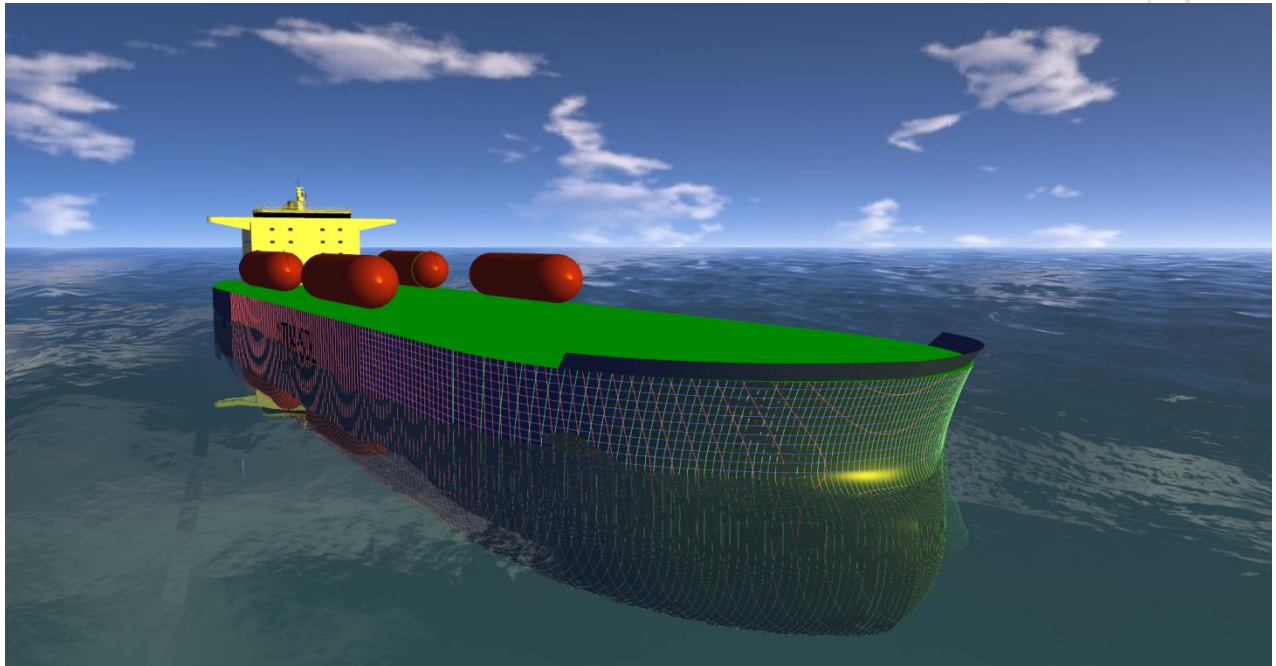


VISIONS 2012 COMPETITION

TEAM NAME:

**MULTI VENTURE: ENERGY EFFICIENT AND ENVIRONMENTALLY FRIENDLY
TANKERS**



ATHENS-JUNE 2012

VISIONS 2012 COMPETITION

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MULTI VENTURE : ENERGY EFFICIENT AND ENVIRONMENTALLY FRIENDLY TANKERS

ABSTRACT

The present project aims to investigate ways to increase the efficiency of an already optimized tanker design concept. Following an extensive multi-objective optimization of an AFRAMAX tanker for the minimization of the Accidental Oil Outflow (according to the MARPOL probabilistic model), the minimization of the IMO Energy Efficiency Design Index (EEDI) and the minimization of the Required Freight Rate, an additional study takes place in order to maximize the efficiency of the design. 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.
2. The machinery arrangements are re-examined, considering LNG as main fuel for two alternative scenarios. The use of hybrid power plants and applications for an all electric ship are also 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 above design aspects are studied by two study-groups and will be finally integrated in a holistic context and assessed for a final proposal for a superior product for the future shipping industry, that is safer, more efficient and more competitive than any existing solution and is also feasible and can provide a new niche market for the European Shipbuilding Industry both in retrofitting of systems or in new built ships.

This project is done by a team of 5th Year student of the School of Naval Architecture and Marine Engineering of the National Technical University of Athens.

CHAPTER ONE:

INTRODUCTION, MOTIVATION AND RESEARCH AREA FOR MULTI VENTURE

The Multi Venture design concept 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. The 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.

Multi Venture is concept that addresses the problem holistically and for the tanker industry. According to the research themes set for the VISIONS 2012 competition, the Multi Venture concept aims at providing an AFRAMAX tanker concept with increased efficiency, drastically reduced emissions and the use of an Liquefied Natural Gas (LNG) as a fuel. Multi Venture is also a product of exhaustive, multi objective optimization using a fully parametric ship design software with a Risk Based principle and a holistic approach and is also subject to a post-analysis of the propulsion system and local geometry.

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.

CHAPTER TWO:

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 NO_x and SO_x 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 NO_x emission standards for new engines, and (3) Tier I NO_x 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 United 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 SO_x and PM, or NO_x, 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 (SO_x, adopted: 1997 / entered into force: 2005)
- North Sea (SO_x, 2005/2006)
- North American ECA, including most of US and Canadian coast (NO_x & SO_x, 2010/2012).
- US Caribbean ECA, including Puerto Rico and the US Virgin Islands (NO_x & SO_x, 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”.

NO_x Emission Standards

NO_x 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 1. Tier I and Tier II limits are global, while the Tier III standards apply only in NO_x Emission Control Areas.

Tier	Date	NO _x Limit, g/kWh		
		n < 130	130 ≤ n < 2000	n ≥ 2000
Tier I	2000	17.0	45 • n-0.2	9.8
Tier II	2011	14.4	44 • n-0.23	7.7
Tier III	2016†	3.4	9 • n-0.2	1.96

Table [1]. MARPOL Annex VI NO_x Emission Limits
In NO_x Emission Control Areas (Tier II standards apply outside ECAs)

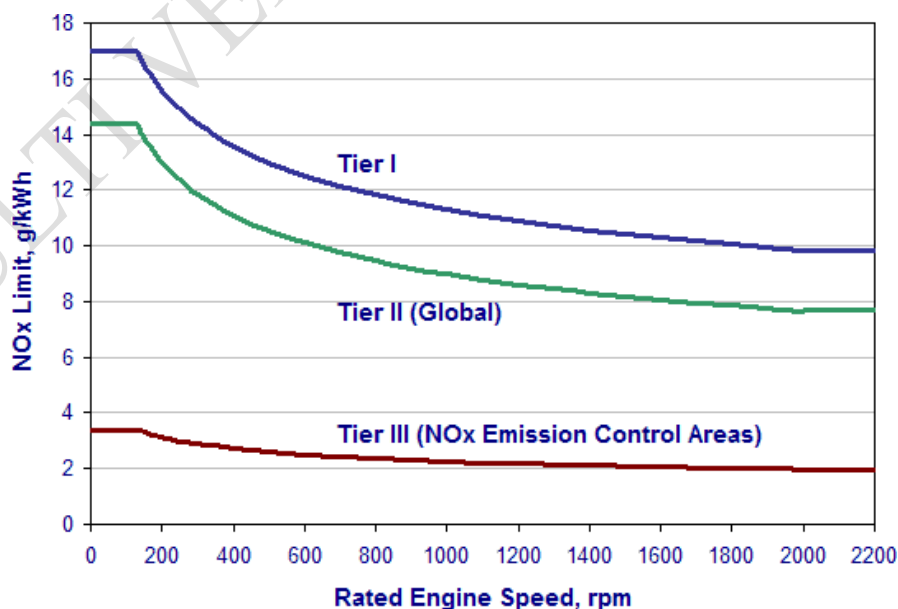


Figure [1]. MARPOL Annex VI NO_x Emission Limits

- 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 NO_x 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 SO_x emissions and, indirectly, PM emissions (there are no explicit PM emission limits). Special fuel quality provisions exist for SO_x Emission Control Areas (SO_x ECA or SECA). The sulfur limits and implementation dates are listed in Table 2 and illustrated in Figure 2.

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

Table [2]. MARPOL Annex VI Fuel Sulfur Limits
a - alternative date is 2025, to be decided by a review in 2018

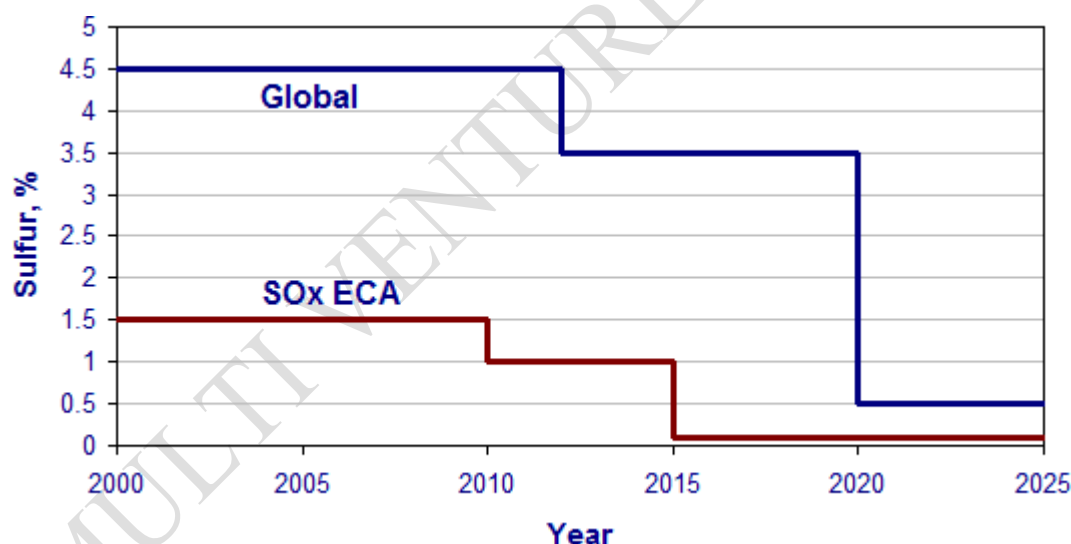


Figure [2]. MARPOL Annex VI Fuel Sulfur Limits

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 SO_x 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 SO_x ECAs, ships can fit an exhaust gas cleaning system or use any other technological method to limit SO_x emissions to ≤ 6 g/kWh (as SO₂).

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 into 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 liters 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.

TANKER EFFICIENCY AND PERFORMANCE

The policy makers and societal pressure to reduce emissions and increase efficiency onboard is, as we discussed a new challenge and demand for the shipping industry. However, it is an already efficient industry, (figure [3]) as the large economies of scale and size give the ship an unparalleled advantage compared to other modes of transport.

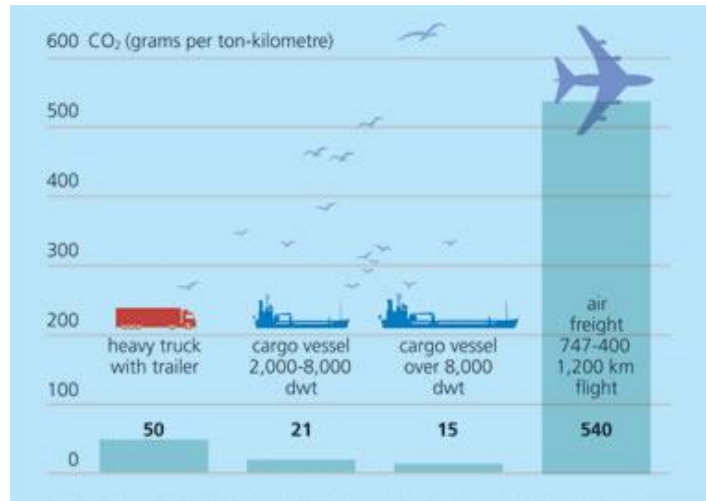


Figure [3]: CO₂ emitted per ton of cargo

However, there is room for improvement. The main problem of shipping is not its efficiency compared to other modes, but the absolute quantity of ship emissions and the often misuse and operational errors that decrease the efficiency and exponentially increase the pollution (Human Factor accidents etc). Since there is a demand for increase of efficiency primarily, before one could propose emissions abatement solutions and sorts of energy saving methods and devices should first define the ship type and application. It is also more reasonable to address first the majority of vessels as a small efficiency in each unit could spark a drastic increase in the overall number.

The world shipping fleet is consisted by variety of vessel types such as bulk carriers, tankers and passengers. It is evident from figure [4], that the majority of vessels afloat is tankers and bulk carriers which is indicative of the need for energy and break bulk shipping, given the fact that oil is the primary energy source in today's globalized society.

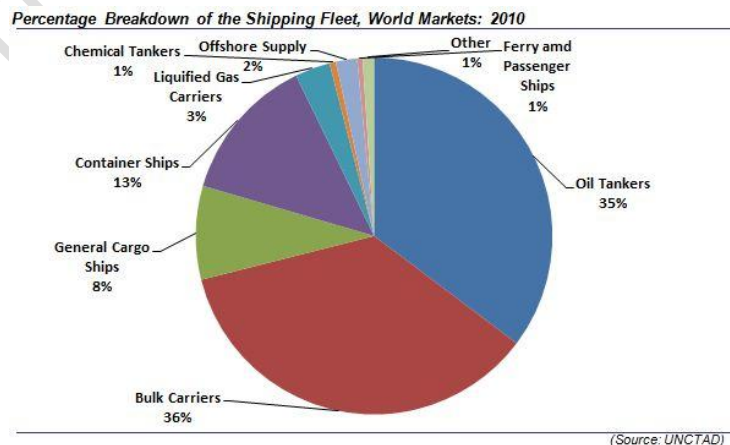


Figure [4]: Breakdown of the world shipping fleet

Staying on the same line of thought, a substantial reduction of emissions could be achieved by a small improvement on tankers (which is relatively plausible) or alternatively by an improvement in containerships. Containerships although are a smaller portion of the global fleet, require much more energy than tankers due to the higher operating speeds. Both vessel types though are of major importance for the global fleet footprint. In the case of tankers it is also very important to maintain the safety onboard as it is the most critical design aspect for these vessels, due to the horrific consequences an oil spill can have.

The present study subsequently, aims at the efficiency increase and the use of alternative fuels for tankers, largely thanks to an exhaustive background on multi-objective optimization and experience, as well as the belief that a major improvement in tankers could have a significant impact in the overall shipping environmental footprint, taking also into account the ballast quantities transported by tankers.

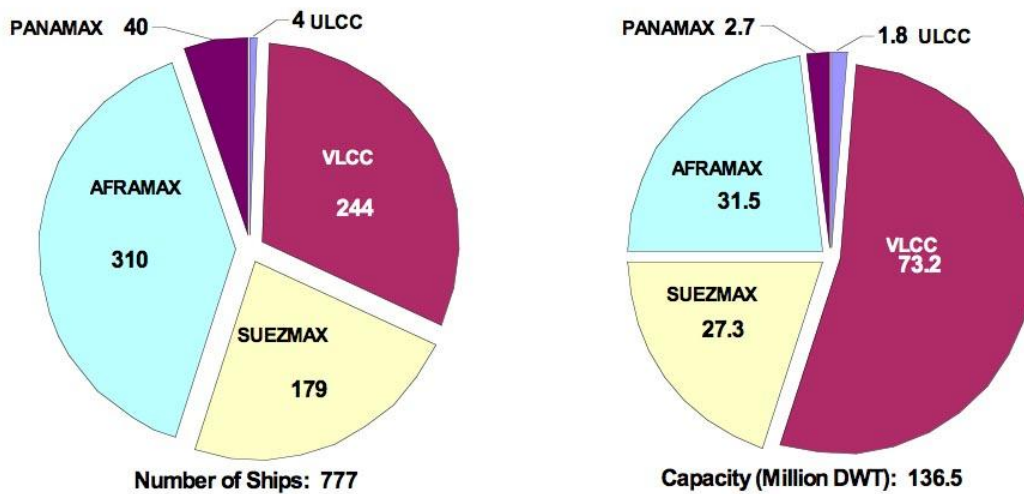


Figure [5]: Breakdown of the global tanker fleet

The tanker type and size that was chosen was AFRAMAX tankers. The reason is that these vessels have the biggest share the world fleet (in terms of number alone) and that they are subject to a renewal, so there is a potential for a new shipbuilding activity in this sector. Furthermore, AFRAMAX tankers operate in some of the most environmentally sensitive areas in the world, including the Caribbean, Mediterranean and Baltic Seas that are of significant natural beauty. These two factors shape the required merits for AFRAMAX tankers, namely Green attitude and Safety as well as the design and optimization criteria set during this study. Since, all of the main trading areas of these ships are existing or future ECAs it is also important to identify solutions that can comply with the new emissions regulations and in the meantime be economic and ideally increase the existing competitiveness and profitability of the designs.

It is important in this point to mention that this work is the direct offspring of the shortlisted idea “The G5 Tanker” in VISIONS 2011 competition, as it is the same design concept calibrated, systematically optimized and with new propulsion systems.

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 (CH₄), and more heavier hydrocarbons such as ethane (C₂H₆), propane (C₃H₈) and butane (C₄H₁₀). 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 largescale 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.

LNG Related Emissions

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 (S_{ox})

SO_x 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 NO_x 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 (N_{ox})

NO_x also combine with water to form damaging corrosive acids. This can damage the lungs and has been associated with asthma and heart disease. NO_x is a major contributor to smog formation. NO_x is reduced through the use of Selective Catalytic Reduction (SCR) technology, described previously. ECA NO_x 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 (Abadie, et al., 2011). 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 1 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 [3] LNG Emission Comparison (Marine Techonology 2011)

References

1. Emission Limit and Tier information from www.dieselfacts.com
2. Losen G. D. , Tveten R. E, "The future potential of LNG as a bunker fuel", Dipl.Thesis NTNU, 11.2011
3. Tri Zen Report, "LNG Markets Perspective", January 2012
4. Marine Technology (Mt), SNAME 2011

CHAPTER THREE:

MULTI-VENTURE: THE CASE OF THE ENERGY EFFICIENT TANKER DESIGN CONCEPT DESCRIPTION

Following an extensive multi-objective optimization of an AFRAMAX tanker for the minimization of the Accidental Oil Outflow (according to the MARPOL probabilistic model), the minimization of the IMO Energy Efficiency Design Index (EEDI) and the minimization of the Required Freight Rate, 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 sustained 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.

CHAPTER FOUR:

MULTI-VENTURE CONCEPT

PART ONE: HULL OPTIMIZATION AND DESIGN

1. THE BASELINE MODEL

2.1. Introduction to the Design Concept, Description and Assumptions

This model, being the core of one of the author's Thesis was developed during his stay at F.S and was the basis on which he developed his skills in this software.

This AFRAMAX tanker is an inspiration of the author and the present model is an evolution and a parametric version of an earlier tender design, made for the 2011 VISIONS Olympics organized by WEGEMT. The idea was of a Green, Safe, Economical and Competitive Tanker named as the G5 Tanker where G corresponds to several layers of environmentally friendly specifications.

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.

2.2. 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 stricter 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.

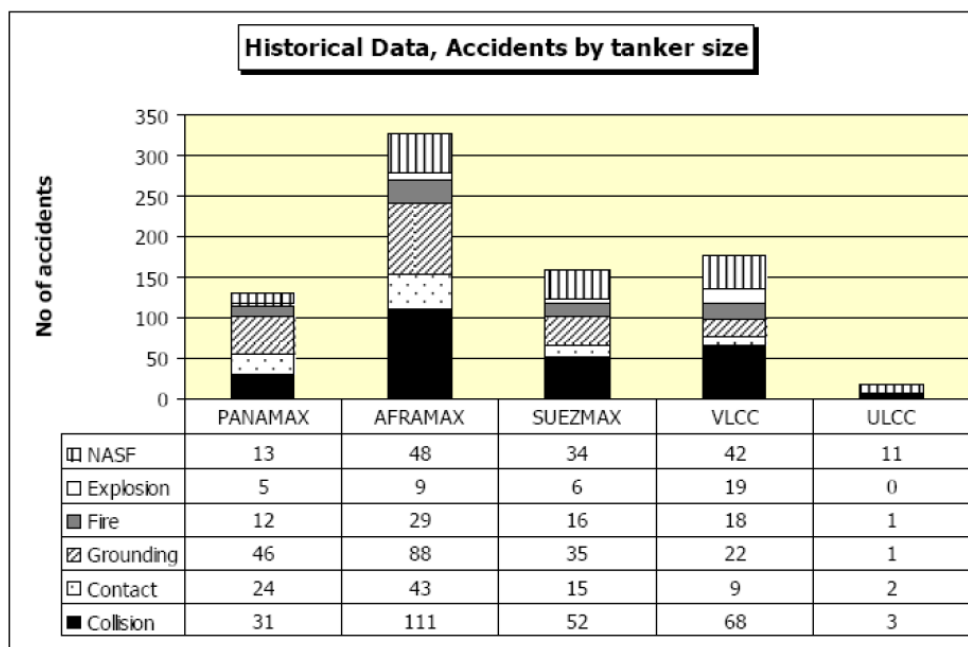


Figure [1]: Historical Data of Tanker Accidents (FSA 2008)

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 quantitative 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.

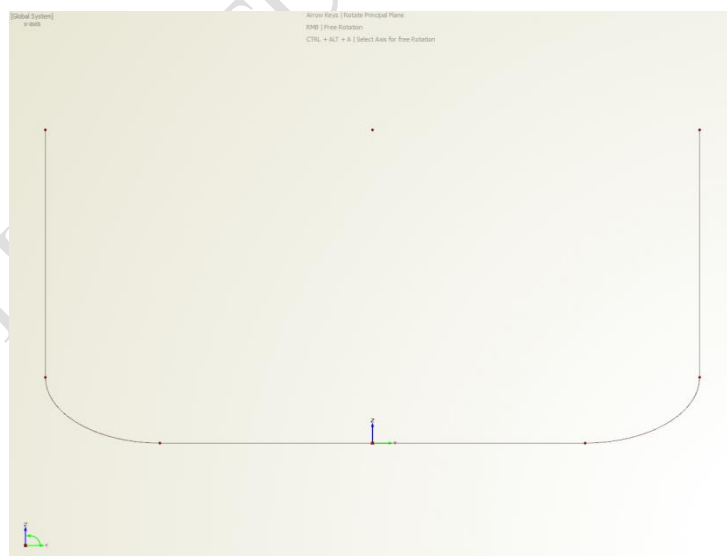
The reason mentioned above, for tankers alone is very supporting for the implementation of twin engine, twin screw, twin rudder tankers which can be realized as a whole by the concept of the twin skeg arrangement. This philosophy has been implemented already by Swedish ship owner STENA, who has built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



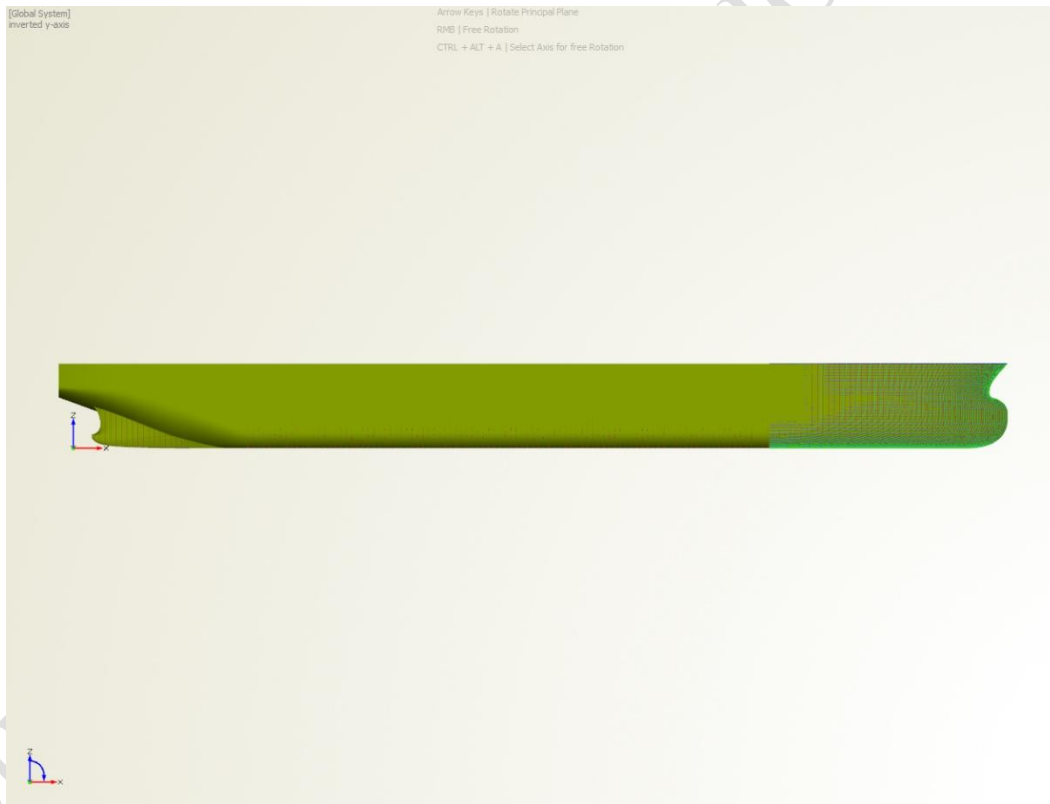
Picture [1]: The midship section of the model incorporating the extended elliptic bilge concept

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.

