of explosion (e.g. crankshaft explosion) of one engines and not mitigate the safety of the other generators. Each subdivided engine room has a pair of engines arranged symmetrically (for heeling purposes) by having a large and medium genset together. The engine room is constrained within the platform deck by two bulkheads. Aft of the engine room and on the same deck, the control rooms and main switchboards are located and aft of that the steering gear room. A control unit that collectively is responsible for the generator operation (with an additional class notation an unmanned engine room can be operated), steering and electronic control is such arranged. This can be regarded as a security measure, since this area is sealed by a transverse bulkhead at the fore end and the transom stern at the aft, creating in this way a "citadel" which is isolated and can have full control of the ship even when under attacked by pirates, without mitigating the safety of the crew and the ship.
Below the engine platform there is a small deck (2m high) that accodomodates the lube storage and sumpt tanks for the main engines and is easily accessible from the main platform. Furthermore, the settling and daily tanks were properly arranged. Below that a third deck accomodates the main HFO storage tanks that are in compliance with the SOLAS regulations for the void space between the side shell and the tank boundaries.



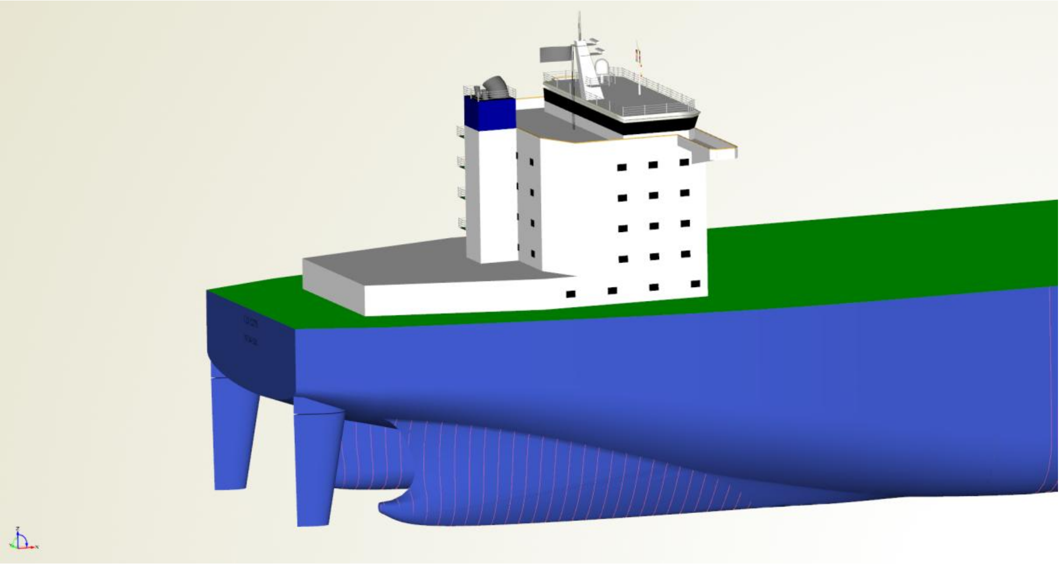
Picture [23]: Snapshot of the compartmentation mode of AVEVA, where the engine platform deck can be seen along with the control room and fuel tank decks.

<u>Modularized Engine Room</u>

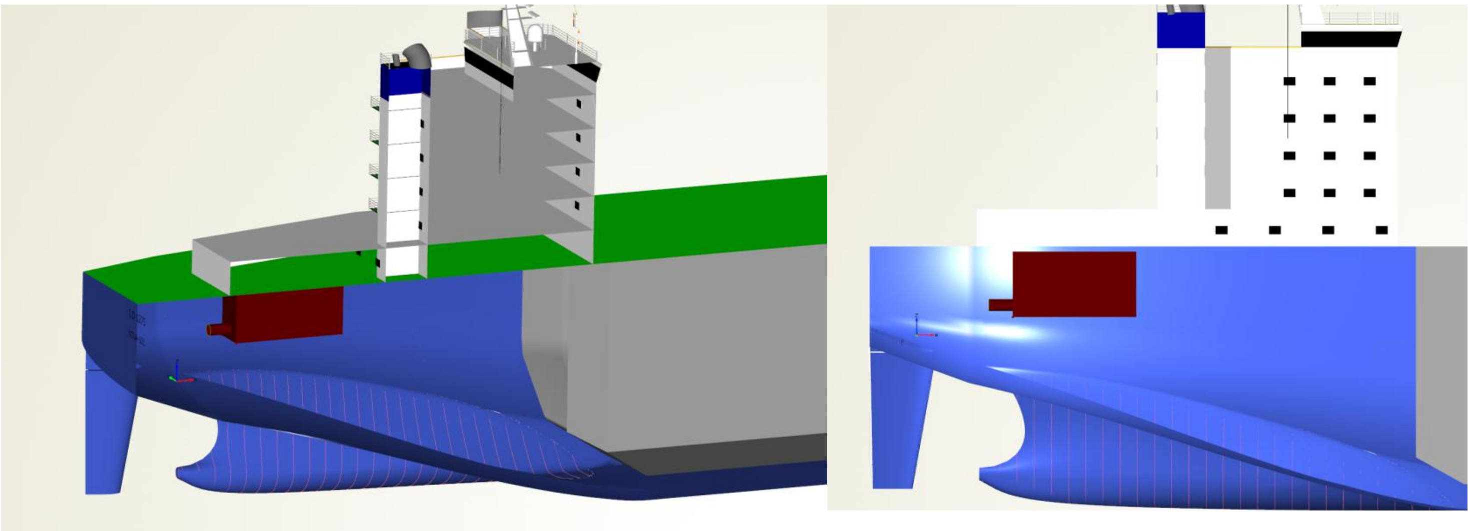
The shift of the engine room from the lower position to the new engine platform deck makes the modularized engine room a favourable option, mainly due to the capability of the engines to be removed and easily replaced and the small weight of them.

In such a case the ship is equipped with engines that are not owned by the ship owner or the manager but by the engine manufacturer. Instead of buying a new built engine the ship owner/manager has a leasing contract with the engine manufacturer for electrical power supply. This has already been successfully applied in the aviation industry where there are leasing programs that have a duration from 1 trip to 10 years. In such a system, that has as a prerequisite the existence of a highly developed supply and logistics chain for spares and engines, the manager has access to a database to available engines in several locations (ports) around the globe depending on the supply network of the engine manufacturer. Based on the availability and trade route the customer can plan the special survey of the vessel to be combined with an engine overhaul that changes completely the engines. That means that for the period until the next survey (usually 5 years) the machinery can be regarded as new and receive the fewer maintenance that does during the initial period. Another aspect of this new contract type is that during lay-up periods (that can last from a few days up to a couple of years) the ship owner can uninstall the generators and avoid the necessary maintenance and watch keeping, while still having electricity onboard from the fuel cell system and the emergency generator.

The design implications of this idea mainly have to do with the arrangement of the accommodation area and the main deck as well at the longitudinal location of the engine room. The main deck should have openings in the form of hatches in order to allow the engines to be removed. These hatches however, have to be both weather- and water-tight in order to be in compliance with the IMO Damage Stability criteria (as specified in MARPOL 73/78). Their strength must also be examined in terms of bending moments and shear stresses. In addition to that the coupling of the engine has to be re-examined and be able to use a universal dock in order to be able to accommodate new and/or larger engines. Last, the enitre superstructure of the accommodation spaces has to be shifted forwards while the aft part of it must have only one cover for the main deck hatches. The visualization of this can be seen at the following picture taken from the Friendship Framework:



Picture [24]: The proposed arrangement of accommodation superstructures



Picture [25]: Centerline cut outs that demonstrate the modularized engine room concept.

7. WASTE HEAT RECOVERY AND THERMAL ANALYSIS

Due to the bigger number of engines and the hybridization of the propulsion is critical in order to increase the overall efficiency of the propulsion plant. The use of LNG allows the Waste Heat Recovery achieve a higher output since the temperature of the outlet exhaust gas can be decreased down to 100 ^{0}C due to the absence of sulphur and sulphur oxides in this fuel. However, during Diesel Operation the temperature has to be above 160 ^{0}C in order to avoid the deterioration and the corrosion of the exhaust outlet. This is an issue of careful dimensioning and provisions for bypass valves in the design stage for the exhaust and funnel systems.

For the scope of work in this context, of the preliminary design description, it is imperative to calculate the amount of energy that can be retrieved and used from such a system. This is possible thanks to the exhaust gas amount and temperature data provided by the engine manufacturer's product guide.

The system of Waste Heat Recovery onboard is segregated in two different subsystems, one for each type of engine. The engines are assumed to work in 75% load, for the normal sea going condition which is the most energy intense.

NORMAL SEA GOING CONDITION					
		LNG		DIESEL	
EGB 1		amount	T exhaust	amount	T exhaust
Input	50DF1	9.5	424	11.9	351
	50DF2	9.5	424	11.9	351
Boiler Heat	m corr	19		23.8	
	Tout	100		170	
	ΔT	324		181	
	t air	45		50	
	Cp o	1.015		1.015	
	Cp exhaust	1.12		1.095	
	Cp mean	1.0675		1.055	
	Q	6571.53	kW	4544.729	kJ/s

Table [30]: Heat Recovery of EGB1

The thermal output from the waste heat recovery operation can be regarded as high, primarily thanks to the big difference of the inlet and outlet temperature and the increased gas amount. This thermal capacity of the exhaust gas is directed to an exhaust gas boiler which produced steam. The steam produced, depending on the boiler load can be either directed to a steam turbine connected with a generator or to use this steam for the cargo heating and general purposes. As this vessel uses the FRAMO integrated cargo heating module, which is based on recirculation of the cargo, the steam is no longer necessary (and thus the auxiliary boilers are reduced to one instead of two). For this particular reason, the steam produced from this boiler can be used for electricity production with a steam turbine.

NORMAL SEA GOING CONDITION					
		LNG		DIESEL	
EGB 2		**amount**	**T exhaust**	**amount**	**T exhaust**
Input	**34DF**	3.4	425	4	375
Boiler Heat	**m corr**	3.4		4	
	Tout	100		160	
	ΔT	325		215	
	t air	45		50	
	Cp o	1.015		1.015	
	Cp exhaust	1.122		1.105	
	Cp mean	1.0685		1.06	
	Q	1180.6925	kW	911.6	kJ/s

Table [31]: Heat Recovery of EGB2

For the smaller engines, in the sea going condition only one is used, as in the manoeuvring two are used. For this kind of operations it is obvious that the amount of heat recovered is much smaller compared to the bigger engines connected to EGB1. For this particular reason the steam produced here can be used for general purposes onboard.
In the next chapter about the propulsion system hybridization, one can find more information about the chosen steam system and the energy that can be generated from it.

8. HYBRIDIZATION OF PROPULSION PLANT

In this chapter the hybrid components of the propulsion plants are dimensioned and described. Usually when one is referring to hybrid propulsion it is suggested that the power generating unit is consisted by different generating sources that can use different kinds of operating principles or energy. In a marine power plant, the hybridization as called can be interpreted as the use of additional means of energy generating units such as fuel cells, waste heat recovery options, micro gas turbines, lithium batteries, solar panels etc.

For the case of the Multi Venture tanker, several options were taken into consideration before the arrangement was finalized. The final hybrid model for this vessel includes a steam turbine that generates electricity from the waste heat of the generators and fuel cells in containers on the aft part of the deck. Lithium batteries were also considered as potential energy source but they cannot provide a steady production of A.C current like in the other options rather than peaks of production of D.C current that needs transformers in order to be used in the plant. This additional conversion causes a further reduction of the overall efficiency. Other novelties were not taken into account as the degree of innovation is high resulting in an overall higher capital cost.

Summing up, the components of the hybrid system that aim in assisting the main electric generation units were chosen to be a Modularized Fuel Cell System (with Natural Gas as a fuel) and a Steam Turbine Generator.

8.1.Fuel Cell Technology In A Hybrid Propulsion Plant

8.1.1. General

A fuel cell is a device for directly converting the chemical energy of a fuel, such a hydrogen or a hydrogen-rich gas, and an oxidant into electrical energy. It also produces heat, which in some applications may be a useful by-product. Invented an demonstrated by Sir William Grove, the principles governing fuel cell operation have been known for about 150 years. The systems are composed of three basic elements, the heart of which is the fuel cell itself. The fuel supply subsystem, usually a processor for producing hydrogen gas and an electrical converter, for providing electrical power in a form applicable to the user, make up the other two elements. Fuel cell characteristics and performance may vary depending on the materials used for electrodes, electrolytes, and catalysts.

8.1.2. The Fuel Cell Stack

Fuel cells are composed of two electrodes, a cathode and an anode, separated by an electrolyte. In the typical PAFC fuel (a hydrogen-rich gas reformed from natural gas or another fossil fuel) is delivered to the porous anode element. The anode is coated with a catalyst such a platinum, which causes the hydrogen molecules to dissociate into hydrogen ions and electrons. The hydrogen ions pass through the phosphoric acid electrolyte to the cathode. A current is created as the electrons, unable to move through the electrolyte, pass instead through a conductor attached to both electrodes. When a load is attached to the circuit, electrical work is accomplished. At the cathode, oxygen (generally in the form of air) is introduced.

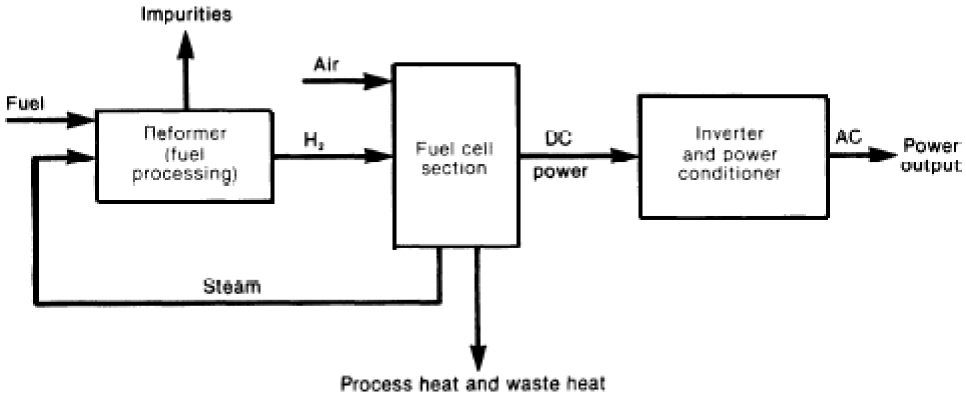


Figure [70]: Typical Fuel Cell Workflow

The oxygen combines with the hydrogen ions, which have migrated from the anode, and with the electrons arriving via the external circuit to produce water. The nitrogen and carbon dioxide components of the air are discharged. Unlike a battery, a fuel cell does not have a fixed amount of chemical supply, and thus does not run down. It continues to operate as long as fuel and oxidant are supplied to it and an adequate level of electrolyte is maintained.
The temperatures at which these reactions occur vary with the type of fuel cell. The choice of phosphoric acid as the electrolyte in PAFCs determines an operating temperature of between 1500 and 2000 Celsius. other types of fuel cells operate at much higher temperatures. Below 1500 C the phosphoric acid is not a good hydrogen ion conductor. Above 2500 C, the electrode materials become unstable. Heat is given off in this electrochemical reaction, some of which is used to maintain the temperature of the electrolyte. However, most of the heat is transported away by air or liquid coolants and, if it can be used in the fuel processor and/or for other heating needs, it improves the overall conversion efficiency of the fuel cell. An important characteristic by which fuel cells are compared with other power plants is the heat rate. PAFC systems providing alternating current have heat rates of about 8500 BTU/kWh. The equivalent for a power generator is also at about 8500 BTU/kWh.

8.1.3. The Fuel Processor

The fuel processor or reformer performs two important functions. One is to convert the stock fuel to a hydrogen-rich gas for use in the fuel cell stacks. The second is to remove impurities. To minimize contamination of the fuel cell electrodes sulphur and carbon monoxide are removed by the fuel processor through the use of special scrubbers and carbon monoxide shifters. Water vapour is produced by the reforming process is also removed from the hydrogen-rich gas prior to its delivery to the fuel cell stack. Fuel processing requires different technology for each stock fuel. Since no power or heat is available from the fuel cell stack when the system is initially, a separate source of power is required to start both the reformer and the stack. This power source must be able to generate steam for the reformer and to preheat the stock fuel. Startup times of several hours or more are required for 40 kW and larger systems, a factor that could affect the use of fuel cells for some forms of marine transportation.

8.1.4. The Power Conditioner

The power conditioner receives electrical power from the fuel cell stack and converts it to match the required output. Fuel cells produce direct current (DC), and if the application uses DC current, as it may be the case for some marine applications, the current may be used as it comes from the fuel cell stack after providing for voltage and power monitors and controls and power cut-off devices. If alternating current is required, an inverter is incorporated into the power conditioner. This conversion device is about 90% efficient with present designs. In many cases the cost of AC motors and the inverter is less expensive than the equivalent DC system, and is therefore likely that the AC converter would be incorporated.

8.1.5. *The Controller*

The fuel cell has a number o functions. It must control supplemental power during start-up operations, stack cooling and gas flow during power and hold operation and finally control the close-down operations. In order to be able to operate numerous temperature, gas flow, and other sensors and microprocessors are used by the controller.

8.1.6. Merits and Drawbacks of Fuel Cells

Advantages of the fuel cell technology and its implementation for marine power generations are:

- ***High Efficiency***, as the combustion phase is avoided (chemical energy is directly converted in electricity). Furthermore, the efficiency of the fuel cell system is independent from the plant size as it is determined by the characteristics of each individual cell.
- ***Low emissions***, thanks to the use of scrubbing technology and the fuel reformer before entering the cell stack.
- ***Quiet operation and major reduction of vibrations***, as the fuel cell does not have any moving parts
- ***Opportunities for cogeneration***, as the waste heat of the fuel cell can be utilized within the plant.
- ***Modularity***.
- ***Short construction lead time*** thanks to mass production.
- ***Flexible fuel usage***
- ***Efficient part load operations***
- ***Easy to operate and maintain***

Disadvantages on the other hand are:

- ***Increased Capital Cost***, due to the "young" technology
- ***Small reduction of Carbon Dioxide*** in comparison with internal combustion plants
- ***Possible material vulnerability***
- ***Fuel Cell life***, as periodic replacement for fuel cell stacks is required for some systems after as little as 5 years.

8.1.7. Wartsila Fuel Cell System

One of the current available market solutions for fuel cells are made by Wartsila. The fuel cell packs offered range from 20 to 50 kW and there are thoughts for expand to 3 digit power outputs. This market option is very suitable for Multi Venture as it uses Natural Gas for the fuel of the fuel cell, which is available onboard due to the dual fuel engines. This means that no additional tanks, systems and pipings are necessary for the fuel cells. The operating principles are the same as in the conventional fuel system described above as shown in the following schematic:

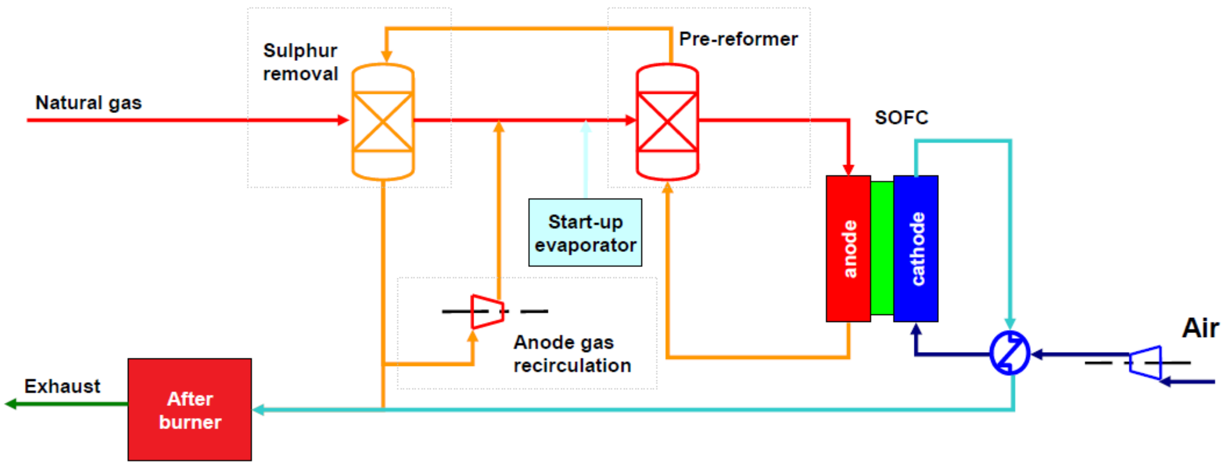
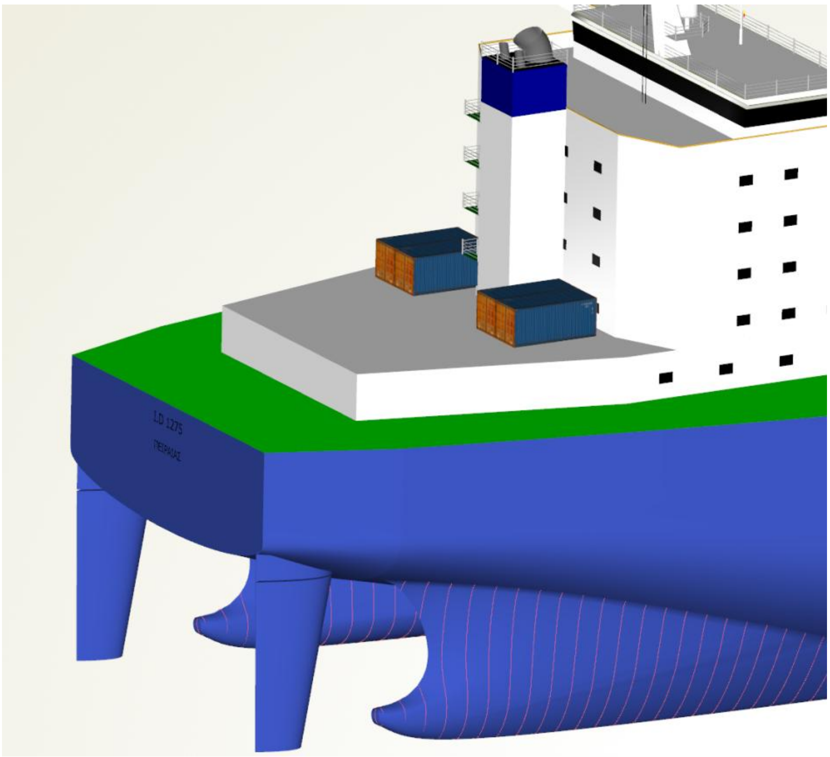


Figure [71]: The Wartsila Fuel Cell Operating Principle and Workflow (Wartsila presentation, [3])

Another benefit of using this market offer is that it is available as a module, which means that it can be more easily installed onboard and it position can predefined in the preliminary study, although it is equally easy to install it as a retrofit. Furthermore, in experimental installations (onboard car ferries) Twenty Feet Equivalent (TEU) container units with a fuel cell installation inside were installed. This can be realized in Multi Venture at the Stern area and next to the funnel. This position is selected in order to be next to the Exhaust Gas boilers, as the exhaust gas can be redirected there together with the generated steam. The containers can be installed on the housing of the engine platform deck described earlier. At the fore part of this housing (close to the funnel) the superstructure is strong enough to support such a system, although at the detailed structural analysis additional brackets must be added. The container concept also means that for such a system no maintenance by the crew is needed as it can be retractable and offered at a leasing basis in conjunction with the modularized engine room described earlier. At the pictures that follow the fuel cell can be seen as well as a rendering of the proposed solution as created in the Friendship Framework:



Picture [26]: Proposed Arrangement for Containerized Fuel Cells

Picture [27]: The Wartsila 50 kW fuel cell unit

Based on the space available for the container systems 4 modules were chosen with a total output of 200 kW. The overall efficiency according to the manufacturer of the system can be up to 69% which is higher than any internal combustion engine available (Figure [72]).

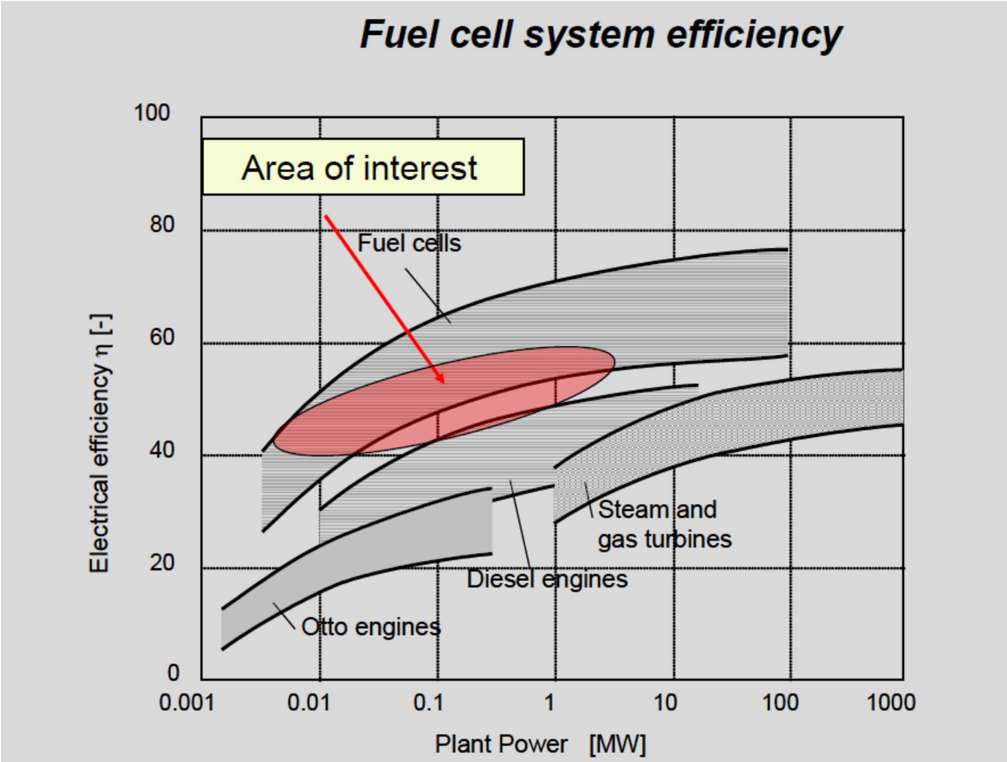


Figure [72]: Efficiency of Fuel Cells in comparison to internal combustion engines (Wartsila [3])

WFC50 mkII	**Targeted value (BoL)**
Fuel	NG /BG
Fuel in LHV (kW)	103
Net power output (kW_{AC})	54
Gross stack output (kW,DC)	67
Electrical eff. (LHV)	53%
Overall eff. (LHV)	69%
Thermal output (kW)	17
Size (WxLxH) (mm)	1600 x 3500 x 2050

Table [32]: Principal Characteristics of chosen Fuel Cells

Last, from the emissions standpoint, it is evident that the harmful emissions are greatly reduced and compared to an internal combustion engine it can be considered much better.

Emissions	
NOx	< 2 ppm
CO2	< 0.36 g/kWh
THC	< 3 ppm
Noise	< 65 db

Table [33]: Fuel Cells Emissions

8.2. Steam Turbine Generator

The waste heat calculated is exploited in an Exhaust Gas Boiler which was dimensioned in an earlier step. The Exhaust Gas Boiler is consisted by three parts, a pre-heater, an evaporators and a super-heater with one working pressure, of high value (approx. 10-30 bar). The overheated steam is afterwards used in a steam turbine directly coupled to a medium voltage generator. The dimensioning of the turbine is done being based on the exhaust gas data for the normal sea going condition where three engines are used, and for LNG as a fuel as the thermal output is the biggest. In the case of the diesel engine the results are expected to be lower in terms of the generated power. At figure [73], one can see the steam system its individual components.

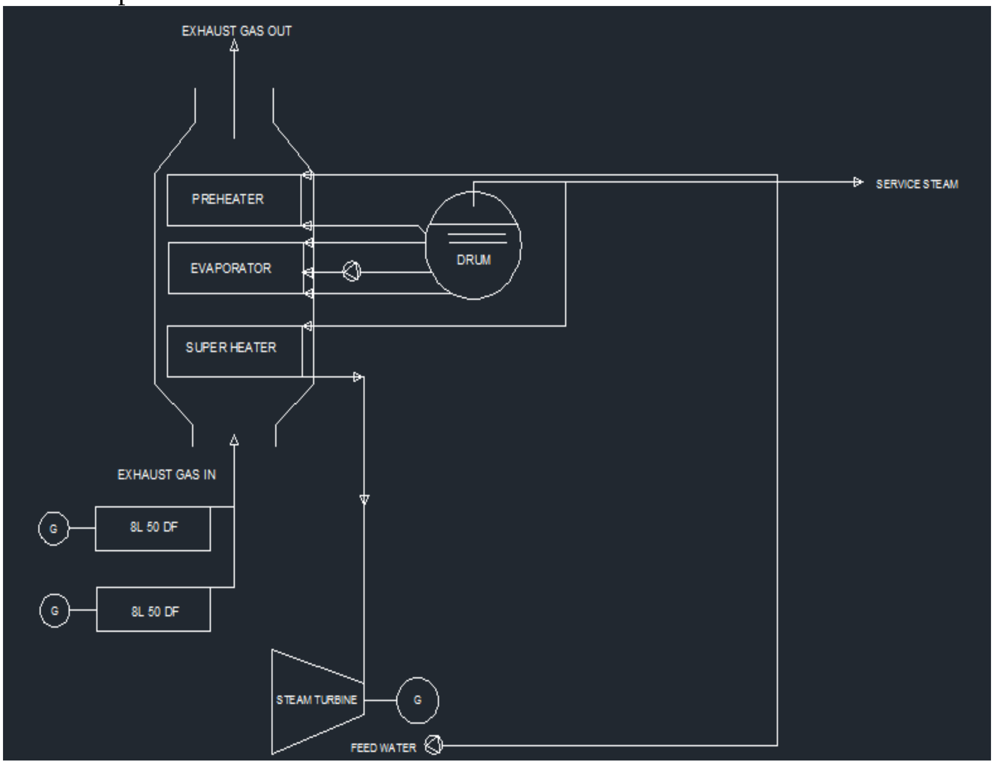


Figure [73]: The steam generation system based on exhaust heat recovery

The entire steam system was dimensioned and fine tuned being based on a parametric model having as variable the operating pressure. The equations and specific data were used. The objective functions for the assessment of the chosen operating pressure, were the outlet exhaust gas temperature and the power of the electric generator. The initial value was set at 10 bar, and was increased with an increment of 5 bar. For the generator an efficiency of 95% was assumed. The outlet pressure of the turbine was also assumed to be 0.05 bar based on previous experience of Prof. Frangopoulos at NTUA, who also suggested the principles for the steam system. The final choice, after evaluating the pressures up to 30 bar was to use a 15 bar system. The particulars of the calculation and the system can be seen at Table [30]. The output of the generator for these calculations was at approximately 1625 kW which together with the 200 kW of the fuel cell system correspond to 10% of the total installed and available power onboard. What is more important is that with the use of such a system in the normal sea going as well as ballast condition one of the engines can be switched off. This is a major contribution to the shipboard energy management plan. However it is utilized only when the two 8L50 DF engines are used for the propulsion. Else, the waste heat is not adequate to produce steam that can run a steam turbine.

9. HYBRID SYSTEM CONTROL AND POWER MANAGEMENT

Due to the big number of system components, as well as the inherent complexity of the all electric propulsion system the use of an advanced controller is necessary. This controller will be responsible for the power management onboard, and as an automation has the electrical loads and the available power as input. The aim is to generate electrical power for the necessary loads without excessive surplus. This can be achieved by a robust state-of-the art controller with real time capabilities that will manage the power generating components according to the needs of the entire system (propulsion, auxiliary and cargo handling) and will be able to cut-off or activate individual components such as the gensets, fuel cells or the steam turbine. The design and specification of such a unit is not however a topic for a study at this stage.
The advantage of the using such a technology is obvious. The surplus of power can be avoided and thus significant fuel savings and subsequent emissions reductions are effective. In addition to that the controller can be a part of a state of the art ship operational management system, where it responds according to the operator's needs, going faster in order to catch up port slots or new cargo packages, or slow steaming and routing based on the weather conditions and the virtual arrival of the vessel in port. Thus it is evident that this component can provide the flexibility the ship operator requires in a very robust and very agile manner adapting constantly to new weather conditions as well as commercial and operational requirements.
The general outline of the new constantly adapting operating profile would be different in the normal sea going, manovreuing, ballast, unloading and port. Based on a simplified operational use an profile the economic as well as environmental assessment took place.

Normal Sea Going Condition

During this condition which corresponds to the laden voyage leg and not the ballast, the biggest energy output is required as the ship's displacement is big and the ship is the maximum design speed. the required energy can be covered by the both L50DF engines and one 34DF engine, aided by the hybrid part, both by the steam turbine (due to an adequate gas flow by the L50 engines) as well as the fuel cells.

Ballast Condition

Due to the innovative hull shape, that drastically reduces the displacement in the specified by MARPOL ballast drafts, and the smaller propeller size due to the twin screw installation, the resistance in the ballast condition is greatly reduced to approx. 65% of the original full load number. This means that one of the twin L50 engines can be cut off one of the L34 engines can be used instead. The output of the steam turbine will be greatly reduced and the fuel cells can continue operating.

Manoeuvring
In the manoeuvring condition the propulsion loads are greatly reduced, which allows the operator to use only the twin L34 engines for both propulsion and the fuel cells while the steam plant is also cut off.

Unloading and Harbour Condition
The unloading condition requires increased electricity supply to the FRAMO power packs that are responsible for the operation of the high pressure hydraulic system that is the driving medium of the emerged deep well pumps used in this application. The port condition is the least energy intensive and only the auxiliary generator aided by the fuel cell pack is used.

As one can see the number of engines is the variable of the onboard ship energy management system that is also correlated to the use of the steam turbine. The fuel cells can be constantly used as they offer a consisted power source of small output with almost zero emissions and a very small fuel consumption.

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10. ECONOMIC AND ENVIRONMENTAL ASSESSMENT

In this chapter the economic sustainability and characteristics of Multi Venture is assessed as long as its environmental footprint and performance. As Multi Venture is an All Electric Ship, EEDI is not applicable in order to assess the efficiency and CO2 performance of the design. Instead of EEDI, a Life Cycle Analysis tool (LCA) is used that calculated the harmful emissions related to the operation of the ship from the propulsion and machinery installations point of view.

a. Economic Assessment

The economic performance of the design has to be assessed since it is aimed to be a sustainable, realistic and viable solution for the tanker industry. Usually, this is a critical point in all innovations and innovative studies as the price for new and groundbreaking technology is very high. This can be explained due to the buyer's reluctance and the lack of experience in the production of such solutions, resulting into a higher capital investment. Nevertheless, it must be noted and understood that a technology that is very promising and performs well, if established as a design and subsequently massively produced (as in today's shipbuilding trends) the initial price can be reduced along with the derived extras paid for that kind of innovation.
The shipyard that stands itself apart in this process will mostly benefit from the introduction and the commercial success of the idea and create a two Tier market in shipbuilding just as the use of ultra efficient ships will create a two Tier market in shipping.

It is also very important to always have in mind the initial building cost , or more commonly Capital Expenditure (CAPEX) is not the single one parameter affecting the economic performance of the design. The cost for operation and maintenance (Operating Expenses-OPEX) and the fuel cost (Voyage Expenditure-VOYEX) are two very important cost parameter that affect the overall performance, often expressed by the Net Present Value (NPV) of the investment, quite significantly, especially in the case of ships were the investment life is long; up to 30 years. A reduction of the voyage and operating costs, is most important especially having in mind the increases of fuel costs per ton annually and the potential introduction of Market Based Measures (MBM) that will impose an additional fuel levy to operators and charterers. The economic performance is not only affected by the cost themselves but also by the profitability of the ship, that might even balance out in NPV terms an increase in all expenditure (CAPEX, OPEX, VOYEX).

As this is typical case for innovative designs, Multi Venture too has an increased capital cost, due to the twin screw arrangement, All Electric Propulsion system and LNG fuel system. However the tank capacity, a product of the Global Design Optimization, is increased by 8% dominating all existing conventional designs while the port operations are faster (thanks to the Deep Well Pumping System) and the off-hire days are fewer due to increased reliability and reduced need for maintenance. Moreover, the fuel costs are decreased, as the engines work at their optimum point in terms of SFOC (which is additionally decreased due to LNG use) and the steam turbine at the full load condition is producing 2MW. The decrease of fuel consumption due to a smaller displacement in the ballast condition is for the benefit of the shipowner as there are saving of approximately 8-9% in the fuel costs thanks to a smaller loading for the engines (and the cut-off, of one large genset in the ballast condition).

The overall assessment of the economic performance of the design is done using the Required Freight Rate (RFR) as an index, as in the optimization studies. What the RFR expresses is the minimum freight rate per ton of payload that can balance the overall expenses including capital, operating and voyage. This is done using a feature of Friendship Framework, developed for the optimization studies, that takes into account the operational profile of the vessel for the business scenario assumed in the Caribbean trade. Several input parameters have to be determined for this calculation, and the most important are going to be highlighted.

The extra cost of the LNG system had to be calculated. The indication the team found, was for the cost of the IMO C Type tanks per cubic meter, which was taken to be at 3000 $\$/m^3$. For this price the cost of each deck tank is estimated to be 1.2 mil.$ and of each vertical tank 0.6 mil.$. The total expenditure for the LNG tank is 6.6 mil.$. This extra cost was added in the capital expenditure together with the initial building cost, first increased for the twin screw arrangement with a 5% extra (due to the absence of the twin two stroke installation) and an additional 15% for the All Electric installation (although each generator unit is much cheaper than a two stroke unit). Finally, as in the optimization studies the steel weight difference from the standard design was penalized.

From the operating scenario point of view, the SFOC had to be changed as well as the engine power in the ballast condition (cut-off of one 8L50 unit). The fuel cost was taken in three scenarios, one using entirely HFO as a fuel, one using only LNG as a fuel and one using both, in a percentage that depends on the respective capacities.

The results of the calculation from the Required Freight Rate are very impressive. In the case LNG is used as a fuel the RFR is reduced by almost 12% thanks to the favorable fuel prices. This is also reflected in the 4% reduction when both fuels are used. In the case of using only HFO the RFR is increased, and the investment is not sustainable, which makes sense.

Required Freight Rate	**HFO**	**LNG**	**LNG/HFO**	**Baseline**
	6.825	6.025	6.45	6.73
	1.41159	**-11.7012**	**-4.16048**	

Table [34]: RFR calculation for different fuel use in Multi Venture

The results illustrate that the investment is performing very well and competitive, as the handicap of the increased initial price is balanced out by reduced fuel expenses while the overall outcome is positive and more beneficial for the owner.

b. ***Environmental Assessment***

A usual index for the environmental performance of a vessel is the EEDI. For this case though it is not applicable since Diesel Electric vessels are excluded from the EEDI reference lines. For this particular reason a Lifecycle Analysis tool had to be implemented in order to see the reduction in the emissions and the compliance with the MARPOL Annex VI requirements.

Input		
Distance covered (A-B)	2015	n.miles
Speed laden (A-B)	15	knots
Speed ballast (B-A)	15	knots
Days at port (loading)	0.75	days
Days at port (unloading)	0.63	days
Days off /year	30	days
Days outside port per trip	1	days
ship life cycle	25	days
% Load ME (Laden)	90	
%Load ME(Ballast)	57	
%Load AE	0.85	
SFOC ME	170	gr/kwh
SFOC AE	185	gr/kwh
Number of ME(s)	1	
Number of AE (s)	2	

Table [35]: Input used for LCA tool

The input is the same as the ones used in the economic assessment and have to do with the operational profile of the vessel, such as the off-hire days and the unavailability.,

The CO2 emissions are calculated by the emission factors non-dimensionalized by the fuel consumption in tons, while the other emissions are calculated based on emissions factors based on the installed power.

FUEL TYPE	SOX(gr/kwh)	NOX(gr/kwh)	PM(gr/kwh)	CO2(gr/kwh)
RESIDUAL OIL 3.5 % sulpfur	13	9--12	1.5	580-630
Marine diesel oil, 0.5%S	2	8--11	0.25--0.5	580-630
Gasoil, 0.1% sulpher	0.4	8--11	0.15--0.25	580-630
Liquefied natural gas(LNG)	0	2	0.075	430-480

Table [36]: Emission factors used in LCA for different fuels

At table [4] one can see the results of the fuel consumption calculation from the LCA tool, for the propulsion requirements:

Fuel Consumption	Main Engine (s)	
	All Electric Gas	
Power	14248	kw
Fuel Type	LNG	
SFOC (gr/kWh)	152.4	gr/kWh
	167.4	gr/kWh
Daily consumption A-B (gr)	46190044.80	gr LNG
Daily consumption A-B (ton)	46.19	ton LNG
Consumption in A-B (ton)	258.54	ton LNG
Daily consumption in B-A (gr)	29921348.16	gr LNG
Daily consumption B-A (ton)	29.92	ton LNG
Consumption in B-A (ton)	167.48	ton LNG
Consumption in port	8.67108564	ton LNG
Consumption in manouvering	8.90192378	ton LNG
Consumption outside port	4.2425856	ton LNG
Total fuel consumption per trip	447.83	ton LNG
Fuel consumption during repairs/year	0	ton LNG
Total fuel consumption per year (1 ship)	11055.90	ton LNG
Total fuel consumption in life cycle (1 ship)	276397.41	ton LNG
Total Fuel Consumption per ship life cycle	2.76E+05	ton LNG
	3.42E+03	ton MDO

Table [37]: Fuel consumption predicted in LCA

The energy requirements for pumps are calculated based on the FRAMO power pack components that are consisted by small diesel engines and electric motors.

Pumps		
Power	1800	kw
Emission Factor	3206000	grCO2/ton
Total Fuel Consumption	3365,34	tons
Total Life Cycle CO2 emissions	10789,26518	tons

Table [38]: Pump energy requirements

The CO2 lifecycle emissions calculated for the case of Multi Venture are summarized in table [6]:

Total Life Cycle CO2 emissions		
ME & AE CO2 emissions	1,04E+06	tons
Pumps CO2 emissions	10789,26518	tons
Total Machinery CO2 Emissions	7,950E+05	tons

Table [39] Life Cycle CO2 emissions for Multi Venture

Last the overall lifecycle emissions are calculated:

Life Cycle Emissions		
CO2	7.950E+05	tons
CH4	4,056E+02	tons
Nox	3,735E+03	tons
PM (all)	1.373E+02	tons
SO2	000E+00	tons

Table [40] Life Cycle emissions for Multi Venture

This calculation is performed for a reference single screw, conventional vessel, the twin skeg result of the optimization and Multi Venture (Table [8])

	Total Emissions Operation			
	Single Screw HFO	**Twin Screw HFO**	**Multi Venture**	
CO2	1.046E+06	9.694E+05	7.950E+05	tons
CH4	1.108E+01	1.070E+01	4.056E+02	tons
NOx	3.160E+04	3.056E+04	3.735E+03	tons
PM (all)	2.840E+03	2.745E+03	1.373E+02	tons
SO2	1.886E+04	1.824E+04	0.000E+00	tons

Table [41]: Total Emissions comparison for a conventional and twin screw designs

One can see, also from the graphs that follow that the performance is improved for the twin screw result of the optimization (I.D 2515) but the more significant reduction is for Multi Venture, thanks to the use of LNG as ship fuel, which eliminated the NOx, SOx and PM emissions. The increase of the methane slip is due to the inaccuracy of the emission factors for the new generation lean burn engines that are used. Nevertheless a smaller increase is expected. The methane emissions can be tackled by using an afterburner that can be coupled to a generator, contributing to the overall electricity plant production.

