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DIVISION OF SHIP DESIGN AND SEA TRANSPORTATIONS

Comparative Economic and Environmental Study of Liquefied Natural Gas (LNG) carrying Vessels with the Use of the Life Cycle Analysis

MASTER THESIS

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Contents

List of Symbols

B	Breadth	[tn]
C	Cargo Capacity	[m^3]
C_B	Block Coefficient	
Δ	Displacement	[tn]
D	Depth	[tn]
Dist	Distance travelled	[m]
Dneca	Distance travelled within Neca area	[m]
Dseca	Distance travelled within Seca area	[m]
Dwhr	Distance using WHR system	[m]
l_B	Bulkheads Welding Length	[m]
l_{LS}	Longitudinal Stiffeners Welding Length	[m]
l_P	Plates Welding Length	[m]
l_{TS}	Transverse Stiffeners Welding Length	[m]
L	Length (assumed to be the L_{BP} – Length Between Perpendiculars)	[m]
N_B	Number of Bulkheads	
P_{AE}	Auxiliary Engines’ Power	[KW]
P_{ME}	Main Engines’ Power	[KW]
T	Draft	[m]
t_1	Loaded Voyage Time	[h]
t_2	Ballast Voyage Time	[h]
t_3	Manoeuvring Time	[h]
t_4	Loading Time	[h]
t_5	Unloading Time	[h]
t_6	Loaded Time in Seca Area	[h]
t_7	Unloaded Time in Seca Area	[h]
t_8	Loaded Time in Seca Area	[h]
t_9	Unloaded Time in Seca Area	[h]
W_{MM}	Main Machine Weight	[tn]
W_{MR}	Residual Machinery Weight	[tn]
W_{MS}	Shaft Machinery Weight	[tn]
W_M	Machinery Weight	[tn]
W_{OT}	Outfit Weight	[tn]
W_{ST}	Steel Weight	[tn]

List of Abbreviations

ADBOG	Average Density of BOG	[kg/m^3]
ARS	Amount of Replaced Steel	[tn]
BOG	Boil Off Gas	
CAPEX	Capital Expenditure	
CH_4	Methane	
CLO	Cylinder Lub Oil	
CO_2	Carbon Dioxide	
CO	Carbon Monoxide	
COGES	Combined Cycle Gas Turbine Electric & Steam Turbine	
DFDE	Dual Fuel Diesel Electric	
DWT	Deadweight Tonnage	[tn]
EC	Energy Demand for Steel Cutting	[KW/tn]
ECA	Emission Control Area	
EDA	Energy Demand for Auxiliary	[KJ/h]
EDP	Energy Demand for Propulsion	[KJ/h]
EW	Energy Demand for Steel Welding	[KW/m]
EGR	Exhaust Gas Recirculation	
FC	Fuel Consumption	[tn]
FS	Frame Spacing	[m]
GHG	Green House Gases	
GT	Gas Turbine	
HFO	Heavy Fuel Oil	
IMO	International Maritime Organization	
ISO	International Organization for Standardization	
LCA	Life Cycle Assessment	
LHVHFO	Lower Heating Value of HFO	[KJ/kg]
LHVLNG	Lower Heating Value of LNG	[KJ/kg]
LHVMDO	Lower Heating Value of MDO	[KJ/kg]
LHVMGO	Lower Heating Value of MGO	[KJ/kg]
LNG	Liquefied Natural Gas	
LO	Lub Oil	
MARPOL	International Convention for the Prevention of Pollution from Ships	
MBOG	Mass of BOG	[kg]
MCR	Maximum Continuous Rating	[KW]
MDO	Marine Diesel Oil	
MGO	Marine Gas Oil	
NECA	Nitrous Oxide Emission Control Area	

Necacomp	Means of Neca compliance	
NMVOC	Non Methane Volatile Organic Compound	
NO_x	Nitrogen Oxides	
NPV	Net Present Value	
OPEX	Operational Expenditure	
Paux	Auxiliary Power	[KW]
Pengine	Engine Power	[KW]
PM	Particulate Matters	
Pprop	Power at Propeller	[KW]
PC	Propulsive Coefficient	
PT	Power Turbine	
SCR	Selective Catalytic Reduction	
SEC	Specific Energy Consumption	[KJ/KWh]
SECA	Sulphur Oxide Emission Control Area	
Secacomp	Means of Seca compliance	
SFOC	Specific Fuel Oil Consumption	[kg/KWh]
SHP	Shaft Horsepower	[KW]
SLO	System Lub Oil	
SO_x	Sulphur Oxides	
ST	Steam Turbine	
TFDE	Tri- Fuel Diesel Electric	
TMPly	Total Mass of Plywood	[kg]
TMInvar	Total Mass of Invar	[tn]
TWPly	Total Weight of Plywood	[kg]
TWInvar	Total Weight of Invar	[tn]
VBOG	Volume of BOG	[m^3]
WHR	Waste Heat Recovery System	

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Abstract

In this Master Thesis the Life Cycle Assessment method is applied to a series of LNG Carriers in order to compute the total environmental impact of their construction and operation. For the fulfillment of this target a computational code is produced in *Matlab*.

In order to enhance the ability of the code to perform calculation for a wide variety of vessels and not only the pre-selected, a linear regression analysis is performed in the existing fleet. This permits the user of the code to carry out life cycle calculations even for not existing vessels, for which some of the data are not available. Furthermore, this analysis demonstrates the trends in both the cargo capacity of the vessels and their propulsion configurations. The above results are presented in Chapters 3, 4 and 7.

In each vessel, a Life Cycle Cost analysis is applied in each of the above combinations of vessels and engine sets. More specifically, the cost of the construction of the vessels and of each propulsion option is calculated, providing the initial acquisition cost. Moreover, the operational cost is calculated, depending mainly to the fuel costs.This is the content of Chapter 6.

Finally, in Chapter 8 a set of propulsion configurations is applied, so the environmental impact of each can be assessed. In addition some of the above configurations are examined in combination with additional devices (such as Scrubber, SCR, WHR), so that the vessels comply with the new stringent environmental legislation, while at the same time a reduction of the fuel consumption, and thus the operational cost, may be reduced.

The above allow to compare a variety of vessels, each one of them being studied with regard of a series of propulsion configurations, demonstrating the different environmental impact of each combination.

The concluding result is a correlation of both the environmental and the economic impact of each vessel, allowing a comparison of both factors for the vessels involved.

I. Introduction

One of the most important challenges that humanity faces is how its activities will be able to simultaneously achieve the maximum economic benefit and the least environmental and social impact. It is today a common sense that the satisfaction of the needs of the present generation must not jeopardize the fulfilment of the needs of the upcoming generations, and not adversely impact the quality of their lives. The last decades this fact has turned research in the technology sector on the one hand to an effort to mitigate the energy and material consumption for the fulfilment of human activities, and on the other hand led to the exploitation of "clean" energy sources. Nevertheless, before these targets are being accomplished, it is necessary to record the environmental impact of the aforementioned activities, in order to seek alternative solutions.

The Life Cycle Assessment *(LCA*) methodology provides a reliable and consistent tool to measure the total environmental footprint of a given system (onwards called ship), following a holistic approach taking into account the environmental implications caused by the system, from the beginning of its construction up to its dismantling (*cradle to death approach*).

The aim of this master thesis is to use data that concern both the construction and the functional parameters of a vessel carrying liquefied natural gas (*LNG Carrier*), thus to assess the total environmental footprint of the vessels by the use of the LCA method. For the accomplishment of this target, a series of typical LNG Carriers is selected and an indicative operation scenario is studied for a life period of 25 years. Their total lifespan is divided into three discrete periods. These concern their construction, the period of their economic operation, and, finally, their dismantling, respectively. In each period the environmental footage of the vessels is assessed by the monitoring of the pollutants produced by them, leading to the conduction of a pollutants' inventory. Furthermore, emphasis is given to the assessment of energy consumption which is required during the construction and dismantling phases.

Referring to the vessels construction, statistical data are used to estimate the impact of the construction of each specific vessel to the environment. In the case of the ship's operation data concerning its itineraries (speed and days of trip) are recorded so that an estimation of each vessel's fuel consumption, and thus air pollutants, are calculated. These calculations must concern the total economic life of each vessel. Finally, concerning the dismantling procedure, the environmental impact of breaking- down each ship is assessed, mainly by assumptions derived from data of the production phase. In any case, the present thesis aims to provide a guide for the ratification both of the amount of materials and energy needed for the construction and the operation of the system-ship, but also of the pollutants that it produces.

Apart from the environmental impact, the economic parameters of each vessel is examined in terms of its construction and operational cost. This enables one to estimate both of the previous factors that determine the sustainability of the system. This is dictated by the need to accomplish both the ecological and economic demands, leading to an appropriate selection of the solution that simultaneously accomplishes the previous requirements. This allows a paradigm shift, where environmental protection should no more be considered as a simple restriction, but a rather useful tool which also gives optimum economic solutions.

II. LNG CARRIERS

II.1 Brief History

At the end of 2016 the total world LNG Carriers' (LNGC) fleet consisted of 439 vessels. Tank storage capacity grows as larger vessels are constructed in order to obtain a better cost rate per amount of transported LNG, implying principles of economy of scale. At the same time there were 121 vessels under order to be delivered by 2022. However, a clear inconsistency between the growing tonnage availability and the stagnant liquefaction capacity is observed. This may explain the squeezed charter rates to historic lows [1].

Concurrently, the expansion of the Panama Canal expansion allows now about 91% of the global LNG fleet to pass through it. Nevertheless, the anticipated shipment of LNG to Asia through the canal is not accomplished, causing yet another disappointment in the market. These facts have led to a sharp decrease of newbuilding orders, i.e from 28 orders in 2015 to only 6 in 2016. Moreover, of these vessels only 66% have specific contracts, meaning that the others have been ordered on a speculative basis [1].

Things may become more optimistic if the niche market of F*loating Storage & Reliquefaction Units* (*FSRUs*) is taken into account. FSRUs may prove an ideal solution for markets that intend to shift from expensive or environmental harmful fuels, that are forced to import LNG and simultaneously are not able to afford the cost of a shore reliquefaction plant. Already shipowners have pre-ordered items for a possible future conversion of existing vessels. With these parts ready, the conversion may last 6-8 months. Older tonnage may also be withdrawn from oceangoing service and operate as FSRUs [1].

