EQUILIBRIUM

– A BALLAST-FREE CRUDE OIL TANKER

Master's Thesis by Tobias E. King

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PREFACE

This report contains the result of my master's thesis in Marine Systems Design at the Norwegian University of Science and Technology (NTNU), Department of Marine Technology, spring 2010.

The task has been to continue the development of a crude oil tanker design that was invented by Det Norske Veritas (DNV) in 2009. My semester project of autumn 2009, "Drivers, Constraints and Conceptual Fuel Saving Opportunities on Crude Oil Tanker Design", has provided important knowledge on the crude oil tanker industry and on conventional tanker design.

Designing a ship is a complicated iteration process where many different aspects have to be considered at the same time. Only the initial ship design process has been dealt with in this thesis. The level of detailed engineering has been kept at a low level, and focus has been on the ship design aspects that are critical for the feasibility of the concept.

I want to thank my two supervisors at NTNU, Professor Anders Endal and Professor Stein Ove Erikstad, for all their help and guidance throughout the work on this master's thesis. I would also like to thank the team at DNV Business Risk Management for entrusting me with this task and for giving me valuable help and assistance during my last year as a student, with a special thanks to the naval architects Serge Schwalenstöcker, Atle Ellefsen and Johan Vedeler.

I hope my master's thesis can be a valuable contribution to the development of this ship design, and further that this ship design can contribute to an increased environmental focus in the crude oil tanker industry.

Trondheim, the 21th of June, 2010,

Tobias E. King

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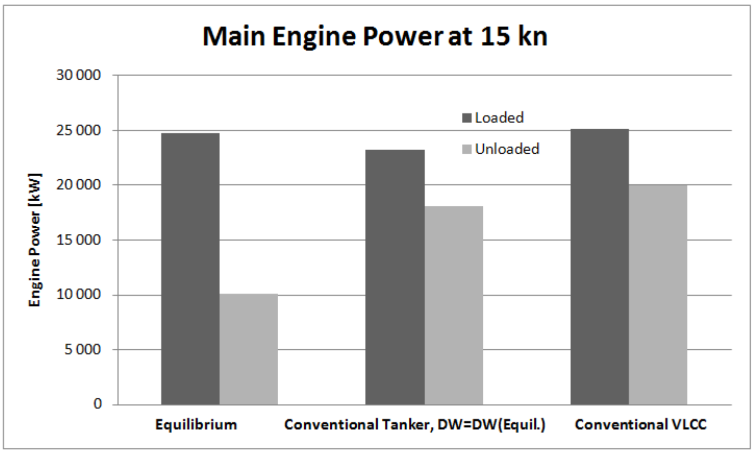
SUMMARY

Equilibrium is the name of a ballast-free oil tanker concept invented by naval architects at Det Norske Veritas (DNV) and further developed in this master's thesis at the Norwegian University of Science and Technology (NTNU).

The task is to analyze the conceptual design work done by DNV and further develop the concept. The main focus is on a cost comparison with a conventional tanker with a deadweight equal to Equilibrium and a conventional VLCC. The cost comparison focuses only on the costs that are expected to be different in these designs: Building costs, fuel costs and the cost of ballast equipment and operation. This comparison serves as an indicator of the profitability and thereby feasibility of the design.

A trapezoid shaped hull and longitudinal cargo boundaries make Equilibrium independent of ballast in transit and during loading and discharging. The ballast-free return legs result in a significant annual saving of fuel and CO_2 emissions. This is Equilibrium's main advantage over a conventional design.

Equilibrium's main disadvantage is that the cargo capacity is about 60 000 tons lower than on a conventional VLCC. This again affects the cost efficiency of the ship. Since Equilibrium is bigger than the Suezmax limitations, the VLCC is regarded as the main competitor.



A cost-efficiency index of the relevant life cycle costs over 10 years divided by the amount of cargo delivered in the same period, shows that Equilibrium is a profitable design. Further analyses needs to be done on the ship's sea keeping abilities with special attention to accelerations in roll motion. The proposed Equilibrium design can compete against existing tankers on both cost-benefit and environmental impact.

Cost Efficiency	[US$/DWT]
Equilibrium	6,9
Conventional VLCC	7,1
Conventional Tanker, DW=DW(Equil.)	7,6

CONFERENCE PROCEEDINGS

The master's thesis will be presented at the Marine Unconventional Design Symposium (MUDS) at UCL in London on the 8th of July 2010.

The following pages contain the conference proceedings which also serve as an extended summary.

Equilibrium – A Ballast-Free Crude Oil Tanker

T E King, Norwegian University of Science and Technology (NTNU), Norway

SUMMARY

Equilibrium is the name of a ballast-free oil tanker concept invented by naval architects at Det Norske Veritas (DNV) and further developed as a master's thesis at the Norwegian University of Science and Technology (NTNU).

A trapezoid shaped hull and longitudinal cargo boundaries make Equilibrium independent of ballast in transit and during loading and discharging. The ballast-free return legs result in an annual fuel saving that compensates the disadvantage of having a lower cargo capacity than a conventional VLCC.

Further analyses need to be done on the ship's sea keeping abilities, but the proposed design can compete against existing oil tankers on both cost-benefit and environmental impact.

1 INTRODUCTION

In 2009 DNV started a ship design project aiming to prove that CO_2 emission targets in shipping could be achieved today by utilizing existing and proven technology. The first innovative ship designs to be developed were the RoRo-ship Momentum and the container ship Quantum.

As a follow up of these designs, DNV has come up with an idea of a ballast-free crude oil carrier concept, with a working name of Equilibrium. The Equilibrium concept has been analyzed and further developed as a master's thesis in naval architecture at NTNU's Department of Marine Technology (King, 2010).

There lies a large energy-saving potential for an oil tanker in operating without the need of ballast. On the return trip a conventional tanker needs ballast water to acquire sufficient propeller submergence and avoid damage from slamming.

Ballast-free ships are desirable also for other reasons. Water ballast contains organisms that can cause unbalance to foreign ecosystems. When IMO's International Convention for the Control and Management of Ship's Ballast Water & Sediments gets its final ratification it will force oil tankers to install ballast management systems that clean the ballast for such organisms.

2 HULL SHAPE

Instead of using water ballast, Equilibrium gains submergence in unloaded condition by its trapezoid hull shape.

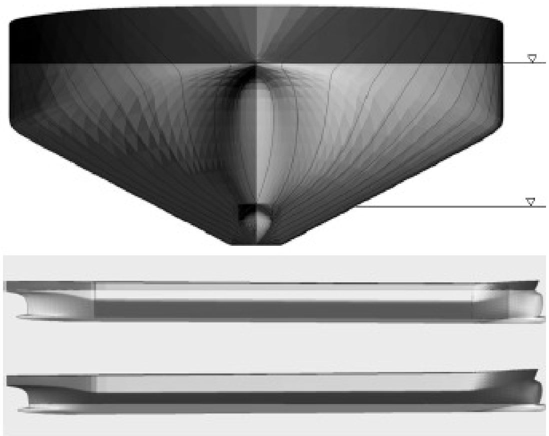


Fig. 1: Draughts in loaded and unloaded condition, body plan view (top) and profile view (bottom)

The front and aft body are designed to give the ship minimum trim in loaded and unloaded conditions. On the proposed hull shape the trim is controlled to 2,2 meters at the aft in unloaded condition and 1,6 meter trim at the bow in loaded condition. A forward trim in loaded condition is common also on conventional crude oil tankers (Michel & Osborne, 2003/2004, p.13).

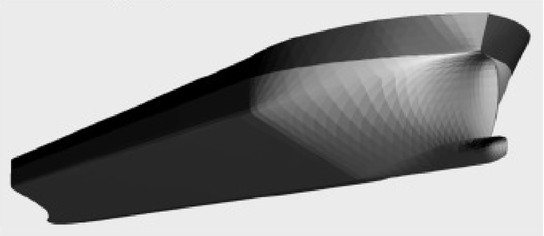


Fig. 2: Front perspective view

A special design feature on Equilibrium is the double bulb. The idea is to give reduced wave resistance in both loaded and unloaded condition. The extra bulb is also an important contribution for minimizing the forward trim in loaded condition.

Tbl. 1: Main dimensions

Main Dimensions		
Displacement	285 300	tons
Deadweight	251 700	tons
Installed Main Engine Power	28 600	kW
Length	365	m
Beam	60	m
Block Coefficient	0,59	-
Draught, Loaded Cond.	21,5	m
Draught, Unloaded Cond.	6,2	m

3 CARGO HANDLING

A conventional tanker is dependent on ballast also to counter longitudinal moments that occur during loading and discharging.

On Equilibrium this is solved by having four longitudinal cargo boundaries instead of two which is common on conventional tankers of Equilibrium's size. The ship can transport three different oil segregations, and longitudinal bending moments are avoided by simultaneously loading/discharging every segregation along the entire length of the cargo block.

Fig. 3: Longitudinal Cargo Boundaries

To avoid healing, every segregation is filled simultaneously in tanks on port and starboard sides, giving transverse moment equilibrium. Flexibility in the share of every oil segregation is given by moment equilibrium between the wing tank on one side of the ship and the centre-wing tank on the other. With reference to Fig. 3, this gives the opportunity of loading Port2 at the same time as either Starb.1 or Starb.2 that have different cargo capacities.

The cargo still has to be divided by transverse bulkheads to satisfy IMO regulations and avoid sloshing and longitudinal free surface effects. Hatches in the transverse bulkheads will insure that the cargo tanks are connected in the longitudinal direction. Alternatively the cargo is transported to/from each of the cargo tanks by the cargo piping system.

4 COMPARISON WITH CONVENTIONAL DESIGN

A cost comparison between Equilibrium and a conventional tanker with the same deadweight has been used to determine the profitability of the ship design. The same comparison has been done against a conventional VLCC that is regarded as the main competitor on the routes Equilibrium is intended to operate. The cost comparison focuses only on costs that are different on Equilibrium and a conventional tanker.

Equilibrium's main advantage over conventional tankers is the low resistance in unloaded condition. On the return leg where a typical tanker is loaded with ballast, Equilibrium is in lightweight condition with a slender submerged hull shape and a small wetted surface area.

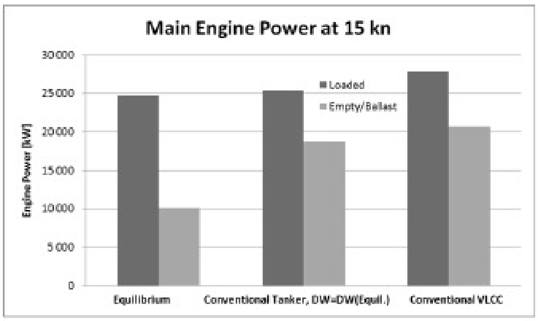


Fig. 4: Main Engine Power at 15 knots

The annual fuel saving is 11 percent compared to a conventional tanker with the same deadweight and service speed, and the environmental impact has an annual CO_2 emissions reduction of 8 400 tons (King, 2010).

Equilibrium's required main engine power is 59 percent lower in unloaded condition than in loaded condition. This will in the continuation of the design process lead to a discussion on which propulsion system is the most suitable for Equilibrium.

Conventional crude oil carriers normally have slow speed engines directly coupled to the propeller shaft. A diesel-electric propulsion system, or even just a gear and a controllable pitch propeller, might give an overall economical benefit because of increased operational efficiency in unloaded condition.

Equilibrium also has the advantage of saving operational expenses from not ballasting. The ship is independent of ballast during transit, loading and discharging. A sea keeping analysis is needed to determine whether it can manage without ballast also in bad weather. If that is the case, Equilibrium will also be spared of the capital expense of ballast pumps, pipes and a ballast management system, although some ballasting capacity has to remain in case of leakage.

Equilibrium's greatest disadvantage is the cargo capacity. The VLCC used in this cost comparison has a deadweight of 310 000 tons which is almost 60 000 tons more than Equilibrium.

To compare the cost efficiency, the building costs, fuel costs and second hand value are calculated for a 10 year life cycle and divided by the amount of delivered cargo in the same period.

Equilibrium is given an advantage for having no ballast pumps, ballast treatment system, ballast pipes and fuel costs from ballast operation. Other operational expenses are assumed to be the same as on a conventional tanker, and would therefore not have any effect on the comparison.

In the building costs, Equilibrium is given a building cost penalty for being a one-of-a-kind ship. This penalty will be removed if Equilibrium were to be mass produced.

This index used for the cost comparison indicates that Equilibrium is more cost efficient than a conventional crude oil tanker (King, 2010).

Tbl. 2: Cost comparison

Ship	*DW [tons]*	*Cost Efficiency [US$/DWT]*
Equilibrium	251 700	6.9
Conventional Tanker	251 700	7.6
Conventional VLCC	310 000	7.1

The main advantage of Equilibrium is the low fuel costs. If fuel prices increase in the future it will increase Equilibrium's profitability over the conventional tankers.

If the cost of installing and operating the ballast systems is added to Equilibrium's life cycle cost, the ship gets the same cost efficiency index as a VLCC. This means that Equilibrium can be competitive on the market even with all the ballast systems available to ease its operation in bad weather, should it be necessary.

5 FEASIBILITY

The initial design indicates that Equilibrium is a concept that is cost competitive against a conventional VLCC, and at the same time has significantly lower CO_2 emissions per transport work.

The profitability of Equilibrium largely depends on the low resistance in unloaded condition. Resistance calculations are done by the empirical methods of both Hollenbach and Guldhammer/Harvard. Still, empirical methods cannot consider all the effects of unconventional design features, so a towing test of an Equilibrium model is needed to determine the resistance more accurately.

In unloaded condition, the hull sides are designed with a deadrise that theoretically should prevent occurrence of slamming in pitch and roll motion (see Fig. 1). However, a sea keeping analysis is needed to determine accelerations during roll motion. The results of such an analysis might lead to a change of hull shape.

REFERENCES

King, T.E., 2010. *Equilibrium - A Ballast-Free Oil Tanker, Master Thesis in Marine Systems Design/Naval Architecture*. NTNU, Department of Marine Technology.
Michel, K. & Osborne, M., 2003/2004. Oil Tankers. *Ship Design and Construction, Volume 2*.

1 INTRODUCTION

1.1 BACKGROUND

The last decades have seen little development in oil tanker design. But today shipping faces a new reality. Increased fuel costs, new environmental rules and regulations, extended emission control areas and a growing public awareness for environmental issues will likely lead to new innovative ideas in the oil tanker industry.

A large energy-saving potential for an oil tanker is to design it to operate without the need for ballast. On the return trip a conventional tanker needs ballast water to acquire sufficient propeller submergence and avoid slamming. A typical amount of ballast needed for a VLCC in ballast condition is as much as 100 000 tons(Lalic, 2010).

There are more reasons for desiring ballast-free ships. The ballast water contains organism that can cause unbalance when introduced to new ecosystems. When IMO's International Convention for the Control and Management of Ships Ballast Water & Sediments gets its final ratification it will force oil tankers to install ballast management systems that require significant installation costs and additional energy.

In 2009 Det Norske Veritas (DNV) started a ship design project aiming to prove that CO_2 emission targets in shipping could be achieved today by utilizing existing and proven technology. The first innovative design concepts to be developed were the RoRo-ship Momentum and the container ship Quantum.

As a follow up of these designs, DNV also developed an idea of a ballast-free crude oil carrier concept with a working name of Equilibrium. The goal is to achieve improved performance with respect to operational efficiency and environmental impact, compared to existing tankers.

1.2 MAIN TASKS AND OBJECTIVES

The objective of this master's thesis is to develop the Equilibrium concept further; to investigate whether a ballast-free tanker of the suggested concept is technically feasible; and to estimate the energy-saving potential.

The concept with its initial design parameters will be analyzed for possible constraints and shortcomings, modified and developed in an initial design stage.

The master's thesis shall contain the following, as agreed on by the supervisors at NTNU and DNV:

1) Do an evaluation of the engineering carried out on Equilibrium so far. Locate upsides and downsides with the concept, and investigate possible operational and regulatory constraints that need to be appraised for the continuation of the design process.
2) Assess possible alternatives to the suggested tank configuration.
3) Confirm that the ship can be loaded and unloaded as required by existing producers, oil quality segregations and terminal equipment, maintaining strength and stability in all conditions.

4) Do a rough cost-benefit appraisal.
5) Outline the hull lines. Perform a re-iteration of the lightship weight and determine optimal draught in unloaded condition and eventual designed-in trim for optimal propeller immersion. Develop a neutral-buoyancy (or controlled buoyancy) fore- and aft ship, in cooperation with DNV team.
6) Carry out a speed-power estimation; find a corresponding propeller configuration to ensure necessary draught aft in lightship condition (propeller diameter, single or twin screw etc.).
7) Stability and strength to be confirmed by DNV technology consulting department.

1.3 METHOD

The work has been divided in two parts:

1.3.1 PART 1: ANALYSIS OF CONCEPTUAL DESIGN

The first part of the work is to analyse the sketches and rough calculations that constitute Equilibrium at its conceptual design phase, and thereby addressing the main tasks of 1) to 4) as presented in chapter 1.2. Calculations and drawings were handed over from DNV at the beginning of the master's thesis work. This work will be an important background study for the further iteration process on the Equilibrium concept.

1.3.2 PART 2: NEW EQUILIBRIUM HULL SHAPE

Using the findings of the analysis in part 1, new rounds in the ship design iteration process is performed on the Equilibrium concept resulting in a new hull shape and speed-power estimations. This part will contain the remaining main tasks of 5) to 7) as presented in chapter 1.2.

1.4 OTHER INNOVATIVE SOLUTIONS

Equilibrium is not the first concept that aims at solving the problem of ballast water. This chapter presents a selection of other ideas.

1.4.1 LNG CARRIER WITH BALLAST-FREE TRANSIT

Parallel to the development of Equilibrium, STX's Saint-Nazaire yard in France has designed a ballast-free LNG-carrier using a very similar idea. This design emerged as a result of the EU-funded IMPROVE project in 2009, which was followed up by a study by STX (Claes & Guillaume-Combecave, 2009). The fact that others have independently developed a variant of the Equilibrium idea indicates that the concept might very well be feasible.

Like Equilibrium, the ballast-free LNG Carrier has a trapezoid shaped hull to ensure a sufficient draught in unloaded condition. The designers say that the ship with a capacity of 220 000 m^3 needs a minimum of ballast, or none at all, when sailing the return leg. The ship is still equipped with a ballast system enabling it to ballast down to be within the reach of the loading arms at the terminal and have a safer sailing condition in bad weather.

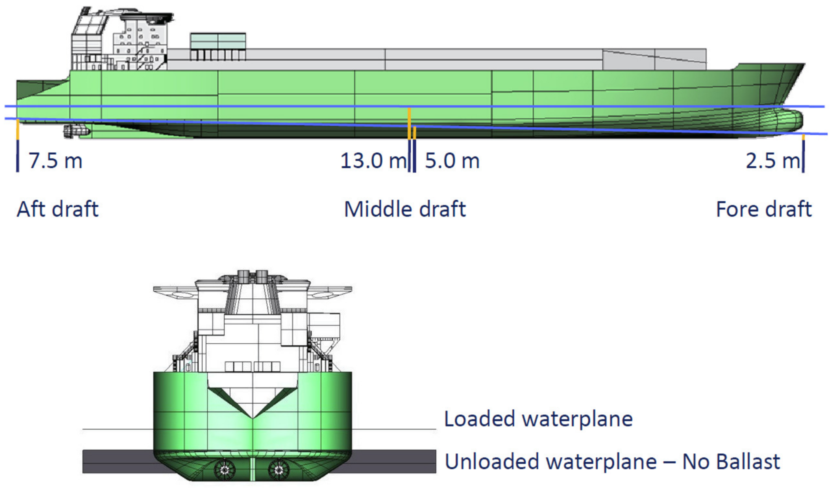


FIGURE 1: BALLAST-FREE LNG CARRIER FROM STX

Since ballast water only is exchanged in port, or far out at sea in cases of bad weather, the ballast is not transported over distances of any significance. According to the designers the ship therefore satisfies IMO recommendations for ballast treatment. However, there are problems with such a solution. When ballast water exits the tanks after loading it leaves behind organisms in the tanks that may be flushed out to a foreign ecosystem during the ballast operation in the next port. Therefore it is likely that this LNG carrier concept will need a ballast treatment system when the IMO regulation on ballast water management gets ratified.

But as the LNG carrier uses very little - or none at all - ballast during transit in normal weather conditions, a large amount of fuel can be saved. The ship has an estimated annual LNG fuel saving of 9 % in comparison with an LNG carrier with the same capacity and a conventional design, according to the designers.

1.4.2 HULL WITH FLOW-THROUGH BALLAST

A bulk carrier design with ballast water constant flowing through its hull was in 2001 invented by Professor Michael Parsons and PhD student Miltiadis Kotinis at the University of Michigan (Thurnau, Parsons, & Kotinis, 2008).

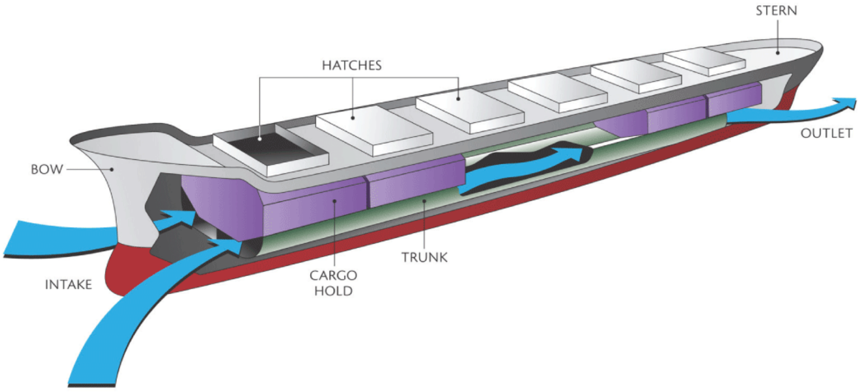


FIGURE 2: HULL WITH FLOW-THROUGH BALLAST

The aim of the ship is to avoid introduction of foreign species to ecosystems through ballast water transfer. With water intakes at the bow and outlets at the aft, the ballast is constantly flowing through the hull making it difficult for organisms to stick to the tank sides. The openings and outlets are sized so that the water is exchanged every hour or two.

A crude oil carrier is required to have a double hull that protects the cargo from leaking out to sea in case of an accident. It is uncertain whether or not such a flow-through hull would be approved for an oil tanker as a leakage from the cargo holds to the flow through ballast sections could result in outflow to the sea.

This concept does not have the benefit of reduced resistance in unloaded condition, unlike the STX LNG-carrier. The extra ballast is still there, the only difference is the continuous replacement of it.

1.4.3 TANKER WITH ALTERNATIVE LOAD ON RETURN LEG

1.4.3.1 Crude and Bulk

Instead of using ballast on the return leg, some ships gain displacement and income by shipping bulk, mainly iron ore and coal. These ships are known as ore-bulk-carriers, OBO-carriers or combination carriers. The consistency of crude oil makes the cargo tanks unsuitable for transporting most other types of cargo. Unfortunately, the main trading routes for crude oil do not connect markets that are in need of transporting a suitable cargo on the return leg. The main oil consumers in Asia, North America and Europe do not export iron ore or coal to the Middle-East where most of the crude is shipped from.

1.4.3.2 Crude and Fresh Water

Fresh water is a resource that is needed in many of the oil exporting countries. An idea is to use the ballast tanks to transport fresh water from oil consuming countries to oil producing countries, also known as fresh water backhauling (FWBH).

FWBH has been studied as a master’s thesis at NTNU by (Sharma & Lande, 2010), where it is concluded that FWBH is feasible both technically and economically. The main problem is the character of the oil tanker market. Most of the tankers operate on the spot market where it might be challenging to find a charter for fresh water on the return leg that matches the charter for oil delivery.

The concept is more sustainable than existing crude oil shipping since a purpose is made out of all the return leg ballast.

PART 1

The first part of the master's thesis consists of the following chapters:

2. Analysis of Conceptual Design
3. Solution for Cargo Handling
4. Feasibility of Ballast-Free Operation

2 ANALYSIS OF CONCEPTUAL DESIGN

At the time of starting the master's thesis work, the Equilibrium concept had already been subjected to a rough study, covering a parallel mid ship only, with main dimensions, steel weight and intact stability broadly estimated.

The analysis of DNV's conceptual design divided in three main parts:

- Analysis of main dimensions
- Resistance calculations
- Cost comparison with conventional tanker

This process will locate the most important variables in the design that have to be focused on in order to maximize Equilibrium's potential for increased operational efficiency and environmental performance.

2.1 OUTLINE OF CONCEPTUAL DESIGN

The Equilibrium concept intends to use the following means to accomplish improved operational efficiency and environmental impact:

- Ballast free ship to save fuel consumption on return leg and avoid expected IMO regulations on ballast treatment
- Longitudinal main cargo boundaries rather than transverse tank subdivision to avoid the use of ballast during loading and discharging. This way ballast water will not be needed to compensate for longitudinal bending moments.
- Shape the hull as a trapezoid in order to maintain propeller and bow draught during empty return voyage, allowing a much slimmer hull that gives less resistance
- Suggest alternative low-weight tank boundaries instead of steel panel construction in non-load carrying longitudinal elements (see Figure 4)

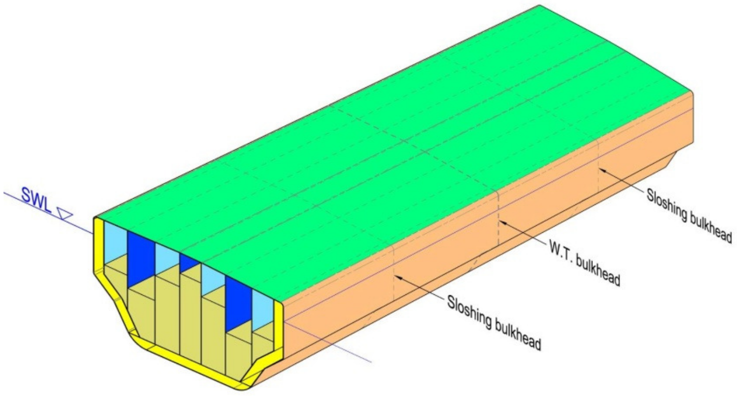


FIGURE 3: CONCEPTUAL DESIGN, CARGO SECTION

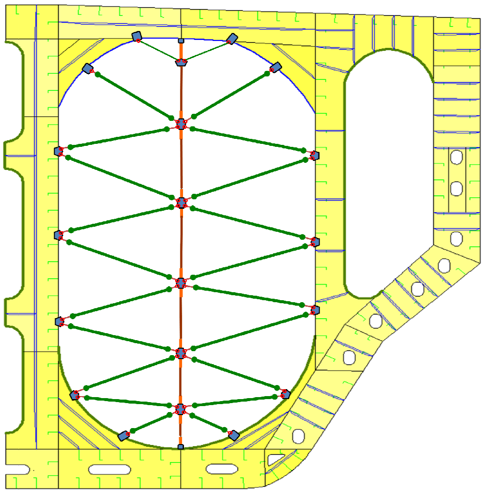


FIGURE 4: STARBOARD MIDSHIP SECTION WITH ALTERNATIVE BULKHEAD MATERIAL

The main parameters are listed in Table 1:

TABLE 1: CONCEPTUAL DESIGN PARAMETERS

Main Parameters			
Deadweight	DW	208 300	tons
Steel Weight		39 700	tons
Lightship Weight	LW	42 700	tons
Displacement	Δ	251 000	tons
Service Speed	V	15	kn
Length	Loa	360	m
	Lpp	350	m
Loaded Condition:			
Beam	B_{Loaded}	40	m
Draught	T_{Loaded}	20	m
Freeboard	F	3,4	m
Block Coefficient	$C_{B,Loaded}$	0,85	-
Unloaded Condition:			
Beam (at Water Line)	$B_{Unloaded}$	30	m
Draught	$T_{Unloaded}$	5,7	m
Block Coefficient	$C_{B,Unloaded}$	0,80	-

2.2 MAIN DIMENSIONS

The main dimensions are tested against trend lines, physical constraints and market constraints. Many of these constraints have been addressed in (King, 2009).

2.2.1 CARGO CAPACITY

The deadweight of 208 300 tons is unusual in the crude oil tanker market. An abnormal cargo capacity might be a disadvantage in a conservative market where one-of-a-kind ships are a rarity.

Figure 5 marks the deadweight and displacement of all crude oil carriers in (Lloyds Register Fairplay) and shows that Equilibrium's deadweight is almost alone in the area between Suezmax carriers of about 150 000 deadweight tons and VLCC of about 300 000 deadweight tons.