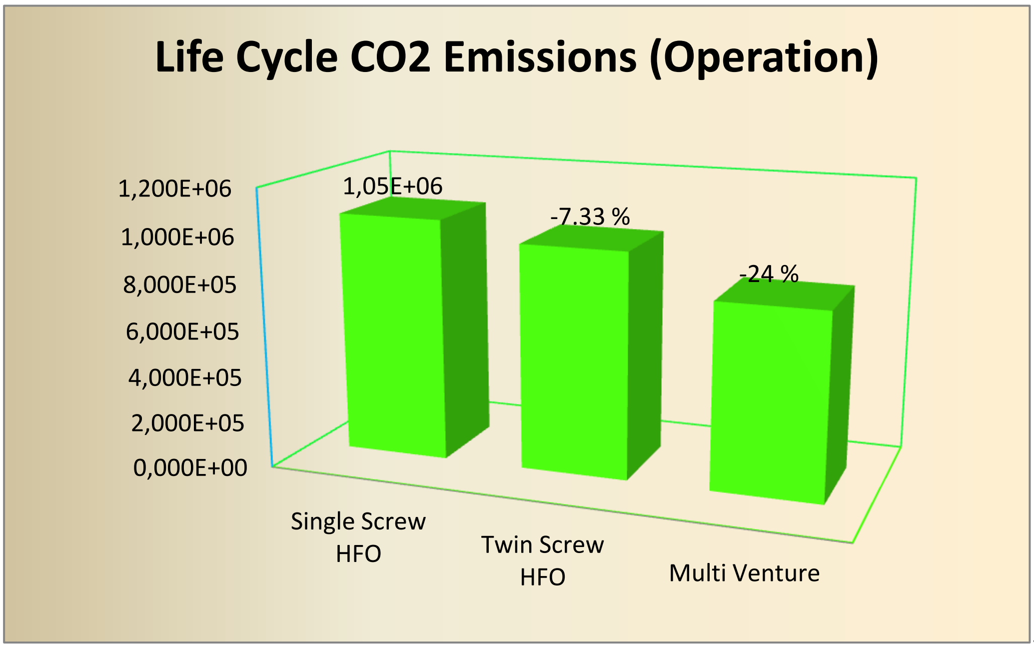

Figure [74]: Comparison of CO2 emissions

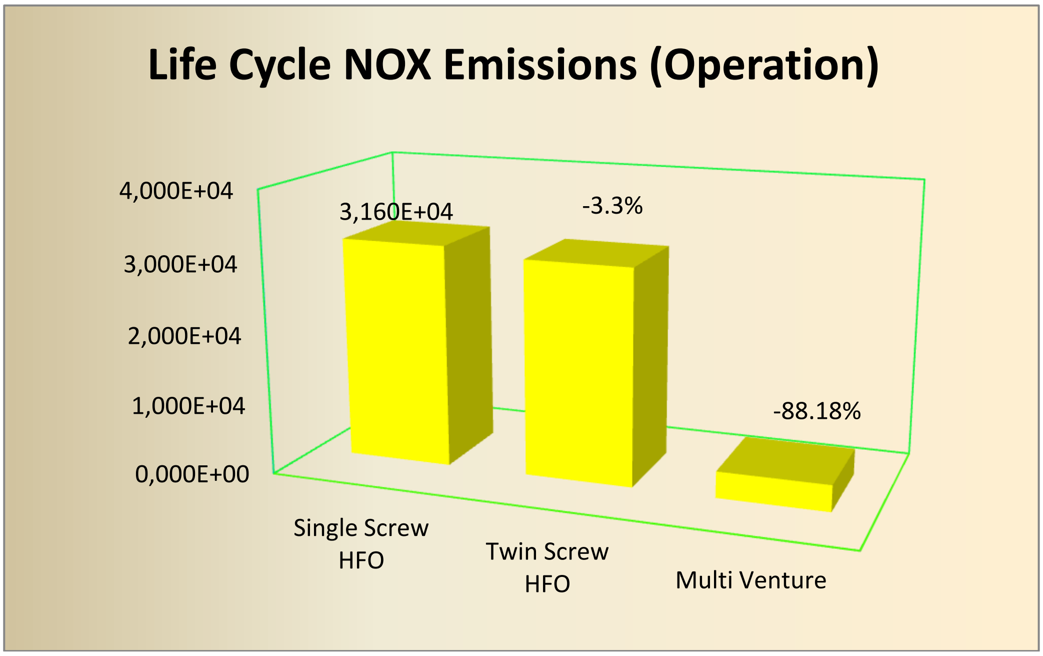

Figure [75]: Comparison of NOx emissions

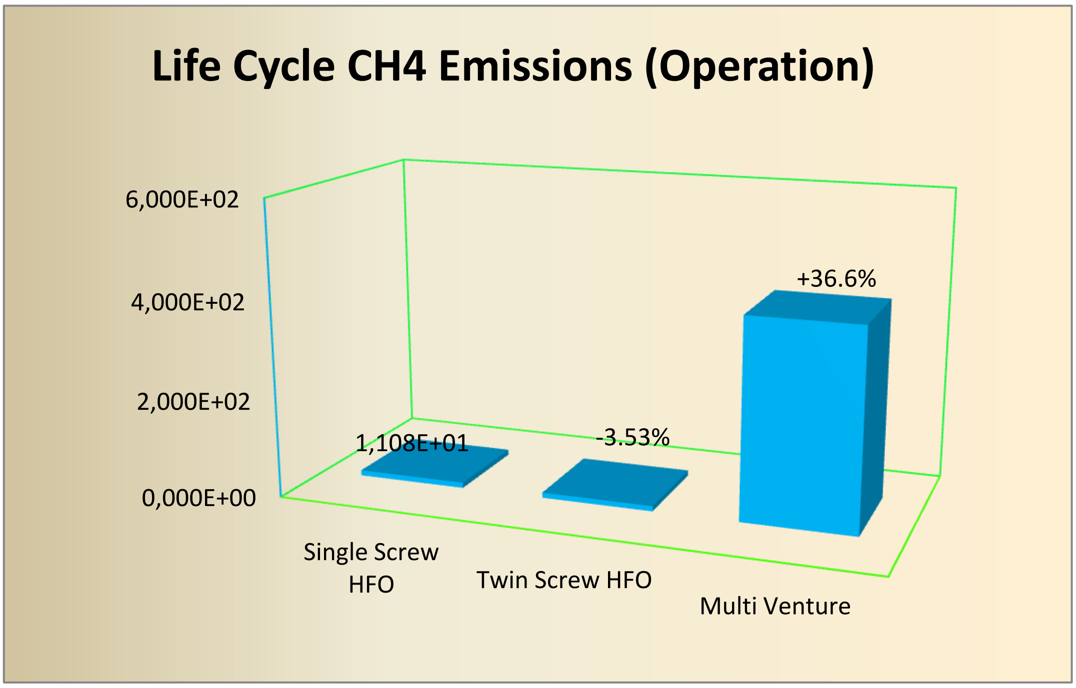

Figure [76]: Comparison of methane emissions

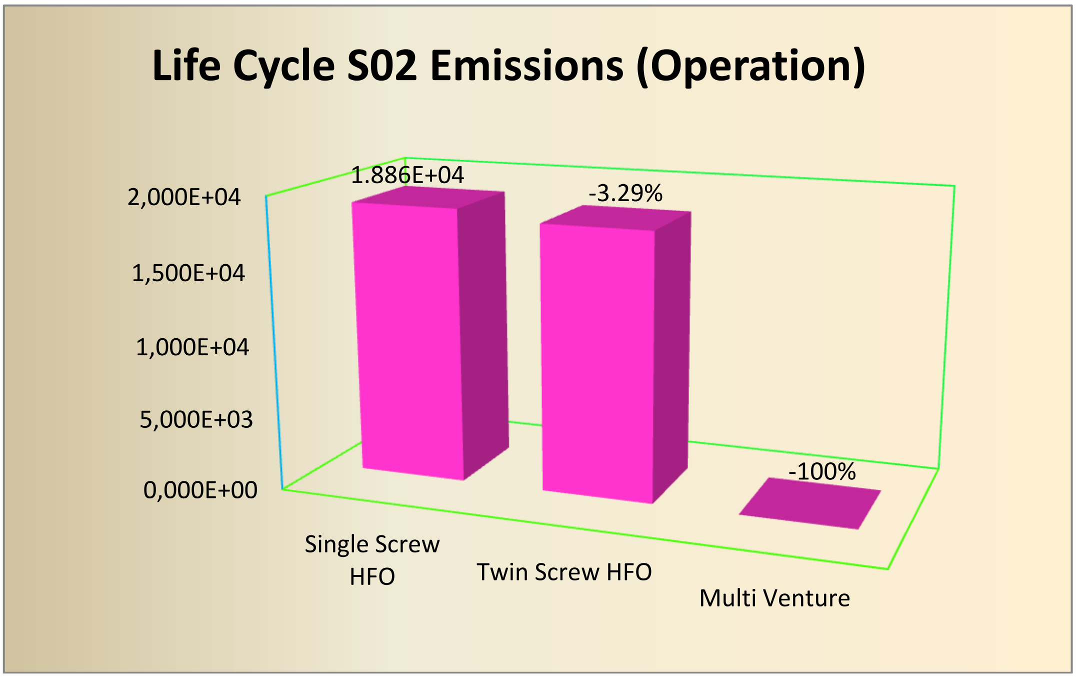

Figure [77]: Comparison of SOx emissions

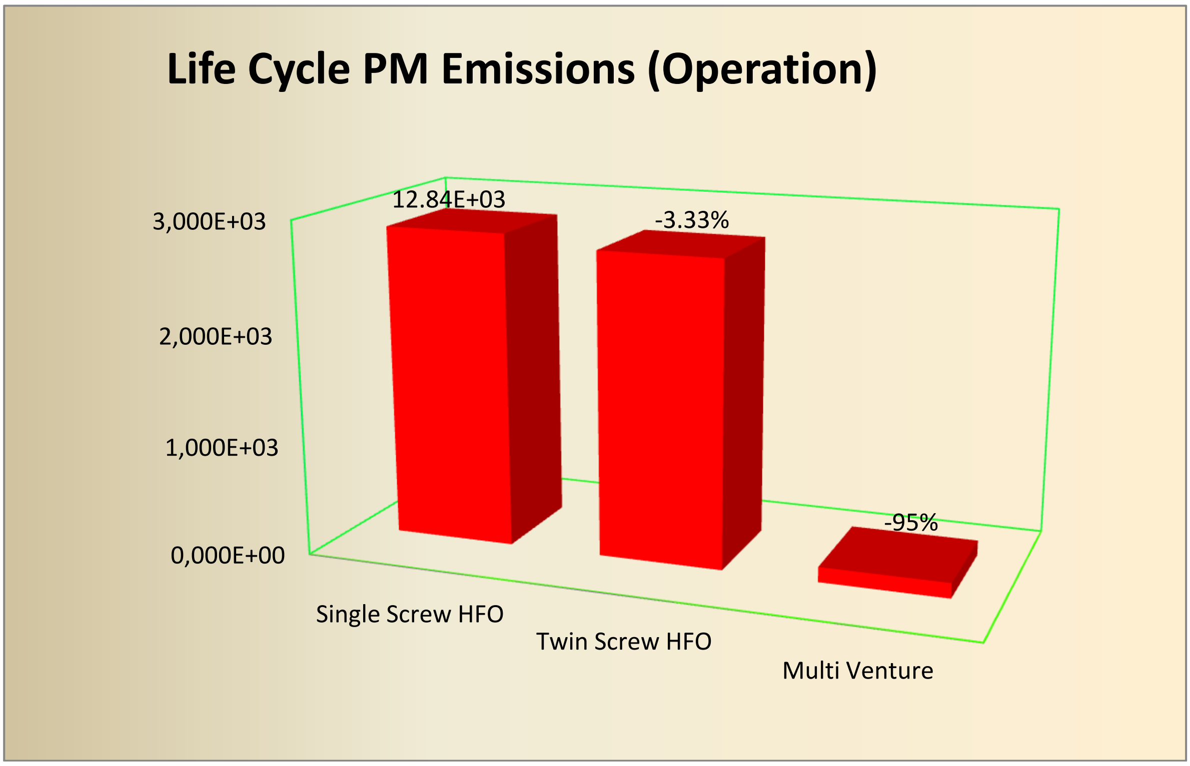

Figure [78]: Comparison of PM emissions

The results make it clear that Multi Venture is the most environmentally friendly option that complies with all existing Tiers and requirements that are expected for the years to come. That was made possible primarily thanks to the use of LNG as a new fuel type and the better hullform and propulsion system.

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11. DISCUSSION OF THE RESULTS

Concluding this present report, a novel study has been made for the holistic optimization of AFRAMAX tankers. In a joint effort, a superior hullform and tank arrangement, rsult of an exhaustive global optimization was coupled with an intelligent and state of the art propulsion system that uses LNG as a ship fuel instead of HFO.

Multi Venture is a smart and balanced design. During the design process it was possible to combine concepts and features that balance out the drawbacks of each individual concept. It is necessary then to assess it in a holistic way, taking into account the global performance. Three main areas and objectives were critical for Multi Venture:

- Safety, especially for the protection against oil spills
- Efficiency, expressed as fuel efficiency
- Competitiveness, expressed as reduced operating expenses and increased profitability.

Multi Venture, equipped with a state of the art design and propulsion system is to break ground in how tanker design is understood. The design for "cheap and simple" is not to last for long in today's demanding market with regulation constraints and a constant need for improvement. The survival of future shipping companies depends largely on the reduction of the operational costs, since the capital expenditure can be sorted by new methods of raising capital both for private and public companies. Multi Venture addresses this exact demand, being a ship friendly to its user and the environments, with smaller risks for pollution, fewer dangerous greenhouse emissions, half of the ballast water amount required and an increased competitiveness and maintainability.

There are some drawbacks however. The increased capital cost indicate that as a solution requires companies and investors with large experience and big market share and also a vision to stand out and differ. The operation of this vessel also requires a very highly skilled and trained crew that nowadays is hard to find. Finally, the superior performance in terms of operational expense is valid only as long as LNG is cheaper than HFO for the bunkering of the vessel.

Future work on this theme is to expand the concept of Multi venture for larger vessels, where the economies of scale can favor the design more. In addition to that, in the VLCC segment where the navigational constraints are very few, the change of the main dimensions can sparkle an even more significant improvement combined with a big space for onboard installation of LNG C Type tanks. Multi Venture should also be understood as a platform for large and full ships. The same hullform can be used for shuttle tanker (with a small modification for the bulb), a Crude/Product carrier (LR2 class) or even a bulk carrier by substituting the tanks with bulk carrier cargo holds. It is thus very important to understand that Multi Venture provides a way of thinking that can be applicable to medium and large commercial vessels, that can be optimized and use innovative propulsion systems that use the All Electric Ship (AES) principle with conventional and hybrid components. In the two Tiered market that is predicted to be developed after the new generation of environmental regulations, Multi Venture is going to be at the upper frontier.

MULTI VENTURE CONCEPT

RESULTS OVERVIEW

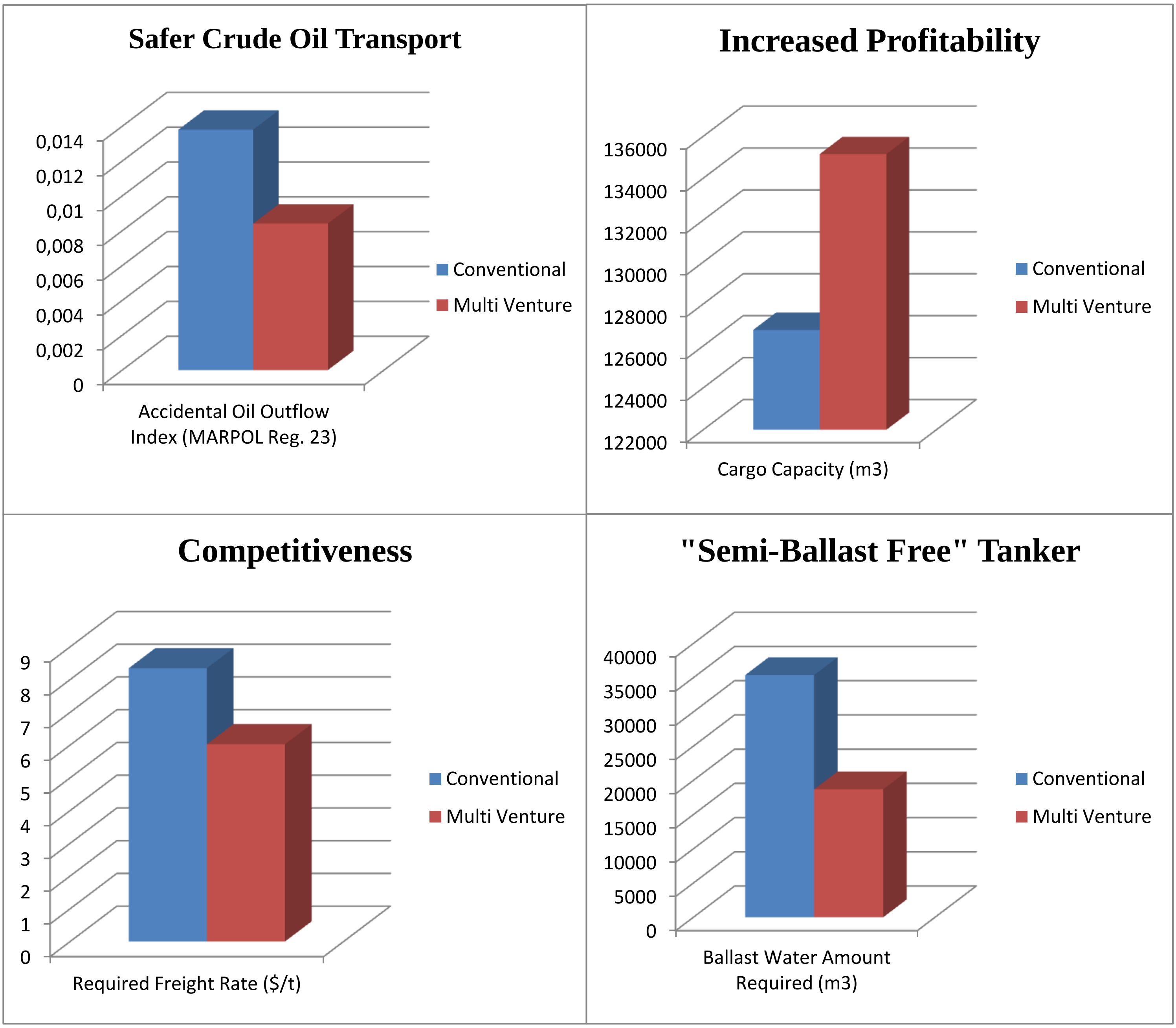


Figure [79]: Overview of the superior performance of Multi Venture compared to a conventional ship

CHAPTER FIVE:

CONCLUSIONS, DISCUSSION AND PERSPECTIVES

«Irgendwann warden Meer und Himmel ganz und gar eins warden, aber dann ist unsere Meerfahrt längst beendet, und wir haben das Ziel der langen Reise erreicht: Oslo»

Klaus Reiner Goll, Meer is überall

1. SUMMARY

A novel new methodology has been developed for the optimization of Tanker Design and Operation that uses Risk Based Principles and is realized in a holistic way by means of fully parametric Ship Design software based on simulation driven design (Friendship Framework). The methodology was applied on two parametric ship models for two respective case studies.

The first case study involved the holistic optimization of an innovative, twin screw AFRAMAX tanker with an elliptic bilge and 5X3 tank arrangement. The careful choice of design components in combination with a rational mental plan that includes a pre analysis with independent studies and an exhaustive optimization in multiple stages that properly utilize genetic algorithms, had as a result the creation of an impressive new design concept that is sustainable in today's market. The new design concept featured a 40% reduced accidental oil outflow, 3.5% improved EEDI and 19% improved RFR. In addition to these merits, a post analysis of the optimization result, with local refinements (bulb optimization) and a different propulsion system lead to Multi Venture that is Safer, more profitable due to reduced fuel costs and a subsequent decrease of the RFR up to 32% compared to a conventional single screw vessel. All of this while it can be considered as a "Semi Ballast Free" tanker since it has a 52% reduction in the ballast water leading to decreased structural maintenance costs as well as decreased ballast water management costs.

The methodology has been also applied for a conventional, single screw VLCC at a much smaller scale, in order to demonstrate the applicability of the method. The results are encouraging, since a reduction of the OOI of up to 15% and 18% of the freight rate is realized. However the optimization potential is not as high as in the case of the AFRAMAX as technology leap and innovation is smaller. Nevertheless this vessel provides an excellent initial platform for further research since there is more room for innovation as there are little navigational constraints while the vessel size allows design measures such as denser subdivision in the longitudinal and transverse direction etc.

2. DESIGN DIRECTIVES

An important aspect of the present study is the design directives it can provide a Naval Architect during the preliminary design and specification of a tanker. These directives derive primarily from the sensitivity analysis since the decision maker (in our case the Naval Architect) can identify how to chose the principal dimensions as well as the trend lines in several variables that consist the basic tanker design such as tank parameters and local hullform variables. A globalized approach, which is what preliminary design is all about, can be much faster when starting from a good initial solution (in this case optimum) making the detailed design faster and easier. A general impression is, what is universally accepted, that the scale economies are the single most important factor influencing the economic performance while the reduction of the tank size (by a bigger tank number) is beneficial for the oil outflow performance. In addition to that the use of three tanks across is imperative for vessels from AFRAMAX size and above if one wants to have an improved oil outflow. A very interesting hint in this direction is the optimal width of the mid tank which in the case of an AFRAMAX tanker would be at 40 to 45% of the cargo breadth, while in the case of the VLCC is at 50 to 55%. The exact percentage and trend depends mainly on the breadth of the ship and the probability of breaching the central compartment. An empirical rule would be though that there is a local optimum after which the mid tank is so large that can get penetrated, thus increasing the accidental oil outflow. In Appendix I one can find more details about these sensitivities and how the principal dimensions affect the objectives set.

The design directives however are not just a product of the sensitivity analysis. The general mentality expressed in this Thesis can be a very good directive. This mentality dictates the holistic assessment of the vessel. A good example is the way the economic performance is approached, were the capital expenditure (CAPEX) is not the single most important factor rather than the operating expenses (OPEX) whose reduction through innovation has an overall more positive effect at the owner. The profitability is also of primary importance in combination with the reliability. These combined can overcome the increased initial cost charged by the shipyards. A last example of such holistic thinking is the assessment of the operating speed, which was done for the AFRAMAX vessels. This assessment, for a range of fuel prices created curves (for each fuel price) and an envelope in which one can be positioned and find which speed minimizes the fuel and operating costs while the loss of annual trips (income) is kept at a sustainable level. This was possible only be calculating the RFR over the lifecycle of the vessel and with a full awareness of the operational profile.

3. VLCC OPTIMIZATION

As mentioned previously an application has been also made for a Very large Crude Carrier (VLCC) that can be found in Appendix II. Due to the much smaller scale of this, it was chosen for coherent purposes not to include it in the main body of the Thesis.

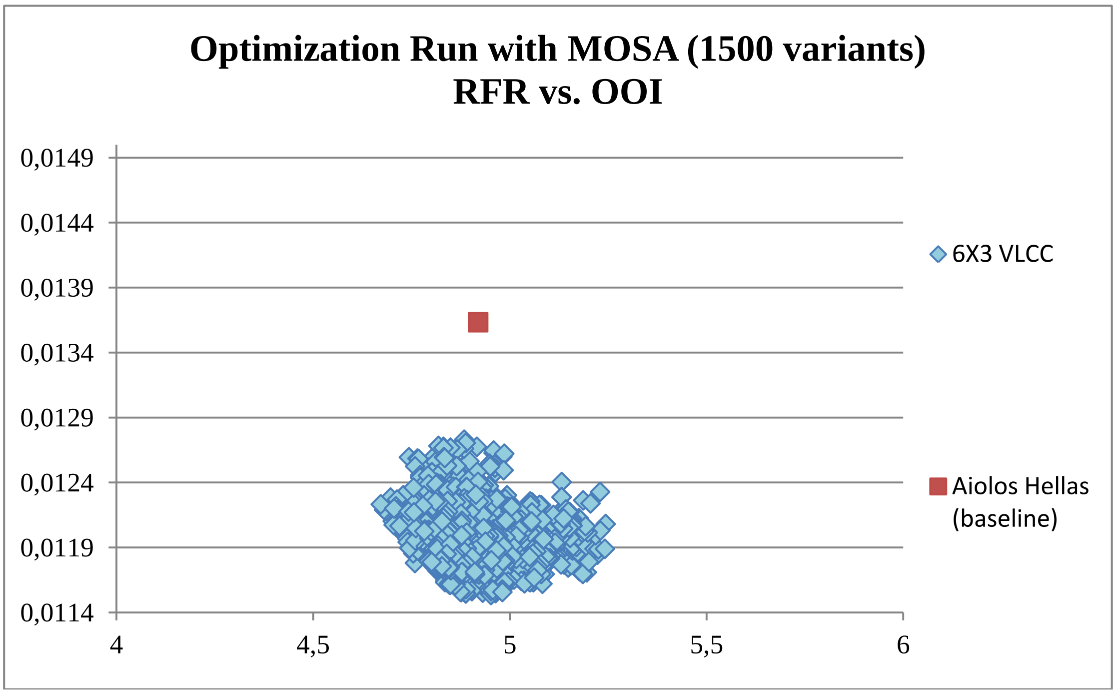


Figure [80]: Scatter Diagram from the VLCC first optimization run

From the results of the design of experiment one can spot a potential for optimization although, it is not as big in absolute, global terms as in the case of the AFRAMAX tanker, since the default tank arrangement in this case is 6X3 (standard design) which cannot perform that good in this vessel (and tank) size.

4. THESIS CONTRIBUTION

When examining the overall work undertaken for the purposes of this Diploma Thesis, one can outline the following contributions:

- Development and application of a robust and fast Global Optimization method for tanker design.
- Adoption of the method within one program that is used for the geometrical modeling, simulation and optimization, using only Excel as an external software. This is the first such application for Friendship Framework that previously was forced to integrate NAPA in order to perform the basic hydrostatic and Naval Architecture calculations.
- Creation of a new concept for AFRAMAX tanker that is the product of this methodology and a multi staged optimization that created a total of 20.000 fully dimensioned working variants with the selected dominant variant featuring an exceptional performance in terms of Oil Outflow while the EEDI and the RFR are smaller and the required ballast capacity is almost the half.
- Creation of Multi Venture, which is a more exotic variant of the optimization result and improves its emissions footprint and economic performance with a new propulsion standard and LNG as a fuel.
- Analysis of design variables sensitivities and use of them as design directives for a quick dimensioning during the preliminary design.
- Initial, global optimization of a VLCC using the MOSA algorithm.

5. FUTURE PERSPECTIVES

Future perspectives of this study can be:

- The creation and application of response surfaces, derived from systematical CFD runs, for the resistance prediction part of the methodology. This can contain more information about the frictional and viscous pressure resistance (form resistance). The evolution of these response to a numerical series for single and twin screw tankers could be useful both in optimization and very preliminary design. At any case they will not be able to substitute the model tests.
- The use of actual statistical data and their derived probability densities for the calculation of the probability for grounding and collision during the Accidental Oil Outflow calculation. The calibration of the index against these results can make the calculation more realistic.
- Use of the ITOPF (International Oil Pollution Fund) data and empirical formulas (Kontovas, Ventikos et al) for the calculation of the oil spill removal costs and the introduction of these costs along with the respective probabilities in the Required Freight Rate is another step to a more rational Risk Based approach for the design and optimization of tankers and their tank arrangements.
- The modeling of the engine room, aft and fore peaks in POSEIDON and the use of coefficients from the derived weight can provide a more realistic weight approximation.
- The detailed engine room compartmentation and arrangement can be integrated within the Friendship Framework and improve the stability check results (although not critical). This can also contribute to the optimization of the engine room for the reduction of the energy losses and the space maximization (current work of Diploma Thesis of Michalis Pytharoulis and the REFRESH project).
- Use of engine room simulation and optimization of the machinery and engine dimensioning and selection.
- Application for other ship types, related to tankers such as chemical carriers, gas carriers and LNG tankers.

APPENDIX I:

SENSITIVITY ANALYSIS OF THE DEVELOPED METHODOLOGY

APPENDIX I: SENSITIVITY ANALYSIS FOR THE DEVELOPED METHODOLOGY

The developed methodology is examined in its sensitivites, namely how the change of design variables values is affecting the design and optimization objectives. It is important to understand the sensitivity, volatility and how the different empirical methods and computational tools interact in the entire system during the simulation from the optimization algorithms. The final result can be also used as an initial design directive namely an empirical rule for a conventional, non parametric prelimiary study.
The results shown are exported from the Friendship Framework and have the genetic algorithm runs as a source. As these results are produced by an evolutionary algorithm one can notice in the areas with the most sensitivity and to the areas that correspond to the most desirable results the concetration of designs is bigger. This illustrates the success and the divergence of the algorithm and the method to an optimum solution and that the global optimum points are properly understood. A sensitivity analysis of a smaller scale has been also made during the initial Design of Experiment of each Case Study in order to determine the refined boundaries and constraints for the optimization runs.

PART I: CASE STUDY ON AFRAMAX TANKERS

At the first part the application of the holistic methodology on the innovative, Twin Skeg AFRAMAX tanker concept is asssesed in terms of sensitivity. For each design objective, the influence of each design variable is understood in combination with the general term. Each circular point respresent a successful design, while the x point represents an unfeasible design as defined by the constraints imposed.

1. *Required Freight Rate (RFR) sensitivity*

The RFR is used as a Key Performance Indicator for the operational efficiency and the market competitiveness. Namely it represents how economical the ship is to build, operate and how profitable its operation is (in terms of cargo capacity). A general impression is that the larger vessel sizes have a positive influence to the RFR thanks to the strong correlation to the tank capacity. This phenomenon is very common in ship design, as scale economies have been the primary driver of the evolution of tanker design up until recently, that there is an upper unofficial limit of tank sizes due to the risk of pollution. Other variables than the main dimensions that have a strong (the strongest) influnce are the tank variables while the local hullform shape has a less important but existing correlation. More specifically the sensitivities monitored can be seen in Figures [1] to [13] and their interpretation is the following:

- **Length**, Figure [1], is influencing the RFR in terms of scale economies, with the maximum length being close to the one with the smallest RFR. The latter is 244 m which is the current standard Lbp used in Shipyard designs for the AFRAMAX class.
- **Breadth**, Figure [2], is also influncing RFR in a linear way with the beamiest ship being the most economical. It is also interesting to see that the breadth increase is more effective in the RFR reduction than that of the length.
- **Height**, Figure [3], is influencing in a much less steep way the RFR. Usually, the designs with a bigger deck height have a bigger tank capacity.
- **Draft**, Figure [4], is beneficial for the RFR as it increases, which is natural as the displacement and thus deadweight is increased.
- **Block Coefficient**, Figure [5], is beneficial up to a point as it increases (Cb~0.855) and for bigger values it has a negative effect for the RFR due to the increased resistance.
- **LCB position**, Figure [6], is beneficial for the RFR when it is shifted towards the bow.
- **Double Bottom Height**, Figure [7], is negative for the economic performance as it increases, due to the decrease of tank capacity.
- **Double Hull Width**, Figure [8], is negative for the economic performance as it increases, due to the decrease of tank capacity.
- **Mid Tank Width**, Figure [9], diplays an optimum value for the minimization of the RFR at about 45-47% which is coincidentally the same as the optimum value for the minimization of the oil outflow index. Smaller values indicated that the side tanks will be larger which means that the overall tank capacity is decreased.
- **Flat of Bottom (FOB) extent**, Figure [10], has a smaller and less obvious effect than other parameters. Combined with the EEDI sensitivity (next paragraph) one can understand that smaller FOB extents due to the elliptic bilge shape, are indicative of a smaller resistance and installed power due to the decrease of the wetted surface. This is also beneficial for the required ballast water capacity.
- **Flat of Side (FOS) extent**, Figure [11], has the same effect on the RFR as the FOB value but on a smaller magnitude.
- **Beginning of Parallel Midbody**, Figure [12], is decreasing the RFR when shifted to the fore, as the aft boddy gets more slender, reducing thus significantly the installed power.
- **End of Parallel Midbody**, Figure [13], has not the same effect as the beginning, as the change of the forebody is much less intense and drastic than the equivalent trigerred change of the aftbody.

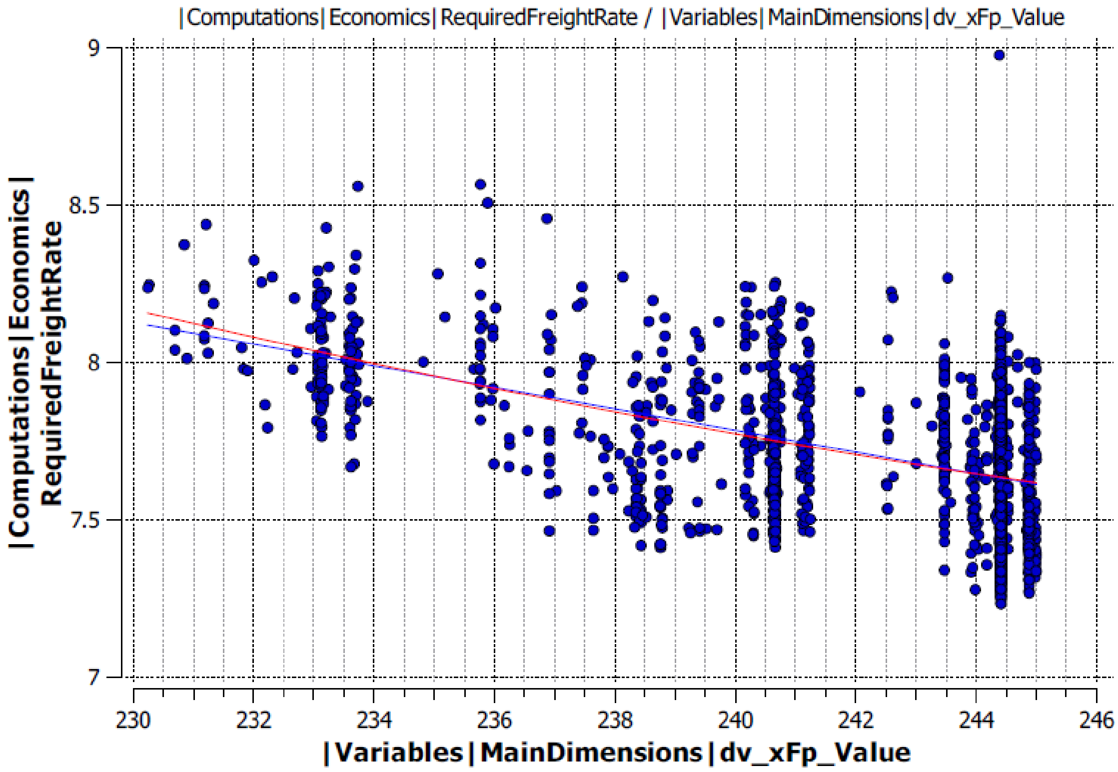
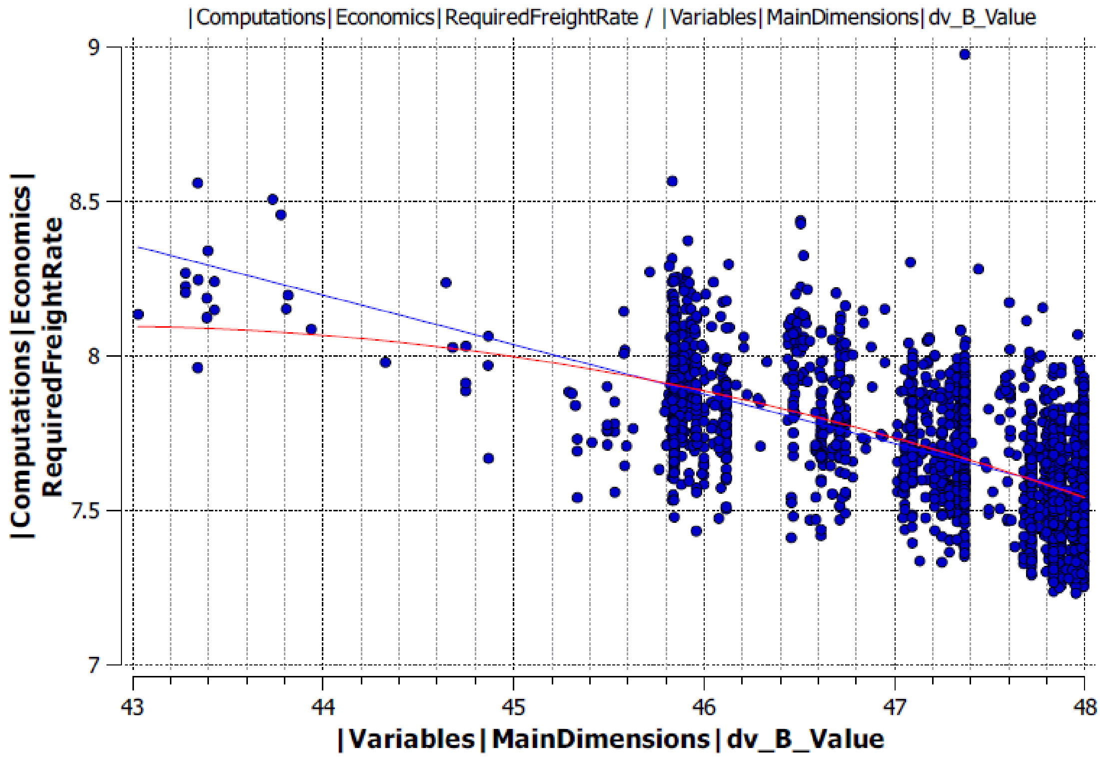


Figure [1]



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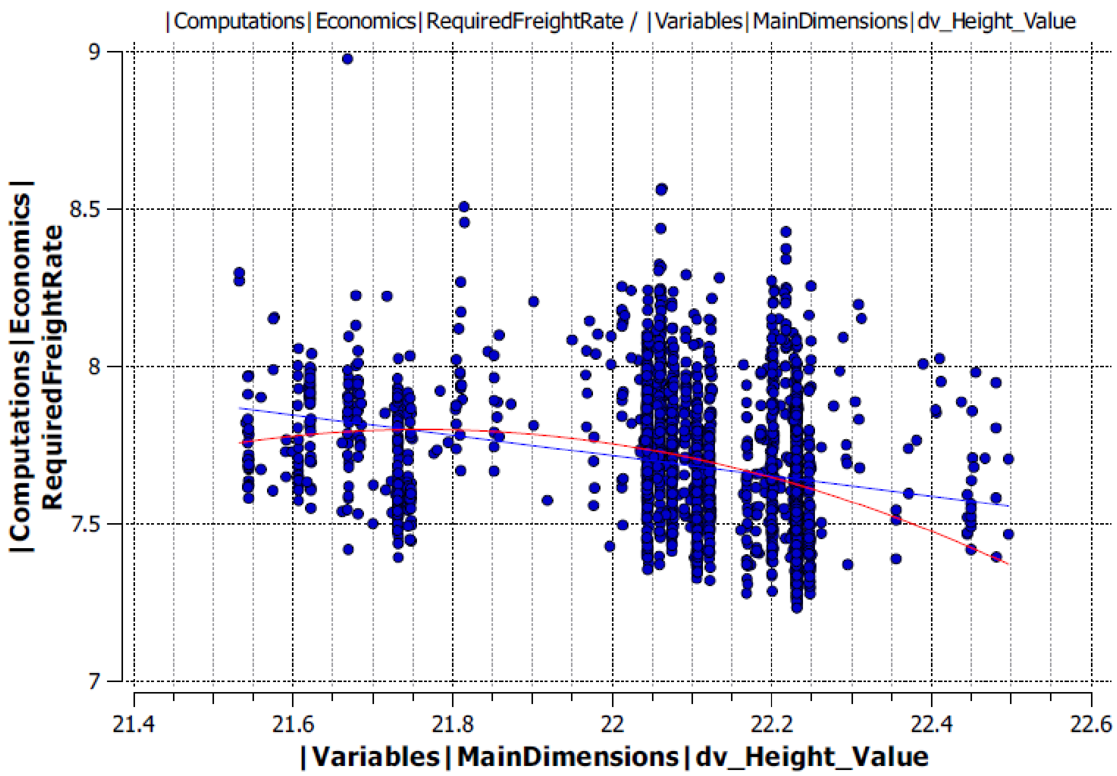

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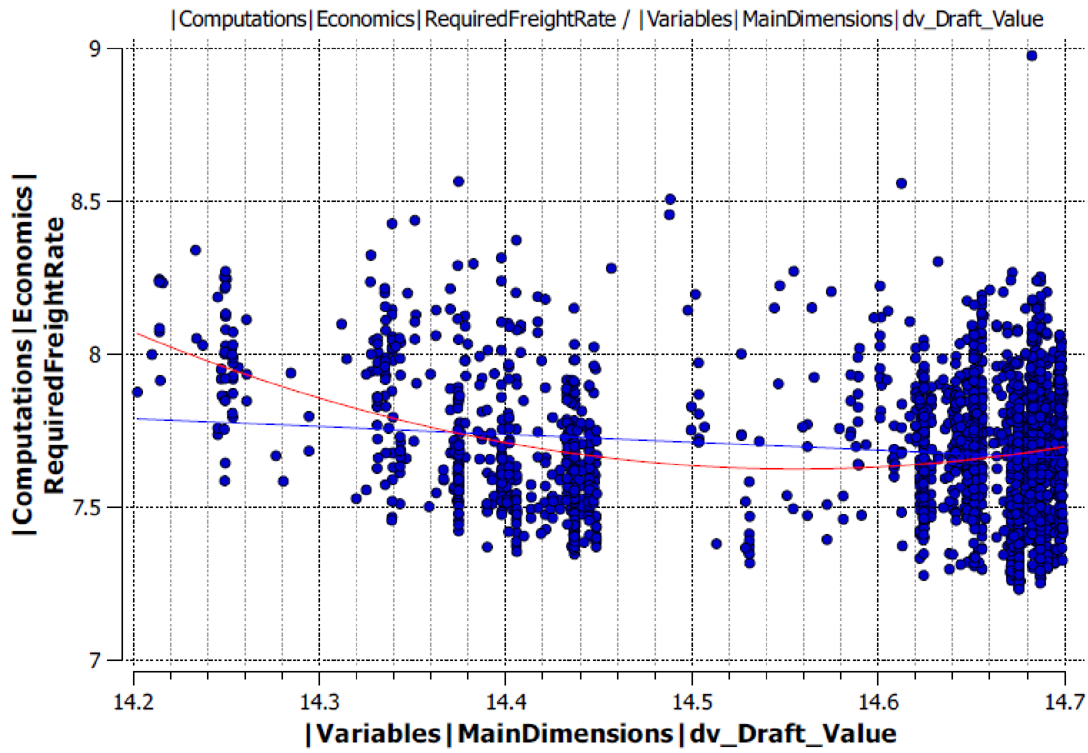

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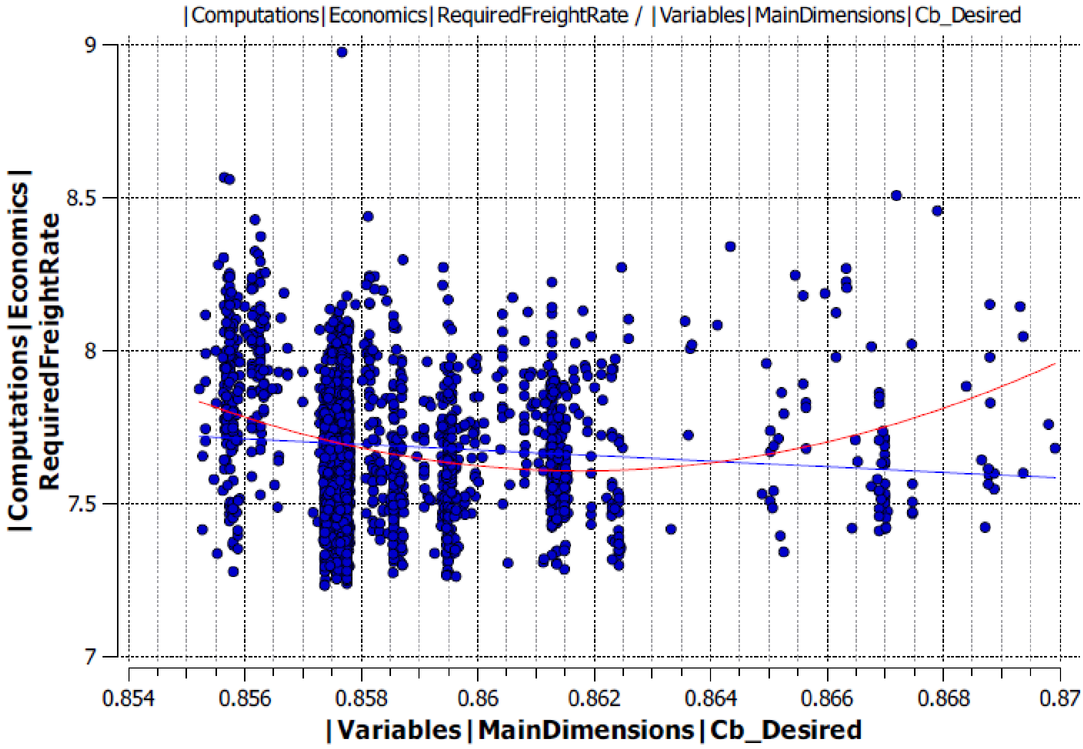