The first reported shipment of LNG was delivered to UK from USA on Jan 15th 1959. The vessel was a converted cargo vessel, named *Methane Pioneer*. Its capacity was 5000 m^3 [see Picture 1]. It's success persuaded Shell® to order the first purpose built steam powered LNG Carriers, with a capacity of 27000 m^3, to be engaged in the shipment of Algerian gas in mid 60's, while in the late 60's two steam powered vessels, with capacity of 71000 m^3, were built to transfer LNG from Alaska to the power demanding Japan market. Since then the size of the LNG Carriers has seen a gradual increase over the last decades [2] (see also Picture 2]. Considering the average capacities, that of 125000 m^3, popular in the 70's, was shifted to 138000 m^3 in the 90's and, even more increased up to 145000 m^3 in mid 00's. In 2007 the capacity of LNGCs was boosted in its ever-high level of 266000 m^3, with the introduction of *Q-flex* and *Q-max* type vessels [see Picture 3], both types ordered by *Qatar GAs Transport Company (Nakilat®)* and constructed in three South Korean shipyards: Hyundai Heavy Industries (HHI), Daewoo Shipbuilding & Marine Engineering Company (DSME) and Samsung Heavy Industries (SHI), namely. After that, the capacity seems to have reached an upper threshold and newbuilding orders nowadays stand to more modest capacities, with 170000 m^3 considered as a typical one, still being enhanced in comparison to those of the 00's [3].

Picture 1 Methane Pioneer [4]

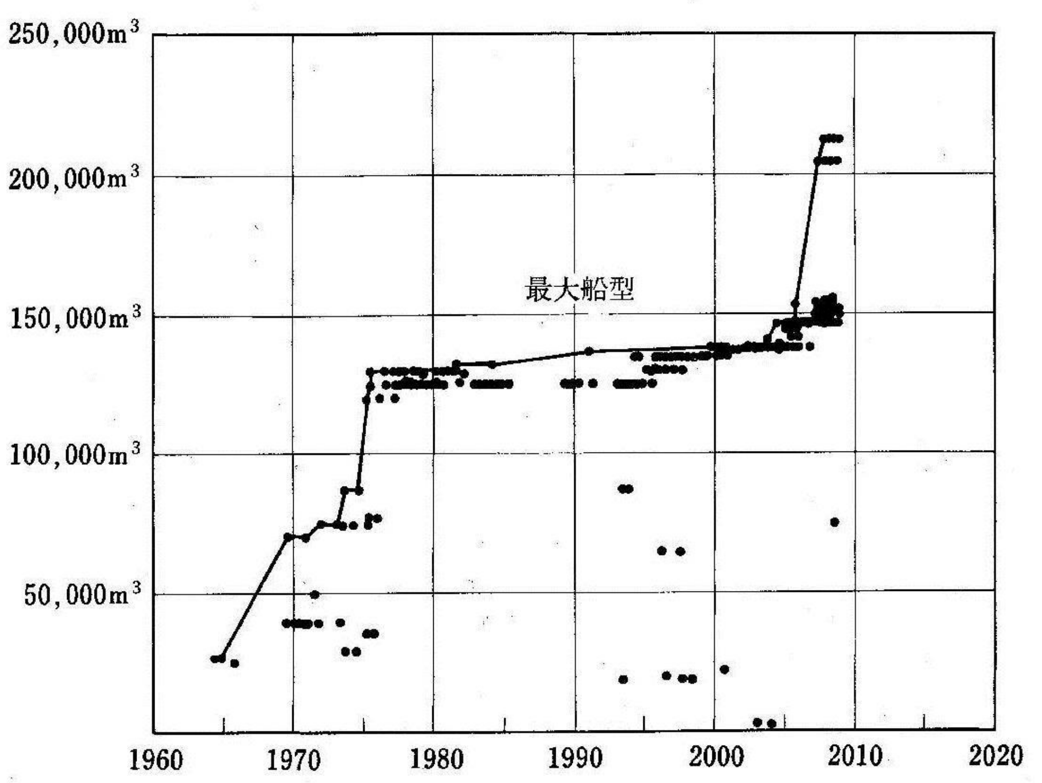


Figure 1 Historical capacity development of LNG fleet [3]

Picture 2 Size comparison of a conventional and a Q-flex LNG Carriers in DSME shipyard, South Korea [3]

When considering an order for a new vessel, the intended trading pattern of the latter should be well examined (at least in the case the vessel is intended to operate for years under the same contract), as the specifications of the ports in which the vessels will operate may inevitably impose size limitations, the LOA and the Draft being the most important as the first one might be restricted by the available turning basin, while the latter by the depth of the port in which the vessel loads or unloads its cargo.

LNG is transported at a temperature of about -163 °C and at near atmospheric pressure. Since the cargo tanks cannot be perfectly insulated, a certain amount of LNG returns to its original gaseous form (*Boil-off Gas/BOG*). A typical daily boil-off rate is about 0.13% of the cargo capacity (albeit the fact that in this thesis different boil-off rates are taken into account for various operational phases of the vessel – as assumed in [5]). The BOG cannot remain in the cargo tanks. Furthermore, because of its adverse effect as a greenhouse gas, it cannot be released to the atmosphere. Thus two solutions are implied: The BOG might either be reliquefied, and returned to the cargo tanks, or be burnt. Obviously, it is worth to be used as an extra fuel for propulsion. For many years, the only propulsion configuration able to burn concurrently BOG and a liquid fuel was the Steam Turbine [2]. Thus, as seen in the previous paragraphs, almost the entire fleet of LNG vessels had installed steam turbines. The main reasons justifying this option were the ability of steam boilers to utilize the BOG. Furthermore, at that time the majority of the large vessels (tankers, containerships, passenger liners) were equipped with steam turbines. The shift to diesel engines was necessitated due to the oil crisis of the 70's, as the thermal efficiency of diesel engines was significantly higher, compared to steam turbines. The LNG Carriers, with the BOG would stand as the last haven for steam turbines in marine applications.

The transition from steam to diesel engines occurred in the 00's. In 2004 a 1100 m^3 LNGC entered into service marking the entrance of diesel electric Propulsion in the LNG Carriers' market. It was followed by two significantly larger LNG Carriers delivered to *GDF SUEZ* (75000 m^3 and 155000 m^3, respectively). In 2007 the aforementioned *Q-flex* ships introduced the use of two- stroke slow-speed diesel engines with a reliquefaction plant to handle the BOG [2]. Further developments were the introduction of two- stroke slow-speed dual fuel engines, which are able to combine the thermal efficiency of the two –stroke engines with the ability to burn BOG. There have been two competing designs made by the two giant manufacturers namely *MAN* and *Wartsila*, each of them utilizes different concepts to achieve this goal [6]. Recently improvements have been made in the steam cycles: One is the utilization of a reheated cycle as presented by Japanese makers, in order to compete with the dual fuel engines, and the second is a concept of combined gas and steam turbine electric propulsion, which has been approved but not yet applied to existing vessels up to now [7].

In the course of the years there have also been variations in the containment system utilized by the vessels. The most traditional system was the *Moss-Rosenberg* design which was first installed in 1971. It is well perceivable due its independent spherical tanks that exceed the vessels hull. The second system is the membrane-type, *with Gaztransport and Technigaz (GTT*) being the dominant manufacturer. At the end of 2016, 74% of the active vessels were equipped with a membrane- type containment system. In addition, 93% of the vessels on order would be equipped with the membrane – type system demonstrating the prevailance of this system [1], (see also Pictures 4, 5 and 6).

Picture 3 Comparisson of a Moss-type and a Membrane type LNG Carrier [3]

Picture 4 Interior of a Moss Type LNG tank [3]

Picture 5 Interior of a GTT Membrane Type LNG tank [3]

II.2 Insulation

Both containment systems mentioned in the previous section employ an extensive insulation to keep the low temperature of the LNG, minimizing the regasification of the cargo. However, a certain amount of LNG inevitably will return to its initial gaseous form. This phenomenon is called Boil-off. The daily rate of Boil-off (BOR) stands approximately at 0.15% of the cargo. Though, it is worthy to mention that this rate depends on the type of insulation, which in turn depends on the containment system. Consequently, recent developments in the systems have reduced daily BOR as low as 0.08% [1].

The evolution in the containment systems led to the transition of BOR 0.25% in the 1970s to 0.15% in the 1980s, and then to 0.125% in 2003, and today's values lower than 0.08% [8].

Below, some further details concerning the type of tanks mentioned in the end of section 2. 1, are given.

Moss Type

Tanks of this type are constructed from an aluminium alloy containing approximately 9% Ni. A common practice is to retain an amount of the cargo equal roughly to 5-10% of it in the tank after the unloading. This allows the cooling of the tanks when empty, thus avoiding a sudden cooling during the loading procedure, which could cause damage to the tanks. The tanks retain a pressure of about 22kPa. The BOR is approximately 0.1%. The thickness of the tank is 28-32 mm in the poles and almost 160mm at the equatorial ring [8, 10].

Regarding the most important membrane type designs, we have:

GTT No. 96

In this type there are two thin invar membranes forming the primary and secondary barriers. Between them there is a (primary) insulation of plywood boxes filled with perlite. A similar layer of perlite filled boxes is used as a secondary insulation. Invar is a stainless steel alloy containing 36% Ni and 0.2% C. The thickness of the membranes is of 0.7mm. Due to their low coefficient of thermal expansion, no corrugation or expansion joints are necessary. The thickness of the plywood boxes varies between 200-300mm. In more recent variations, instead of plywood, the boxes are made of glass wool reducing the BOR to 0.115% in contrast to 0.125% of the former system [8,9, 10] (also see Pictures 7 and 8).

GTT MK III

In this system, the primary insulation in use is constructed by corrugated stainless steel with 1.2 mm thickness, allowing the thermal expansion of the tanks. A second layer is then applied, consisting of triplex material. The BOR is about 0.15%, and the thickness of the insulation is approximately 270mm [8, 9, 10].

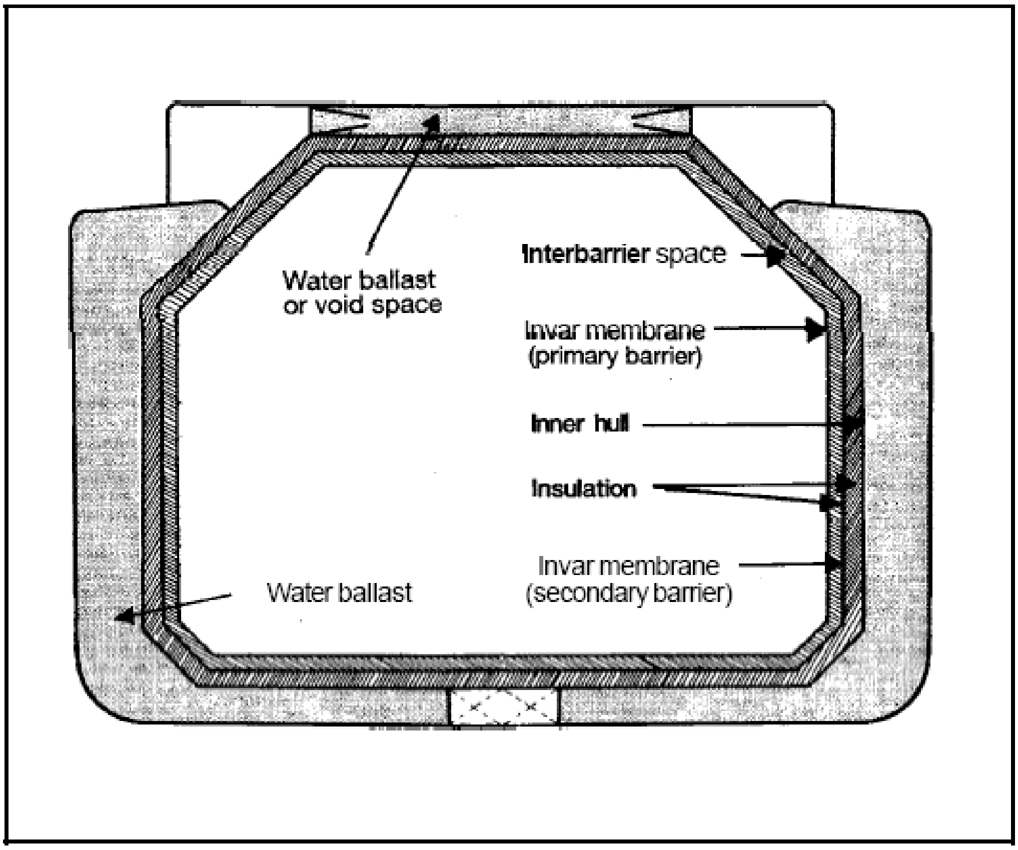


Figure 2 Interior of a GTT No.96 Membrane Type LNG tank [9]