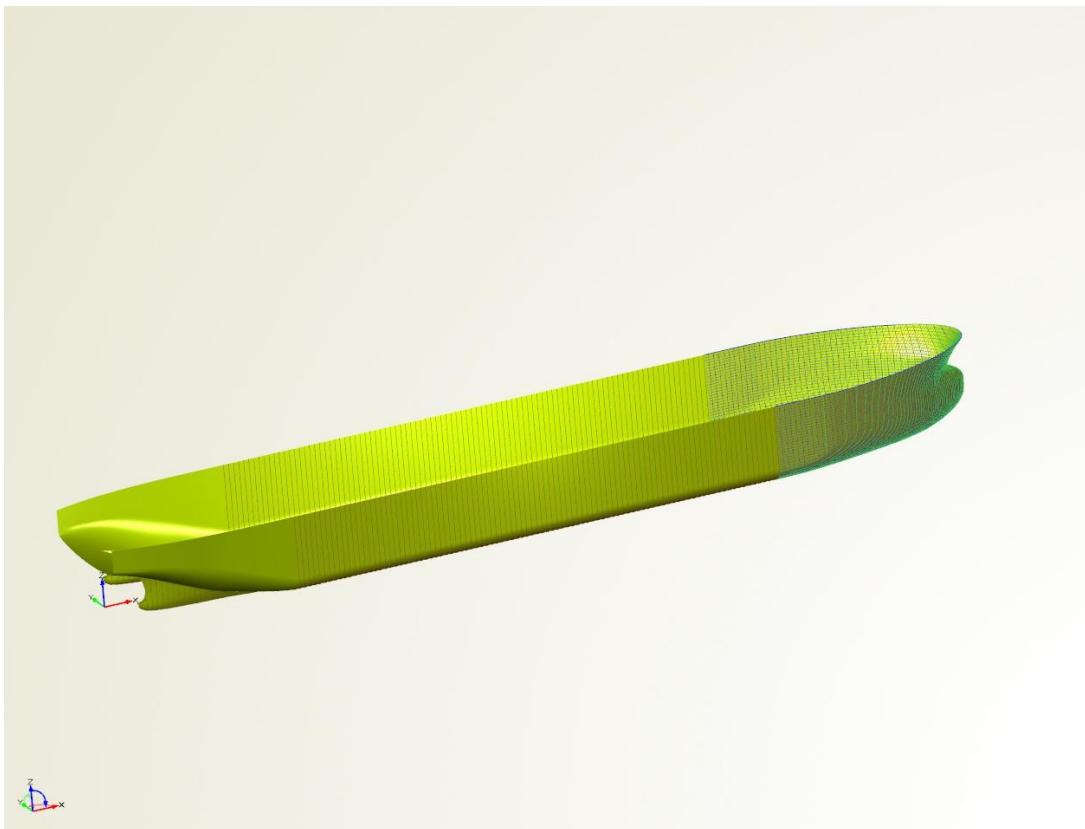
➤ *Final Ship Surface*

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.

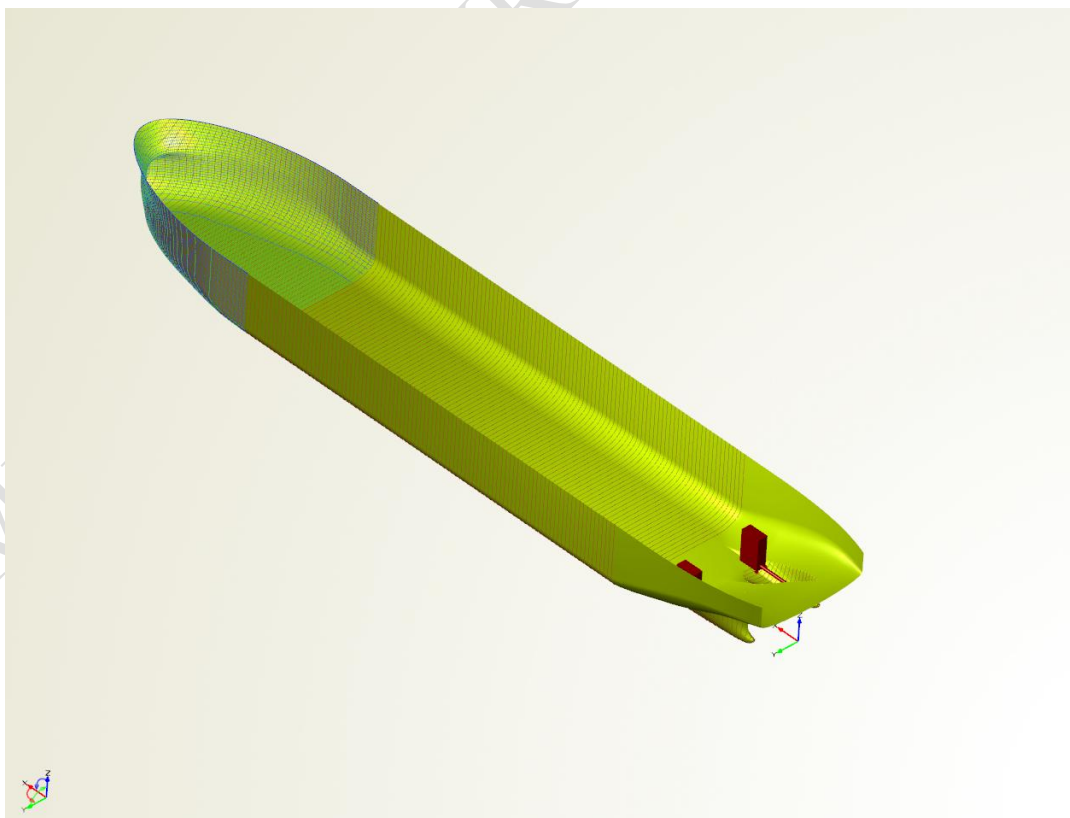


Picture [2]: Profile view of the vessel in question

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 [3]: 3D view of the vessel



Picture [4]: 3D view of the vessel together with its engines

2.3. 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 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 [1]: Results of TANKOPT study

The table [1] 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 [2], 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 [2]: 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 [3]).

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 [3]: 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 [4].

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 [4]: 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 (Nikolopoulos, Papanikolaou [], 2011) 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.

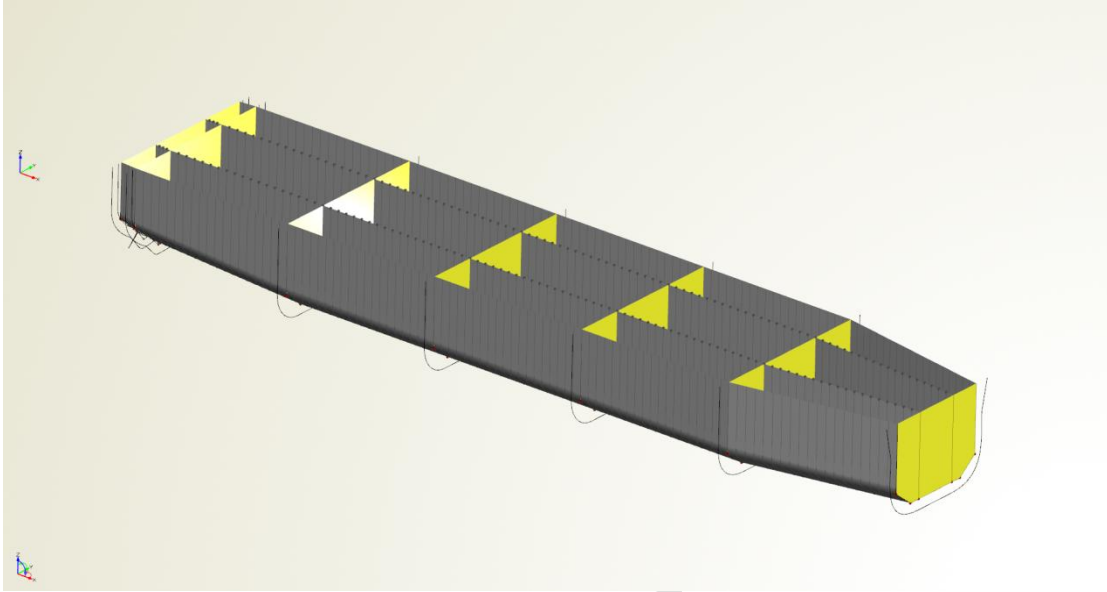
From the other hand, the most important implication would be the elimination of the pump room. This enables the designer to change the location of the engine room bulkhead which separates the engine room from the cargo area. By doing so, and by also considering the required spaces for fuel and machinery 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 [5]: Snapshot of the tank arrangement

2. DESIGN APPROACH AND METHODOLOGY

2.1. Calculations Workflow

As we mentioned earlier, in the background chapter, 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:

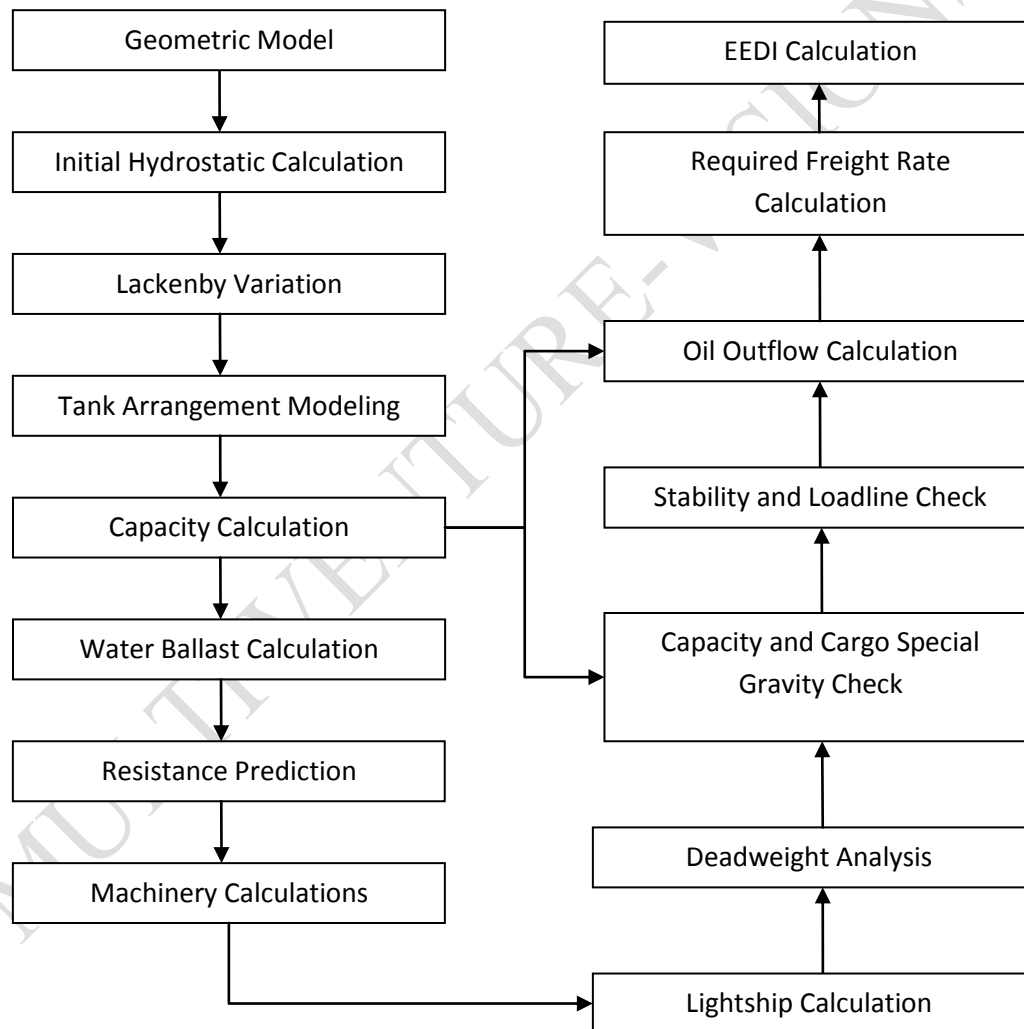


Figure [2]: The integration and calculations workflow

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 C_b 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 C_b 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 nad 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, it is believed and expected that the results of Holtrop are generally conservative and at the safe side compared with CFD analysis.

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-Gilfilan 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-Gilfilan formula are calibrated for low speed, two stroke engines.

The outfitting weight is 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 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 28agnitu 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/m³. 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, alumnous 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:

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

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, where 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

4.1. 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.

At this point we must also make clear that this is a global approach and not detailed one. It is our aim and of particular interest to conduct more extensive optimization studies aiming at the local shape of the hullform and assess it using a CFD code. Unfortunately this was not possible at this stage due to the lack of a license for SHIPFLOW that is update and can accommodate the tight integration with FFW for a twin skeg design.

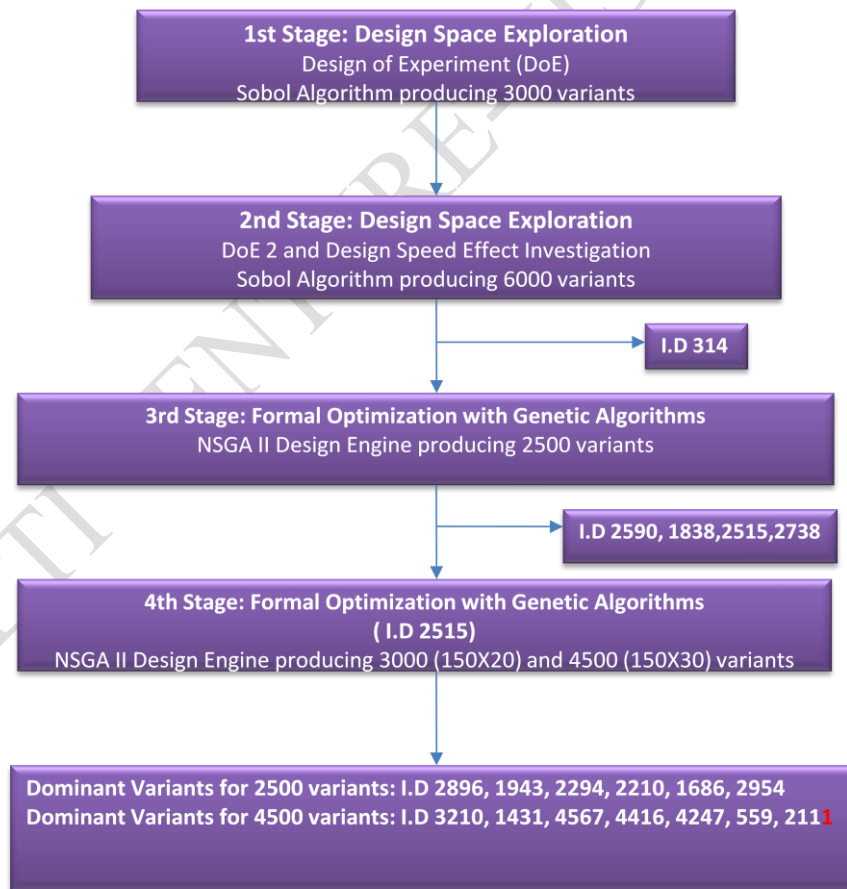


Figure [3]: The optimization stages

4.2. Design Variables Chosen

After the debugging process we mentioned earlier the final choice of the refined design variables can be seen on Table [5]. 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 [5]: 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).

4.3. Design Objectives

The design objectives were different in the DoE and the genetic algorithms. First, as its is a quasi-random design space exploration the objectives are only monitored and not 35agnitud. 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.

4.4. 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 []. 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 [6]: 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.

4.5. 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 stepped procedure we mentioned earlier. The variables that the algorithm used are the ones in Table [5], 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.

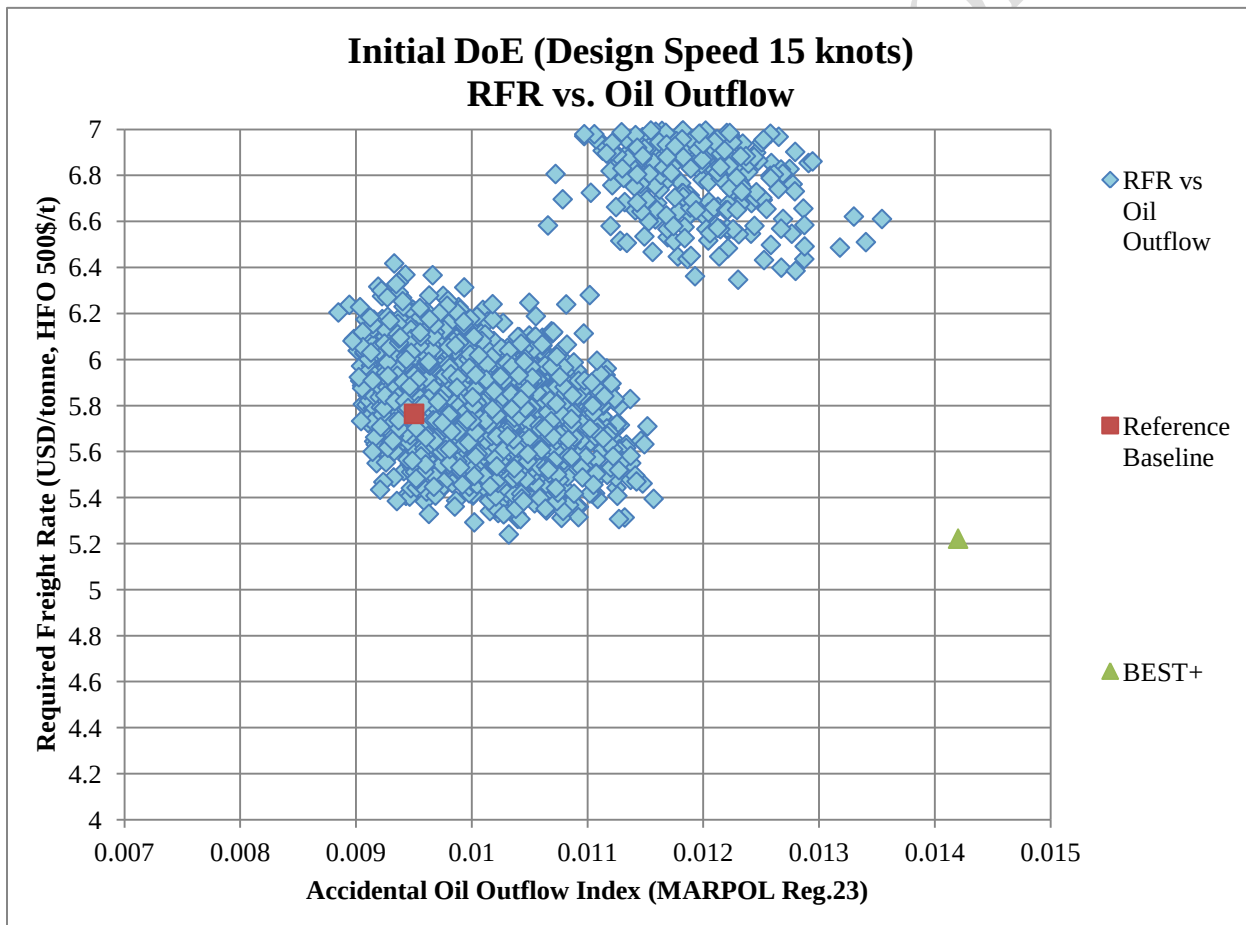
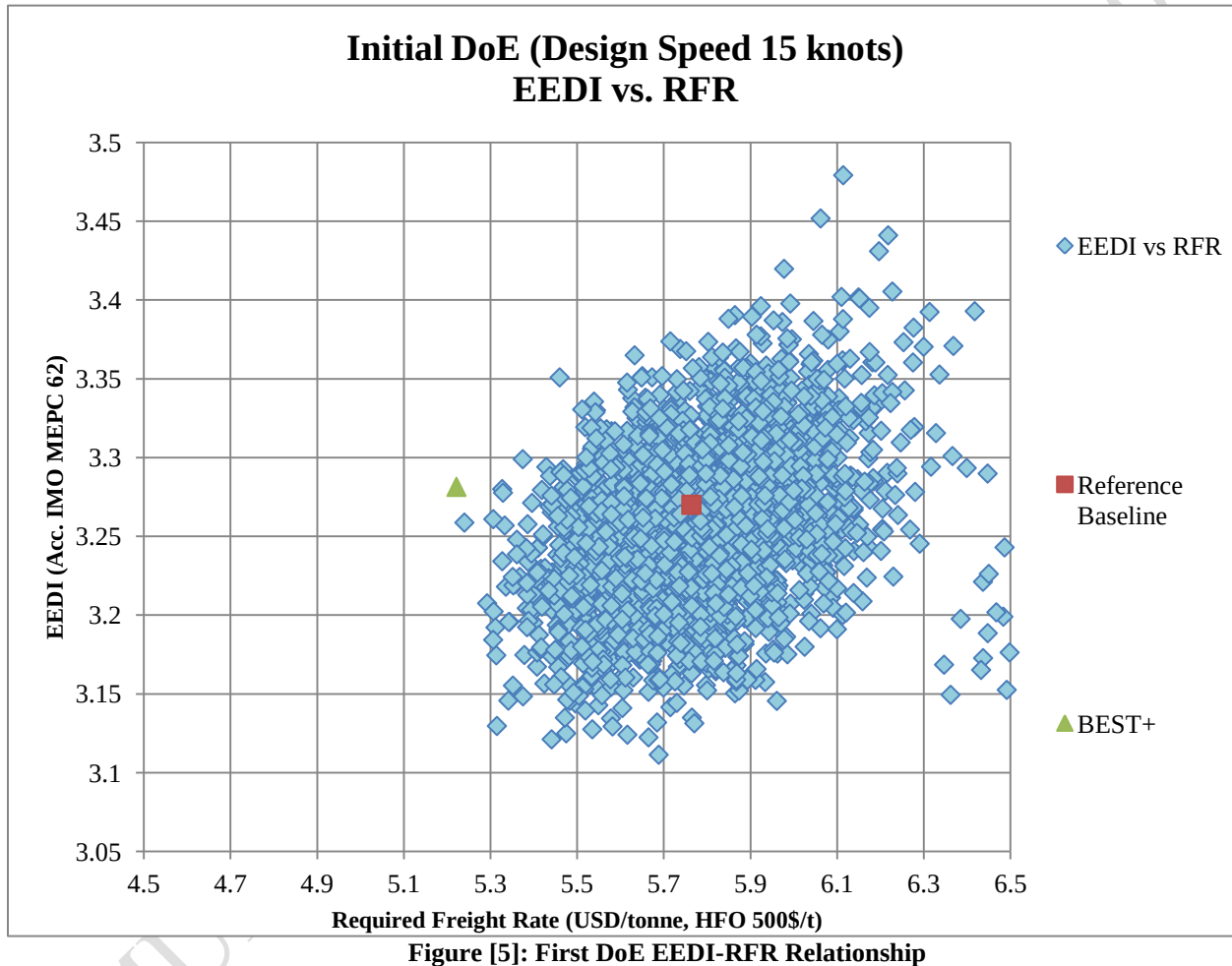


Figure [4]: First DoE RFR-Oil Outflow Relationship

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 m³ more).



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.

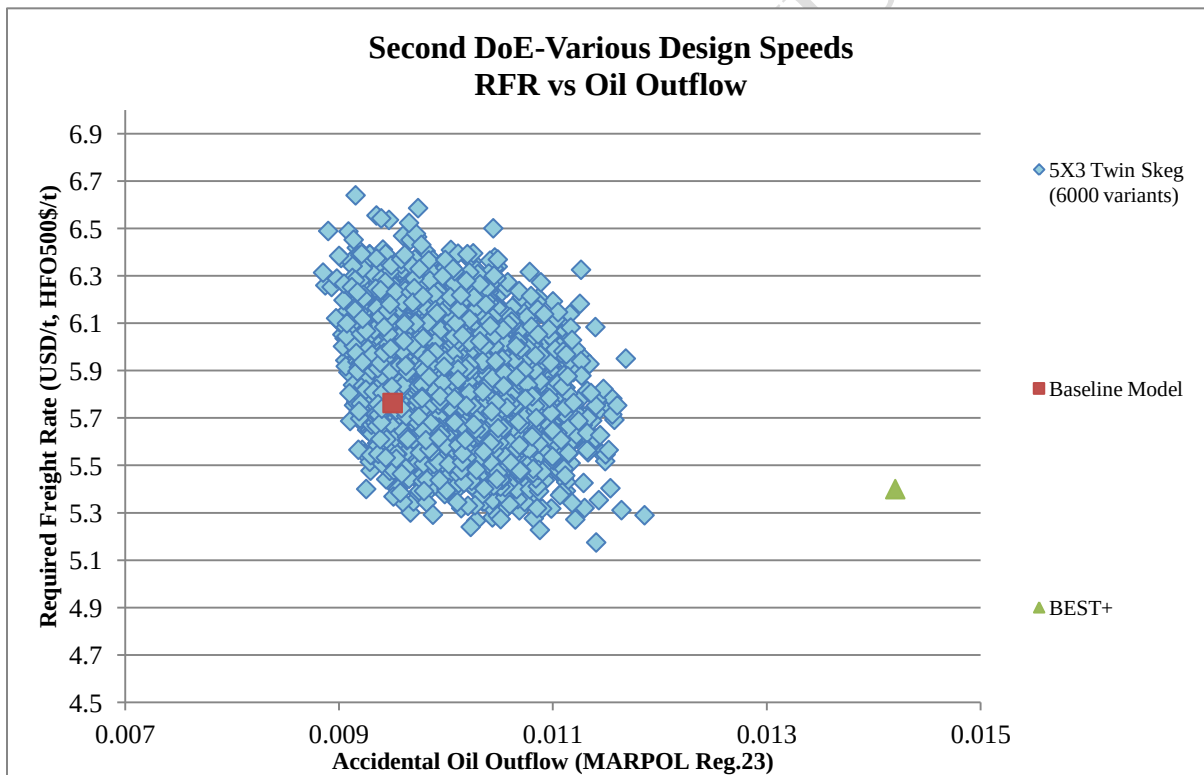
4.6. Second Design of Experiment-The effect of design speed

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 previous study submitted (Nikolopoulos, Papanikolaou (1)), 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.