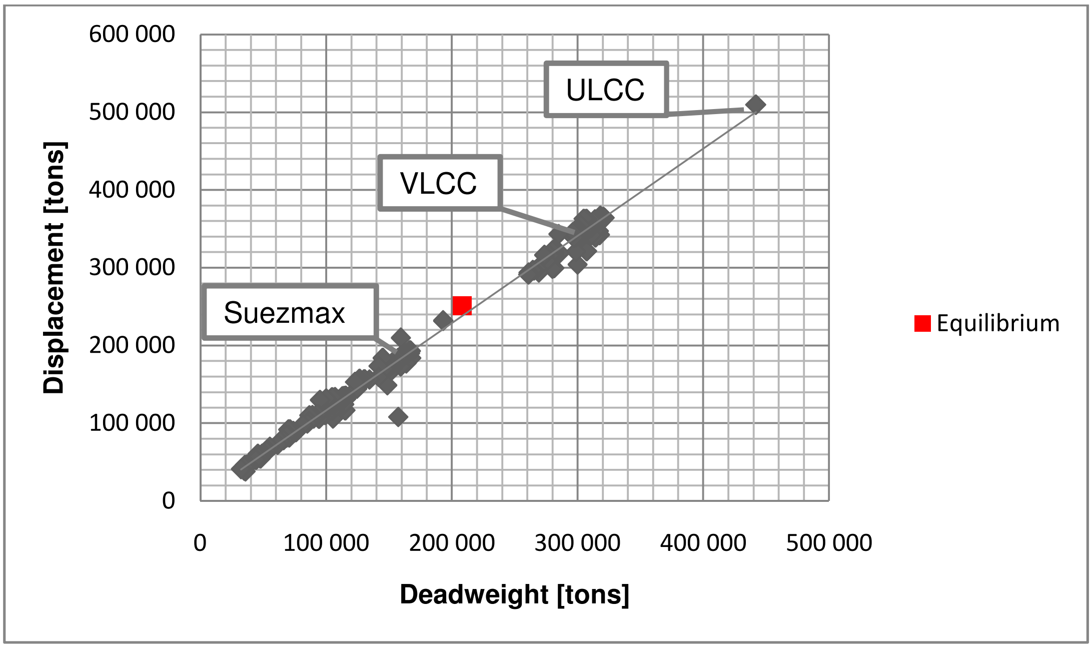


FIGURE 5: DEADWEIGHT VS DISPLACEMENT FOR CRUDE OIL TANKERS

The only tanker with a displacement close to Equilibrium, the Alaskan Legend, is designed according to strict regulations for tankers operating in Alaska, and therefore has a twin screw diesel-electric propulsion system which makes it unsuitable for cost comparison.

However, there are a small number of oil tankers with deadweight of about 200 000 tons on order for delivery in the period 2011 – 2014 (Lloyds Register Fairplay). This means that there is a market for tankers of this size.

Economy of scale is also a factor that should be taken into consideration when discussing the cargo capacity. Equilibrium is too big for the Suez Canal and has to compete against VLCCs that have a much higher cargo capacity. The efficiency factor of cost per transported cargo might deem Equilibrium uncompetitive. This calculation will be addressed later in the report.

2.2.2 SPEED

The service speed is set to 15 knots which is about average for a conventional oil tanker. Effective power in Watts is a third power function of speed, which means that fuel consumption can be reduced significantly by reducing the speed. However, for the ship to be attractive on the market, it has to be able to operate at the same speed as the conventional market-adapted crude oil carriers. A lower speed capacity would reduce the ships flexibility in serving a market with huge fluctuations in demand.

For the sake of simplicity, the speed is set to 15 knots also on the return leg when the ship is unloaded. Because of the reduced displacement in this condition, both existing tankers and Equilibrium have the opportunity of increasing the speed using the same engine power as in loaded condition. Since the Equilibrium in unloaded condition will have no ballast and therefore a much lower displacement than a standard tanker, it will also have the possibility of higher speed. It may be interesting in a later study to do a logistical analysis of Equilibrium's return leg to see whether or not higher speed and possibly more trips is more beneficial than low speed and higher specific fuel consumption.

In this master's thesis, Equilibrium will have the same speed on the return leg as a conventional tanker. The advantage of slimmer hull shape in this condition will pay off in less resistance and fuel consumption instead of increased speed and more deliveries.

2.2.3 LIGHTSHIP WEIGHT

The lightship weight is an important factor for two main reasons:

1) Cost of steel is the most expensive part of the building cost.
2) While other tankers can rely on ballast to create sufficient draught when unloaded, Equilibrium only has its own lightship weight and fuel to create submersion.

In the conceptual design, a rough estimate from DNV puts the steel weight of the hull to 39 700 tons. Assuming an addition of 1000 tons for the deck house and another 1000 tons for the machinery, gives a lightship weight of 42 700 tons. The additional 2000 tons is a very rough estimation, but considered usable in this comparison.

It is expected that Equilibrium's lightship weight exceeds the current trend line value for tankers. Equilibrium has two extra longitudinal bulkheads and a slender hull shape that require extra steel. At the same time, the trapezoid mid ship shape should give a reduced steel weight than the conventional box-shaped mid ship.

The estimated lightship weight of 42 700 tons is tested by using a lightship weight trend line value found in (Lloyds Register Fairplay) and adding or subtracting weights according to Equilibrium design features. This is not a very accurate way of calculating the lightship weight, but serves for testing the calculations done by DNV. The trend line is the same as in Figure 5, where the lightship weight is found by subtracting the deadweight from the displacement.

Suezmax tankers generally have a lightship weight between 20 000 and 30 000 tons and VLCCs between 40 000 and 50 000 tons. According to the trend line, a 208 000 DWT tanker like Equilibrium should have a lightship weight around 29 500 tons with a likely offset within 5000 tons, had it been a conventional design.

Important design features that will affect Equilibrium's lightship weight compared to a conventional tanker are

- two additional longitudinal steel bulkheads
- slender hull shape
- trapezoid hull shape

The weight contributions from these design features are explained in the followingsub-chapters.

2.2.3.1 Additional Steel from Longitudinal Bulkheads

A conventional 208 000 DWT tanker would normally have two longitudinal bulkheads to satisfy IMO regulations on maximum outflow and prevent free surface effects. Equilibrium has a total of four longitudinal bulkheads. This is because of the longitudinal cargo separation that makes loading and discharging without the use of ballast water feasible. This is explained in later in chapter 3.

As the extra wing bulkheads don't reach all the way down to the keel, they together count as 1,5 bulkhead in the calculations. The weight of the bulkheads is calculated by multiplying the steel volume with the steel density. A factor of 1,3 is multiplied to the volume of the bulkheads to take the stiffeners and other steel construction units into account (Vedeler, 2010).

TABLE 2: WEIGHT OF ADDITIONAL LONGITUDINAL BULKHEADS

Additional Longitudinal Bulkheads		
Length of Cargo Section	300	m
Depth	25	m
Number of Additional Bulkheads	1,5	-
Stiffeners, Factor	1,3	-
Plate Thickness	0,02	m
Steel Density	7,8	tons/m^3
Additional Steel Weight	2300	tons

2.2.3.2 Additional Steel due to Slender Hull Shape

Equilibrium has a slender hull shape in comparison to existing tankers which will add to the steel weight. While the trend lines give a 208 000 DWT tanker a length of 300 meters and a beam of 52 meters, Equilibrium has a length of 360 meters and beam of 40 meters. The weight increase is estimated by designing a simple rectangular box shape hull with bulkheads and double hull for both Equilibrium and a comparison ship with trend line values. The weight is found by multiplying the steel volume from the box hulls with the steel density, and a factor of 1,3 takes stiffeners and other steel construction units into account. The weight difference between the two box hulls is added to Equilibrium as a weight penalty.

TABLE 3: ADDITIONAL WEIGHT DUE TO SLENDER HULL SHAPE

Weight Increase due to Slender Hull Form			
Plate Thickness	T	0,02	m
Stiffeners, factor		1,3	-
Steel Density	P	7,8	tons/m^3
Comparison Ship			
Length	Lpp	300	m
Beam	B	52	m
Depth	D	22	m
Longitudinal Bulkheads		2	-
Weight		17522	tons
Equilibrium			
Length	Lpp	350	m
Beam	B	40	m
Depth	D	24	m
Longitudinal Bulkheads		3,5	-
Weight		21294	tons
Additional Steel Weight		3800	tons

2.2.3.3 Steel Reduction from Trapezoid Hull Shape

Equilibrium's trapezoid shaped hull, as sketched in Figure 4, gives a steel weight reduction compared to an existing tanker hull shape design with a close to rectangular mid ship.

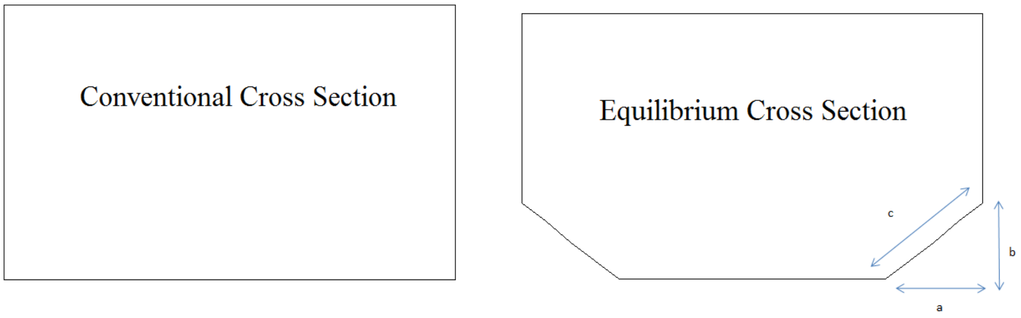


FIGURE 6: MID SHIP SECTION COMPARISON

The steel weight reduction is calculated from the wet surface area reduction from the same design feature that is calculated in connection with the resistance calculations in chapter 2.3.1.2 and Appendix B. It is taken into consideration that the ship has a double hull in the area where the steel weight is saved.

TABLE 4: WEIGHT DECREASE DUE TO TRAPEZOID SHAPED HULL

Weight Reduction due to Trapezoid Shaped Hull		
Wet Surface Area Reduction	3700	m^2
Plate Thickness	0,02	m
Steel Density	7,8	$tons/m^3$
Weight of Steel Reduction	1200	tons

2.2.3.4 Alternative Lightship Weight Calculation

Other factors that will make Equilibrium's lightship weight differ from a conventional design are

- Weight decrease: Steel plates surrounding ballast tanks might not have to be dimensioned for corrosion
- Weight increase: Possible twin screw propulsion system
- Weight increase: Possible thicker plates in some areas due to slender hull form and therefore increased longitudinal bending moments around the mid section

These weights will partly equal each other out and are also regarded small compared to the major extra steel units.

TABLE 5: ALTERNATIVE LIGHTSHIP WEIGHT ESTIMATION

Lightship Weight Estimation from Trend Line Value		
Trend Line Value	29 500	tons
Longitudinal Bulkheads	2 300	tons
Trapezoid Hull Shape	-1 200	tons
Slender Hull Form	3 800	tons
Estimated Lightship Weight	34 400	tons

According to trend lines and Equilibrium's special design features, the lightship weight is estimated to be approximately 34 400 tons. The trend lines suggest a possible difference of maximum 5000 tons, so it is more correct to say that the lightship weight should be between 29 400 and 39 400 tons.

This indicates that the estimated lightship weight of 42 700 tons is too high. In the continuation of the design process, special attention should be given to calculating the lightship weight.

See Appendix A for detailed calculations of the alternative lightship weight estimation.

2.2.4 DRAUGHT

2.2.4.1 Draught in Loaded Condition

Equilibriums draught is set to 20 meters in loaded condition. This is more than the Suez Canal's maximums draught of 18,9 meters that apply for ships with a beam of 50 meters or less, but less than the 21 to 22 meters that is common draughts on VLCCs.

If Equilibrium is to use the Suez Canal with the present limitations, the draught would have to be reduced. The Suez Canal Authorities (Suez Canal Authorities) are these days doing a feasibility study on increasing the maximum draught to 21,9 meters to allow passage for the loaded VLCC's and ULCC's. As the Equilibrium is a futuristic ship design, there is no point limiting the ship to a Suezmax draught constraint of 18,9 meters that may not exist the day the ship is meant to operate.

To fit a possible future Suezmax regulation, a draught of 21,9 meters is recommended for further iteration. This will most likely also make the ship more cost-efficient; draught is a cheap dimension to increase with regards to required extra steel.

2.2.4.2 Draught in Unloaded Condition

The lightship draught is critical to ensure propeller submergence and to avoid slamming damage in bad weather. This is more important on Equilibrium than other tankers since Equilibrium does not have the opportunity of ballasting down in bad weather.

The revised MARPOL 73/78 Annex I and II from 2004 states that the moulded draught amidships in meters shall be no less than 2 + 0,02L, which in Equilibriums case equals 9,0 meters. The draught at the forward and aft perpendiculars shall not be less than the required draught amidships when the vessel is trimmed 0,015L, and the propeller shall be fully submerged.

The initial lightship draught of Equilibrium is 5,7 meters, and therefore has to be increased by at least 3,3 meters to meet the MARPOL regulations. To maintain a buoyancy equal to the lightship in unloaded condition, the increase of draught will most likely have to be compensated by a reduced beam, and so the MARPOL draught regulation may impose a hull shape adjustment on Equilibriums lower hull section.

There have been a number of incidents of slamming causing damage even on tankers applying to MARPOL draught regulations (Michel & Osborne, 2003/2004). Equilibrium's trapezoid shape could theoretically give less slamming than on a conventional flat bottomed tanker, so extra attention has to be given to this problem when investigating sea behaviour later in the ship design study.

2.2.5 LENGTH

Although Equilibrium has a significantly lower cargo capacity than a VLCC, it has a length of 360 meters that is longer than the average VLCC and close to a ULCC. This can be seen in Figure 7 where Equilibrium's length is compared to the length of conventional crude oil carriers in Lloyds ship register (Lloyds Register Fairplay).

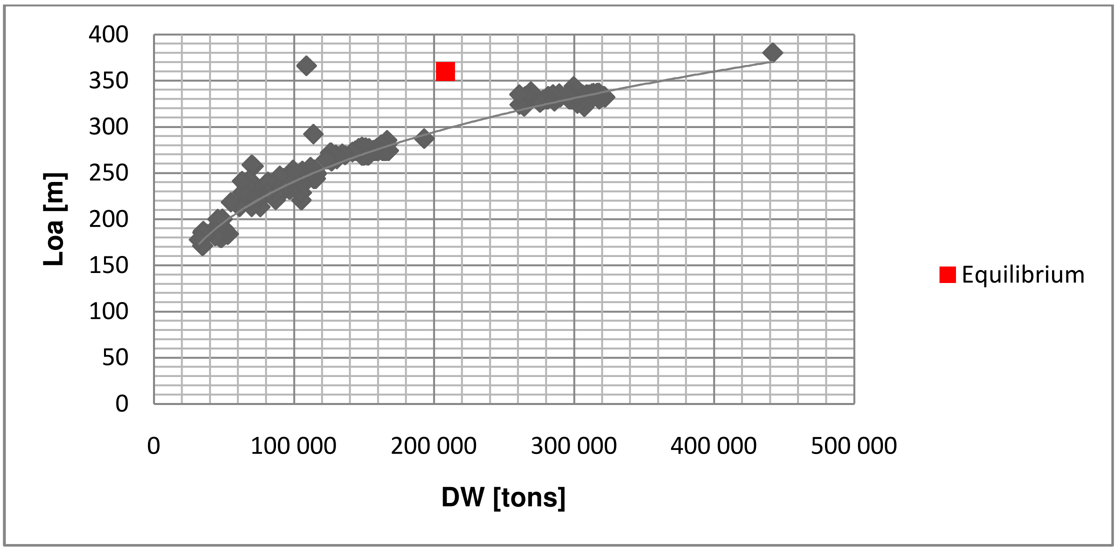


FIGURE 7: DEADWEIGHT VS. LENGTH FOR CRUDE OIL CARRIERS

Having a long and slender ship is beneficial because it gives reduced wave resistance. However, it requires more steel and has a higher building cost than a short and wide ship, as was demonstrated in Table 3. Also, a longer ship gets larger longitudinal bending moments amidships, which might require increased plate thickness, increased steel weight and higher building cost.

There seems to be no arbour restrictions or manoeuvrability requirements preventing Equilibrium from being 360 meters long. In fact, there is nothing physically limiting the length to 380 meters which is normal for a ULCC, or even more.

However, to keep the building costs down it is important to keep the steel weight at a minimum. This will later be shown in the cost-benefit analysis in chapter 2.4. Equilibrium is already a very long and slender ship, so a possible increase in cargo capacity should preferably be obtained by increasing the draught and/or the beam.

2.2.6 BEAM

Equilibrium has a beam of 40 meters in loaded condition. When in unloaded condition the beam at the water line goes down to 30 meters. The decreased beam at the bottom part of the hull is required to ensure sufficient draught in unloaded condition.

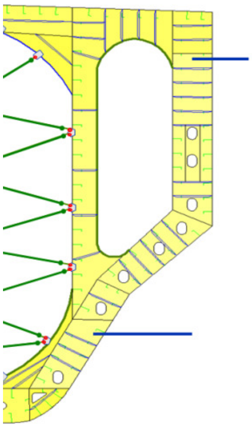


FIGURE 8: STARBOARD MID SECTION WITH DRAUGHT FOR LOADED AND UNLOADED CONDITION

Equilibrium is very slender compared to other ships registered in Lloyds' database (Lloyds Register Fairplay), as can be seen in Figure 9.

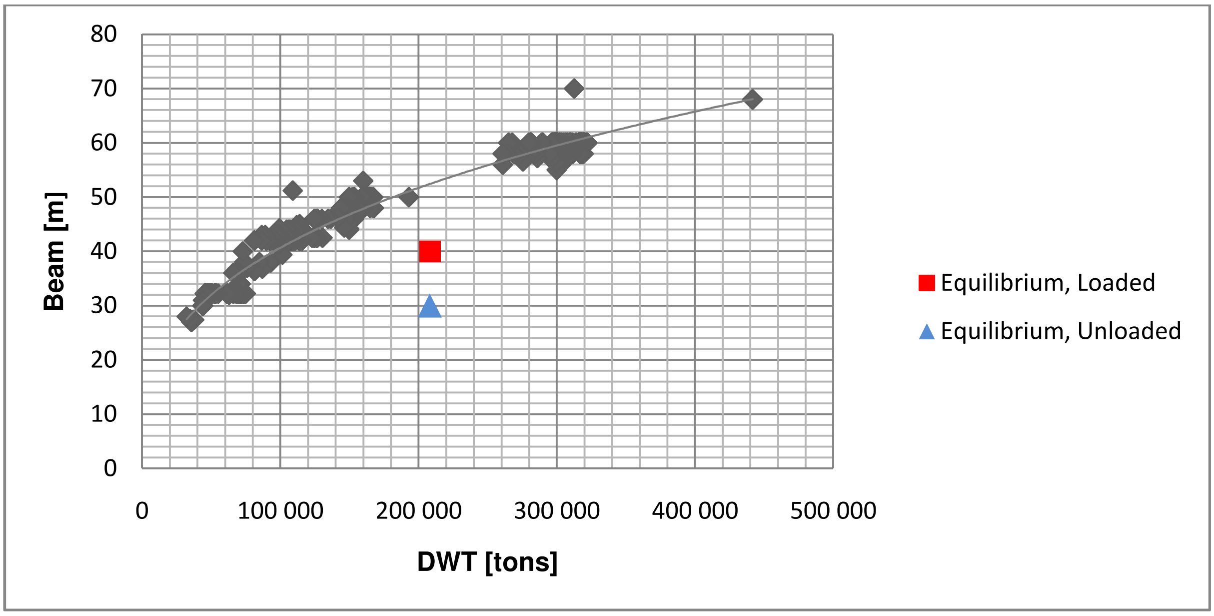


FIGURE 9: DEADWEIGHT VS BEAM

The beam of the lower hull is limited by the required displacement and draught in unloaded condition. This also puts a limit to the beam in loaded condition. If the beam in loaded condition is too much bigger than the beam in unloaded condition, the plates in between the two draughts will have a deadrise that may cause slamming damage in bad weather.

Figure 10 shows the maximum slamming pressure that can occur on wedges with different deadrise angles as they hit the water with vertical acceleration (Faltinsen & Zhao, 1993). $C_{p,max}$ is a coefficient for the maximum slamming pressure, expressed as

$$C_{pmax} = \frac{p_{max} - p_0}{0{,}5\rho V^2}$$

V is the vertical speed, p is the pressure and ρ is the density of the water.

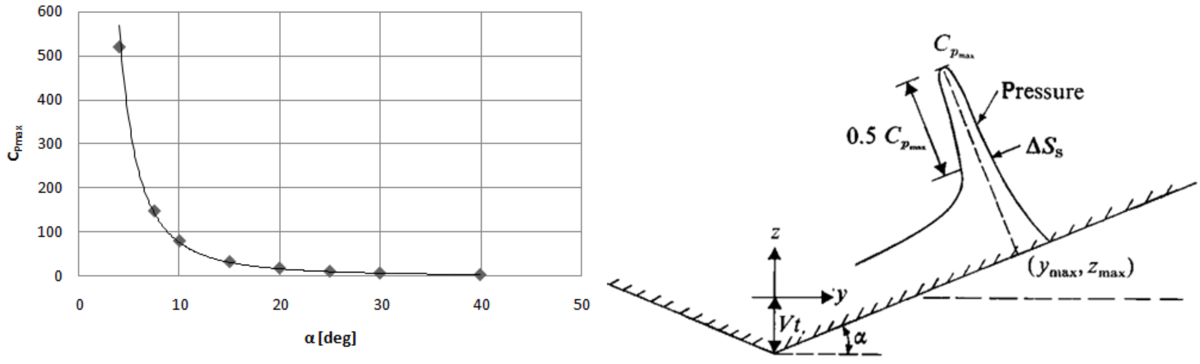


FIGURE 10: SLAMMING ON WEDGE

Based on these results, the minimum deadrise before serious slamming occurs in heave and pitch is assumed to be in the area of 25 to 30 degrees. This should also allow for big heeling angles without occurrence of slamming damage.

Figure 8 shows that the deadrise is approximately 45 degrees on the conceptual design, and that the beam in loaded condition can most likely be extended without danger of slamming. Stability in unloaded condition is also a factor that has to be taken into consideration. A reduced water plane area will give a lower GM-value.

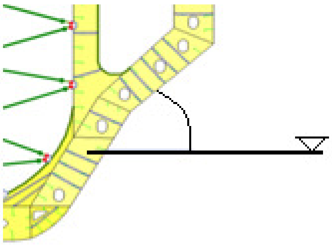


FIGURE 11: CRITICAL DEADRISE ANGLE

The current Suezmax beam limitation for ships of large draught is 50 meters. The Suez Canal authorities do not say what the beam limitation will be if the canal will be dug deeper in the future. But if a loaded VLCC of conventional design shall be able to pass through the limitation can be no less than 60 meters, as can be seen in Figure 9.

2.3 HULL RESISTANCE

The aim of the resistance calculations is to predict the annual fuel consumption. This is an important part of the operational costs in the cost-benefit analysis that will determine the profitability of the Equilibrium design concept.

To be able to compare Equilibrium to the conventional tanker design, the dimensions of a thought comparison ship is extracted from trend lines with data from Lloyds register (Lloyds Register Fairplay). Since tankers are very similar in design, the trend lines give a good indication of how a conventional 208 000 DWT tanker would have been designed, if such a tanker was to exist.

Resistance calculations are done on Equilibrium and the trend line comparison ship using the same method, both for loaded and unloaded condition. This will give an indication of how much fuel can be saved with the Equilibrium concept compared to today's oil tankers.

2.3.1 METHOD

The resistance calculations are based on empirical formulas from (Steen, 2007, s. 3) and (Fuglerud, et al., 2003, s. 177), but some deviations from the standard method have been made to compromise Equilibrium's special hull form. Figure 12 shows the methodology behind the resistance calculations. Air resistance is neglected.

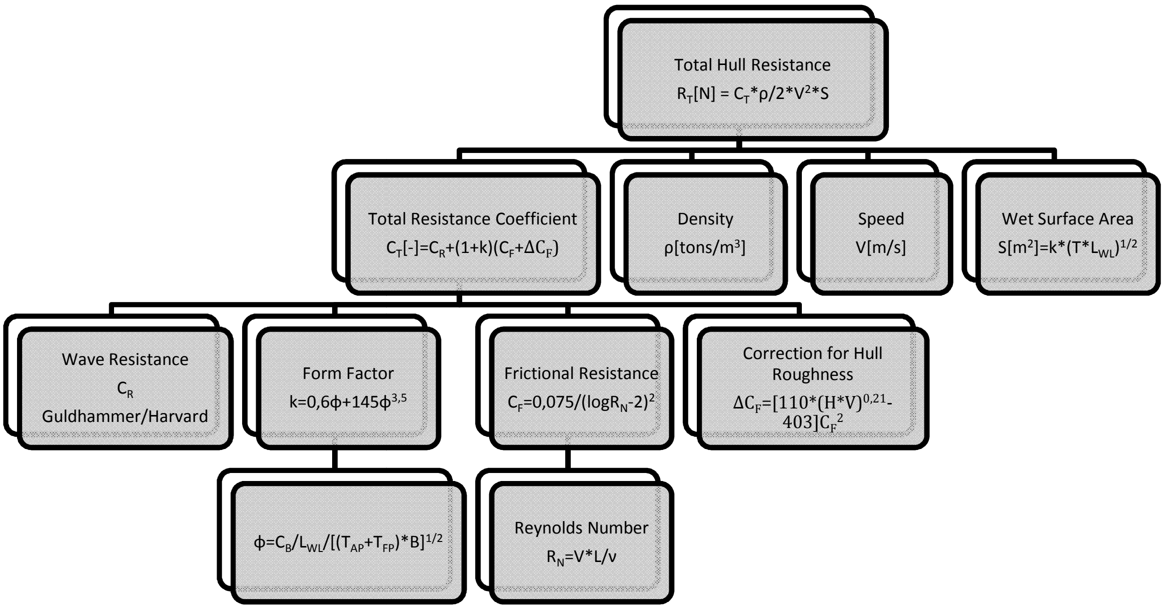


FIGURE 12: METHOD FOR CALCULATING HULL RESISTANCE

2.3.1.1 Total Hull Resistance

The resistance is calculated according to the formula $R_T = C_T * \frac{\rho}{2} * V^2 * S\ [N]$ where C_T is the total friction coefficient, ρ is the density of sea water, V is the ship speed and S is the ship's wet surface area. The effective power (EP) in watts [W] is calculated by $EP[W] = R_T[N] * V$.

2.3.1.2 Wetted Surface Area

The wetted surface area, S, is estimated from the formula $S = k * \sqrt{T * L_{WL}}$, with k as a constant that is decided by the ships B/T-relation (beam/draught) and mid frame coefficient C_M (Fuglerud, et al., 2003, s. 194). T is the draught and L_{WL} is the length of the waterline.

Because of Equilibriums trapezoid hull form, the wetted surface area will be smaller than the empirical data suggests. This reduction of wetted surface area is estimated by geometrical differences between the hull of Equilibrium and a conventional tanker. See Appendix B for the calculation of wet surface area reduction.

2.3.1.3 Total Resistance Coefficient

The total resistance coefficient, C_T, is calculated by the formula $C_T = C_R + (1+k)(C_F + \Delta C_F)[-]$ where C_R is the wave resistance coefficient, k is the form factor, C_F is the frictional resistance coefficient and ΔC_F is the correction for hull roughness.

2.3.1.4 Wave Resistance

The wave resistance coefficient, C_R, is calculated using Guldhammer/Harvard's method. This method is not as accurate as methods such as Hollenbach's method, but it is widely used in marine systems design because it reflects the physics more than other methods (Steen, 2007, s. 21). Hollenbach's method requires parameters that are unknown at this early stage of the project.

Guldhammer/Harvard's method calculates an initial wave resistance coefficient from a slenderness coefficient diagram based on the slenderness coefficient $L/(\Delta/\rho)^{1/3}$, the prismatic coefficient and the Froude Number. Then it makes corrections for hull roughness, B/T-relation, V-shaped hull and bulb (Fuglerud, et al., 2003, s. 197).

Equilibrium has lower wave resistance than the comparison ship. The main factors that contribute to this are its length and low B/T (in loaded condition). The correction for V-shaped hull is in this case also used as a correction for Equilibrium's trapezoid shape hull, giving it a penalty on wave resistance.

The calculations do not take trim into consideration. This can be neglected since both the conventional comparison ship and Equilibrium is expected to trim in both conditions and the penalty would therefore be the same. The difference in trim between the two ships is assumed to be small. See chapter 5.4 for a test of Guldhammer/Harvard's method, as programmed in this master's thesis, up against Hollenbach's method that takes trim into account.

The full wave resistance calculations can be found in Appendix D.

2.3.1.5 Form Factor

The form factor accounts for the increase in frictional resistance as the water flow increases in speed under and along the side of the hull (Steen, 2007). It is commonly used when estimating hull resistance by towing tests. In this thesis, the form factor is used to give Equilibrium a resistance penalty for its unconventional hull shape, which has been decided in dialog with (Endal, 2010).

The form factor, k, is calculated from the Marintek formula $k = 0{,}6\varphi + 145\varphi^{3{,}5}$ where $\varphi = {C_B}\Big/{L_{WL} * \sqrt{(T_{AP} + T_{FP}) * B}}$. C_B is the block coefficient, L_{WL} is the length of the water line, T_{AP} and T_{FP} are the draughts at the aft and front perpendiculars respectively and B is the beam.

In these calculations it is assumed that $L_{WL}=L_{PP}*1{,}02$ and $T_{AP}=T_{FP}$ for both load conditions. Because of the trim, T_{AP} is realistically bigger than T_{FP} in ballast condition for the comparison ship, maybe also for Equilibrium. But it is assumed that the increase in T_{AP} is equal to the decrease in T_{FP}, so that the sum of $T_{AP} + T_{FP}$ is constant.

2.3.1.6 Frictional Resistance Coefficient

The frictional resistance coefficient, C_F, is calculated from the formula $C_F = \frac{0{,}075}{(\log(R_N) - 2)^2}$ where R_N is the Reynolds Number $R_N = \frac{V*L}{v}$ and v is kinematic viscosity assumed to be the same for both ships and load conditions. The comparison ship gets a higher frictional resistance coefficient than Equilibrium due to its shorter length.

2.3.1.7 Correction for Hull Roughness

The correction for hull roughness is calculated from the formula

$\Delta C_F = [110 * (H * V)^{0{,}21} - 403]{C_F}^2$. H is the roughness of the hull and is assumed to be the same for both ships. V is the speed and C_F is the frictional resistance coefficient.

2.3.2 RESULTS FROM RESISTANCE CALCULATIONS

Table 6 shows a summary of the resistance calculations, while the calculations can be found in Appendix C.