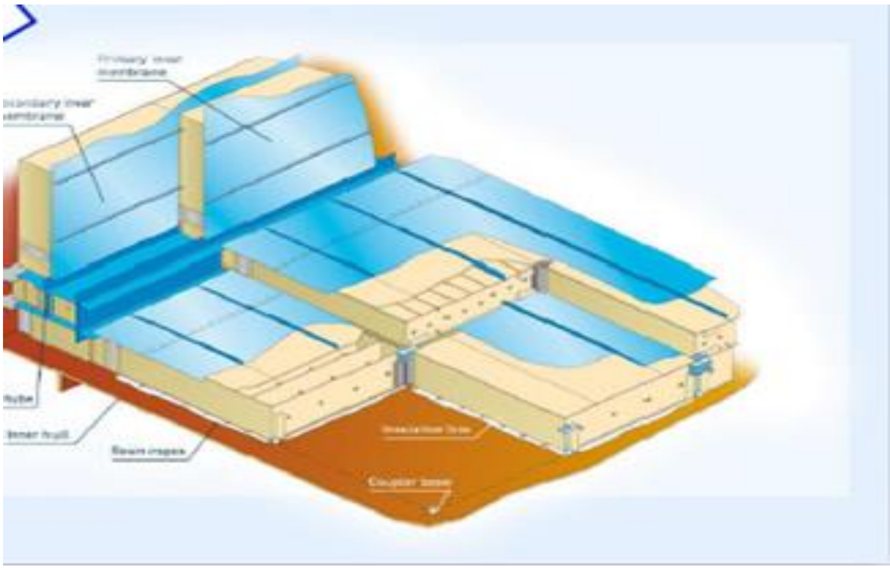


Figure 3 Formation of a GTT No.96 Membrane Type LNG tank [8]

II.3 Propulsion Configuration

Brief History

The only propulsion system for almost forty years was the steam turbine. Historically the first alternative propulsion system adopted to confront the steam turbine propulsion was the DFDE. In 2001, *GDF SUEZ (ENGIE*) ordered the first vessel to employ DFDE. This system would improve its efficiency by approximately 25-30% in comparison with the steam turbine [1].

A newest development occurred with the adaption of DFDE engines in order to be able to run also in HFO, in addition to the DFDE which were restricted to use MDO, thus allowing the engine to operate in three modes (HFO mode, MDO mode and LNG mode). About 25% of the operating LNGC fleet is equipped with TFDE, while 28% of vessels under construction are intended to install TFDE systems (2017) [1].

In the mid 2000's the Q-flex and Q-max series of LNGCs were introduced. Constructed on behalf of Qatar Gas Transport Company in HHI, DSME and Samsung , the vessels utilize a pair of slow speed diesel engines running on HFO [1]. Since the engines are of slow speed, they are directly coupled to a fixed pitch propeller without the need of a reduction gear, in a double skeg stern configuration [1] (also see Picture 9).

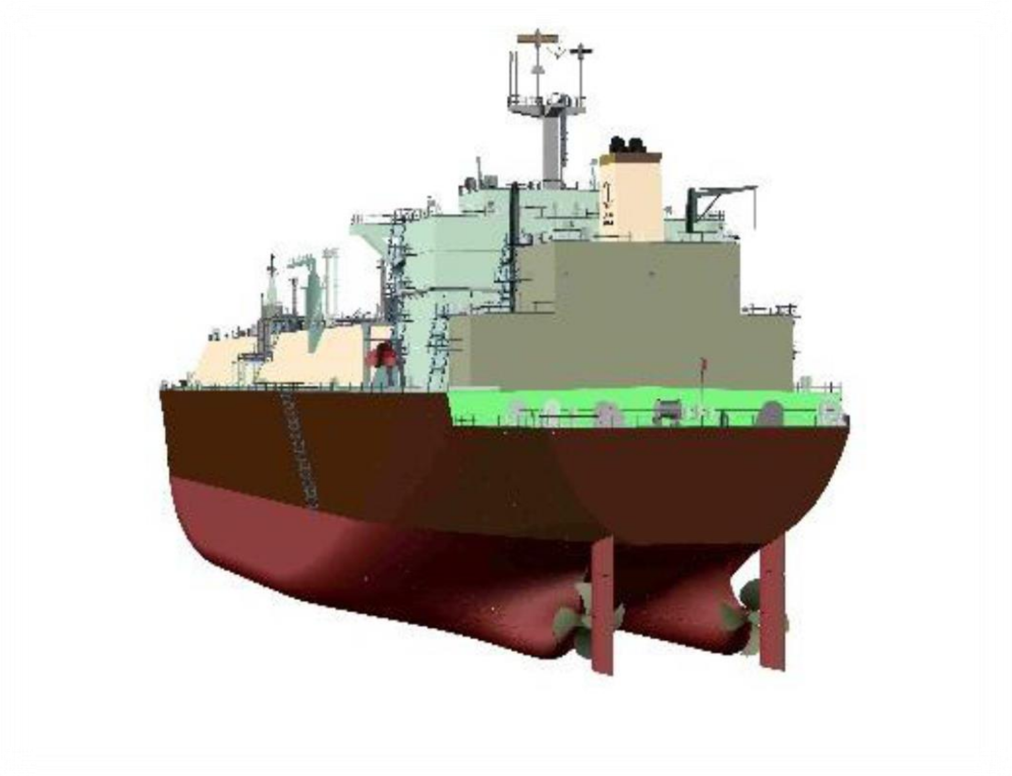


Figure 4 Stern view of a Q-flex/Q-max LNG carrier, demonstrating its two skeg configuration, accommodating the two engine, propeller and rudder set [3].

Additionally, these vessels are equipped with a reliquefaction plant sending back to the cargo tanks the BOG, enhancing the delivered amount of LNG and therefore the economic profits. Furthermore, the installation of two-stroke engines running on HFO increases the simplicity of the installation and minimizes the operational costs, this engine type has proven to be the most energy efficient as until now, simultaneously being able to utilize one of the cheapest liquid fuel types [1].

The next development was the introduction of the ME-GI engines from MAN. In contrast to the aforementioned two-stroke engines, in this case the BOG can be injected under high pressure in the engine’s cylinders, combining the utilization of BOG with the high efficiency of the two-stroke engines, thus enabling a 15-20% fuel reduction when in gas mode compared with the DFDE/TFDE for a similar vessel. Further technical details will be given in the next paragraph. Until now (2017) nine vessels have been equipped with ME-GI engines but approximately 27% of the vessels on order are intended to install them [1].

The latest alternative is the introduction of two-stroke dual fuel engines from Wartsila which, in contrast to the ME-GI engines, inject gas in the cylinders in low pressure. This design was introduced in 2014 [1].

The following propulsion systems will be examined [1, 3, 5]

Steam Turbine (ST)

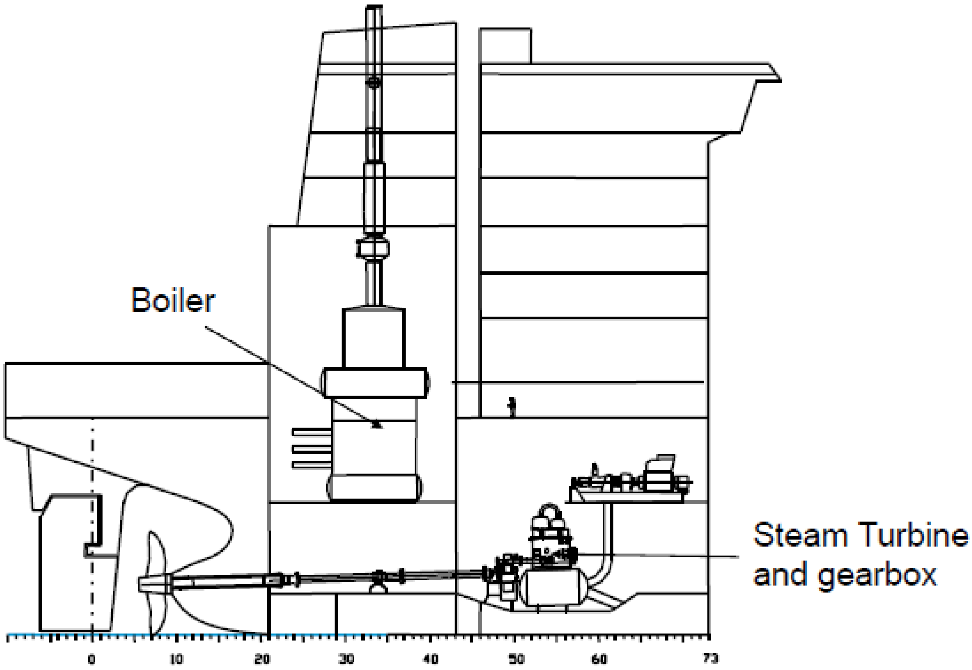


Figure 5 Engine Room layout with Steam Turbine. [3]

The system comprises two dual fuel boilers burning both BOG and Heavy Fuel Oil (HFO) when necessary. They provide steam to a steam turbine for propulsion and a pair of steam powered turbo- generators which produce the electric power. There is a mechanical drive of a Fixed Pitch propeller through a reduction gear [see Figure 5].

Dual/Tri Fuel Four-Stroke Diesel Engines with electric propulsion (DFDE/TFDE)

The diesel-electric concept, already popular in the cruise ship sector, is applied in this case. Propulsion is provided by four medium speed four – stroke dual fuel (BOG/Marine Diesel Oil - MDO) diesel genset, enabling diesel – electric propulsion. The conversion of electric power to mechanic is done by 2 propulsion motors which move a single Fixed Pitch Propeller. No additional gensets are required as the total amount of electric energy is produced by the four engines. The most recent development of this kind of configuration is the introduction of Tri Fuel four –stroke diesel engines, which apart from burning BOG or MDO are also able to burn HFO, thus providing an improved version of the DFDE engines, enhancing the operational flexibility and reducing fuel costs [see Figure 6].