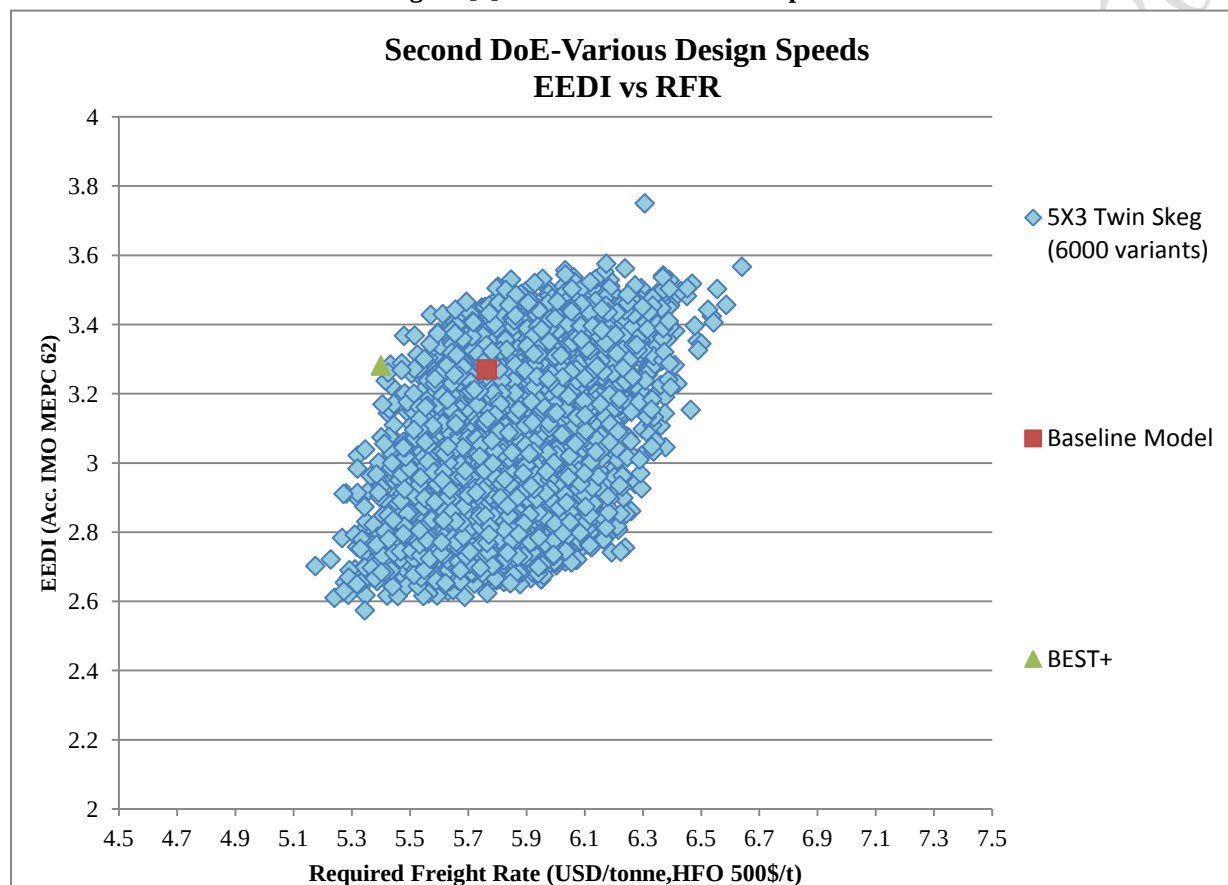
Figure [6]: Second DoE RFR-Oil Outflow Relationship



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 be 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 [18]). 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 C_b 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 [7]: 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).

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

4.7.1. 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% to 85%, 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 []), 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 be 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
Beginning 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 [8]: 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 $\mathbf{y}$ *strictly dominates* (or “is preferred to”) a vector $\mathbf{y}^*$ if each parameter of $\mathbf{y}$ is not strictly greater than the corresponding parameter of $\mathbf{y}^*$ 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 $\mathbf{y}$ strictly dominates $\mathbf{y}^*$. Then the Pareto frontier is the set of points from Y that are not strictly dominated by another point in Y [].

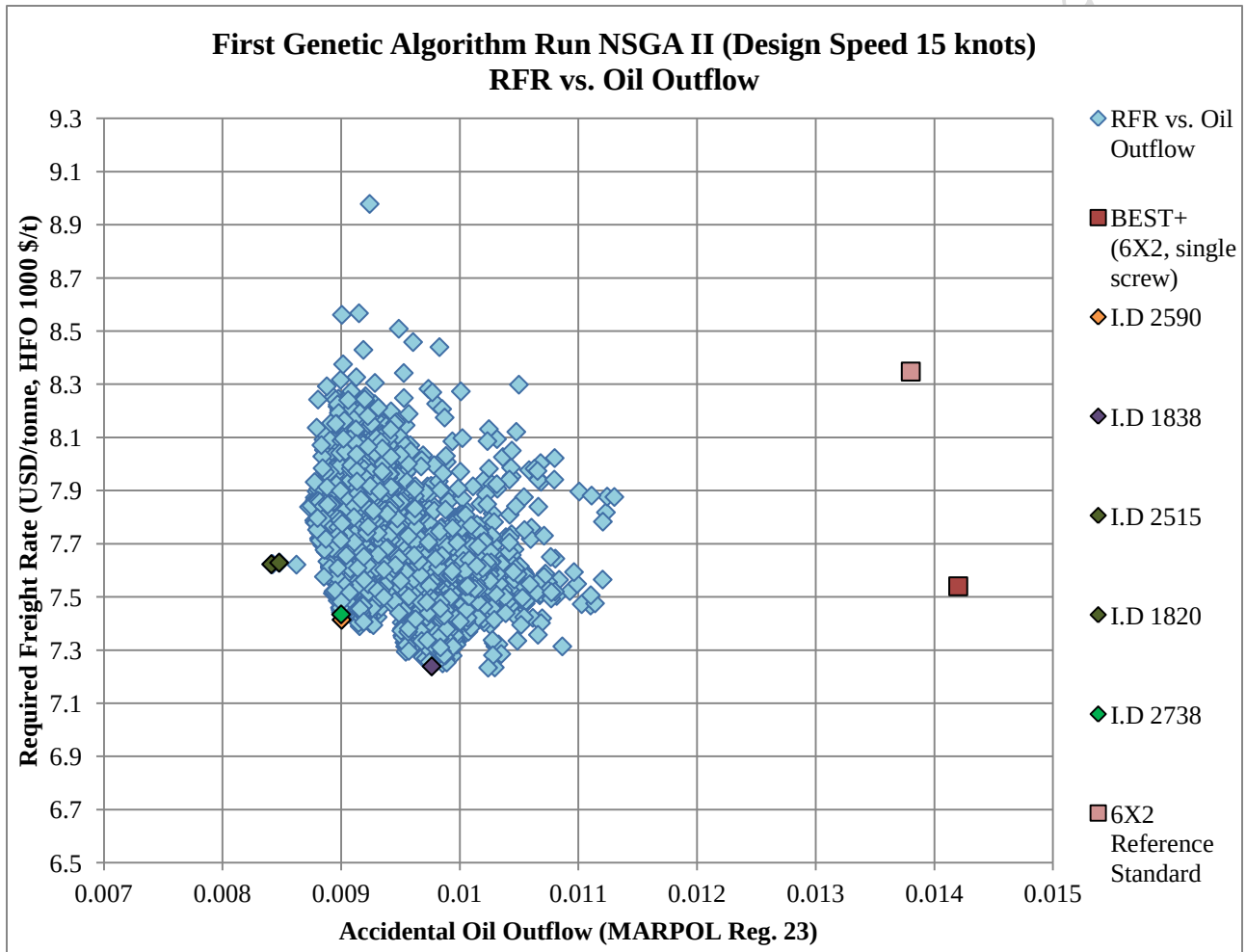


Figure [8]: The RFR-OOI relationship for the first G.A optimization run

This kind of Pareto behaviour can be identified in the scatter plot of the produced feasible designs by the genetic algorithm. In figure [19] 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, where 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.

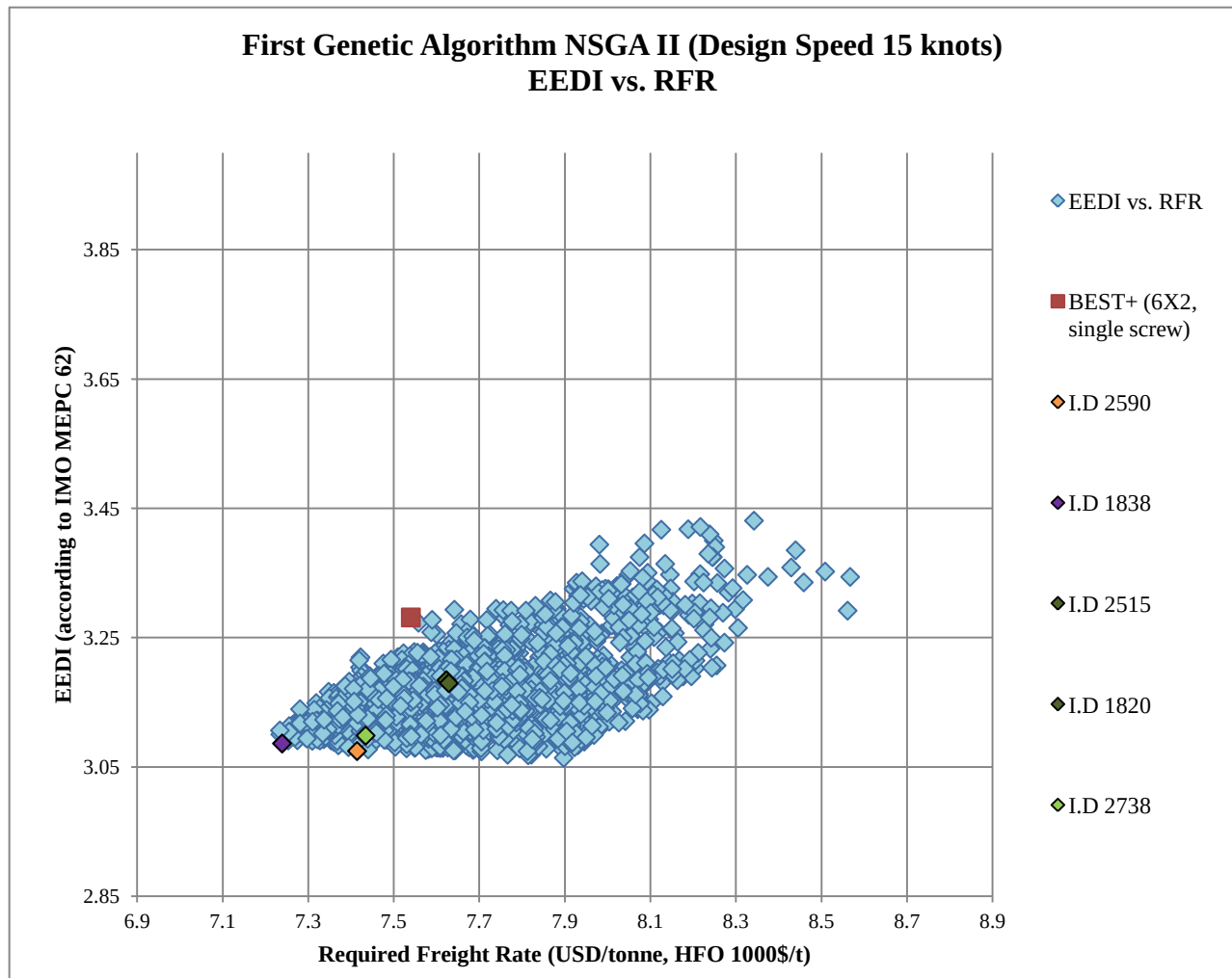


Figure [9]: The relationship between EEDI and RFR for the first G.A optimization run

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.

4.7.2. 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 it 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:

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

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	1 st Scenario	2 nd Scenario	3 rd Scenario	4 th Scenario	5 th 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 [9]: 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:

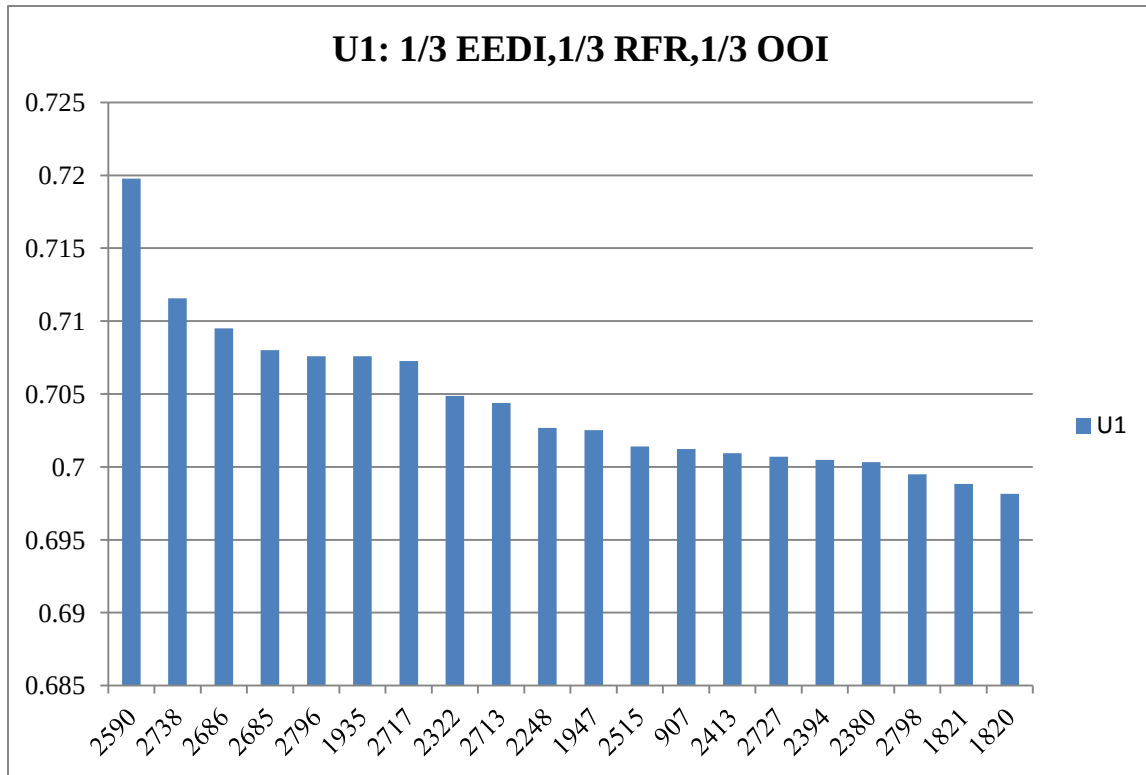


Figure [10]: Design Ranking according to the 1st Scenario

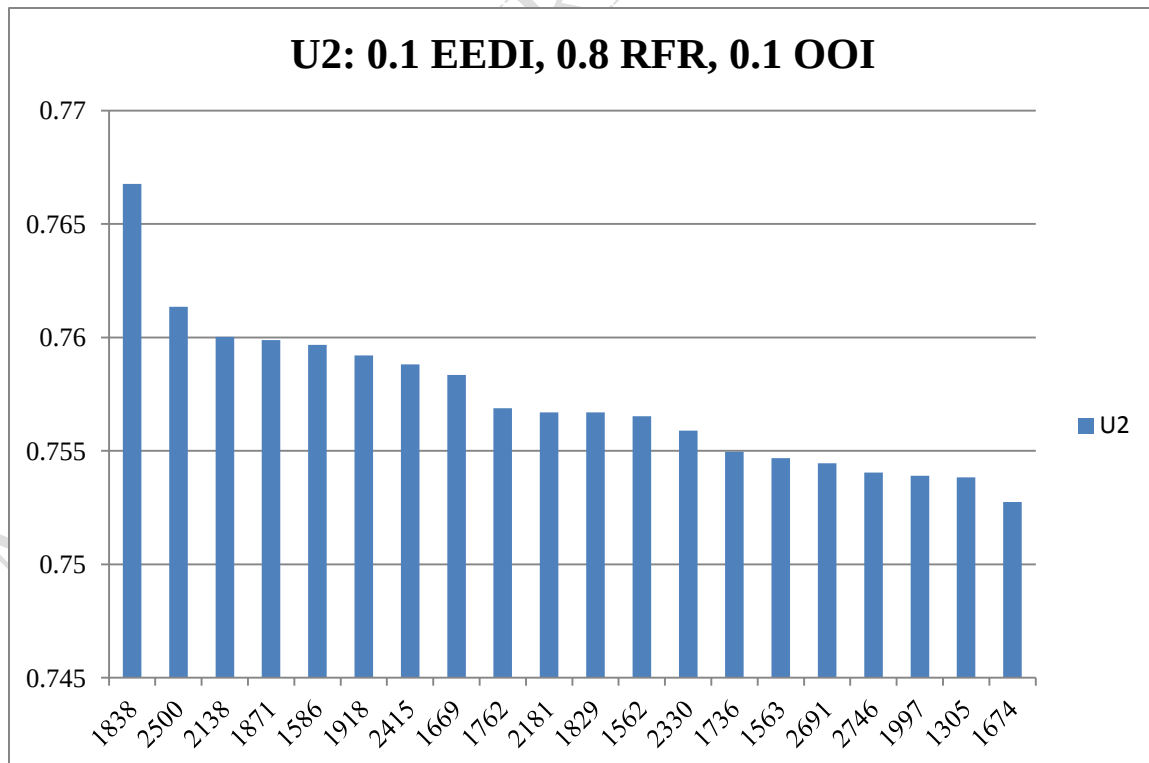


Figure [11]: Design Ranking according to the 2nd Scenario

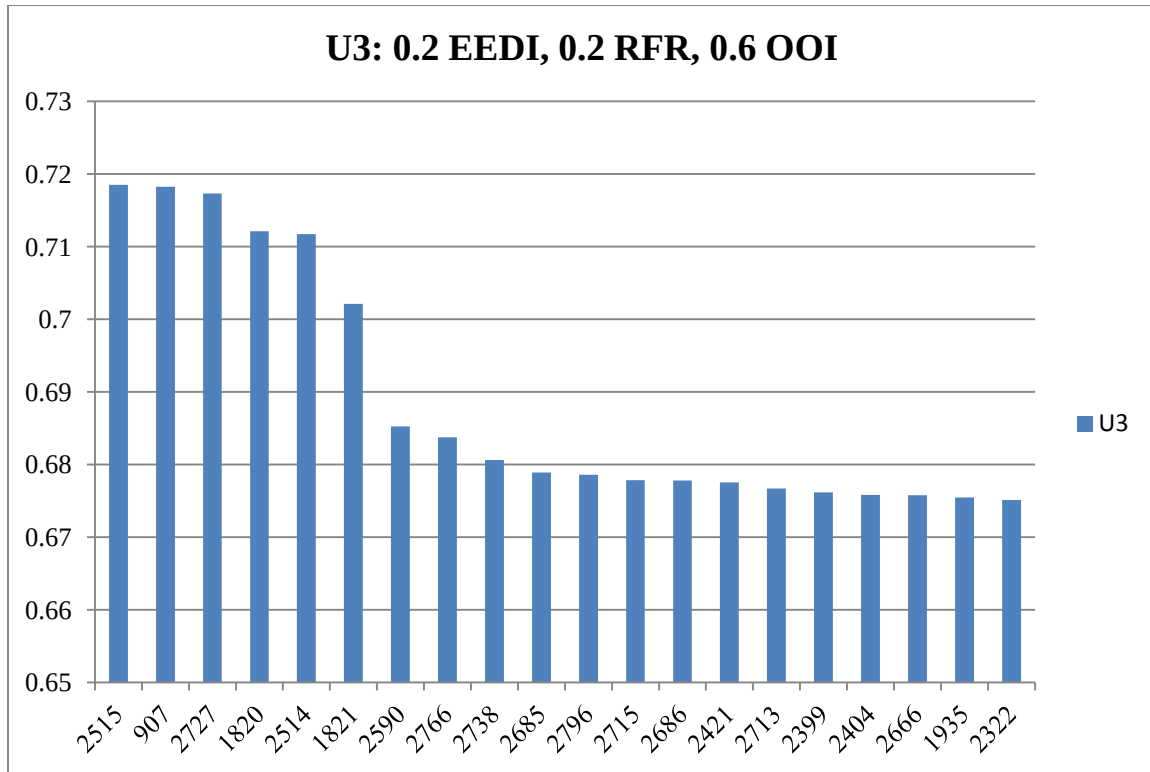


Figure [12]: Design Ranking according to the 3rd Scenario

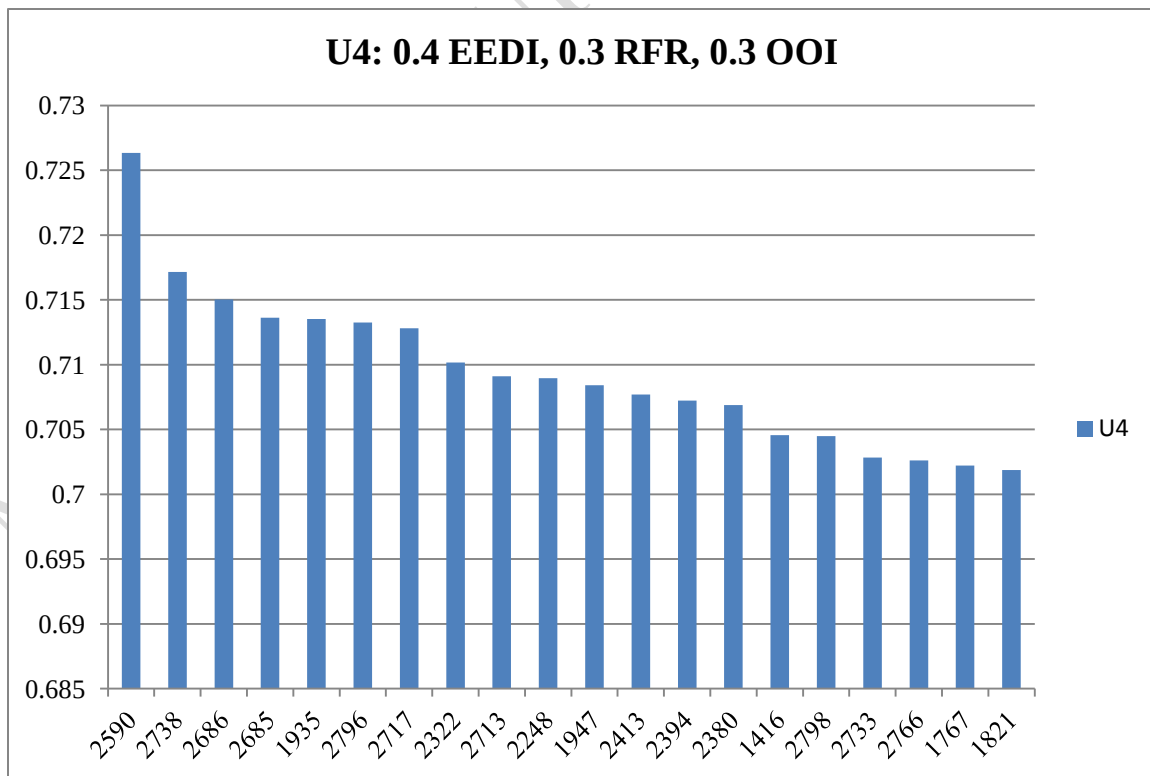


Figure [13]: Design Ranking according to the 4th Scenario

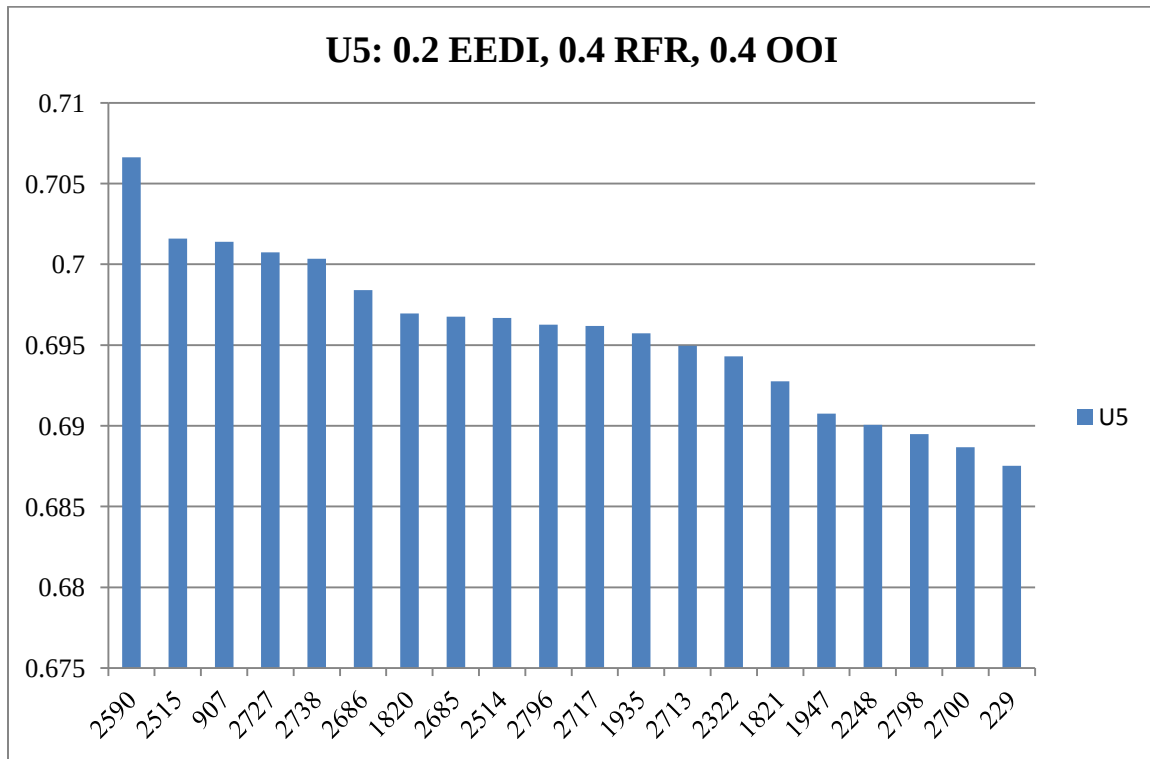


Figure [14]: Design Ranking according to the 5th Scenario

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

Table [10]: 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 []), 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.