TABLE 6: SUMMARY OF RESISTANCE CALCULATIONS, CONCEPTUAL DESIGN

Resistance and Engine Power		Equilibrium		Conventional Tanker		
		Loaded	Unloaded	Loaded	Ballast	
Total Resistance	R_T	1,44	0,57	1,55	1,13	MN
Effective Power	EP	11,1	4,4	11,9	8,7	MW
Estimated Propulsion efficiency	η	0,6				-
Main Engine Power	P	18,6	7,4	19,9	14,5	MW
Installed Main Engine Power		23,3		24,9		MW

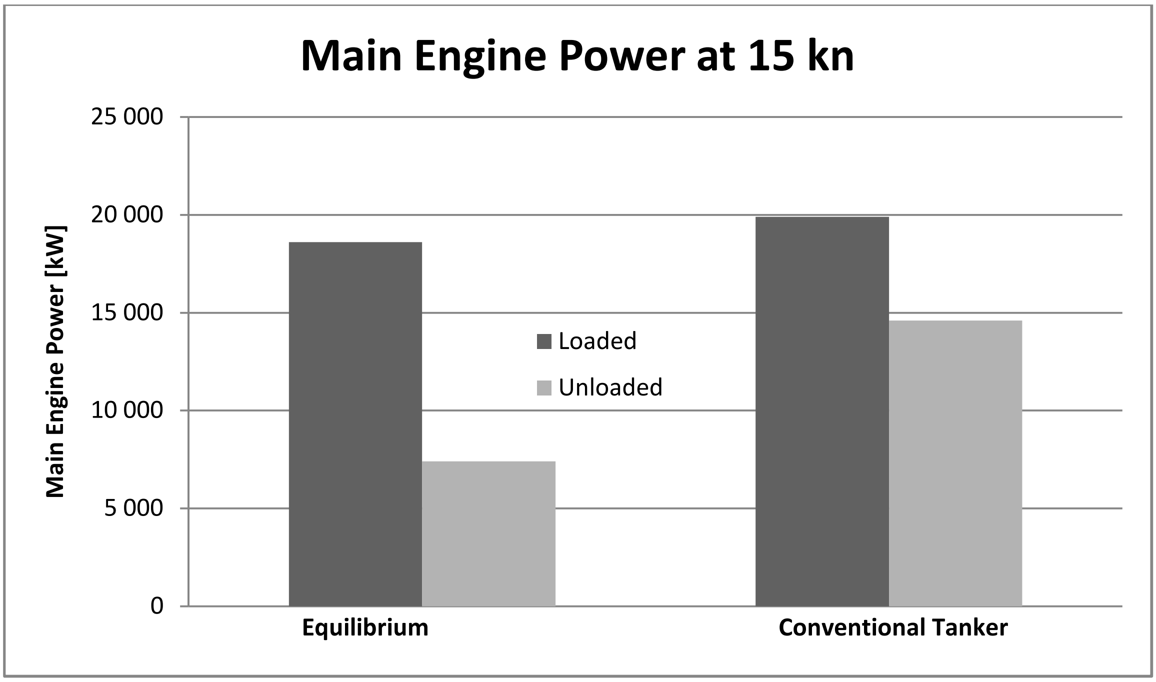


FIGURE 13: ENGINE POWER ON EQUILIBRIUM AND CONVENTIONAL TANKER WITH SAME DEADWEIGHT

2.3.2.1 Resistance in Unloaded Condition

The main fuel savings are in unloaded condition. This is mainly because of the lower displacement leading to decreased wet surface area. The comparison ship is estimated to need as much as 75 000 tons of ballast water to operate in unloaded condition. As a reference, an average Suezmax tanker needs about 60 000 tons of ballast and a VLCC about 100 000 tons (Lalic, 2010). Equilibrium also has a benefit of its long and slender hull shape, giving a lower wave resistance than the comparison ship.

2.3.2.2 Resistance in Loaded Condition

Equilibrium also gets a lower hull resistance than the comparison ship also in loaded condition, despite a bigger wetted surface area and the penalties for trapezoid hull shape. The advantage is its long and slim hull shape.

The form factor gives Equilibrium a penalty of 100 kN on the hull resistance. The effect of the trapezoid hull form is however hard to estimate, and should be studied by towing tests to get an accurate value.

2.3.3 INSTALLED MAIN ENGINE POWER

A total power efficiency factor, η, of 0,6 (Endal, 2010) is used for both Equilibrium and the trend line comparison ship. This is a high efficiency factor, and it is therefore assuming an efficient propeller and an engine with a direct connection to the propeller shaft. The most important is that the same assumption is done on both Equilibrium and the comparison ship.

It is assumed that the ships operate at 80% MCR at service speed in loaded condition. The installed engine power for both Equilibrium and the comparison ship is compared to existing tankers registered in Lloyds Register (Lloyds Register Fairplay) in Figure 14.

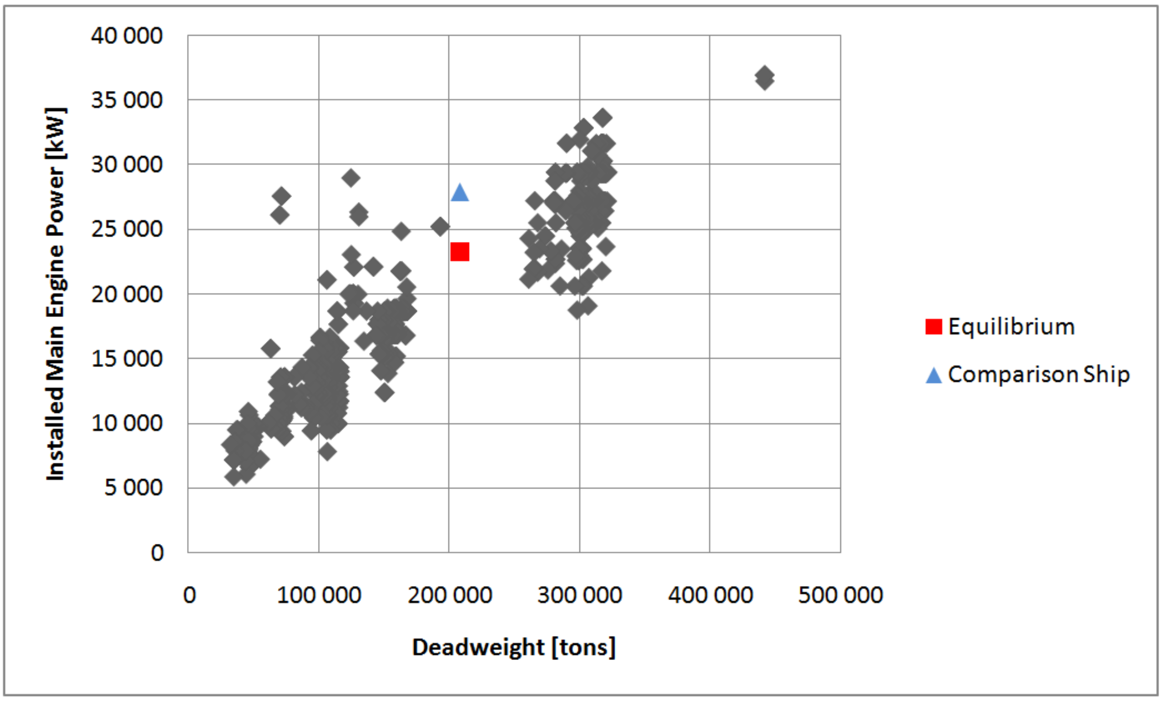


FIGURE 14: INSTALLED ENGINE POWER ON CRUDE OIL TANKERS

The comparison suggests that the resistance calculations are conservative. However, the most important result is the difference in resistance between Equilibrium and the trend line comparison ship which is necessary to determine the profitability of the concept.

2.4 COST-BENEFIT ANALYSIS

The cost-benefit analysis is done as a comparison between Equilibrium and the same comparison ship. The difference between the two life cycle costs will serve as an indication on Equilibriums profitability.

2.4.1 CAPEX COMPARISON

The capital expenditure (CAPEX) is based on the ships' lightship weight, using a parameter of US$ per kg. As discussed in chapter 2.2.3, the first estimated lightship weight for Equilibrium of 42 700 tons is most likely too high. Using this number would therefore make an unfair comparison in disfavour of Equilibrium. Therefore, the Equilibrium building cost is first calculated for a conventional tanker before extra costs are added according to Equilibrium's special design features.

Design features that will affect Equilibrium's building cost compared to the average comparison tanker are:

- Additional longitudinal bulkheads
- Steel weight reduction due to trapezoid shaped hull
- Additional steel due to slender hull form
- Twin screw propulsion configuration instead of the commonly used single-screw system. The draught of 5,7 meters in unloaded condition strongly limits the propeller diameter and it is assumed that two propellers will be needed to gain sufficient propulsion power.
- No installed ballast pumps or ballast pipe system
- No installed ballast treatment system which will likely soon be compulsory on tankers with ballast systems

2.4.1.1 Building Cost

The building cost for an average tanker, which is the basis for the Equilibrium building cost calculation, can be found by US$ per kilogram lightship, as in Figure 15.

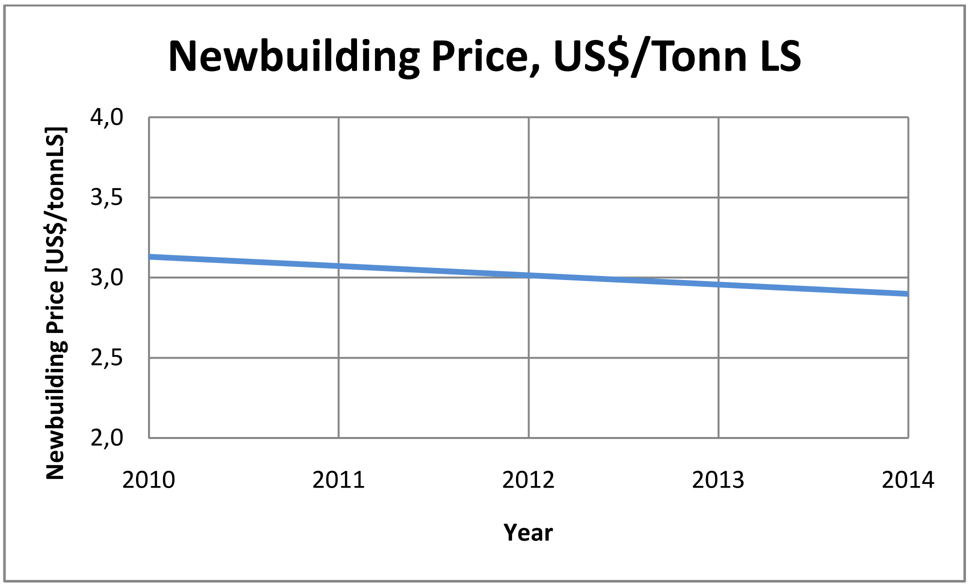


FIGURE 15: NEW BUILDING PRICES IN US$ PER KG LIGHTSHIP

The figure shows average new building prices for crude oil carriers on order for delivery between 2010 and 2014. The data is extracted from (Lloyds Register Fairplay) and only Suezmax tankers and VLCCs are used in the comparison.

TABLE 7: BUILDING COSTS, BEFORE ADJUSTMENTS

Building Costs	Equilibrium	Conventional Tanker	
Lightship Weight		29 500	tons
Building Cost	3,1	3,0	US$/kg
Building Cost, Before Adjustments for Design Features	91 450 000	88 500 000	US$

For the comparison ship the building cost is set to 3 US$ per kg lightship. Equilibrium is given a penalty of 0,1 US$ per kg lightship for being a one-of-a-kind ship that requires more design work and a building process that is off the ordinary oil tanker production conveyor belt. The penalty is assumed based on a building cost distribution for a general cargo vessel in (Levander, 2006, s. 75). This penalty will most likely be removed if Equilibrium is to be mass produced. Equilibrium has a simple hull shape dominated by developable surfaces and shouldn't be much more expensive to mass produce than a conventional tanker.

2.4.1.2 Equilibrium Hull Design Features

The steel weight contributions from the design features that are expected to add to Equilibrium's cost are calculated in the lightship weight consideration in chapter 2.2.3.

The cost of the additional steel is assumed to be 2,8 US$ per kilogram lightship. This estimate is based on the building cost distribution for a general cargo ship in (Levander, 2006, s. 75). Extra steel will affect the material and labour costs, but will not affect costs such as broker fees, ship loan payment, design and building time financing as much.

TABLE 8: COST OF SPECIAL HULL DESIGN FEATURES

Adjustments to Building Cost	Equilibrium	Conventional Tanker	
Price of Additional Steel	2,4	0	US$/kg
Longitudinal Bulkheads	6 440 000	0	US$
Trapezoid Hull Shape	-3 360 000	0	US$
Slender Hull Shape	10 640 000	0	US$

2.4.1.3 Machinery

For a twin screw propulsion system, the cheapest option is assumed to be a configuration of two slow speed engines directly connected to individual propeller shafts. Data for calculating the extra costs of a twin screw propulsion system is given by (Levander, 2010). The cost difference lies in the man-hours needed for installation.

TABLE 9: EXTRA COSTS FOR TWIN SCREW PROPULSION SYSTEM

Additional Cost for Twin Screw Prop.		
Machinery System (main+aux)	500	€/kW
Installation Costs (1 engine)	1	man-hour/kW
Installation Costs (2 engines)	2	man-hours/kW
Labour Cost, Asia	25	€/man hour
Installed Main Engine Power	23 300	kW
Single Engine Configuration	16 550 000	US$
Twin Screw Engine Configuration	17 340 000	US$
Extra Cost for Twin Screw Propulsion	790 000	US$

2.4.1.4 Ballast Systems

Unlike a conventional tanker, Equilibrium will not need ballast pumps, which again leads to reduced CAPEX. Equilibrium will still need a pumping system in case of leakage to the double hull void spaces, but this system is assumed to be of much smaller dimensions than the ballast systems used in conventional tankers.

The cost of ballast pumps is estimated by (Borgen, 2010), assuming two ballast pumps each with a capacity of 3000 m^3/h. The cost of ballast pipes is estimated by (Brodahl, 2010) to be 1500 NOK/meter and the total length of all ballast pipes are assumed to be 2,5 times the length of the ship (Vedeler, 2010). Equilibrium still must have some piping with smaller dimensions. The cost of these pipes is assumed to be half the price of the ballast pipes in a conventional tanker.

In the future all new conventional oil tankers will likely be built with ballast treatment systems to satisfy IMO regulations. This cost is assumed not included in the building cost of 3 US$ per kg lightship and therefore has to be added to the CAPEX of the comparison ship. There exist different systems for ballast treatment. The chosen system for this comparison is designed by Ocean Saver and is already being installed on two VLCCs built in South Korea, with an installation cost of approximately 2 000 000 €, or 2 700 000 US$ per ship (Caspersen, 2010).

TABLE 10: CAPEX OF BALLAST SYSTEMS

CAPEX of Ballast Syst.	Equilibrium	Conventional Tanker	
Ballast Pumps	-1 000 000		US$
Ballast Pipes	-660 000		US$
Ballast Treatment System		2 700 000	US$

2.4.1.5 Total CAPEX

TABLE 11: TOTAL CAPEX COMPARISON

CAPEX Comparison	Equilibrium	Conventional Tanker	
Lightship Weight		29 500	tons
Building Cost	3,1	3,0	US$/kg
Initial Building Cost	91 450 000	88 500 000	US$
Cost of Additional Steel	2,8		US$/kg
Longitudinal Bulkheads	6 440 000		US$
Trapezoid Hull Shape	-3 360 000		US$
Slender Hull Shape	10 640 000		US$
Twin Screw Propulsion	790 000		US$
Ballast Pumps	-1 000 000		US$
Ballast Pipes	-660 000		US$
Ballast Treatment System		2 700 000	US$
Total CAPEX	104 300 000	91 200 000	US$

Equilibrium has higher capital expenses than a conventional tanker with the same cargo capacity. This is mainly because of the steel costs from the extra longitudinal bulkheads and the slender hull shape.

2.4.2 OPEX COMPARISON

The comparison of operational expenses (OPEX) focuses only on the costs that are expected to differ significantly on Equilibrium and a conventional tanker, and those are:

- fuel costs
- ballast handling and treatment

Expenses such as port fees, wages and maintenance are left out since they are expected to be the same on Equilibrium as on other tankers, and will therefore not be important in concluding on the profitability of the ship design.

2.4.2.1 Fuel Costs

The fuel cost calculations are based on operational profiles for Frontline VLCCs operating on the spot market (Lalic, 2005), with 140 days per year in loaded transit condition, 102 days per year in unloaded transit condition and the rest either loading, discharging, waiting, manoeuvring or miscellaneous (non-transit conditions).

2.4.2.1.1 Fuel Consumption in Non-Transit Conditions

The fuel consumption in non-transit condition is assumed the same for Equilibrium as for the conventional tanker. Data for annual fuel consumption in non-transit conditions for VLCCs and Suezmax carriers are reported in (Lalic, 2005).

Since Equilibrium is bigger than Suezmax dimensions it will operate on the same routes as the VLCCs, therefore the fuel consumption while waiting at sea, waiting in port and manoeuvring is set the same as a VLCC. Fuel consumption while loading and discharging is decided mainly by the cargo capacity. Since the cargo capacity of Equilibrium is about half way between that of a Suezmax and a VLCC, so is the fuel needed for loading and discharging.

TABLE 12: FUEL CONSUMPTION IN NON-TRANSIT CONDITIONS

Fuel Consumption, Non-Transit	Suezmax	VLCC	Equilibrium	
Waiting at Sea	85	33	33	tons/year
Waiting in Port	272	339	339	tons/year
Manoeuvring	845	666	666	tons/year
Loading	128	225	177	tons/year
Discharging	995	1 629	1 312	tons/year
Miscellaneous	38	38	38	tons/year
Fuel Consumption, Non-Transit	2 363	2 930	2 564	tons/year

2.4.2.1.2 Fuel Consumption in Transit Conditions

The calculation of annual fuel consumption in transit conditions is based on the resistance and required engine power estimated in chapter 2.3. It is assumed that the two ships in the comparison have a specific fuel consumption (SFC) of 170 g/KWh. Since it is not yet decided what type of propulsion system will be installed on Equilibrium, it is neglected that SFC might differ in transit- and unloaded condition. It is also neglected that the fuel consumption is higher when operating in bad weather. Most importantly, the same assumptions are done for both Equilibrium and the comparison conventional tanker. The fuel price is from the port of Singapore in February 2010 (Bunkerworld, 2010).

TABLE 13: ANNUAL FUEL CONSUMPTION

Total Fuel Costs	Equilibrium	Conventional Tanker	
Main Engine Power:			
Transit, Loaded	18,6	19,9	MW
Transit, Unloaded	7,4	14,6	MW
Fuel Consumption:			
Transit, Loaded	10 639	11 383	tons/year
Transit, Unloaded	3 086	6 088	tons/year
Other Conditions	2 564	2 564	tons/year
Annual Fuel Consumption	16 289	20 035	tons/year
Fuel Price	480		US$/ton
Annual Fuel Cost	7 819 000	9 617 000	US$/year

The annual fuel consumption and cost is 19 % lower on Equilibrium than the conventional comparison tanker.

2.4.2.2 Ballast Handling and Treatment

Equilibrium is assumed be spared from the operational costs from the ballast systems. These costs include ballast treatment according to predicted IMO regulations and the cost of pumping the ballast water used during loading, discharging and transit in unloaded condition.

The operational expenses of ballast treatment are calculated based on estimations on number of operations per year, ballast treatment capacity, maintenance cost and power output by (Caspersen, 2010) from Ocean Saver. Specific fuel consumption and ballast tank capacity are the same values as used when calculating resistance and fuel consumption in earlier chapters.

TABLE 14: OPERATIONAL COSTS OF BALLAST TREATMENT

Cost of Ballast Treatment		
Operations per year	10	-
Ballast Treatment Pump Capacity	3 000	m^3/h
Number of Pumps	2	-
Total Pump Capacity	6 000	m^3/h
Power Output	1300	kW
Specific Fuel Consumption	170	g/kWh
Ballast Tank Capacity	75 000	tons
Treatment Time	12,5	h
Fuel Consumption	27,6	tons/year
Fuel Price	480	US$/ton
Fuel Costs	13 260	US$/year
Maintenance Costs (given 10 op/year)	3 500	€/year
	4 740	US$/year
Total Operational Costs	18 000	US$/year

The cost of pumping ballast water is calculated according to the power output of the ballast pumps and the number of operations each year. The ballast treatment system only has to operate when in transit, the actual ballast system is also operating during loading and discharging, so the number of operations is higher.

The power output is calculated using the pressure at the outlet of the system and the systems efficiency. These factors are assumed by (White, 2010). Maintenance cost on the ballast pumps have been left out of the cost comparison due to lack of data.

TABLE 15: COST OF BALLASTING

Cost of Ballast Pumping		
Operations per Year	30	-
Ballast Pump Capacity	6000	m^3/h
Ballast Tank Capacity	75 000	tons
Pressure	7	bar
Efficiency	0,7	-
Power Output	1700	kW
Pumping Time	12,5	h
Specific Fuel Consumption	170	g/kWh
Fuel Consumption	108	tons/year
Fuel Price	480	US$/ton
Total Operational Costs	52 000	US$/year

The data for fuel consumption in non-transit conditions in chapter 2.4.2.1.1 includes the fuel consumption used on the ballast operation. In the cost comparison Equilibrium will get a cost reduction not needing normal ballast operation, while the conventional comparison ship will get a cost penalty for the cost of ballast management.

See Appendix F for detailed calculations.

2.4.2.3 Total OPEX

The total yearly expenses are expressed in present value for a 10 year period which is a common time frame to evaluate a ship's profitability in the tanker industry (Vedeler, 2010). The discount rate is assumed to be 6 %. See Appendix G for detailed calculations.

TABLE 16: OPEX COMPARISON

OPEX Comparison	Equilibrium	Conventional Tanker	
Lifetime	10		years
Discount rate	6		%
Fuel Price	480		US$/ton
Fuel	7 819 000	9 617 000	US$/year
Ballast Pumping and Treatment	-52 000	18 000	US$/year
Total OPEX	7 767 000	9 635 000	US$/year
Present Value OPEX	57 170 000	70 910 000	US$

2.4.3 MAIN FINDINGS IN COST-BENEFIT COMPARISON

TABLE 17: SUMMARY OF COST COMPARISON

LCC	Equilibrium	Conventional Tanker	
CAPEX	104 300 000	91 200 000	US$
OPEX (10 years)	57 170 000	76 940 000	US$
2nd Hand Value (10 years)	38 827 000	33 950 000	US$
Life Cycle Costs (10 years)	122 640 000	128 159 000	US$

The second hand value after 10 years is for all the ships in the comparison assumed to be two thirds of the new building costs and calculated to present value. The cost comparison shows that Equilibrium has higher capital expenses. This is because of the increased steel weight from the special design features. The main benefit of Equilibrium is the low resistance in unloaded condition leading to lower fuel costs. The fuel costs outweigh the extra building costs in the cost-analysis over a 10 year period, indicating that Equilibrium is a profitable design.

However, the cost comparison only concludes on the profitability against a conventional design with the same cargo capacity. In competition with a VLCC, Equilibrium has the disadvantage of a lower cargo capacity. To compare the profitability a VLCC and Equilibrium, the following efficiency parameter is used:

$$i = \frac{Life\ Cycle\ Costs_{Present\ Value}\ [US\$]}{Total\ Freighted\ Cargo[tons]}$$

$$= \frac{OPEX_{Present\ Value} + CAPEX - Second\ Hand\ Value_{Present\ Value}[US\$]}{DWT[tons] * 8\ deliveries * 10\ years}$$

It has to be remembered that several operational expenses are not included in the life cycle cost. The index serves as a comparison on the selected ship types, not as a required freight rate. It is estimated an average of 8 deliveries per year, which is calculated based on the distance between the Persian Gulf and Japan, a service speed of 15 knots and the operational profile from chapter 2.4.2.1. The cargo capacity is set to be the same as the deadweight. The life cycle cost of a VLCC is calculated later in chapter 5.5.

TABLE 18: COST-EFFICIENCY COMPARISON, VLCC AND CONCEPTUAL DESIGN

Cost Efficiency, *i*	[US$/DWT]
Equilibrium, Conceptual Design	7,4
Conventional tanker, DW=DW(Equil.)	7,7
Conventional VLCC	7,1

Table 18 indicates that Equilibrium with its initial design parameters will have a hard time competing against VLCCs because of their larger cargo capacity.

2.5 RECOMMENDATIONS FOR FURTHER ITERATION

For the following steps in the design process, focus should be on the following areas:

- Increase the cargo capacity to compete against VLCCs on cost per transported ton cargo
- Decrease the lightship/deadweight-ratio that on the conceptual design is higher than on a conventional tanker. This will reduce the building cost and increase the ships cost efficiency.
- Low resistance in unloaded condition. This is Equilibrium's main advantage over a conventional design

By studying the main dimensions on the conceptual design, some concrete recommendations are as follows:

- Increase the beam and draught to increase the cargo capacity. These are the cheapest dimensions to increase in regards of required extra steel, so such expansions will most likely also reduce Equilibrium's lightship/deadweight-ratio.
- Evaluate a hull shape that satisfies IMO regulations draught regulations in lightship condition.
- Length should preferably not be increased. If the ship turns out be less cost-efficient than a VLCC, the length can possibly be reduced to decrease the ships lightship/deadweight-ratio.

3 SOLUTION FOR CARGO HANDLING

An important criterion for Equilibrium is that the cargo handling process is done according to existing infrastructure and regulations. A cargo handling solution that requires change of port infrastructure or international regulations would be a major set-back for the designs feasibility.

3.1 DEMANDS FOR CARGO HANDLING SYSTEM

The following demands are deemed the most important to consider when evaluating the Equilibrium concept:

- Flexibility of the loading arms
- Number of oil segregations
- Stability
- Maximum cargo outflow
- Pressure at the manifold

3.1.1 FLEXIBILITY OF LOADING ARMS

The loading arms at the quay have to be flexible enough to follow the height difference of the manifold from unloaded condition with a draught of 5,7 to loaded condition with a draught of 20 meters. A conventional tanker will by using ballast water to compensate for longitudinal bending moments also compensate for the huge draught difference. However, an interview with the port captains on duty at the two oil refineries Mongstad and Slagentangen insures that standard loading arms are designed with such flexibility.

3.1.2 NUMBER OF OIL SEGREGATIONS

The ship should be able to hold three different types of oil. The percentage of one oil segregation should be no less than 20 % of the total cargo (Vedeler, 2010). Preferably, the ship should be able to vary the share of each segregation according to the job demand.

The ship should be able to fully load or discharge one segregation before starting on the next, meaning that some tanks will be full while others will be empty at the same time. This will inflict both longitudinal and transverse bending moments in the hull. The longitudinal bending moments, which on conventional tankers are compensated by using ballast, will be avoided on Equilibrium as the tanks are divided lengthwise. This way the cargo is evenly distributed while loading and discharging.

The layout of the longitudinal cargo holds will give transverse bending moments during loading and discharging. Transverse bending moments is a dimensioning factor also on conventional tankers. The moments arise in ballast condition when the centre cargo tanks are empty and the wing ballast tanks are full. This deformation is known as racking (Larsen, Syvertsen, & Amdahl, 2006, s. 3.6). Knowing that existing tankers are dimensioned for such moments, it is assumed that this will not be a problem for Equilibrium.

3.1.3 STABILITY

The ship has to be stabile at all times, including during loading and discharging. Attention has to be paid to free surface effects from partly filled tanks, especially in the longitudinal direction.

The longitudinal division of tanks also demands a strict filling sequence to avoid a big heeling angle or even capsizing. This could possibility happen if for instance a wing tank is filled without a counterweight on the other side.

3.1.4 MAXIMUM CARGO OUTFLOW

IMO has rules on maximum cargo outflow in case of an accident. This limits the length of each cargo tank to 0,2*Length of ship. The length of each cargo tank is also limited by forces caused by longitudinal free surface effects and sloshing.

3.1.5 PRESSURE AT THE MANIFOLD

It is a common demand among ship owners that the ship can discharge with a pressure of 100 psi at the manifold. This means that the cargo pump system should have the same capacity as on a conventional tanker.