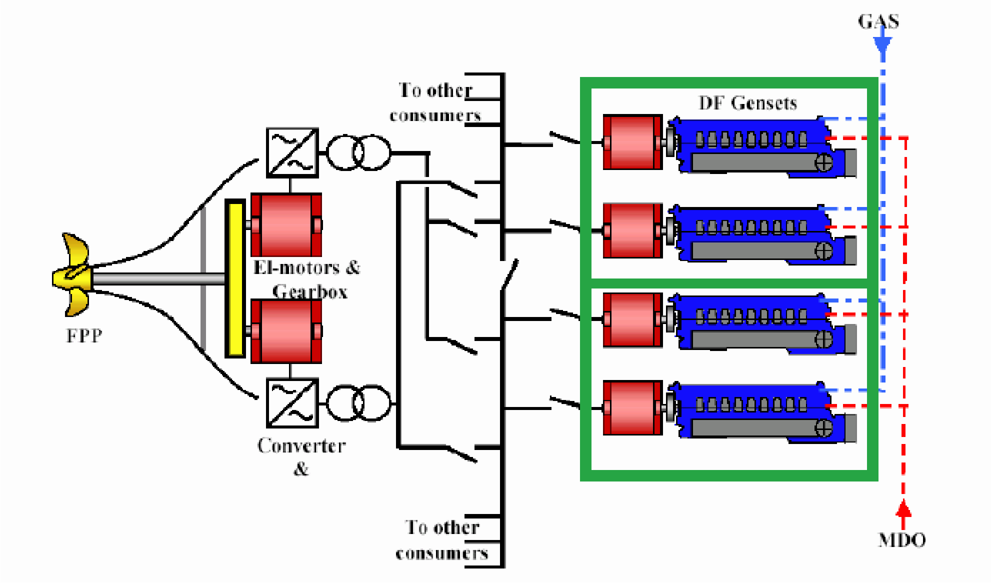


Figure 6 Engine Room layout with Dual Fuel Diesel Electric Propulsion. [5]

Slow Speed Two-Stroke Diesel Engines (SSD)

Two Slow Speed Diesel Engines burning HFO constitute the prime movers of this system. Each one of them is directly coupled to a Fixed Pitch Propeller. Three HFO gensets are used for electricity production [see Figure 7].

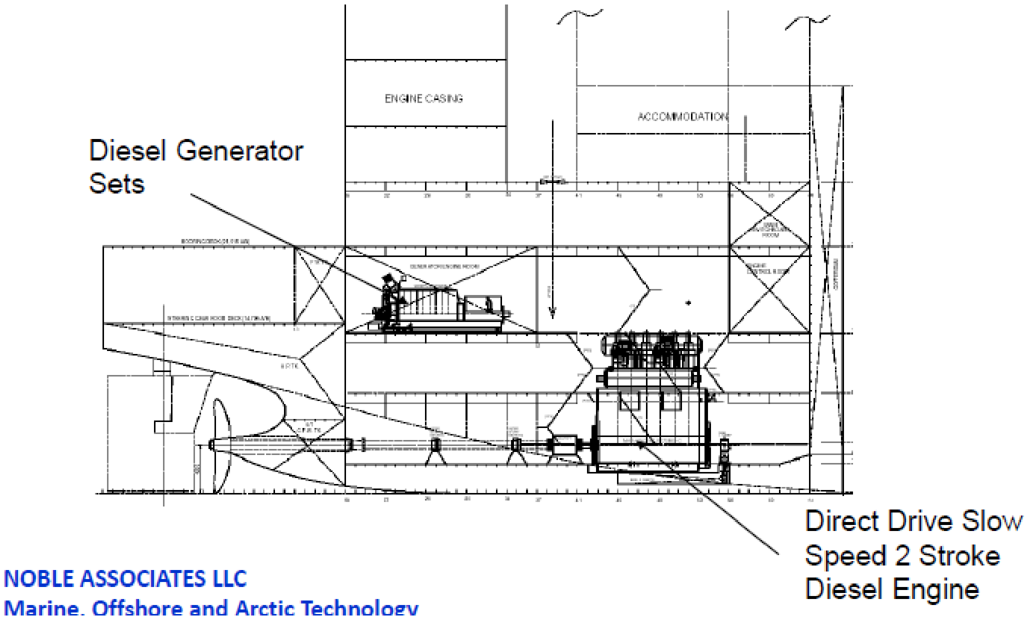


Figure 7 Engine Room layout with Two-Stroke Slow Speed Diesel Engines. [3]

Gas Turbine (GT)

The diesel electric concept is also applied in this case. The system consists of two gas turbine gensets (one main and two auxiliary), burning either BOG or MDO. The gensets move a Fixed Pitch Propeller via two propulsion motors [see Figure 8].

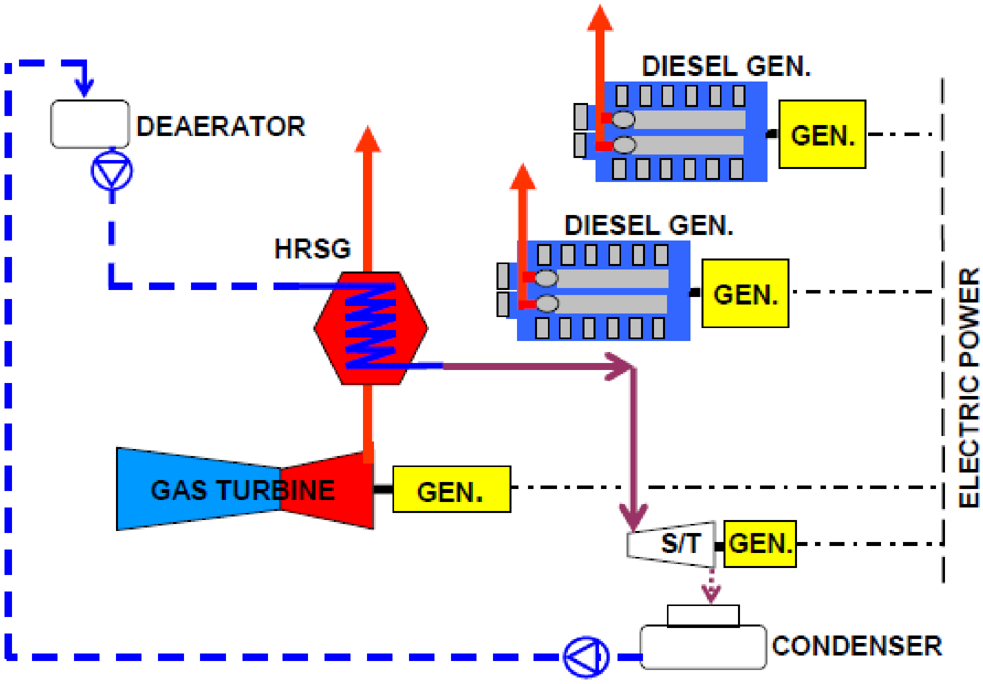


Figure 8 Engine Room layout with Gas Turbine. [3]

Combined Gas and Steam Turbine Plant (COGES)

An enhancement of the preceding system is accomplished with the addition of one exhaust gas boiler that utilizes the high energy content of the hot exhaust gases, produced by the gas turbines, στη συνεχεια expanded in a steam turbine

The major advantages and disadvantages of each of the aforementioned system are summarized in the following table [1, 3, 5, also see 11]

Table 1 Advantages and disadvantages of the examined Propulsion Configurations

	Advantages	Disadvantages
Steam Turbine	• Well established system, as traditionally LNGCs used this configuration. • Large flexibility as it is able to run either by pure BOG/HFO or a combination of both in every proportion. • Low vibration levels.	• High Fuel Consumption. • High emissions. • Possible lack of experienced personnel due to the deterioration of steam powered vessels. • High engine weight. • Requirements for large engine rooms due to boilers. • Possible need of Scrubber – SCR if using HFO in ECA zones.
Slow Speed Two-Stroke Diesel Engine combined with Reliquefaction	• Low fuel consumption. • Low fuel cost. • Total LNG load delivered due to liquefaction. • No need for reduction gears.	• High emissions. • High maintenance costs. • Mandatory use of a combination of Scrubber and SCR catalyst in SECA zones or switch fuel to MDO.
Dual Fuel Four – Stroke Diesel Electric Generators	• Exploitation of BOG. • Big flexibility as it is able to run either in MDO mode or BOG mode (pilot fuel necessary). • Low emissions. • Less machinery space required. • Increased maneuverability.	• High maintenance Cost. • New Concept – Little experience gained so far. • Still need SCR to fulfill IMO Tier III – Nox abatement- requirements, when running on MDO.
Gas Turbine	• Big flexibility as it is able to run either in MGO mode or BOG mode . • Lower Emissions. • Increased maneu-	• The system is a proposed concept, not applied yet in existing LNG vessels. • High Capex. • Requirement for

	verability. • Low vibrations. • Less Machinery Room space demands. • Easy maintenance and engine replacement • Reduced crew members	highly trained personnel. • Reversing gear required when direct mechanical drive is applied (not the case examined in this thesis)
Combined Gas and Steam Turbine Plant	• Big flexibility as it is able to run either in MGO mode or BOG mode . • Lower Emissions. • Increased maneuverability. • Low vibrations. • Less Machinery Room space demands.	• The system is a proposed concept, not applied yet in existing LNG vessels. • High Capex. • Requirement for highly trained personnel. • Reversing gear required when direct mechanical drive is applied (not the case examined in this thesis)

Dual Fuel Engines

As the interest for marine dual fuel engines is ever-increasing in recent years, it is worthy to mention the different concepts on which engines function, running on both oil fuels and gas fuels. Nowadays three gas engines variants can be installed.

- Gas engines. They are 4-stroke engines which operate solely on gas which is injected into the engine cylinders at low pressure (4-6 bars). The combustion of the gas-air mixture is based on the Otto Cycle, while a spark plug is necessary for the ignition to take place [11, 12, 13].
- Gas-Diesel Engines (GD). These engines are able to operate either in diesel mode or alternatively burning a mixture of gas and diesel at a wide variety of mixtures. They imply the Diesel Cycle as the gas is injected in the engine cylinders at high pressure (up to 300bars) [11, 12, 13].
- Dual Fuel Engines (DF). They are 4-stroke engines which are also able to run either in diesel mode or gas mode, but not in diesel-gas mixture mode as the GD engines. In order to achieve the combustion of the mixture 1% of it consists of liquid fuel which, causes the initial ignition (pilot fuel). In this concept again the gas is injected in low pressure in the cylinders [11, 12, 13].

Most of the dual-fuel engines have been designed by the two aforementioned major makers, *Wartsila* and *MAN*. The first dominates the four-stroke fragment, while the latter the two-stroke. The two makers have selected different basic principles for the operation of their engines. Wartsila has selected the Otto Cycle for the gas burning mode [6].