Figure [5]

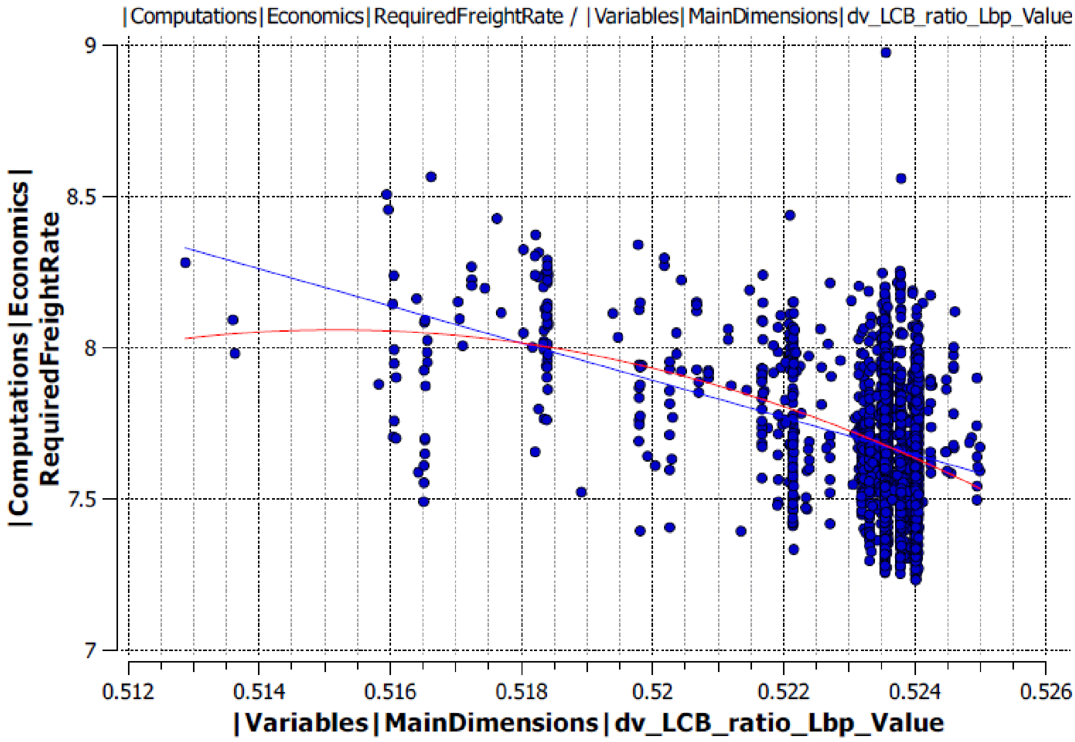
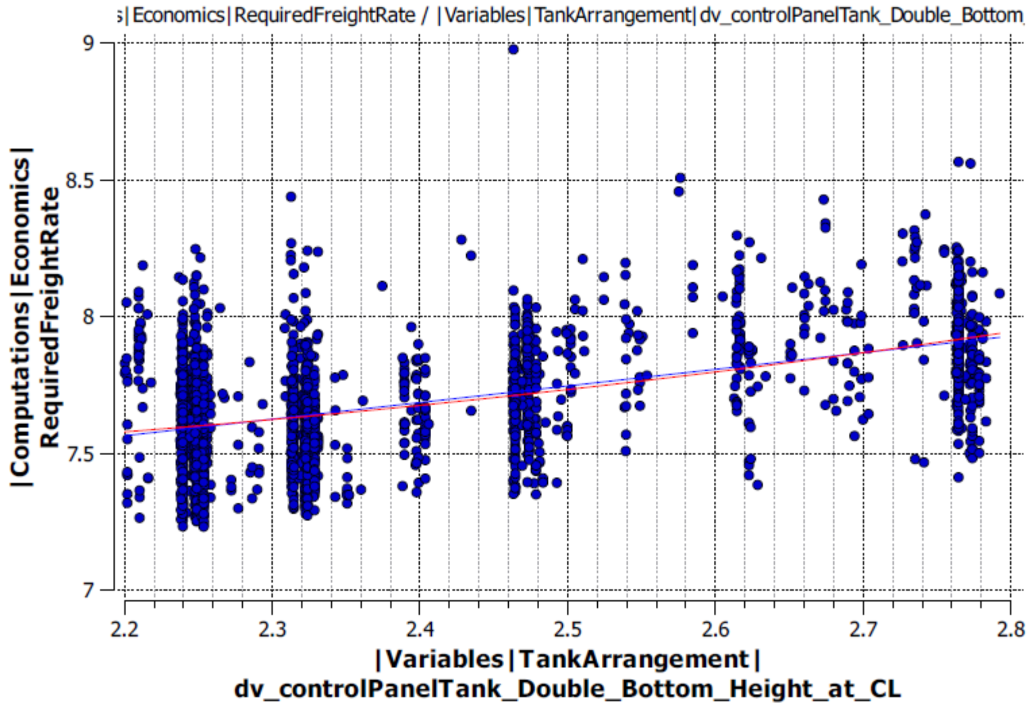


Figure [6]



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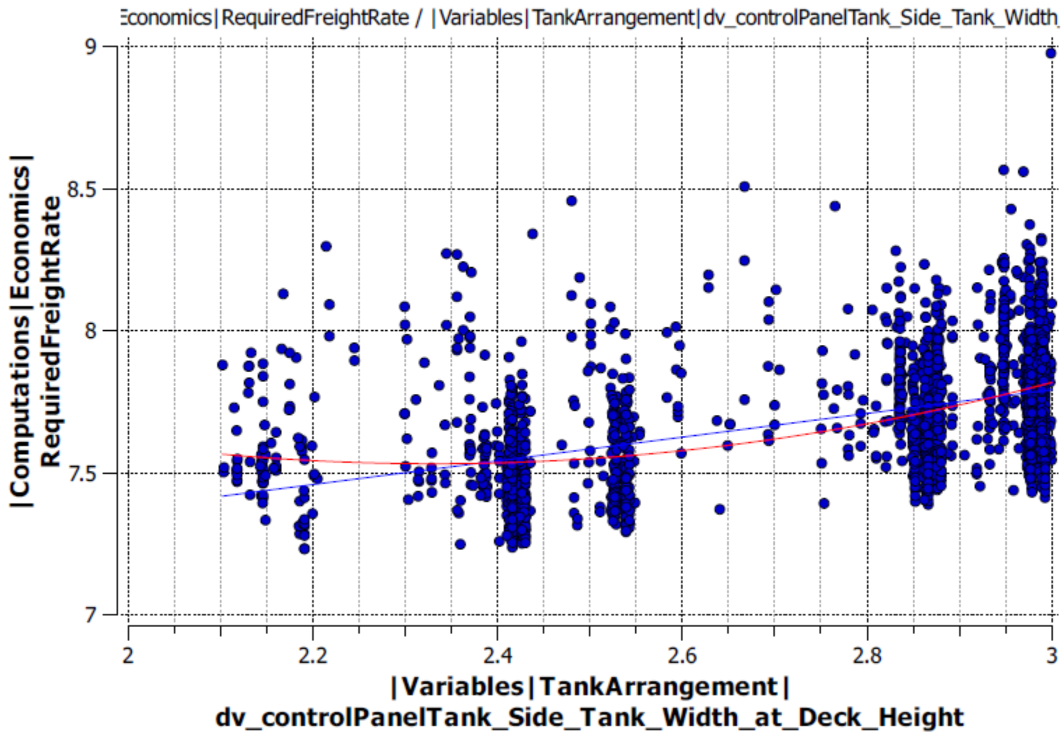
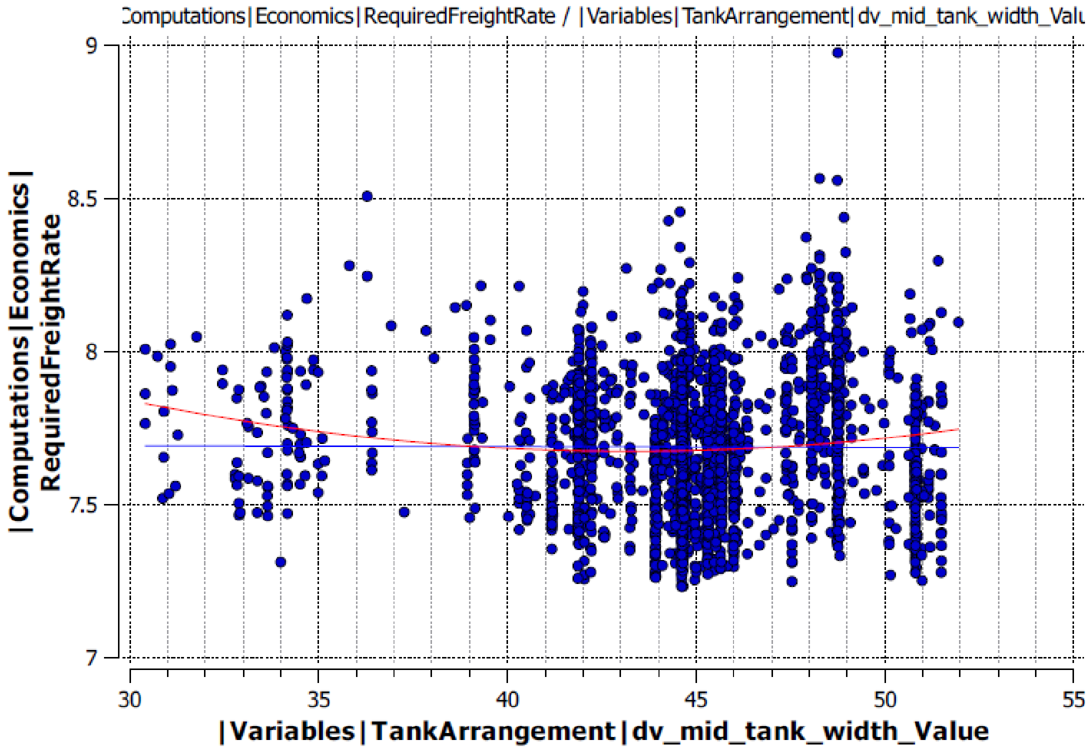


Figure [8]



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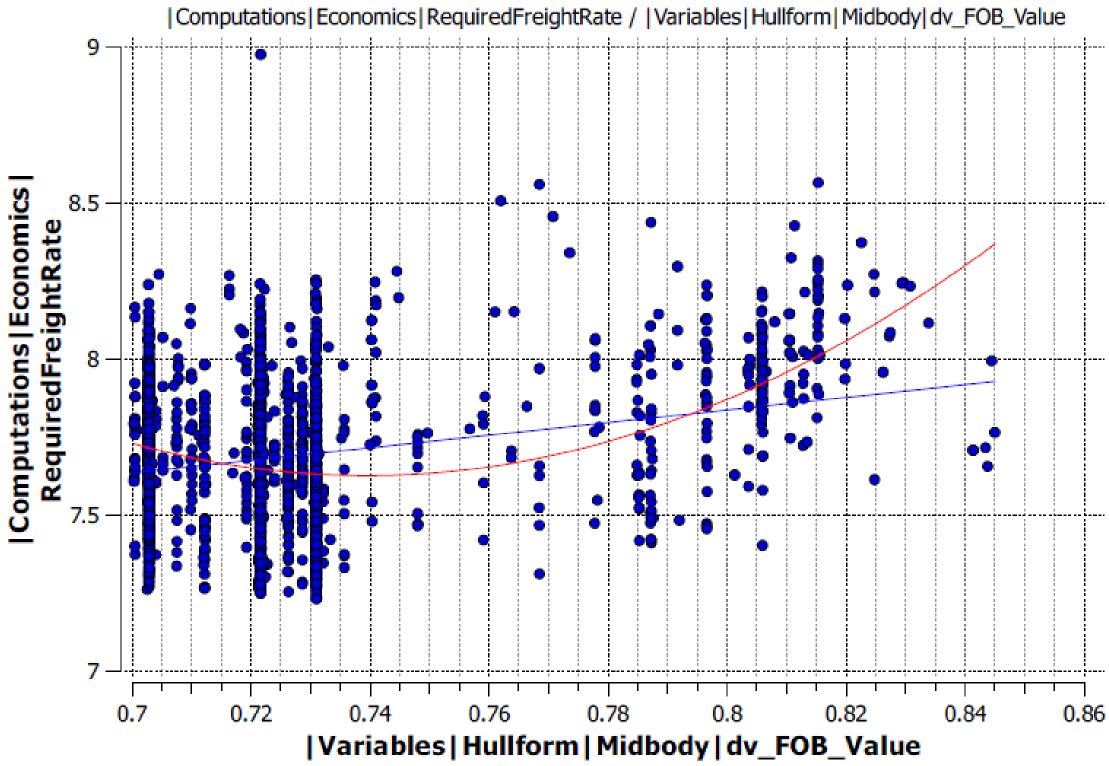

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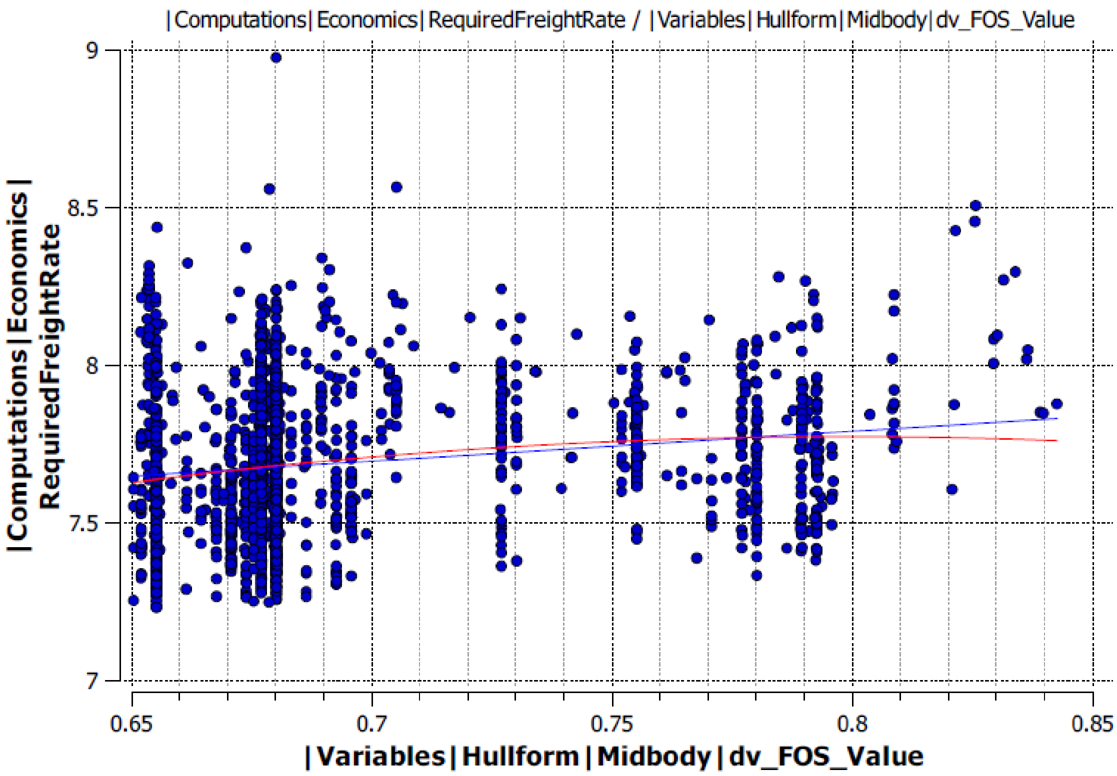


Figure [11]

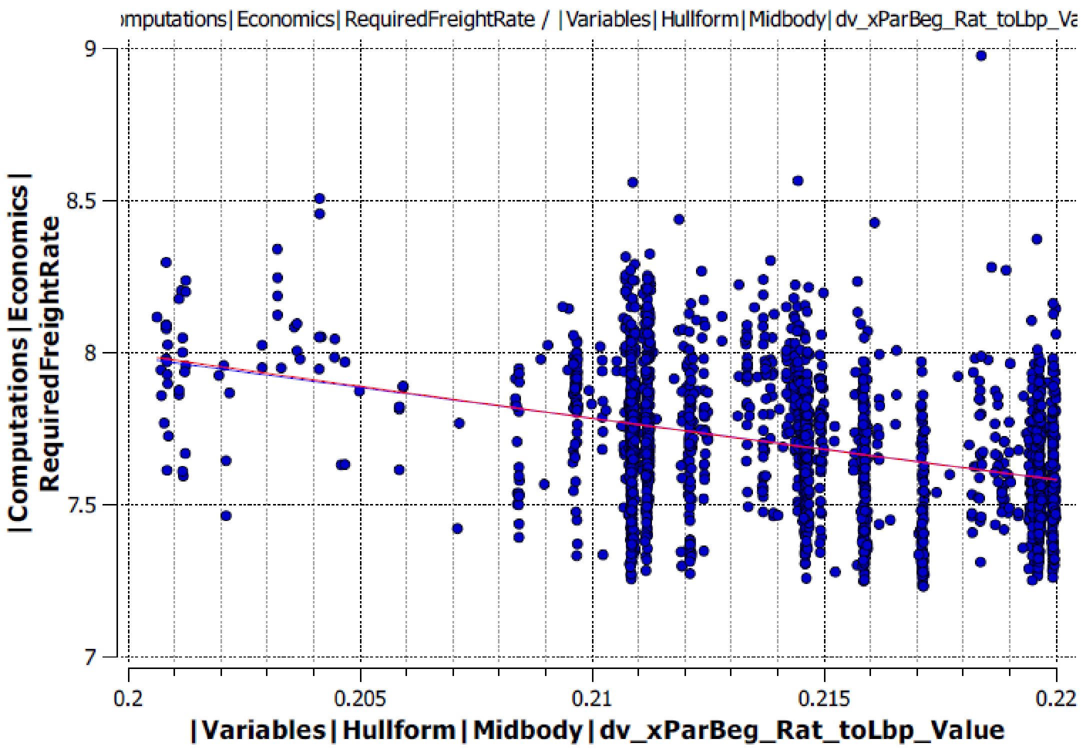


Figure [12]

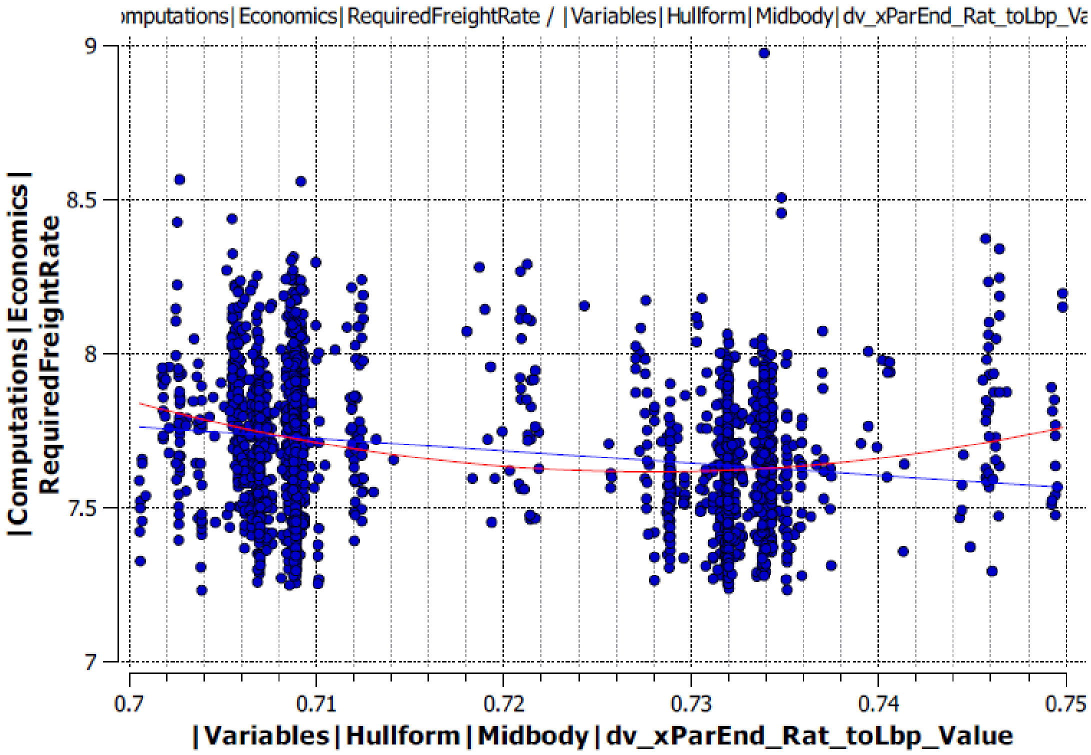

›mputations|Economics|RequiredFreightRate / |Variables|Hullform|Midbody|dv_xParEnd_Rat_toLbp_Va
|Computations|Economics|RequiredFreightRate
|Variables|Hullform|Midbody|dv_xParEnd_Rat_toLbp_Value
9
8.5
8
7.5
7
0.7
0.71
0.72
0.73
0.74
0.75

Figure [13]

2. IMO Energy Efficiency Design Index (EEDI) sensitivity

The EEDI is used as a Key Performance Indicator for the efficiency of each design and is calculated according to the guidelines decided on IMO MEPC 62. A general impression is that the larger vessel sizes have a positive influence to the EEDI thanks to the strong correlation to the deadweight and the smaller increase of the installed power. Since speed was not decided to be used in the optimization as a design variable the installed power was not varied significantly and it is also now clearer which designs have a better hydrodynamic performance. The local hullform parameters influnce the EEDI via the wetted surface and thus the installed power. It is also very interesting to see that the sensitivities found for the RFR objective are qualitive the same as in the EEDI which illustrated the “win-win” situation for the decision maker with the increase of the fuel and transport efficiency in conjunction with the economic performance. More specifically the sensitivities monitored can be seen in Figures [1] to [13] and their interpretation is the following:

- **Length**, Figure [14], is influencing the EEDI in terms of scale economies, with the maximum length being close to the one with the smallest RFR. The latter is 244 m which is the current standard Lbp used in Shipyard designs for the AFRAMAX class.
- **Breadth**, Figure [15], is also influncing EEDI in a linear way with the beamiest ship being the most efficient due to the increase of the deadweight. However the effect is not comparable to that of the RFR as the excessive beam designs have a lack of hydordynamic performance that is not predicted in this present model, in the form of increased flow separation and thus inceased viscous pressure and frictional resistance.
- **Draft**, Figure [16], is beneficial for the EEDI as it increases, which is natural as the displacement and thus deadweight is increased.
- **Height**, Figure [17], is much less influencial than the other dimensions in the EEDI
- **Block Coefficient**, Figure [18], is beneficial up to a point as it increases (Cb~0.855). However in general smaller Cb ships (more slender) seem to lower the EEDI due to the senstivity of the Holtrop Resistance prediction method to the block coefficient.
- **LCB position**, Figure [19], is beneficial for the EEDI when it is shifted towards the bow due to the inherent sensitivity of the Holtrop method to the LCB position.
- **Flat of Bottom (FOB) extent**, Figure [20], is beneficial for the EEDI in smaller values due to the decrease of the wetted surface as discussed previously in the RFR sensitivity.
- **Flat of Side (FOS) extent**, Figure [21], has the same effect on the EEDI as the FOB value but on a smaller magnitude.
- **Beginning of Parallel Midbody**, Figure [22], is decreasing the EEDI when shifted to the fore, as the aft boddy gets more slender, reducing thus significantly the installed power.
- **End of Parallel Midbody**, Figure [23], has not the same effect as the beginning, as the change of the forebody is much less intense and drastic than the equivalent trigerred change of the aftbody.

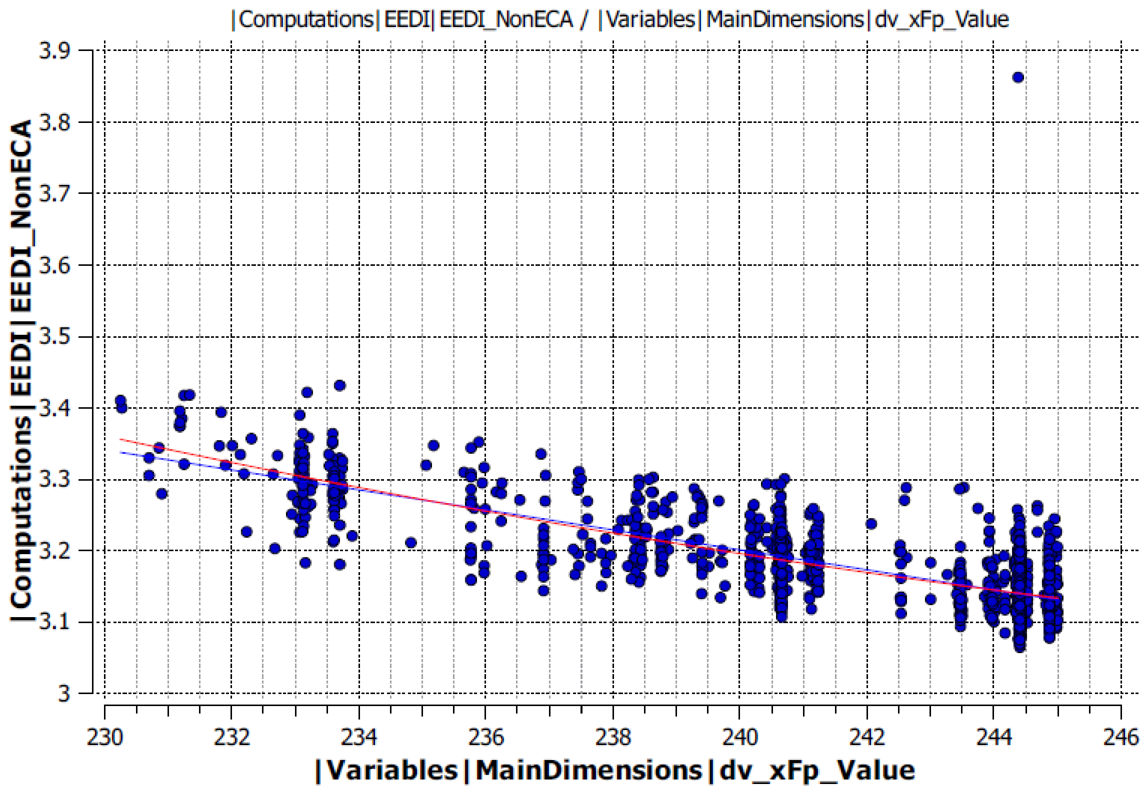


Figure [14]

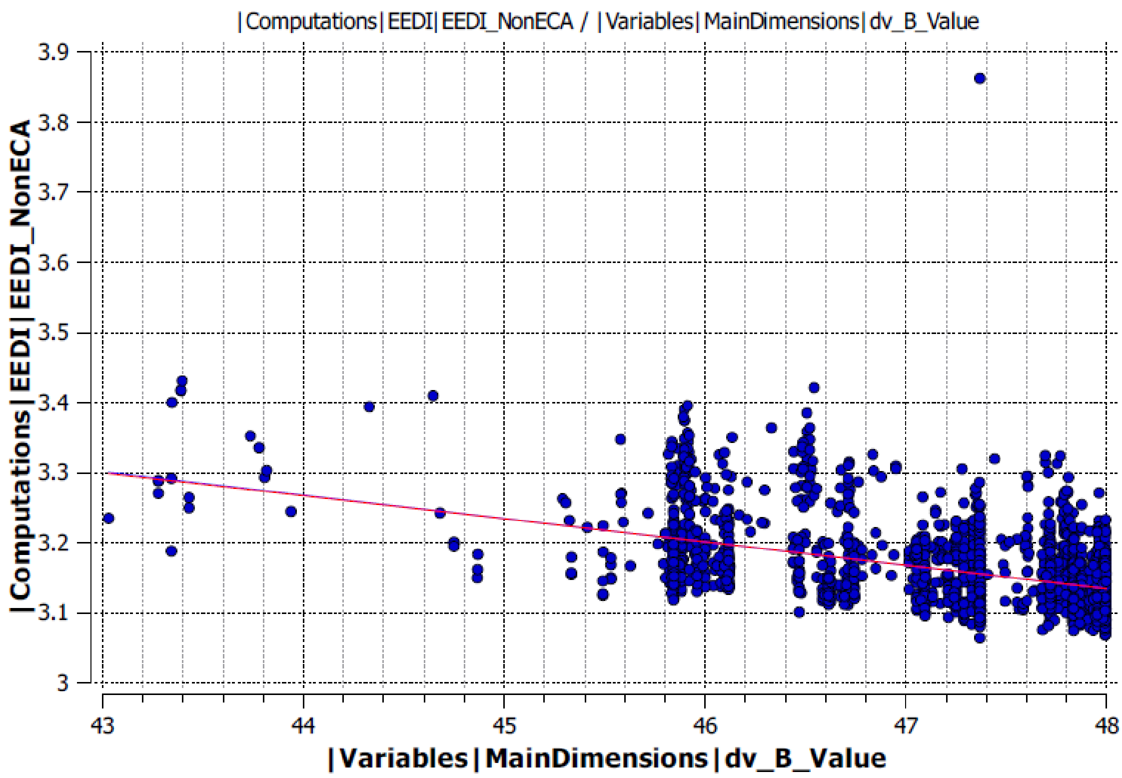


Figure [15]

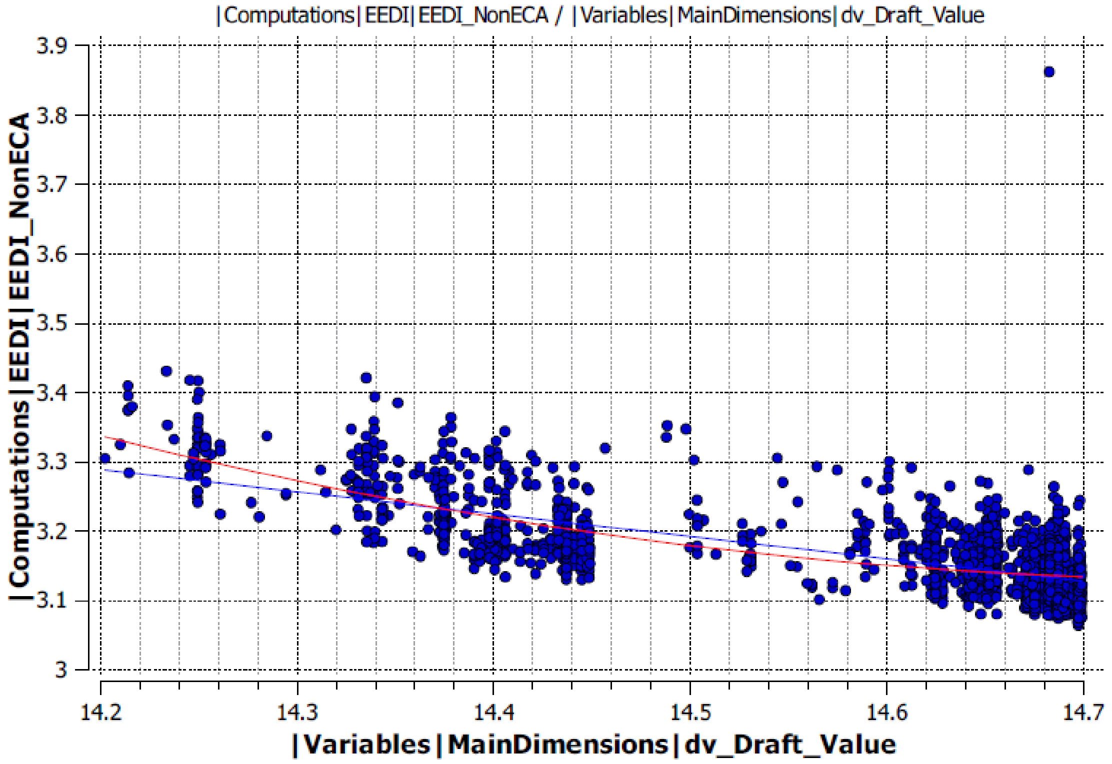


Figure [16]

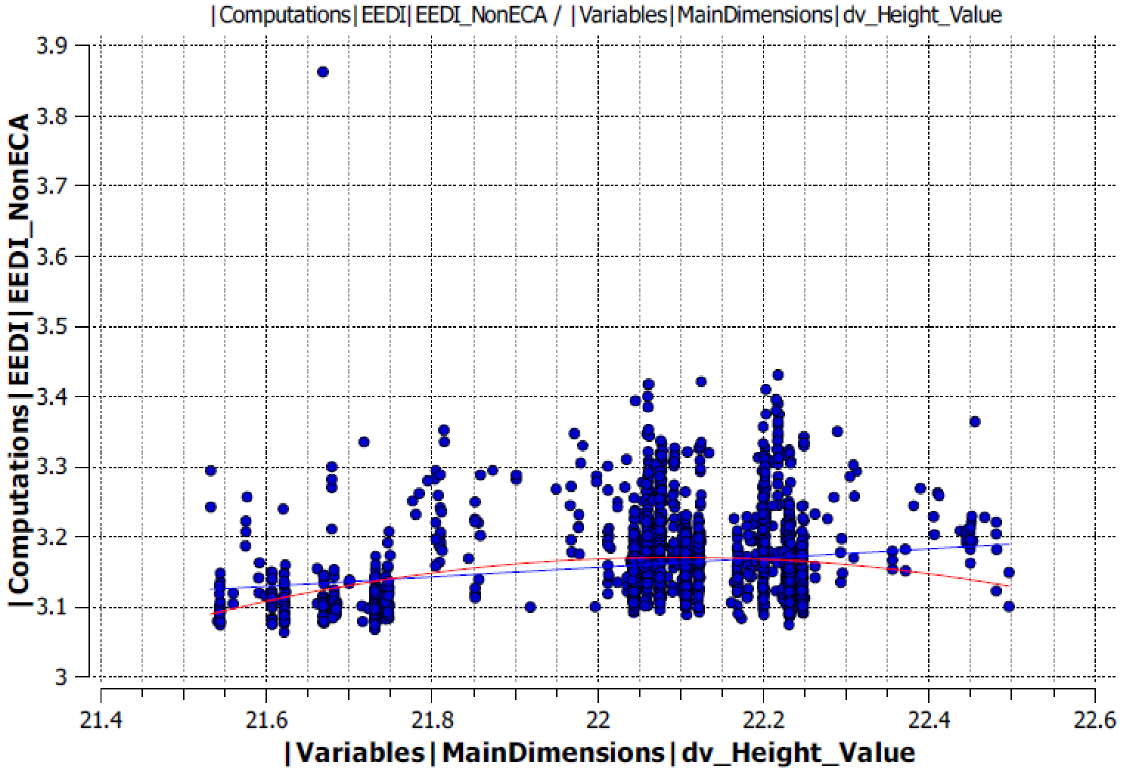


Figure [17]

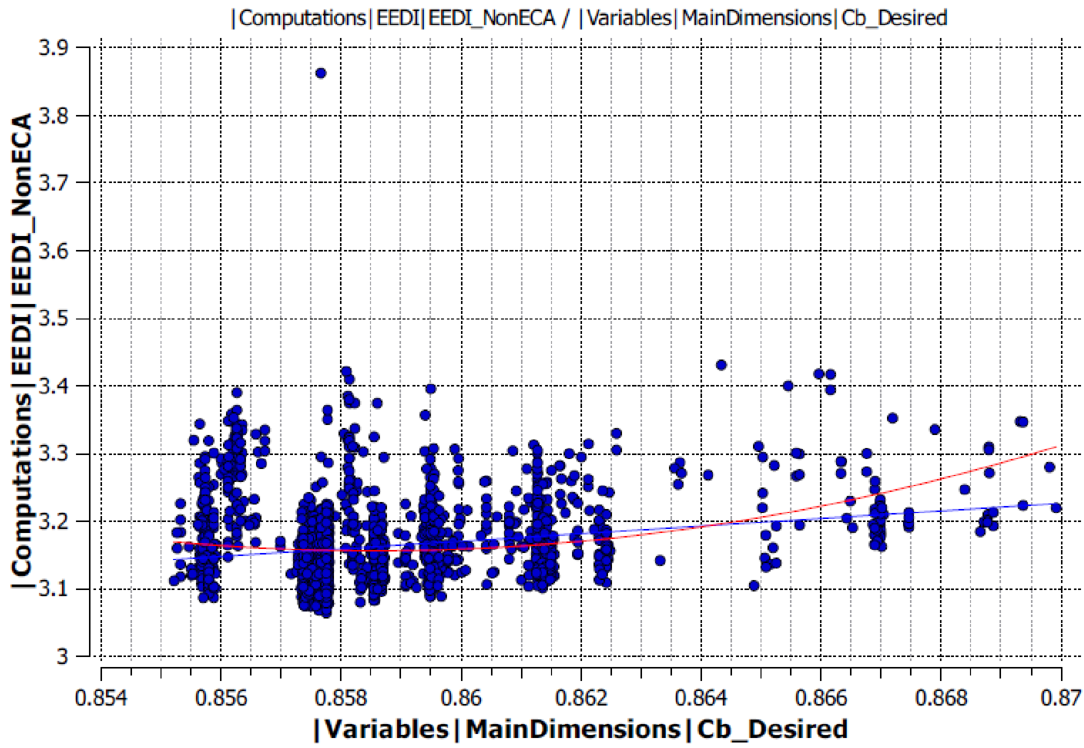


Figure [18]

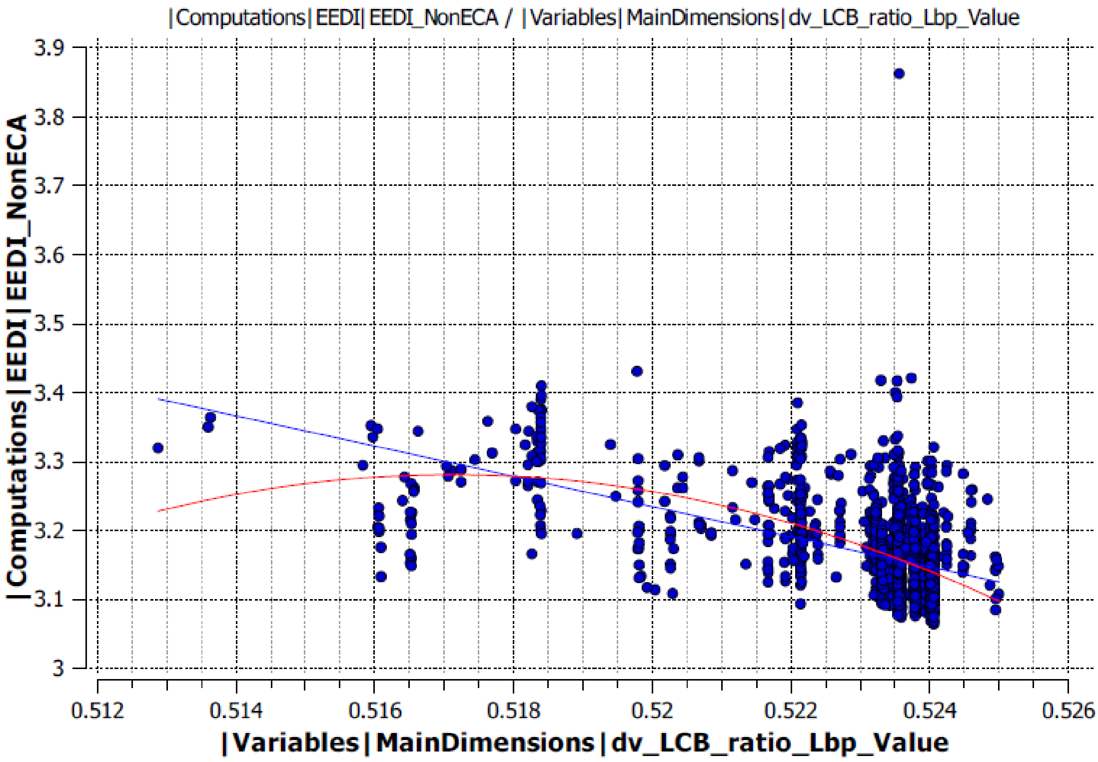


Figure [19]

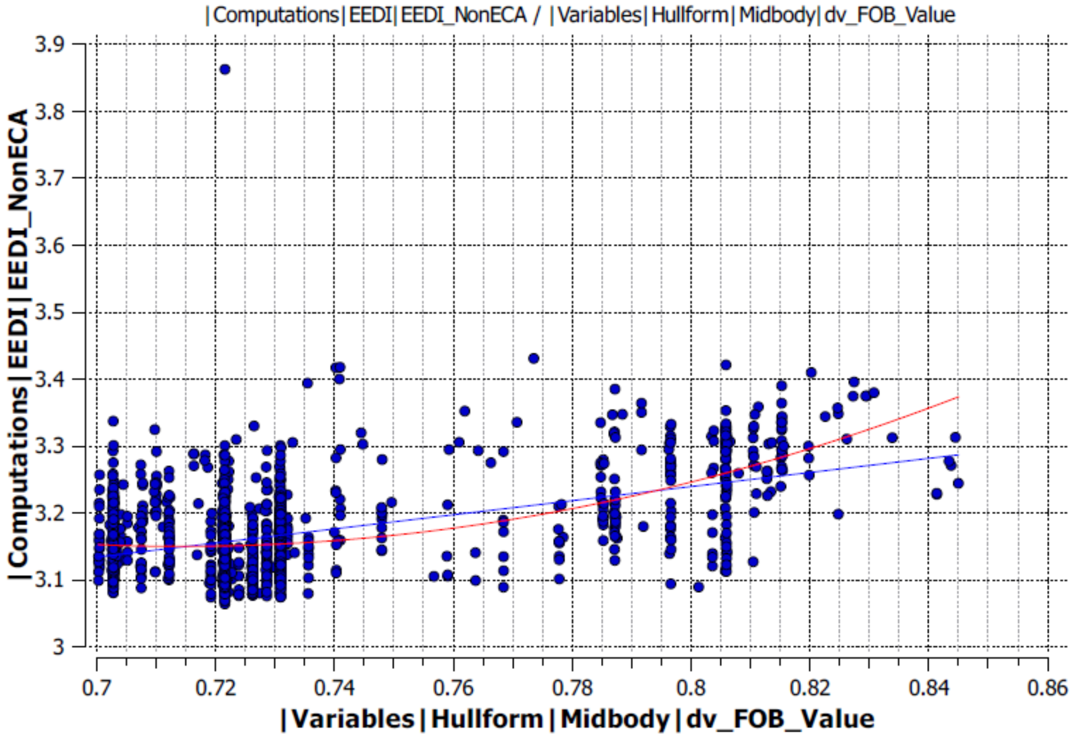


Figure [20]

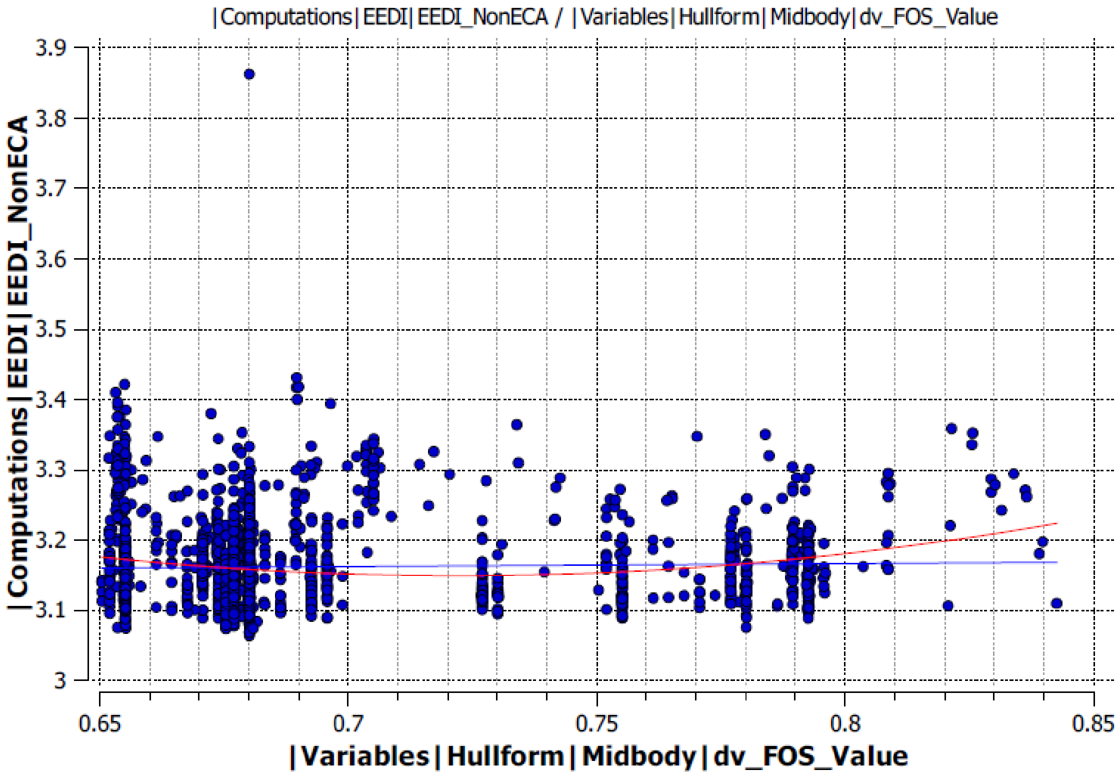


Figure [21]