3.2 TANK CONFIGURATION

A basic model of the cargo block has been made in the program DelftShip to investigate tank configurations. DelftShip has been used to test different filling sequences for trim and healing angles. To meet the demands presented in chapter 3.1, the following tank configuration is suggested:

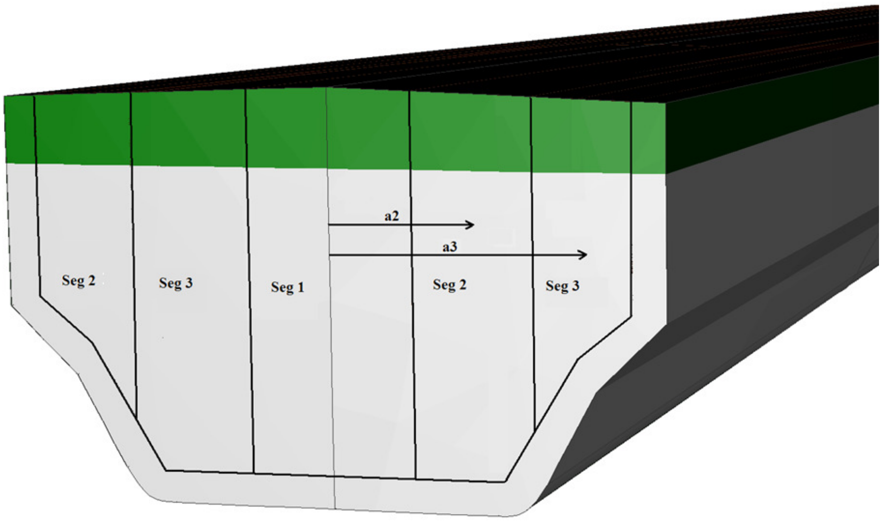


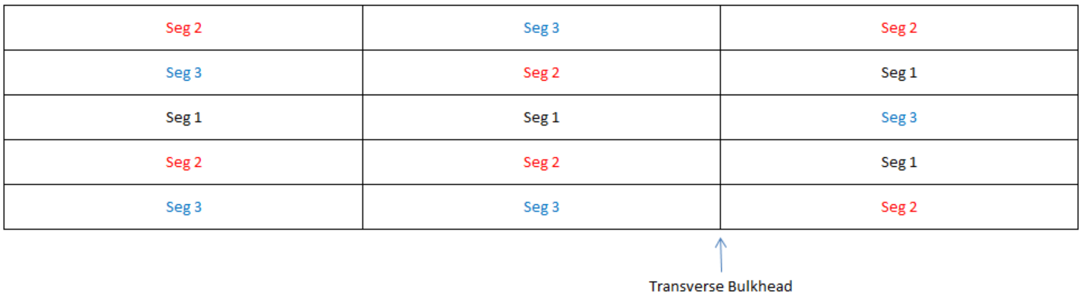
FIGURE 16: SUGGESTED TANK CONFIGURATION

The cargo section has five different tanks separated by four longitudinal bulkheads. The main idea is to gain flexibility on how much the ship can carry of each oil segregation. The ship can only load one segregation at the time and should finish loading one segregation before starting the next. So to avoid longitudinal bending moments, the ship has to be loaded with all three segregation along the entire length of the cargo block.

To maximize the flexibility of oil segregation shares, the tanks are shaped to give moment equilibrium around the longitudinal centre line for alternative load sequences. Moment equilibrium does not only occur when wing tanks on both sides are filled with the same segregation, it is also occurs when a wing tank on one side is filled simultaneously as a mid/side tank is filled on the other. With reference to Figure 16,

$$Seg3_{Port}[tons] * a3_{Port}[m] = Seg3_{Starboard} * a3_{Starboard} = Seg2_{Port} * a2_{Port}$$

This gives a great flexibility in transport of different oil segregation, as exemplified in Figure 17:



Seg 2	Seg 3	Seg 2
Seg 3	Seg 2	Seg 1
Seg 1	Seg 1	Seg 3
Seg 2	Seg 2	Seg 1
Seg 3	Seg 3	Seg 2

FIGURE 17: FLEXIBILITY OF OIL SEGREGATION SHARES

The ship has more tanks than a conventional tanker and therefore more pipes. One option is to partially fill one tank at the time until the segregation is completely loaded or discharged. Another option is to fill or empty several tanks simultaneously, if the ships pump and piping system allows for it.

If the ship is equipped with a more basic pump- and pipe system, the transverse bulkheads can have hatchways that open during loading and discharging, making cargo flow freely over the entire length of the cargo block. The bulkheads would still be there to prevent free surface effects. But such a solution would mean that the flexibility of oil segregation shares, as presented in Figure 17, would not be possible. Also, there might be scepticism among governing bodies for such hatchways between cargo tanks. If such a hatchway was not to shut properly during transit, the outflow of the tanker in case of an accident would increase. Also, the consistency of crude oil might present difficulties in opening and closing the hatches.

The ship has to have transverse bulkheads separated with a distance of 0,2*L according to IMO regulations. This will prevent free surface effects in the longitudinal direction and limit the maximum outflow in case of an accident. On Equilibrium this rule might not be rational. The transverse bulkheads are there to insure sufficient damage stability and to limit cargo outflow in case of an accident. The extra longitudinal bulkheads on Equilibrium also limit the outflow in case of an accident, so it could be argued that the IMO rule for minimum distance between transverse bulkheads should not apply for Equilibrium the same way as it does on conventional tankers, given that the damage stability is sufficient. However, this IMO rule is not a problem for Equilibrium, and arguing against safety regulations is probably not a wise step when introducing a new ship design, especially not in the oil tanker industry where safety against oil spills is a big issue.

4 FEASIBILITY OF BALLAST-FREE OPERATION

Several aspects have to be taken into consideration when considering the feasibility of ballast free operation for a crude oil carrier.

As discussed earlier, the ship needs a sufficient draught to avoid slamming and have the propeller fully submerged in unloaded condition. At the same time it has to have satisfying sea behaviour, especially in bad seas when a conventional tanker can ballast the ship down to obtain suitable stability.

If the ship is dependent on ballast in bad weather, it will also need a costly ballast treatment system to satisfy expected IMO regulations. The ship would still benefit from low resistance in normal transit conditions.

It is interesting that the cost of the two additional longitudinal bulkheads that are required to ensure ballast independency during loading and discharging, actually are more expensive than installing and operating the ballast machinery for 10 years, including ballast treatment.

TABLE 19: PROFITABILITY OF BALLAST OPERATION

Additional Longitudinal Bulkheads	6 440 000	US$
CAPEX, Ballast Machinery and Equipment	4 360 000	US$
OPEX, Ballast Operation (10 years)	520 000	US$

Even though ballast water possibly could be utilized during loading and discharging to reduce the overall costs, Equilibrium would still be capable of ballast-free operation in transit and benefit from low fuel consumption. But the cost difference in Table 19 is small considering the uncertainties in the calculations, so this will not be used as an argument to install a ballast system.

Investigation of an alternative membrane material for the additional longitudinal bulkheads is a part of the Equilibrium design process at DNV, but has not been considered in this thesis. The cost comparison suggests that these potential membranes should be cheaper than the steel bulkheads they replace for the ballast-free loading and discharging to be profitable.

Another good reason to install a ballast system is general scepticism against ballast-free operation in the shipping industry. Too quote a naval architect that was evaluating the Equilibrium concept: “It would be like teaching a 3 year-old kid how to ride a bike without support wheels”.

General scepticism will be ignored in this thesis. With the longitudinal cargo boundaries there is no need for ballast during loading and discharging. Equilibrium has good stability characteristics, so a sea keeping analysis is required to determine whether or not Equilibrium needs to ballast down in bad weather. Until then, the iteration process will continue while assuming Equilibrium can operate without a ballast system.

PART 2

The second part of the master's thesis consists of the following chapters:

5. New Equilibrium Hull

6. Results from the Iteration Process

7. Other Ideas

5 NEW EQUILIBRIUM HULL

Based on the analysis of DNV's concept, a new hull is designed for Equilibrium and presented in this chapter. This covers the three remaining tasks of the master's thesis:

- Outline hull lines
- Carry out a speed-power estimation
- Stability and strength to be confirmed by DNV technology consulting department

5.1 METHOD

Commonly, a ship design process will aim to develop a ship in order to satisfy a payload demand. In this case the situation is different. Chapter 2 indicates that Equilibrium, with its conceptual design parameters, will have a hard time competing with a conventional VLCC because of its lower cargo capacity. An important goal of the iteration process is therefore to maximize the cargo capacity of Equilibrium within the given hull shape constraints and iterate until Equilibrium is cost competitive against a VLCC.

This leads to the following method for iteration:

1. Develop hull lines (estimate main parameters for first iteration).
2. Calculate the weights and volumes and determine the cargo capacity.
3. Calculate the resistance on the following hulls:
    - Equilibrium
    - A thought conventional tanker with the same cargo capacity as Equilibrium
    - A VLCC that is expected to be Equilibrium's main competitor.
4. With the resistance and cargo capacity at hand, do a cost-benefit analysis and determine the profitability of Equilibrium compared to the two comparison ships.
5. Re-iterate.

This method keeps the focus on what Chapter 2 uncovered as the main focus areas for increasing Equilibrium's profitability:

- Maximize the cargo capacity by increasing the dimensions.
- Minimize the building costs by reducing the steel weight.
- Minimize the fuel costs by lowering the resistance, especially in unloaded condition where Equilibrium has its main advantage over a conventional design.

All these focus areas aim at increasing the efficiency by decreasing the total cost per transported ton cargo.

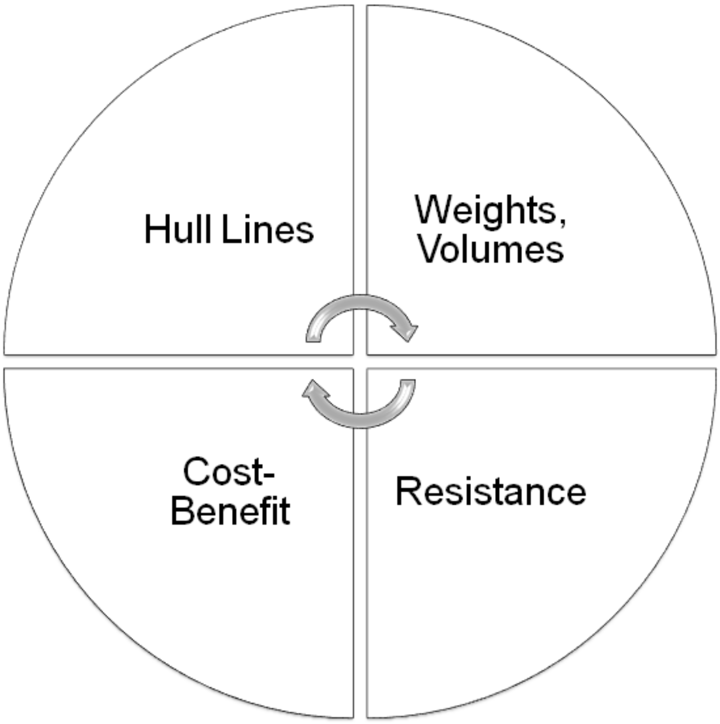


FIGURE 18: ITERATION METHOD FOR EQUILIBRIUM

5.2 HULL LINES

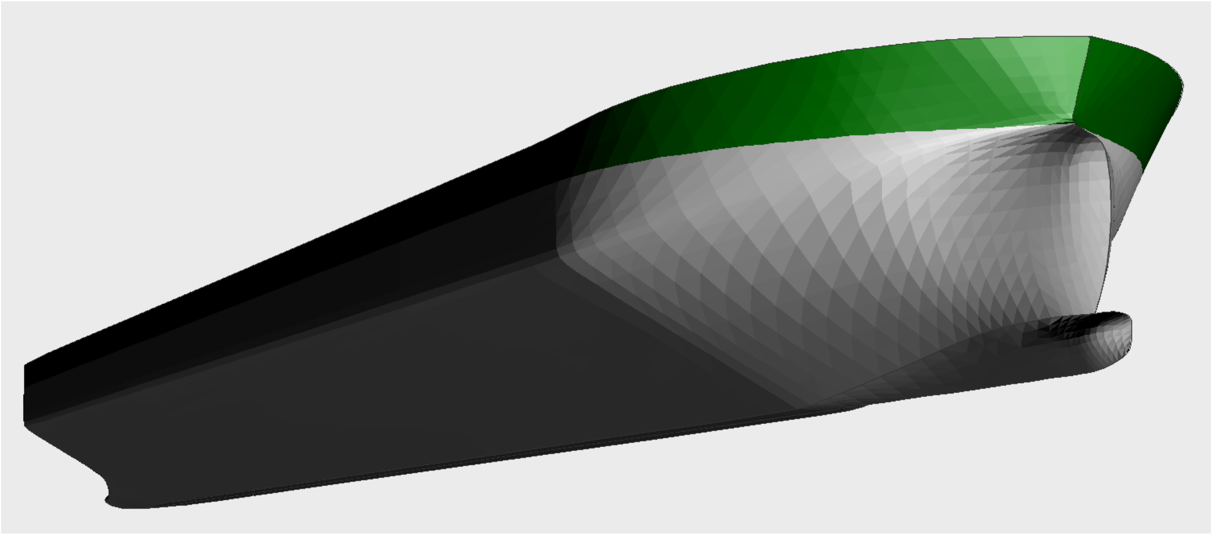


FIGURE 19: EQUILIBRIUM, FRONT PERSPECTIVE VIEW

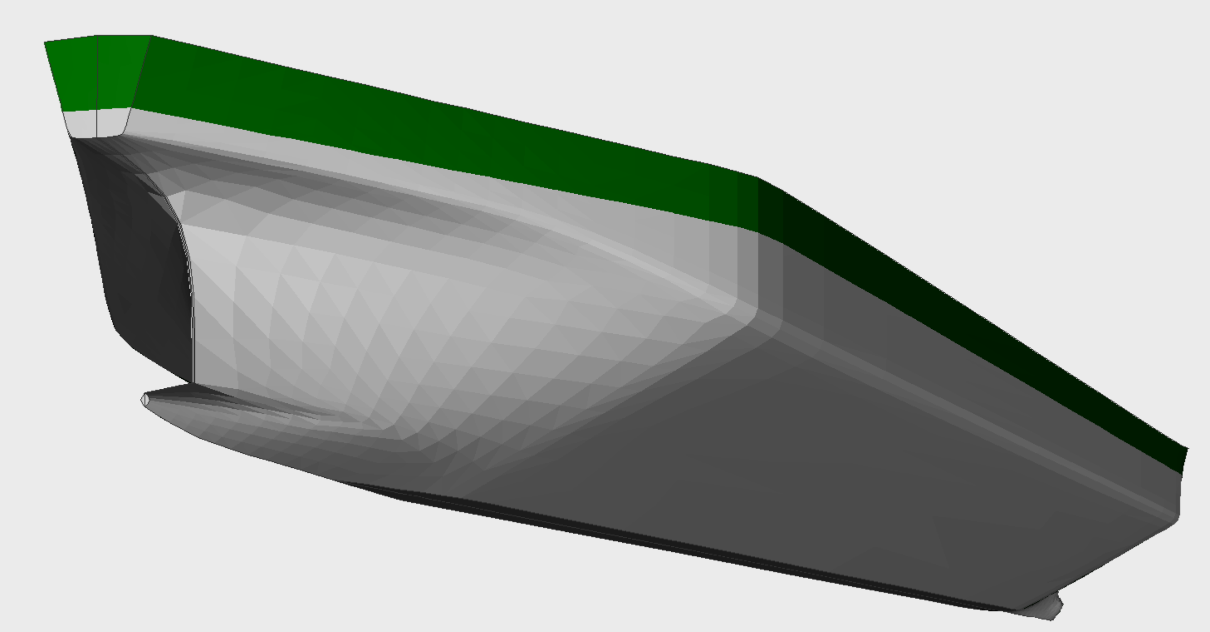


FIGURE 20: EQUILIBRIUM, AFT PERSPECTIVE VIEW

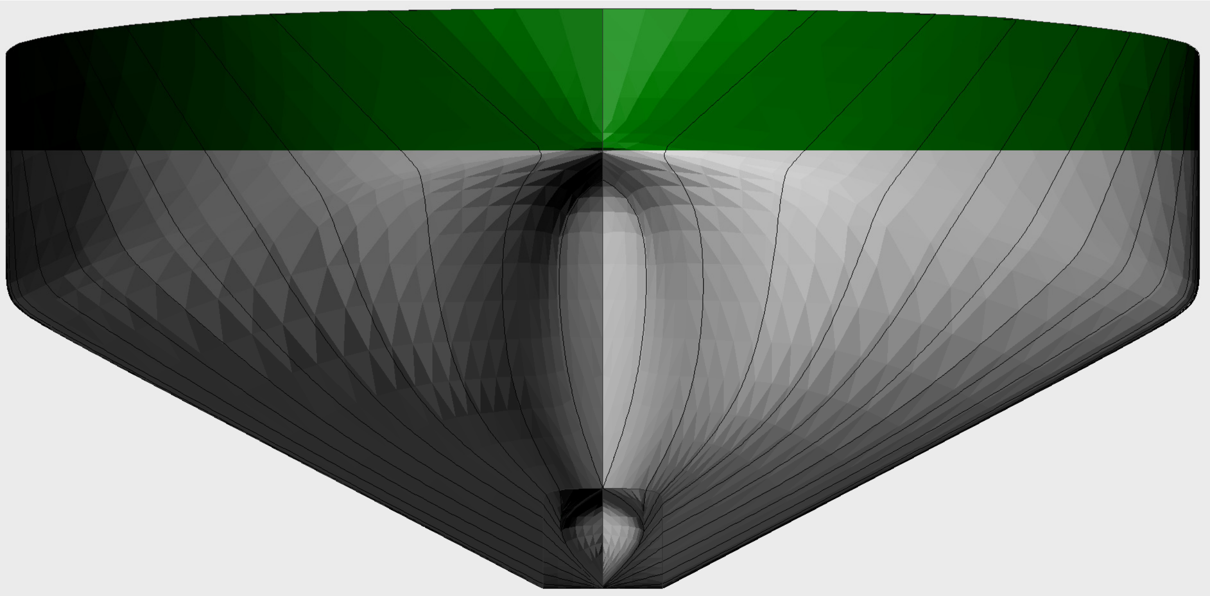


FIGURE 21: EQUILIBRIUM, BODY PLAN VIEW

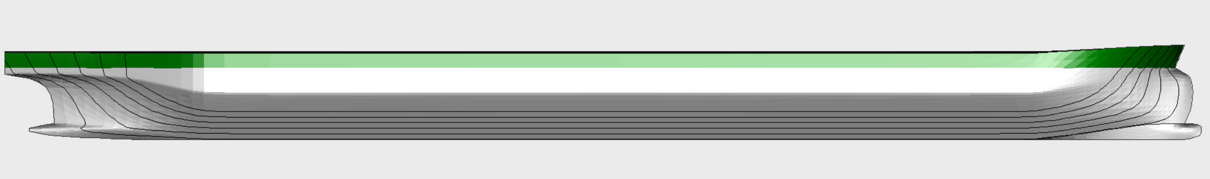


FIGURE 22: EQUILIBRIUM, PROFILE VIEW

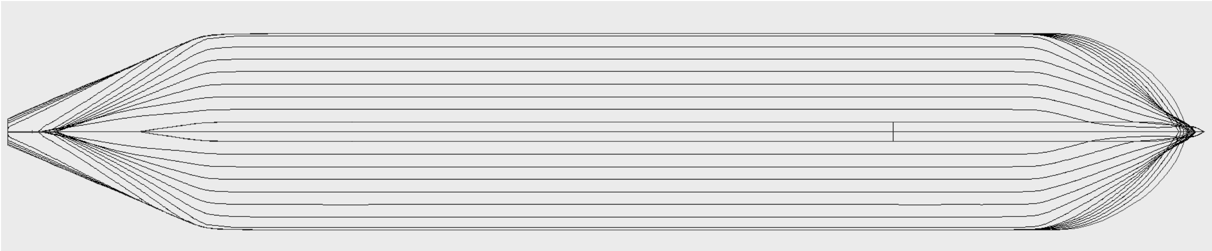


FIGURE 23: EQUILIBRIUM, PLAN VIEW

TABLE 20: EQUILIBRIUM MAIN PARAMETERS

Main Parameters		Loaded	Unloaded	
Draught, Mean	T	21,5	6,2	m
Trim	T_{FP}-T_{AP}	1,6	-2,2	m
Freeboard	F	5,0	20,3	m
Depth	D	26,5	26,5	m
Beam at Waterline	B	60	32,4	m
Beam Over All	Boa	60	60	m
Length Over All	Loa	365	365	m
Length Between Perp.	Lpp	357	360	m
Block Coefficient	C_B	0,59	0,46	-
Prismatic Coefficient	C_P	0,84	0,84	-
Displacement	Disp	285 300	39 600	tons
Lightship Weight	LW	33 600	33 600	tons
Deadweight	DW	251 700	6 000	tons
Intact Stability	GM	15,2	6,2	m
Gross Volume	GV	371 300		m^3
Service Speed	V	15	15	kn
Crew		20	20	-
Installed Main Engine Power	P	31 000		kW
Main Engine Power		24 800	10 100	kW
# Propellers		1		-

For the initial iteration round the lightship weight is calculated from empirical formulas and adjusted for Equilibrium design features, as described in chapter 2.2.3. The lightship weight is calculated more exact later in the iteration process.

DelftShip is the preferred software for developing hull lines. It is a basic program compared most other ship design programs, such as MaxSurf, NAPA, Nauticus and ShipX. But it is a very user friendly program that allows for a quick and efficient iteration process which is ideal in the early phases of the design process. Delftship gives satisfactory results on trim and intact stability in different load conditions, and the hull shape is easy to adjust.

5.2.1 SHIP SECTIONS

The hull is divided in three sections lengthwise with the following coordinates:

TABLE 21: SHIP SECTIONS

Ship Sections	Longitudinal Coordinates [m]		Length [m]
Aft Section	0	60	60
Cargo Section	60	315	255
Forward Section	315	365	50
			365

Only the cargo section is designed and adjusted in the beginning. It is by far the most dominant part of the vessel in terms of displacement and length. If this part is modelled according to all the most important criteria, such as stability, so will the whole ship most likely be when the fore- and aft ship is added on to the model. Important economical and operational criteria for the cargo section are that it is simple, easily built and has the possibility of fitting in available dry docks.

After the cargo block is designed with satisfactory results, the aft and for ship is added to the model. The cargo block is designed with zero trim in both loaded and lightship condition. Therefore it is important to design the end sections to give as little trim as possible in both main load conditions.

5.2.2 DRAUGHT

As recommended in chapter 2, the draught in loaded condition is increased to about the same as that of a conventional VLCC. This increases the ships deadweight/lightship, thereby increasing the cost efficiency.

In unloaded condition the mean draught is 6,2 meters which is 2 meters lower then IMO's minimum requirement of T_{min}=2+0,02L. The aim of the regulation is to avoid slamming damage in ballast condition. Because of the trapezoid-shaped hull, Equilibrium will have less occurrence of slamming, with reference to chapter 2.2.6. The IMO draught limitation is therefore neglected on this design.

The deadrise angle is set to 27 degrees. This is assumed to be sufficient to avoid slamming in heave and pitch, but an analysis should be performed to see if the angle is sufficient to avoid slamming during roll motions in side waves.

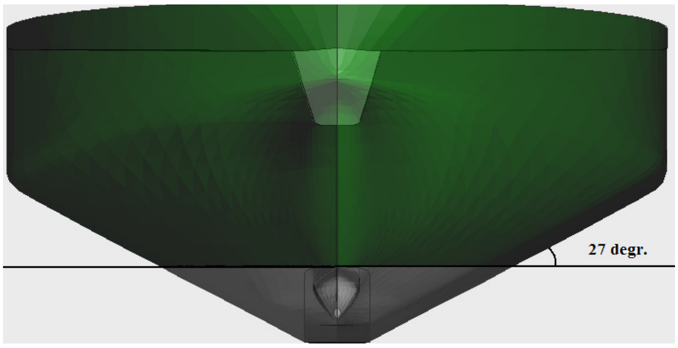


FIGURE 24: HULL SIDE ANGLE TO AVOID SLAMMING

5.2.3 TRIM

Equilibrium has a trim in both loaded and unloaded condition. The suggested hull shape trims 2,2 meters aft in unloaded condition and 1,6 meters by the bow in loaded condition. A forward trim in loaded condition is common also on conventional crude oil tankers(Michel & Osborne, 2003/2004).

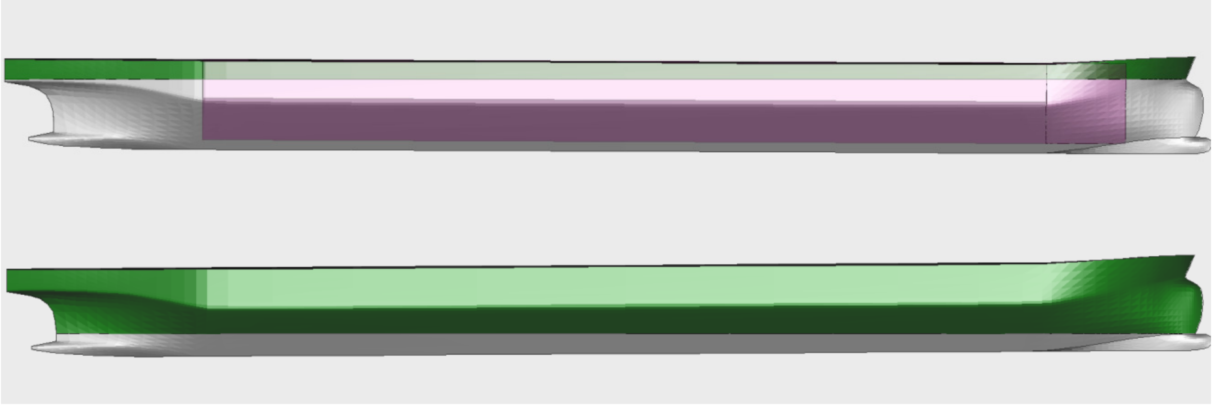


FIGURE 25: DRAUGHTS IN LOADED- AND UNLOADED CONDITION (CARGO IN SHADE)

Considering the length of the ship, trim values in both load conditions are small and acceptable in this early phase of the design process. The trim in both conditions should if possible be reduced in later iteration when the centre of gravity is calculated more exactly.

Likely it would be an advantage to have zero trim in loaded condition when the resistance is highest, even though this could give increased backward trim in unloaded condition. An analysis should be done to determine the trim angles that give the overall lowest fuel consumption.

The method to minimize the trim has been as follows:

1. Draw the lines of the lower part of the hull that is submerged in unloaded condition. Aim for a controlled aft trim in unloaded condition, to avoid a too high forward trim in loaded condition. The longitudinal gravity centre of cargo is in front of the flotation centre and adds a forward trim moment to the ship.
2. Shape the hull lines between the unloaded draught and the loaded draught to determine to trim in loaded condition. To counter the forward trim, the bow needs as much volume as possible and the aft-end as little as possible.

5.2.4 WATER FLOW

Shaping of the afterbody and bow requires a trade-off between minimizing the trim and minimizing the resistance. A spacious bow to lower forward trim in loaded condition might result in a too sharp entrance angle for the water flow. Similarly, a too sharp exit angle at the aft ship, also to avoid forward trim in loaded condition, might create low pressure and separation as the water flow leaves the hull. Both consequences will create increased resistance and fuel consumption.

This trade-off has on Equilibrium mainly gone in favour of optimizing the trim. This has resulted in a small transom area and abrupt changes in the aft waterlines. The service speed is rather low on tankers, making low pressure and separation a smaller problem than on for instance containerships. It has become clear from the iteration process and from the analysis in chapter 2 that the lightship has to be kept at a minimum to keep the building costs down. Decreasing the exit angles at the afterbody would mean a longer stern section and therefore either more steel or less cargo space. The current hull model should be analysed in a towing tank to find how large the exit angle can reasonably be without getting too high resistance and wake problems.

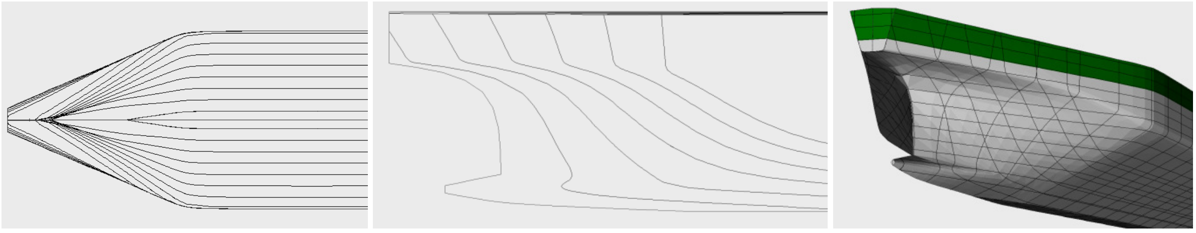


FIGURE 26: HULL LINES OF AFT SHIP

5.2.5 DOUBLE BULB

A special design feature on Equilibrium is the double bulb. The idea is to reduce wave resistance in unloaded condition as well as loaded condition. More extensive resistance calculations would be needed to determine whether or not this is profitable. But the extra bulb is also there to avoid forward trim in loaded condition. The ship needs the buoyancy in the bow that the extra bulb provides.

The bulb is not yet ideally shaped, it is only implemented in the model to illustrate its function and contribute with its buoyancy. Considering the relative low draught on Equilibrium in unloaded condition, special attention should be given to shape the lower bulb to avoid slamming damage in head seas.

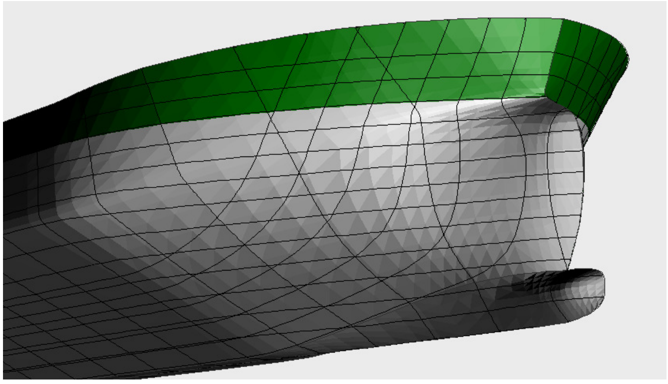


FIGURE 27: DOUBLE BULB

5.2.6 BEAM

The beam of 60 meters is a significant increase from Equilibrium's conceptual design. This will increase Equilibrium's cargo capacity with a minimum of additional steel. 60 meters is a bream that is common on VLCCs, as can be seen in Figure 9.

5.2.7 PROPELLER

An aft draught of 7,3 meters in unloaded condition is too small to allow for an optimal propeller diameter, a problem Equilibrium shares with conventional tankers. Twin screw propulsion would have given a higher efficiency on each propeller, but it would increase the building cost. See chapter 6 for other suggested hull shapes from the iteration process with increased draught and twin screw propulsion.