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

4.8.1. 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 where the boundary was expanded due to a potential for efficiency improvements in terms of reduced resistance.

4.8.2. 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.

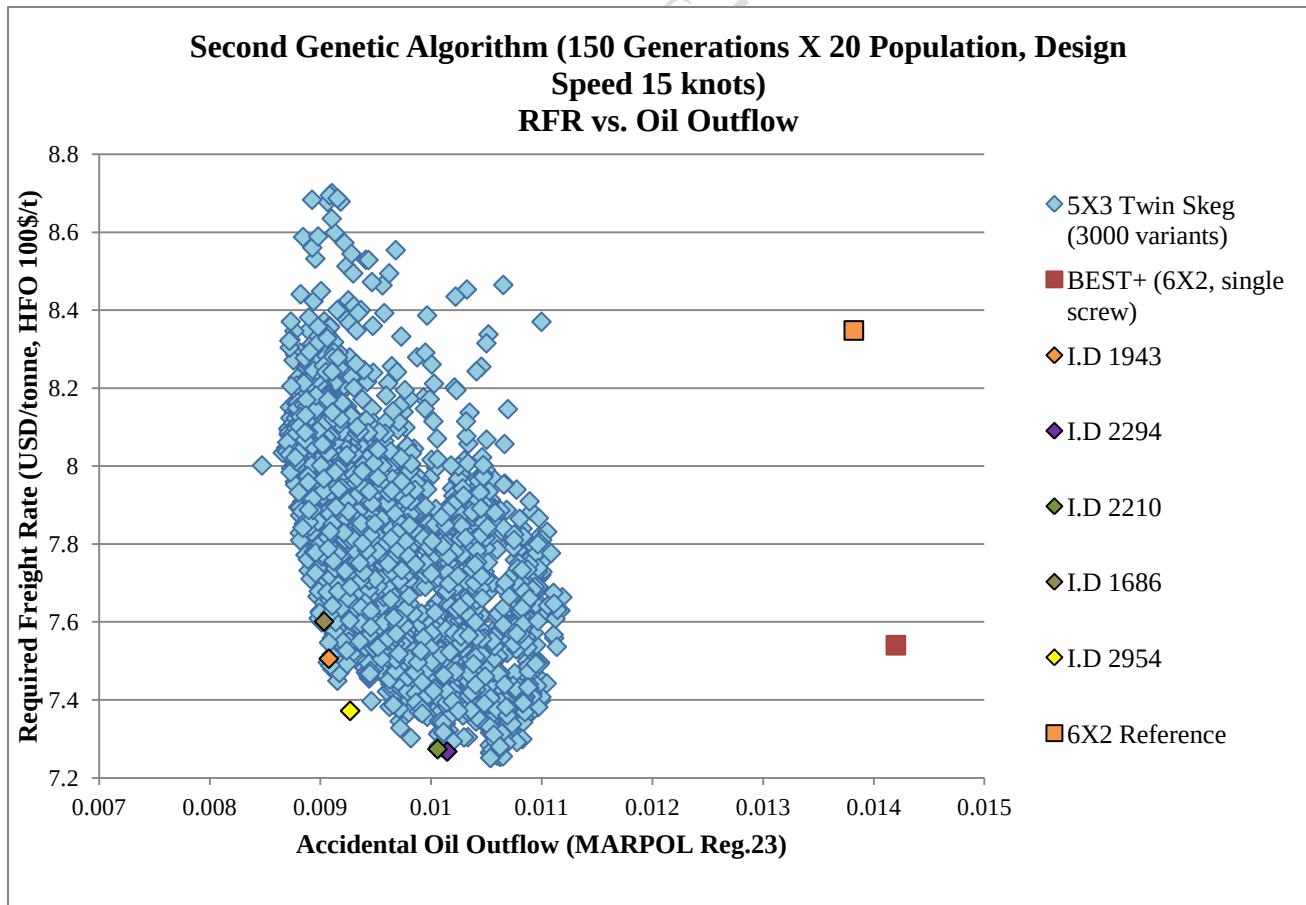


Figure [15]: RFR-OOI Scatter Diagram for the Second Stage Optimization

When looking at the relationship between the accidental oil outflow and the required freight rate (figure []), 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.

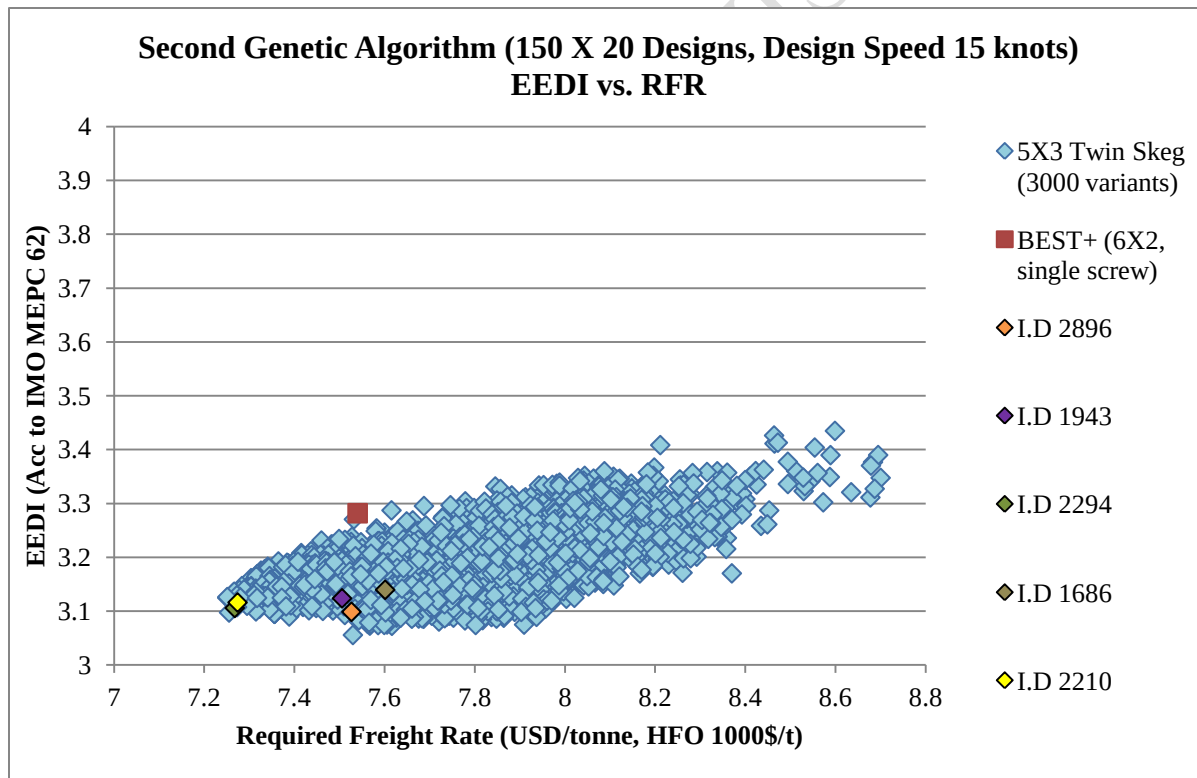


Figure [16]: The EEDI-RFR relationship for the 2nd Optimization Run

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 [] 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 where 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 in Figure [17]. 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.

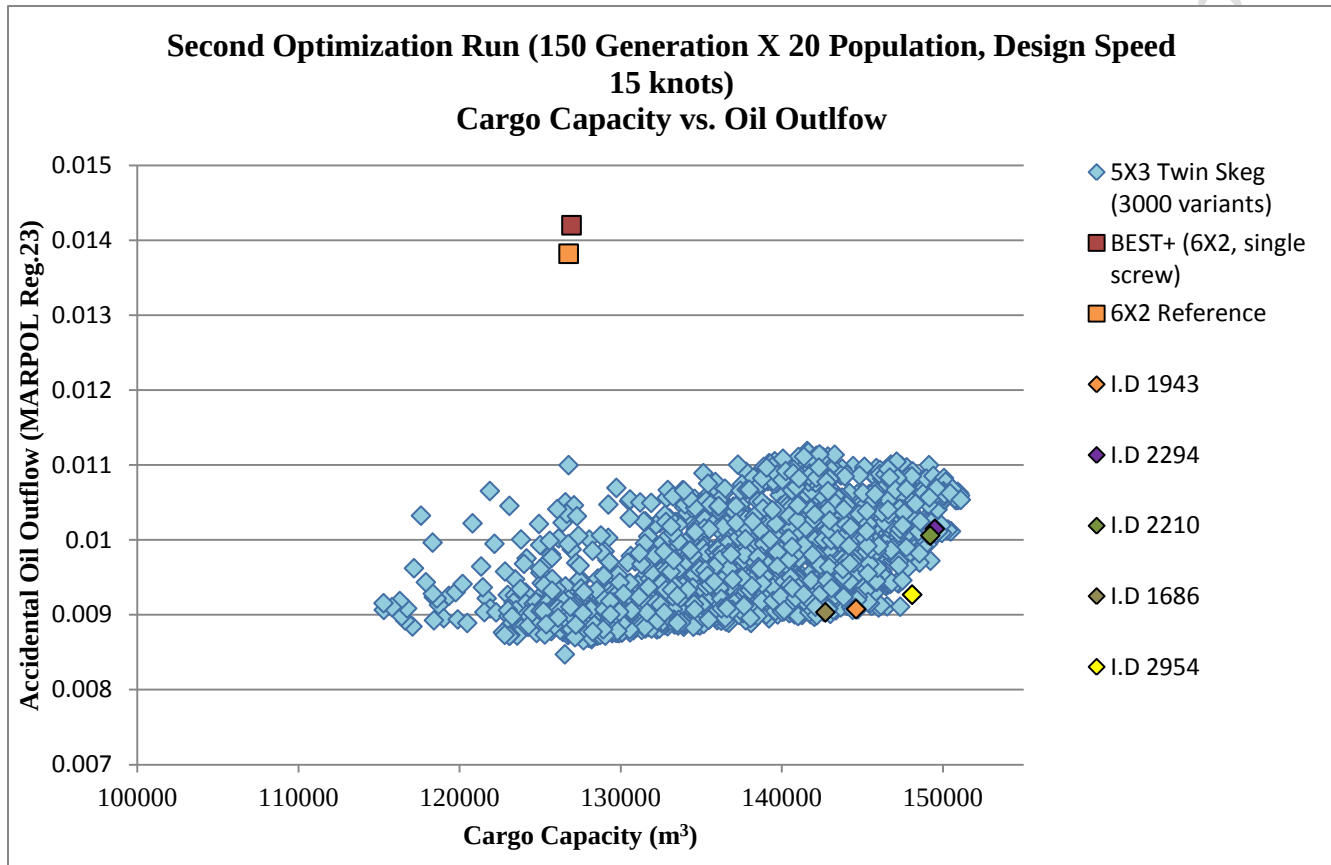


Figure [17]: Cargo Capacity vs. Oil Outflow

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 [17]. 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 [17]. 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.

4.8.3. 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	1 st Scenario	2 nd Scenario	3 rd Scenario	4 th Scenario	5 th 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 [12]: 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.

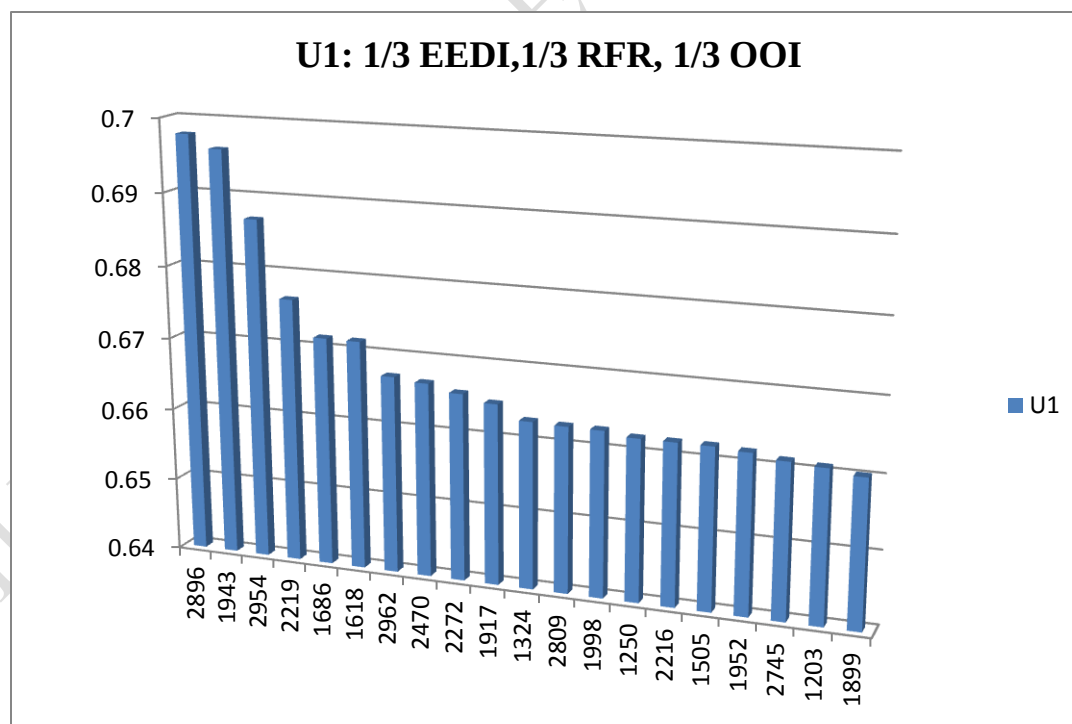


Figure [18]: Design Ranking according to the first scenario

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

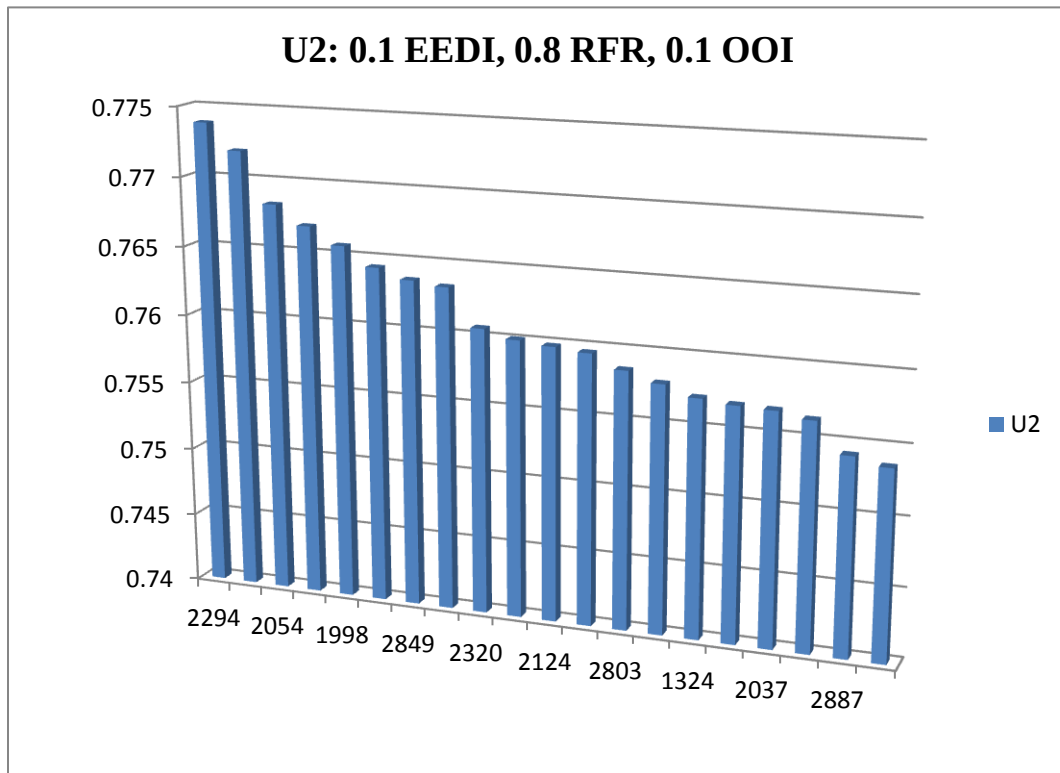
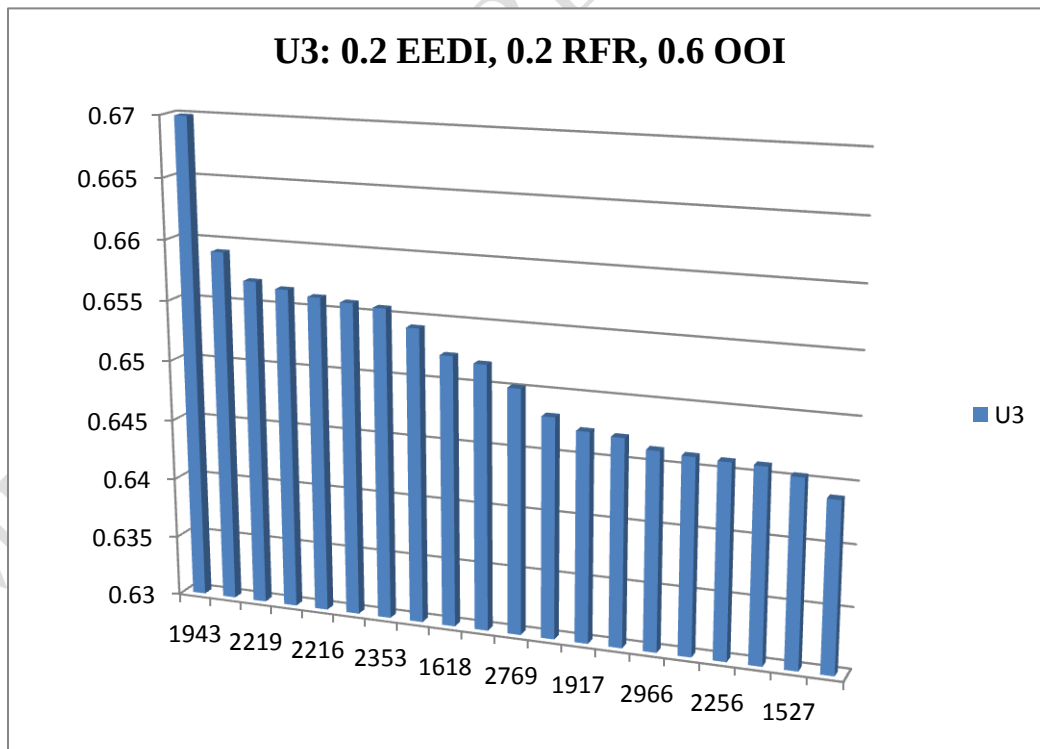


Figure [19]: Design Ranking according to the second scenario



Figure[20]: 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.

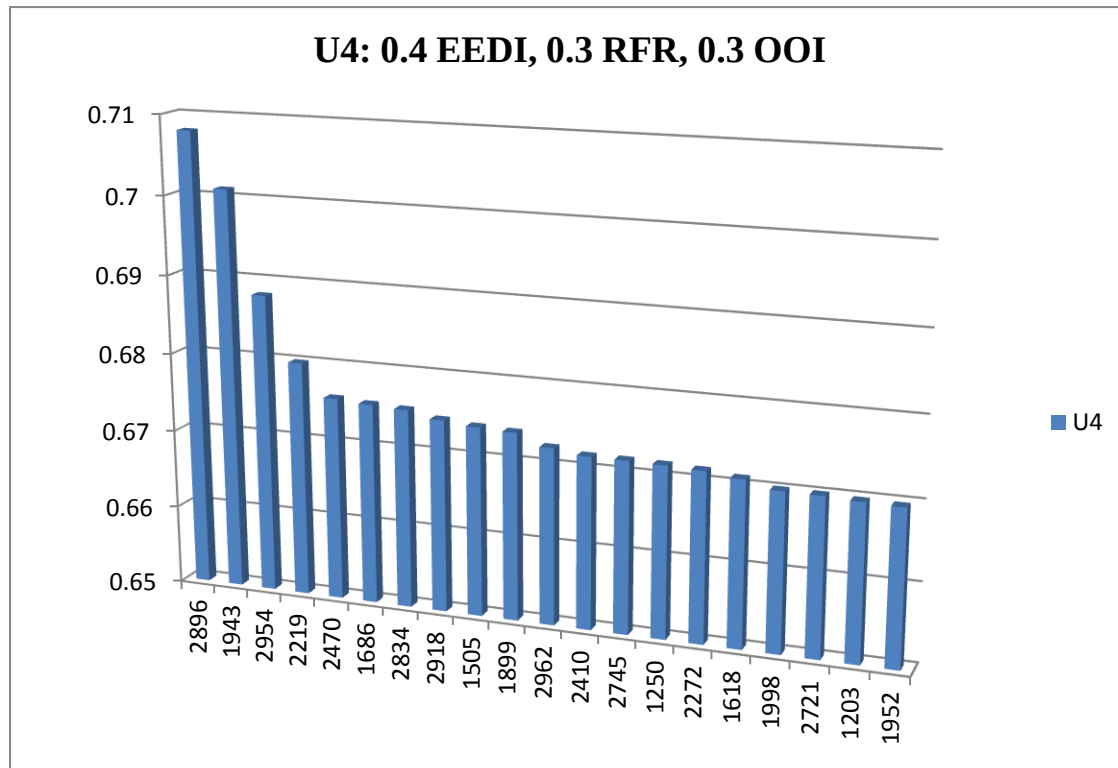


Figure [21]: Design Ranking according to the 4th scenario

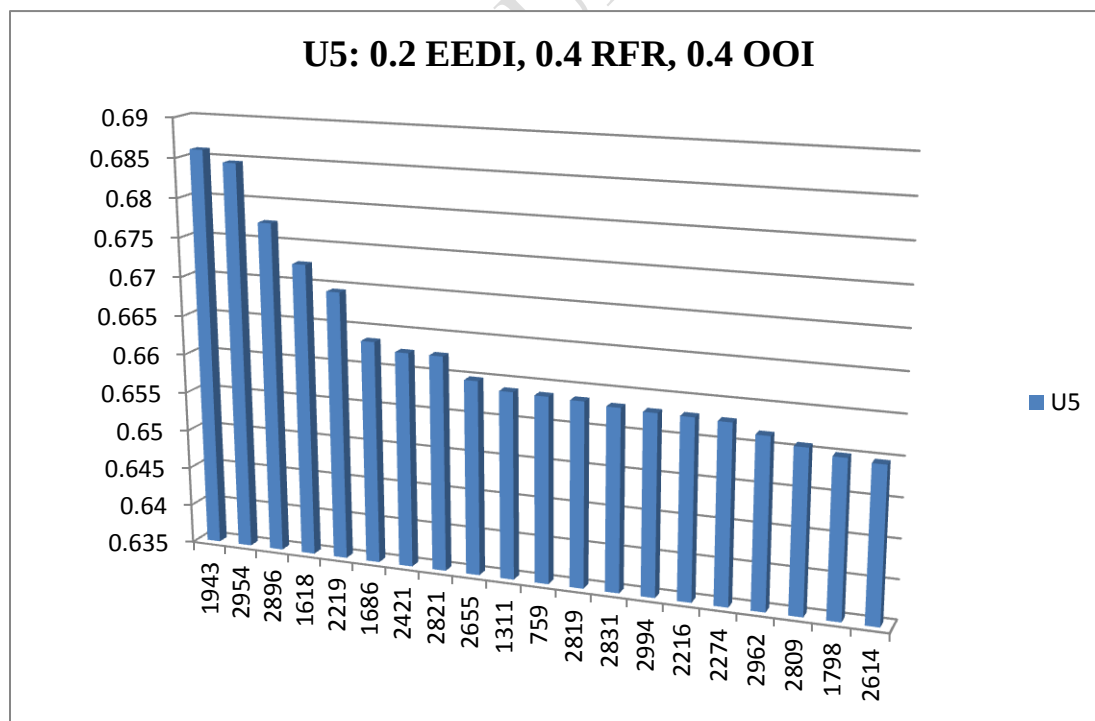


Figure [22]: Design Ranking according to the 5th scenario

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	1 st Scenario	2 nd Scenario	3 rd Scenario	4 th Scenario	5 th 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 [13]: The prevailing designs following the optimization procedure according to 5 scenarios

4.8.4. Results-150 Generations with 30 Population

Having seen the performance of the genetic algorithm in the first run and its 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.