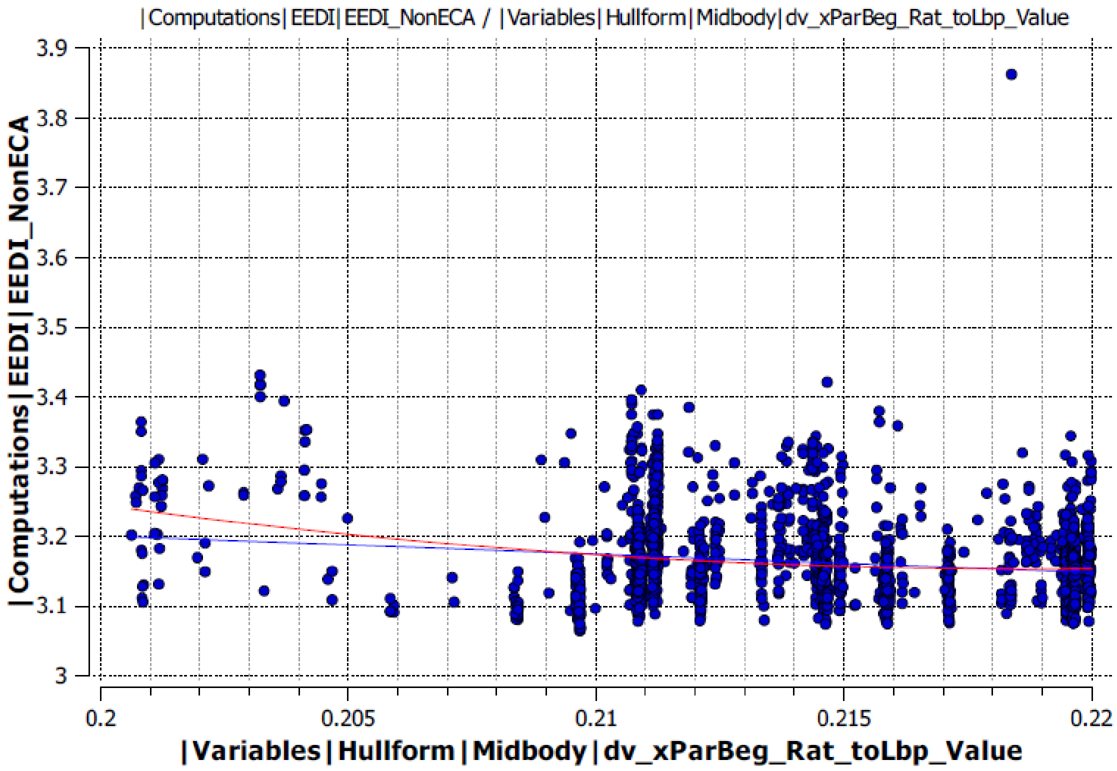


Figure [22]

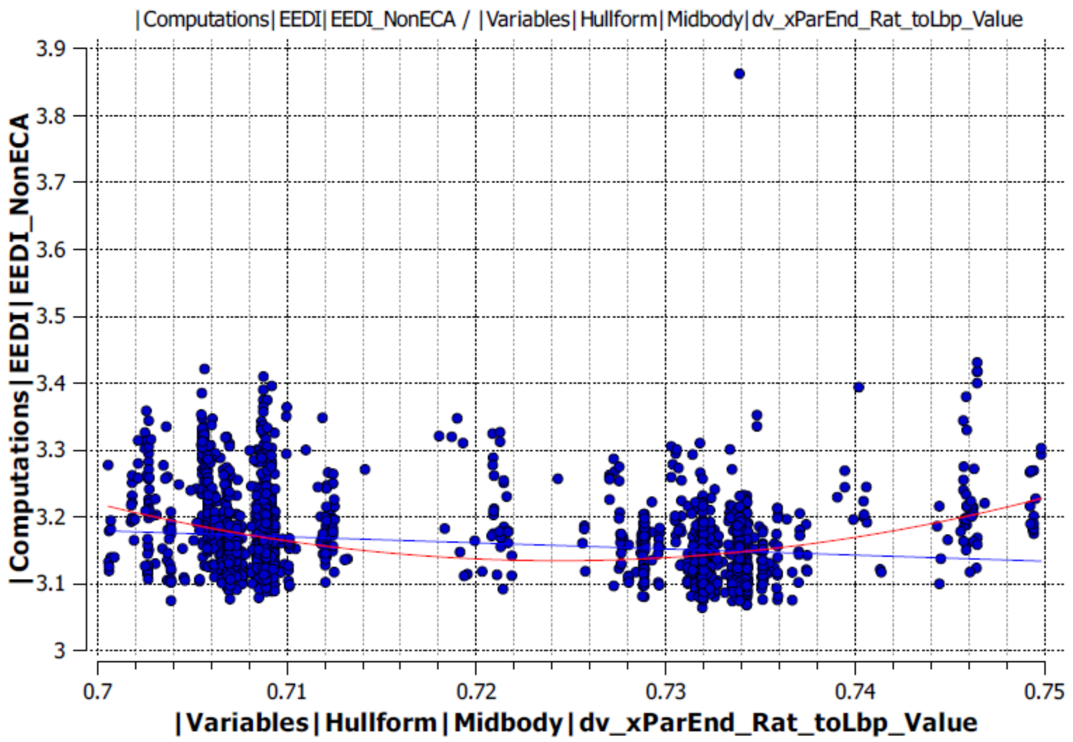


Figure [23]

3. ***Accidental Oil Outflow Index (OOI-according to MARPOL Reg. 23)***

The Accidental Oil Outflow Index is a Key Performance Indicator for the safety of each design and follows the MARPOL probabilistic calculation. Two accidents and their respective probabilities are considered; grounding and collision. The parameters whose sensitivity is assessed in terms of the OOI are the tank variables and some of the main dimensions, as local hullform parameters have no influence on the Index (negligible changes of displacement only). The tank variables are directly correlated to the Oil Outflow Index as it is entirely dependent on the tank size, position and geometry. However it is interesting to see that the double bottom height is much less influencing the OOI than the side tank width, which can be attributed to the origins of Regulation 23, as collision accidents are more frequent and have bigger consequences than grounding accidents. This was done in order to illustrate the good oil outflow performance of the mid-deck tanker which was introduced in the early 90s as an alternative to the double hull arrangement (the mid deck tanker had a very small double bottom but a large wing ballast tank and a mid deck with a total performance better than a double hull tanker).

The main dimensions also affect the performance in terms of OOI as the larger vessel sizes come with larger tanks that correspond to a bigger probabilistic outflow. More specifically the effect of each variable on the OOI is discussed:

- **Double Bottom Height**, Figure [24], has a positive effect for the OOI as it increases but there are cases with a smaller double bottom that have the smallest OOI as their double hull width is larger and has a bigger effect on the outflow calculation.
- **Double Hull Width**, Figure [25], The increase of the double hull width triggers a steep decrease of the OOI and thus has the greatest influence of all design variables and is used as the primary means of increasing the safety by mitigated the potential oil outflow.
- **Mid Tank Width**, Figure [26], displays an optimum value for the minimization of the OOI at about 45-47% which is reasonable. In small mid tank widths, the side tanks are large leading to an increase of the oil outflow. As the centre tank gets larger and the side tanks smaller, the oil outflow is decreased but up to a certain width, as there is afterwards an increased probability for breaching the longitudinal bulkhead and having an outflow from both the side and centre tanks.
- **Breadth**, Figure [27], triggers an increase of the OOI as its is also increased due to larger side tank sizes.
- **Height**, Figure [28], has a positive effect up to a point as it increases but afterwards it causes an increase for the OOI as the tank size is larger and the hydrostatic difference in the case of high tide is also larger, thus leading to a higher outflow.
- **Block Coefficient**, Figure [29], leads to a direct increase of the OOI for fuller ships as the tank size is larger and the displacement too.

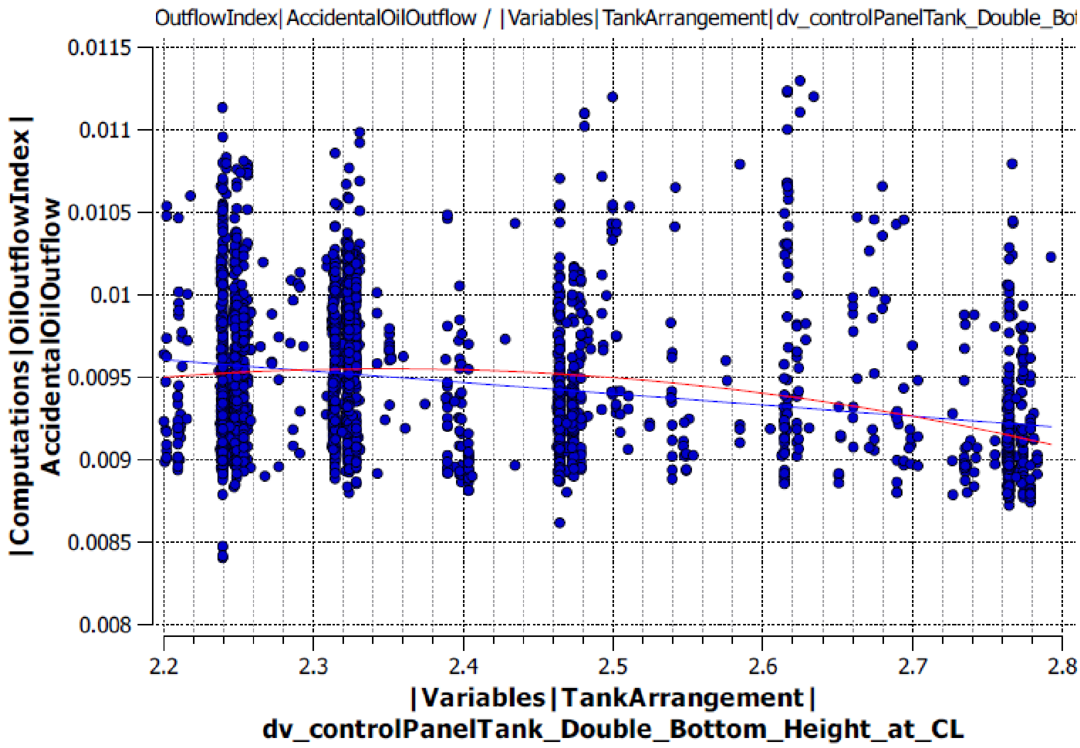


Figure [24]

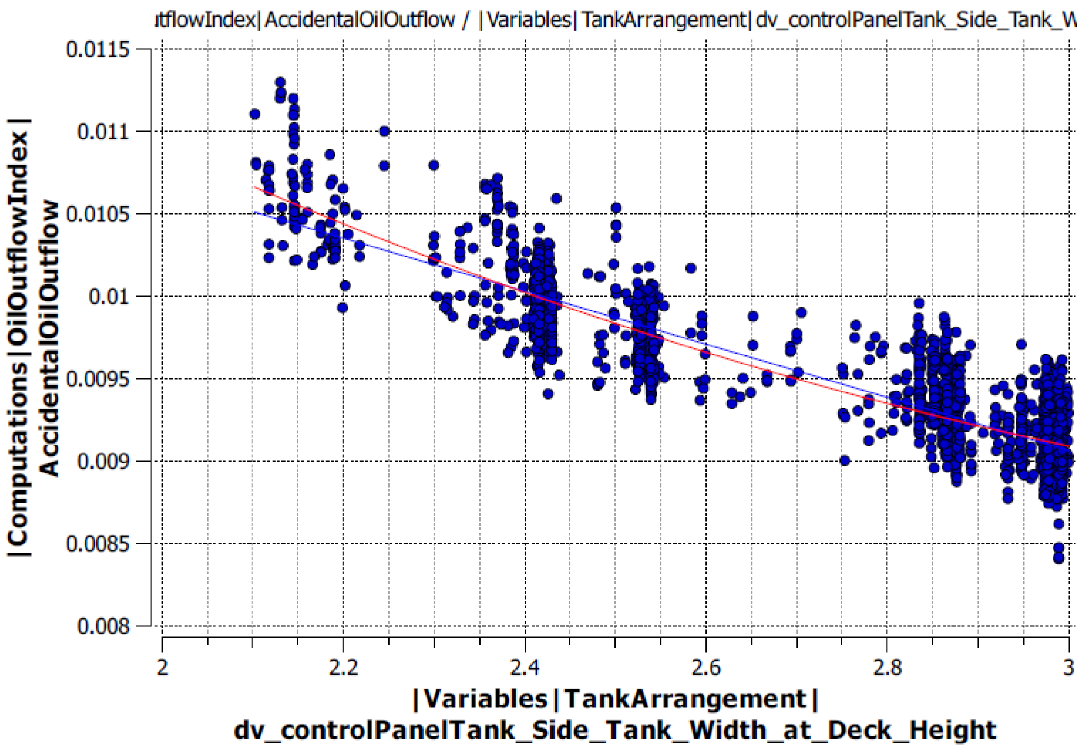


Figure [25]

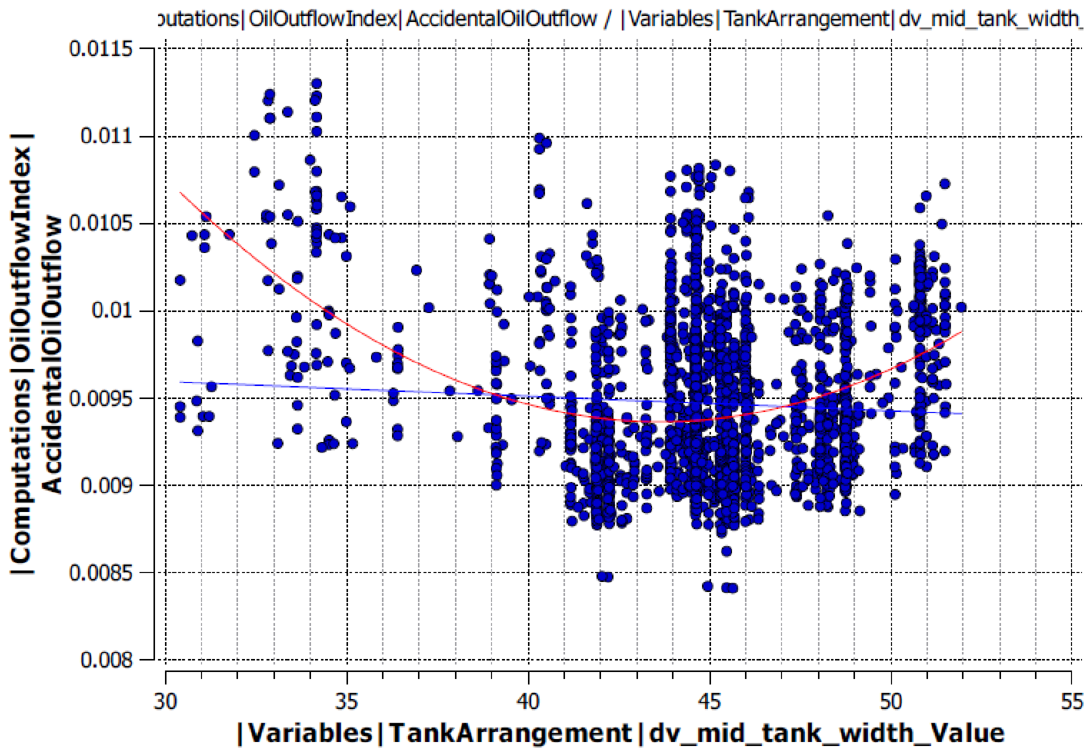
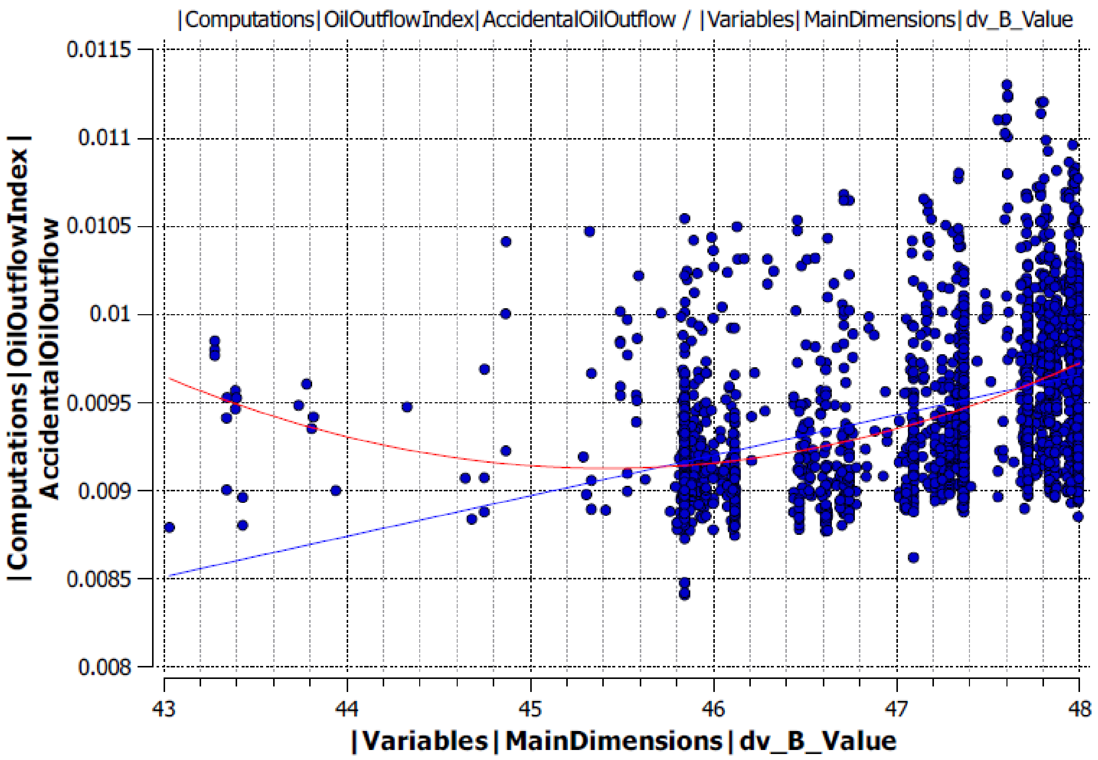


Figure [26]



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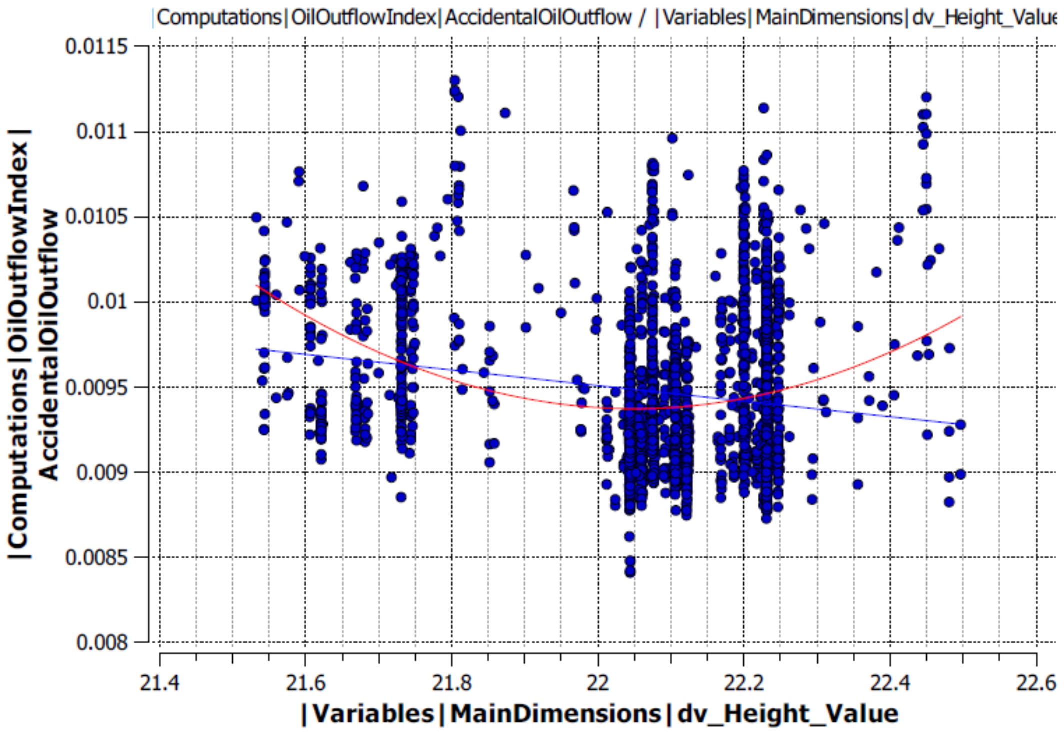

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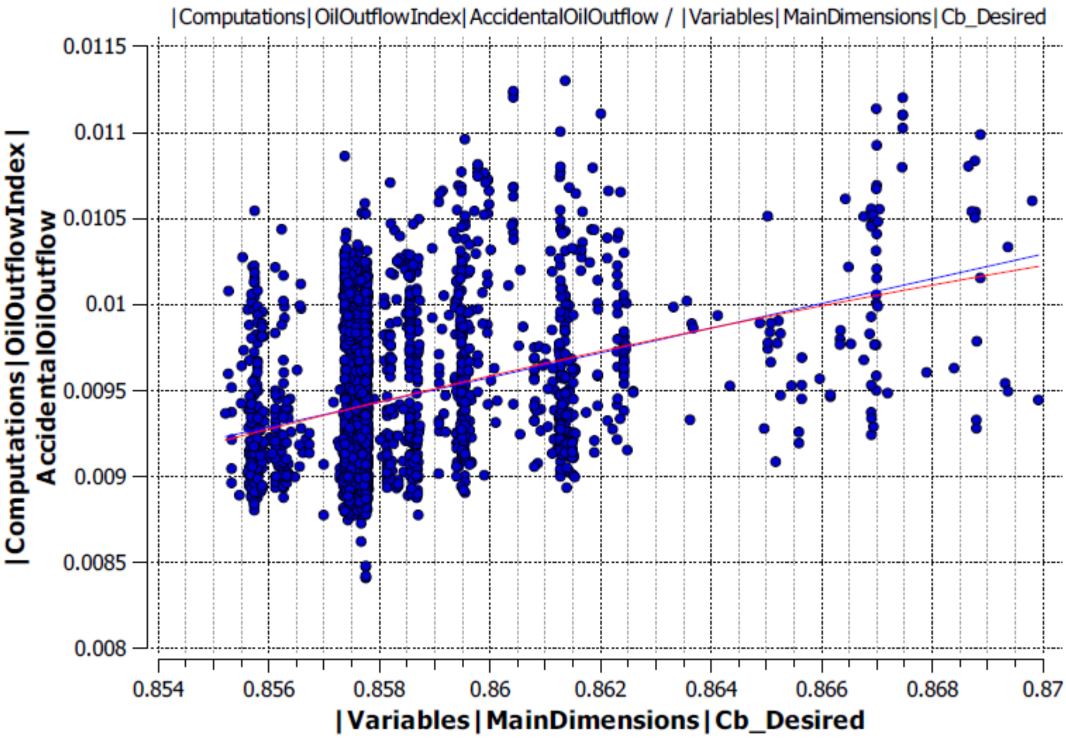


Figure [29]

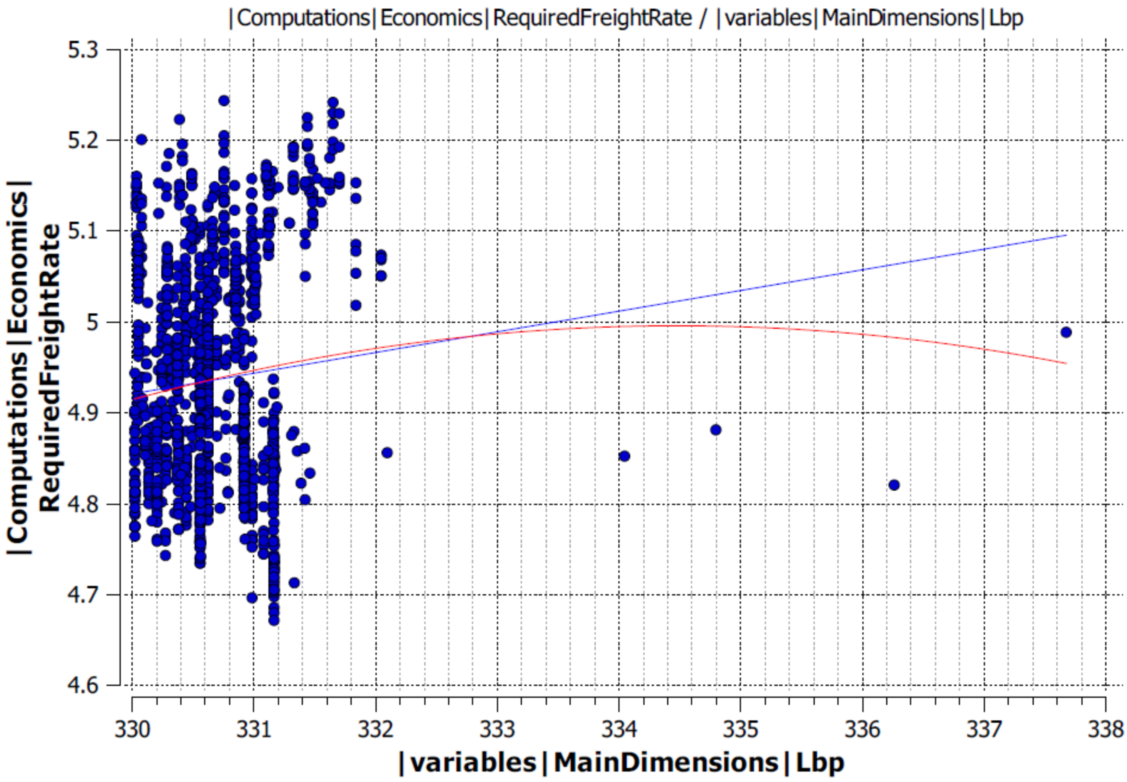
PART II: CASE STUDY ON VLCC TANKERS

As a second part the holistic methodology is applied at a small scale for the optimization of a conventional, single screw VLCC. This concept is also assessed in terms of sensitivity in order to see the applicability and the convergence of the method. For each design objective, the influence of each design variable is understood in combination with the general term. Each circular point represent a successful design, while the x point represents an unfeasible design as defined by the constraints imposed.

1. *Required Freight Rate (RFR) sensitivity*

The RFR is used as a Key Performance Indicator for the operational efficiency and the market competitiveness. Namely it represents how economical the ship is to build, operate and how profitable its operation is (in terms of cargo capacity). A general impression is that the larger vessel sizes have a positive influence to the RFR thanks to the strong correlation to the tank capacity. This phenomenon is very common in ship design, as scale economies have been the primary driver of the evolution of tanker design up until recently, that there is an upper unofficial limit of tank sizes due to the risk of pollution. Other variables than the main dimensions that have a strong (the strongest) influence are the tank variables while the local hullform shape has a less important but existing correlation. More specifically the sensitivities monitored can be seen in Figures [1] to [13] and their interpretation is the following:

- **Length**, Figure [30], is kept at a very narrow band for the VLCC case due to the robustness of the software.
- **Breadth**, Figure [31], is also influencing RFR in a linear way with the beamiest ship being the most economical. It is also interesting to see that the breadth increase is more effective in the RFR reduction than that of the length.
- **Height**, Figure [32], is influencing in a much less steep way the RFR. Usually, the designs with a bigger deck height have a bigger tank capacity.
- **Draft**, Figure [33], is beneficial for the RFR as it increases, which is natural as the displacement and thus deadweight is increased.
- **Block Coefficient**, Figure [34], for this vessel size is beneficial for the RFR when kept at smaller values.
- **LCB position**, Figure [35], is beneficial for the RFR when it is shifted towards the bow up to 52.6%. Afterwards it is negative due to increased resistance.
- **Double Bottom Height**, Figure [36], is negative for the economic performance as it increases, due to the decrease of tank capacity.
- **Double Hull Width**, Figure [37], is negative for the economic performance as it increases, due to the decrease of tank capacity.
- **Mid Tank Width**, Figure [38], displays two local optimum points, one at 50 and at 55% of the cargo breadth.



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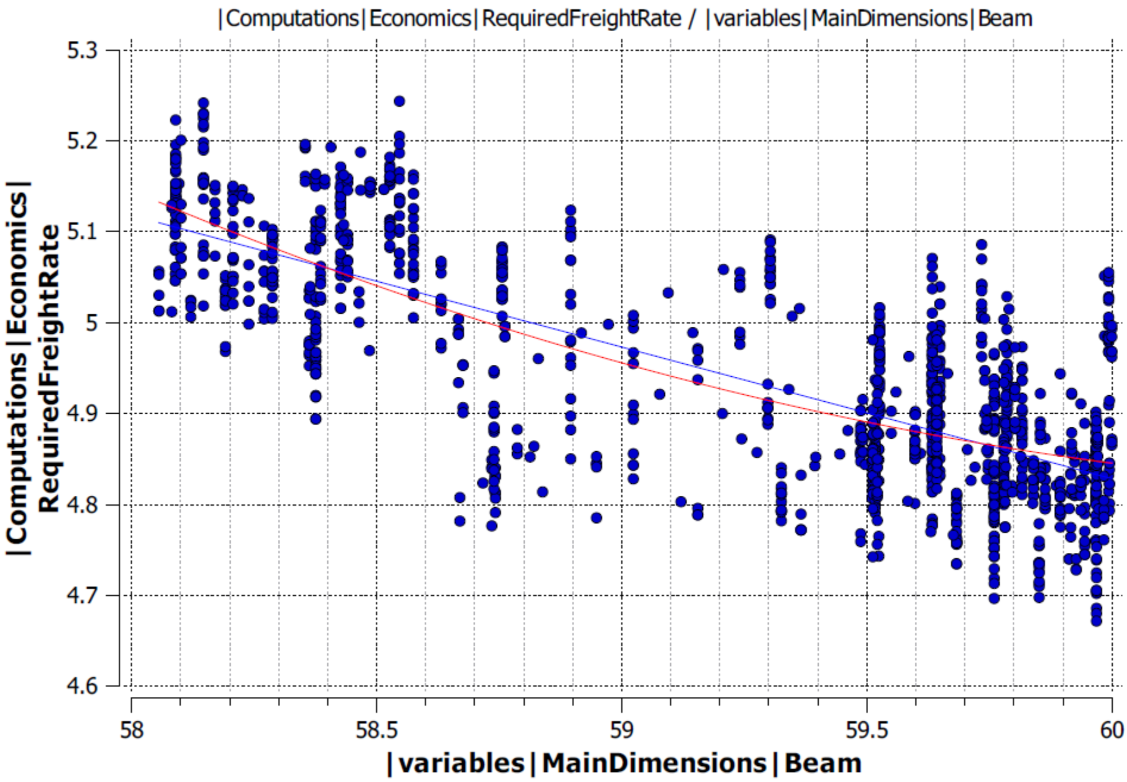

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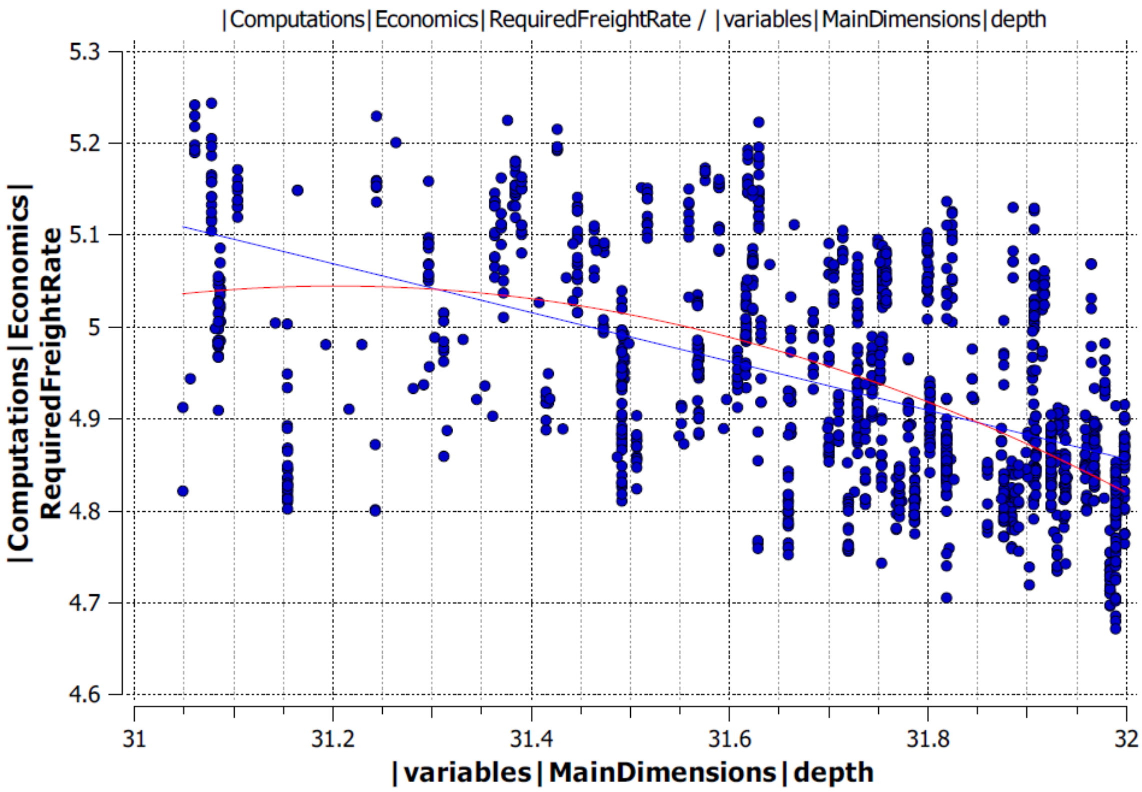

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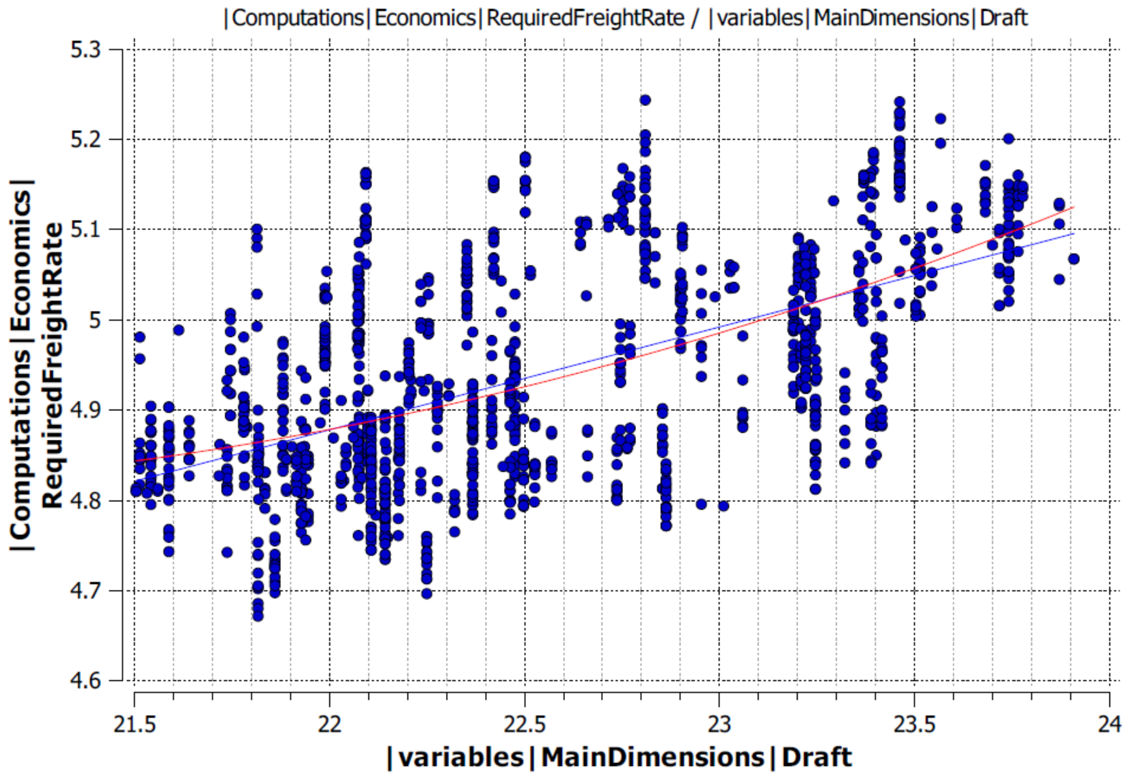

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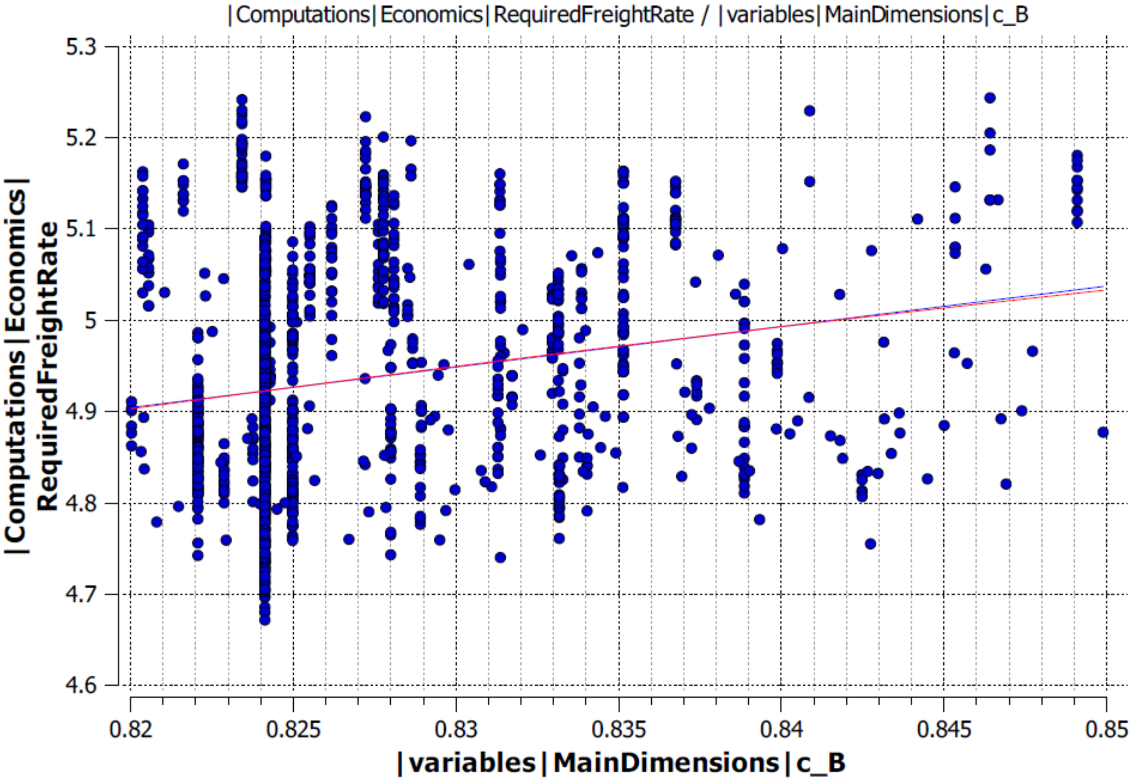
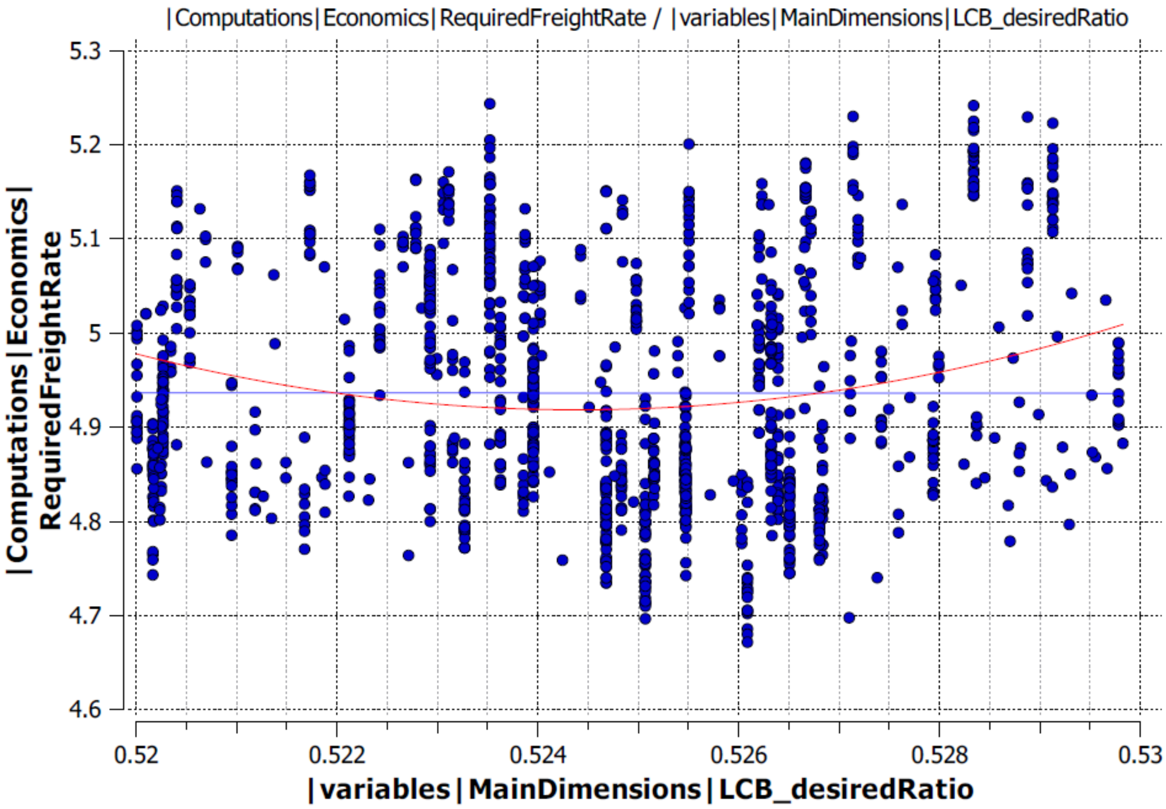


Figure [34]