The aft part of the present hull is shaped so that a main engine can be fitted for a direct shaft connection to the propeller. What is not seen on the DelftShip model is a skeg with a width of about 1 meter that will support the rudder shaft and increase the directional stability in loaded condition.

5.2.8 LENGTH

The length is approximately the same as in the conceptual design. Although increasing the cargo capacity was given high priority, the length has remained the same since it is a more expensive dimension to expand than the beam and draught.

5.2.9 INTACT STABILITY

According to the problem description for the thesis, stability is to be checked by DNV. However, the intact stability in unloaded condition has been one of the main dimensioning factors throughout the design process. This is because Equilibrium's water line area is significantly reduced in this condition. Therefore intact stability calculations are done in DelftShip for loaded and lightship condition, with the following GM-values:

TABLE 22: GM-VALUES

Load Condition	GM	
Loaded	15,2	m
Lightship	6,2	m

The GM-value in loaded condition is high and may result in abrupt accelerations. This is confirmed by the GZ-curve in Figure 28; a strong restoring moment occurs already at small angles. A sea keeping analysis should be performed to determine the effect of the high GM-values on the ships roll motions in loaded condition.

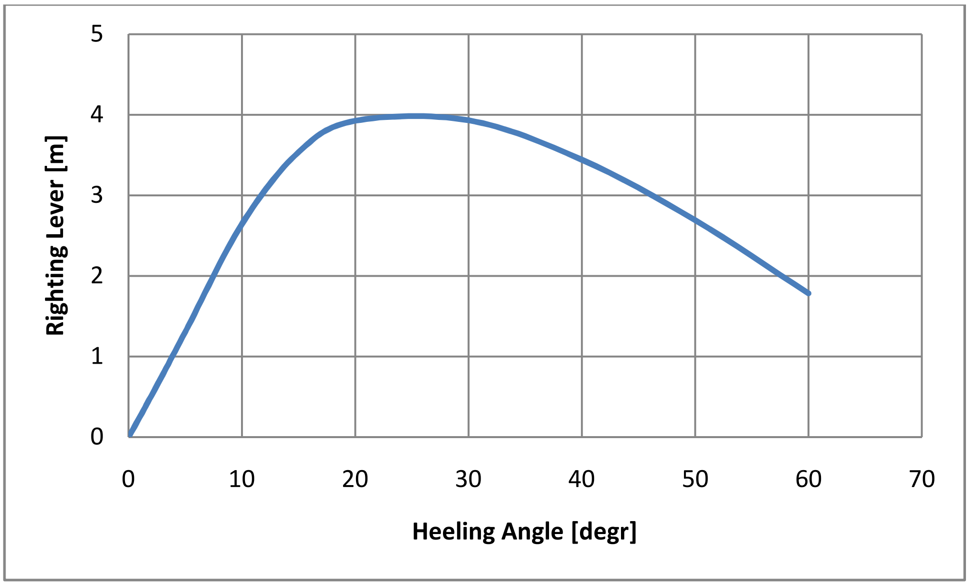


FIGURE 28: GZ CURVE, LOADED CONDITION

In lightship condition, the GZ-curve in Figure 29 indicates that the ship will have a more suitable rolling period. A strong heeling moment first starts to occur at around 12 degrees of heel, which is when the deadrise angle turns to 90 degrees.

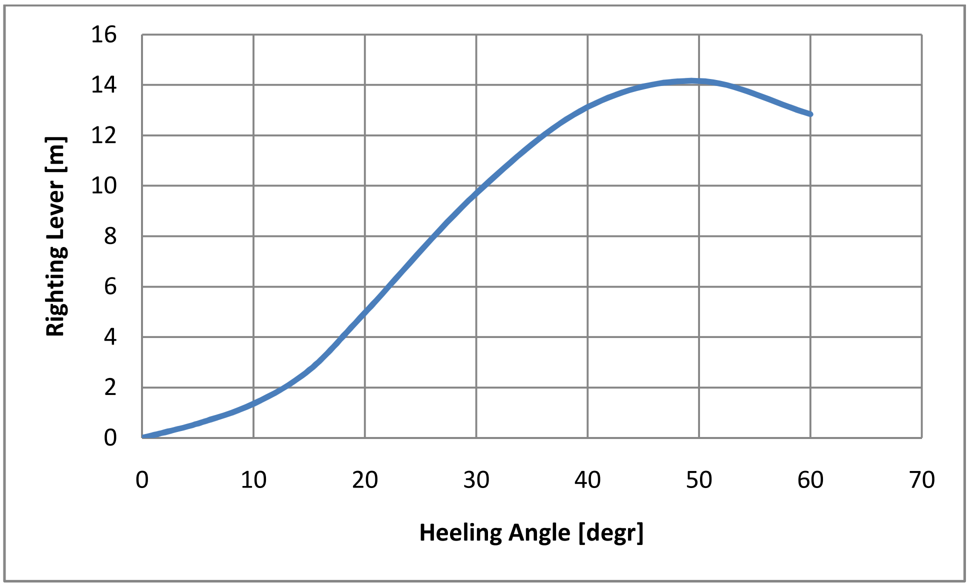


FIGURE 29: GZ CURVE, LIGHTSHIP CONDITION

A longer rolling period in lightship condition is a benefit for Equilibrium. It will help in preventing accelerations when the ship rolls. As mentioned earlier, a sea keeping analysis should be performed on this issue.

Equilibrium is within intact stability regulations. Damage stability is left for later in the design process.

5.3 WEIGHTS AND VOLUMES

5.3.1 LIGHTSHIP WEIGHT

The lightship weight calculations consist of two main steps:

- Calculating steel weight
- Estimating remaining lightship weight categories

5.3.1.1 Steel Weight

The hull is divided into the following construction elements in order to calculate the steel weight:

- Outer shell
- Inner bottom and inner side
- Bottom girders
- Stringers
- Longitudinal bulkheads
- Frames
- Transverse bulkheads

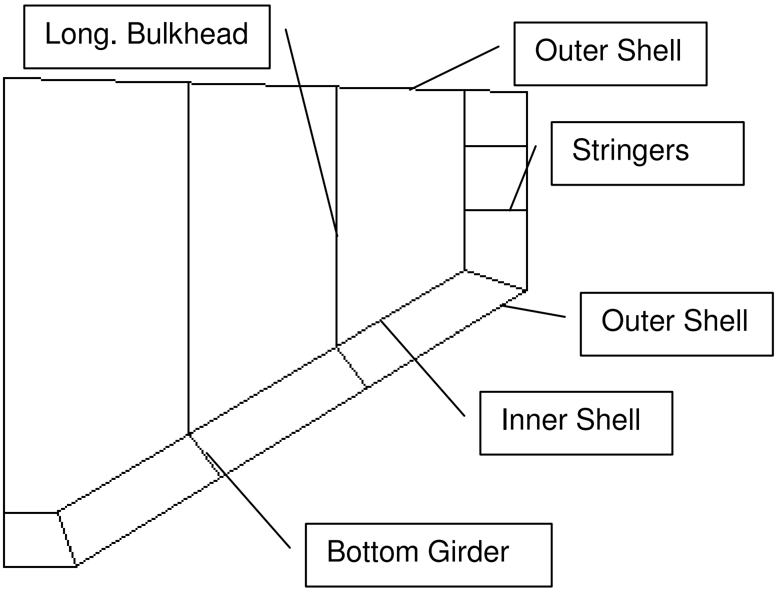


FIGURE 30: SKETCH OF MID SHIP CONSTRUCTION ELEMENTS

All these construction elements consist of both plates and profiles. DNV has provided average plate- and profile thickness for all the construction elements, except the frames and transverse bulkheads where own assumptions are made. The values provided by DNV come from a typical VLCC, the name of which is confidential.

By measuring the circumference of the construction elements on the Equilibrium midsection model, the midsection steel area is calculated and integrated throughout the length of the cargo section to find the steel volume. The volume of frames and transverse bulkheads are found in the same way. The steel weight is found by multiplying the steel volume with the steel density of 7,8 tons/m^3.

This method of integration is used to find the steel weight of the cargo block. The aft- and fore body have more complex shapes and need a different approach. The steel weights of these sections are found by using a volume factor expressing the sections gross volumes compared to the gross volume of the ship. The gross volume and volume of each ship section are extracted from DelftShip.

$$S_{Aft} = S_{Cargo} * \frac{V_{Cargo}}{GV} * \frac{V_{Aft}}{GV}$$

- S = Steel weight of ship section
- V = Enclosed volume of ship section
- GV = Gross volume

The vertical centre of gravity for the steel in the cargo block is found by calculating the area centre of the steel in the mid section. The vertical centres of gravity of the steel in the aft- and fore ship are decided by making assumptions in comparison to the vertical centre of gravity of steel in the cargo block. The longitudinal centres of gravity for the steel are assumed by measuring the DelftShip models of each ship section.

The weight and gravity centre of each of the construction units in the cargo block can be found in Appendix H while a summary is presented in Table 23:

TABLE 23: STEEL WEIGHT OF CARGO BLOCK

Cargo Block Steel Weight	[tons]	VCG [m]
Plates and Profiles	19 927	15,9
Frames	1474	10,1
Transverse Bulkheads	1539	19
Total	22940	15,7

Table 24 shows the length, volume, volume/gross volume and weight for each of the ship sections:

TABLE 24: TOTAL STEEL WEIGHT

Ship Sections	Length [m]	Volume [m^3]	Weight [tons]
Aft Section	60	32 376	2 549
Cargo Block	255	305 930	22 940
Forward Section	50	33 990	2 676
Total	365	372 296	28 165

5.3.1.2 Total Lightship Weight

The lightship is divided into different categories. Typical lightship weight categories for a common Suezmax crude oil carrier are listed in(Michel & Osborne, 2003/2004), and form a basis for the Equilibrium lightship weight calculations. Some of the weights are assumed the same on Equilibrium as on a Suezmax tanker, such as mooring equipment and lifesaving equipment, while other weights are increased in relation to the size difference. For these items, the weight is increased by a factor of

$$k = \frac{Deadweight_{Equilibrium}}{Deadweight_{Average\ Suezmax}}.$$

The deadweight of an average Suezmax tanker is extracted from the data in Figure 5. Table 25 shows the lightship weight categories that are included in the calculations, and if they are the same as on a Suezmax or adjusted for Equilibrium's size by the factor k. Vertical and longitudinal centres of gravity are found by measurements on the hull model in DelftShip and assuming the location of each weight category.

TABLE 25: LIGHTSHIP WEIGHT CATEGORIES

Lightship Weight Category	Same as Suezmax	Size Adjusted by factor k
Hull Steel	Own calculations	
Hull Steel, Deckhouse	X	
Hull Steel, Forecastle		X
Foundations		X
Welding and Tolerances		X
Mooring Equip., Amidships	X	
Mooring Equip., Aft	X	
Anchor and Mooring Equip., Forward	X	
Other Deck Equipment	X	
Paint		X
Piping		X
Rudder/Propeller/Steering Gear		X
Accommodation Outfit	X	
Lifesaving Equipment	X	
Cargo Systems		X
Heating/Cleaning/IGS		X
Main Engine		X
Auxiliary Engine	X	
Other Machinery Equipment	X	
Machinery Outfit	X	
Electrical	X	

Appendix I contains the lightship weight calculations for Equilibrium, including weights and centres of gravity. A summary is presented in Table 26:

TABLE 26: LIGHTSHIP WEIGHT CALCULATION SUMMARY

Lightship Weight	Weight [tons]	VCG [m]	LCG [m]
Cargo Block	24 030	15,7	187,0
Aft Section	6 300	16,9	35,9
Forward Section	3 270	17,5	331,5
Total	33 600	16,1	172,8
LS/disp	0,118	-	

The lightship/displacement-ratio of 0,118 is about the same ratio as for an average conventional crude oil tanker, as can be calculated from the displacement/deadweight trend line in Figure 5:

$$Displ = DW * 1{,}14 = (Displ - LS) * 1{,}14$$

$$\frac{LS}{Displ} = 1 - \frac{1}{1{,}14} = 0{,}123$$

This means that Equilibrium's design features that add extra weight, as the longitudinal bulkheads and extra length, are being compensated by the steel weight reduction from the trapeziod-shaped hull form. With Equilibrium's lightweight about the same as a conventional tanker, the ship will be competitive on building cost.

5.3.2 DEADWEIGHT

TABLE 27: DEADWEIGHT CALCULATIONS

Deadweight			Coefficient	Weight	VCG	LCG
	Value		[tons/unit]	[tons]	[m]	[m]
Lub Oil	38,4	ton/trip	2,5	96	15,9	5
Crew	20	persons	0,1	2	36	35
Provision & Stores	20	persons	0,2	4	30	35
Fresh Water	240	ton/trip	1,0	240	13,25	35
Sewage in Holding Tanks	120	ton/trip	0,3	36	5	40
Fluids in pipes				100	3	80
				478	**11,3**	**38,8**
Fuel Oil	4608	ton/trip	1,2	5 530	13,25	30
Cargo				245 712	19,7	215
Total				251 720	19,5	210,6

Coefficients for calculating the weight of lub oil, crew, provisions, fuel oil and sewage are extracted from (Levander, 2006, s. 71), while the values are calculated in chapter 5.3.3 about space allocation. Weight of fluids in pipes is the same as on a Suezmax tanker (Michel & Osborne, 2003/2004).

The cargo weight is found by subtracting the known deadweight categories and the lightship weight from the total displacement. The cargo tanks are modelled in DelftShip to assure that there is sufficient volume for the calculated cargo capacity.

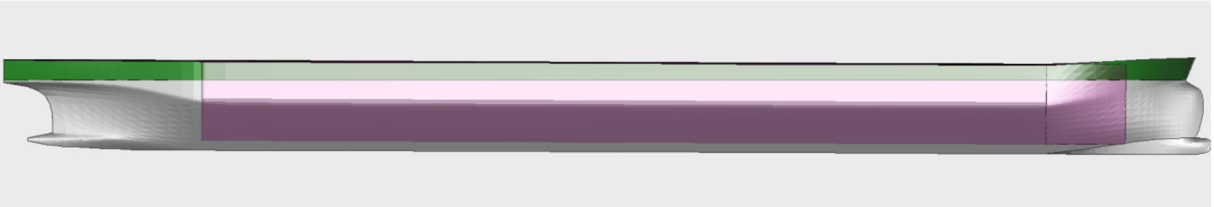


FIGURE 31: MODEL SHOWING THE CARGO HOLDS

TABLE 28: WEIGHT SUMMARY

Weights	Weight [tons]	VCG [m]	LCG [m]
Deadweight	251 740	19,5	210,6
Lightship Weight	33 600	16,1	172,9
Displacement	285 320	19,1	206,1

5.3.3 SPACE ALLOCATION

The next step is to check that the suggested hull is spacious enough for all the cargo- and ship systems. The DelftShip model gives the gross volume of the hull model. The cargo tanks are implemented in the model, both for more exact trim calculations and to test the measured cargo volume in the model against own calculations. The required areas and spaces are found by following the procedure of System Based Ship Design (Levander, 2006).

Table 29 summarizes all the required spaces in Equilibrium. See Appendix J for detailed calculations

TABLE 29: SUMMARY OF SPACE ALLOCATION

Space Allocation	Area [m^2]	Volume [m^3]
Crew Facilities	690	1 970
Ship Service	140	392
Catering	60	178
Hotel Service	40	112
Technical spaces in the accommodation	110	308
Total Interior Spaces	1 000	3 000
Machinery Spaces		11 440
Steering Gear	114	366
Switchboard Rooms, Emergency Generator, Battery Room, Cargo Control	143	446
Engine Casing and Funnel	300	1 400
Workshop and Stores	86	275
Total Technical Spaces	640	13 900
Tanks		7 634
Outdoor Deck Spaces	735	1 185
Cargo		282 141
Void Spaces (Double Hull)		69 000
Required Gross Volume		**376 900**
Measured Gross Volume (Delft Ship)		**371 300**

The required gross volume is about 1,5 % higher than the actual measured gross volume from the hull model in DelftShip. But the model does not include a deckhouse and funnel, so the measured gross volume is actually bigger than what is required.

In the space calculations there is some uncertainty in how big the void spaces are, so the figures for gross volume presented in the following table are approximate. But the difference between the measured and required gross volume is small, so it can be concluded that the hull shape has sufficient space for all the required systems.

A general arrangement for the ship is not made in this project. This is not a part of the project description. Testing required gross volume against actual gross volume in the model and assuming centres of gravity is regarded as sufficient at such an early stage of the design process.

5.4 RESISTANCE

In order to determine the profitability of the Equilibrium concept, fuel costs and hull resistance also has to be calculated for the comparison ships, as in chapter 2.3. The chosen comparison ships are a convention tanker with the same deadweight as Equilibrium and a conventional VLCC which is regarded as the main competitor on the routes Equilibrium is designed to operate. The main parameters of these conventional tankers are extracted from trend lines in (King, 2009).

DelftShip does not give satisfactory results on its resistance calculations. The software uses the Delft series resistance calculations that are intended for fin-keeled yachts or the KAPER resistance method which is intended for kayaks. Equilibrium's prismatic coefficient is outside the range of both methods, and a comparison with own calculations using Guldhammer/Harvard's method gives a difference of as much as 40%.

But DelftShip does provide important values as wetted surface area and midsection area coefficient that are useful when calculating the resistance with other methods. Guldhammer/Harvard has been used for calculating resistance during the iteration process, as explained in chapter 2.3.1.

To check the resistance results from Guldhammer/Harvard's method, the Equilibrium hull is exported from DelftShip to ShipX. This is a software developed by MARINTEK that among other things performs resistance calculations using different empirical formulas, among them Hollenbach's method. Hollenbach's method is the newest empirical method for calculating hull resistance that is freely available, and it is based on a large amount of data gathered at the towing tank in Vienna (Steen, 2007, s. 21). Normally Hollenbach's method gives more accurate results than Guldhammer/Harvard's method, but it is also more complex and time consuming in the early stages of a ship design. The Hollenbach resistance calculations are programmed in ShipX and measure the main parameters of the hull model. Appendages are added to account for the skeg and rudder.

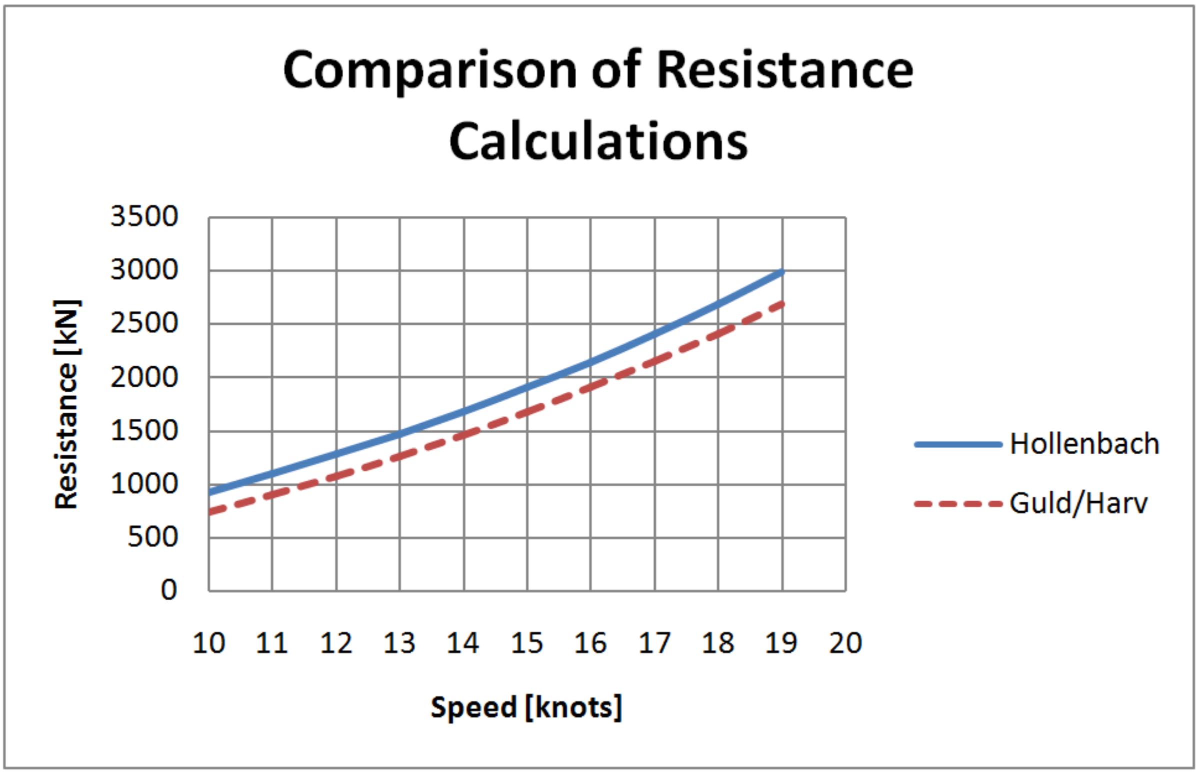


FIGURE 32: COMPARISON OF RESISTANCE CALCULATION METHODS

The comparison in Figure 32 shows that Hollenbach's method in loaded condition gives a slightly higher resistance of approximately 150 kN for all speeds. A difference of about 75 kN occurs when doing the resistance method comparison for the hull in unloaded condition.

This is because Guldhammer/Harvard's method, as it has been programmed in this master's thesis, does not take trim into consideration while Hollenbach's method does. When calculating the hull resistance again with Hollenbach's method, but this time with zero trim, the result indicates that the Guldhammer/Harvards's resistance calculations are satisfying for this case, especially up to the service speed of 15 knots:

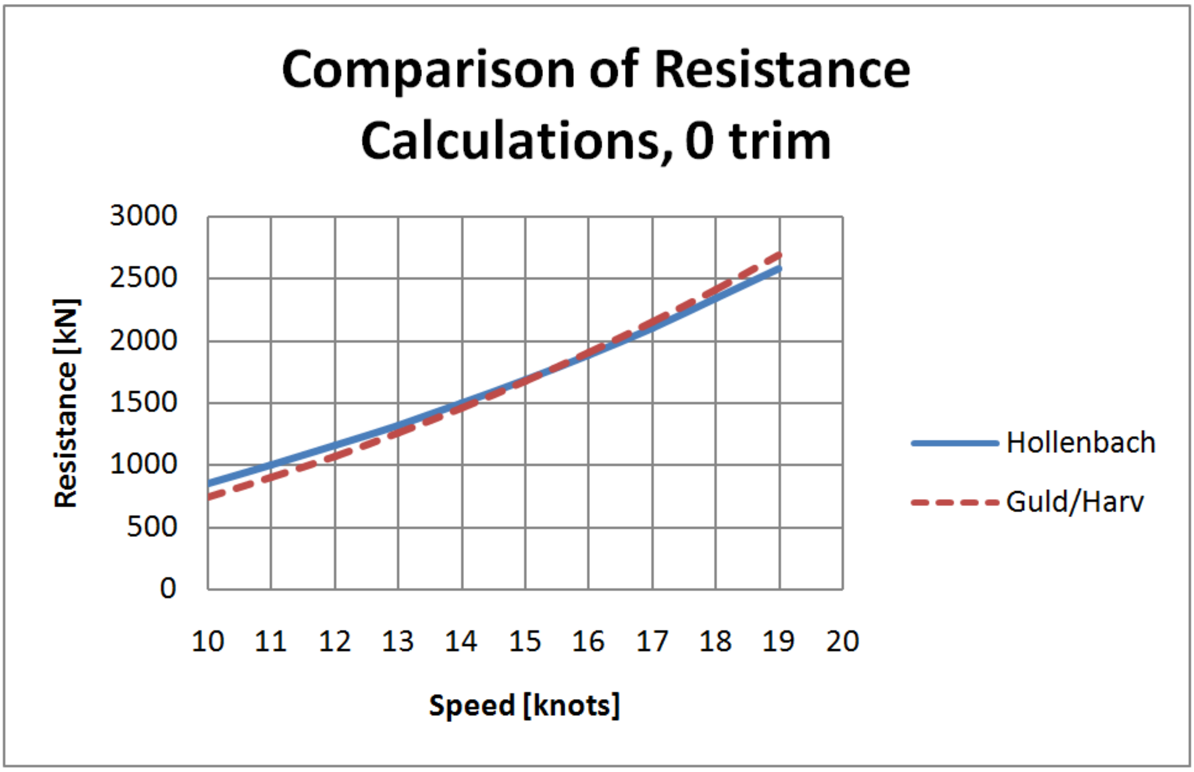


FIGURE 33: COMPARISON OF RESISTANCE CALCULATION METHODS, ZERO TRIM

Based on this comparison between Hollenbach's and Guldhammer/Harvard, it is fair to assume that trim contributes with approximately 150 kN to the resistance of the ship. Therefore, 150 kN is added to the total resistance found in Guldhammer/Harvard's method. The difference in trim between Equilibrium and a conventional tanker is not taken into account.

However similar the results of the two different empirical methods are, accurate resistance data on an unconventional hull shape should be done by towing tank test. Although empirical methods might give a good indication of the hull resistance, they are based on existing hull shapes and do not take very unconventional hulls into account.

Air resistance is neglected in these calculations. This gives a small contribution at 15 knots, and can anyway be assumed to be the same for Equilibrium as for a conventional tanker and will therefore not have any effect on the cost comparison.

There are some differences between the resistance calculations of Equilibrium and the two comparison ships. While Equilibrium has all its main dimensions such as length, beam, draught, mid ship area coefficient and prismatic coefficient measured of the DelftShip model, dimensions of the two comparison ships are extracted from trend lines in (King, 2009) or assumed. The wetted surface area on the two comparison ships are calculated as explained in chapter 2.3.1.2, while it on Equilibrium is measured on the DelftShip model.

The complete resistance comparison can be found in Appendix K, while a summary is presented in Table 30.

TABLE 30: SUMMARY OF RESISTANCE COMPARISON

Resistance and Engine Power		Equilibrium		Conventional Tanker		Conventional VLCC		
		Loaded	Unloaded	Loaded	Ballast	Loaded	Ballast	Unit
Deadweight	DW	251 720		251 720		310 000		tons
Total Resistance	R_T	1 924	783	1 799	1 405	1 952	1 548	kN
Effective Power	EP	14,8	6,0	13,9	10,8	15,1	11,9	MW
Estimated Propulsion efficiency	η	0,6						
Main Engine Power	P	24,8	10,1	23,2	18,1	25,1	20,0	MW
Installed Main Engine Power (20% Sea Margin)		31,0		29,0		31,4		MW

The installed main engine power is checked against other crude oil carriers that are listed in (Lloyds Register Fairplay), as presented in Figure 34. A sea margin of 20% is added to the calculated main engine power to find the installed main engine power.

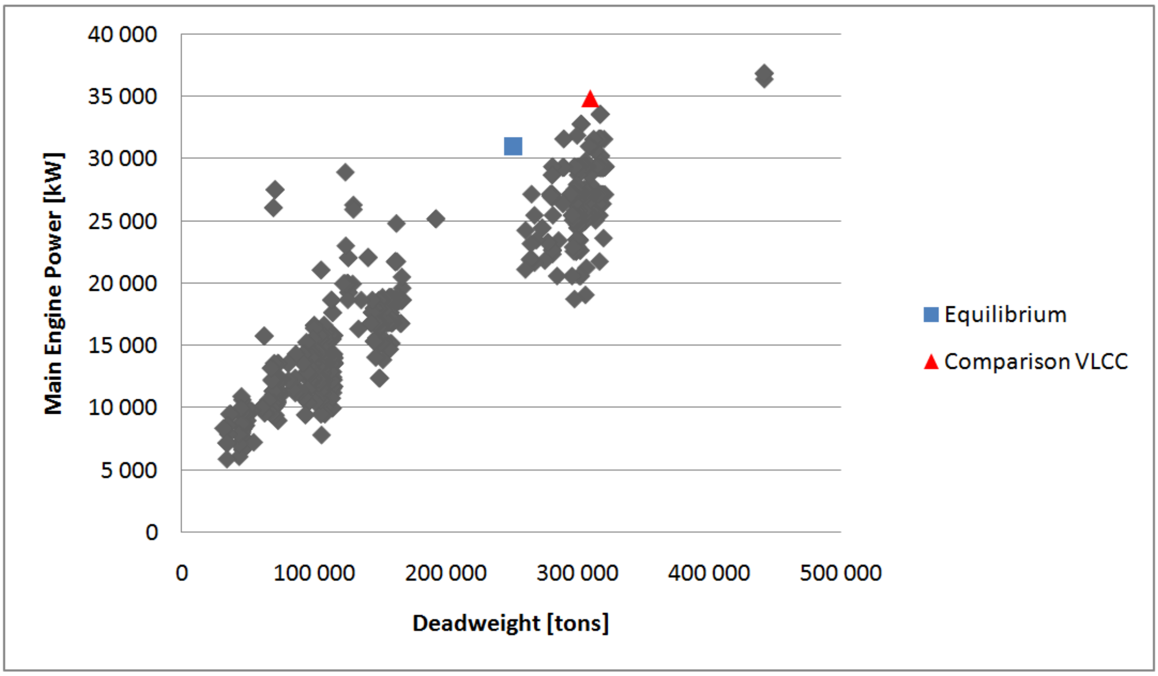


FIGURE 34: INSTALLED MAIN ENGINE POWER VS DEADWEIGHT

The comparison indicates that the resistance calculations are conservative. The most important is that the same method is used for all comparison ships to make the cost comparison fair. Figure 35 shows how much engine power is needed for the three comparison ships for both loaded and unloaded condition when sailing at the service speed of 15 knots.