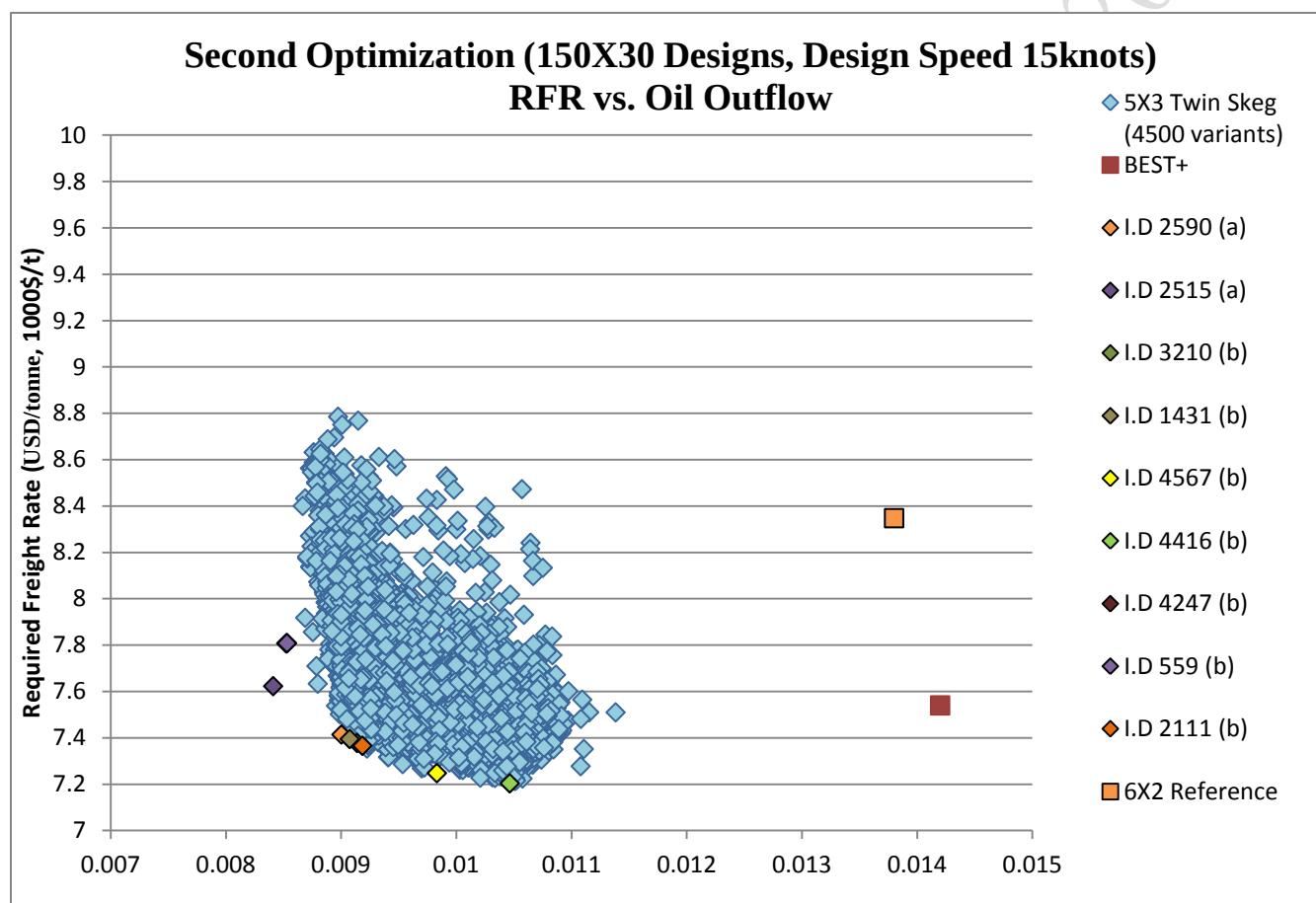


Figure [23]: RFR-OOI Relationship for the second optimization using 30 population

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.

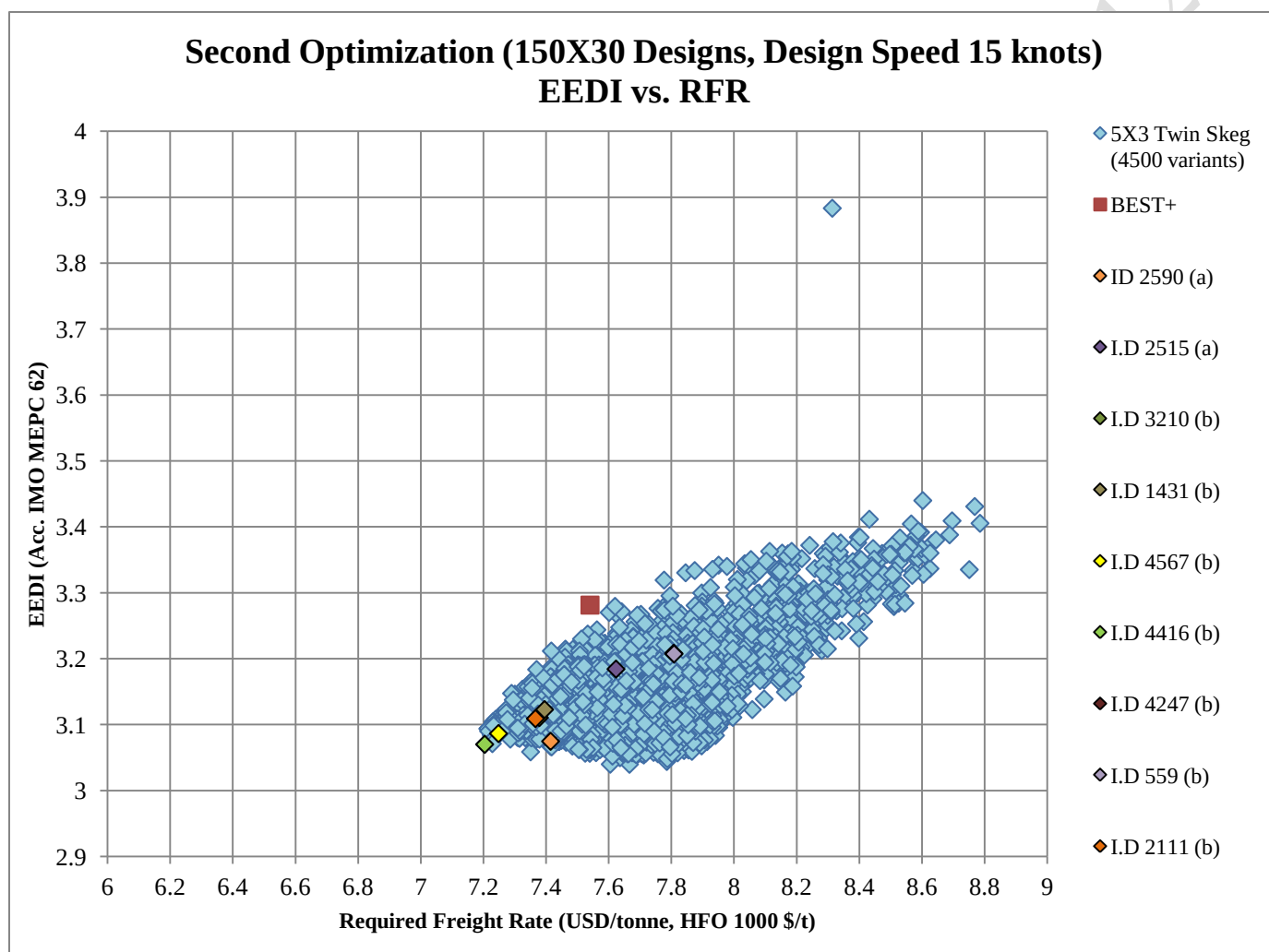
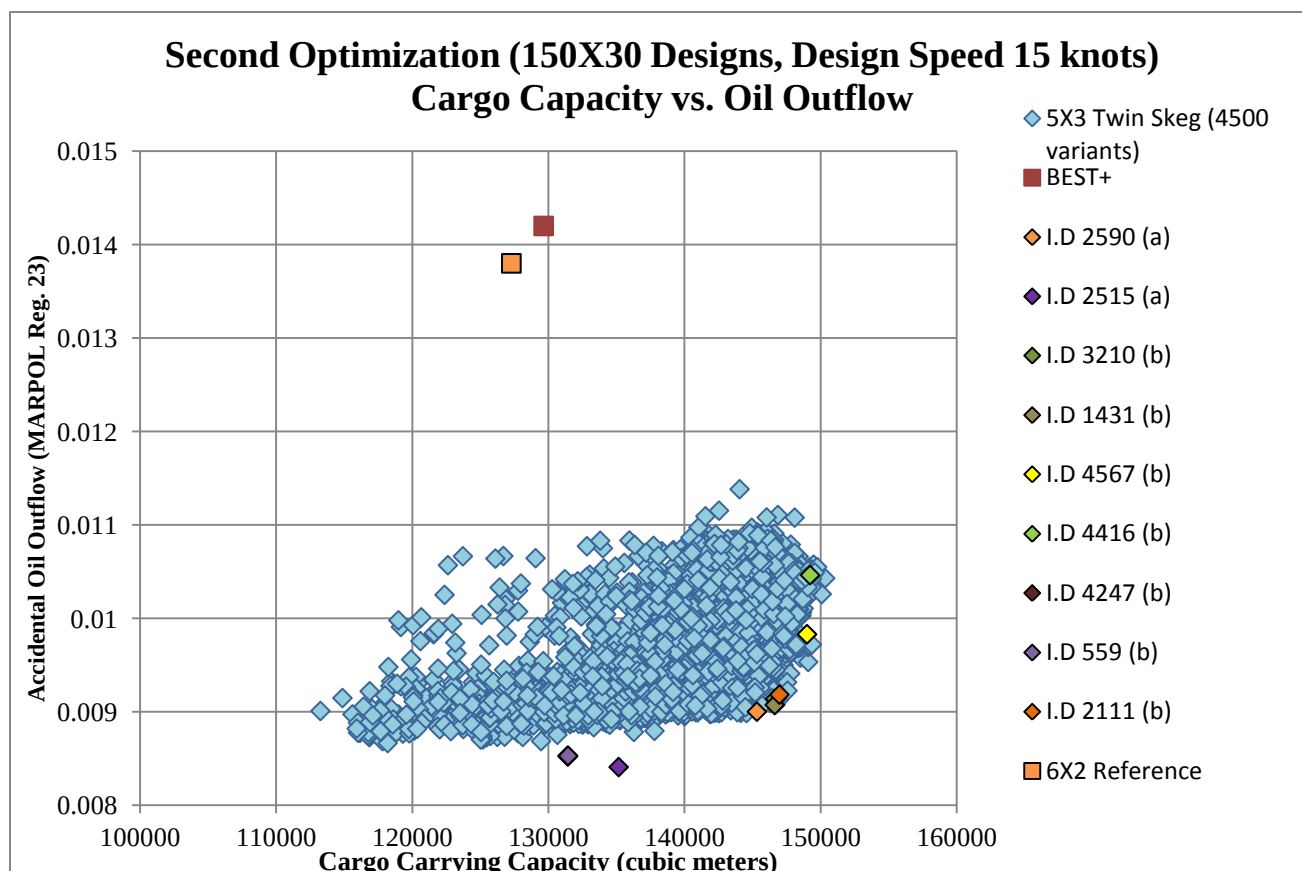


Figure [24]: EEDI vs. RFR relationship for the second optimization with 30 population

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.



From figure [36], 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.

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

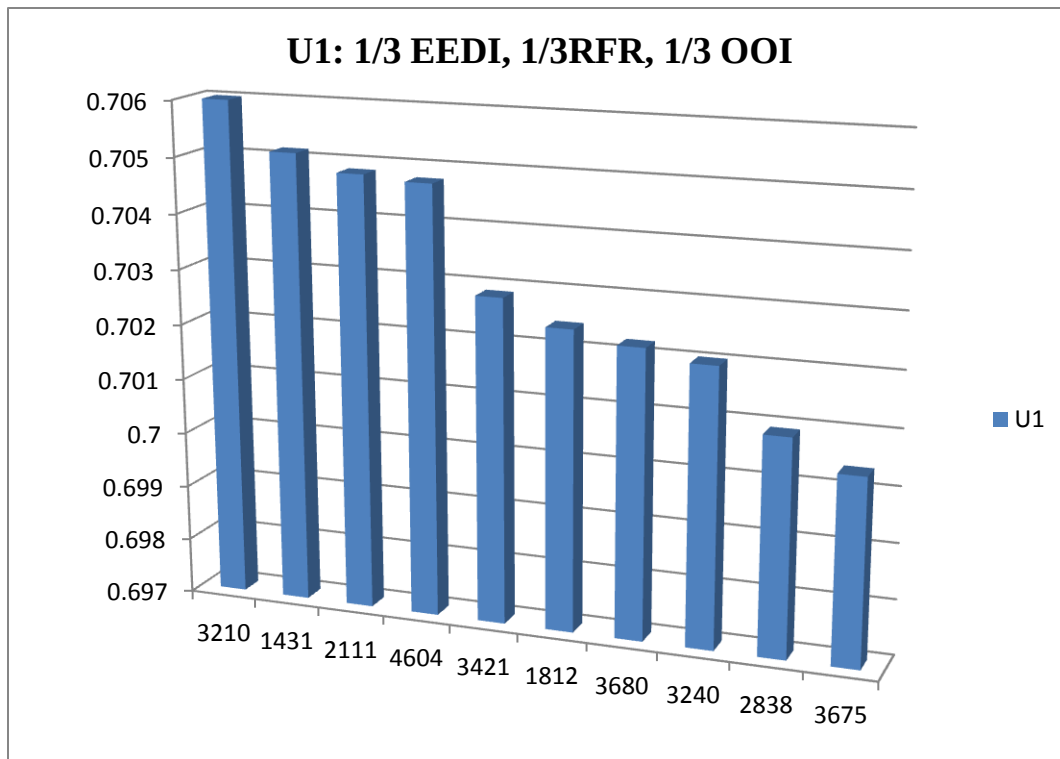
As in the previous run, five scenarios are chosen to be used as weights for the utility functions that are assisting to rank the dominant variants and find a good solution.

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

Objective	1 st Scenario	2 nd Scenario	3 rd Scenario	4 th Scenario	5 th 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 [14]: The weights for each scenario

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



Figure[26]: Design Ranking according to the first scenario

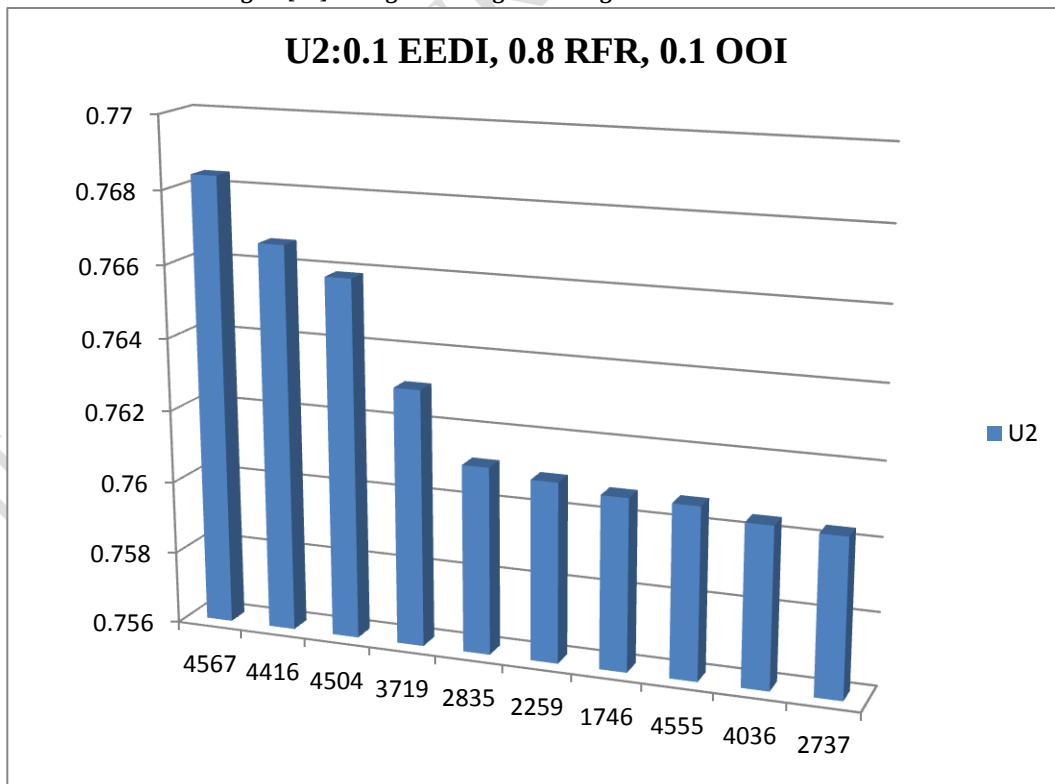


Figure [27]: Design Ranking according to the second scenario

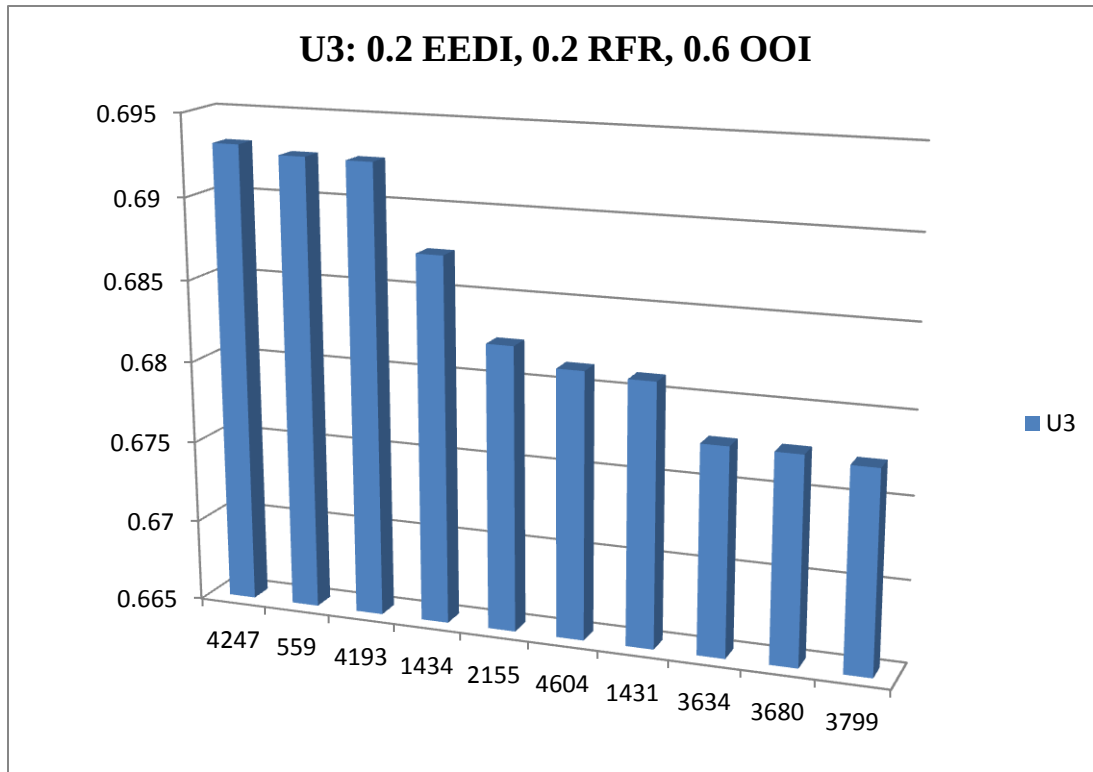


Figure [28]: Design Ranking according to the third scenario

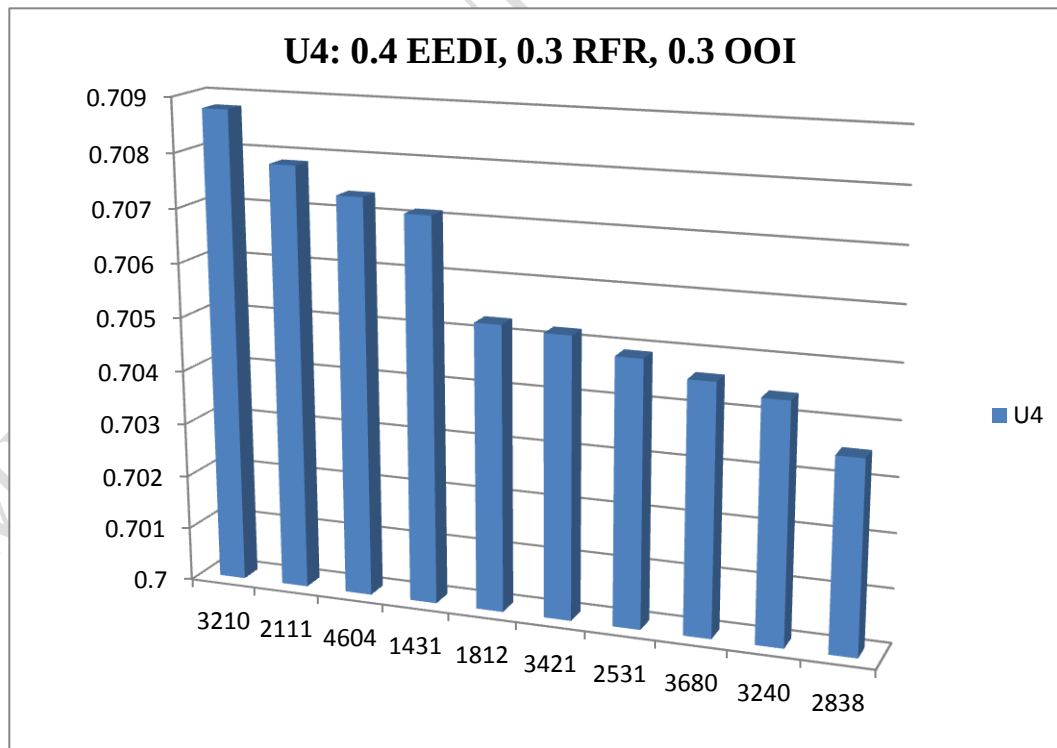


Figure [29]: Design Ranking according to the fourth scenario

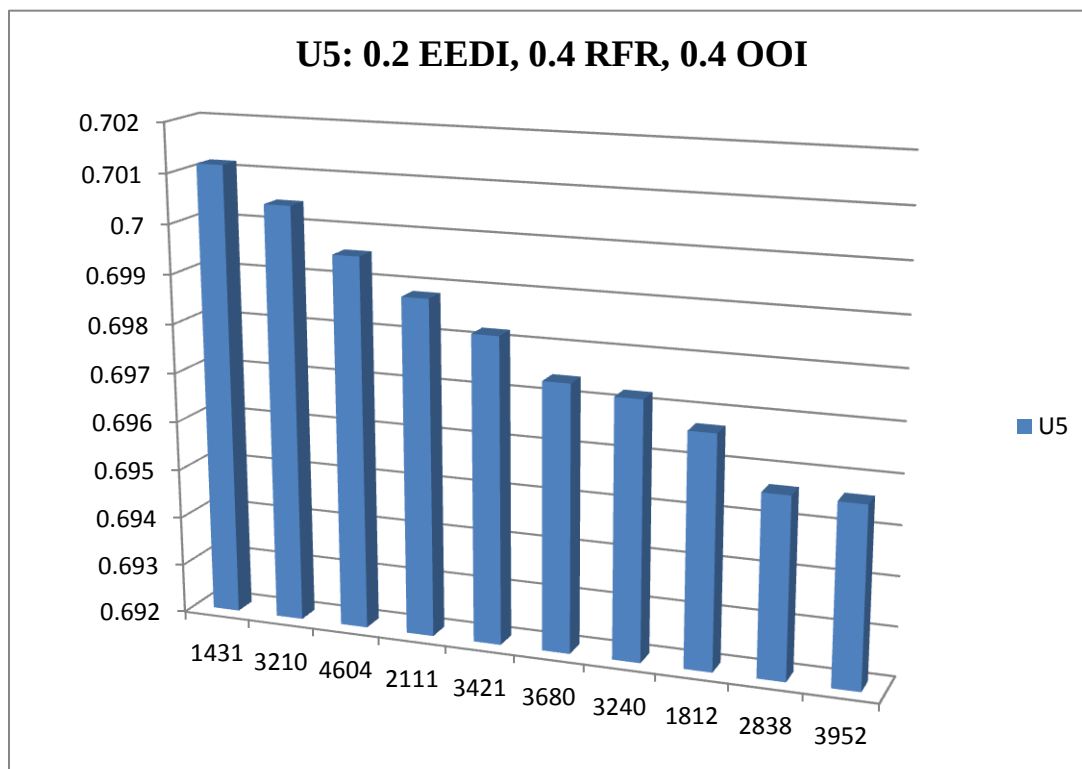


Figure [30]: Design Ranking according to the fifth scenario

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	1 st Scenario	2 nd Scenario	3 rd Scenario	4 th Scenario	5 th 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 [15]: 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.