While in gas mode the Wartsila engines work on a “lean-burn” Otto combustion process. This means that the gas is mixed with air before the inlet valves and after the compression phase the mixture is ignited by a small amount of liquid called *pilot fuel*

On the contrary, *MAN* engines utilize the *Diesel Cycle* when burning gas for its two-stroke engines and the *Otto Cycle* for its four-stroke engines.

Comparing the two Cycles, the main difference is that, when the compression takes place, the cylinders are filled only with air, as there is no premixing. The Otto-Cycle uses a higher compression ratio (typically between 15- 20). After the air has been compressed the gas is injected in high pressure in the chamber. This compression raises the temperature to the ignition temperature of the now formed fuel mix, thus enabling the combustion to take place without the use of pilot fuel [16].

Another important aspect is the fact that the low pressure engines perform in lower speeds, thus deducing significantly the formation of Sox and making the use of EGR/SCR systems unnecessary when operating in gas mode.

Wartsila offers two engine options [6]:

- The four-stroke DF engine family. These engines are used both in mechanical drive and diesel electric drive. Typical example of the first are modern LNGCs whose propulsion installation consists of 4 dual fuel electric generators, and the later small vessels such as Ro-Paxs, where two shafts are moved by two or four dual fuel engines via reduction gears.
- The two-stroke X- DF engine family. This is a rather novel propulsion unit as the first installation took place in 2015. Originally intended for large LNGCs, smaller variants are to be fitted in small tankers, small LNGCs and even containerships under construction.

MAN also offers two engine options [6]:

- The four-stroke 51/60 DF engines, which similarly to their Wartsila competitors are available for both mechanical and electrical propulsion
- The two-Stroke ME-GI (M-type, Electronically Controlled, Gas Injection) engine family derived from the diesel fueled G-type engines. Variants of the aforementioned family are to be installed to 25 LNGCs to be delivered until 2019, along with orders for containerships and tankers.

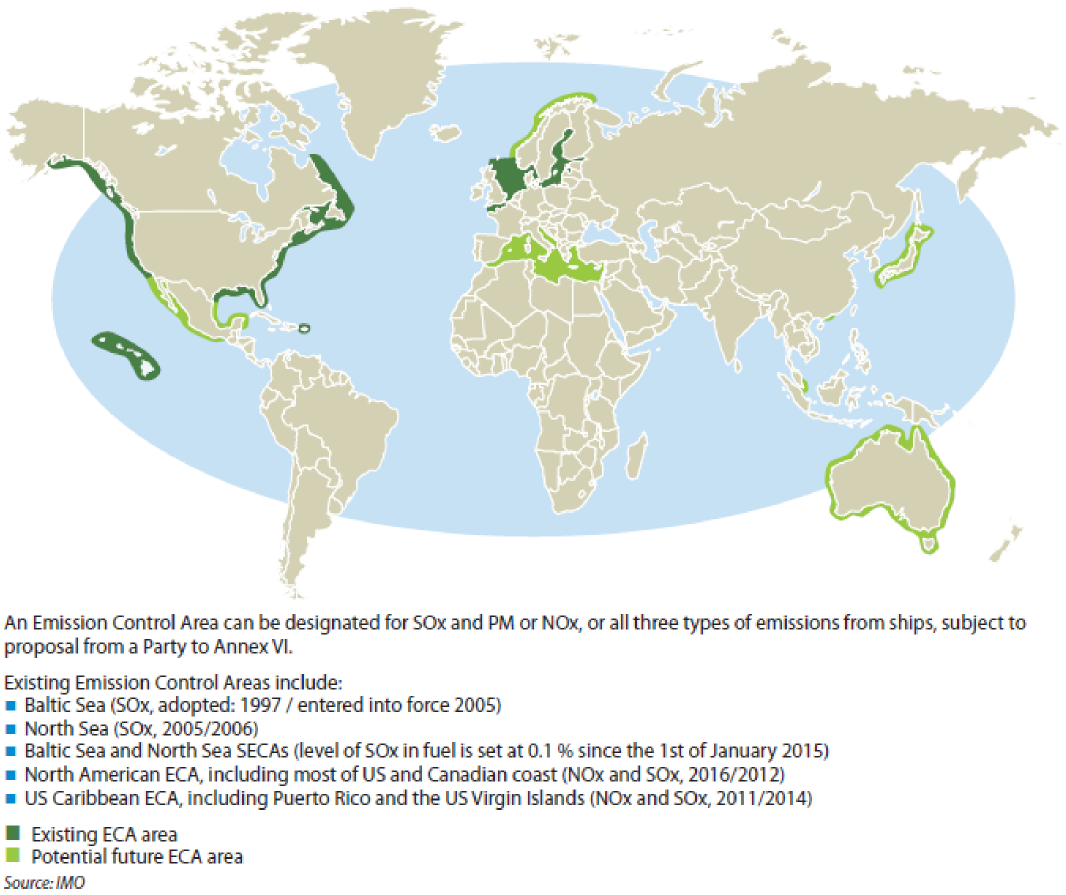
The advantages and disadvantages of these methods are outlined in the following table [6].

Table 2 Comparison of MEGI and XDF engines.

Engine	Advantages	Disadvantages
MEGI (Diesel Cycle)	• Lower SFOC • No methane Slip • Well established tradition on 2-stroke engines • First to imply the use of LNG in 2-stroke dual fuel engines	• High Capex • SCR/EGR needed to satisfy IMO Tier III Nox abatement requirements even on gas mode • Power Cosumption in Auxiliaries • Reliance on the reliability of the high pressure gas fuel system
DF (Otto Cycle)	• Satisfy IMO Tier III NOx abatement requirements on gas mode. ECR/SCR not required • Lower Capex • Lower pressure • No auxiliaries (only standby/ emergency)-Main switchboard distributes electric power produced by the dual fuel generators	• Higher SFOC • Methane Slip

III.4 Legislation

In order to mitigate the adverse environmental impact from NOx and SOx, IMO adopted emission control areas (ECAs) where the amount of the aforementioned pollutants in the vessels' exhaust gases is restricted [see Picture 14].



An Emission Control Area can be designated for SOx and PM or NOx, or all three types of emissions from ships, subject to proposal from a Party to Annex VI.

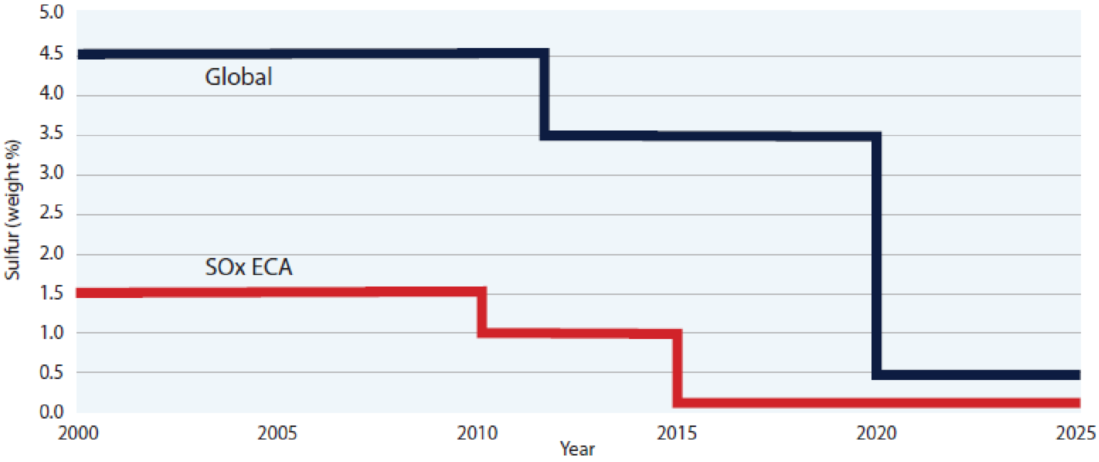
Existing Emission Control Areas include:
- Baltic Sea (SOx, adopted: 1997 / entered into force 2005)
- North Sea (SOx, 2005/2006)
- Baltic Sea and North Sea SECAs (level of SOx in fuel is set at 0.1 % since the 1st of January 2015)
- North American ECA, including most of US and Canadian coast (NOx and SOx, 2016/2012)
- US Caribbean ECA, including Puerto Rico and the US Virgin Islands (NOx and SOx, 2011/2014)

🟩 Existing ECA area
🟩 Potential future ECA area

Source: IMO

Figure 9 Global ECA Zones. [14]

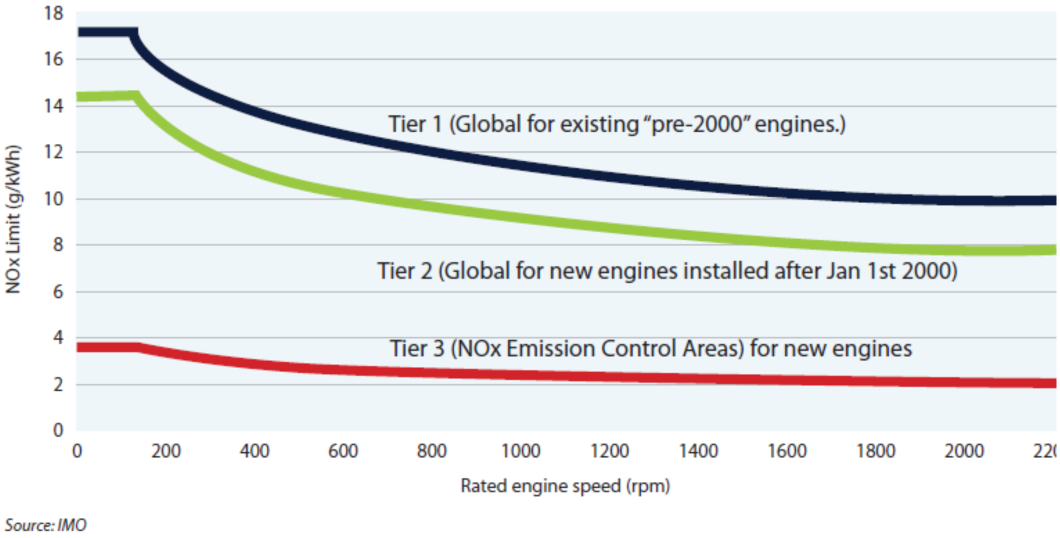
The areas under SOx and NOx emission control are called Seca and Neca, respectively. Since January, 1st 2015, the maximum content of Sulphur in marine fuels is restricted to 0.1 % in SECA zones. Moreover, it is expected that the global (outside SECAs) limit will be reduced by 2020 to 0.5% from 3.5% which is the present limit. The major SECA zones today are: The Baltic Sea, the North Sea, the North America SECA, which includes most of the US and Canada coasts, and the US Carribean Seca including Puerto Rico and the US Virgin Islands. Also the US territory in the Pacific Ocean (Hawai) is considered SECA zone. Future ECAs may include i.a the Mediterranean, the coasts of Australia, Japan, Mexico, California and Norway. Albeit the previous regulations permit the installation of after-treatment devices, namely scrubbers that purify the exhaust gases eradicating the Sox emissions. Nevertheless local legislation may be even more stringent, e.g. the California E.P.A regulations that specify the sulfur content in fuel in a distance of less than 24 Nautical Miles off the California Baseline, thus making the after –treatment methods unsufficient and force to fuel shift. It should be mentioned though that probably, in the near future, the California area will be incorporated in the North America SECA and its legislation integrated to the latter , so the use of scrubbers is expected to be permitted [14, also see picture 14]



Source: IMO

Figure 10 Present and future limits for sulfur content of marine fuel. [14]

Concerning NOx emissions the following should be mentioned. The maximum amount of NOx is given as a function of engine's speed (rpm) and the launching date of the vessel. Thus three abatement phases are implied (Tier I, Tier II, Tier III), respectively. Tier I gives the maximum permitted amount in a global level for vessels launched before the year 2000. Tier II mandates the NOx emissions for vessels launched after January 1^{ST} 2000, again globally, while Tier III affects only Nox Emissions Control Areas (NECAs) and concerns vessels launched after January 1^{ST} 2016. The only effective NECA zone up to date is of the North America. It is expected though that this measure will be introduced into the Baltic Sea in the future [14, also see Picture 16].