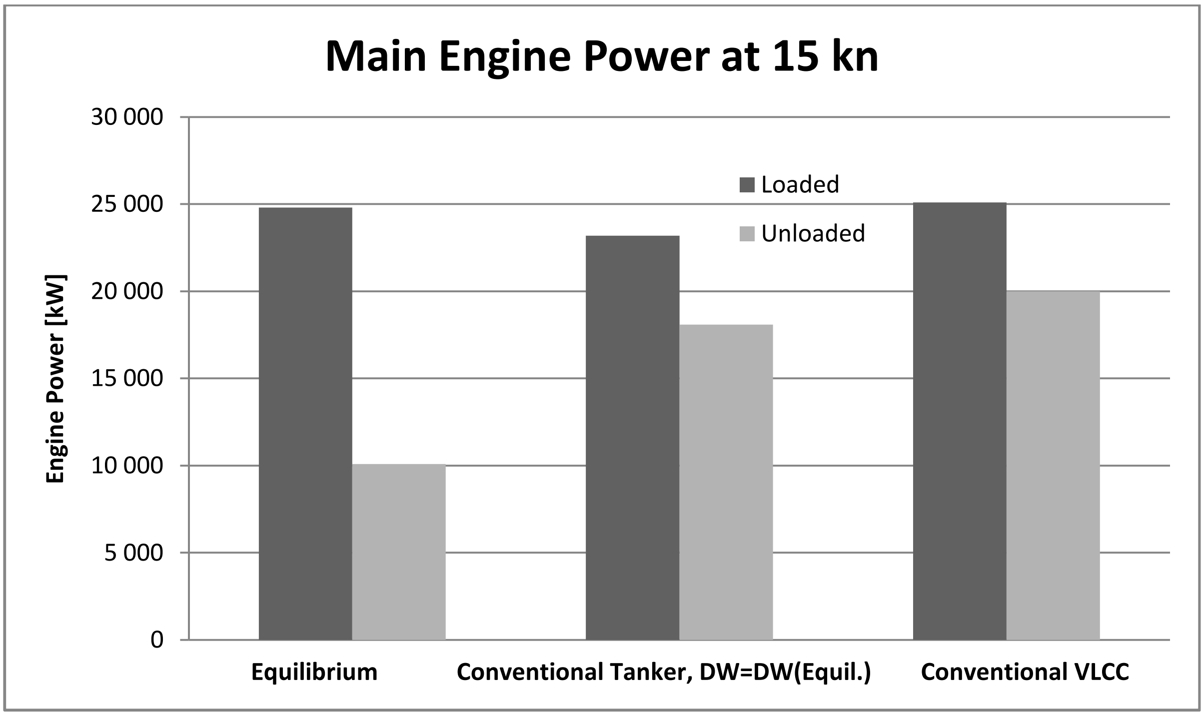


FIGURE 35: MAIN ENGINE POWER AT 15 KNOTS

The comparison shows Equilibrium's fuel saving potential in unloaded condition, where the two comparison ships need to transport the additional weight of ballast water. The conventional VLCC has a higher resistance than the two other ships, but it also has a higher cargo capacity. The difference in resistance between Equilibrium and the conventional tanker with the same deadweight is relatively small in loaded condition. Equilibrium has an advantage because of its length and thereby less wave resistance, but it has a disadvantage in its large wetted surface area.

The following speed-power graph for Equilibrium is calculated using Hollenbach's method on the Equilibrium hull model in the software ShipX.

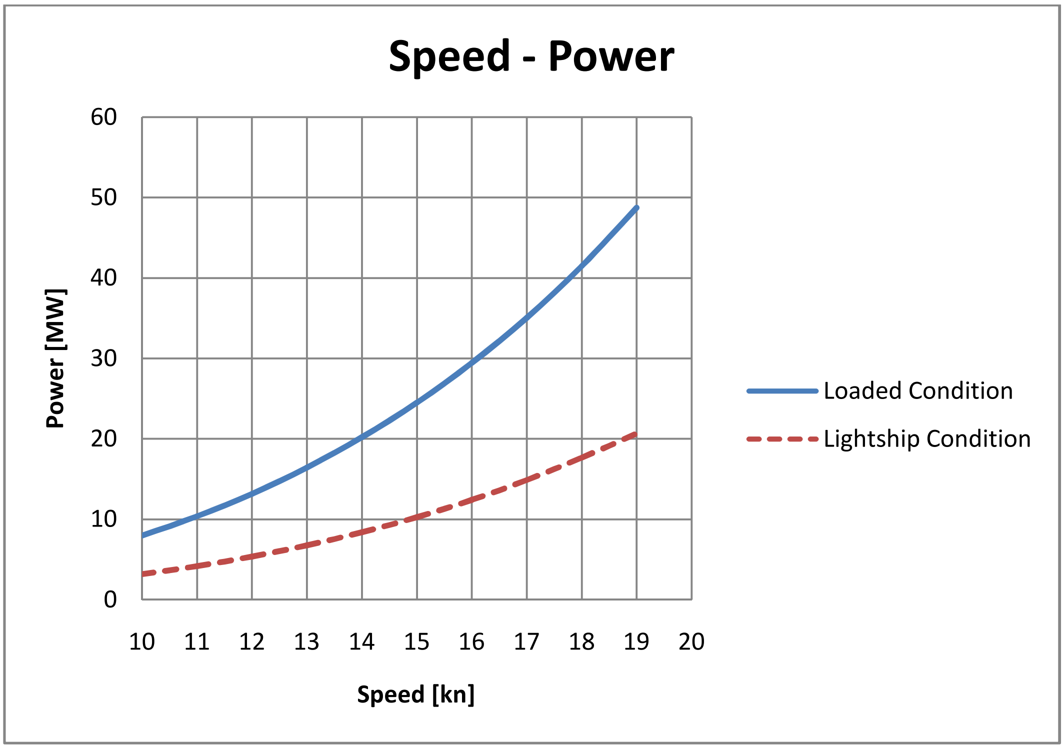


FIGURE 36: SPEED-POWER GRAPH USING HOLLENBACH'S METHOD

Guldhammer/Harvard's method is used for the resistance comparison because of its simplicity. Hollenbach's method is chosen for giving the final speed-power graph because it is regarded more precise.

5.4.1 PROPULSION SYSTEM

Evaluating different propulsion systems has not been a part of this master's thesis. Crude oil carriers operate on long routes at constant speed and in port they are assisted by tugs. A slow speed diesel engine with a direct propeller connection seems like the obvious choice.

A disadvantage with such a propulsion system is that the draught in unloaded condition is too small to have an optimal propeller diameter in loaded condition. Another disadvantage is that the engine load in unloaded condition is quite different from in loaded condition, as can be seen in Figure 35. Since the propulsion systems are tuned for operation in loaded condition, the specific fuel consumption (SFC) increases in unloaded condition. The load difference between loaded and unloaded condition is even bigger on Equilibrium than a conventional tanker making the specific fuel consumption increase even more in unloaded condition.

Figure 35 shows that Equilibrium's resistance in unloaded condition is about 40% of the resistance in loaded condition. At the same time, Figure 36 shows that Equilibrium theoretically can have a speed of about 20 knots in unloaded condition using the same engine power as in loaded condition.

This should in the further design work lead to a discussion on alternative propulsion systems. Installing a gear, controllable pitch propeller or even changing to diesel-electric propulsion system can improve the efficiency in unloaded condition, and might give overall fuel saving.

5.4.2 *FUEL CONSUMPTION*

The fuel consumption in transit condition is calculated by using following input data:

TABLE 31: INPUT DATA, FUEL CONSUMPTION DURING TRANSIT

Input Data		
Days in Transit, Loaded	140,2	days
Days in Transit, Unloaded	102,2	days
SFC, Loaded Condition	170	g/kWh
SFC, Unloaded Condition	180	g/kWh

The amount of days and SFC in transit are data from Frontline VLCCs reported in (Lalic, 2005, s. 16). A penalty of 10 g/kWh is added to the SFC in unloaded condition since the engine in this condition is operating below optimal rpm. According to Figure 35, Equilibrium will in ballast condition be operating at a lower rpm than the conventional tankers and thereby have a higher SFC. Since it is not decided what propulsion system there should be on Equilibrium, this factor is not taken into consideration when calculating the fuel consumption.

The remaining fuel consumption calculations are the same as done when analysing the conceptual design parameters in chapter 2.4.2.1.

TABLE 32: FUEL CONSUMPTION IN NON-TRANSIT CONDITION

Fuel Consumption, Non-Transit Conditions [tons/year]	Suezmax	VLCC	Equilibrium
Waiting at Sea	85	33	33
Waiting in Port	272	339	339
Manoeuvring	845	666	666
Loading	128	225	193
Discharging	995	1 629	1 418
Miscellaneous	38	38	38
Fuel Consumption, Non-Transit [tons/year]	2 363	2 930	2 686

The annual fuel consumption and fuel cost for Equilibrium and the two comparison ships are presented in Table 33.

TABLE 33: ANNUAL FUEL COST

Annual Fuel Cost	Equilibrium	Conventional Tanker DW = DW(Equilibrium)	Conventional VLCC	
Main Engine Power				
Transit, Loaded	24,8	23,2	25,1	MW
Transit, Unloaded	10,1	18,1	20,0	MW
Fuel Consumption				
Transit, Loaded	14 186	13 271	14 358	tons/year
Transit, Unloaded	4 459	7 991	8 830	tons/year
Other Conditions	2 686	2 686	2 930	tons/year
Annual Fuel Consumption	21 331	23 948	26 118	tons/year
Fuel Price	480			US$/ton
Annual Fuel Cost	10 239 086	11 495 153	12 536 487	US$/year

5.4.3 ENVIRONMENTAL IMPACT

The calculated fuel consumption opens for a significant environmental impact from the Equilibrium design. When comparing the environmental performance of Equilibrium it is best to compare it with a conventional tanker with the same deadweight. A VLCC has a larger cargo capacity and would require advanced emission indexing to measure the environmental performance up against Equilibrium.

With an assumed CO_2 production of 3 020 g/kg fuel for heavy fuel oil (Øyvind Buhaug, 2009), Table 34 shows the saving potential of both the fuel consumption and CO_2 emissions.

TABLE 34: ENVIRONMENTAL IMPACT

Environmental Impact			
CO_2 (86% Carbon in Fuel):	3 020	g/kg fuel	
	Fuel Consumption	CO_2 Emissions	
	[tons/year]	[tons/year]	
Equilibrium	21 331	64 421	
Conventional Tanker	23 948	72 324	
Saving Potential	2 617	7 903	10,9 %

A fuel consumption- and CO_2 emissions reduction of 10,9% is a significant figure. The CO_2 emissions from all the world's ocean going tankers is about 190 million tons per year (Øyvind Buhaug, 2009). If every tanker had been of Equilibrium design, theoretically the emissions would have been reduced by approximately 21 million tons per year. As a comparison, the total CO_2 emissions of Norway in 2007 was approximately 36,9 million tons per year (International Energy Agency, 2009).

5.5 COST COMPARISON

The cost comparison method of Equilibrium and the two comparison tankers is the same as in chapter 2.4 in the analysis of the conceptual design parameters.

TABLE 35: COST COMPARISON

CAPEX Comparison	Equilibrium	Conventional Tanker	Conventional VLCC	Unit
Deadweight	251 720	251 720	310 000	tons
Lightship Weight	33 600	35 744	44 020	tons
Building Cost	3,1	3,0	3,0	US$/kg(LS)
	104 160 000	107 230 000	132 060 000	US$
Ballast Pumps	-1 000 000			US$
Ballast Pipes	-660 000			US$
Ballast Treatment System		2 700 000	2 700 000	US$
Total CAPEX	102 500 000	109 930 000	134 760 000	US$
OPEX Comparison	**Equilibrium**	**Conventional Tanker**	**Conventional VLCC**	**Unit**
Lifetime	10			years
Discount Rate	6			%
Fuel	10 239 086	11 495 153	12 536 487	US$/year
Ballast Pumping and Treatment	-52 000	18 000	18 000	US$/year
Total	10 187 086	11 513 153	12 554 487	US$/year
Present Value OPEX	74 980 000	84 740 000	92 400 000	US$
Second Hand Value	38 179 000	40 919 000	50 166 000	
Life Cycle Costs	139 540 000	153 740 000	176 990 000	US$

The cost comparison shows that Equilibrium is more profitable than a conventional tanker with the same deadweight. But to be competitive on the market, Equilibrium has to prove more profitable than a conventional VLCC which has a higher cargo capacity. Using the same cost efficiency index as explained in chapter 2.4.3, gives the following comparison:

TABLE 36: COMPARISON OF COST EFFICIENCY

Cost Efficiency Index, i	[US$/DWT]
Equilibrium	6,9
Conventional VLCC	7,1
Conventional Tanker, DW=DW(Equil.)	7,6

Table 36 shows that Equilibrium can compete with a VLCC on cost efficiency, and provides a reason for developing the design further. The main advantage of the VLCC is the larger cargo capacity, but this is on Equilibrium compensated by the lower fuel expenses. If the fuel prices rise in the future, this will work in Equilibrium's favour and make the ship design even more profitable. This will also be the case if environmental performance will be rewarded in the future, for instance by a CO_2-tax.

When adding the cost of installing a ballast treatment system and the operational costs from ballast operation, the cost efficiency factor of Equilibrium increases to 7,1 – the same as the VLCC. So if for instance a sea keeping analyses shows that Equilibrium needs a ballast system to gain draught in bad weather, it would still be cost competitive.

The difference in life cycle cost between the three vessels will vary according to the discount rate. To test the effect of the discount rate, the cost comparison is done with two extremes; a discount rate of 15 % and 1 %.

TABLE 37: EFFECT OF DISCOUNT RATE ON EFFICIENCY INDEX

Cost Efficiency Index, 15% Discount Rate	[US$/DWT]
Equilibrium	6,8
Conventional VLCC	7,1
Conventional Tanker, DW=DW(Equil.)	7,4
Cost Efficiency Index, 1% Discount Rate	
Equilibrium	6,8
Conventional VLCC	6,9
Conventional Tanker, DW=DW(Equil.)	7,6

Since Equilibrium has both lower capital and operational expenses than the comparison ships, it is a profitable concept regardless of the discount rate. But it's clear from Table 37 that a high discount rate makes Equilibrium more profitable.

6 RESULTS FROM ITERATION PROCESS

This chapter explains the iteration process that leads to the final hull shape. Although the main dimensions have been adjusted continuously, the following two hull shapes are chosen to best represent the design process.

6.1 ITERATION 1

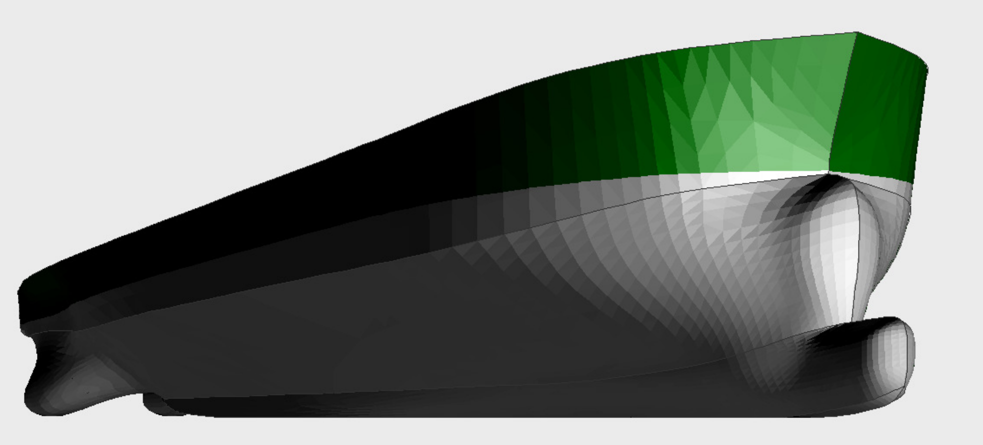


FIGURE 37: ITERATION 1, FRONT PERSPECTIVE VIEW

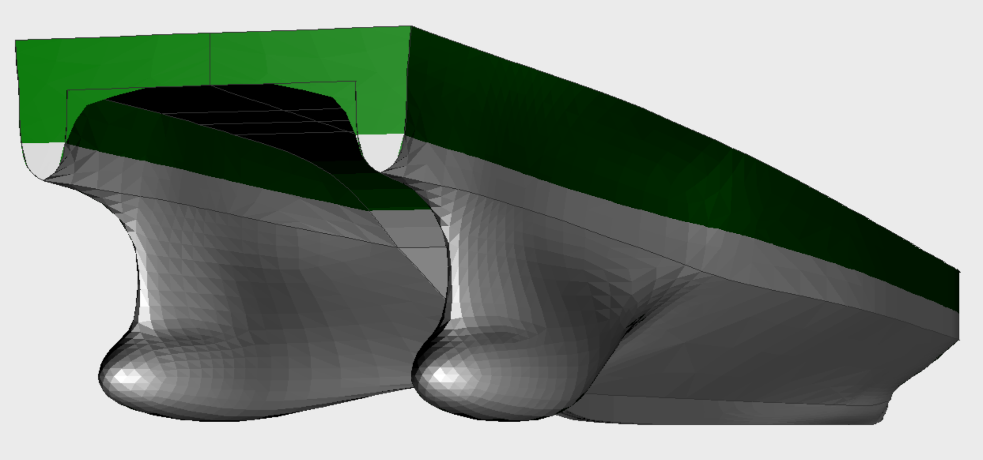


FIGURE 38: ITERATION 1, AFT PERSPECTIVE VIEW

TABLE 38: MAIN DIMENSION, ITERATION 1

Main Dimensions		Loaded	Unloaded	
Draught, Mean	T	21,8	8,9	m
Trim		1,78	-1,51	m
Beam at Waterline	B	50	24	m
Length Over All	Loa	370	370	m
Block Coefficient	C_B	0,46	0,39	-
Displacement	Disp	183 900	30 400	tons
Deadweight	DW	153 100	6 000	tons

The first hull shape aims at following the IMO draught regulation. To obtain the draught of about 9 meters in unloaded condition, the hull has a box-shaped, 2 meter wide keel along the entire length of the cargo section, as can be seen in the bottom plan view:

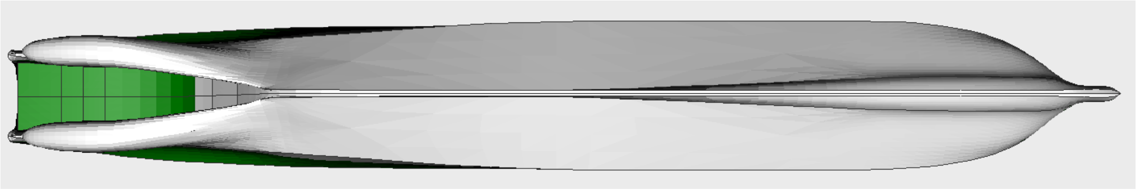


FIGURE 39: ITERATION 1, BOTTOM PLAN VIEW

The beam is increased by 10 meters from the conceptual design to increase the cargo capacity. Still the intact stability calculations on the cargo block give a negative GM. To compensate for this, two wings are added to the aft. Each wing, or pod, is designed to fit a 10 MW engine with exhaust outlet and a propeller shaft giving the ship a twin screw propulsion configuration. Advantages with twin screw propulsion are increased redundancy to the propulsion system and that each of the propellers can have more optimal propeller diameters, but at the same time it is more expensive than a single screw propulsion system.

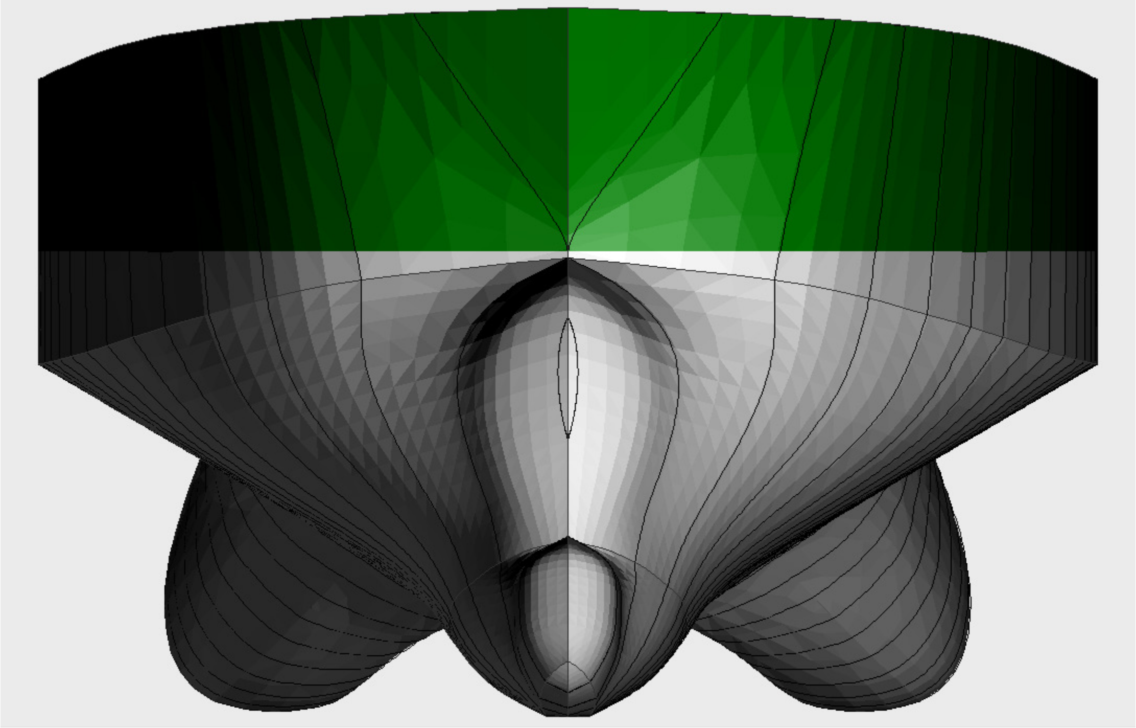


FIGURE 40: ITERATION 1, BODYPLAN VIEW

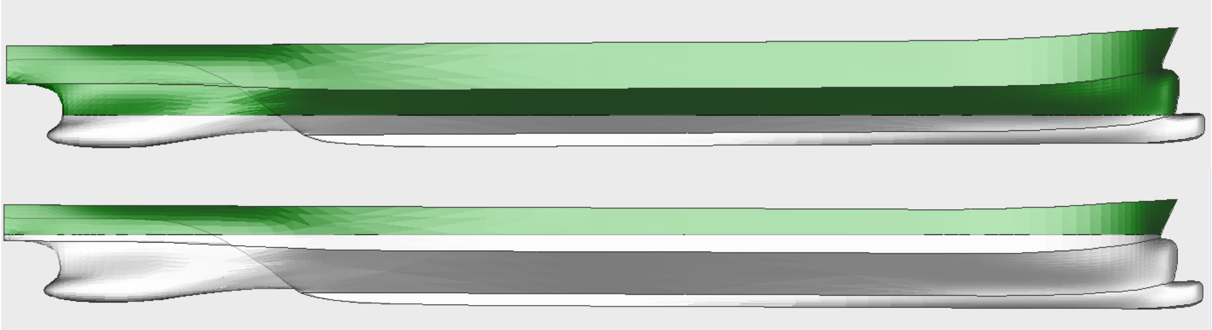


FIGURE 41: ITERATION 1, PROFILE VIEW

The twin screw propulsion adds extra cost to this ship, both in terms of increased engine installation cost and extra steel for the wings. But the main disadvantage is that the cargo capacity is too low compared to the building costs. The wings and the bilge added to the steel weight without giving the ship any extra space for payload. The cost comparison shows that a conventional tanker is more cost efficient.

6.2 ITERATION 2

The calculations in iteration 1 indicate that the IMO draught regulation has to be neglected to make this hull concept profitable, so the next iteration allows for a lower draught in unloaded condition. The extended keel is removed and replaced by a hull shape that gives a higher cargo capacity. The wings are still necessary for stability and some adjustments were made to their shape.

TABLE 39: MAIN DIMENSIONS, ITERATION 2

Main Dimensions		Loaded	Unloaded	
Draught, Mean	T	20,9	6,95	m
Trim		0,93	-1,27	m
Beam at Waterline	B	50	27,6	m
Length Over All	Loa	365	365	m
Block Coefficient	C_B	0,76	0,31	-
Displacement	Disp	227 300	30 400	tons
Deadweight	DW	197090	6 000	tons

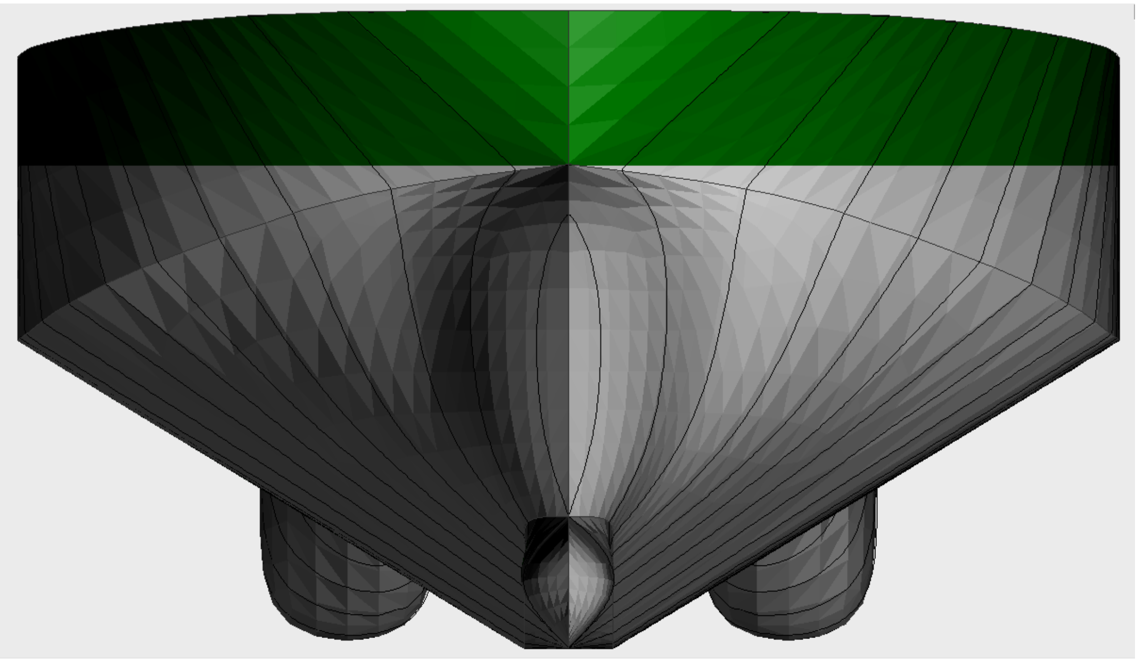


FIGURE 42: ITERATION 2, BODY PLAN VIEW

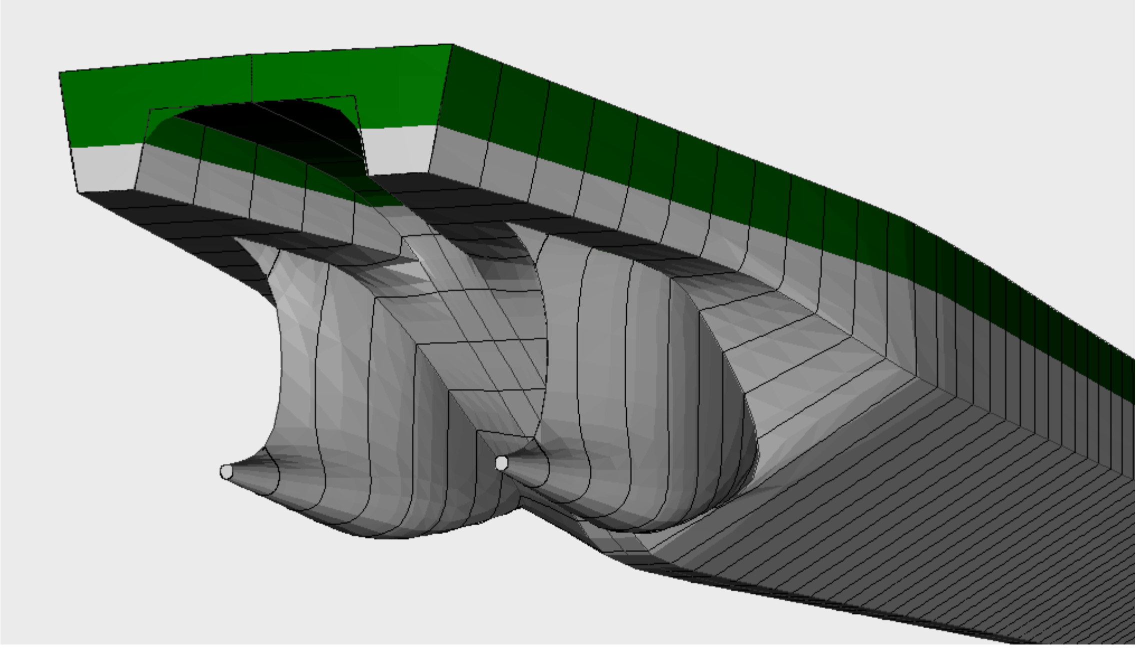


FIGURE 43: ITERATION 2, AFT PERSPECTIVE VIEW

Note that the hull figured above has undeveloped hull lines. The main point is to estimate main parameters. The hull shape is more cost efficient than a conventional tanker with the same deadweight, but is still not competitive against a VLCC. Because of this the beam is increased to 60 meters on the final hull. With the increased beam, there is no need for the wings to provide stability. So a twin screw propulsion system is finally replaced by a single propeller.