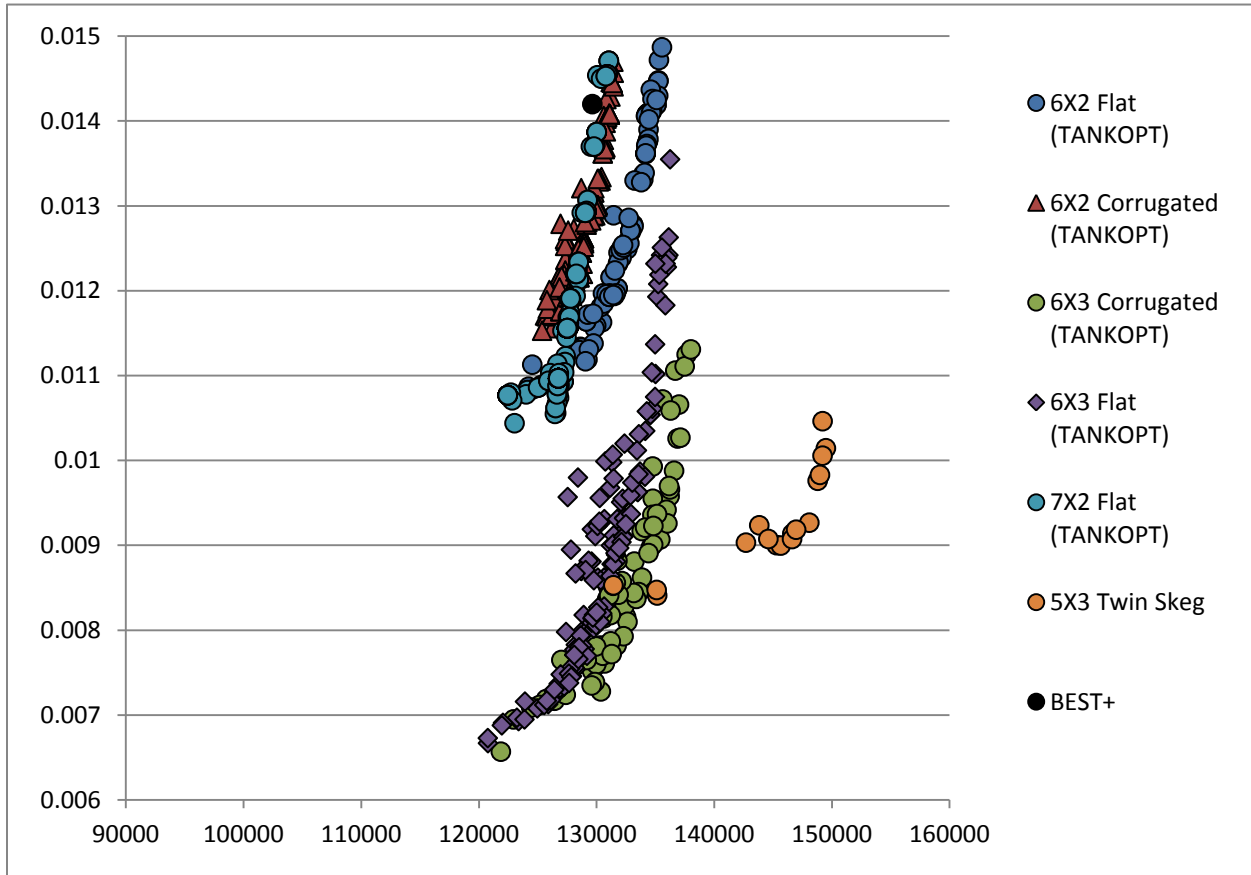


Figure [31]: Scatter Diagram of the results of various optimization projects

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 m³.

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	-8.67%	7.378 \$/t	-11.61%
Ballast Water	35378 m ³	18699 m ³	-47%	29287 m ³	-17.2%

Table [16]: Comparison table of 6X2 reference with dominant variants

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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 [17]: 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 be 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.

5.1. 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.

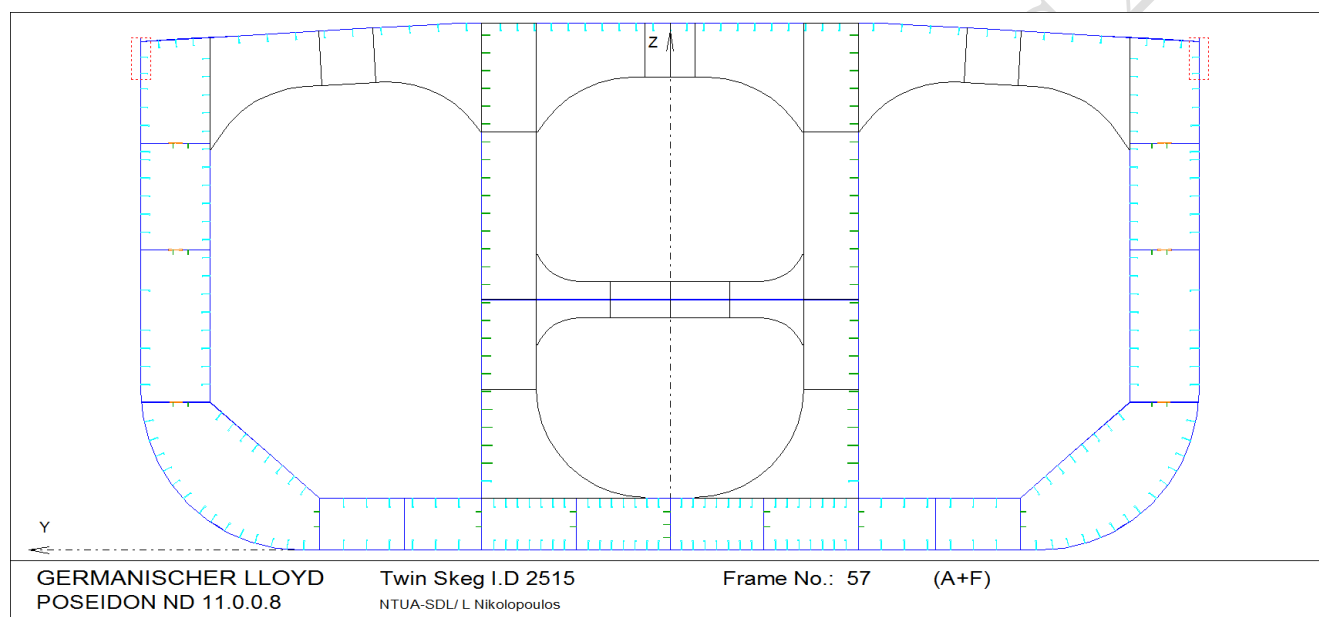
The cargo block steel weight was calculated following the structural modeling of a prismatic cargo block initially for the reference ship and afterwards for a ship with the BEST+ dimensions. However, this design methodology takes into account the effects of ship size but not that of the changing bending 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 [7]: 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 [18]: 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 absorbed in the total correction factor imposed to the lightship weight which is 10%.

5.2. 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 angle 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 SHIPFLOW 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 C_w 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.

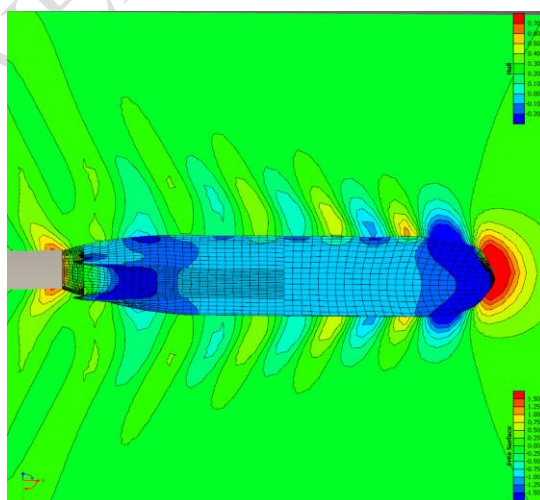
The dominant variants were thus exported and the computations were performed in the SHIPFLOW 4.1 version and can be summarized at the table below

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 [19]: 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 [8]: Snapshot of the Wave Pattern as computed in SHIPFLOW

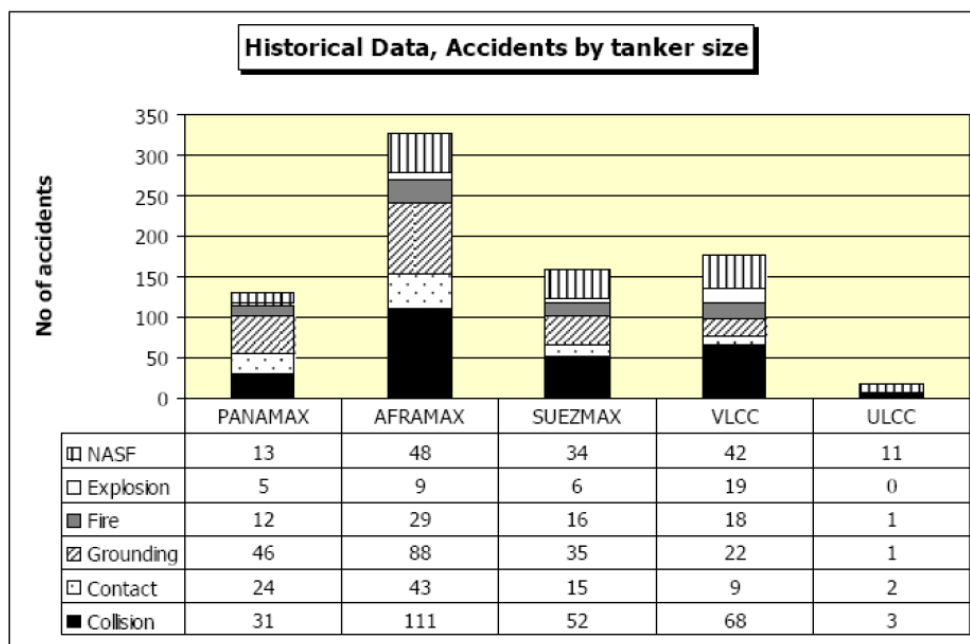
5.3. Risk Analysis of the Design Concept

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.

5.3.1. 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.



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 of a twin screw design, where all systems like propeller, steering, main engine and fuel lines and bunkers are independent and separated by fireproof bulkheads. This means that 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.

5.3.2. Collision Accidents

Another very frequent type of accident for AFRAMAX tankers is the collision with another ship. During a collision the ship examined can be either the striking ship or the struck ship. The most critical condition for the safety and the environmental protection from a potential pollution, is the case in which the ship is struck. For this condition, it is considered that the passive protection of the segregated ballast tanks, namely the double hull width, is the most important factor influencing the potential loss of cargo due to one side tank damage.

It is assumed in this study that the probability/frequency of collision is independent from the twin screw arrangement as it is taken for the struck ship scenario, were the improved maneuverability and the propulsive redundancy has a little or negligible effect. The scope and aim is to compare the initial 6X3 arrangement (NAVION BRITANNIA) and compare it with a dominant variant (especially one with good OOI performance) in order to find the difference of the potential loss of cargo for that case.

The input data given in the Excel spreadsheet developed by Dr. Heliopoulou at NTUA-SDL are the following:

Particular	NAVION BRITANNIA	5X3 Twin Skeg, I.D 2515
Arrangement	6X3	5X3
Side Tank Volume (m ³)	7995.3	7337
Side Tank Width (m)	2.65	2.989
Total Cargo Capacity (m ³)	139390.4	135439
Double Bottom Height (m)	2.68	2.23948

Table [20]: Input data for risk analysis

The results of the event tree analysis can be seen below:

5.4. 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 the 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:

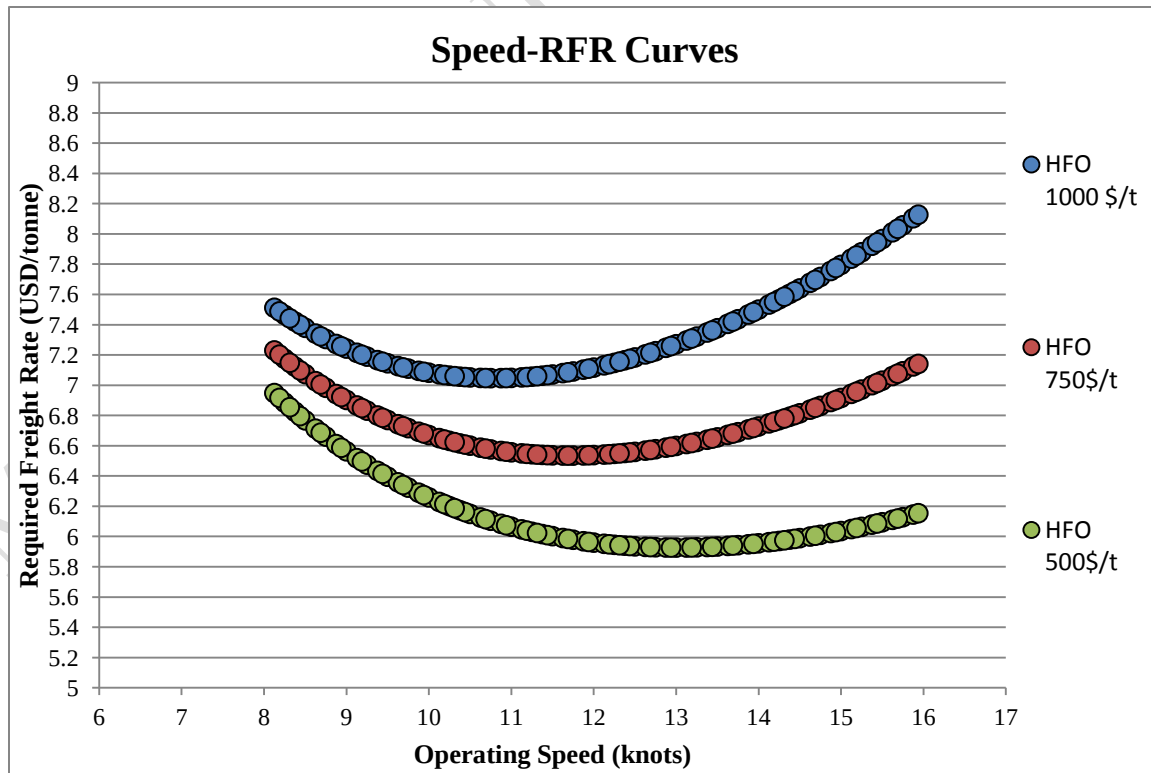


Figure [32]: Variation of the RFR as a function of the operating speed

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, [1]):

- 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° in order to maintain the optimum scavenge air temperature, and the jacket cooling water temperature at the upper limit (85-95°). 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°C 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°C, 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. Whilst operating at these loads, turbocharger washing and soot blowing of the 72agitude72 should be undertaken in order to reduce fooling.

5.5. 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.



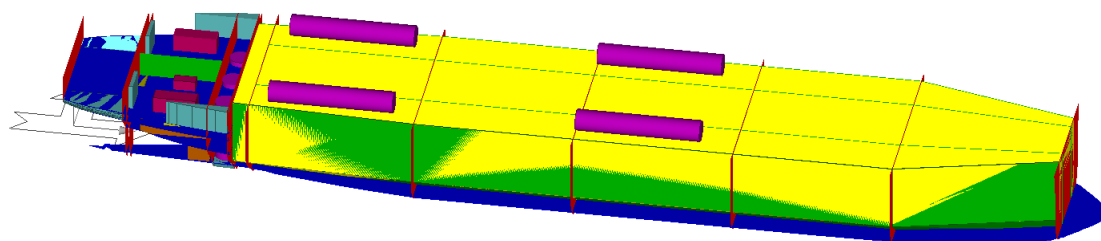
Picture [8]: Example of IMO C-Type tanks used in the Bit Viking Project

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.

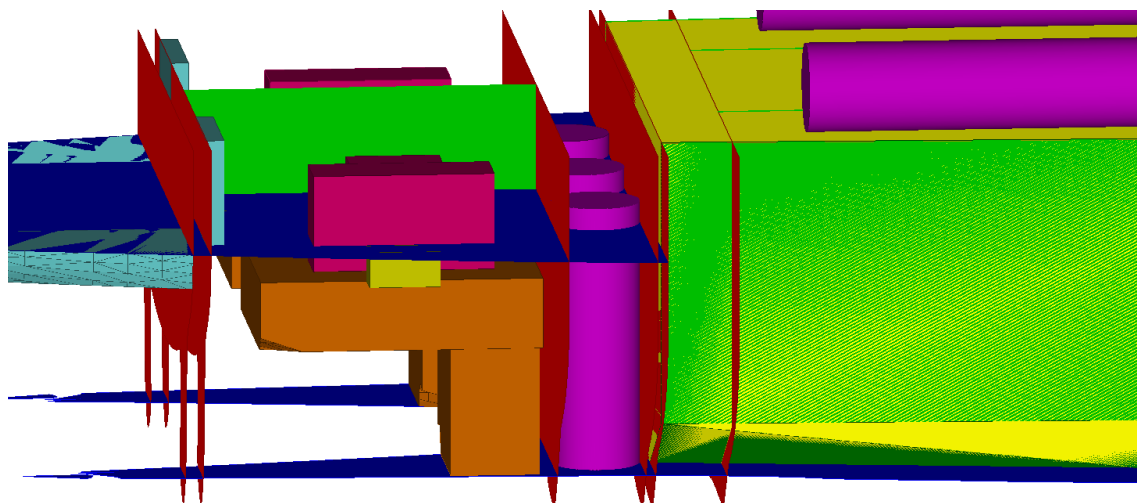
The deck tanks have a nominal capacity of 400 m^3 , a total length of 30m, a diameter of about 5m and a net weight of approximately 135 tons.

The vertical tanks installed in the engine room are protected by two void, cofferdam spaces aft and fore have a capacity of 200 m^3 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 [9]: Snapshot from AVEVA illustrating the LNG tank arrangement on the deck



Picture [10]: 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, where 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 (m ³)	2200
Range (d)	19.50960256
Working hours	468.2304614
Range (nm)	7023.456922

Table [21]: 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.

5.6. 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 76agnitud 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.

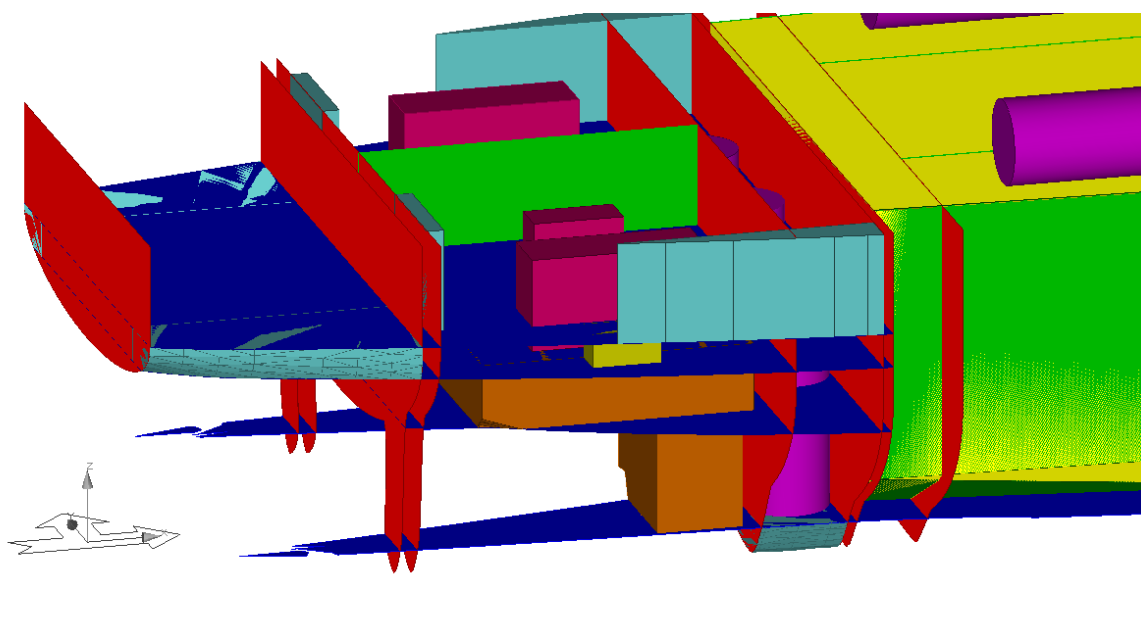
In order to be able to work within the AVEVA framework the hull geometry needed to be exported from the Friendship Framework via an SHF format and after editing was transformed to a Britfair file that the AVEVA program uses as an input. The cargo oil tanks were modeled in AVEVA using the same positions 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 accomodates 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 76agnitud76es 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 [11] : 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, where 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 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 Equilibrium

Density of water	1.025	79agn/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
BMI	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	79agn/cm
MTC	1607.463	79agn-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 m². 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 be reduced by the same 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 [1]).

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

Table [22]: BWT costs per m³ for different technologies (MARTOB, 2004)

From table [22], since the costs are non-dimensionalized 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 (corrsponds 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 [23]: 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 C_b , 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.

5. 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.

Design Variables

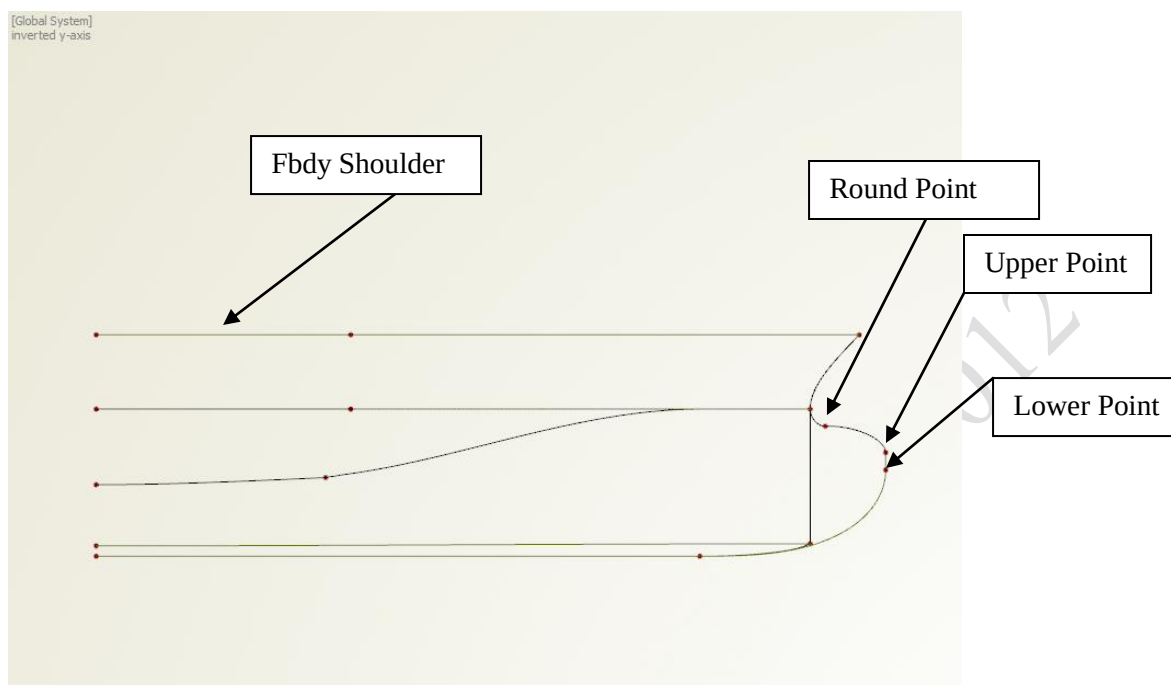
During the creation of the variants, as in every simulation or optimization the manipulation of certain design variables, chosen by the user, triggered the design variation, generation and assessment. For this case the design variables are geometrical properties of the bulb such as the position of the 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 []).

At picture [12], 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 [24]: 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.