Source: IMO

Figure 11 Regulations for NOx emissions for new-build ships in ECAs. [14]

There are two options for the shipping companies to fulfill these regulations.

- Adoption of low-sulfur/nitrogen fuels

The use of low-sulfur fuel allows the compliance with the SECA rules without the need of installing after-treatment technologies on vessels, in this way the companies are not obliged to make costly conversions that may cause certain implications in terms of space and weight limitations on existing vessels, imposing though the inherent disadvantage of the higher cost of these fuels. Possible fuels may be the Marine Diesel Oil (MDO) and the Marine Gas Oil (MGO). Another possible solution is the use of low-sulfur HFO (LSHFO), nevertheless, there are objections for the environmental impact of the process of producing the fuel both in terms of energy consumption and Sox emissions during the distillation [14].

It is worthy to mention that even the low sulfur fuels, fulfilling the SECA requirements, may need after-treatment to fulfil the NECA regulations. The other option is the use of alternative fuels (not based on the catalytic process of oil) such as LNG or even methanol that may succeed in fulfilling both requirements.

- Installation of after-treatment methods that purify the exhaust gases (Scrubber-SOx/SCR-NOx)

Scrubbers allow the continuation of the use of HFO in the SECA areas, but may not fulfil the additional local requirements in some places such as California. There are two options: The open loop and the closed loop Scrubbers with the former using seawater, while the latter using water enriched with chemicals such as sodium hydroxide. In the first case the used water is returned to sea, something that may impose new restrictions in the future at least for areas with specific environmental interest. Another disadvantage associated with the use of the open loop scrubbers is that their performance depends on the chemical properties of the water, causing them problems when performing in brackish waters [14].

Closed loop scrubbers are able to perform under every condition and additionally they do not discharge sulfur in the water. Nevertheless, they produce a sludge that has to be disposed on shore and therefore require the relevant port-facilities, whereas the presence of sodium hydroxide may require extra safety meassures [14]

An SCR catalyst gives more than an 80% NOx reduction. This system converts NOx into nitrogen gas (N_2) by adding a urea solution [14].

Table 2 Marine fuels and compliance with regulations [14]

Fuel	SECA Compliance	NECA Compliance	Particulates
HFO	Scrubber needed	Catalyst needed	High Emissions
MDO	Complies	Catalyst needed	Fewer than HFO
LNG	Complies	Complies	Very low

Scrubber: Wet scrubber and Dry scrubber installations are considered

Catalyst: SCR catalyst and EGR are considered

It is assumed that in the dual – fuel diesel electric engines the fuel burned in ECA zones is LNG (with only a pilot fuel MDO), thus compliance with both SO_x and NO_x emissions is achieved without the need of Scrubber, or SCR installation.

III. Statistical Analysis of Active and Under Construction Vessels

One part of this work, was the formation of a list of both active and under construction vessels in order to provide useful data for the LNG fleet. The list is based on data given in [1] and from the "HIS Fairplay World Shipping Encyclopaedia, 2011".

III.1 Propulsive Configurations

As a first step, data concerning the propulsive configurations of the LNG fleet are shown. The vessels examined use 6 types of such configurations, namely: Steam Turbine (ST), Twin Slow Speed Diesel Engine (SSD), Tri-Fuel Diesel Electric four-stroke engines (TFDE), Dual-Fuel Diesel Electric four-stroke engines (DFDE), Two - stroke engine burning LNG by MAN (MEGI), Two-stroke engine burning LNG by Wartsila (XDF).

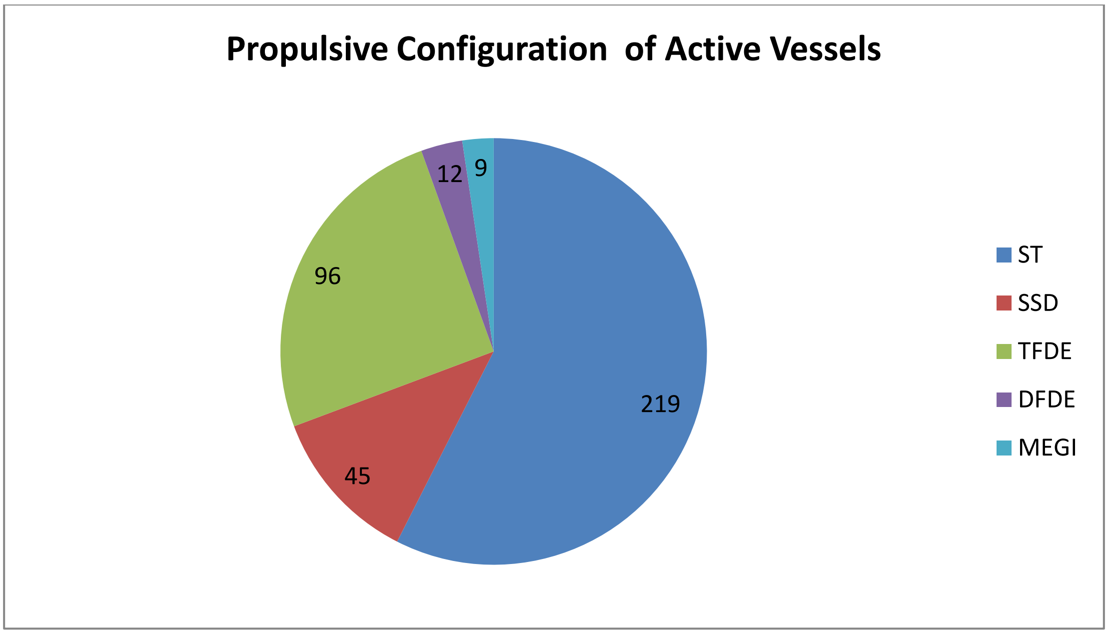


Figure 12 Percentage of Propulsive Configurations of active vessels

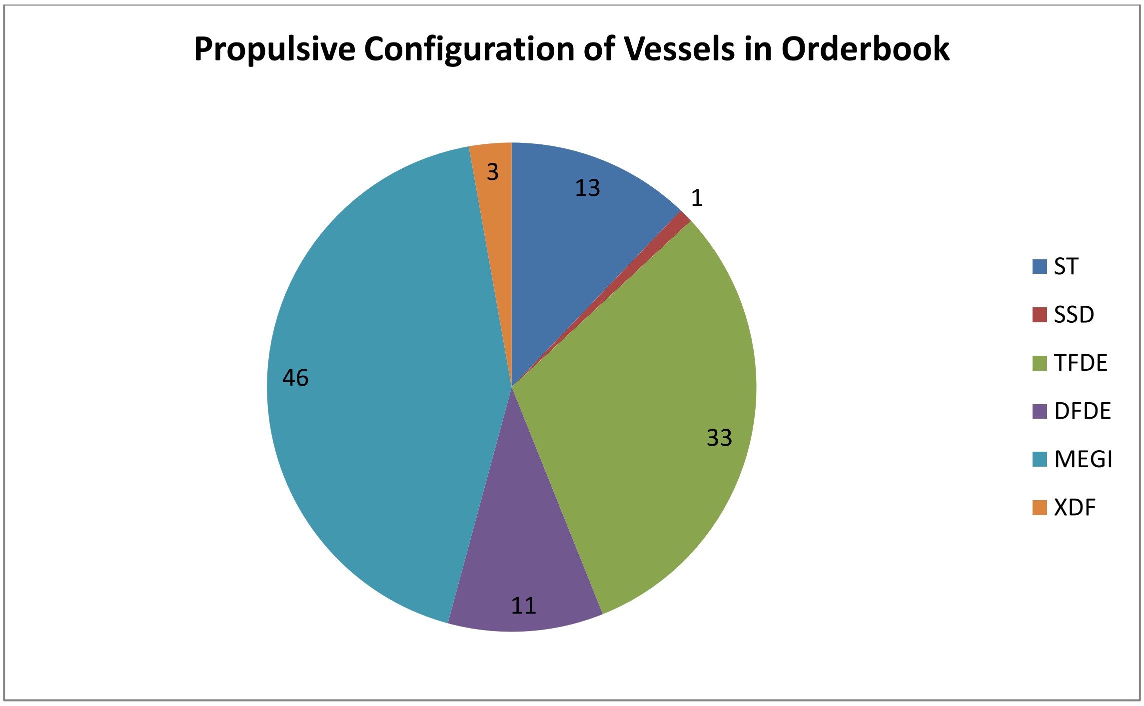


Figure 13 Percentage of Propulsive Coefficients of vessels under order

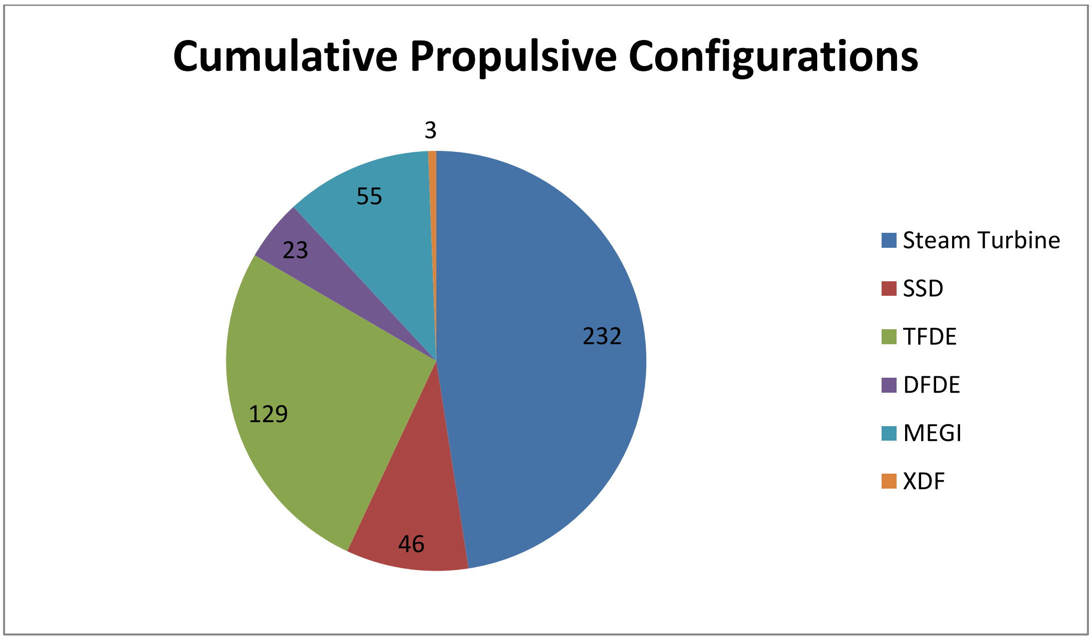


Figure 14 Percentage of Propulsive Configurations of active and under order vessels