6.3 DEVELOPMENT OF MAIN PARAMETERS

Table 40 shows how the main parameters have developed from the conceptual design to the final hull shape of this master's thesis:

TABLE 40: DEVELOPMENT OF HULL SHAPE

Hull Shape Development	Conceptual Design	Iteration 1	Iteration 2	Final Hull	
Length Over All	360	370	365	365	m
Beam Over All	40	50	50	60	m
Draught, Loaded Condition	20	21,8	20,9	21,5	m
Draught, Unloaded Condition	5,7	8,9	7,0	6,2	m
Deadweight	208 300	153 100	197 100	251 500	tons
Lightship Weight	42 700	30 800	30 200	33 900	tons
Installed Main Engine Power	23 900	26 100	27 600	28 600	kW
Number of Propellers	2	2	2	1	-

The goal of increasing the ships cost efficiency in cost/transported ton cargo has been the main focus. This is clear from Figure 44 that shows the development of three important parameters from the first iteration to the final hull shape.

Deadweight [tons] is chosen as a parameter to represent the cargo capacity, lightship weight [tons] is a parameter that represents the building costs and the main engine power [kW] represents the fuel costs. The figure shows how the cargo capacity has increased while the building- and fuel costs have remained at about the same level. This development was possible mainly because the IMO draught regulation was ignored after the first iteration.

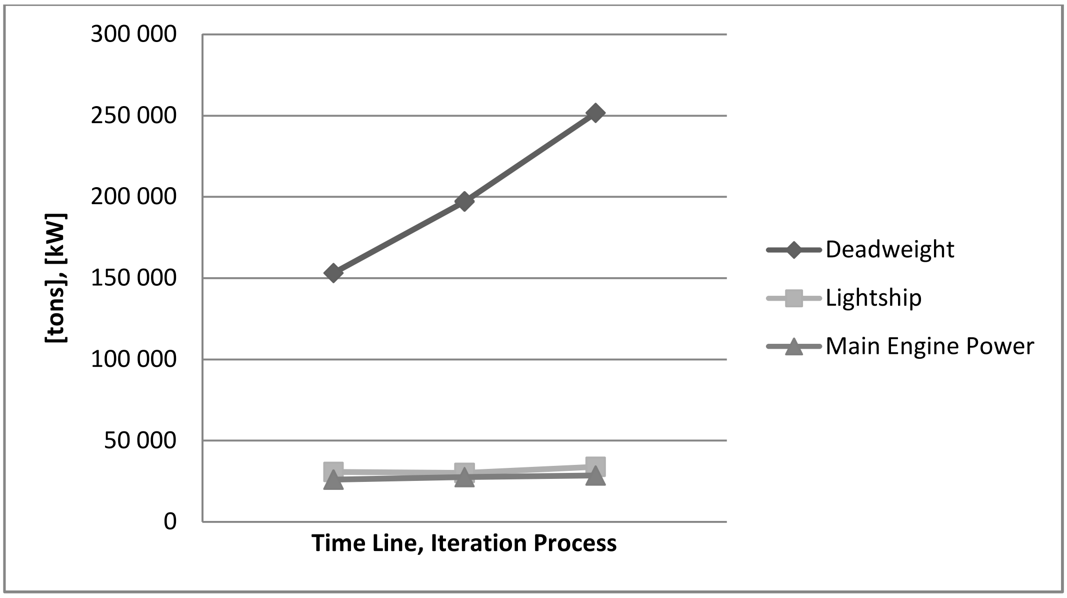


FIGURE 44: DEVELOPMENT OF HULL SHAPE

7 OTHER IDEAS

Other hull shapes have briefly been looked into in the early stages in the project. Assuming a deadweight of 300 000 tons and a lightship weight of 50 000 tons, a mid ship section was sketched showing how the displacement needs to be distributed in relation to the water line in unloaded condition:

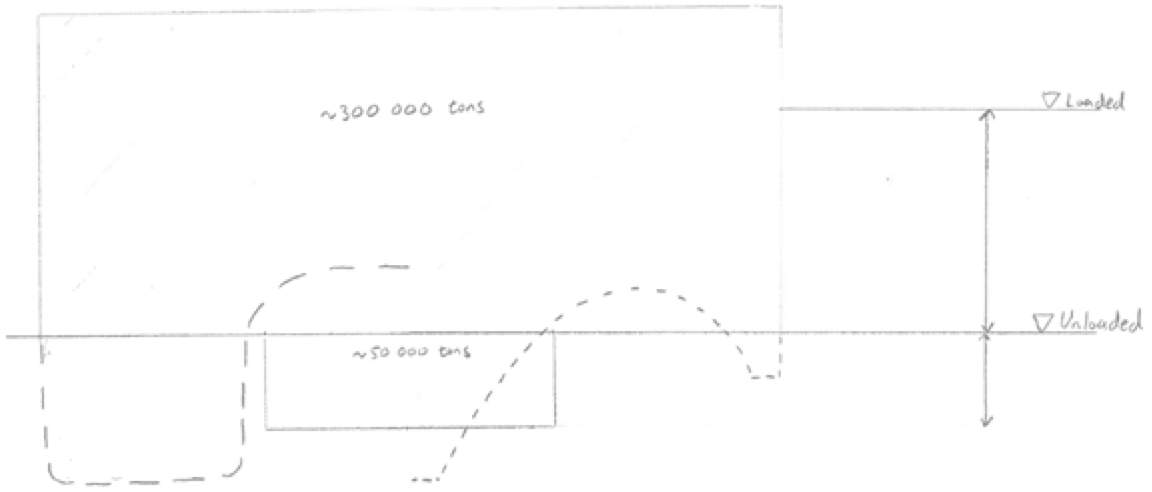


FIGURE 45: SKETCH OF ALTERNATIVE MID SHIPS

The port side suggests a catamaran hull shape to gain sufficient draught and stability. Because of the double hull requirement there would be limited amount of cargo that would fit in the lower parts of the hull. Such a hull shape could lead to a twin screw propulsion system in the aft.

The starboard side suggests a trimaran hull shape. Such a hull would have a constant heel in unloaded condition.

The trapezoid-shaped hull was chosen for its simplicity and high cargo capacity. But both alternative hull shapes are interesting if the suggested hull shape is deemed unfeasible for instance after the sea keeping analysis.

FURTHER WORK

The cost comparison that concludes on Equilibrium's profitability heavily relies on resistance calculations by empirical methods. These methods are based on tests of conventional hull shapes, and might not be representative for a hull shape such as Equilibrium. A towing test of an Equilibrium model would determine the hull resistance more accurately and increase the credibility of the cost comparison.

An analysis to check the feasibility of the 27 degree deadrise should also be done. High accelerations in roll motions might be a problem for the suggested hull shape.

The difference in required main engine power between loaded and unloaded condition is much higher on Equilibrium than on a conventional tanker. An alternative propulsion system can give more optimal engine operation in unloaded condition, and might give an overall reduction in fuel costs that is bigger than the increased capital expenses. This is a thought that should be looked further into.

If the suggested hull shape is to be developed further, the model should be designed in different software different from DelftShip. The software(s) should be able to give more accurate values for centres of gravity, resistance, damage stability and sea keeping.

It would be interesting to test the Equilibrium hull shape on a ship type that has a higher lightweight/deadweight ratio than an oil tanker, like a product tanker. On such a ship it would be easier to gain sufficient draught in unloaded condition without making drastic hull shape changes from the proven conventional ship.

In unloaded condition it should be investigated how the trapezoid hull affects interaction with other vessels. Equilibrium will not be equipped with any thrusters. Because of this the ship is dependent on tug assistance in port. The hull shape could also make access to the ship more difficult for pilots, customs etch.

CONCLUSION

Equilibrium with its final hull shape is cheap to build and can operate on all the routes that VLCCs operate today. Its main advantage is the low resistance in unloaded condition, being independent of the massive amounts of ballast water required on conventional tankers. The disadvantage is the relatively low cargo capacity.

The cost-benefit comparison against a conventional VLCC shows that the fuel savings from lower resistance in unloaded condition is bigger than the reduced income from transporting less cargo. Hence, Equilibrium is a profitable ship design concept, and will be even more so as the fuel prices increase. There is a considerable reduction in the CO_2-emissions, something that might also give economical benefits in the future.

Equilibrium is not dependent on any unproven technology for its operation. Basically it is just the innovative trapezoid-shaped hull that makes the difference.

Its feasibility depends mainly on the following:

- Will Equilibrium need ballast water to obtain more draught in bad weather? If so, the cost-benefit analysis shows that Equilibrium will be competitive even with the cost of ballast pumps, a ballast treatment plant and all the related operational costs.
- Will Equilibrium handle the accelerations in roll motions? A sea keeping analysis is needed to answer this.

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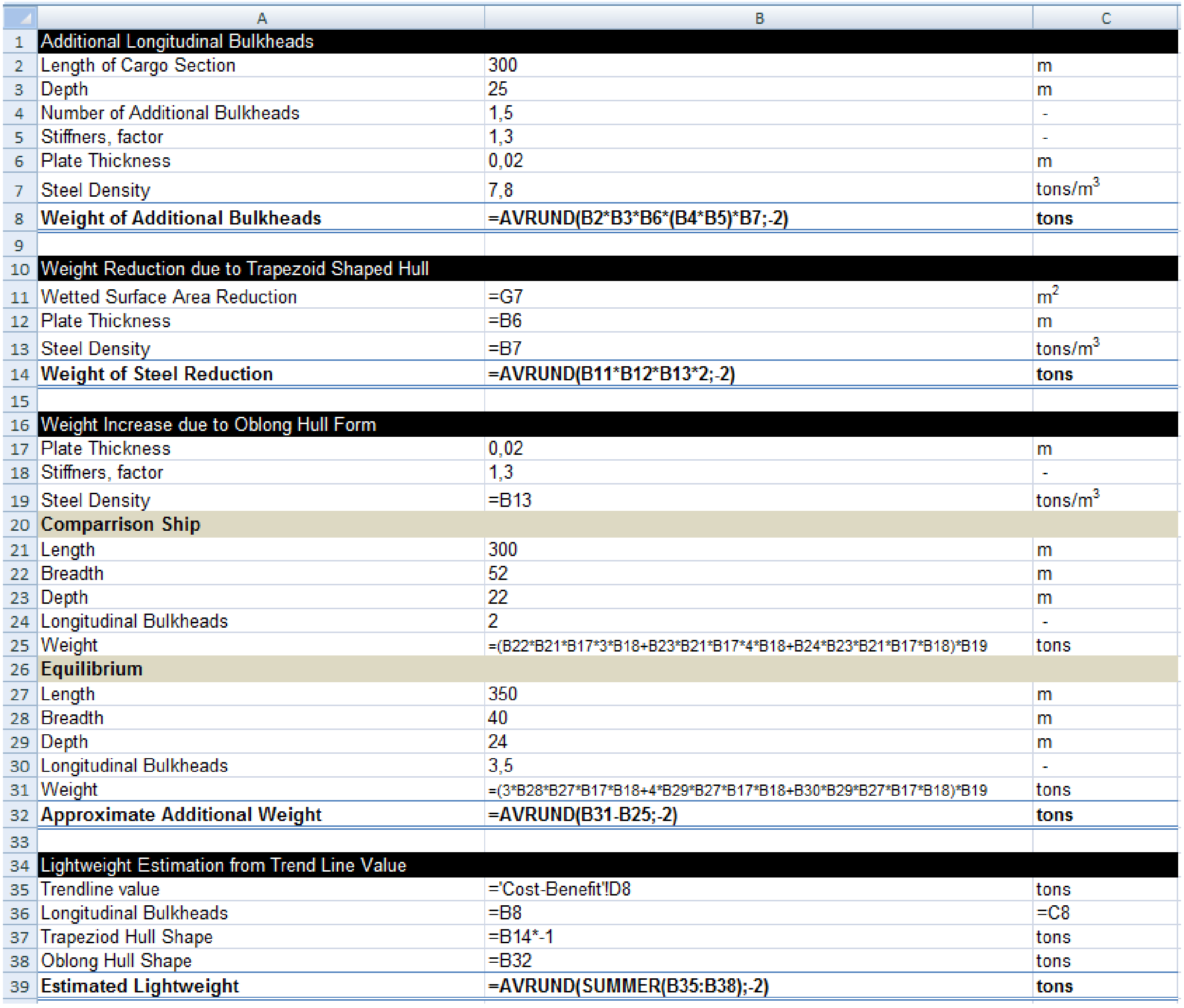
APPENDIXES

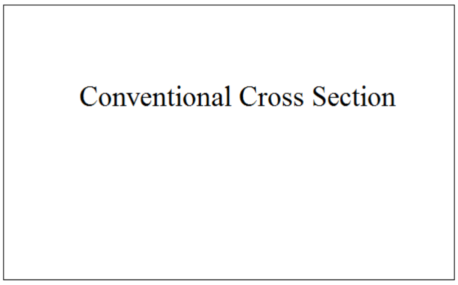
APPENDIX A: HULL SHAPE COMPARISON, CONCEPTUAL DESIGN

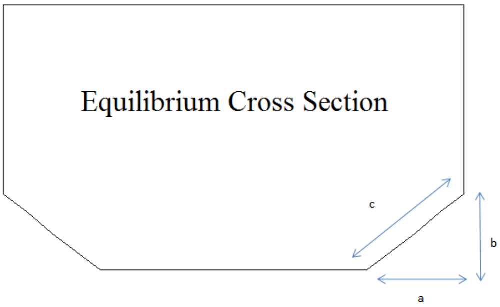


	A	B	C
1	Additional Longitudinal Bulkheads		
2	Length of Cargo Section	300	m
3	Depth	25	m
4	Number of Additional Bulkheads	1,5	-
5	Stiffners, factor	1,3	-
6	Plate Thickness	0,02	m
7	Steel Density	7,8	tons/m^3
8	**Weight of Additional Bulkheads**	**=AVRUND(B2*B3*B6*(B4*B5)*B7;-2)**	**tons**
9			
10	Weight Reduction due to Trapezoid Shaped Hull		
11	Wetted Surface Area Reduction	=G7	m^2
12	Plate Thickness	=B6	m
13	Steel Density	=B7	tons/m^3
14	**Weight of Steel Reduction**	**=AVRUND(B11*B12*B13*2;-2)**	**tons**
15			
16	Weight Increase due to Oblong Hull Form		
17	Plate Thickness	0,02	m
18	Stiffners, factor	1,3	-
19	Steel Density	=B13	tons/m^3
20	**Comparrison Ship**		
21	Length	300	m
22	Breadth	52	m
23	Depth	22	m
24	Longitudinal Bulkheads	2	-
25	Weight	=(B22*B21*B17*3*B18+B23*B21*B17*4*B18+B24*B23*B21*B17*B18)*B19	tons
26	**Equilibrium**		
27	Length	350	m
28	Breadth	40	m
29	Depth	24	m
30	Longitudinal Bulkheads	3,5	-
31	Weight	=(3*B28*B27*B17*B18+4*B29*B27*B17*B18+B30*B29*B27*B17*B18)*B19	tons
32	**Approximate Additional Weight**	**=AVRUND(B31-B25;-2)**	**tons**
33			
34	Lightweight Estimation from Trend Line Value		
35	Trendline value	='Cost-Benefit'!D8	tons
36	Longitudinal Bulkheads	=B8	=C8
37	Trapeziod Hull Shape	=B14*-1	tons
38	Oblong Hull Shape	=B32	tons
39	**Estimated Lightweight**	**=AVRUND(SUMMER(B35:B38);-2)**	**tons**

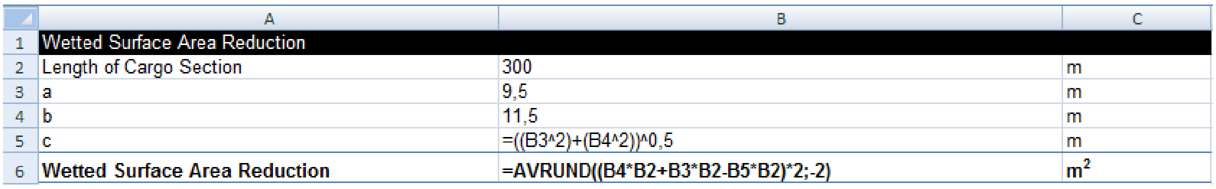
The Excel file can be found on the CD attached to the report.

APPENDIX B: WETTED SURFACE AREA REDUCTION, CONCEPTUAL DESIGN





Wetted Surface Area Reduction		
Length of Cargo Section	300	m
a	9,5	m
b	11,5	m
c	14,9	m
Wetted Surface Area Reduction	**3700**	**m^2**



	A	B	C
1	Wetted Surface Area Reduction		
2	Length of Cargo Section	300	m
3	a	9,5	m
4	b	11,5	m
5	c	=((B3^2)+(B4^2))^0,5	m
6	**Wetted Surface Area Reduction**	**=AVRUND((B4*B2+B3*B2-B5*B2)*2;-2)**	**m^2**

The Excel file can be found on the CD attached to the report.

APPENDIX C: RESISTANCE AND ENGINE POWER, CONCEPTUAL DESIGN

Resistance and Engine Power		Equilibrium		Conventional Tanker		
		Loaded	Unloaded	Loaded	Ballast	Unit
Input						
Service Speed	V	15	15	15	15	kn
		7,72	7,72	7,72	7,72	m/s
Length Between Perpendiculars	Lpp	350	350	300	300	m
Longitudinal Position of Buoyancy Centre	LCB	0	0	0	0	%
Beam	B	40	30	52	52	m
Draught	T	20	5,7	18,0	10,0	m
	B/T	2,00	5,3	2,9	5,2	-
Block Coefficient	C_B	0,85	0,80	0,87	0,85	-
Midtspantskoeffisient	C_M	0,95	0,9	0,97	0,95	-
Prismatic Coefficient	C_P	0,89	0,89	0,90	0,89	-
Displacement	Δ	251 000	50 700	237 800	104 500	tons
	Δ/ρ	244 900	49 500	232 000	102 000	m^3
Deadweight	DW	208 300	8 000	208 300	75 000	tons
Lightship Weight	LW	42 700	42 700	29 500	29 500	tons
Wet Surface Area						
	k	2,73	2,75	2,57	2,75	-
Correction for Trapezoid Hull Shape		-3700	-3700			m^2
Wet Surface Area	S	21 800	7 900	21 700	15 400	m^2
Frictional Resistance						
Kinematic Viscosity	v	1,8883E-06	1,8883E-06	1,8883E-06	1,8883E-06	m^2/sec
Reynolds Number	R_N	1,4302E+09	1,4302E+09	1,2259E+09	1,2259E+09	-
Frictional Resistance Coefficient	C_F	0,0015	0,0015	0,0015	0,0015	-
Wave Resistance (Appendix D)						
Wave/Rest Resistance Coefficient	C_R	0,00037	0,00069	0,00066	0,00073	-
Form Factor						
	φ	0,0952	0,0414			-
Form Factor	k	0,0958	0,0270			-
Roughness Resistance						
Roughness	H	150	150	150	150	μm
Correction Factor	ΔC_F	0,00017	0,00017	0,00018	0,00018	-
Total Resistance Coefficient						
	C_T	0,0022	0,0024	0,0023	0,0024	-

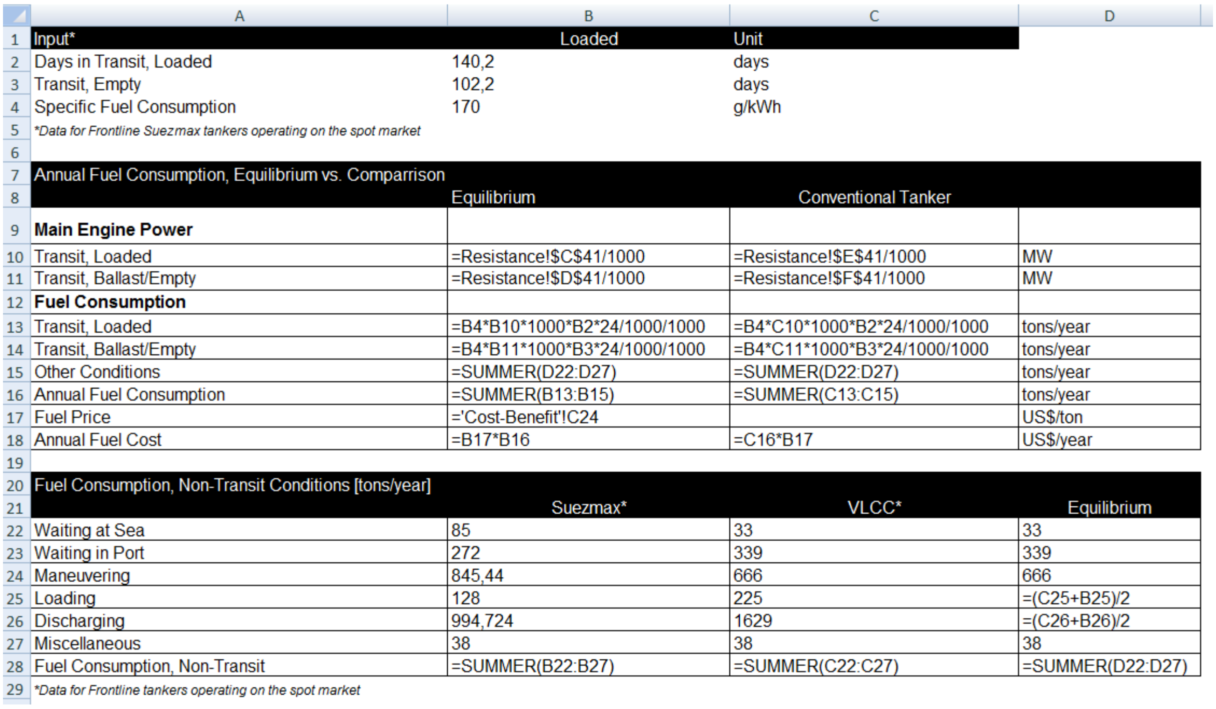
Resistance and Engine Power		Equilibrium		Conventional Tanker		
		Loaded	Unloaded	Loaded	Unloaded	Unit
Total Resistance	R_T	1,44	0,57	1,55	1,13	MN
Effective Power	EP	11,1	4,4	11,9	8,7	MW
Estimated Propulsion efficiency	η	0,6				
Main Engine Power	P	18 600	7 400	19 900	14 600	kW
Installed Main Engine Power		23 300		24 900		kW

APPENDIX D: WAVE RESISTANCE, CONCEPTUAL DESIGN

Guldhammer/Harvard's Method		Equilibrium		Conventional Tanker		
		Loaded	Unloaded	Loaded	Ballast	Unit
Length	Lpp	350	350	300	300	m
	Lwl	357	357	306	306	m
Speed	V	15	15	15	15	kn
		7,72	7,72	7,72	7,72	m/s
Froudes Number	Fn	0,13	0,13	0,14	0,14	-
Prismatic Coefficient	C_P	0,89	0,89	0,90	0,89	-
Volume Displacement	Δ/ρ	244 900	49 500	232 000	102 000	m^3
Beam/Draught	B/T	2,00	5,26	2,89	5,20	-
Slenderness Coefficient		5,71	9,72	4,98	6,55	-
Initial Wave Resistance Coefficient	C_R^*	6,0E-04	4,0E-04	8,0E-04	5,0E-04	-
Correction for Hull Roughness	C_A	-3,5E-04	-3,5E-04	-3,0E-04	-3,0E-04	-
Correction for B/T	$C_{B/T}$	-8,0E-05	4,4E-04	6,2E-05	4,3E-04	-
Correction for Trapezoid Hull Shape	C_V	1,0E-04	1,0E-04	0,0E+00	0,0E+00	-
Correction for Bulb	C_{BULB}	1,0E-04	1,0E-04	1,0E-04	1,0E-04	-
Wave Resistance Coefficient	C_R	**3,7E-04**	**6,9E-04**	**6,6E-04**	**7,3E-04**	**-**

The Excel file can be found on the CD attached to the report.

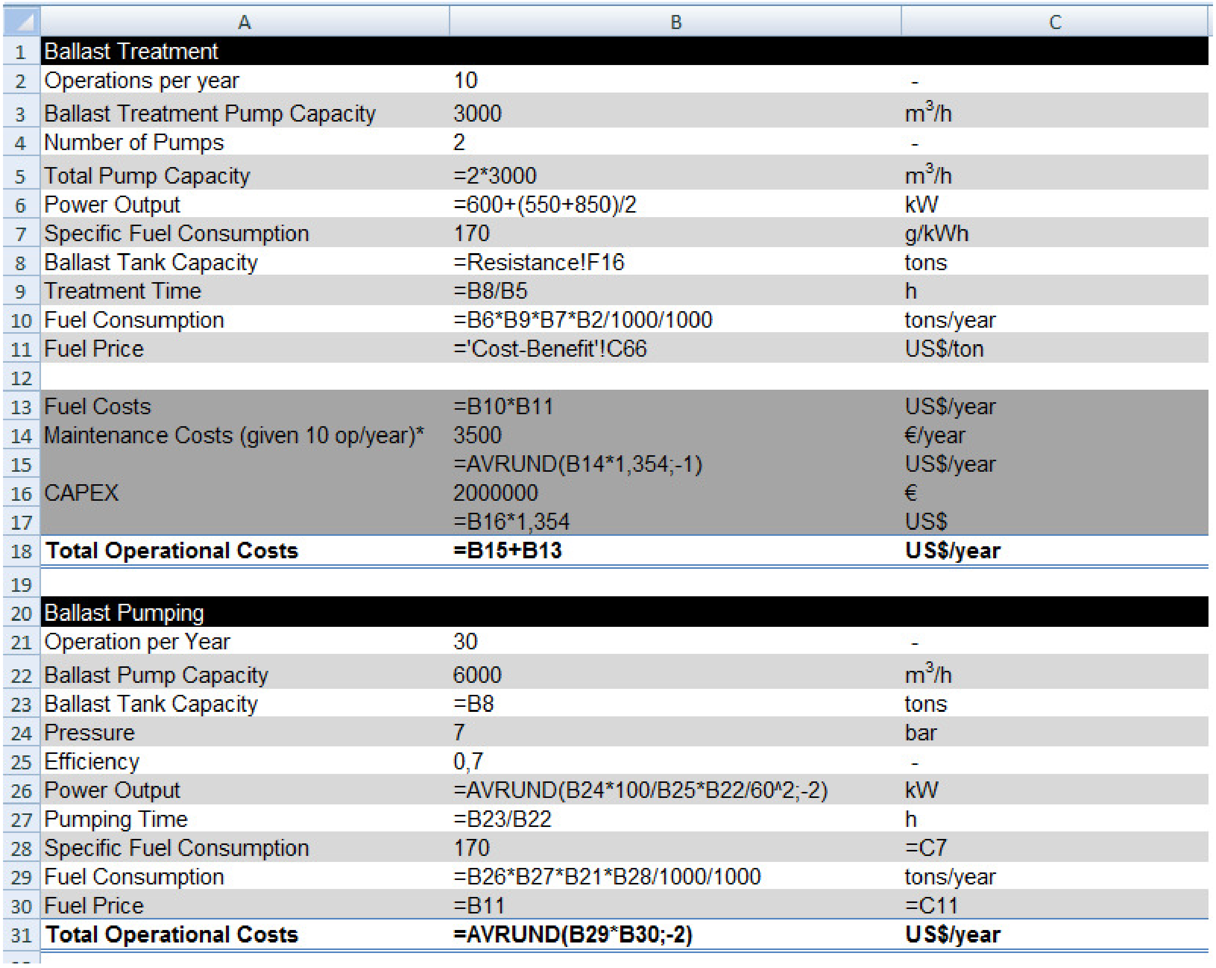
APPENDIX E: ANNUAL FUEL CONSUMPTION, CONCEPTUAL DESIGN



	A	B	C	D
1	Input*	Loaded	Unit	
2	Days in Transit, Loaded	140,2	days	
3	Transit, Empty	102,2	days	
4	Specific Fuel Consumption	170	g/kWh	
5	**Data for Frontline Suezmax tankers operating on the spot market*			
6				
7	Annual Fuel Consumption, Equilibrium vs. Comparrison			
8		Equilibrium	Conventional Tanker	
9	**Main Engine Power**			
10	Transit, Loaded	=Resistance!$C$41/1000	=Resistance!$E$41/1000	MW
11	Transit, Ballast/Empty	=Resistance!$D$41/1000	=Resistance!$F$41/1000	MW
12	**Fuel Consumption**			
13	Transit, Loaded	=B4*B10*1000*B2*24/1000/1000	=B4*C10*1000*B2*24/1000/1000	tons/year
14	Transit, Ballast/Empty	=B4*B11*1000*B3*24/1000/1000	=B4*C11*1000*B3*24/1000/1000	tons/year
15	Other Conditions	=SUMMER(D22:D27)	=SUMMER(D22:D27)	tons/year
16	Annual Fuel Consumption	=SUMMER(B13:B15)	=SUMMER(C13:C15)	tons/year
17	Fuel Price	='Cost-Benefit'!C24		US$/ton
18	Annual Fuel Cost	=B17*B16	=C16*B17	US$/year
19				
20	Fuel Consumption, Non-Transit Conditions [tons/year]			
21		Suezmax*	VLCC*	Equilibrium
22	Waiting at Sea	85	33	33
23	Waiting in Port	272	339	339
24	Maneuvering	845,44	666	666
25	Loading	128	225	=(C25+B25)/2
26	Discharging	994,724	1629	=(C26+B26)/2
27	Miscellaneous	38	38	38
28	Fuel Consumption, Non-Transit	=SUMMER(B22:B27)	=SUMMER(C22:C27)	=SUMMER(D22:D27)
29	**Data for Frontline tankers operating on the spot market*			

The Excel file can be found on the CD attached to the report.