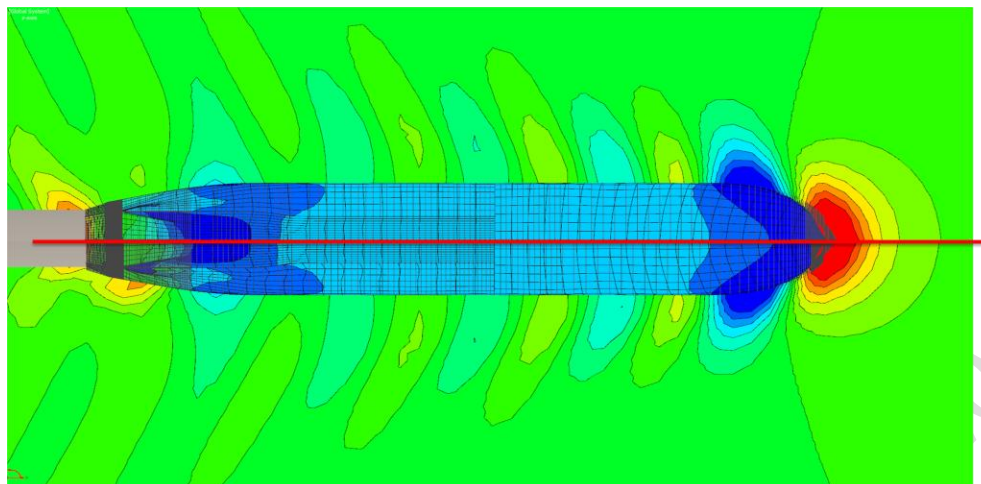
Picture [12]: The functions and points that define the fore body

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 C_w as well as the wave cut integral C_{wtw} . This choice can offer a double benefit to the designer as he can choose 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 C_w 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 [13]: Comparison of the wave pattern of the baseline (down) and improved model

References

5. Papanikolaou, A., Eliopoulou, E. et al, "Casualty Analysis of AFRAMAX Tankers", *Journal of Engineering for the Maritime Environment, Proceedings of the Institution of Mechanical Engineers, Part M*, Vol. 221, pp. 47-66, 05.2007.
6. Papanikolaou, A. (ed.), "Risk-based Ship Design – Methods, Tools and Applications", SPRINGER, ISBN 978-3-540-89041-6, 02.2009.
7. Harries S., Tillig F., Wilken M., Zaraphonitis G., "An Integrated Approach for Simulation in the Early Ship Design of a Tanker", COMPIT 2011
8. Tillig F., "Parametric Modeling and Hydrodynamic Analysis of Twin Skeg Vessels", Dipl. Thesis TU Berlin, 05.2010
9. Harpersheidt J. "LNG as a fuel-Bunkering, Storage and processing", *Ship Efficiency Conference* 2011
10. Nikolopoulos L. et al, "The G5 Tanker: Green, Safe, Efficient, Economical and Competitive", VISIONS 2011 Competition (Shortlisted Idea).

CHAPTER FOUR:**MULTI-VENTURE CONCEPT****PART TWO: DUAL FUEL, ALL ELECTRIC, HYBRID PROPULSION PLANT****1. 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 Eatlack [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 maneuverability)
- 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.

1.1. 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 [] 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.

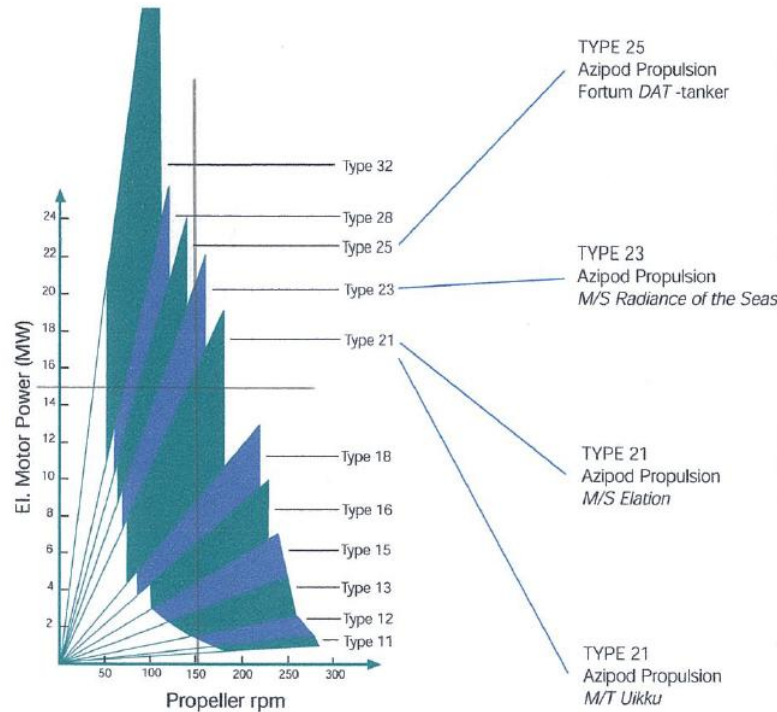


Figure [1]: Selection diagram for electric motors (source: ABB)

1.2. 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.

1.3. Total Load

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

	Normal Sea Going		Maneuvering				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 Intermittent 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 [1]: Electrical Load Analysis for dimensioning of the AES

1.4. Power Production in All Electric Gas Hybrid Plant

1.4.1. 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.

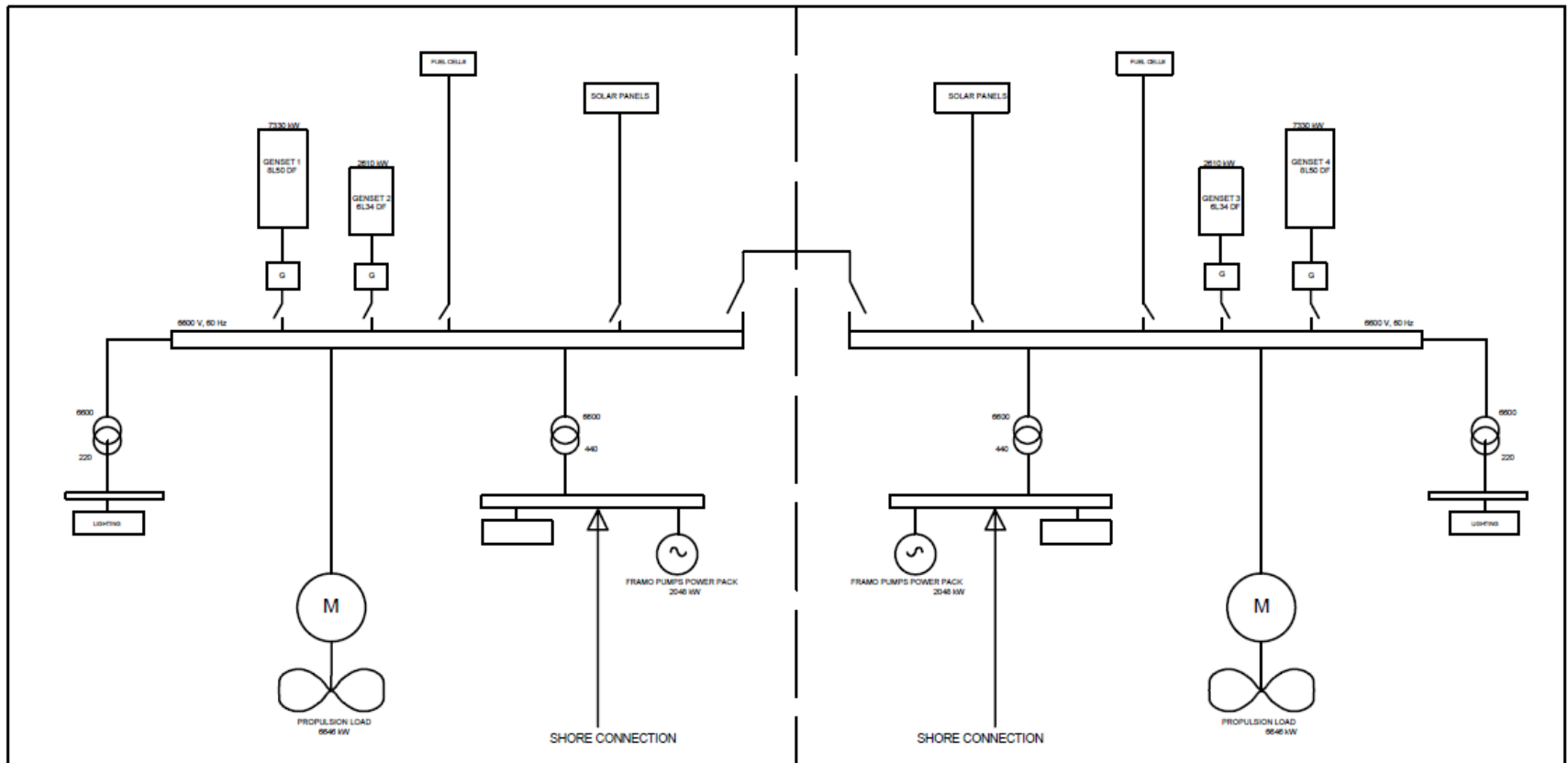


Figure [2]: Schematic of the Electrical Installation of the Hybrid Propulsion Plant

2. 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 onbaord 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 bunekring 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 [2]: Installed Generators and Usage depending on condition

2.1.8L50 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:

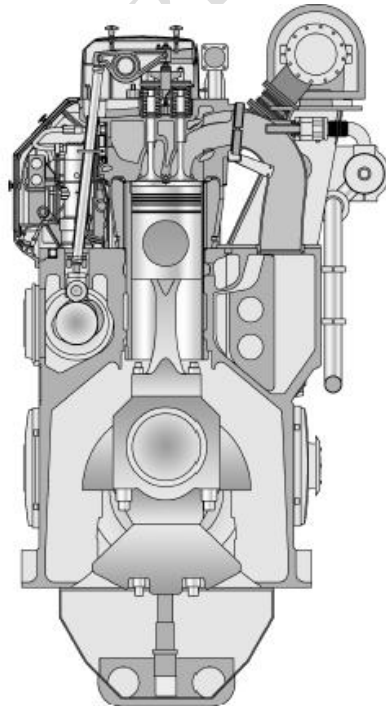


Figure [3]: Cross section of L50 DF engines (Wartsila, ..)

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 Wartsila 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 Wörtsilä. 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, Wörtsilä 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 Wärtsilä 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 fullflow 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 Wärtsilä 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.

2.2.6L34 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, counterclockwise 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:

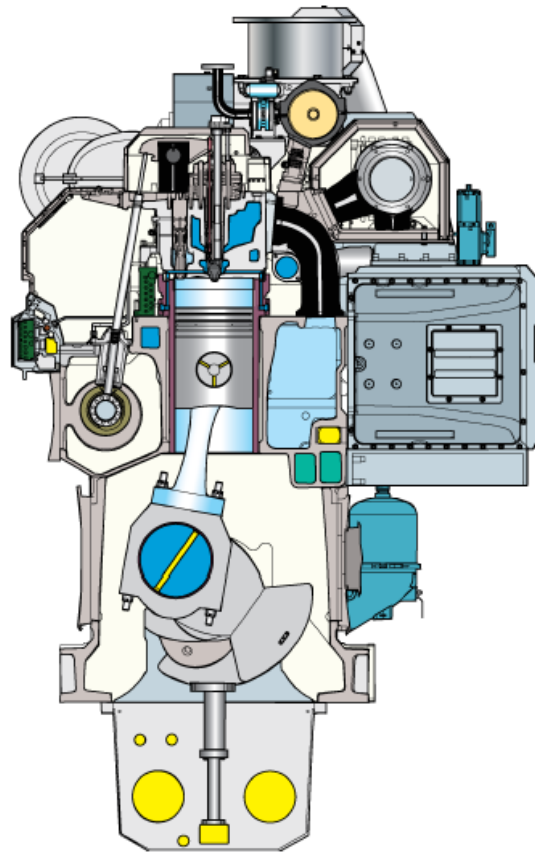


Figure [4]: Cross Section of 6L34 DF engine

2.3. 6L20DF Generator

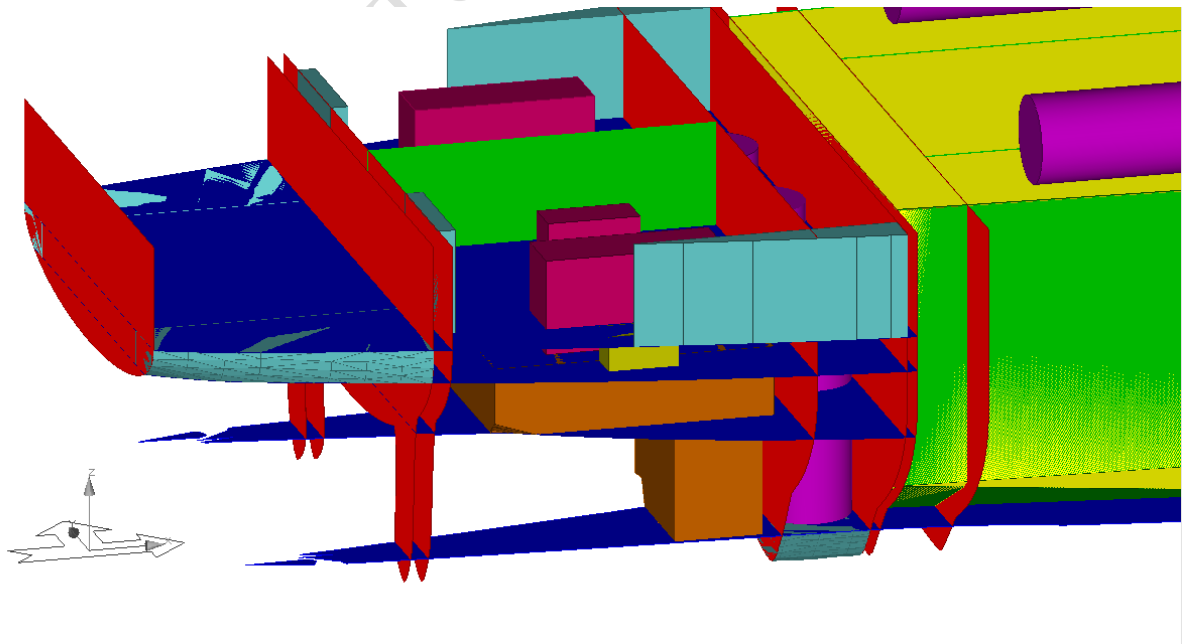
This smaller generator is used for the port loads in order to avoid having very small loads in the other components. In the harbour condition its use can be assisted also by the fuel cell system and the shore supply (cold ironing mode). The latter is subject to port infrastructure and the overall management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

3. 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 accommodates 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 accommodates 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.



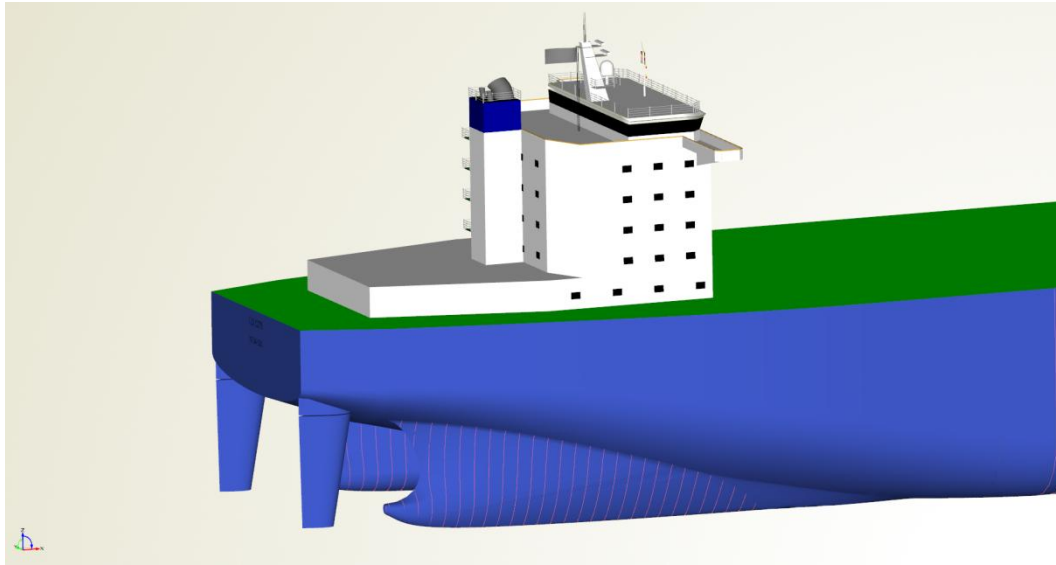
Picture [1] : Snapshot of the compartmentation mode of AVEVA, where the engine platform deck can be seen along with the control room and fuel tank decks.

Modularized Engine Room

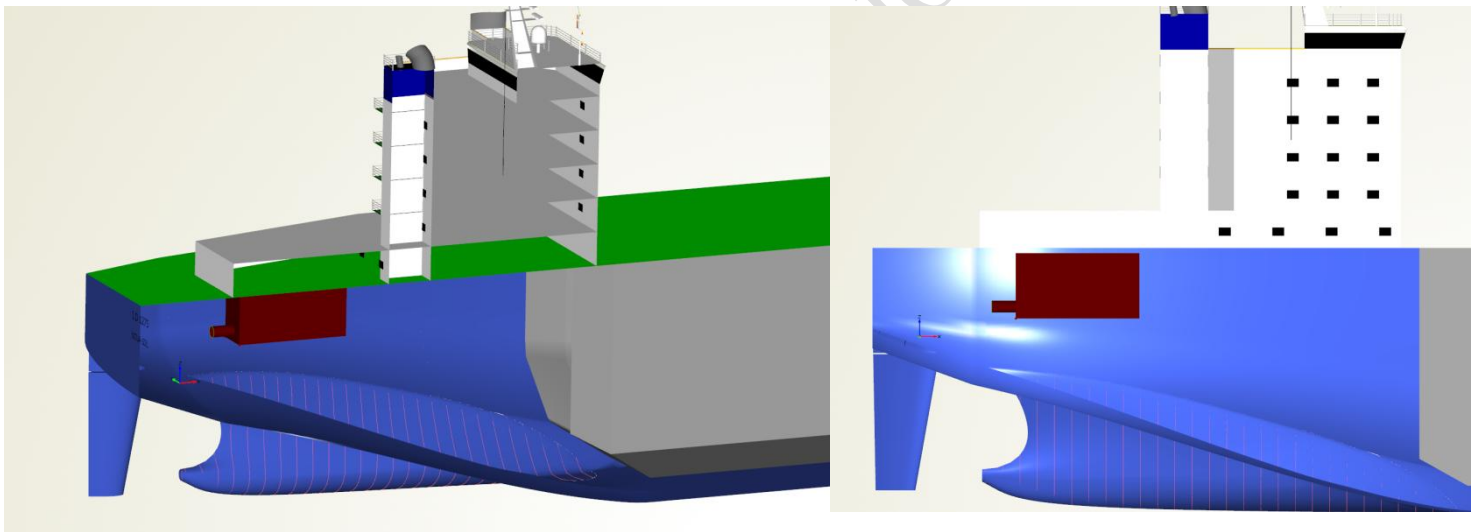
The shift of the engine room from the lower position to the new engine platform deck makes the modularized engine room a favorable option, mainly due to the capability of the engines to be removed and easily replaced and the small weight of them.

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 entire 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 [2]: The proposed arrangement of accommodation superstructures



Picture [3]: Centerline cut outs that demonstrate the modularized engine room concept.

4. 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 °C due to the absence of sulfur and sulfur oxides in this fuel. However, during Diesel Operation the temperature has to be above 160 °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 [3]: 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 [4]: Heat Recovery of EGB2

For the smaller engines, in the sea going condition only one is used, as in the maneuvering 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.

5. 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.

5.1. FUEL CELL TECHNOLOGY IN A HYBRID PROPULSION PLANT

5.1.1. 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 and 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.

5.1.2. 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 as 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.

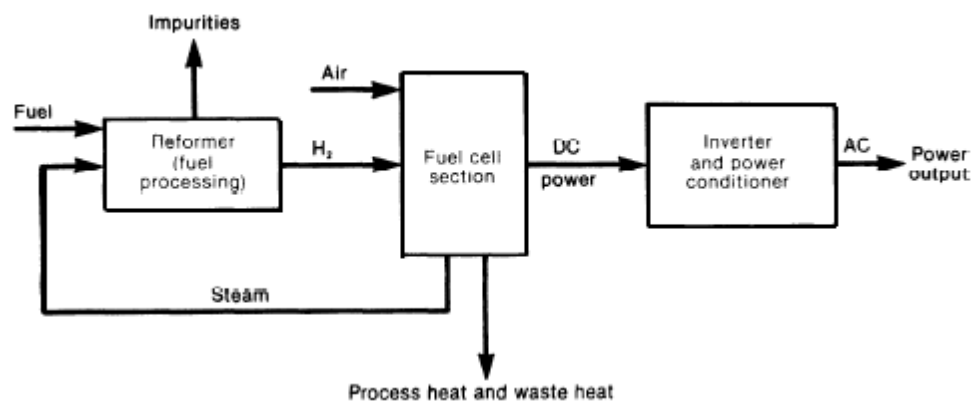


Figure [4]: Typical Fuel Cell Workflow

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.

5.1.3. 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 sulfur and carbon monoxide are removed by the fuel processor through the use of special scrubbers and carbon monoxide shifters. Water vapor 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.

5.1.4. 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 cutoff 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.

5.1.5. The Controller

The fuel cell has a number of functions. It must control supplemental power during startup 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.

5.1.6. 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.

5.1.7. *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:

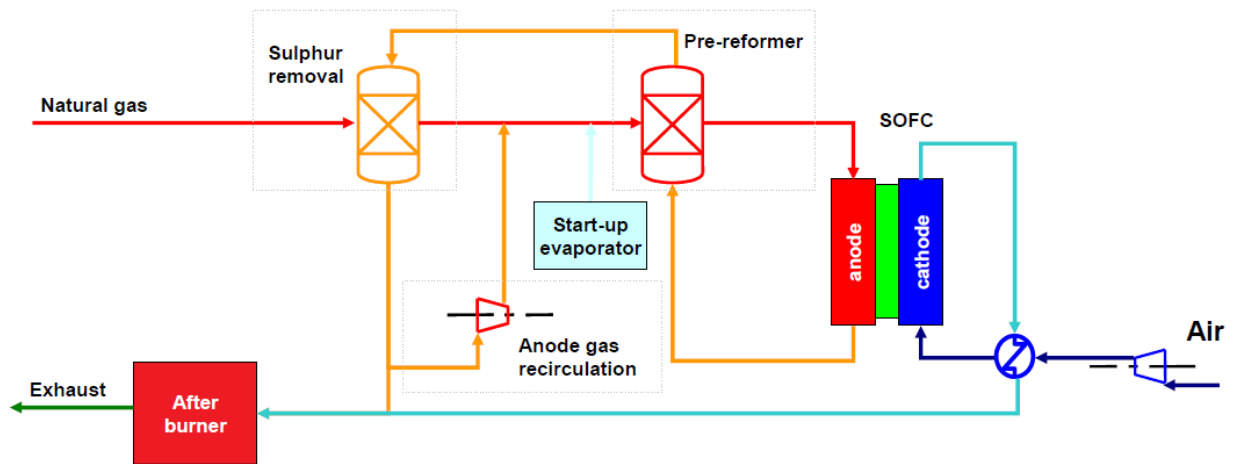
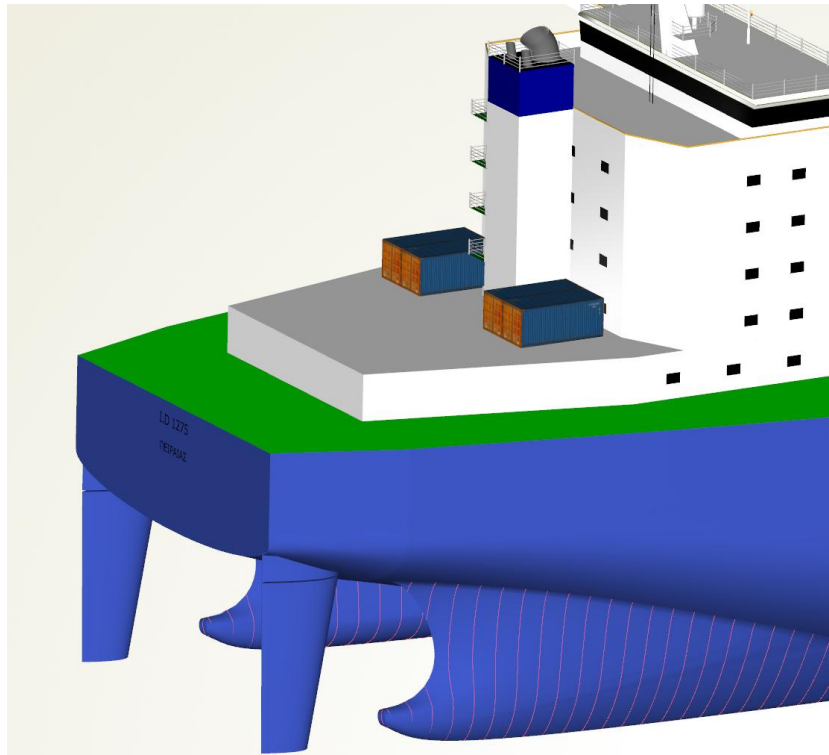


Figure [5]: The Wartsila Fuel Cell Operating Principle and Workflow (Wartsila presentation, [3])

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 its position can be predefined in the preliminary study, although it is equally easy to install it as a retrofit. Furthermore, in experimental installations (onboard cargo 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 [4]: Proposed Arrangement for Containerized Fuel Cells



Picture [5]: 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 []).