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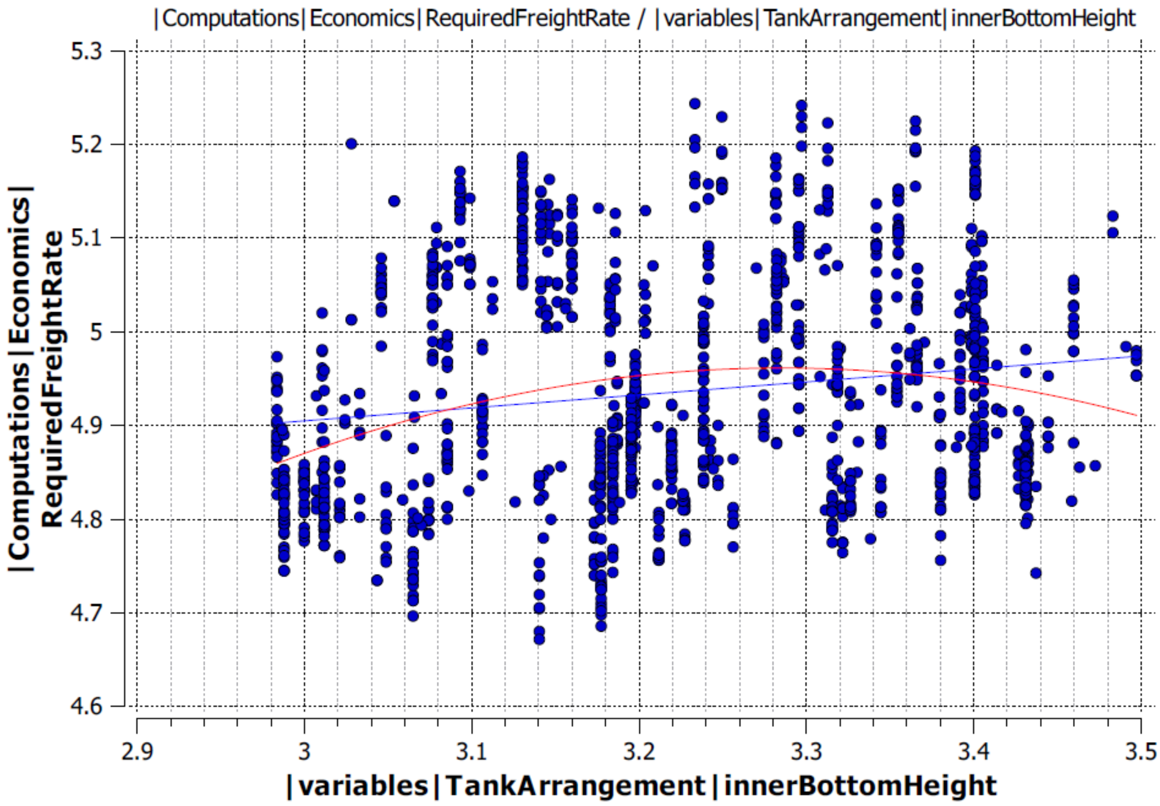

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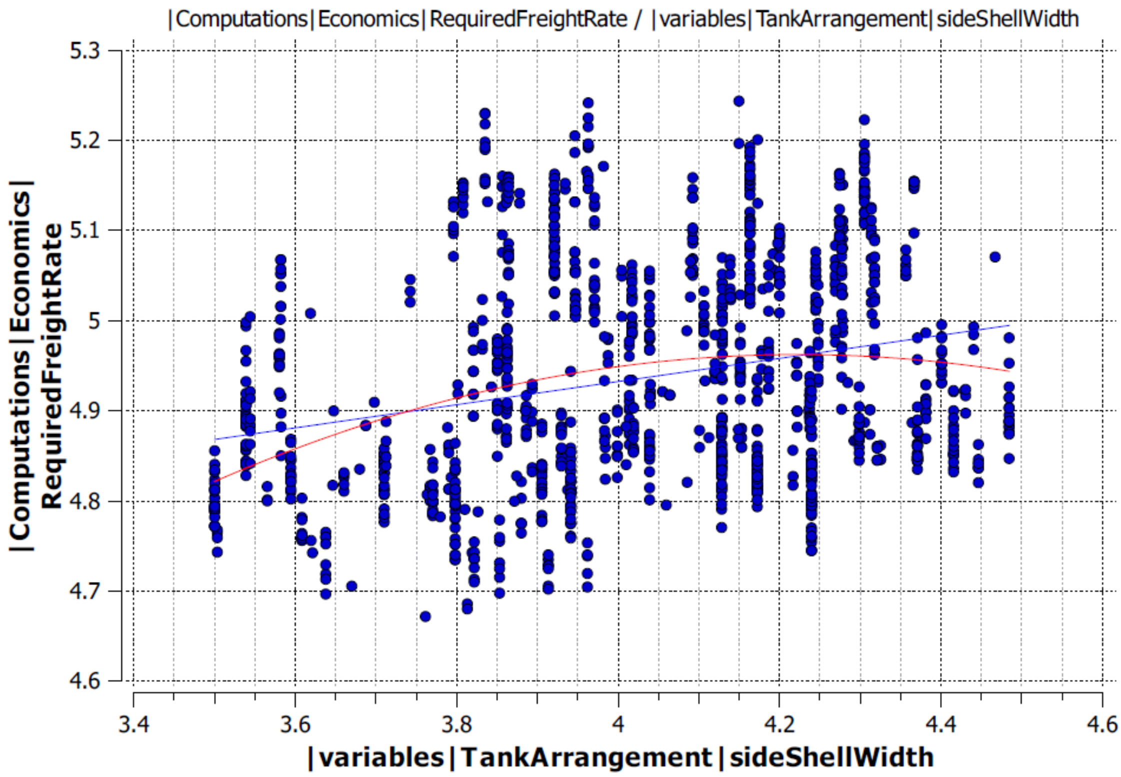

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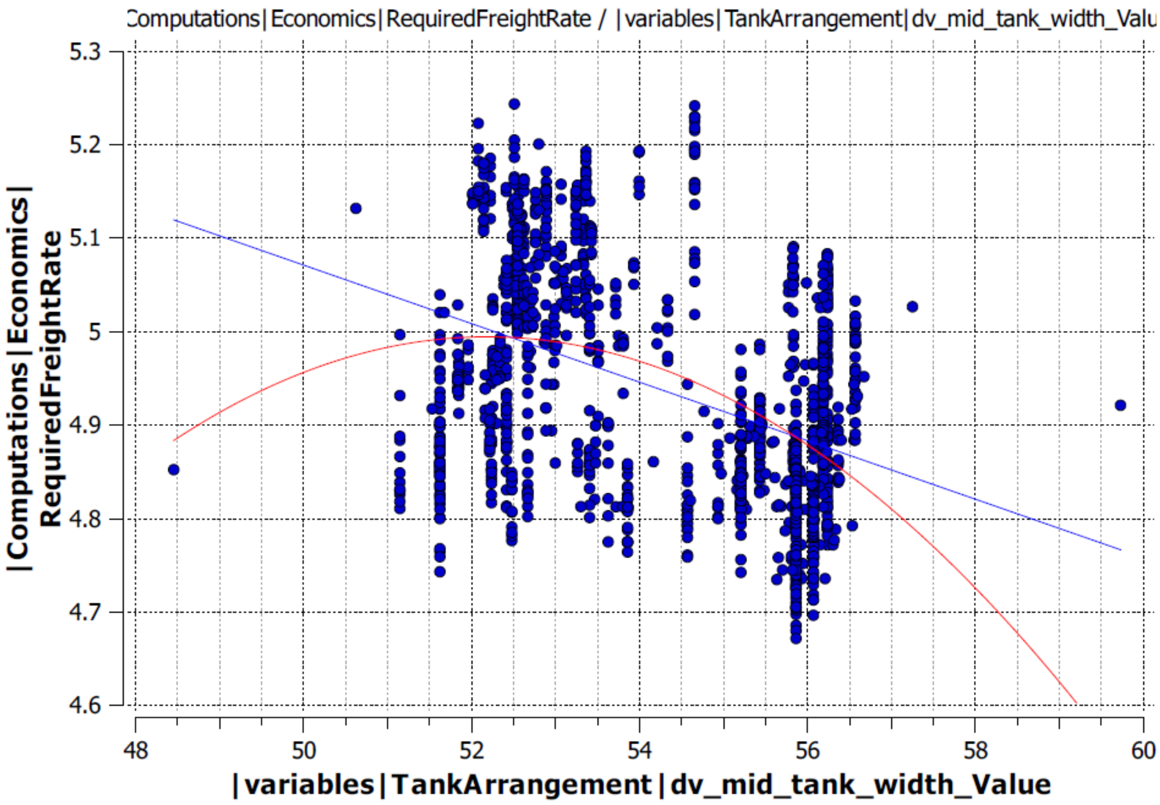

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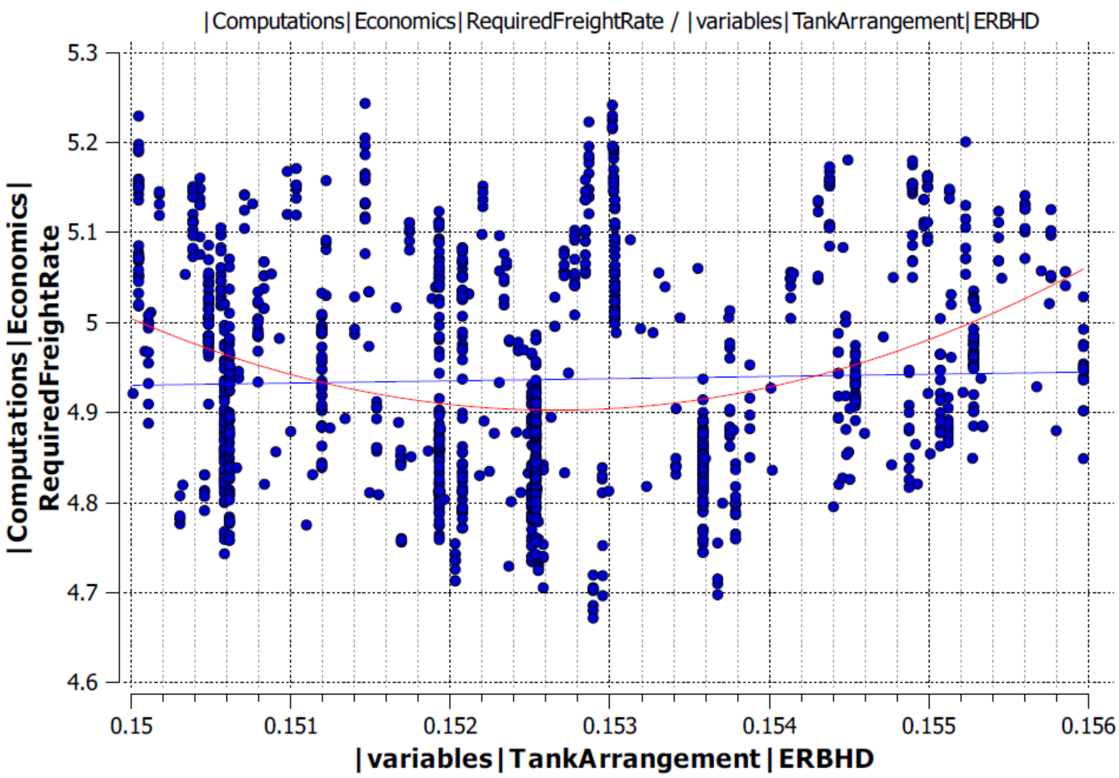


Figure [38]

2. IMO Energy Efficiency Design Index (EEDI) sensitivity

The EEDI is used as a Key Performance Indicator for the efficiency of each design and is calculated according to the guidelines decided on IMO MEPC 62. A general impression is that the larger vessel sizes have a positive influence to the EEDI thanks to the strong correlation to the deadweight and the smaller increase of the installed power. Since speed was not decided to be used in the optimization as a design variable the installed power was not varied significantly and it is also now clearer which designs have a better hydrodynamic performance. The local hullform parameters influence the EEDI via the wetted surface and thus the installed power. It is also very interesting to see that the sensitivities found for the RFR objective are qualitive the same as in the EEDI which illustrated the “win-win” situation for the decision maker with the increase of the fuel and transport efficiency in conjunction with the economic performance. More specifically the sensitivities monitored can be seen in Figures [1] to [13] and their interpretation is the following:

- **Length**, Figure [14], is kept at smaller values due to the concentration of the algorithm to these values.
- **Breadth**, Figure [15], is not influencing EEDI as in the case of the AFRAMAX, with the VLCC being more insensitive in beam changes.
- **Draft**, Figure [16], demonstrates the heavy dependency of the EEDI to the deadweight since as the beam increases the displacement and thus deadweight is increases resulting to a decrease of the EEDI.
- **Height**, Figure [17], is much less influential than the other dimensions in the EEDI
- **Block Coefficient**, Figure [18], for this vessel size is beneficial for the RFR when kept at smaller values.
- **LCB position**, Figure [19], is not affecting the EEDI as in the vase of the AFRAMAX tanker, since the resistance values are less sensitive to changes.

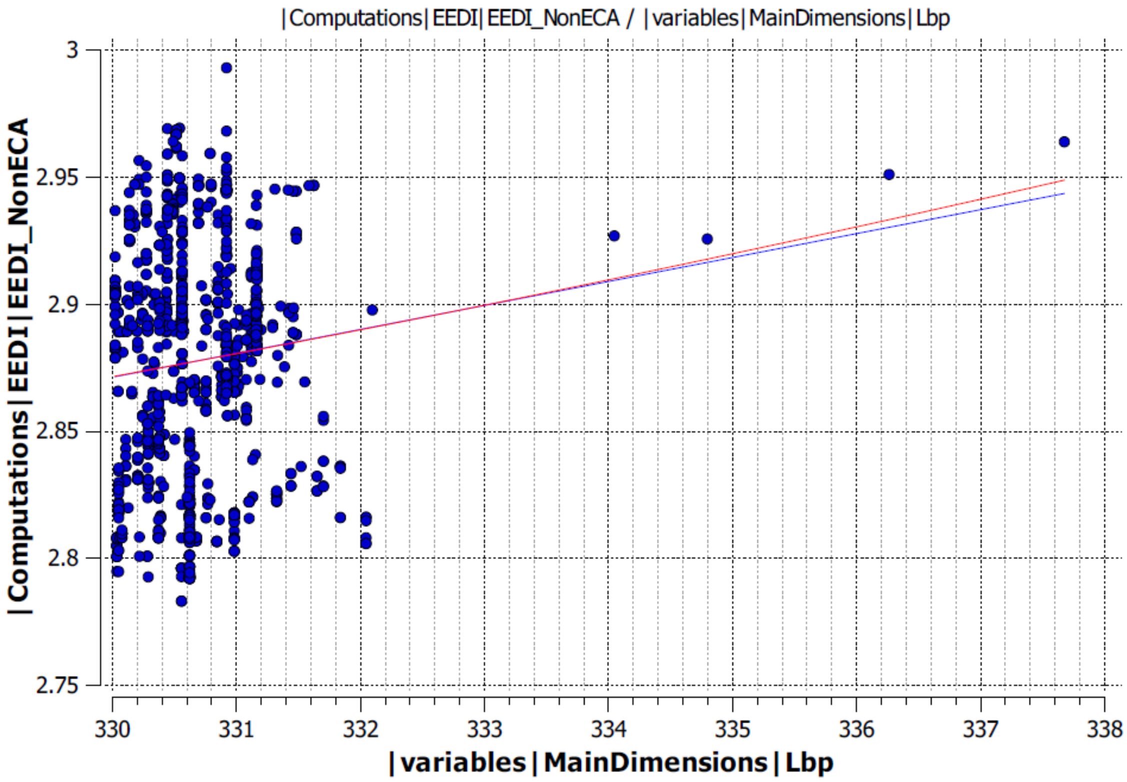
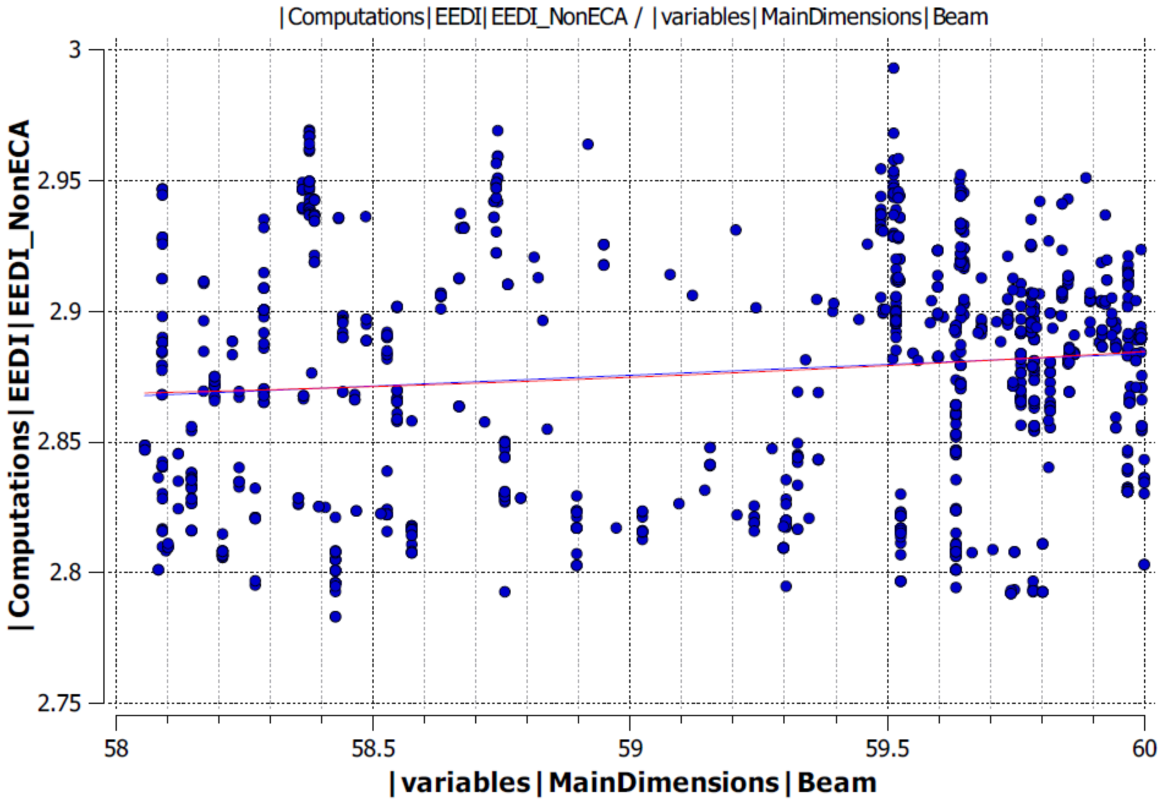


Figure [39]



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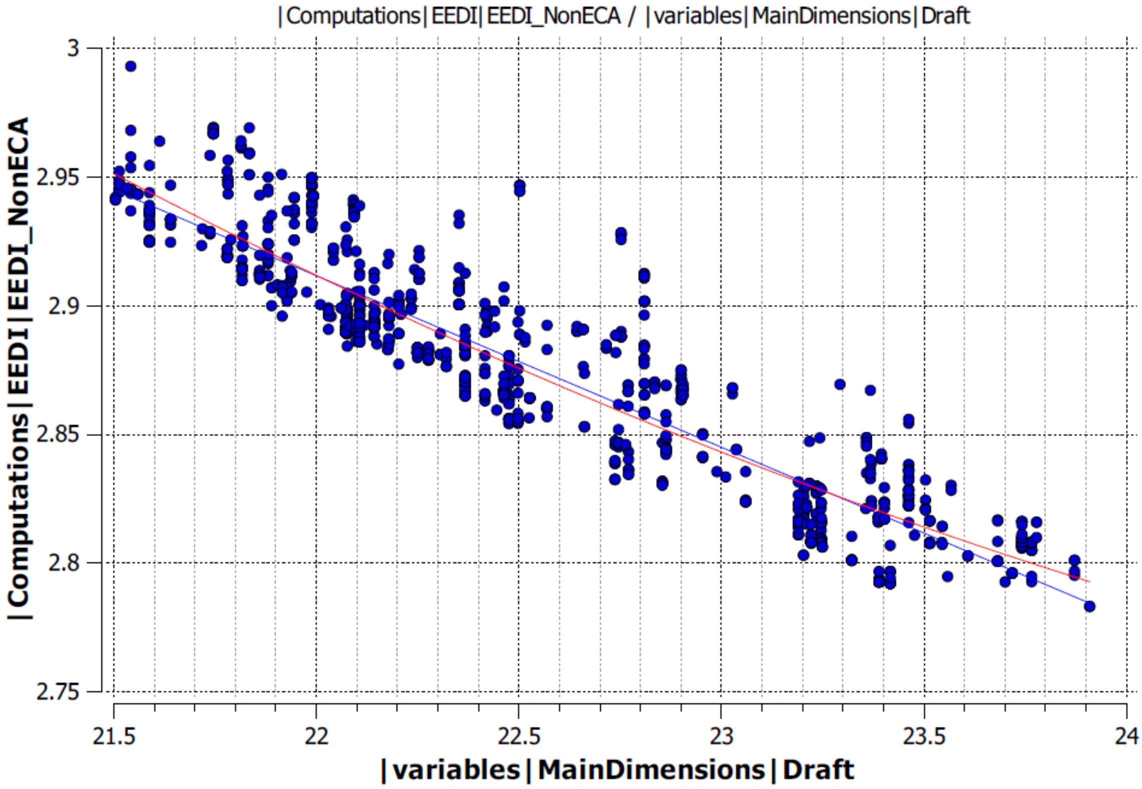

Figure [41]

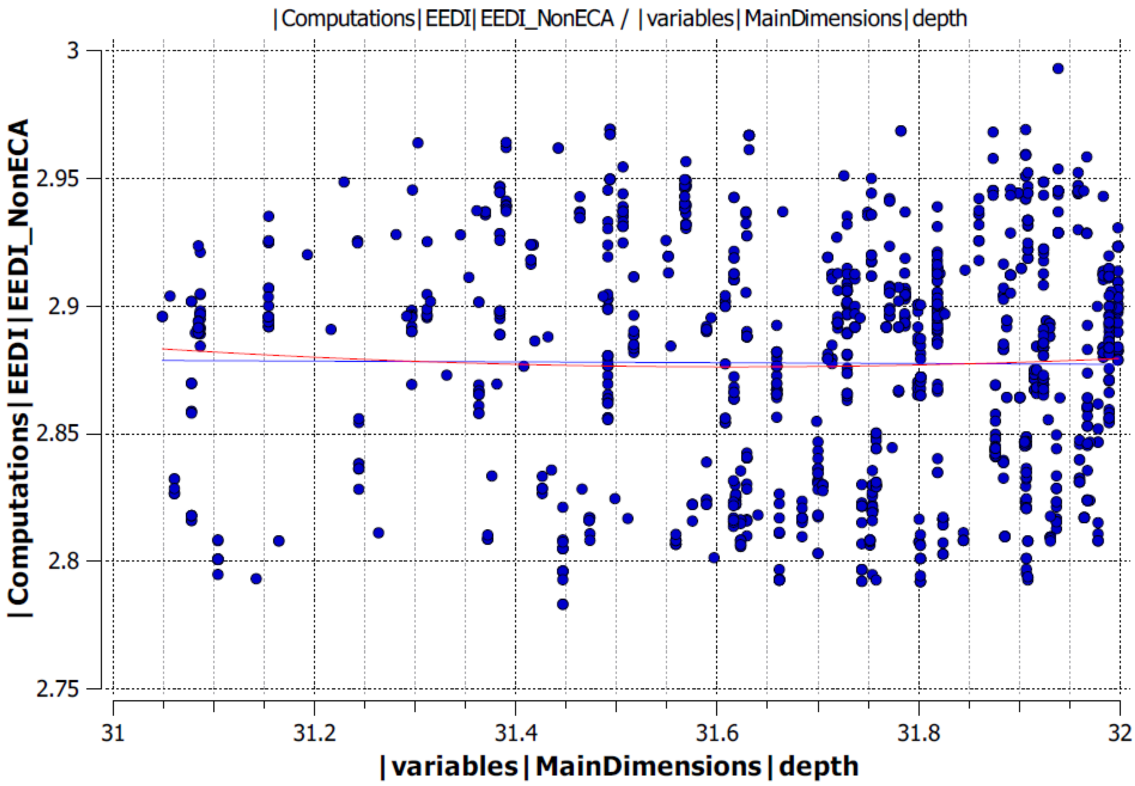

Figure [42]

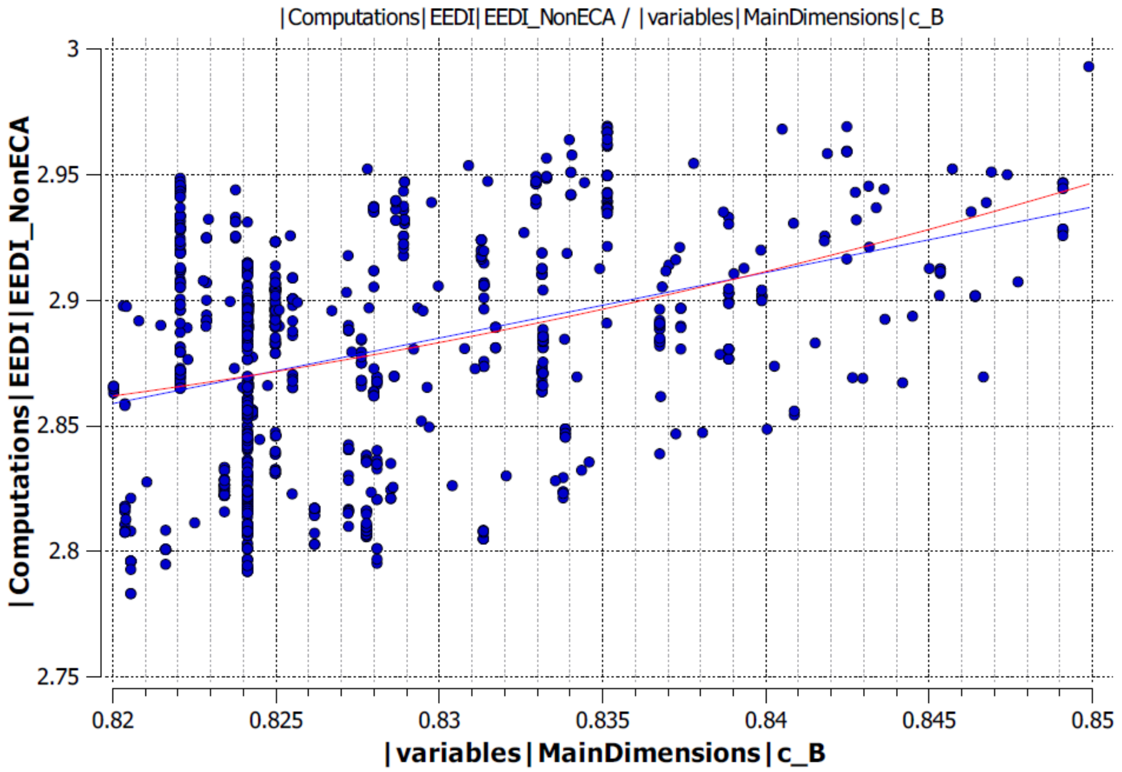

Figure [43]

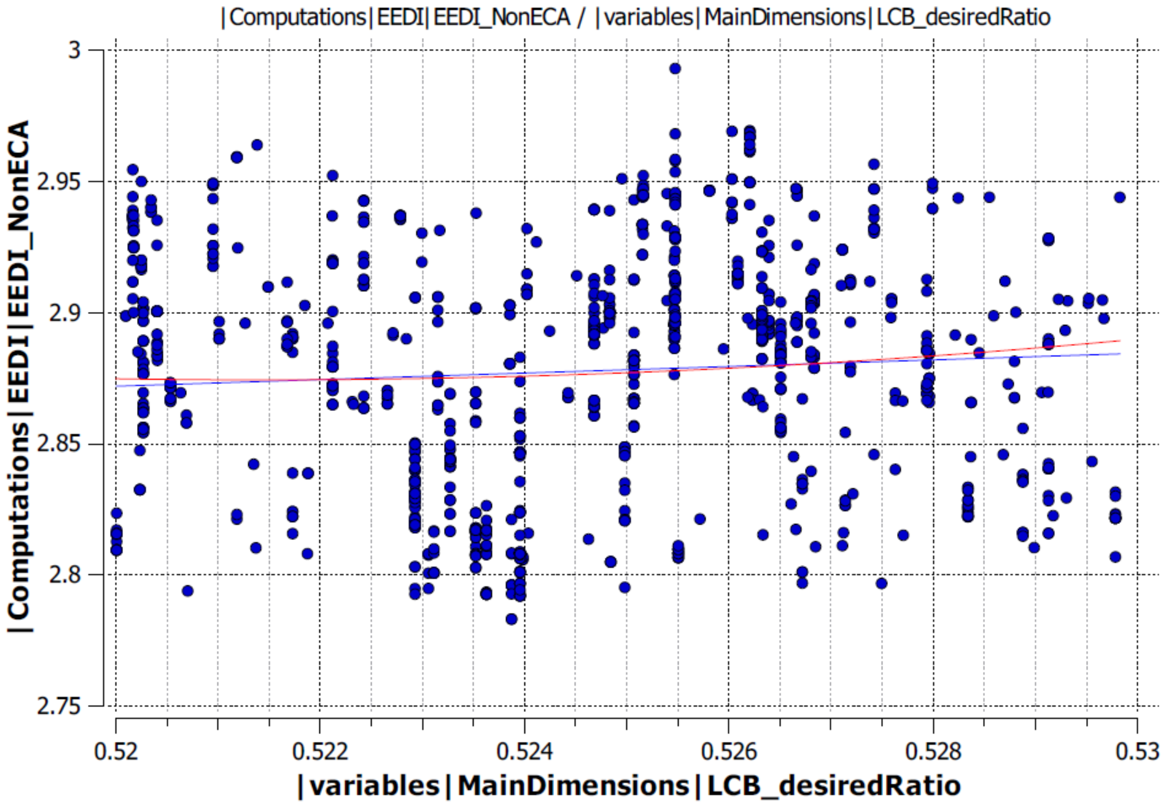

Figure [44]

3. Accidental Oil Outflow Index (OOI-according to MARPOL Reg. 23)

The Accidental Oil Outflow Index is a Key Performance Indicator for the safety of each design and follows the MARPOL probabilistic calculation. Two accidents and their respective probabilities are considered; grounding and collision. The parameters whose sensitivity is assessed in terms of the OOI are the tank variables and some of the main dimensions, as local hullform parameters have no influence on the Index (negligible changes of displacement only). The tank variables are directly correlated to the Oil Outflow Index as it is entirely dependent on the tank size, position and geometry. However it is interesting to see that the double bottom height is much less influencing the OOI than the side tank width, which can be attributed to the origins of Regulation 23, as collision accidents are more frequent and have bigger consequences than grounding accidents. This was done in order to illustrate the good oil outflow performance of the mid-deck tanker which was introduced in the early 90s as an alternative to the double hull arrangement (the mid deck tanker had a very small double bottom but a large wing ballast tank and a mid deck with a total performance better than a double hull tanker).

The main dimensions also affect the performance in terms of OOI as the larger vessel sizes come with larger tanks that correspond to a bigger probabilistic outflow. More specifically the effect of each variable on the OOI is discussed:

- **Double Bottom Height**, Figure [45], has a positive effect for the OOI as it increases but there are cases with a smaller double bottom that have the smallest OOI as their double hull width is larger and has a bigger effect on the outflow calculation.
- **Double Hull Width**, Figure [46], The increase of the double hull width triggers a steep decrease of the OOI and thus has the greatest influence of all design variables and is used as the primary means of increasing the safety by mitigated the potential oil outflow.
- **Mid Tank Width**, Figure [47], displays an optimum value for the minimization of the OOI at about 50% and afterwards at 55% which is reasonable. In small mid tank widths, the side tanks are large leading to an increase of the oil outflow. As the centre tank gets larger and the side tanks smaller, the oil outflow is decreased but up to a certain width, as there is afterwards an increased probability for breaching the longitudinal bulkhead and having an outflow from both the side and centre tanks.
- **Breadth**, Figure [48], triggers an increase of the OOI as its is also increased due to larger side tank sizes.
- **Height**, Figure [49], has a positive effect up to a point as it increases but afterwards it causes an increase for the OOI as the tank size is larger and the hydrostatic difference in the case of high tide is also larger, thus leading to a higher outflow.

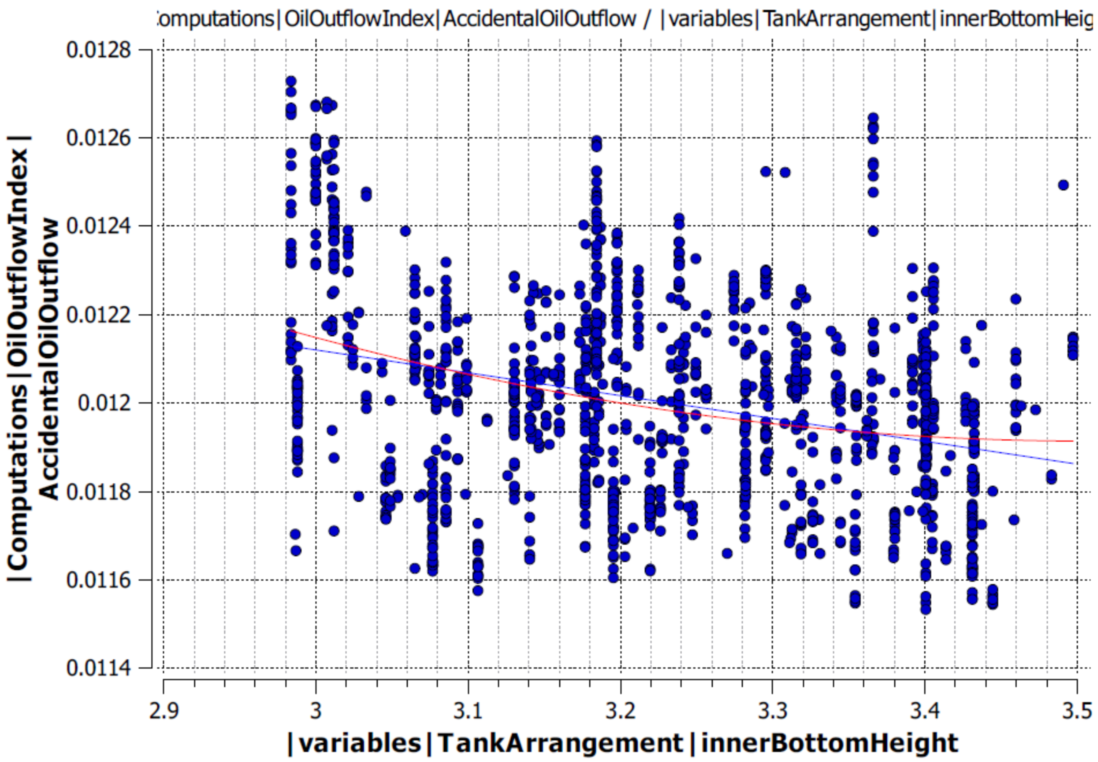

Figure [45]

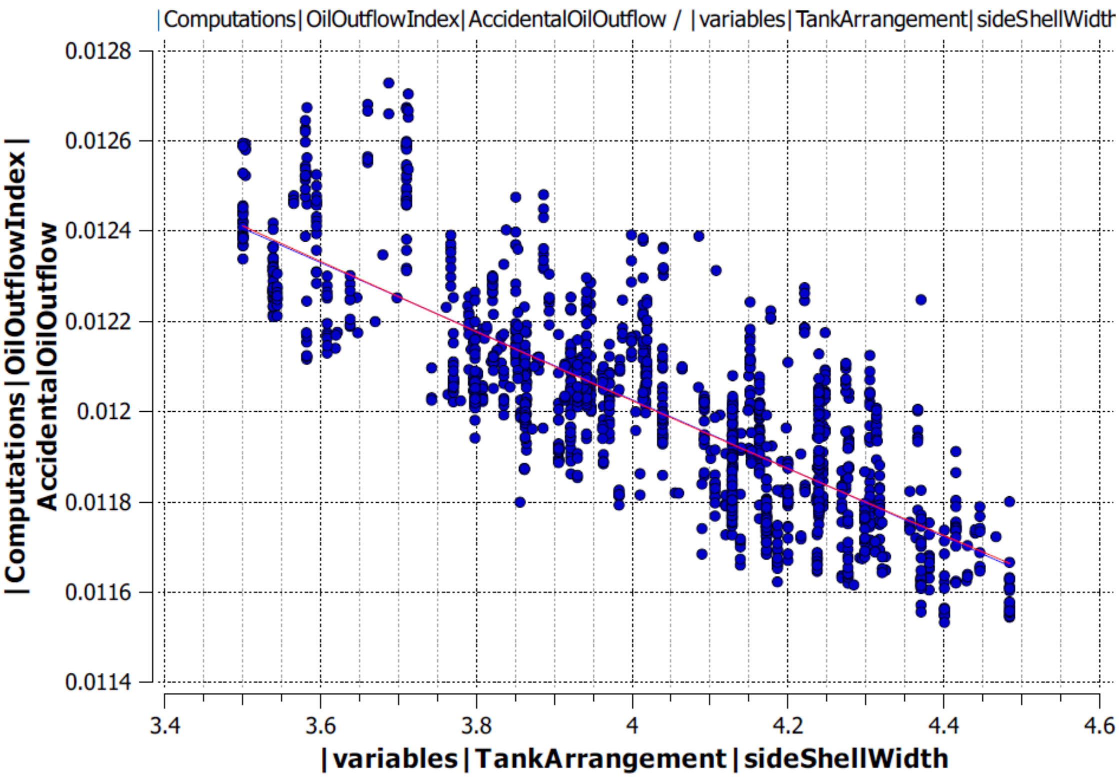

Figure [46]

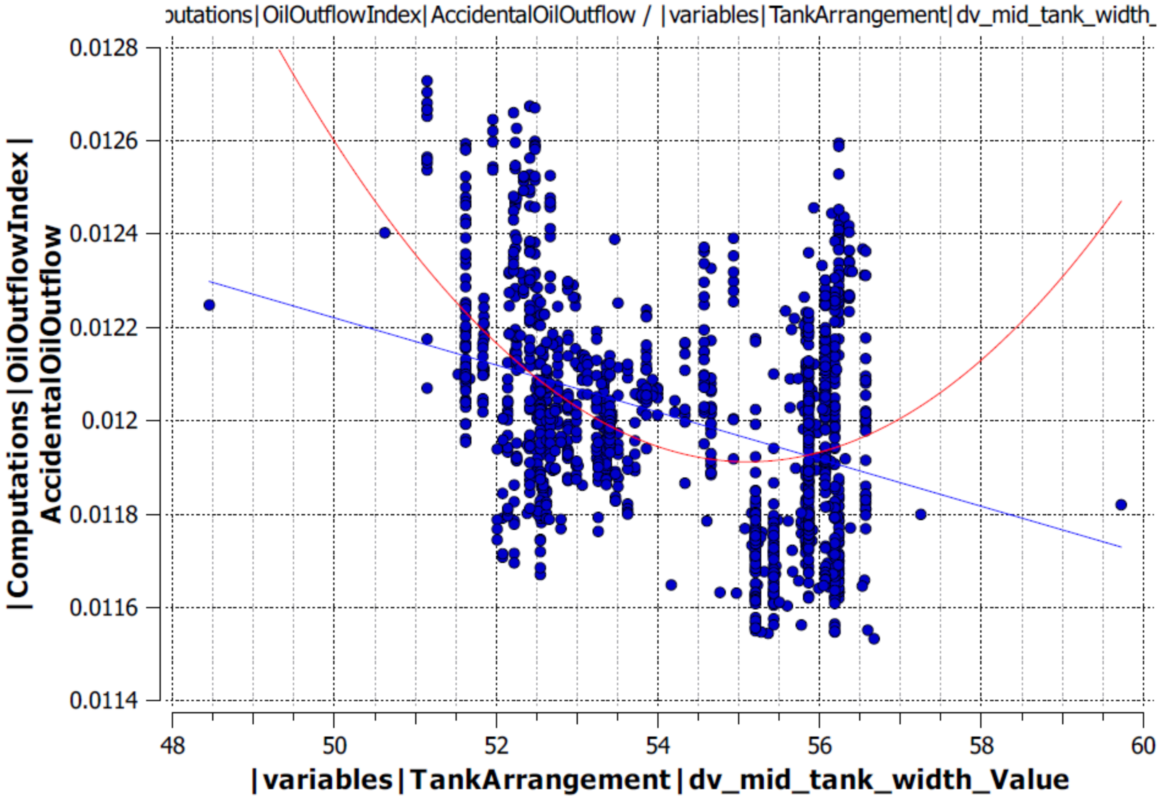

Figure [47]

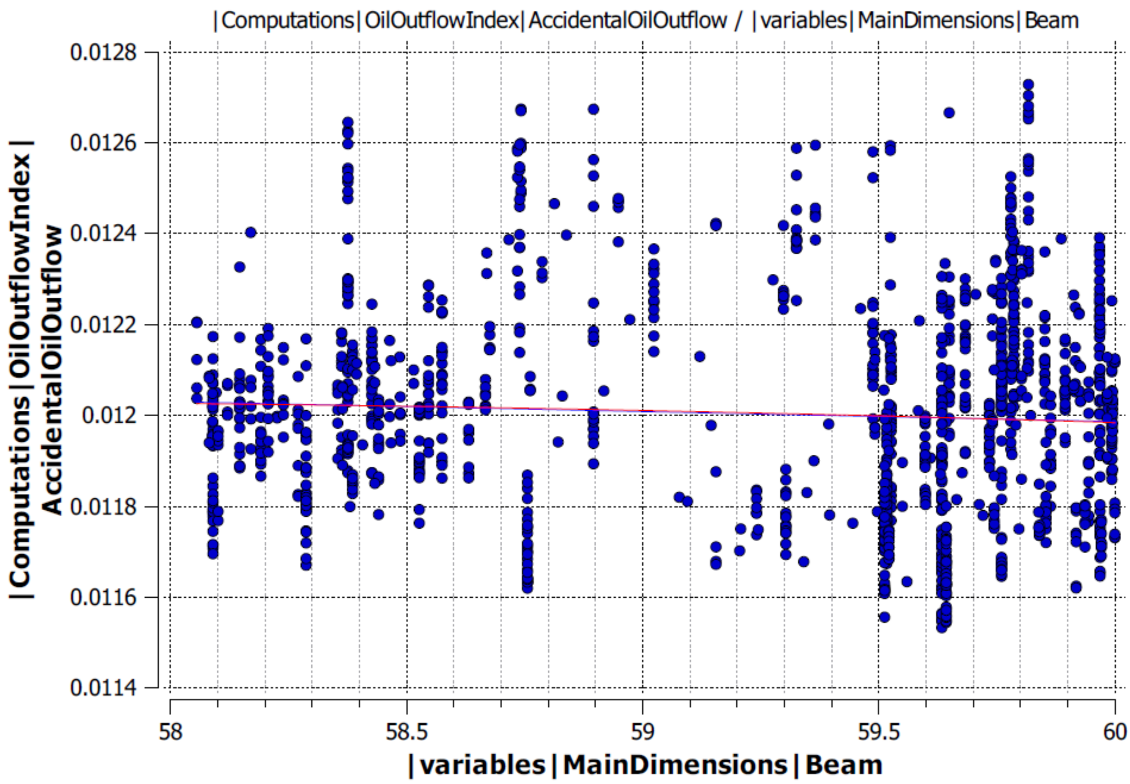

Figure [48]

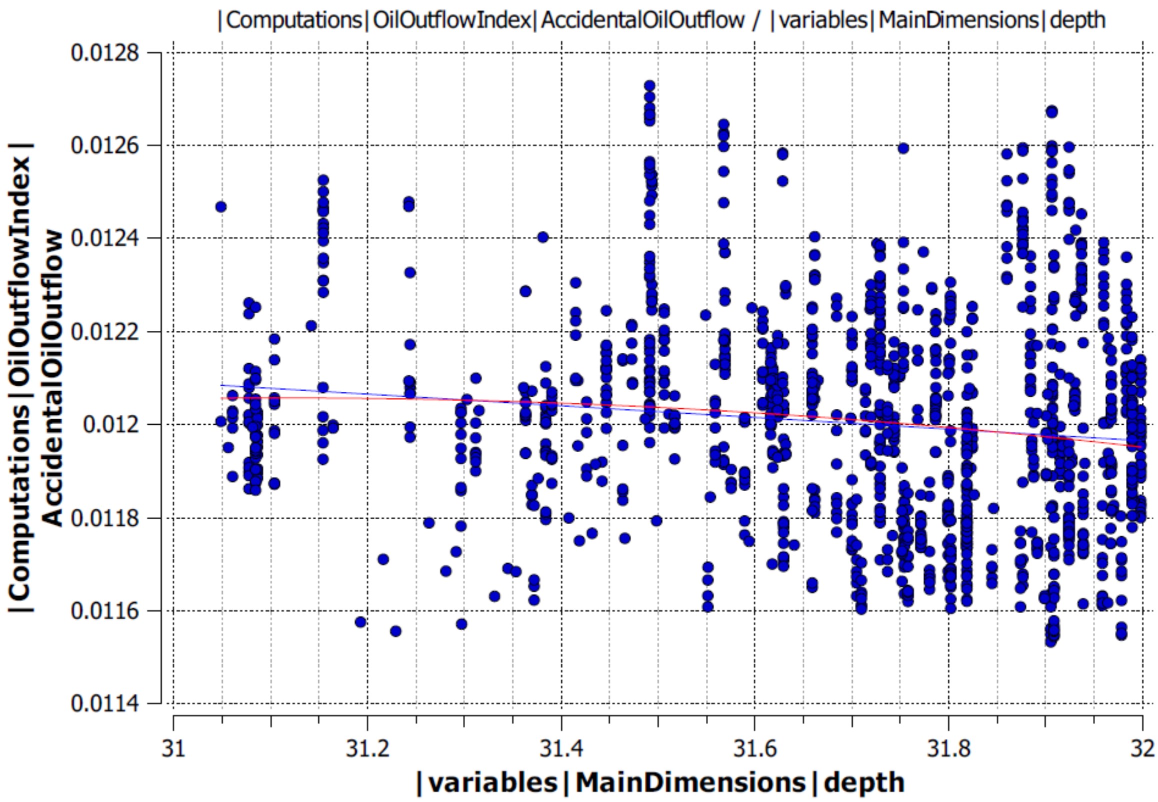
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Figure [49]

APPENDIX II:

CASE STUDY ON THE OPTIMIZATION OF VLCC TANKERS

APPENDIX II: CASE STUDY ON THE OPTIMIZATION OF VLCC TANKERS

In addition to the exhaustive and multi staged case study on the design and optimization of innovative AFRAMAX tankers a secondary study has been made for the VLCC segment. Initially a fully parametric model of a VLCC has been developed in the Friendship Framework also within the context of the obligatory Ship Design Project at NTUA. Afterwards, the developed holistic methodology was applied to the fully parametric geometrical model in order to illustrate the applicability of the method and its robustness over a range of vessel sizes and types as the VLCC is a conventional single screw vessel. The study is at this appendix as it is much less detailed and contains only one smaller Design of Experiment (DoE) that produced 1000 variants and an optimization run using the NSGA II and MOSA algorithms.