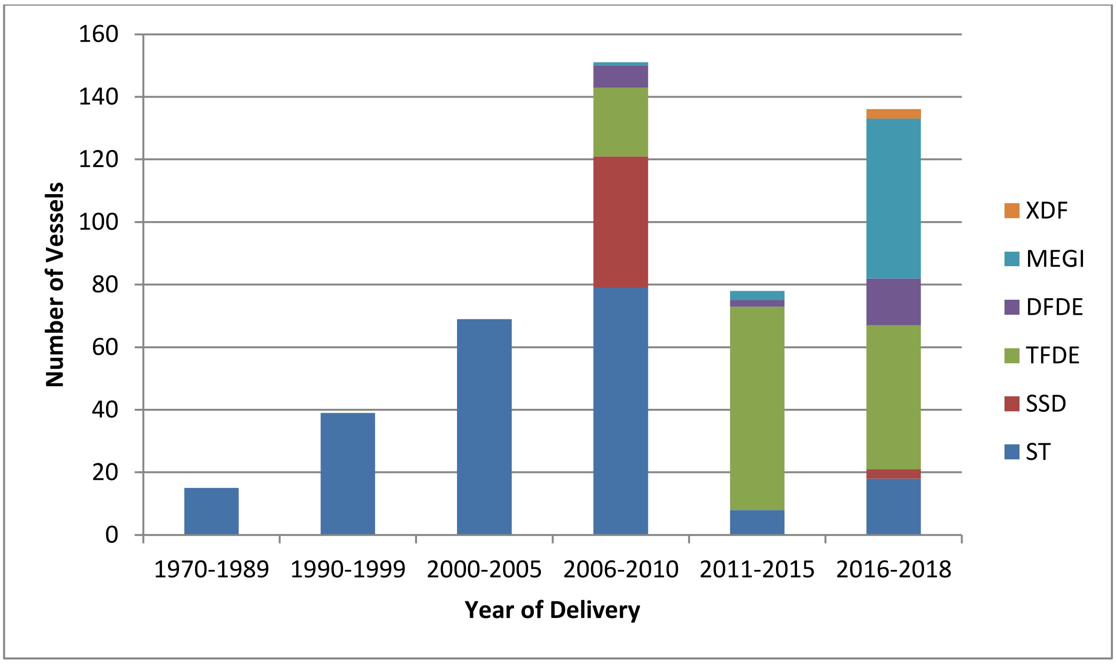


Figure 15 Propulsive Configurations by year of delivery

III.2 Capacity

In the next step, data concerning the capacity of the LNG fleet are obtained. As seen below, the vessels are divided into 6 categories according to their capacities cm (0-138000, 138001-145000, 145000-170000, 170001-200000, 200001-230000, 230001-270000).

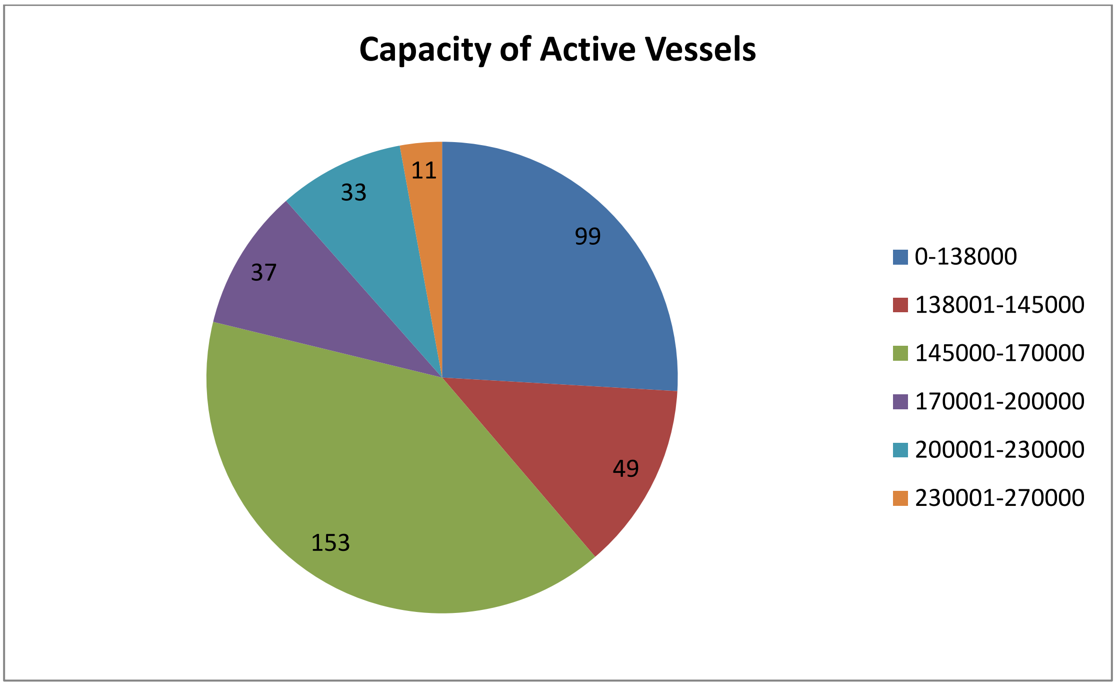


Figure 16 Percentage of active vessels according to their capacity

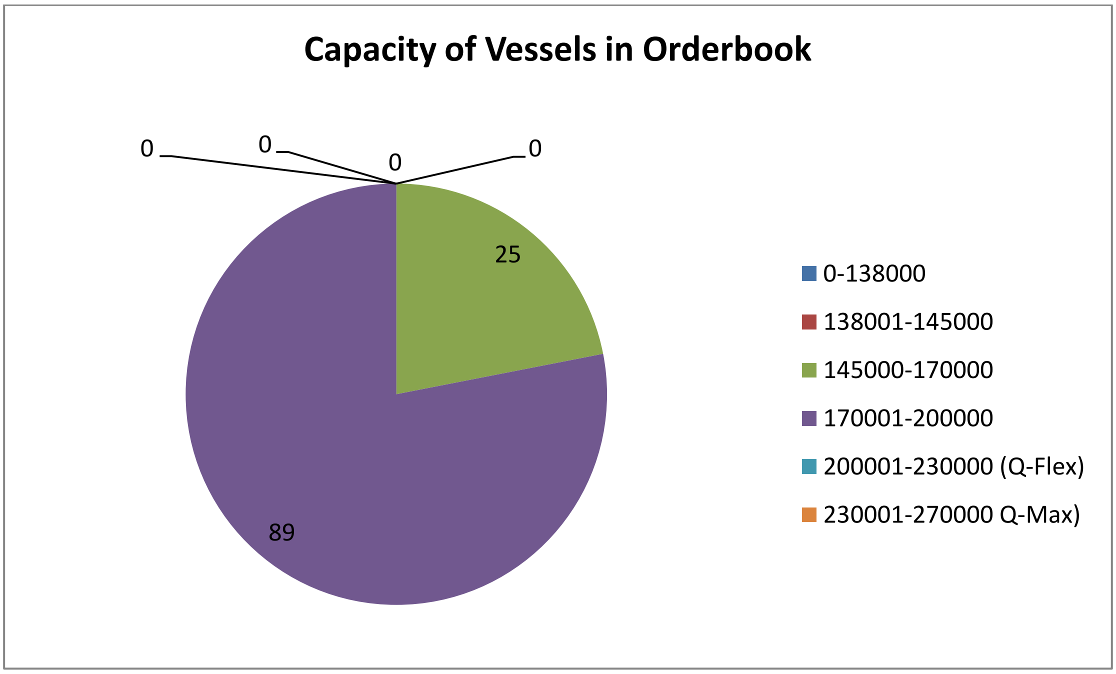


Figure 17 Percentage of vessels under construction according to their capacity

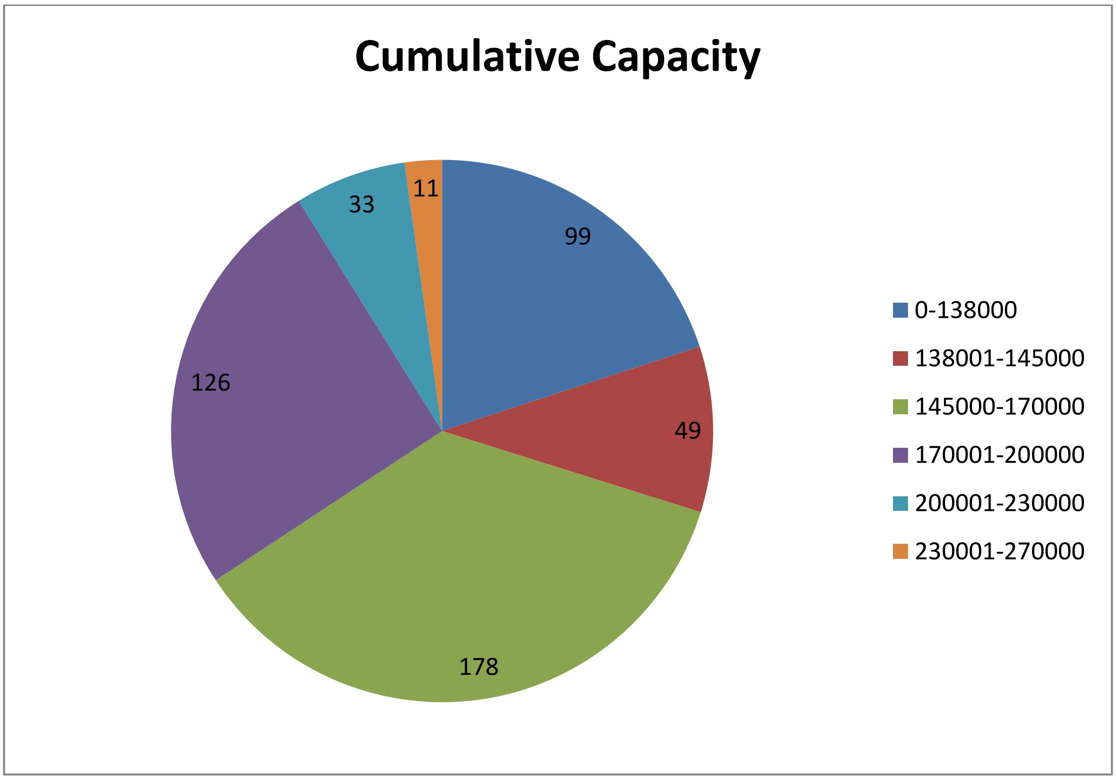


Figure 18 Percentage of active and under construction vessels according to their capacity