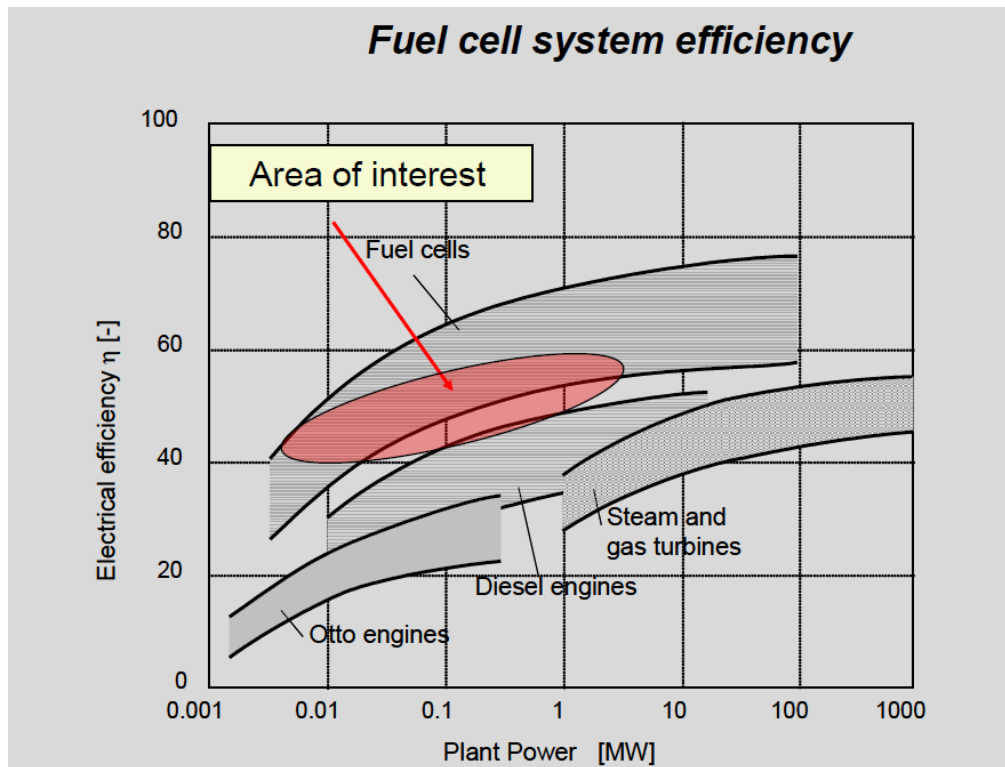


Figure [6]: Efficiency of Fuel Cells in comparison to internal combustion engines (Wartsila [3])

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 [5]: 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 [6]: Fuel Cells Emissions

5.2. 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 [], one can see the steam system its individual components.

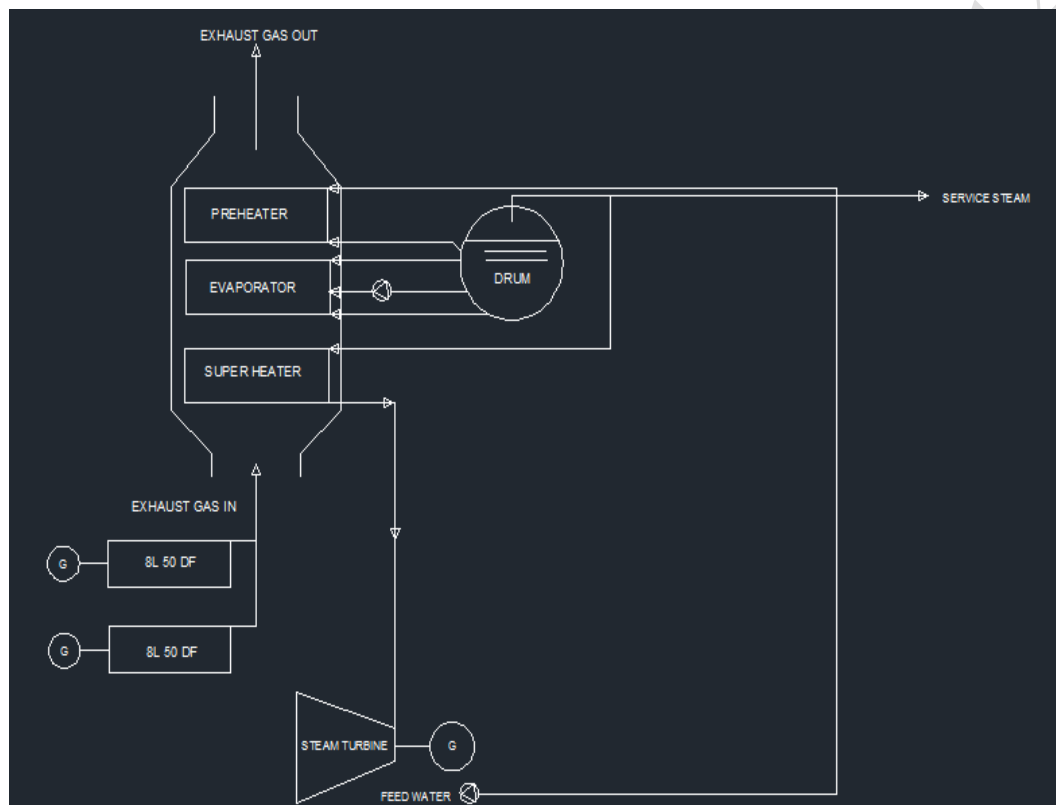


Figure [7]: The steam generation system based on exhaust heat recovery

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 []. 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.

5.3. 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 thsi 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.

Maneuvering

In the maneuvering 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 Harbor 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 auxilliary 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.

References

1. Eastlack E., “*The Future of Marine Propulsion: Gas Hybrid Power Plants (EM681)*”, Thesis US Merchant Marine Academy, 05.2012
2. Adnanes A. K., “*Maritime Electrical Installations and Diesel Electric Propulsion*”, ABB report, 04.2003
3. Fontel E., “*Wartsila Fuel Cell Development Program*”, 8th Green Ship Technology Conference, 03.2011
4. U.S. Congress, Office of Technology Assessment, *Marine Applications for Fuel Cell Technology—A Technical Memorandum*, OTA-TM-O-37 (Washington, DC: U.S. Government Printing Office, 02.1986).
5. Frangopoulos C., “*Marine Energy Systems*”, Lecture Notes (in Greek) NTUA, 2009
6. Wartsila L50DF Engine Project Guide
7. Wartsila L34DF Engine Project Guide

CHAPTER FIVE:**MULTI VENTURE****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.

1. 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 where 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 \$/m³. 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 [1]: 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.

2. 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 [2]: 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 % 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 [3]: 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																																											
	<table> <tr> <th colspan="2">Main Engine (s)</th></tr> <tr> <th colspan="2">All Electric Gas</th></tr> <tr> <td>14248</td><td>kw</td></tr> <tr> <td>LNG</td><td></td></tr> <tr> <td>152.4</td><td>gr/kWh</td></tr> <tr> <td>167.4</td><td>gr/kWh</td></tr> <tr> <td>46190044.80</td><td>gr LNG</td></tr> <tr> <td>46.19</td><td>ton LNG</td></tr> <tr> <td>258.54</td><td>ton LNG</td></tr> <tr> <td>29921348.16</td><td>gr LNG</td></tr> <tr> <td>29.92</td><td>ton LNG</td></tr> <tr> <td>167.48</td><td>ton LNG</td></tr> <tr> <td>8.67108564</td><td>ton LNG</td></tr> <tr> <td>8.90192378</td><td>ton LNG</td></tr> <tr> <td>4.2425856</td><td>ton LNG</td></tr> <tr> <td>447.83</td><td>ton LNG</td></tr> <tr> <td>0</td><td>ton LNG</td></tr> <tr> <td>11055.90</td><td>ton LNG</td></tr> <tr> <td>276397.41</td><td>ton LNG</td></tr> <tr> <td>2.76E+05</td><td>ton LNG</td></tr> <tr> <td>3.42E+03</td><td>ton MDO</td></tr> </table>	Main Engine (s)		All Electric Gas		14248	kw	LNG		152.4	gr/kWh	167.4	gr/kWh	46190044.80	gr LNG	46.19	ton LNG	258.54	ton LNG	29921348.16	gr LNG	29.92	ton LNG	167.48	ton LNG	8.67108564	ton LNG	8.90192378	ton LNG	4.2425856	ton LNG	447.83	ton LNG	0	ton LNG	11055.90	ton LNG	276397.41	ton LNG	2.76E+05	ton LNG	3.42E+03	ton MDO
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Table [4]: 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 [5]: 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 [6] 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 [7] 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 [8]: 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.

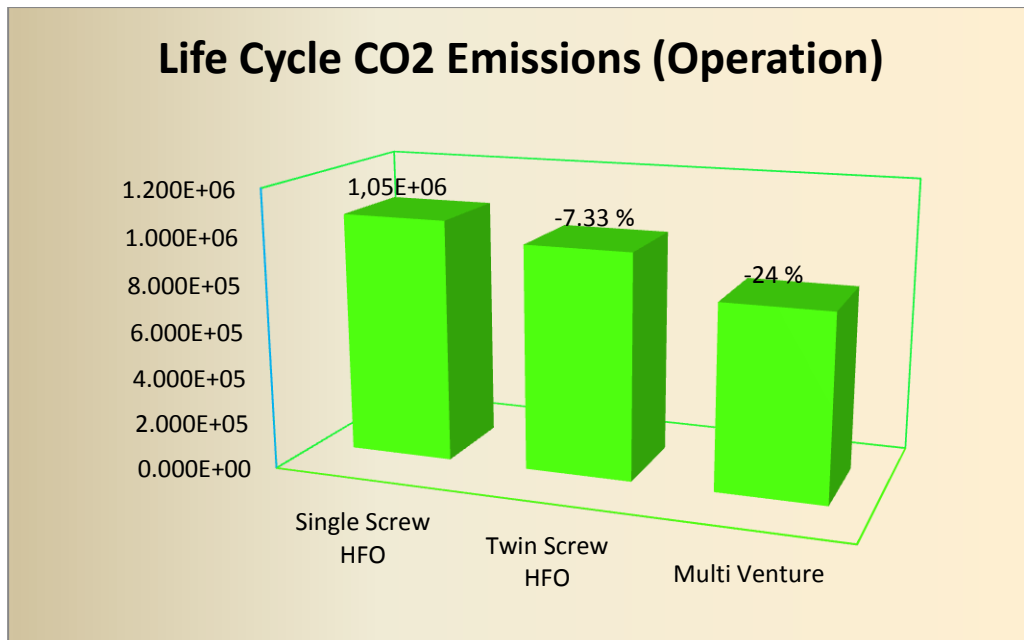


Figure [2]: Comparison of CO2 emissions

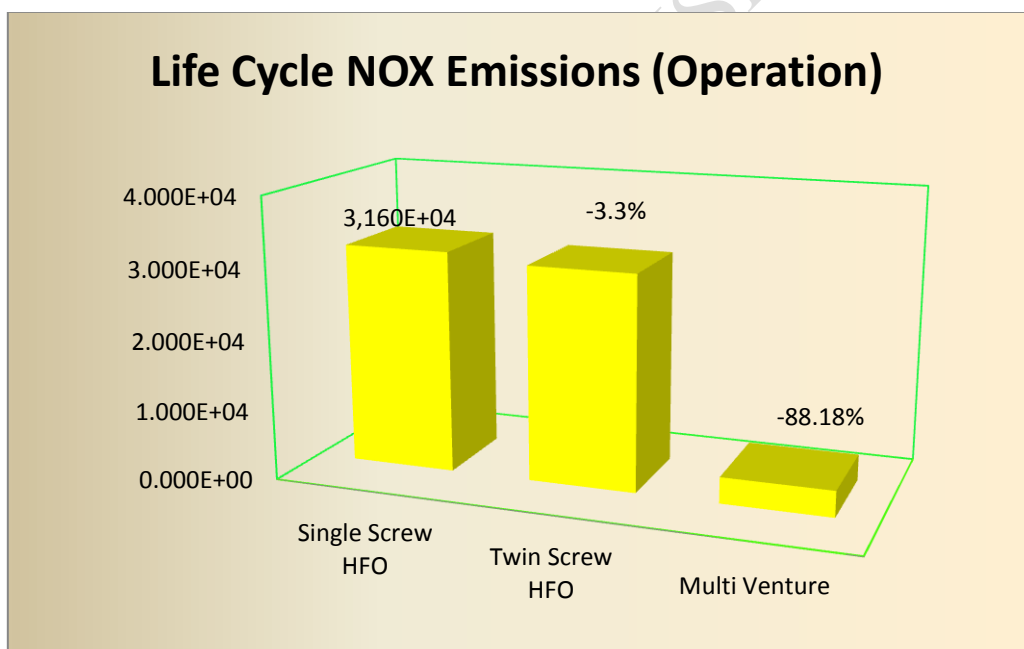


Figure [3]: Comparison of NOx emissions

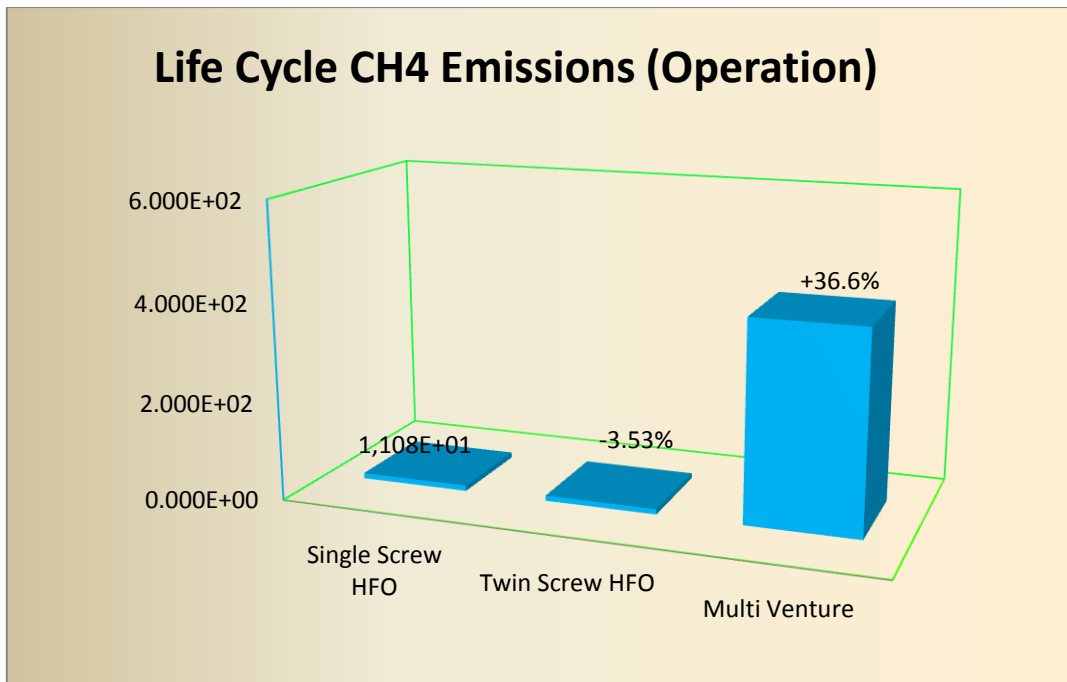


Figure [4]: Comparison of methane emissions

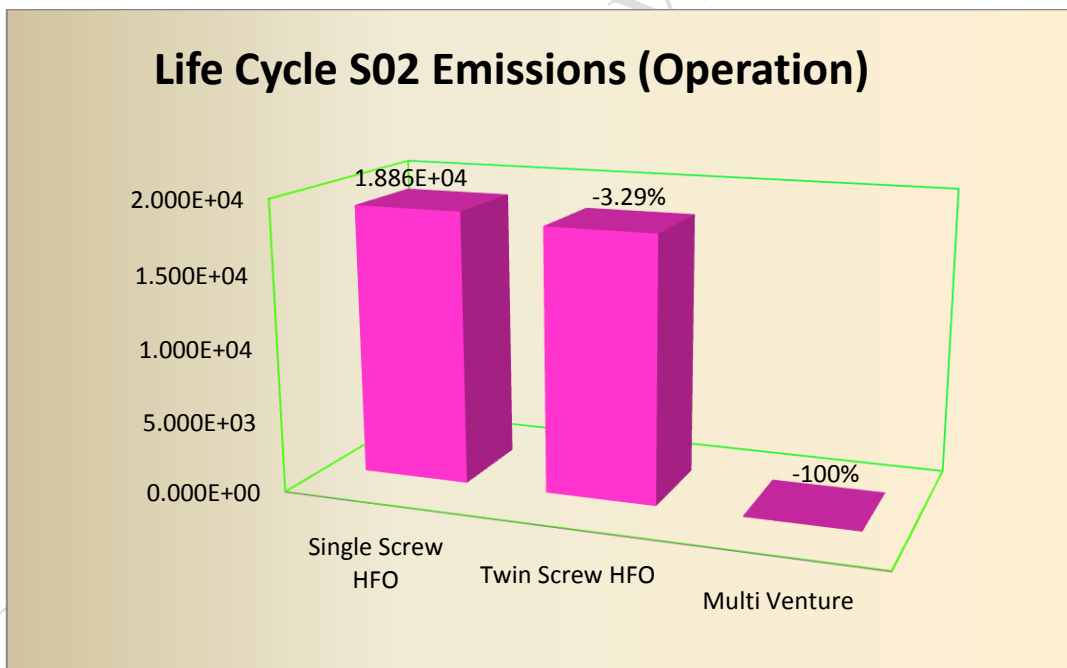


Figure [5]: Comparison of SO_x emissions

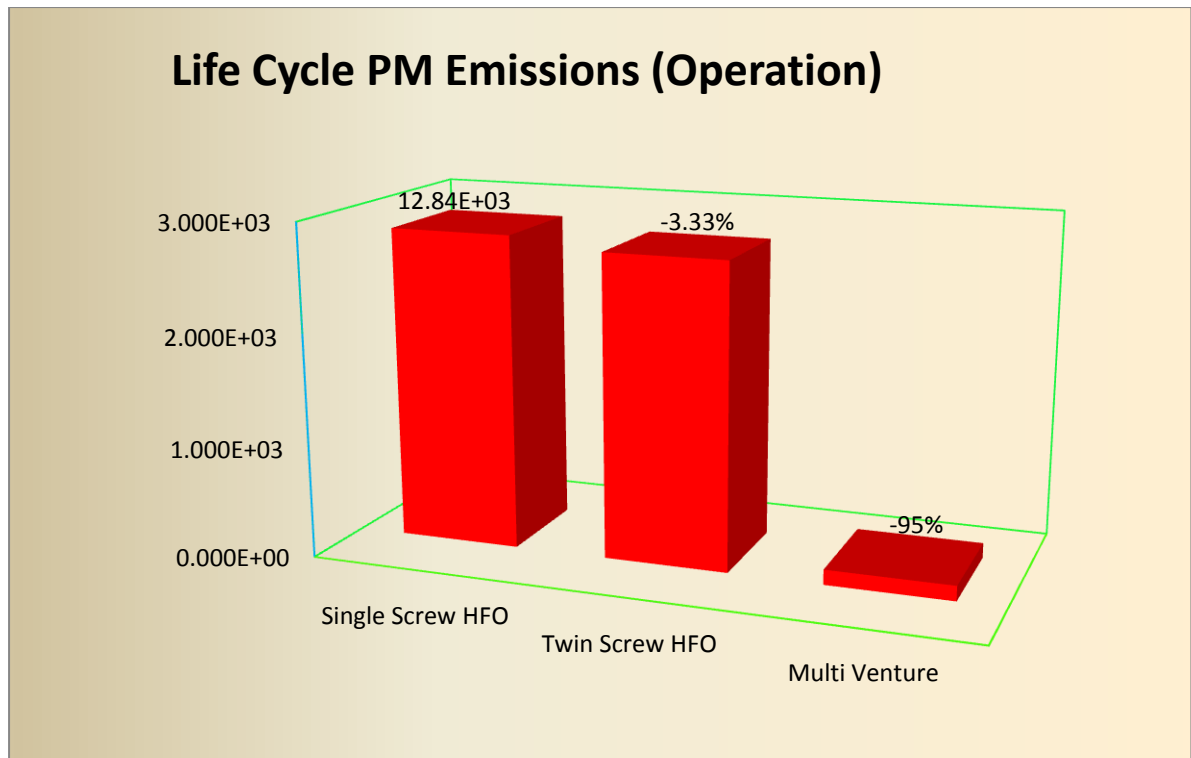


Figure [6]: Comparison of PM emissions

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.

References

1. Winebrake et al. , "The Total Energy and Emissions Analysis for Marine Systems Model" ,2007
2. Selim Alkaner and Peilin Zhou , " A comparative study on life cycle analysis of molten carbon fuel cells and diesel engines for marine application", 2005
3. "Extremis Database"
4. Jown W.Boulston , "Fueling with LNG",Marine Technology (mt), SNAME, October 2011
5. "Interim guidelines on the method of calculation of the energy efficiency design index for new ships" MEPC.1/Circ.681, IMO 2009

CHAPTER 6:**CONCLUDING REMARKS AND DISCUSSION**

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, result 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.

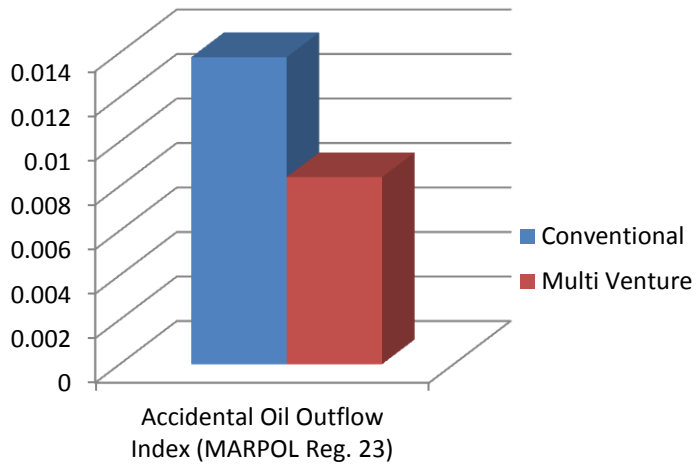
There are some drawbacks however. The increased capital cost indicate that as a solution requires companies and investors with large experience and big market share and also a vision to stand out and differ. The operation of this vessel also requires a very highly skilled and trained crew that nowadays 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.

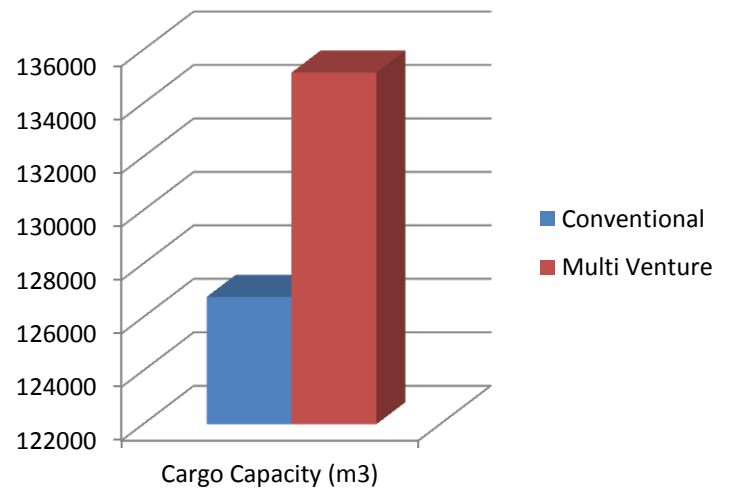
MULTI VENTURE CONCEPT

RESULTS OVERVIEW

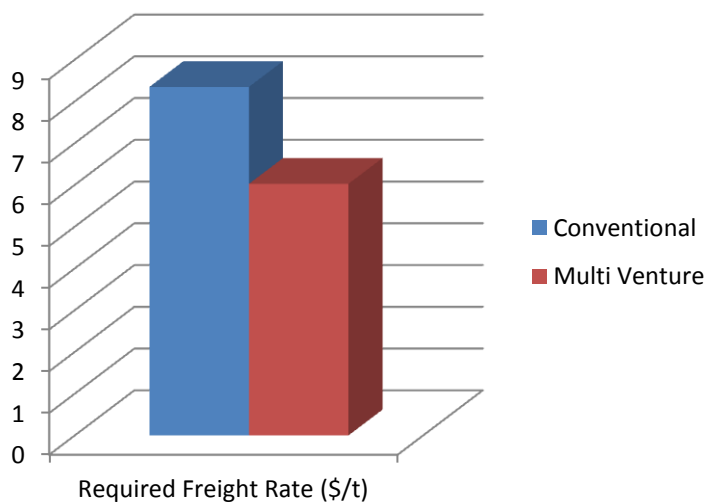
Safer Crude Oil Transport



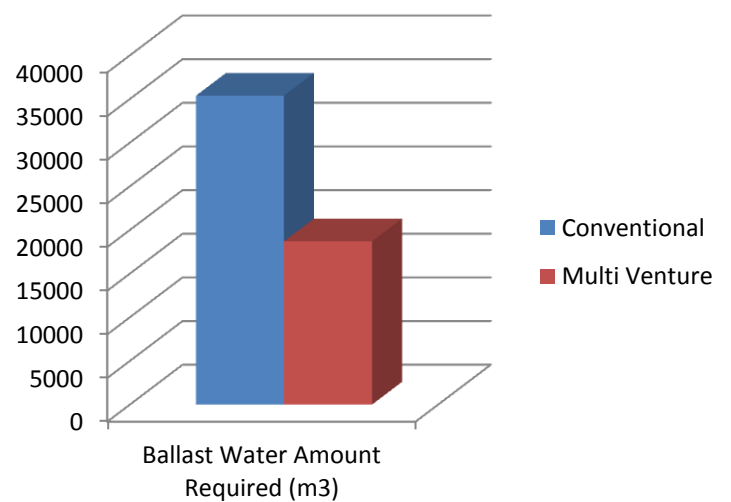
Increased Profitability



Competitiveness



"Semi-Ballast Free" Tanker



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