1. *Design Variables*

The design variables chosen herein for the systematic variation and optimization were the main dimensions and tank variables aiming at a more preliminary, fast and global approach:

Variable	Lower Boundary	Upper Boundary
Length (m)	300	340
Beam (m)	57	62
Draft (m)	21	24
Height (m)	30	32
Cb	0.815	0.855
LCB position (% Lbp)	0.51	0.54
Double Bottom Height (m)	2.5	3
Double Hull Width (m)	3	4
Mid Tank Width (% Bcargo)	30	55 %
Transverse Bulkhead Shift	-1 frame	+1 frame

Table [1]: Boundaries for design variables of the VLCC case

2. *Design Objectives*

As in the case of the AFRAMAX tankers the objectives of the optimization is primarily to minimize the Oil Outflow Index, Required Freight Rate and EEDI. It is also desirable to monitor and find the vessels with larger tank capacities and smaller installed power and see their relationship with the dominant variants from the optimization.

3. *Design Constraints*

The design constraints that were imposed during this process mainly restricted the size of the ship (less than 360000 DWT) in order to avoid excessive sizes which increase the risk of the oil pollution as the consequences in the case of accident rise significantly. In addition to that, in order to avoid very large tank sizes that cannot be supported by the payload weight, it was decided to use a lower boundary for the special gravity of the cargo. Last but not least, the oil outflow constraint was introduced and as the ship has a cargo capacity larger than 200000 cubic meters it was not constant but rather a linear function of the ship's capacity.

4. Design of Experiment (DoE)

After the computational model developed was adapted to the new surface model, the first design of experiment took place, in order to see what is the potential for the future optimization and the margin of improvement. In addition to that the DoE helped us see what is the design space and what are the initial trends for the variables.
The population of variants for the design of experiments was chosen to be 1000 in order to have a quick overview of the design space and afterwards be able to run some optimization runs. In the future this is going to be revisited for a more detailed application.

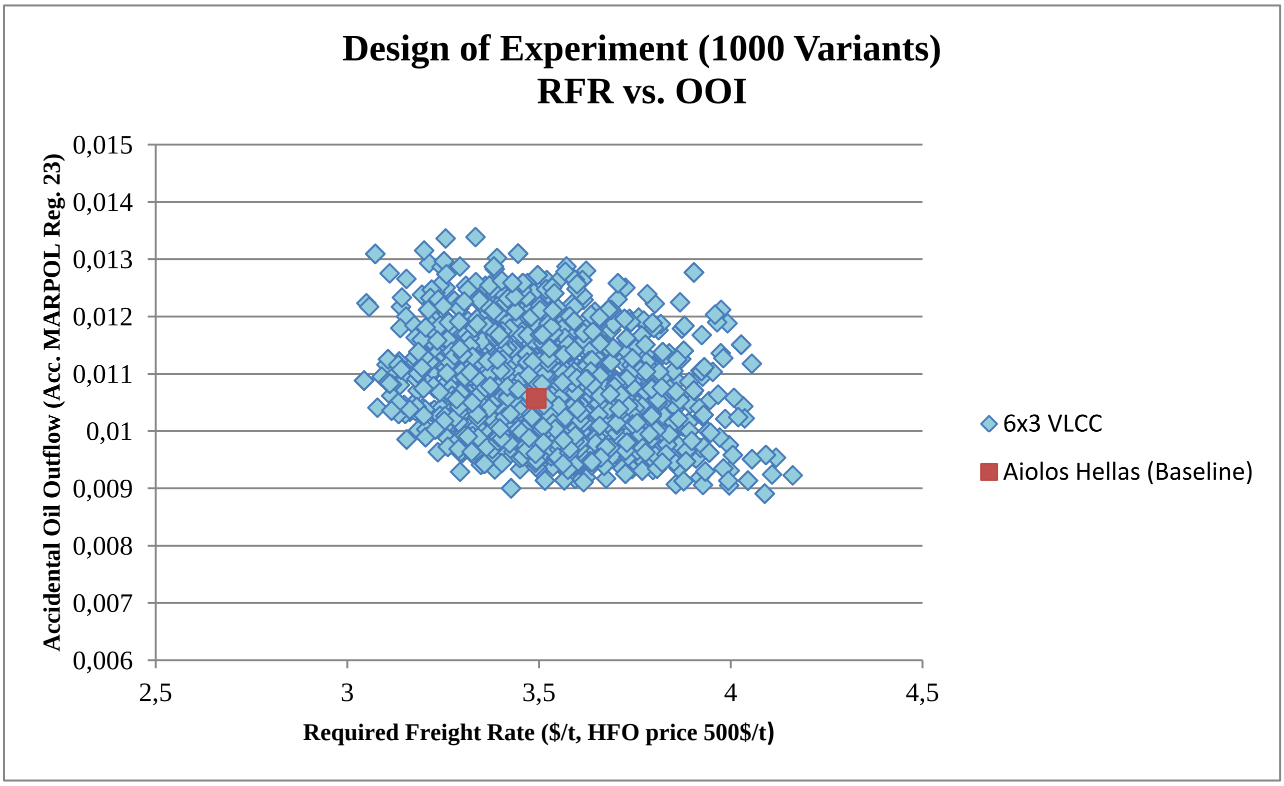


Figure [1]: Scatter Diagram of the relationship of RFR vs. OOI (Design of Experiment)

It is obvious from Figure [1] that in comparison with the baseline model (Aiolos Hellas-Ship Design Project) there is room for improvement since it is not one of the dominant designs. It is also evident that the RFR can be reduced significantly as there are no significant constraints for the dimensions and the ship size. However, at this type and since only the standard design (with two long. bulkheads) is assessed the size of the ship is very negative for the OOI performance of the ship meaning that the larger tanks have a negative effect on the oil outflow.

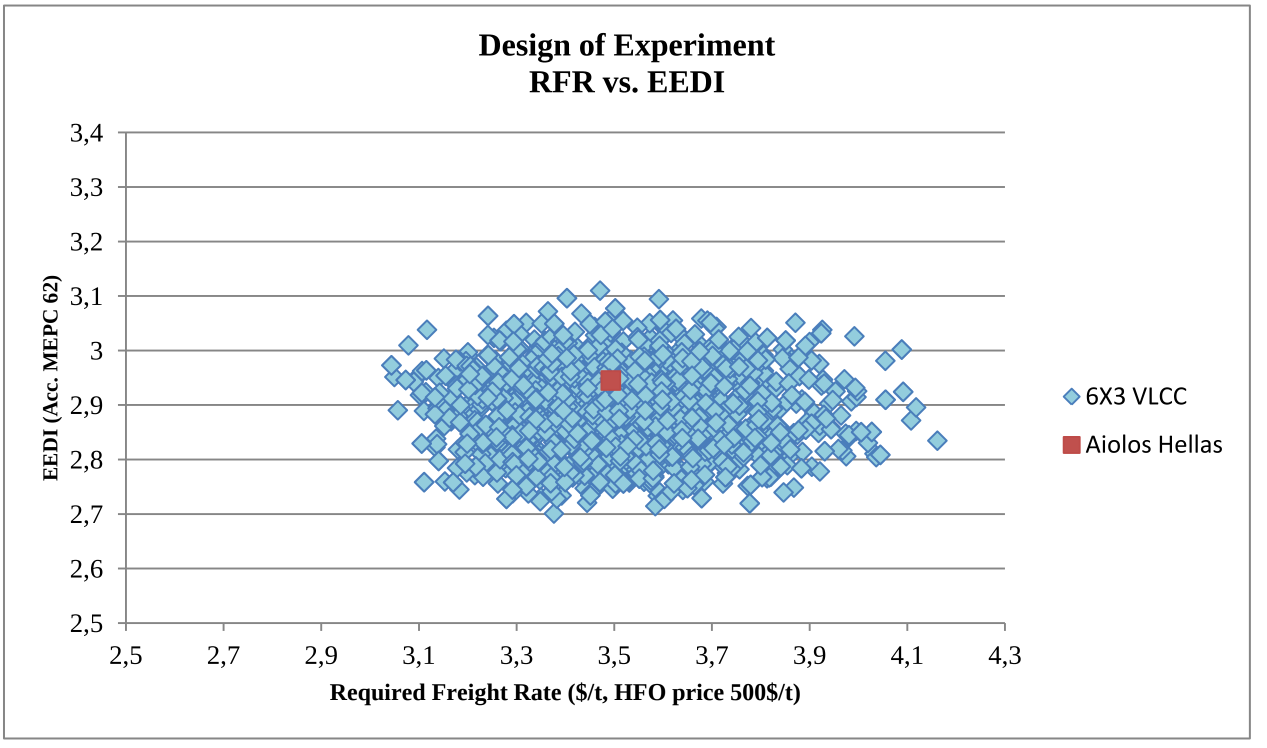


Figure [2]: Scatter diagram of the relationship of the Required Freight Rate and the EEDI

From the EEDI point of view there is room for improvement too, but not as big as in the case of the RFR and the OOI. In particular, the EEDI can be improved up to 8.29% in contrast to 12.85% for the RFR and 15.74 % for the OOI. This improvement is smaller but is not optimization rather than random exploration of the design space, which means that the actual optimization results are expected to be better. In addition to that the oil outflow performance can be further improved only if alternative tank arrangements are considered such as an additional centreline bulkhead (NX5 design) or a more dense subdivision in the longitudinal direction.

5. Optimization Runs

Following the Design of Experiment it is evident that there is room for optimization, since only by the random generation of designs improvements of up to 18% were realized. The variant I.D 1015 was exported and set as a baseline. This was chosen on the basis of being the pareto front design with the lowest OOI since we want to push the optimization boundary towards this direction, namely the direction of designs with low oil outflow that still remain competitive.

The optimization algorithm was chosen to be a different one from the NSGA II that was used extensively during the AFRAMAX optimization. Instead the MOSA algorithm was used, which uses thermodynamic principles of the cooling processes of metals. Namely, starting from an initial epoch (equivalent to a generation of the genetic algorithm) new epochs are created that have some variables constant, others almost constant and some changing depending on the duration (namely the design population) of each epoch. At this initial, global stage it was chosen to create 1500 variants as a result of 150 epochs of 30 designs duration each.

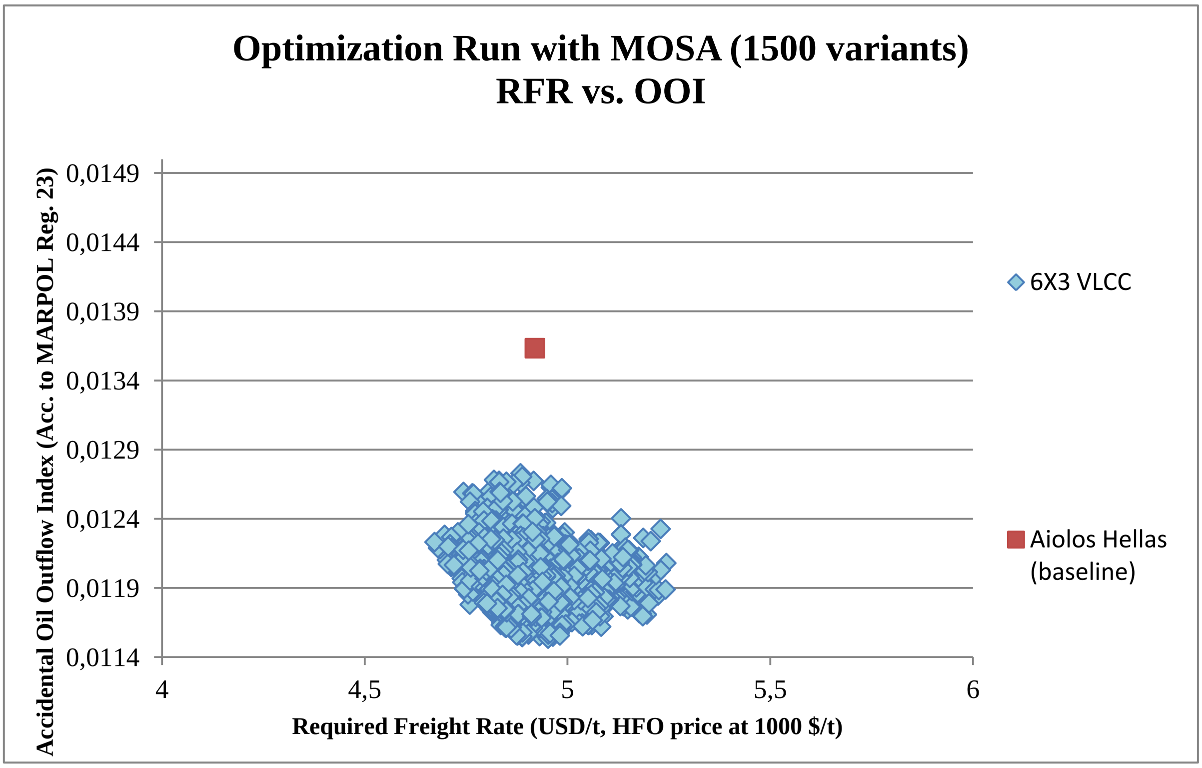


Figure [3]: Scatter diagram of the RFR vs. OOI relationship in the MOSA optimization run

As we can see the results seem to be very impressive, since all of the designs have a better OOI performance in comparison with the baseline model. We can also the applicability and strong robustness of the method, since similar pareto fronts have been made during the AFRAMAX case study. In this case the Pareto front is also very distinct and steep leaving the decision maker and designer to chose the best model according to his preferences, that can be done as in Chapter four, with the use of utility functions.

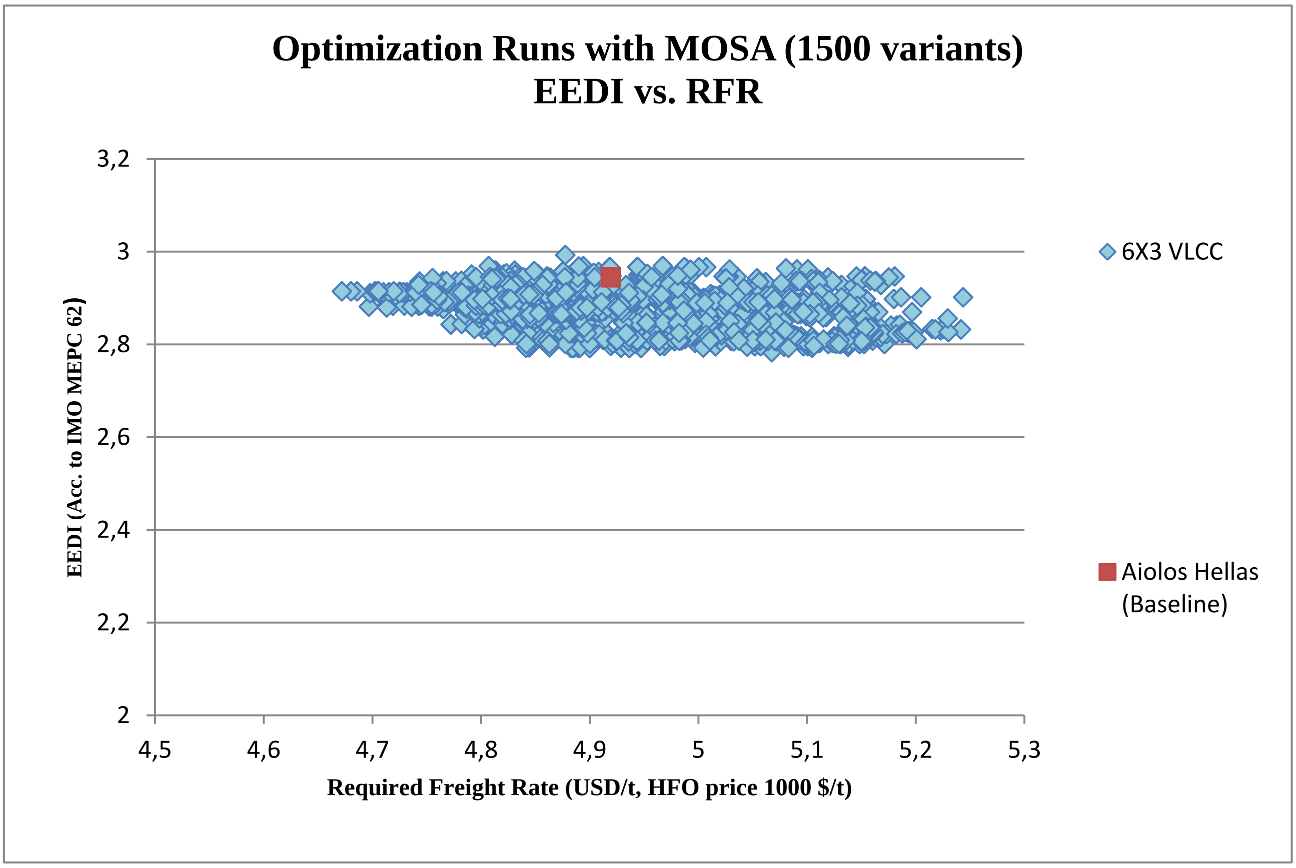


Figure [3]: Scatter diagram of the RFR vs. OOI relationship in the MOSA optimization run

The applicability of the method can be also seen at figure [4] where there is a straight Pareto front indicating the win-win situation of the improvement of the efficiency and economic performance and thus the direct correlation of the RFR and the EEDI. This phenomenon has a greater magnitude than in the case of the AFRAMAX since the scale economies are larger due to the much bigger vessel size.

APPENDIX III:

GEOMETRICAL MODELLING IN THE FRIENDSHIP FRAMEWORK

APPENDIX III: DESCRIPTION OF GEOMETRICAL MODELLING IN THE FRIENDSHIP FRAMEWORK

In this appendix the generation of the geometry for the twin screw AFRAMAX and the single screw VLCC is described.

4.1.Geometrical Model

As with every ship model in the Friendship Framework the surface development is made for the three different regions of the ship separately but with using common parameters. Thus the Aftbody, Midbody and Forebody development are going to be presented separately.

4.1.1. Forebody

The forebody part of the model was much more simpler to create than the aft one. The bow of the ship is consisted by 3 different Metasurfaces in the longitudinal direction up to the beginning of the bulbous bow. The bulb is consisted by the lower part (fillet surface) the bulb cap and a fillet surface (it could have also been a Coons Patch) between the cap and the stem. During the developing of the bow, a bulb less stem was created and based on that the bulb was created using the longitudinal profile curve (basic curve). The area around the waterline is chosen to have a band, namely an area of vertical extent.

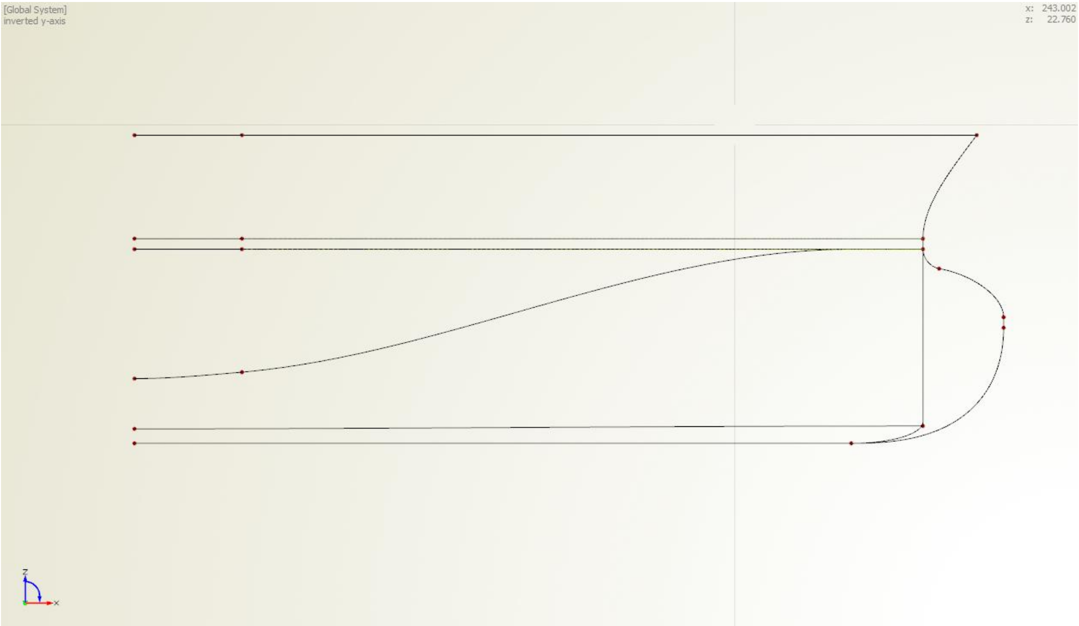
Below we will describe the workflow as in the project object tree:

- ***Basic Curves***

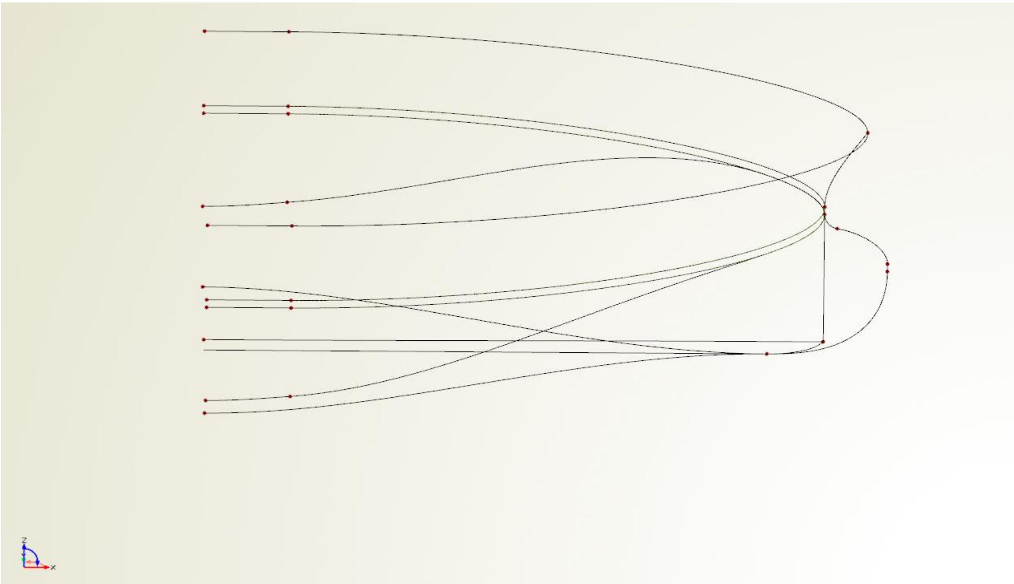
As in all of the friendship modeling undertaken, an extensive use of basic curves is being done in order to be used by the curve engines to create Metasurfaces. The basic curves used for the forebody can be summarized in the following table:

Basic Curve Name	Description
1_DECK	Function of the deck line at the deck height
2_BAND	Function of the design waterline band
3_FOS	Function of the Flat of Side
4_CONN	Function of the Diagonal from parallel midbody to fore perpendicular at the DWL
5_PROF_BULB	Function of the Bulb Profile
6_FOB	Function of the Flat of Bottom
7_KEEL	Keel line from parallel midbody to bulb profile beginning
flareAtDeck	Function of the deck flare distribution

We can also see below a snapshot of the 3D View of the basic curves from the Framework:



Picture: Profile view of the basic curves of the forebody



Picture: 3D view of the forebody

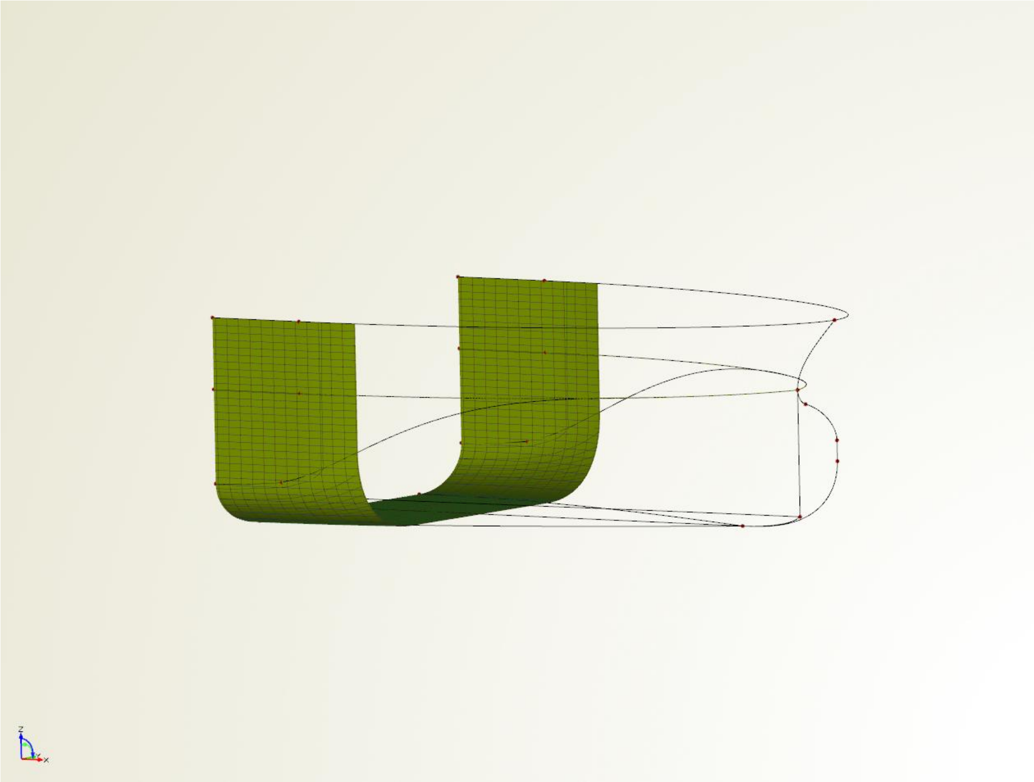
The above mentioned basic curves are used by two curve engines to generate the bow surfaces and are called Fbdy_Ellipse and Fbdy_Main accordingly. The first one is used for the transitional surface from the end of the parallel midbody to the first of the “normal” surfaces of the bow. In such a way we can achieve a successful blending and ensure a geometric continuity and a smooth transition.

➢ *Surfaces*

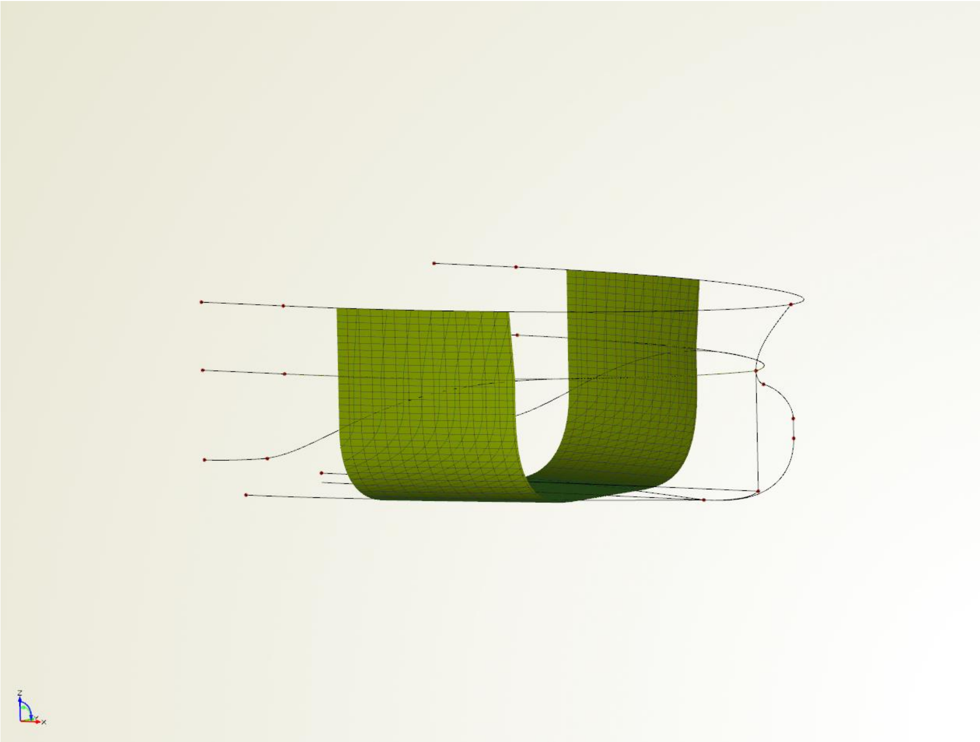
The fore body is formed by the surfaces on the table below. Most of them are Metasurfaces generated by curve engines with the exemption of the Bulb Cap and the Bulb Patch that are Fillet surfaces and a Coons Patch accordingly.

Surface Name	Description	Curve Engine at the Beginning	Curve Engine at the End
Main 1	Main bow, bleding surface from the end of the parallel midbody to 0.35 of the bow long. position of the flat of bottom (Metasurface)	ce_Fbdy_Ellipse	ce_FbdyMain
Main 2	Main bow surface from 0.35 to 0.75 of the bow long. position of the flat of bottom (Metasurface)	ce_FbdyMain	ce_FbdyMain
Main 3	Main bow surface from 0.75 to the end of the bow long. position of the flat of bottom (Metasurface)	ce_FbdyMain	ce_FbdyMain
Stem	The upper part of the stem (above the design waterline-Metasurface)	ce_StemWithAngle	ce_StemWithAngle
Bulb Low	The lower part of the bulb (Metasurface)	ce_bulbLow	ce_bulbLow
Bulb Cap	The top part of the bulb up to the bulb tip (Fillet Surface)	NaN	NaN
Bulb Patch			

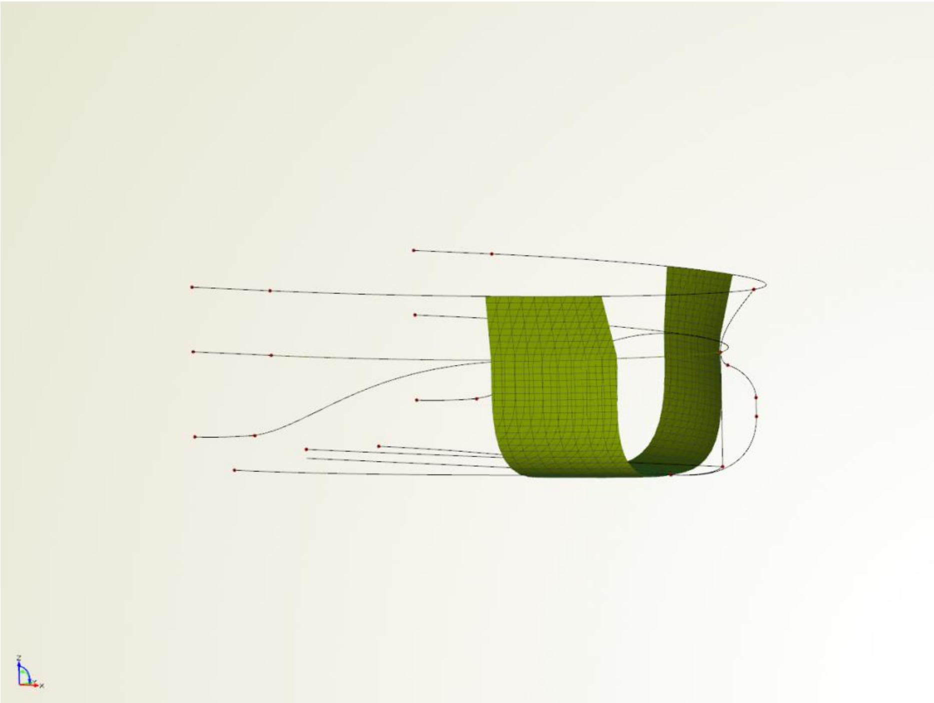
One can see the above mentioned surfaces at the snapshots below:



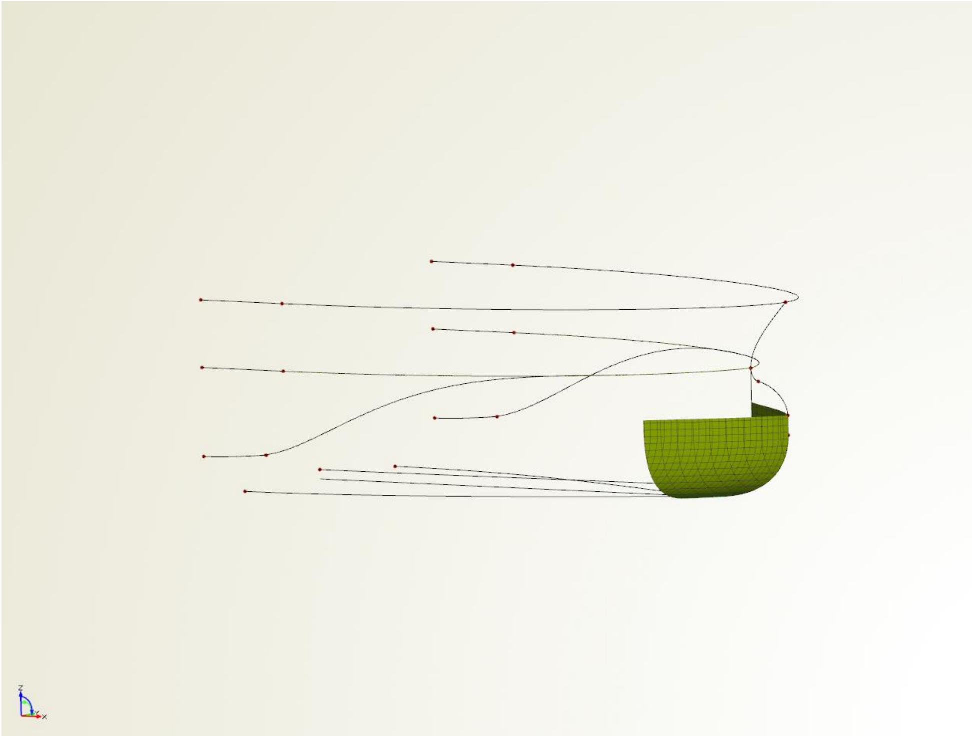
Picture: "Main 1" Surface



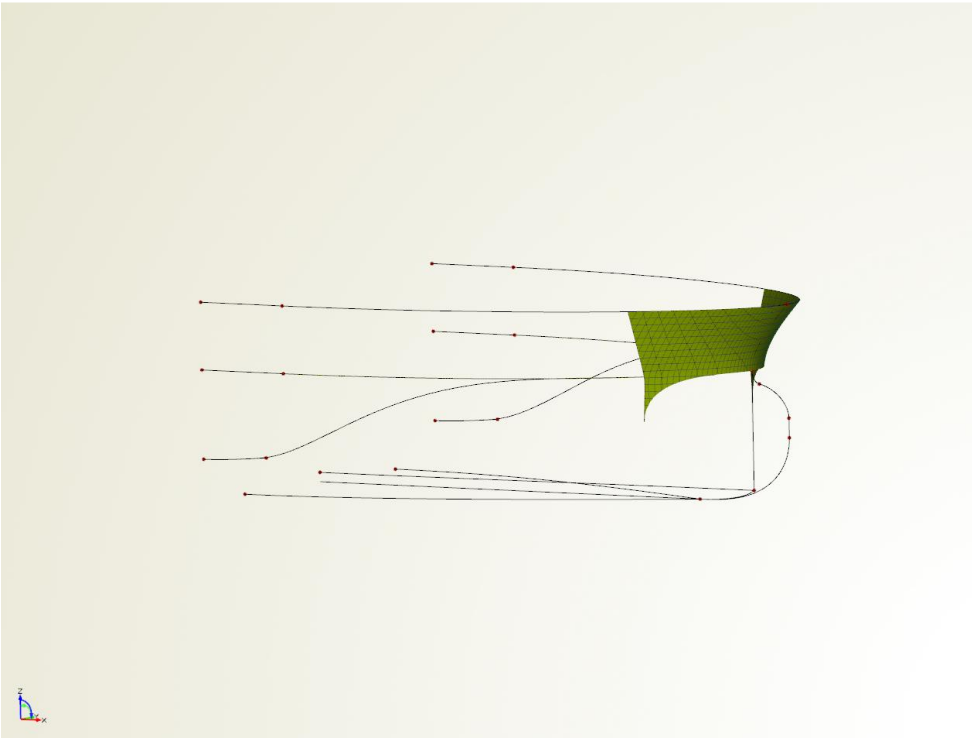
Picture: “Main 2” Surface



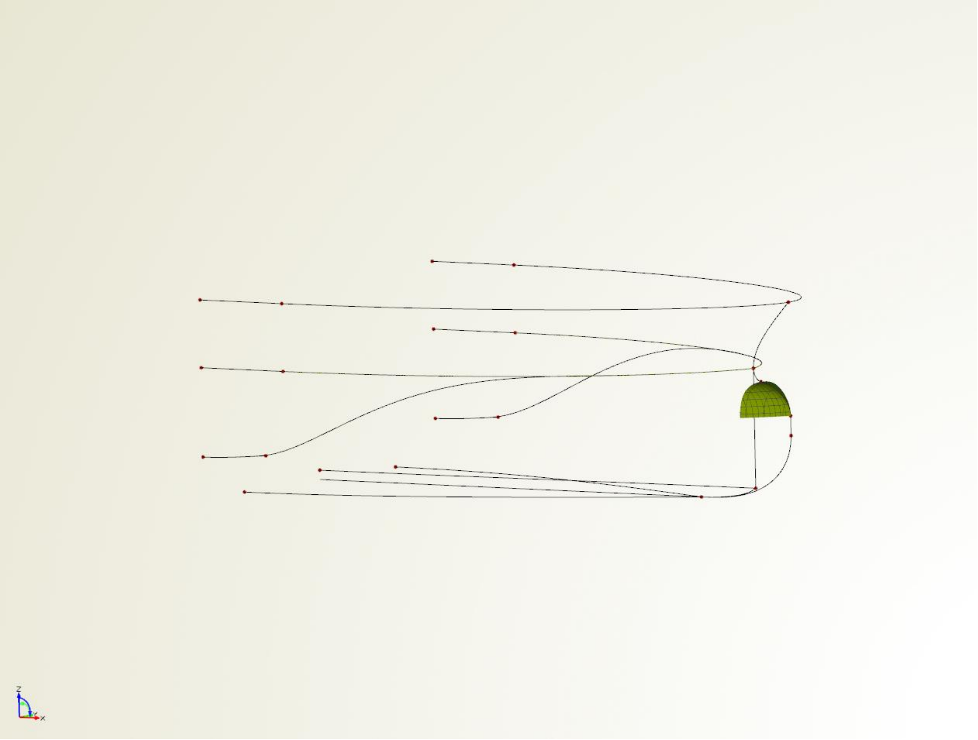
Picture: “Main 3” Surface



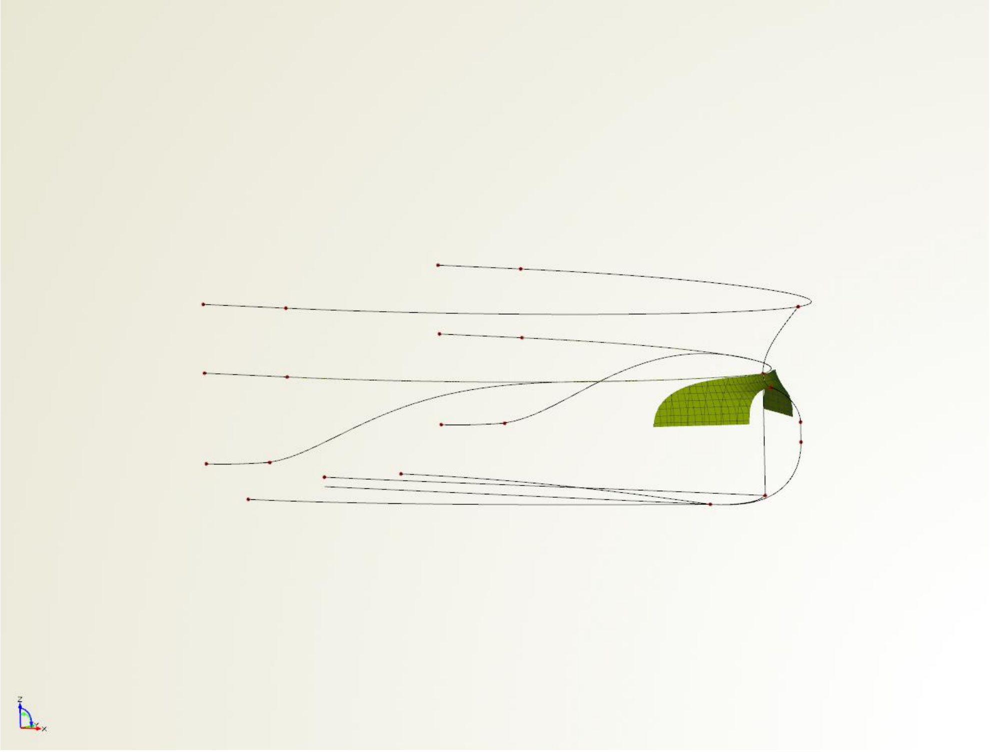
Picture: "Bulb Low" Surface



Picture: "Stem" Surface



Picture: “Bulb Cap” Surface



Picture: “Bulb Patch” Surface

Picture: Result, the finished forebody

4.1.2. Midbody

The midbody surface is usually a very simple surface, connecting the two peaks of the ship. It is consisted by the Flat of Bottom (FOB) and Flat of Side connected by the bilge. In the majority of designs the bilge is of circular shape and of relatively small extent. However this is not the case, as it is a design principle to use an elliptic shaped bilge. The reason for such a design choice is the geometric property of the ellipse to have the least surface for practically the same volume.
The shape of the bilge was controlled by the curve engine of the Metasurface that creates the midbody and is determined by the dimensions of the two axes. The input information however is the ellipse height (bilge height) and breadth. In order to have a more functional parameterization that responds better to dimension change the latter have been expressed as a function of the FOB and FOS. The FOB and FOS dimensions are a fractal of the half breadth and the height of the model accordingly. Thus one can achieve a better control of the shape of the midbody.
It is important to stress out at this point, the importance of the elliptic shape for the entire hull. Wherever there is a bilge expression, in other words an interpolation between two flat surfaces, it is executed by an elliptic shape routine. For example, at the aft area, the stern overhang between the two skegs and between the skeg and the side has elliptic shaped sections. The same for the last bow sections before the parallel midbody as a means to blend the bulb geometry with the elliptic mid surface.