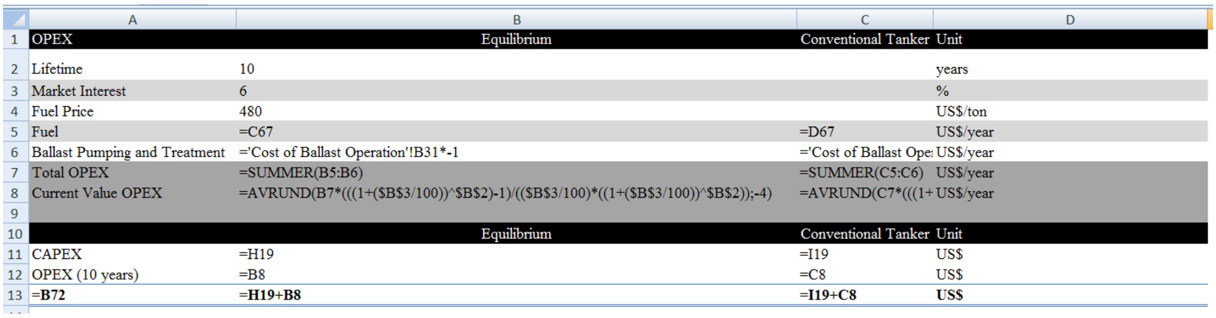
APPENDIX F: COST OF BALLAST OPERATION, CONCEPTUAL DESIGN



	A	B	C
1	Ballast Treatment		
2	Operations per year	10	-
3	Ballast Treatment Pump Capacity	3000	m^3/h
4	Number of Pumps	2	-
5	Total Pump Capacity	=2*3000	m^3/h
6	Power Output	=600+(550+850)/2	kW
7	Specific Fuel Consumption	170	g/kWh
8	Ballast Tank Capacity	=Resistance!F16	tons
9	Treatment Time	=B8/B5	h
10	Fuel Consumption	=B6*B9*B7*B2/1000/1000	tons/year
11	Fuel Price	='Cost-Benefit'!C66	US$/ton
12			
13	Fuel Costs	=B10*B11	US$/year
14	Maintenance Costs (given 10 op/year)*	3500	€/year
15		=AVRUND(B14*1,354;-1)	US$/year
16	CAPEX	2000000	€
17		=B16*1,354	US$
18	**Total Operational Costs**	**=B15+B13**	**US$/year**
19			
20	Ballast Pumping		
21	Operation per Year	30	-
22	Ballast Pump Capacity	6000	m^3/h
23	Ballast Tank Capacity	=B8	tons
24	Pressure	7	bar
25	Efficiency	0,7	-
26	Power Output	=AVRUND(B24*100/B25*B22/60^2;-2)	kW
27	Pumping Time	=B23/B22	h
28	Specific Fuel Consumption	170	=C7
29	Fuel Consumption	=B26*B27*B21*B28/1000/1000	tons/year
30	Fuel Price	=B11	=C11
31	**Total Operational Costs**	**=AVRUND(B29*B30;-2)**	**US$/year**

The Excel file can be found on the CD attached to the report.

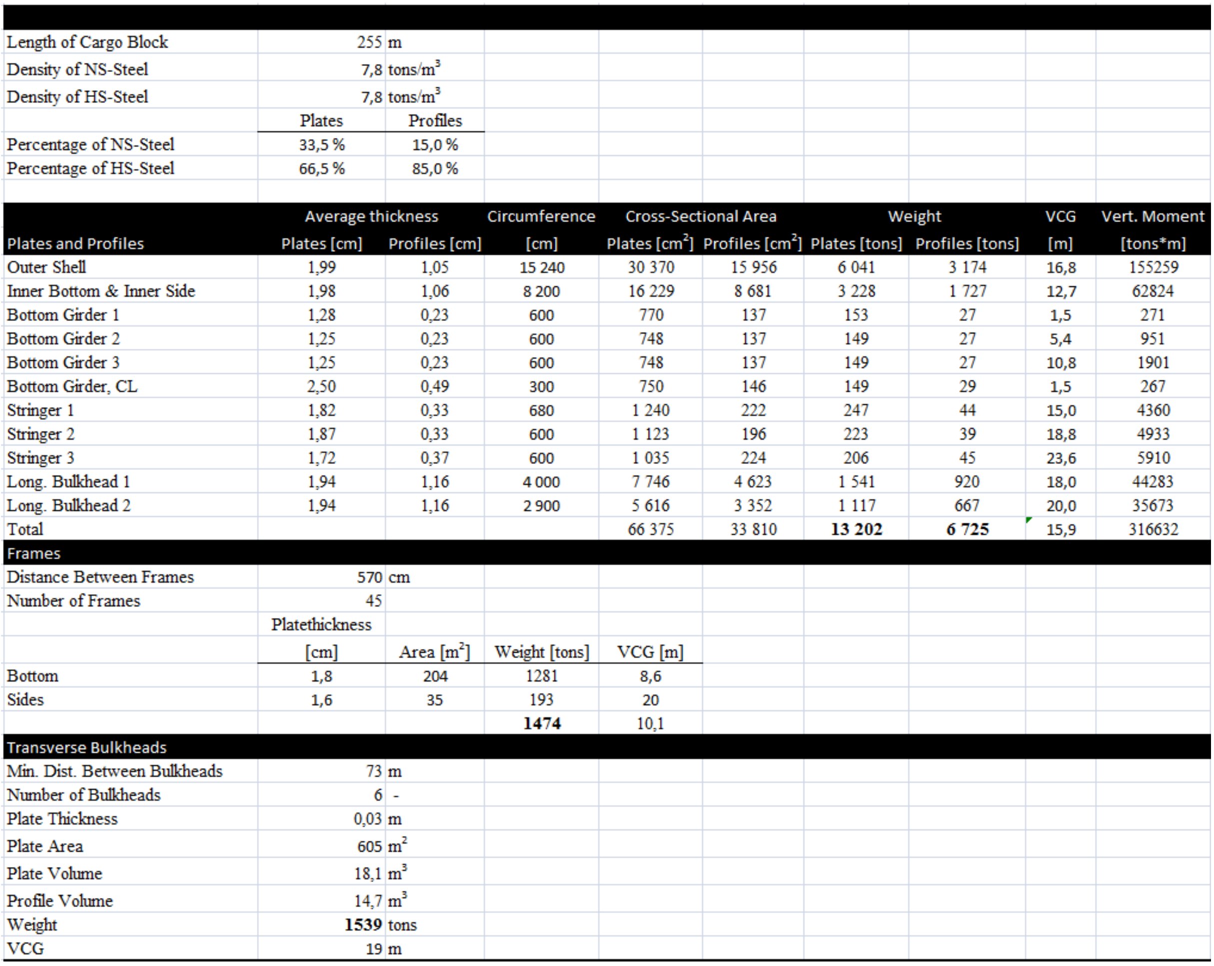
APPENDIX G: TOTAL OPERATIONAL EXPENSES, CONCEPTUAL DESIGN



	A	B	C	D
1	OPEX	Equilibrium	Conventional Tanker	Unit
2	Lifetime	10		years
3	Market Interest	6		%
4	Fuel Price	480		US$/ton
5	Fuel	=C67	=D67	US$/year
6	Ballast Pumping and Treatment	='Cost of Ballast Operation'!B31*-1	='Cost of Ballast Ope:	US$/year
7	Total OPEX	=SUMMER(B5:B6)	=SUMMER(C5:C6)	US$/year
8	Current Value OPEX	=AVRUND(B7*(((1+($B$3/100))^$B$2)-1)/(($B$3/100)*((1+($B$3/100))^$B$2));-4)	=AVRUND(C7*(((1+	US$/year
9				
10		Equilibrium	Conventional Tanker	Unit
11	CAPEX	=H19	=I19	US$
12	OPEX (10 years)	=B8	=C8	US$
13	**=B72**	**=H19+B8**	**=I19+C8**	**US$**

The Excel file can be found on the CD attached to the report.

APPENDIX H: CARGO BLOCK STEEL WEIGHT, FINAL HULL



Length of Cargo Block	255	m							
Density of NS-Steel	7,8	tons/m^3							
Density of HS-Steel	7,8	tons/m^3							
	Plates	Profiles							
Percentage of NS-Steel	33,5 %	15,0 %							
Percentage of HS-Steel	66,5 %	85,0 %							
	Average thickness		Circumference	Cross-Sectional Area		Weight		VCG	Vert. Moment
Plates and Profiles	Plates [cm]	Profiles [cm]	[cm]	Plates [cm^2]	Profiles [cm^2]	Plates [tons]	Profiles [tons]	[m]	[tons*m]
Outer Shell	1,99	1,05	15 240	30 370	15 956	6 041	3 174	16,8	155259
Inner Bottom & Inner Side	1,98	1,06	8 200	16 229	8 681	3 228	1 727	12,7	62824
Bottom Girder 1	1,28	0,23	600	770	137	153	27	1,5	271
Bottom Girder 2	1,25	0,23	600	748	137	149	27	5,4	951
Bottom Girder 3	1,25	0,23	600	748	137	149	27	10,8	1901
Bottom Girder, CL	2,50	0,49	300	750	146	149	29	1,5	267
Stringer 1	1,82	0,33	680	1 240	222	247	44	15,0	4360
Stringer 2	1,87	0,33	600	1 123	196	223	39	18,8	4933
Stringer 3	1,72	0,37	600	1 035	224	206	45	23,6	5910
Long. Bulkhead 1	1,94	1,16	4 000	7 746	4 623	1 541	920	18,0	44283
Long. Bulkhead 2	1,94	1,16	2 900	5 616	3 352	1 117	667	20,0	35673
Total				66 375	33 810	**13 202**	**6 725**	15,9	316632
Frames									
Distance Between Frames	570	cm							
Number of Frames	45								
	Platethickness [cm]	Area [m^2]	Weight [tons]	VCG [m]					
Bottom	1,8	204	1281	8,6					
Sides	1,6	35	193	20					
			1474	10,1					
Transverse Bulkheads									
Min. Dist. Between Bulkheads	73	m							
Number of Bulkheads	6	-							
Plate Thickness	0,03	m							
Plate Area	605	m^2							
Plate Volume	18,1	m^3							
Profile Volume	14,7	m^3							
Weight	**1539**	tons							
VCG	19	m							

The Excel file can be found on the CD attached to the report.

APPENDIX I: LIGHTSHIP WEIGHT CALCULATIONS, FINAL HULL

Lightship, Cargo Block	Suezmax [tons]	Equilibrium [tons]	VCG [m]	Vert. Moment [tons*m]	LCG [m]	Long. Moment [tons*m]
Hull Steel		22 940	15,7	360 749	187,5	4 301 250
Foundations	90	124	15,7	1 952	187,5	23 273
Welding and Tolerances	300	414	15,7	6 506	187,5	77 577
Mooring Equip., Amidships	50	50	26,5	1 325	150,0	7 500
Other Deck Equipment	100	100	26,5	2 650	150,0	15 000
Paint	190	262	15,7	4 121	187,5	49 132
Piping	100	138	3,0	414	150,0	20 687
Total		**24 030**	**15,7**		**187,0**	

Lightship, Aft Ship	Suezmax [tons]	Equilibrium [tons]	VCG [m]	Vert. Moment [tons*m]	LCG [m]	Long. Moment [tons*m]
Hull Steel		2428	17,7	43 033	35	84 969
Hull Steel, Deckhouse	500	500	36,0	18 000	35	17 500
Foundations	90	13	17,7	233	35	460
Welding and Tolerances	300	44	17,7	776	35	1 533
Rudder/Propeller/Stearing Gear	275	462	3,0	1 385	5	2 308
Mooring Equip., Aft	50	50	26,5	1 325	10	500
Paint	190	28	17,7	492	35	971
Accommodation Outfit	350	350	36,0	12 600	35	12 250
Lifesaving Equipment	40	40	32,0	1 280	35	1 400
Cargo Systems	350	587	15,0	8 811	50	29 371
Heating/Cleaning/IGS	200	336	15,0	5 035	50	16 783
Main Engine	500	839	6,0	5 035	40	33 567
Auxiliary Engine	150	150	10,0	1 500	40	6 000
Other Machinery Equipment	200	200	10,0	2 000	40	8 000
Machinery Outfit	150	150	10,0	1 500	40	6 000
Electrical	120	120	26,5	3 180	40	4 800
Total		**6 300**	**16,9**		**35,9**	

Lightship, Forward Part	Suezmax [tons]	Equilibrium [tons]	VCG [m]	Vert. Moment [tons*m]	LCG [m]	Long. Moment [tons*m]
Hull Steel		2549	15,2	38 806	330	841 078
Hull Steel, Forecastle	200	336	29,0	9 734	345	115 805
Welding and Tolerances	300	46	15,2	700	330	15 170
Anchor and Mooring Equipment	250	250	26,5	6 625	330	82 500
Foundations	90	14	15,2	210	330	4 551
Welding and Tolerances	300	46	15,2	700	330	15 170
Paint	190	29	15,2	443	330	9 607
Total		**3 270**	**17,5**		**331,5**	

The Excel file can be found on the CD attached to the report.

APPENDIX J: GROSS VOLUME CALCULATIONS, FINAL HULL

The gross volume is divided in three main categories:

1. Crew facilities
    - Crew accommodation
    - Crew common spaces
    - Corridors
    - Stairs
2. Service facilities
    - Wheelhouse
    - Offices
    - Sickbay
    - Cargo control room
    - Galleys
    - Stores
    - Garbage
    - Hotel storage
    - Air condition room
    - Deck stores and workshop
    - Swimming pool
3. Machinery and tanks
    - Engine room
    - Cargo handling
    - Steering gear
    - Switchboard
    - Cargo control
    - Workshop and stores
    - Emergency generator, battery room
    - Engine casing, funnel
    - Fuel
    - Lub oil
    - Fresh water
    - Sewage holding
    - Void spaces (double hull)
    - Mooring decks

The required spaces are calculated using empirical data from the world fleet (Levander, 2006) and main parameters of Equilibrium, such as size of crew, size of installed engine power, speed, route etc.

Crew Facilities

The number of crew on a VLCC varies from 20 to over 40. As Equilibrium will have new systems and surveillance technology onboard, a crew size of 20 is assumed. It is given high priority to leisure activities for the crew, so the ship is equipped with a gymnasium, swimming pool and hobby room. Coefficients for m^2/crew, m^2/seat, cabin size etch are all from (Levander, 2006, s. 64).

TABLE 41: CREW SPACES

Crew Accommodation						
Cabin Category:	Number of Cabins [-]	Beds per Cabin [-]	Size [m^2]	Height [m]	Area [m^2]	Volume [m^3]
Officer Large Suite	2	1	24	2,8	48	134
Officer	6	1	12	2,8	72	202
Crew	8	1	12	2,8	96	269
Repair	2	2	12	2,8	24	67
Total Crew	**20**		**12,0**	**m^2/crew**	**240**	**672**
Suez Crew	1	4	12,0	2,8	12	34
Cabin Corridors, Wall Lining	30	% of cabin area		2,8	72	202
Crew Cabin Area	**19**	**24**	**16,2**	**m^2/crew**	**324**	**907**

Crew Common Spaces						
Name / Use of Space	Seats	m^2/seat	m^2/crew	Height [m]	Area [m^2]	Volume [m^3]
Officer Mess	8	2,0	0,80	2,8	16	44,8
Officer Dayroom	8	2,0	0,80	2,8	16	44,8
Crew Mess	16	1,8	1,44	2,8	29	80,64
Crew Dayroom	16	1,8	1,44	2,8	29	80,64
Gymnasium			1,00	2,8	20	56
Swimming Pool			1,00	2,8	20	56
Hobby Room			1,00	2,8	20	56
Crew Common Spaces			**7,48**	**m^2/crew**	**150**	**419**

Crew and Emergency Stairways						
Name / Use of Stair	Decks	m^2/deck	m^2/crew	Height [m]	Area [m^2]	Volume [m^3]
Main Stairs	8	16	6,40	2,8	128	358
Engine Room Stairs	6	15	4,50	3,2	90	288
Crew and Emergency Stairways			**10,90**	**m^2/crew**	**218**	**646,4**

Total Crew Facilities	**35**	**m^2/crew**	**690**	**1970**

Service Facilities

Coefficients for m^2/crew and room heights are extracted from (Levander, 2006, s. 65). The calculations are based on a container ship. It is assumed that the cargo control room in Equilibrium takes as much space as a cargo handling room in a container ship.

TABLE 42: SERVICE SPACES

Ship Service				
Name / Use of Space:	m^2/crew	Height [m]	Area [m^2]	Volume [m^3]
Wheelhouse	4,00	2,8	80	224
Offices	1,00	2,8	20	56
Sickbay	1,00	2,8	20	56
Cargo Control	1,00	2,8	20	56
Ship Service Spaces	**7,00**		**140**	**392**

Catering Spaces				
Name / Use of Space	m^2/crew	Height [m]	Area [m^2]	Volume [m^3]
Galleys	1,00	3,0	20	60
Provision Store	1,50	3,0	30	90
Garbage	0,50	2,8	10	28
Catering Spaces	**3,00**		**60**	**178**

Hotel Spaces				
Name / Use of Space	m^2/crew	Height [m]	Area [m^2]	Volume [m^3]
Laundry and Linen Store	1,00	2,8	20	56
Hotel Store	1,00	2,8	20	56
Hotel Services	**2,00**		**40**	**112**

Total Service Facilities	**12**	**m^2/crew**	**240**	**682**

Technical Spaces in the Accommodation				
Name / Use of Space	m^2/crew	Height [m]	Area [m^2]	Volume [m^3]
Air Conditioning Rooms	3,00	2,8	60	168
Deck Stores and Workshops	1,00	2,8	20	56
Swimming Pool	1,00	2,8	20	56
Other Technical Spaces	0,50	2,8	10	28
Total Technical Spaces	**5,50**		**110**	**308**

Machinery and Tanks

The main engine power is calculated in chapter 5.4 while the size of the auxiliary engines and boilers are assumed by (Lalic, 2010). The coefficient for deciding the space for the main engine room is the same as for a container ship, and it is assumed that the cargo handling machinery like the pumps as the boilers require as much spaces in m^3/kW as the main engine. The remaining coefficients for deciding the other machinery spaces are extracted from (Levander, 2006, s. 67).

The size of the tanks for fuel oil, lub oil, fresh water and sewage are calculated based on the ships fuel consumption, range and endurance. The specific fuel consumption is a conservative value based on an assumed average between the specific fuel consumption in loaded and unloaded condition. The range is sufficient for the ship to be able to operate all the major routes on the market. Coefficients for consumption of lub oil, fresh water and sewage holding are extracted from (Levander, 2006, s. 67), so are the spaces required for outdoor deck spaces.

The void spaces are very big in Equilibrium because of the required double hull and the spaces between the collision bulkhead and the bulb. These spaces are roughly calculated by studying the hull model in DelftShip,

TABLE 43: MACHINERY AND TANK SPACES

Installed Power		
Main Engine Power	28 600	kW
Auxiliary Engines	2 000	kW
Boilers	20 000	kW

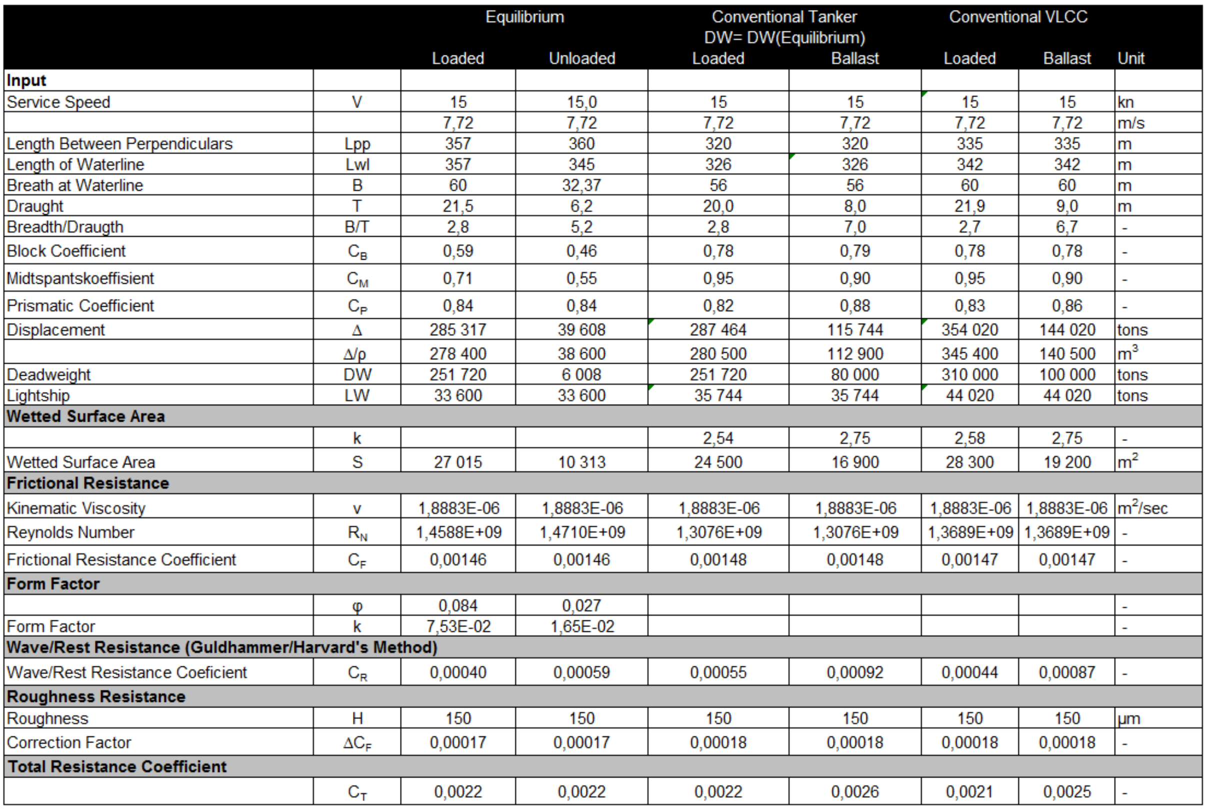
Machinery Spaces						
Name/Use of Space:		m^2/kW	m^3/kW	Height [m]	Area [m^2]	Volume [m^3]
Engine Room			0,400			11 440
Cargo Handling			0,400			8 000
Steering Gear		0,004	0,013	3,2	114	366
Switchboard Rooms		0,002	0,006	3,2	57	183
Cargo Handling Control Rooms		0,002	0,006	3,2	57	183
Workshops and Stores		0,003	0,010	3,2	86	275
Emergency generator, Battery room		0,001	0,003	2,8	29	80
	Decks	m^2/deck				
Engine Casing, Air Intakes	3	100		3	300	900
Funnel		50		10		500
Technical Spaces			**0,84**	**m^3/DWT**	**640**	**21 900**

Tanks and Void Spaces						
Name/Use of Space:	Consump. [g/kWh]	Consump. [ton/day]	Range [nm]	Endurance days	Margin factor	Volume [m^3]
Fuel Oil	180	83	20 000	55,6	1,4	7168
Lub Oil	1,5	1	20 000	55,6	4	154
	l/crew/days					
Fresh Water	200	4		60	1,2	288
Sewage Holding	75	2		60	0,2	24
Void Spaces (Double Hull)						64000
Tanks and Void Spaces						**71634**

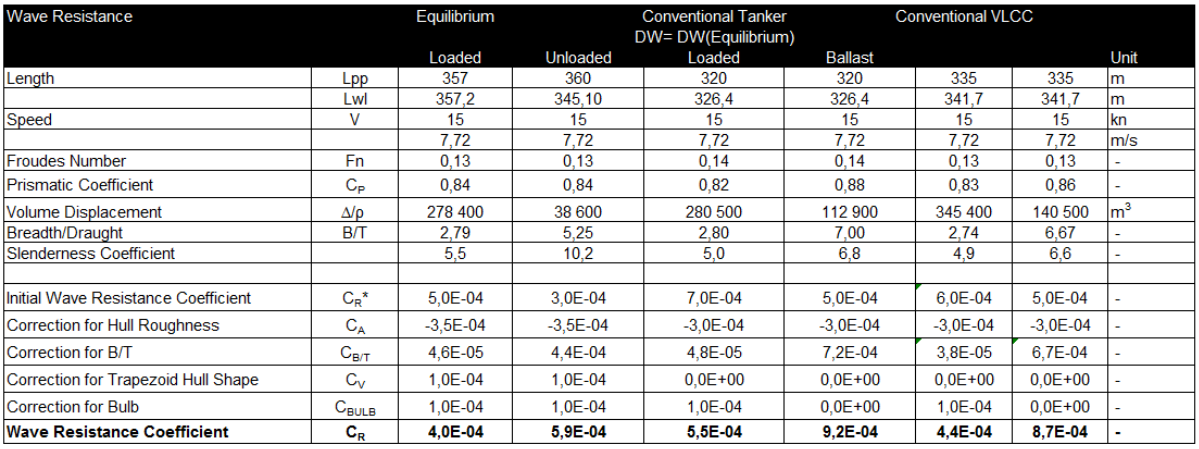
Outdoor Deck Spaces						
Name/Use of Deck:	Length [m]	Breath [m]	m^2/crew	Covered %	Area [m^2]	Volume [m^3]
Mooring Deck Forward	15	25	18,75	100	375	1125
Mooring Deck Aft	10	32	16,00	0	320	
Crew Deck			2,00	50	40	60
Outdoor Deck Spaces					**735**	**1185**

The Excel file can be found on the CD attached to the report.

APPENDIX K: RESISTANCE COMPARISON, FINAL HULL



		Equilibrium		Conventional Tanker DW= DW(Equilibrium)		Conventional VLCC		
		Loaded	Unloaded	Loaded	Ballast	Loaded	Ballast	Unit
Input								
Service Speed	V	15	15,0	15	15	15	15	kn
		7,72	7,72	7,72	7,72	7,72	7,72	m/s
Length Between Perpendiculars	Lpp	357	360	320	320	335	335	m
Length of Waterline	Lwl	357	345	326	326	342	342	m
Breath at Waterline	B	60	32,37	56	56	60	60	m
Draught	T	21,5	6,2	20,0	8,0	21,9	9,0	m
Breadth/Draugth	B/T	2,8	5,2	2,8	7,0	2,7	6,7	-
Block Coefficient	C_B	0,59	0,46	0,78	0,79	0,78	0,78	-
Midtspantskoeffisient	C_M	0,71	0,55	0,95	0,90	0,95	0,90	-
Prismatic Coefficient	C_P	0,84	0,84	0,82	0,88	0,83	0,86	-
Displacement	Δ	285 317	39 608	287 464	115 744	354 020	144 020	tons
	Δ/ρ	278 400	38 600	280 500	112 900	345 400	140 500	m^3
Deadweight	DW	251 720	6 008	251 720	80 000	310 000	100 000	tons
Lightship	LW	33 600	33 600	35 744	35 744	44 020	44 020	tons
Wetted Surface Area								
	k			2,54	2,75	2,58	2,75	-
Wetted Surface Area	S	27 015	10 313	24 500	16 900	28 300	19 200	m^2
Frictional Resistance								
Kinematic Viscosity	v	1,8883E-06	1,8883E-06	1,8883E-06	1,8883E-06	1,8883E-06	1,8883E-06	m^2/sec
Reynolds Number	R_N	1,4588E+09	1,4710E+09	1,3076E+09	1,3076E+09	1,3689E+09	1,3689E+09	-
Frictional Resistance Coefficient	C_F	0,00146	0,00146	0,00148	0,00148	0,00147	0,00147	-
Form Factor								
	φ	0,084	0,027					-
Form Factor	k	7,53E-02	1,65E-02					-
Wave/Rest Resistance (Guldhammer/Harvard's Method)								
Wave/Rest Resistance Coeficient	C_R	0,00040	0,00059	0,00055	0,00092	0,00044	0,00087	-
Roughness Resistance								
Roughness	H	150	150	150	150	150	150	μm
Correction Factor	ΔC_F	0,00017	0,00017	0,00018	0,00018	0,00018	0,00018	-
Total Resistance Coefficient								
	C_T	0,0022	0,0022	0,0022	0,0026	0,0021	0,0025	-



Wave Resistance		Equilibrium		Conventional Tanker DW= DW(Equilibrium)		Conventional VLCC		
		Loaded	Unloaded	Loaded	Ballast			Unit
Length	Lpp	357	360	320	320	335	335	m
	Lwl	357,2	345,10	326,4	326,4	341,7	341,7	m
Speed	V	15	15	15	15	15	15	kn
		7,72	7,72	7,72	7,72	7,72	7,72	m/s
Froudes Number	Fn	0,13	0,13	0,14	0,14	0,13	0,13	-
Prismatic Coefficient	C_P	0,84	0,84	0,82	0,88	0,83	0,86	-
Volume Displacement	Δ/ρ	278 400	38 600	280 500	112 900	345 400	140 500	m^3
Breadth/Draught	B/T	2,79	5,25	2,80	7,00	2,74	6,67	-
Slenderness Coefficient		5,5	10,2	5,0	6,8	4,9	6,6	-
Initial Wave Resistance Coefficient	C_R*	5,0E-04	3,0E-04	7,0E-04	5,0E-04	6,0E-04	5,0E-04	-
Correction for Hull Roughness	C_A	-3,5E-04	-3,5E-04	-3,0E-04	-3,0E-04	-3,0E-04	-3,0E-04	-
Correction for B/T	$C_{B/T}$	4,6E-05	4,4E-04	4,8E-05	7,2E-04	3,8E-05	6,7E-04	-
Correction for Trapezoid Hull Shape	C_V	1,0E-04	1,0E-04	0,0E+00	0,0E+00	0,0E+00	0,0E+00	-
Correction for Bulb	C_{BULB}	1,0E-04	1,0E-04	1,0E-04	0,0E+00	1,0E-04	0,0E+00	-
Wave Resistance Coefficient	$\mathbf{C_R}$	**4,0E-04**	**5,9E-04**	**5,5E-04**	**9,2E-04**	**4,4E-04**	**8,7E-04**	**-**

The Excel file can be found on the CD attached to the report.