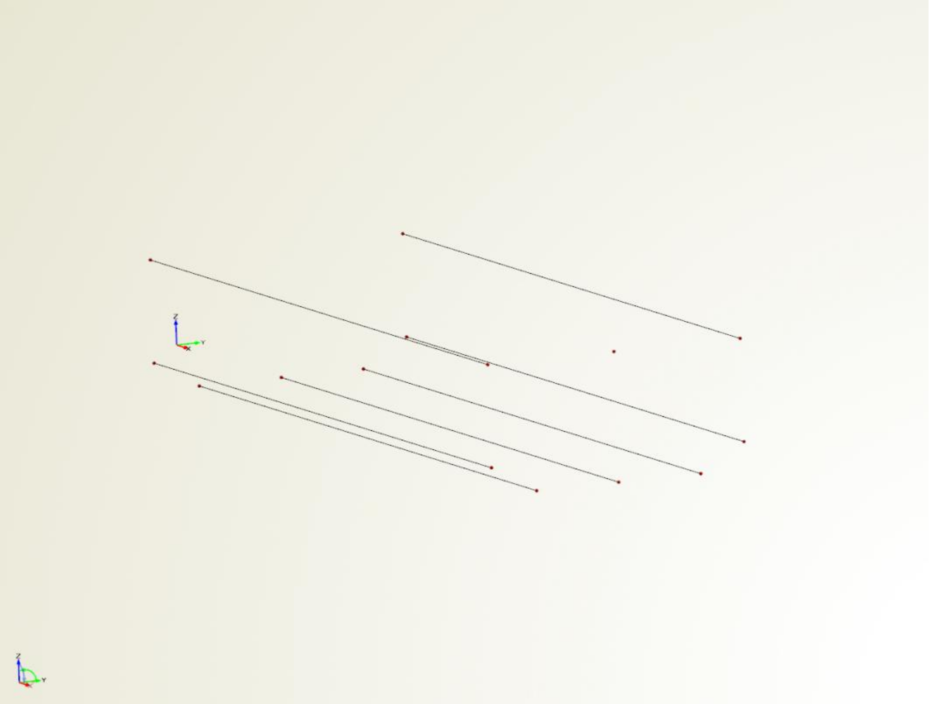
➢ ***Basic Curves***

For the midbody the case of the modeling is much simpler. The basic curves are straight lines and are the following:

Basic Curve Name	Description
Bilge	Straight line function of the flat of side where the connecting bilge begins
Deck	Straight line function of the deck at deck
FOB	Straight line function of the Flat of Bottom boundary to the connecting bilge
Keel	Keel line at the centreline

Graphically, one can see the basic curves through the 3D window of the Framework:

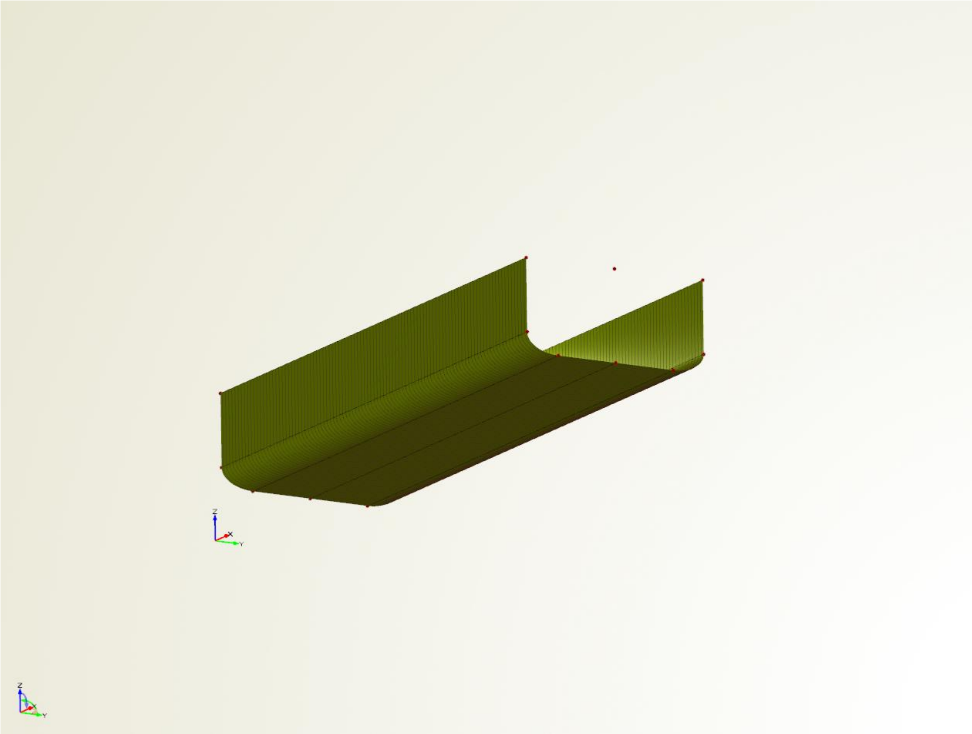
Picture: Profile View of the basic curves for the Midbody



Picture: 3D view of the basic curves for the midbody

- ***Surface***

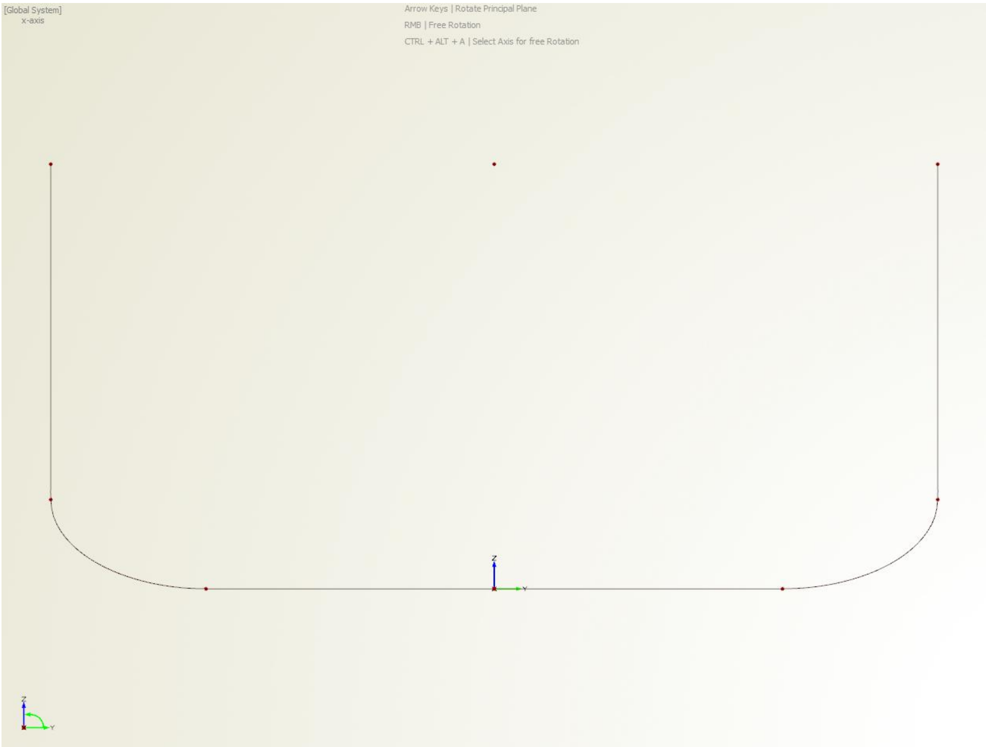
The midbody surface is created as a Metasurface, using the elliptic bilge curve engine that has as an input the basic curves. The extent of the Metasurface is from the begging till the end of the parallel midbody.



Picture: Midbody Surface

➢ *Midship Coefficient Calculation*

One of the early integrations within the geometry scope is to calculate the midship transverse area in order to determine the midship coefficient of the ship. This is done by using a projection curve: a line is projected on the midship area and thus creates a midship section. Then from this section one can calculate the transverse area from the .getArea() command of the Framework. Then the coefficient can be easily derived by dividing the area by the breadth and the draft.



Picture: Midship Section, where the elliptic shaped bilge is evident

4.1.3. Aftbody

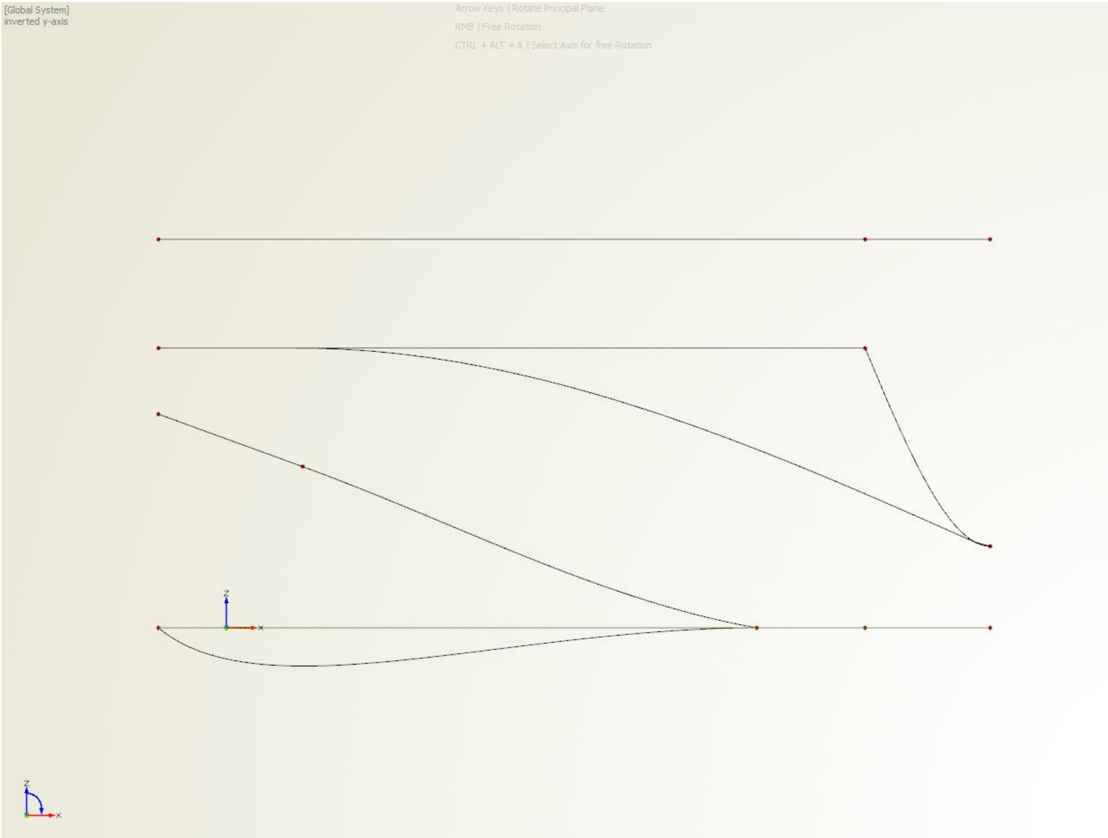
The aftbody was the most complex surface to handle due to the peculiarity of the design and the demand for a twin skeg configuration. In the lines to follow we can see a brief description of the strategy to generate the surfaces. Afterwards a detailed analysis based on the Friendship Object Tree is to follow.

Typically, a twin or even single skeg design is produced by first creating the barehull, namely the aftbody excluding the skegs. By having a definition for the Flat of Bottom of the skegs, one can produce the projection curves which are going to be used for the trimming of the hull and in the meantime as basic curves for the creation of part of the skeg surface. In order to create the projection curves, one should already design the skeged hull by means of a Metasurface, having the tangents of the sections and the FOB function as basic curves. This makes sure that the sections at the aft region have the necessary geometry. By producing the projection curves and a sort of a sweeping section the user is then able to produce the entire skeg, and control it in terms of longitudinal propeller position, forward clearance at the stern tube and tangents at the tube and propeller point. This is the basic idea behind the generation of the skegs.
Of course, one should always consider whether the design is possible and realistic or not. A first control is to see if an engine can fit in the aft are which as usual is designated for the engine room. Having in mind the type of the engines specified for the vessel (MAN B&W 5S50ME) the dimensions were found by the product catalog and a preliminary surface for the engine and the shaft was created.
Another stage that requires attention is the control for the orientation of the skegs, which will be performed at later stage during some fine hydrodynamic tuning of the model. The orientation in terms of degrees of freedom in angle of pitch, roll and yaw was controlled by programming the image transformation of the created surfaces and applying it on the created surfaces (input) thus producing the final skeg surfaces. The other three degrees of freedom are controlled by the parametric structure of the model, in terms of shaft distance from the centreline (as a percentage of the ship's breadth) and in terms of propeller (bulb tip) position.

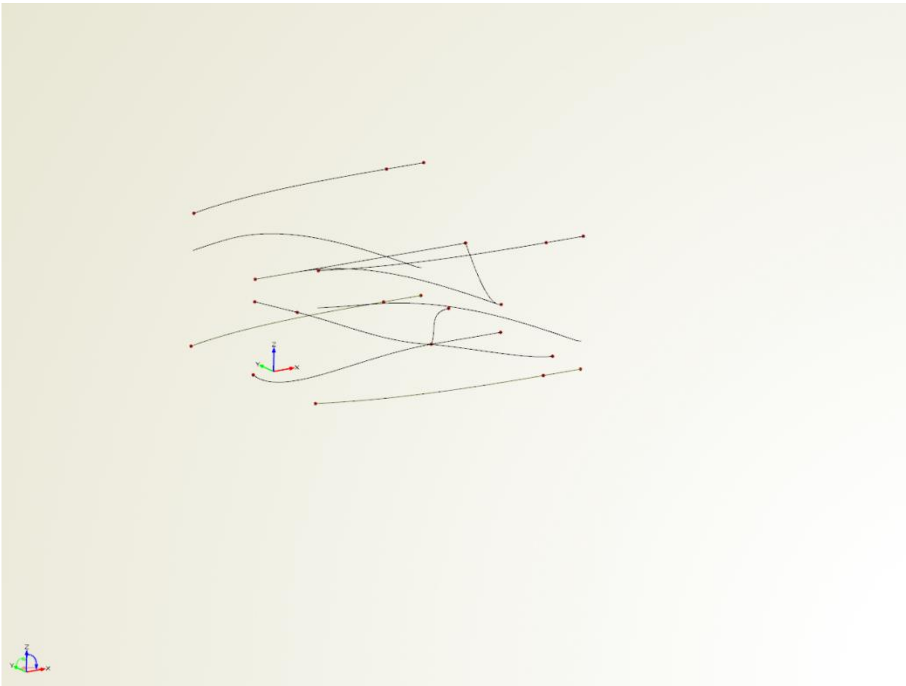
- ***Basic Curves-Bare hull***

The basic curves used for barehull where the following:

Basic Curve Name	Description
1_DECK	Function of the deck line at deck height
2_FOB	Function of the Flat of Bottom of the bare hull
3_KEEL	Function of the keel line of the bare hull
4_BILGEUPP	Function of the connecting diagonal of the bare hull
5_TANGENT	Function of the tangent distribution



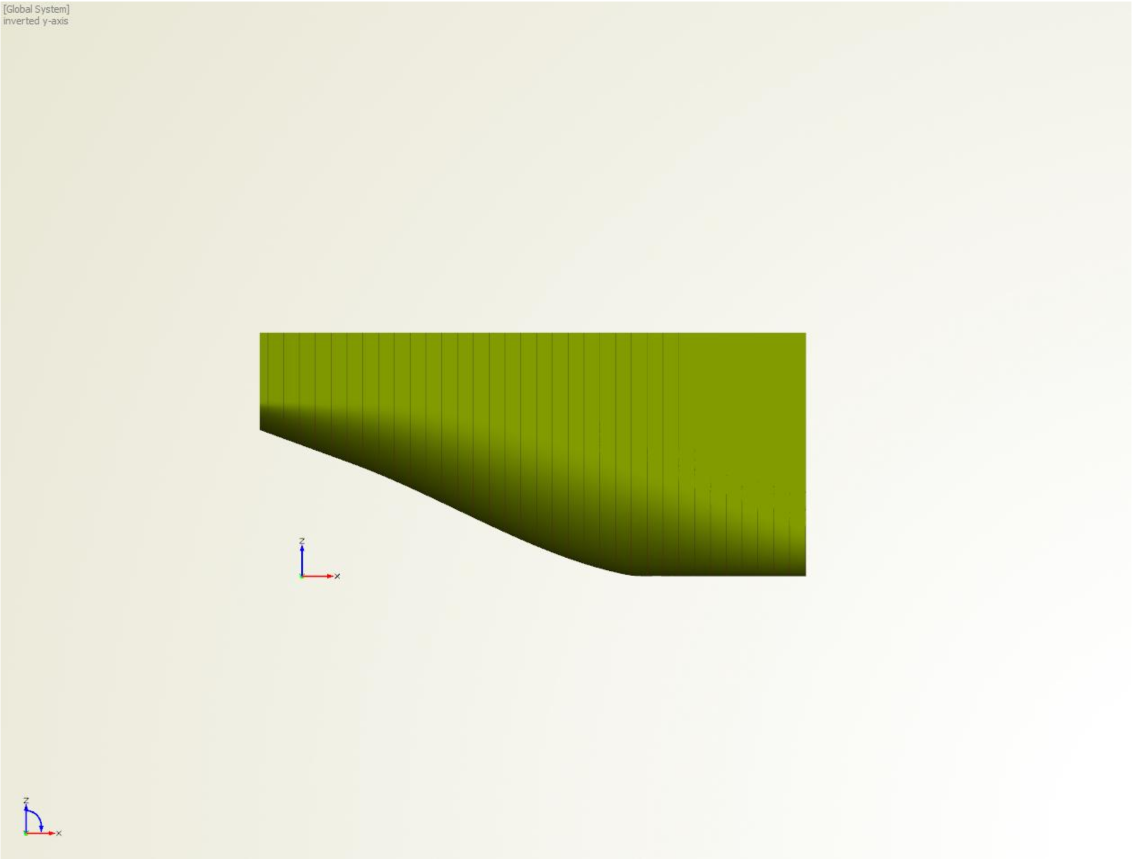
Picture: Profile view of the basic curves for the bare hull


Picture: 3D view of the basic curves of the bare hull

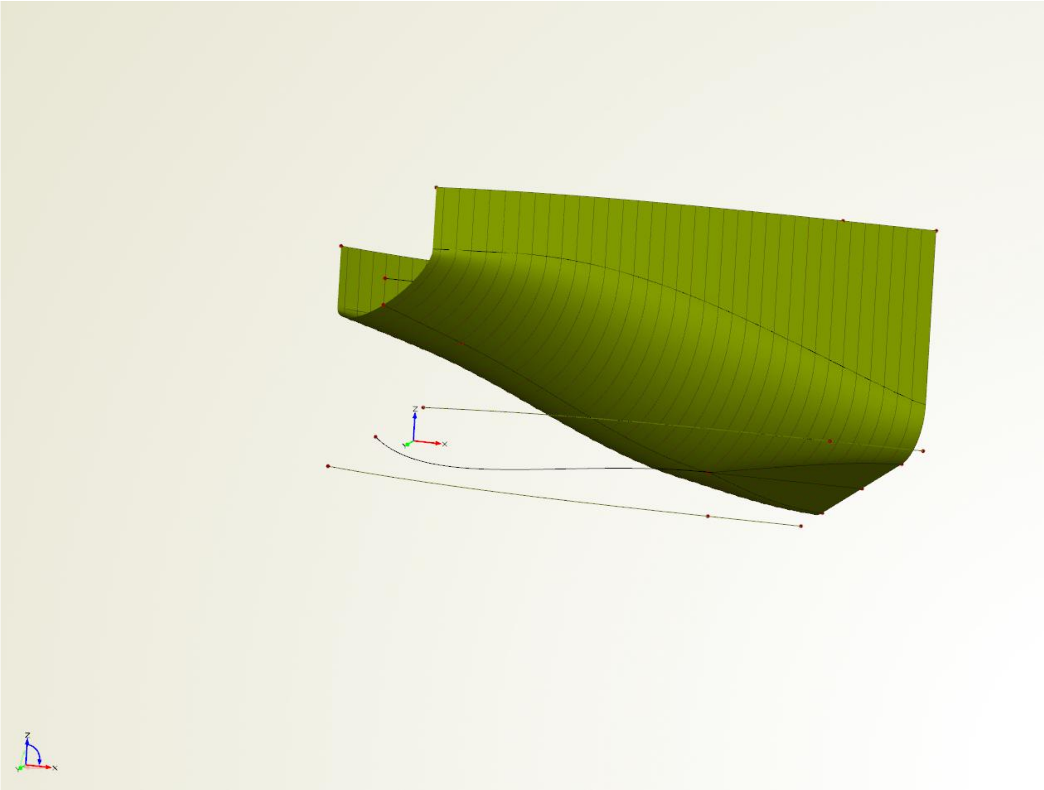
- ***Surface-Bare Hull***

The bare hull surface is a Metasurface realized by a curve engine definition at both its boundaries. The mentioned curve engine interpolates the flat areas with an ellipse. Alternatively, one could use a blending method and have the elliptic curve engine at the boundary with the midbody and a spline interpolating curve engine at the transom.

The produced bare hull with the two elliptic curve engines can be seen below:



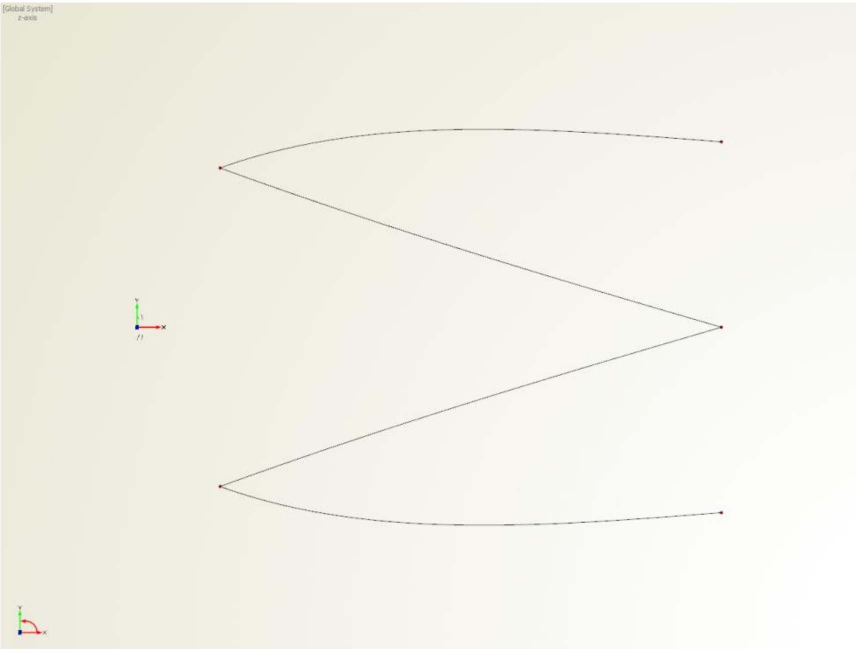
Picture: Profile of the barehull surface



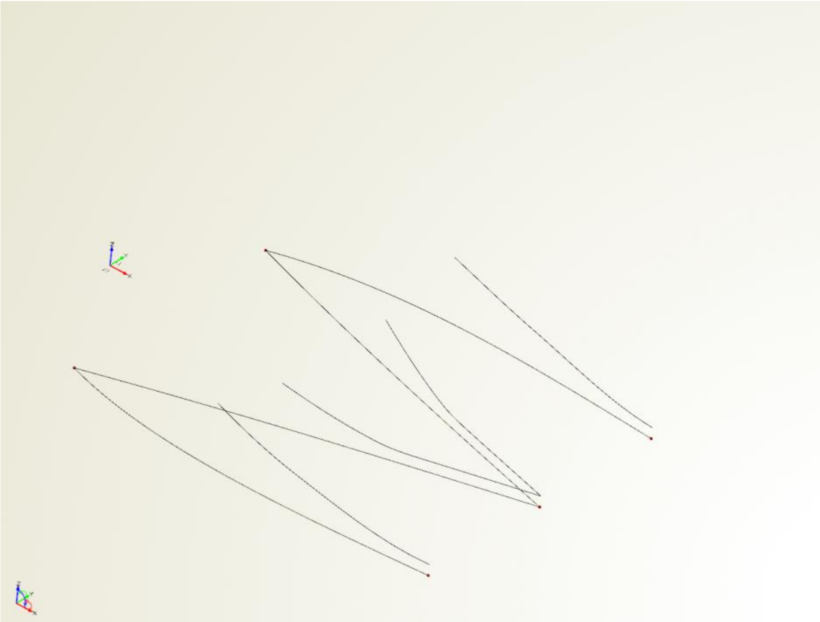
Picture: 3D view of the bare hull where one can notice the elliptic sections

- ***Basic Curves-Skeged Hull***

In order to produce the two skegs we will have first to create an adapted bare hull where the skegs will be fitted. To do so, we create two trimming curves one for the inner part and one for the outer part and for the inner part of the skeg. The trimming curves are realized as projection curves on the original bare hull surface, using as source a flat 2D curve. One can see this geometry below:

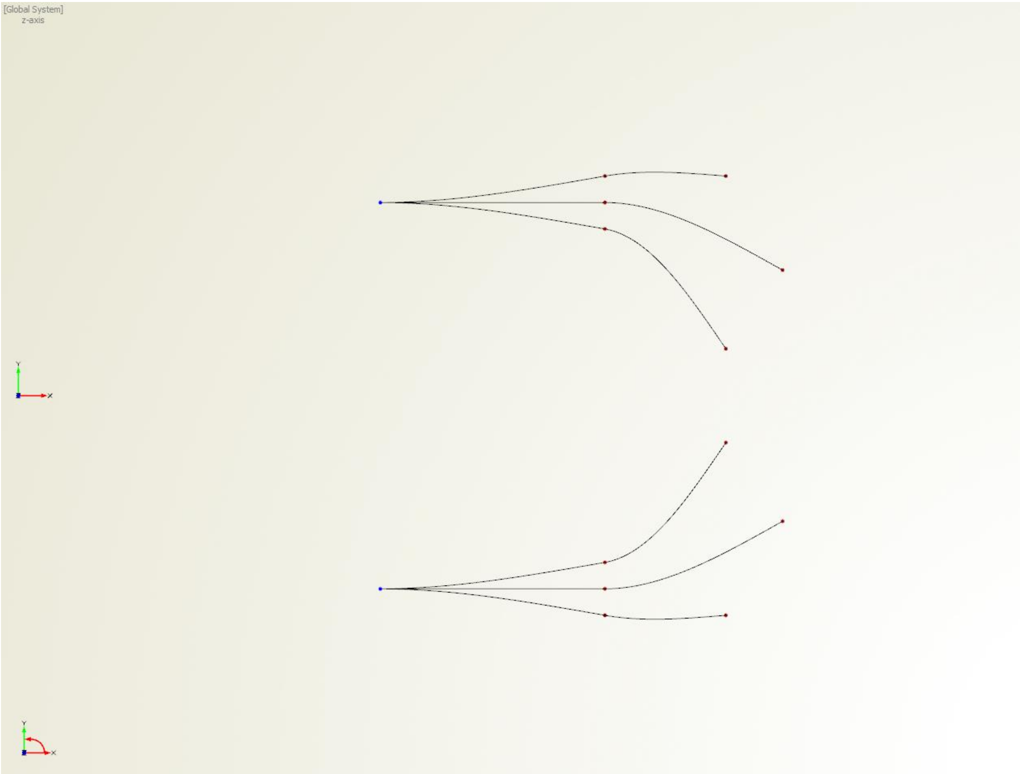


Picture: The inner and outer trimming curves for the bare hull



Picture: 3D view of the trimming curves

Another definition that has to be made for the skeg hull geometry are the curves of the flat bottom of the skegs. These define the skeg geometry and shape as they are used as the origin for the creation the entire skeg body. Their parameterization is quite strong and depends on the main engine, shaft and bilge dimensions to make sure that the resulting shape is fully functional.



Picture: The inner and outer fob curves

Basic Curve	Description
_cent	Curve between the inner and outer parts of the skeg flat of bottom
_fob_i	Curve of the inner part of the skeg flat of bottom
_fob_o	Curve of the outer part of the skeg flat of bottom
_trim_i	Inner trimming curve of the bare hull
_trim_o	Outer trimming curve of the bare hull

- **Surfaces-Skeged Hull**

Using the trimming curves and flat of bottom definitions we previously described, we produce the skeg hull surface which is consisted by smaller fillet surfaces:

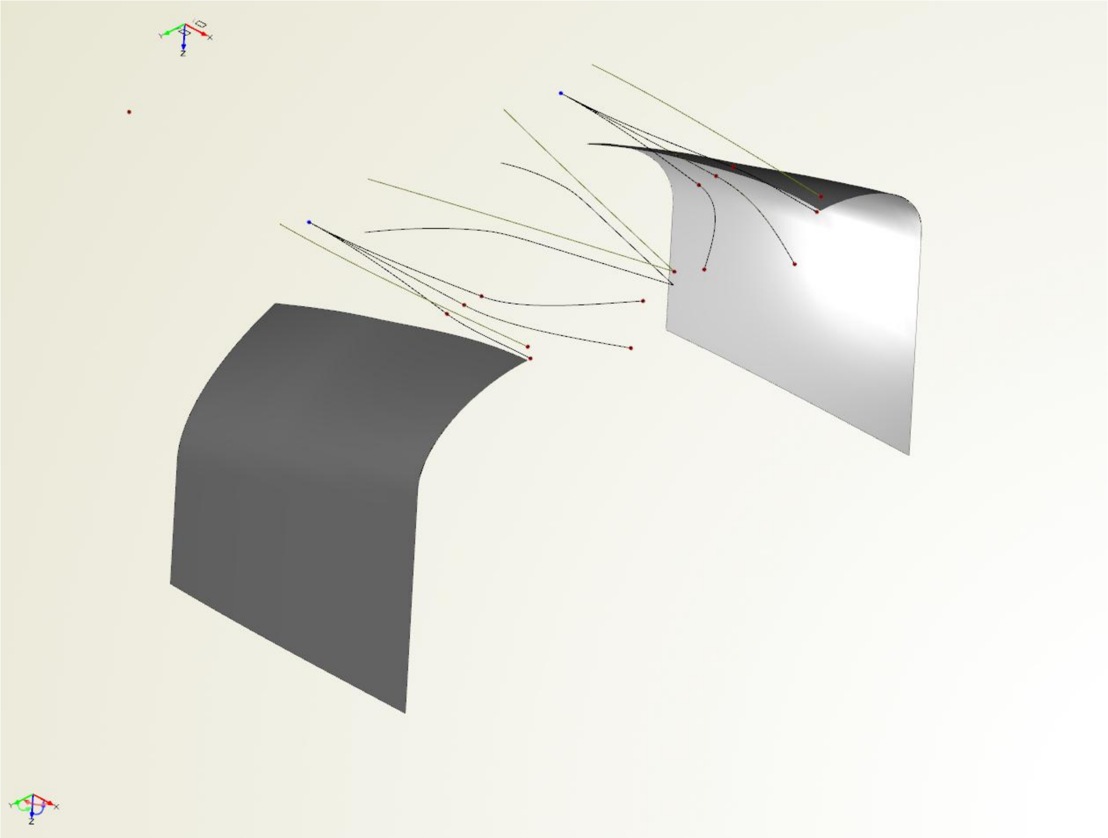
Surface Name	Description
surf_i_Skegbeside	Fillet surface within the inner trimming curve
surf_o_SkegBeside	Fillet surface from the outer trimming curve to the deck height
surf_o_SkegBody	Fillet Surface from the outer trimming curve to the outer flat of bottom curve
surf_i_SkegBody	Fillet surface from the inner trimming curve to the inner flat of bottom curve
Surf_Fob_i	Fillet surface from the inner flat of bottom curve to the middle flat of bottom curve
Surf_Fob_o	Fillet surface between the outer flat of bottom curve to the middle flat of bottom curve

One can see the surfaces between the basic curves below:

Picture: "surf_Fob_i" surface

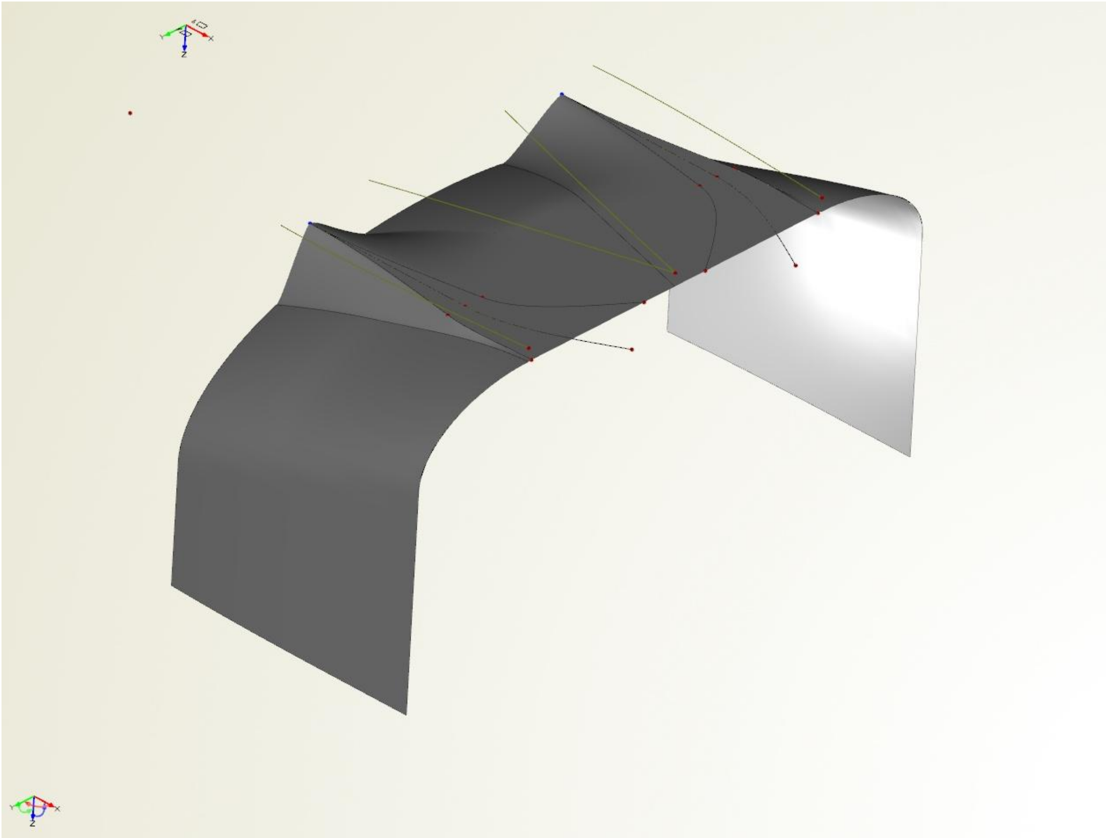
Picture: “surf_Fob_o” surface

Picture: “surf_i_SkegBeside” surface



Picture: “surf_o_SkegBeside” surface

Picture: “surf_o_SkegBody” surface

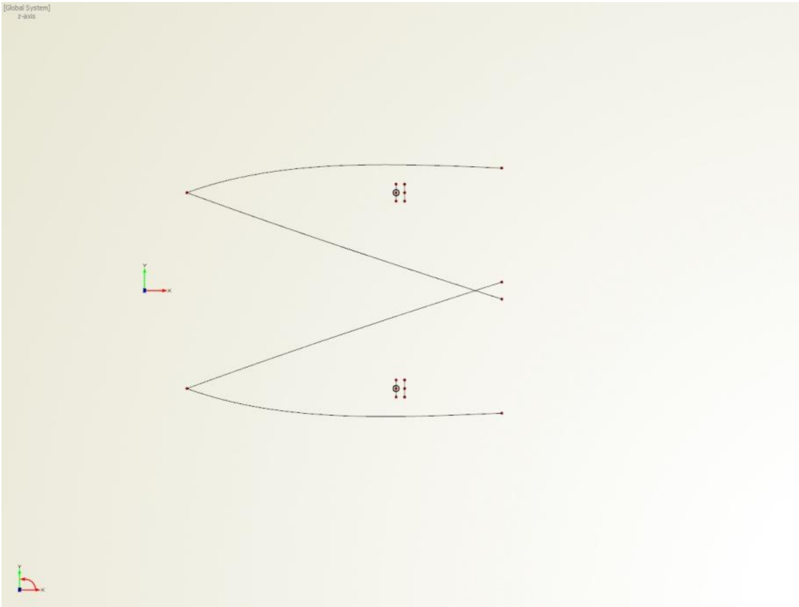


Picture: Result, the bare hull with the skeg extensions

Having produced the adapted barehull, trimmed and ready for the skegs we will now move on, and describe the generation of the skeg bossing.

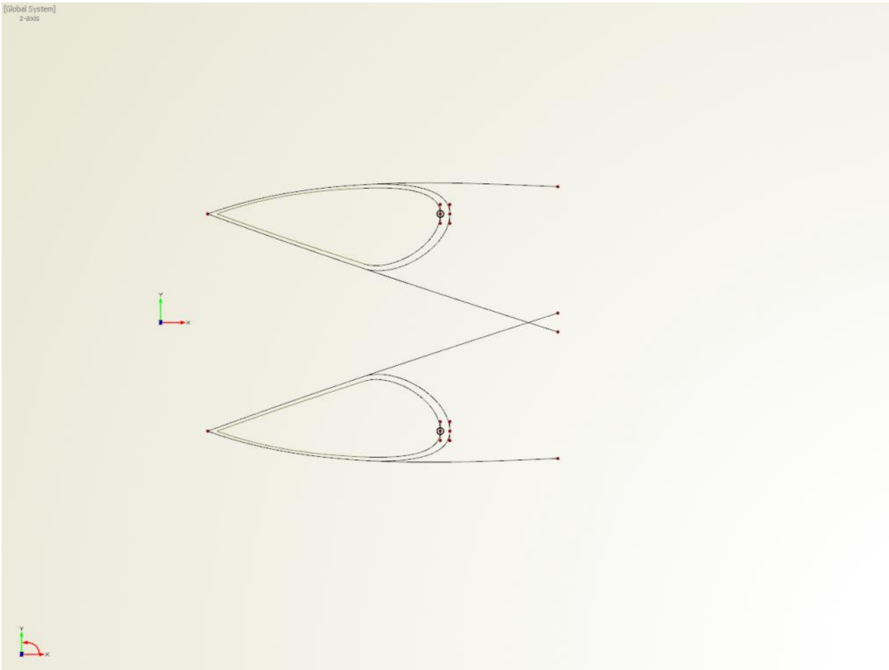
➢ *Basic Curves-Skeg Bossing*

Using the trimming curves and the definition of an inner and outer vector in the centre of what will be the skeg of the vessel, we are able to define the source of the projection curves that will trim the barehull and will also be used as basic curves for the bossing surface generation.



Picture: The trimming curves and vectors that will define the source of the projection curves

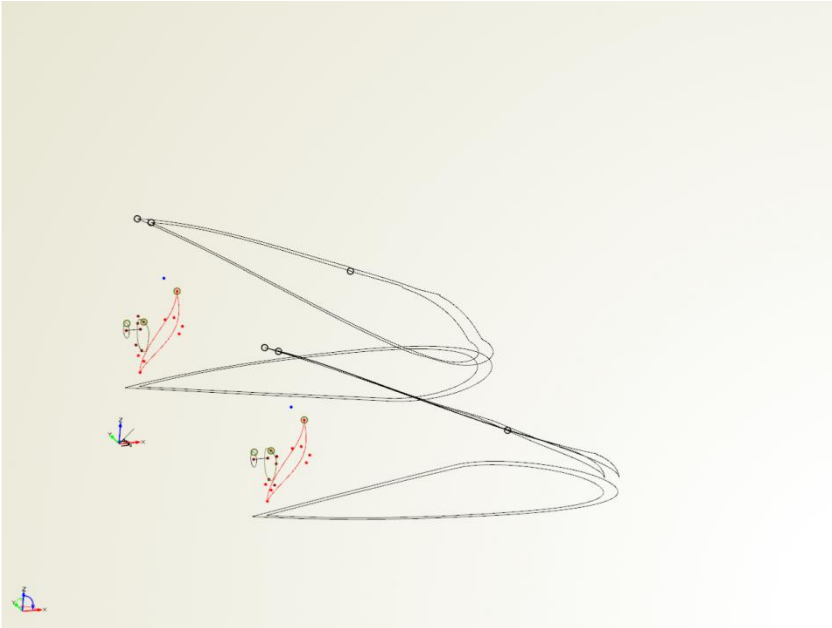
The source of the projection curve is generated partially, as a fillet curve targeting the defined vectors.



Picture: The trimming curves and vectors together with the fillet curves

The fillet parts are joined together by a poly-curve that is the projection base curves.

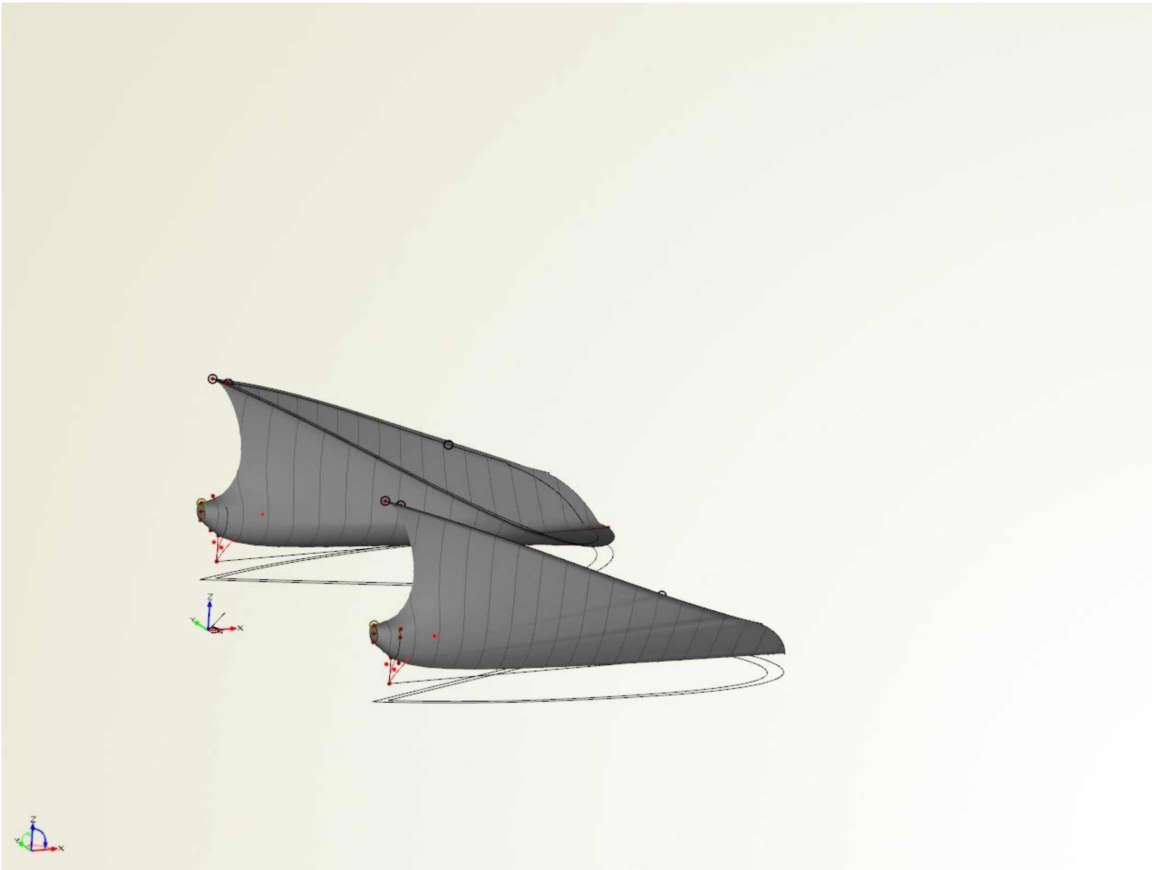
The next step is to project the curves on the bare hull and thus create the basic curves for the skeg bossing surface generation.
Furthermore, in order to control the shape of the skeg bossing at the aft ends a circle and an ellipse control the end of the stern tube. Along with these, an intermediate curve that is close to the propeller clearance point controls the local shape.
The above mentioned are the basic curves for the generation of the Metasurface used for the geometric description of the skeg bossing.



Picture: Basic curves of the skeg bossing

- ***Surface-Skeg Bossing***

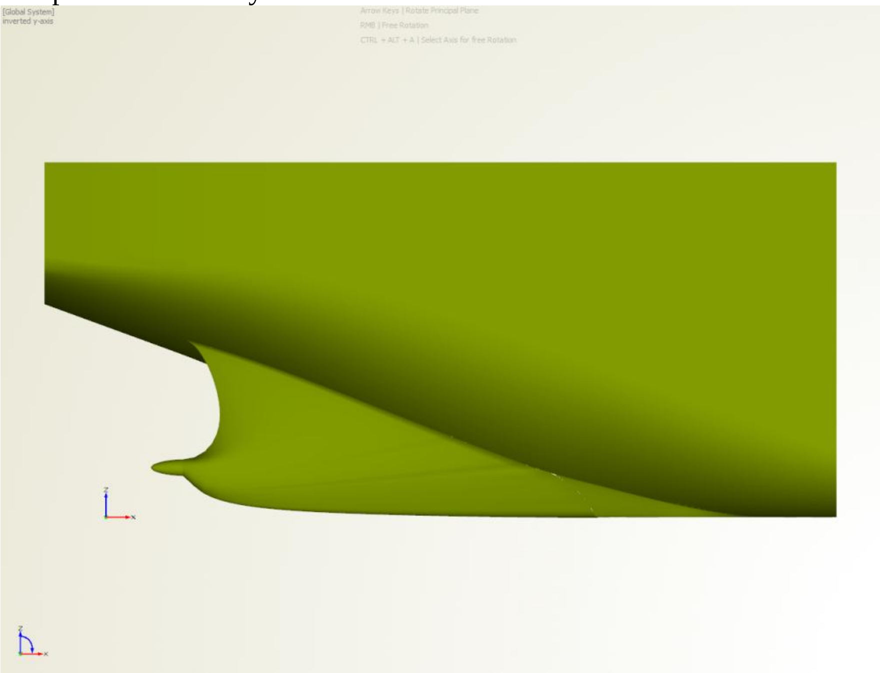
The surface of the skeg bossing is produced in two parts: an inner and an outer as in contrary with a single hull vessel there is no centreline symmetry. For this particular reason, two curve engines are also needed.



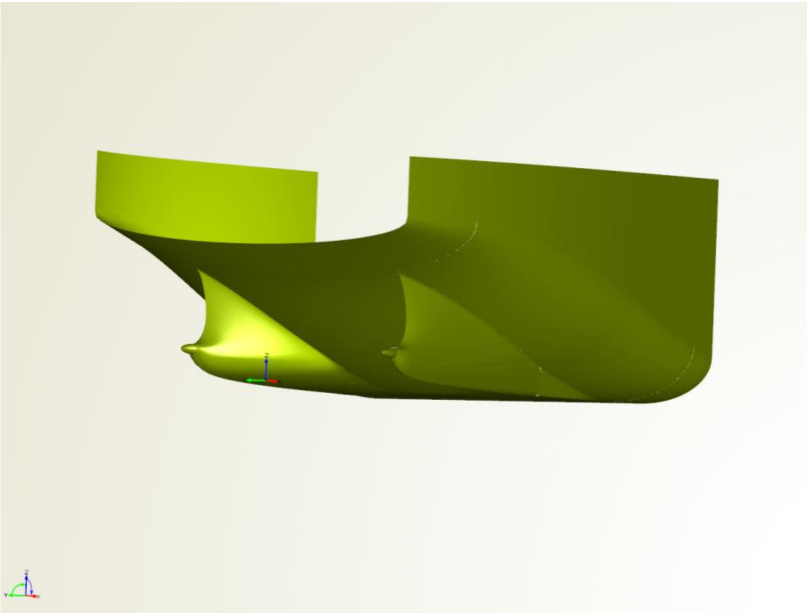
Picture: Skeg bossing surface

➢ ***Final Aftbody Surface***

Having competed the skeg bossing, and by also defining a boss cap for the Shipflow offset functionality, we are able to see the entire aftbody by means of a surface group that unites all of the surface parts in one entity.



Picture: Profile view of the aftbody



Picture: 3D view of the aftbody

8.1. Geometrical Modelling

8.1.1. Forebody

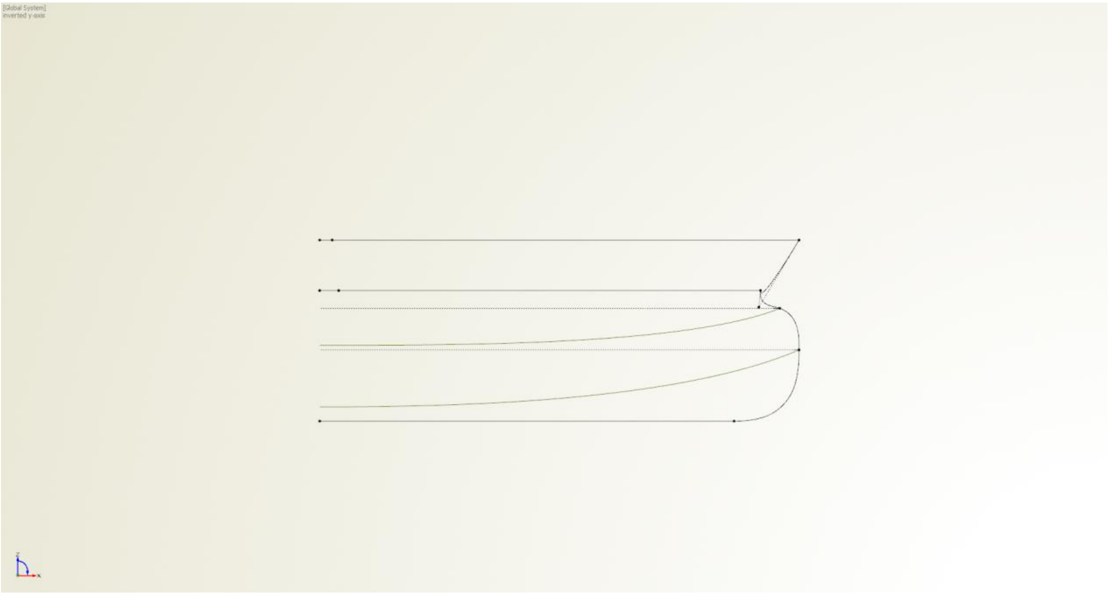
The forebody surface is created as a Metasurface at once by rotation. This means that the preparation is a bit complex but the result is much simpler and there is no need for blending between different parts and surfaces.

- **Basic Curves**

The basic curves of the forebody surface are the following:

Curve Name	Description
Cpc	The function of the keel line and of the longitudinal profile of the vessel
Deck	The function of the deck line of the vessel
Diag 1	Function of the first diagonal, from the bulb (mid height) to the beginning of the parallel midbody
Diag 2	Function of the second diagonal, from the bulb tip to the beginning of the parallel midbody
DWL	Function of the Design Waterline of the vessel
FOB	Function of the Flat of Bottom for the bow area
fullnessLow	Function of the waterline fullness below Diag 1
fullnessMid	Function of the waterline fullness between the two diagonals
InnerFob	Function of the inner Flat of Bottom
Tangents	Function of the tangent distribution for the deck, the two diagonals and the design waterline
Weights	Weights for the lower and upper diagonals

At the snapshots below one can see the profile and 3D view of the basic curves for the forebody creation.



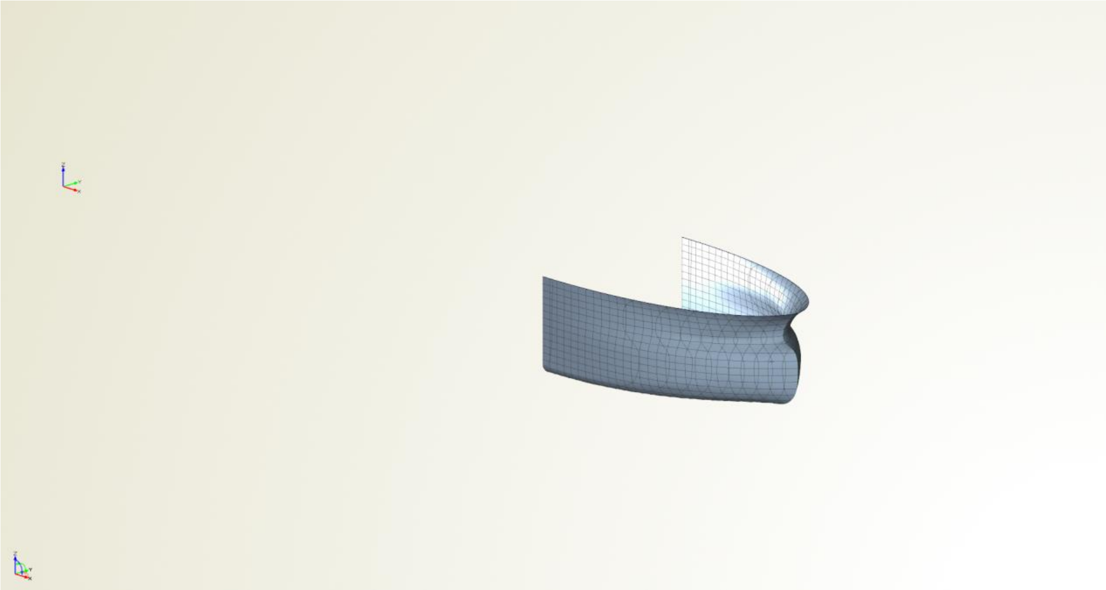
Picture: Profile of the forebody basic curves

Picture: 3D view of the basic curves for the forebode

The basic curves are used as input for the curve engine that produces the forebody shape. This curve engine uses the principle of the rotation transformation to produce the desired shape.

- **Surfaces**

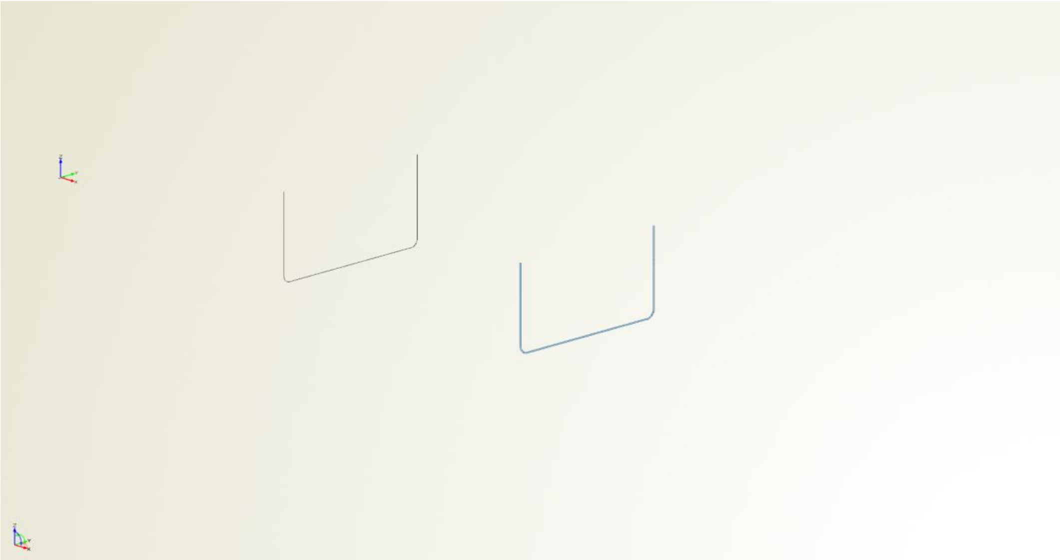
The resulting surface can be seen below:



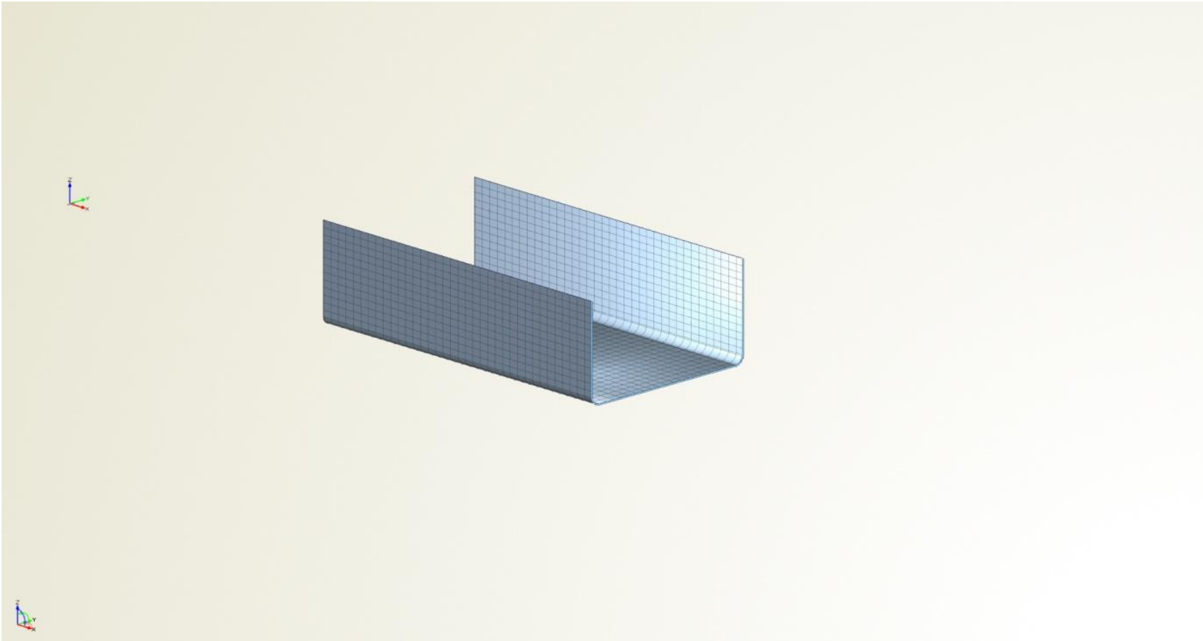
Picture: The forebody surface

8.1.2. Midbody

The midbody is one of the simplest surfaces that can be created. Following the generation of the aft and fore surfaces, two surface curves are created respectively, and thus the midbody surface can be derived by means of a ruled surface. One can see that procedure in the pictures that follow:



Picture: The fore and aft surface curves used for the midbody surface generation



Picture: The midbody surface

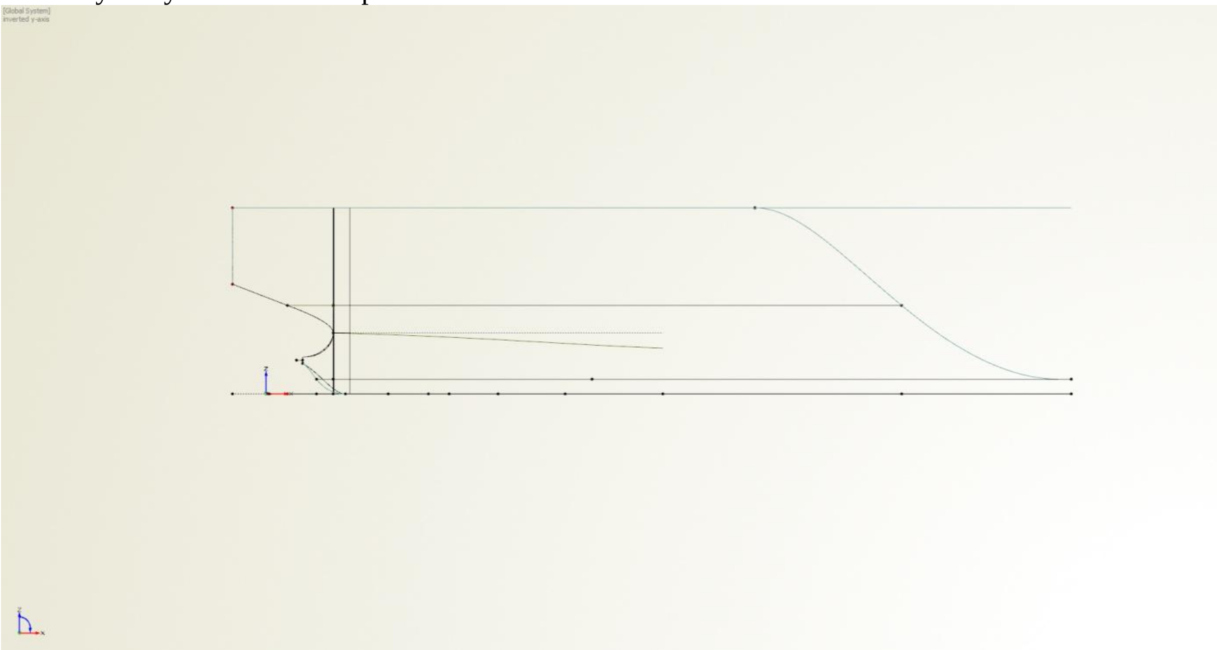
8.1.3. Aftbody

The aftbody is consisted by 6 surfaces and is the most complex entity of this particular model. The different surfaces are developed in the longitudinal direction and are Metasurfaces using different curve engines.

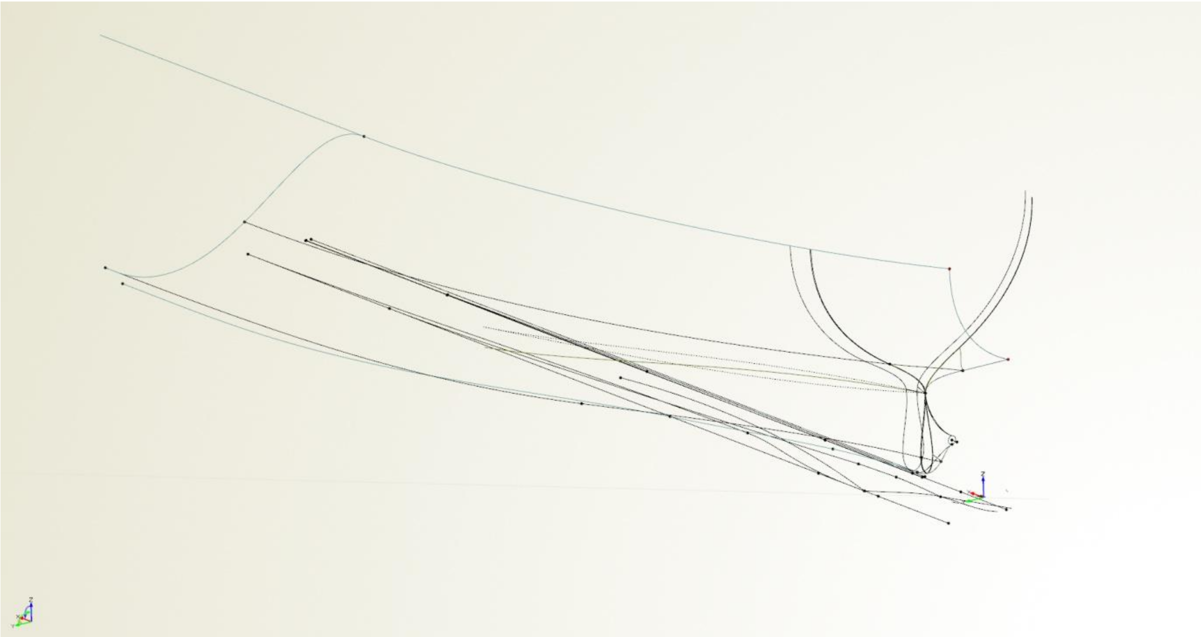
- **Basic Curves**

Curve Name	Description
Bulb	Bulb Profile and two first sections
cpc	The profile of the aftbody
deck	Function of the deck at the stern area
diag	Function of the diagonal from the clearance point of the stern bulb to 65 meters
FOB	Function of the Flat of Bottom for the stern area
FOS	Function of the Flat of Side for the Stern area
fullness	Function of the fullness distribution for the diagonal and the two waterlines
Tangents	Function of the tangent distribution for the diagonal, the waterlines and the transverse sections as well.
Transom	Function of the transom
wlAtOvProp	Function of the upper waterline
wlAtUpBilge	Function of the lower waterline

The most influential of the basic curves were the tangents (for the aft sections), the waterline curves, the diagonal and the fullness as well. By refining these curves a fair and what seems like a "hydrodynamic fine" shape was created.



Picture: The profile of the basic curves for the aftbody



Picture: 3D view of the aft basic curves

Having set the basic curves, the curve engines, one for each surface used them to generate the surfaces.

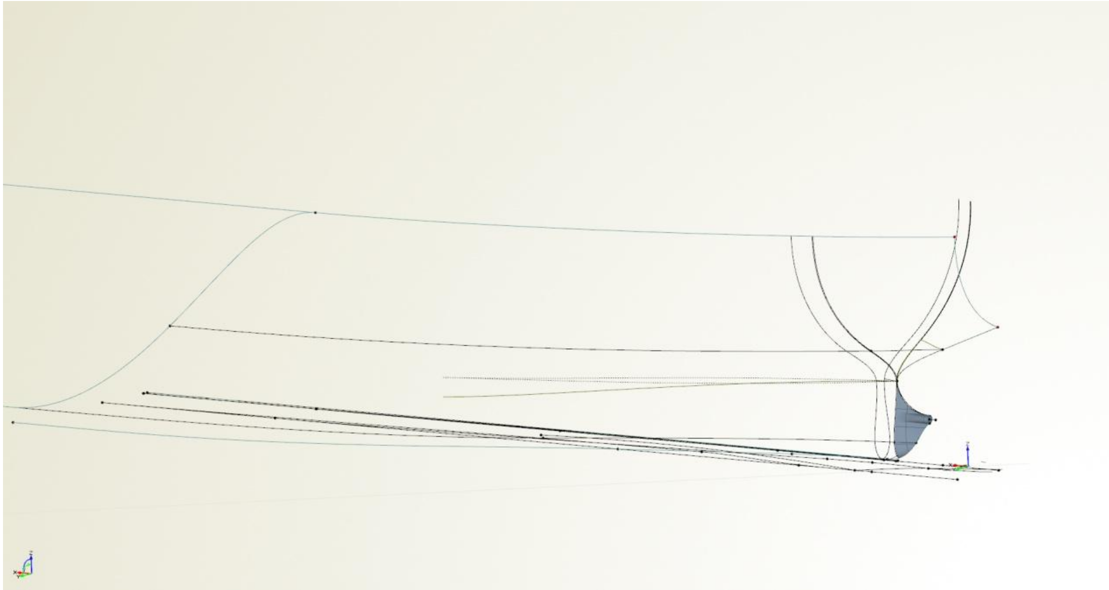
- <u>Surfaces</u>

The surfaces generated are the following:

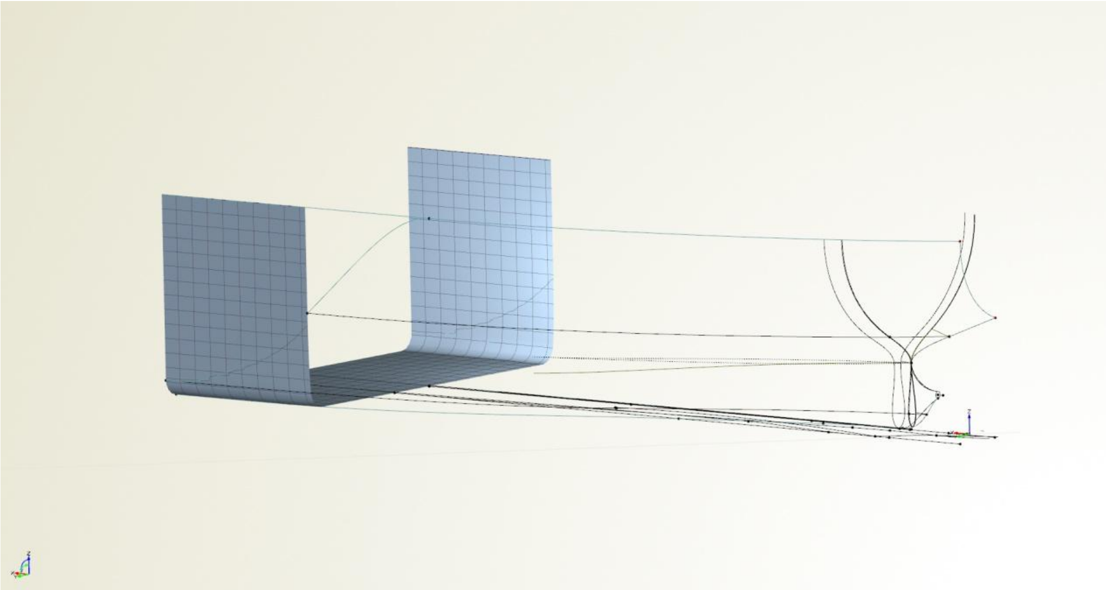
Surface Name	Description

Abdy_bulb	The last part of the stern bulb, including the stern tube
Surf_1WL	The connecting surface between the midbody with only one waterline (lower part)
Surf_2WL	The next surface with 2 waterlines
Surf_2WL_1Diag	The surface with 2 waterlines and one diagonal
Surf_stern	The final surface of the stern overhang until the transom
Surf_blendAftLow	The blending surface above the propeller

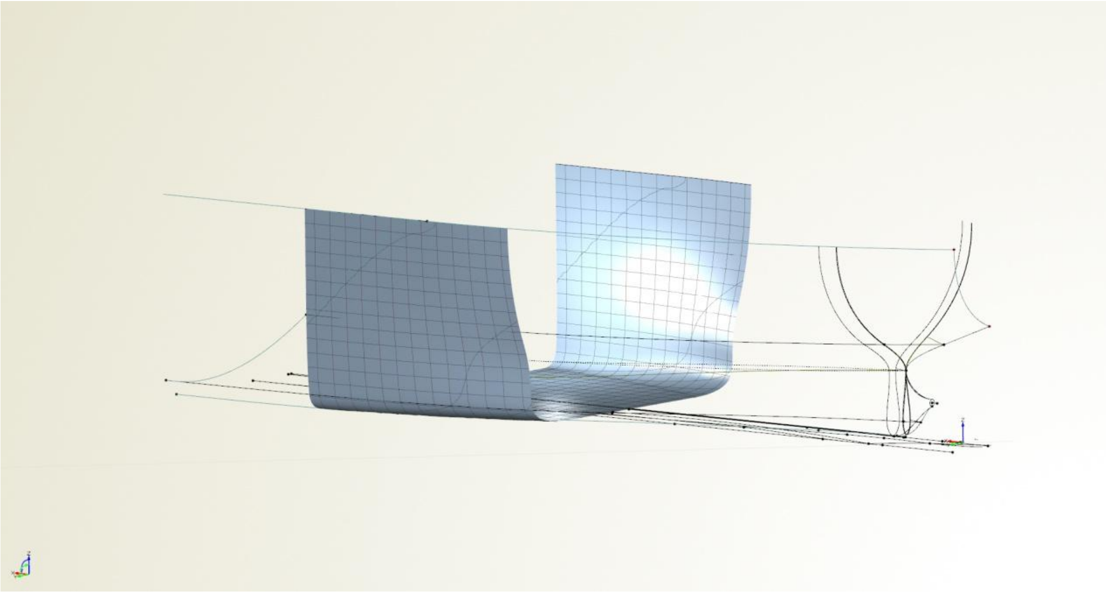
The above mentioned surfaces can be seen at the following pictures:



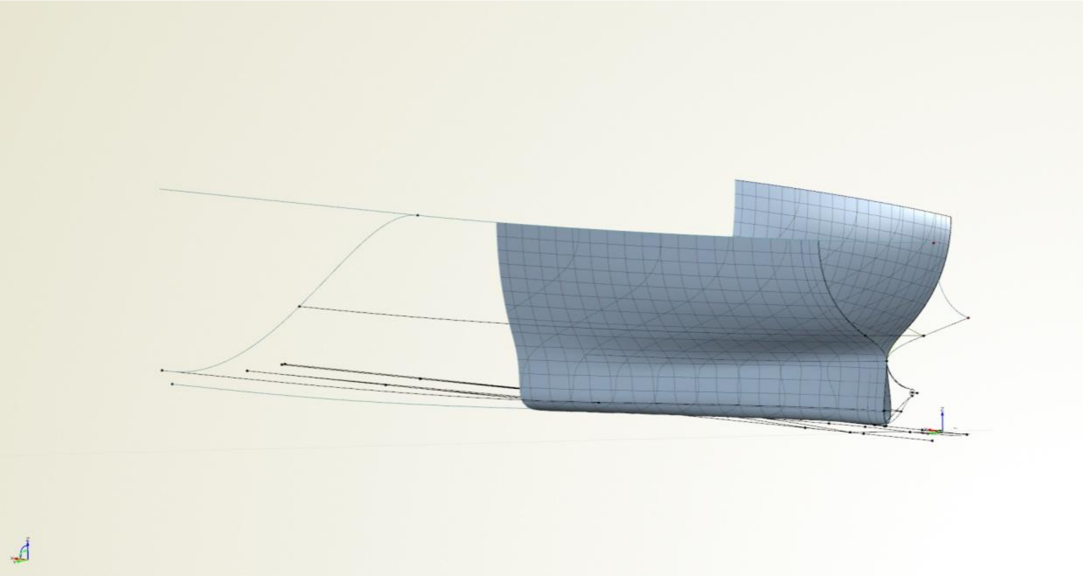
Picture: The aft bulb surface



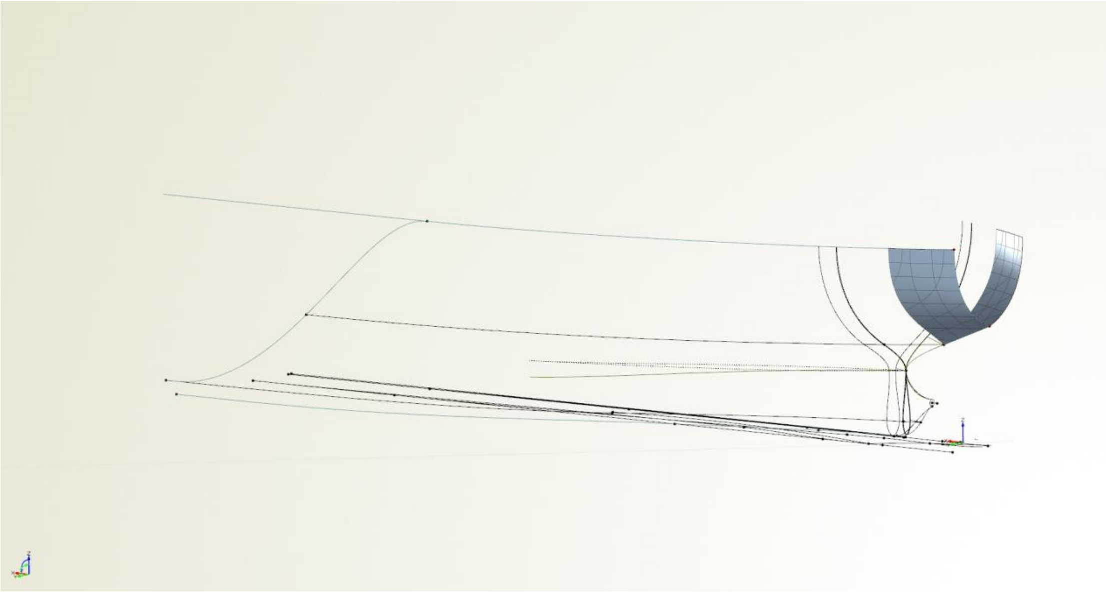
Picture: "Surf_1WL"



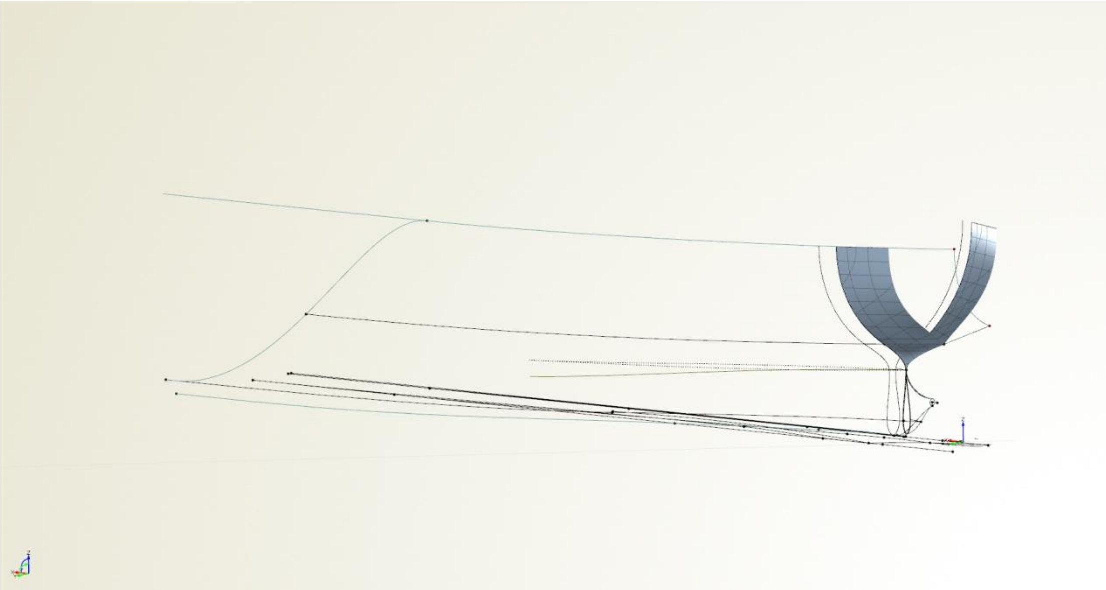
Picture: "Surf_2WL"



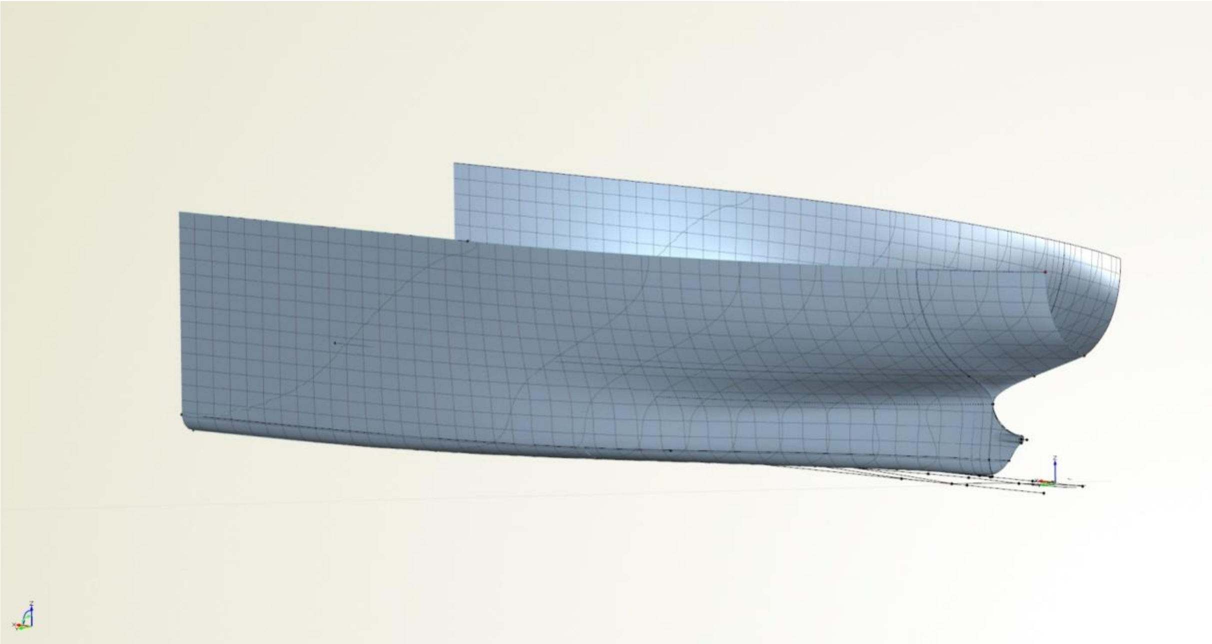
Picture: "Surf_2WL_1Diag"



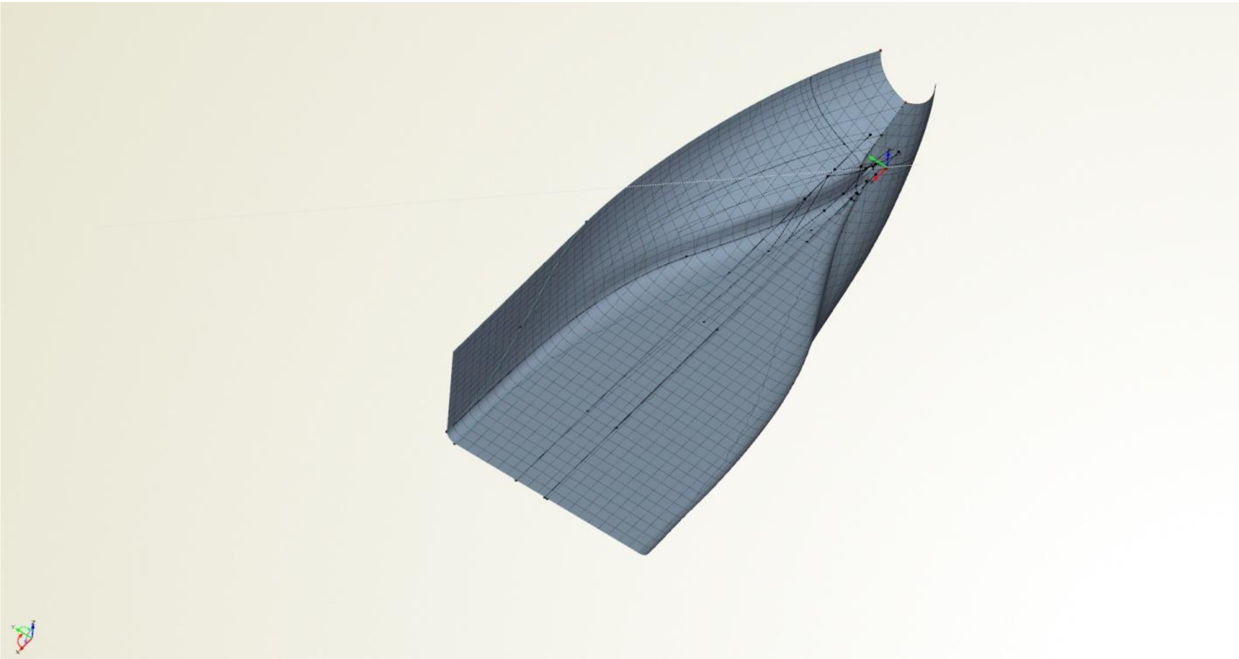
Picture: "Surf_stern"



Picture: "Surf_blendAftLow"

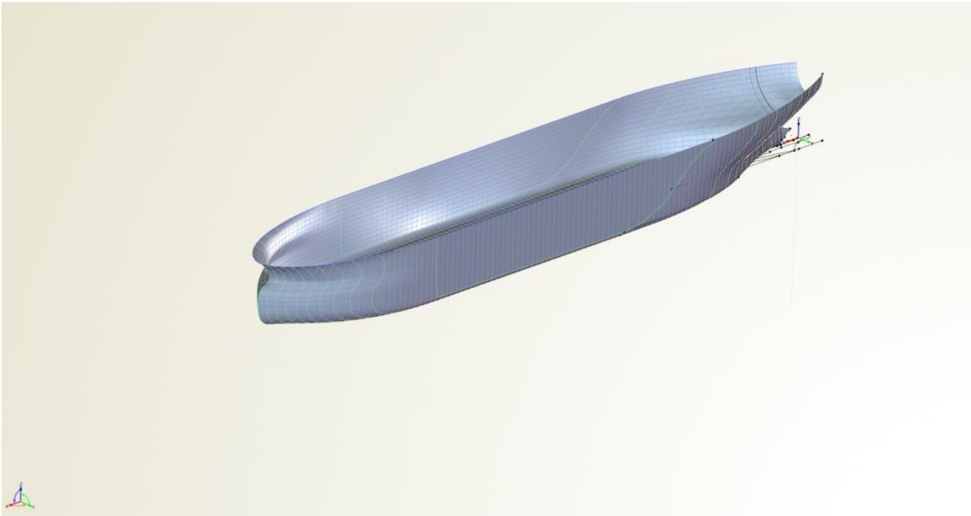


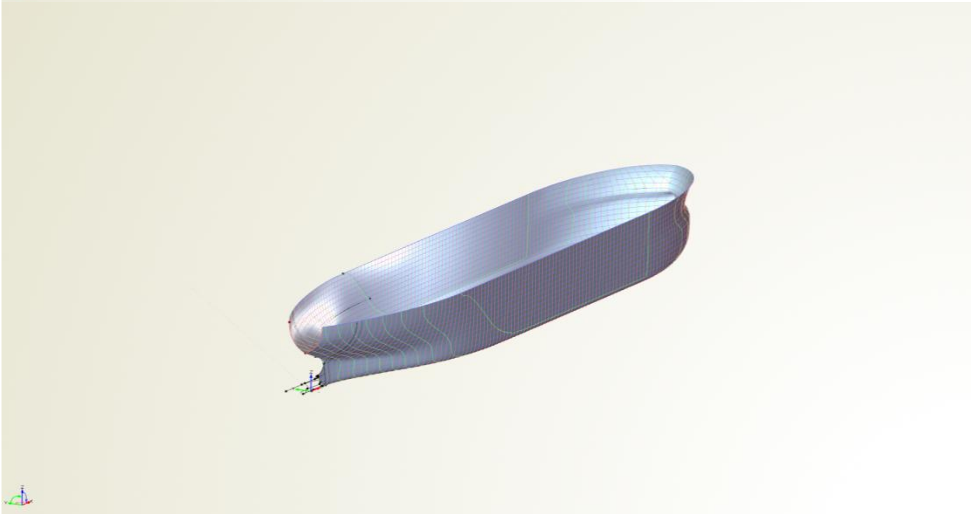
Picture: The aftbody of the vessel



Picture: Another view of the aftbody

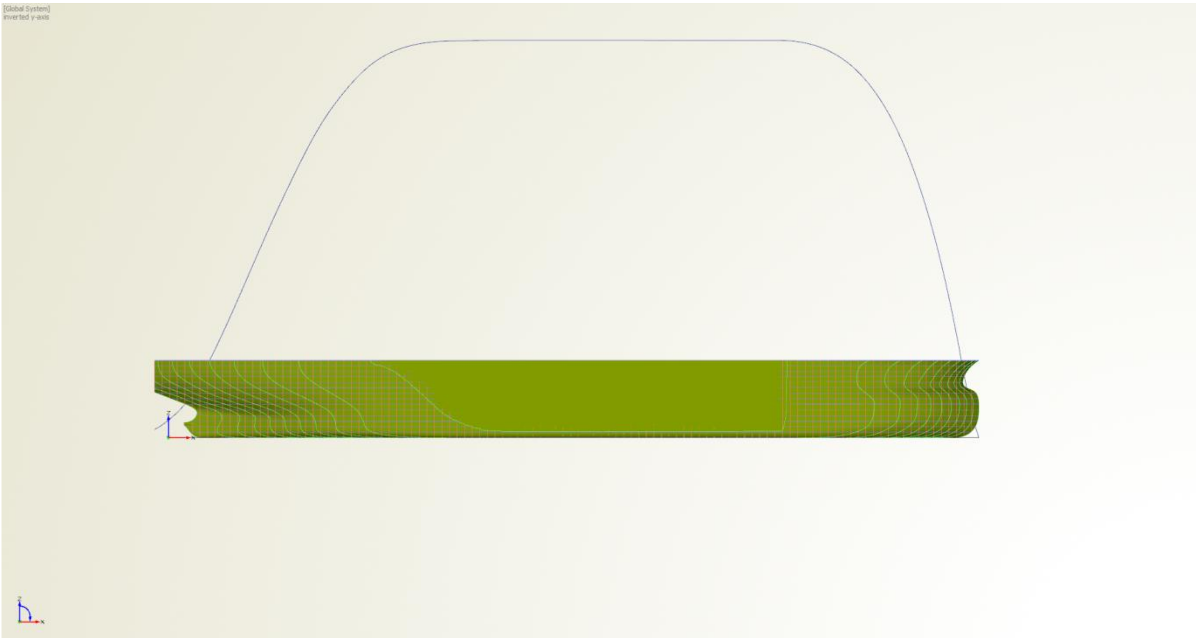
The result is to merge the three groups, the aft, fore and midbody and the hullform is created:





8.2. Hydrostatic Calculations and Lackenby Variation

The next step, similarly with the AFRAMAX modeling is the hydrostatic calculation and the Lackenby variation in order to achieve the desired LCB and Cb values.
First, a simple hydrostatic calculation takes place that defines the immersed volume and thus we can calculate the Cb, and the longitudinal centre of buoyancy.
Then, one can define the desired values for these two parameters and calculate the relative difference, which will be used as an input for the Lackenby Shift. Then the shift takes place and a second hydrostatic calculation validates the results and provide the final basic hydrostatic information for the design.
We can see the resulting hull and Sectional Area Curve (SAC) at the pictures below:



Picture: Profile of the transformed hull and the new SAC

Picture: 3D view of the transformed hull