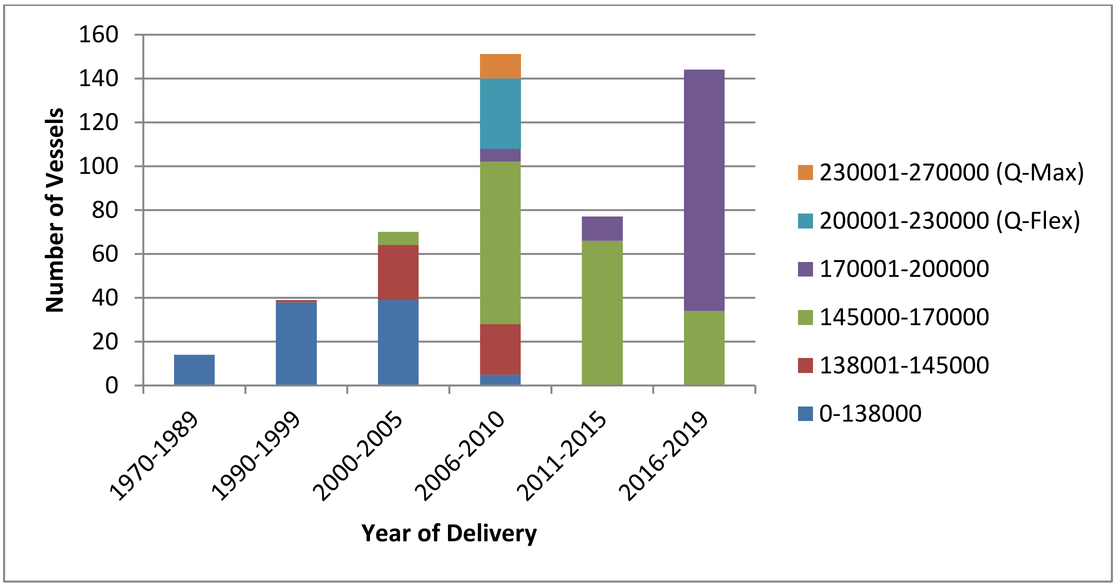


Figure 19 Vessel Capacity by year of delivery

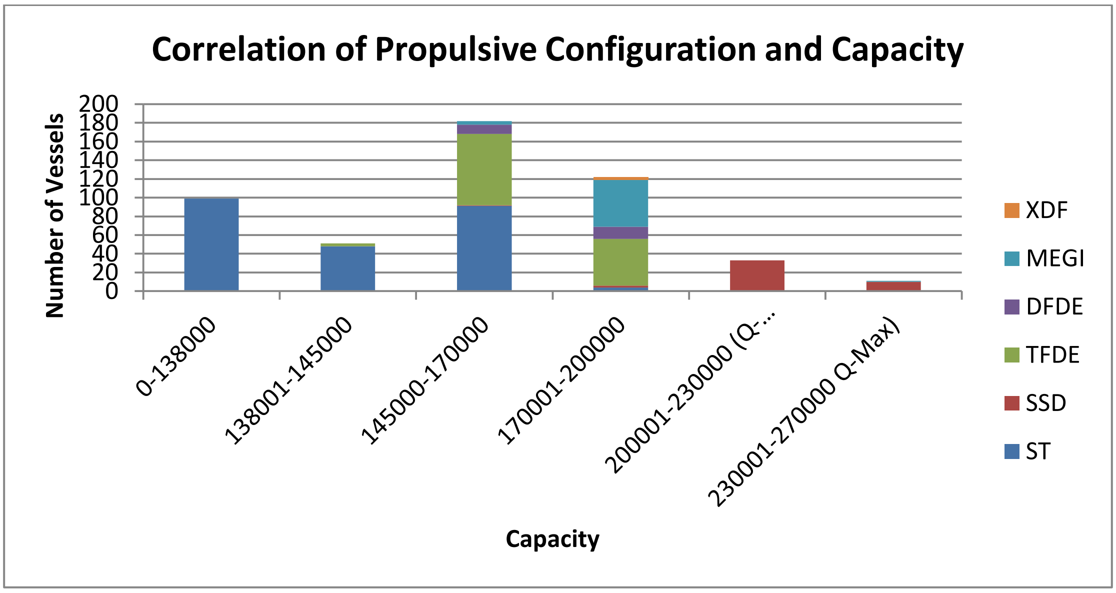


Figure 20 Correlation of Propulsive Configuration and Capacity

IV. Approximated Computations

As mentioned in the abstract, an effort is made in order to enable one to perform calculations for vessels of which data may be missing. For this reason, a linear regression analysis is applied. A methodology similar to the one followed in [10] is used. The steps of this analysis are shown below.

IV.1 Mean Values

At first the entering data is the capacity (C). All the other values are calculated according to it. Combining the statistical analysis of the preceding chapter with data provided by [1] and the *Ship Design Laboratory*, the mean value of L/B, B/T and C_B are given in the next table.

Table 3 L/B, B/T and C_B according to Capacity

	0≤C≤ 138000	**138001≤C≤ 145000**	**145001≤C≤ 170000**	**1700001≤C≤ 200000**	**200001≤C≤ 230000**	**230001≤C≤ 270000**
L/B	6.0590	6.2131	6.2095	6.3218	6.2565	6.1407
B/T	3.7795	3.7918	3.7755	3.7859	3.9652	4.3190
C_B	0.7153	0.7455	0.7404	0.8235	0.7964	0.7964

IV.2 Regression Analysis

As mentioned previously, in this point, it is assumed that the main characteristics of the examined vessel, apart from the capacity are presumed to be unknown. Therefore a methodology for their calculation is developed, mainly derived from [10]. This procedure leads to the successive computation of of the main characterisitcs where each of them is used as an entrance data for the calculation of the following ones.

Calculation of Δ

The aforementioned procedure begins with the calculation of the Displacement *(Δ)* according to its relative Capacity *(C)*. The curve obtained by the Regression Analysis is shown in Figure 21. The equality relating the two characteristics is $\Delta = 0.6408 \cdot C + 18690$ and the coefficient is $R^2 = 0.874$.

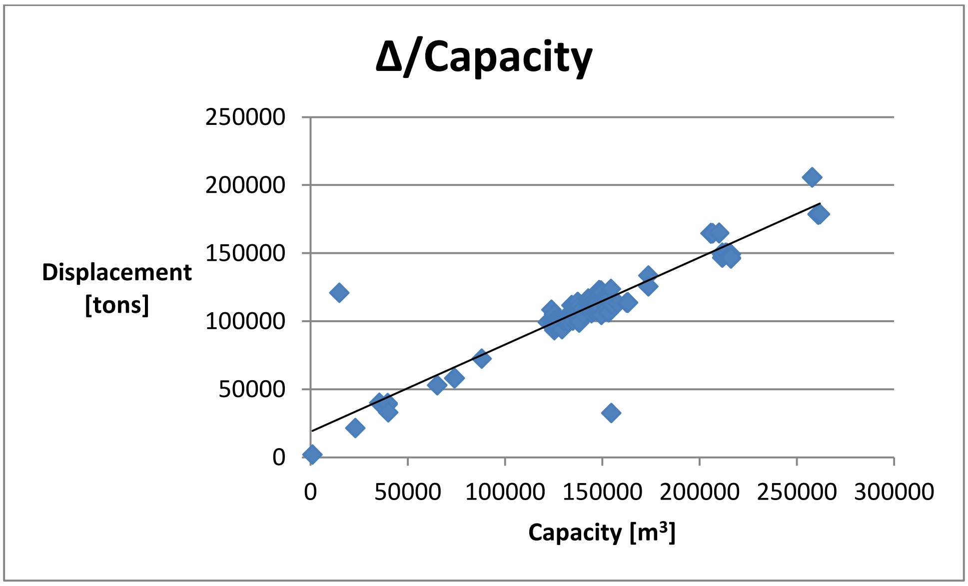


Figure 21 Δ/C of existing LNG fleet

Calculation of DWT

Next, using the previously calculated Δ, the Deadweight (DWT) is now calculated. The curve connecting these characteristics is shown in Figure 22. The relevant equation is $DWT = 0.7313 \cdot \Delta - 1078.1$ and the corresponding coefficient is $R^2 = 0.9435$.

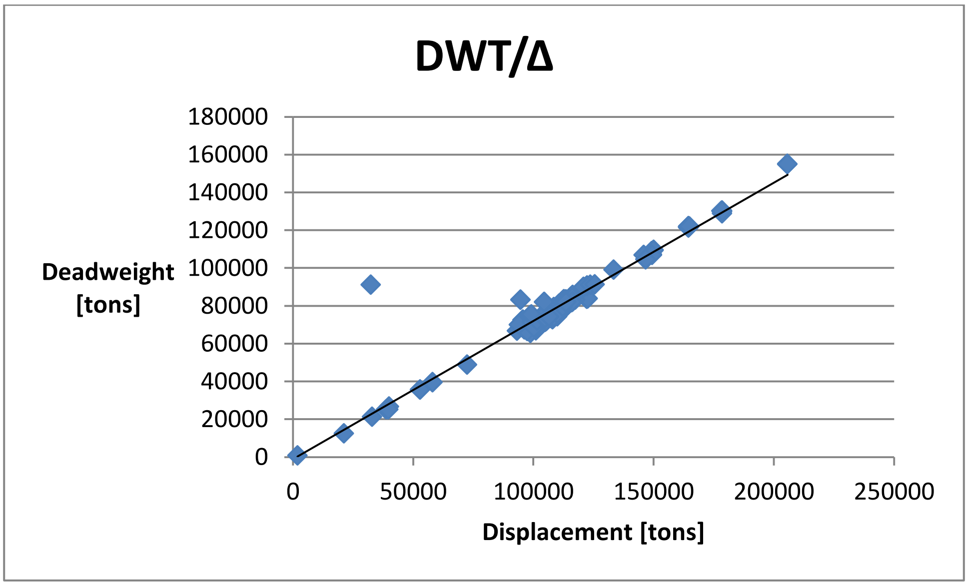


Figure 22 DWT/Δ of existing LNG fleet

Calculation of B

With the dimensions of the examined vessel still remaining unknown, using the mean values of the L/B and B/T ratios along with the C_B corresponding to the selected *C,* the Breadth *(B)* is found by using the following formula from [10]

$$B = \sqrt[3]{\frac{\Delta \cdot \frac{B}{T}}{1.028 \cdot C_B \cdot \frac{L}{B}}}$$

Calculation of L

With B known, the Length (*L*) can be now calculated. The equation connecting L and B is $L = 8.1148 \cdot B^{0.924}$ and the coefficient is $R^2 = 0.8764$. The regression curve is displayed in Figure 23

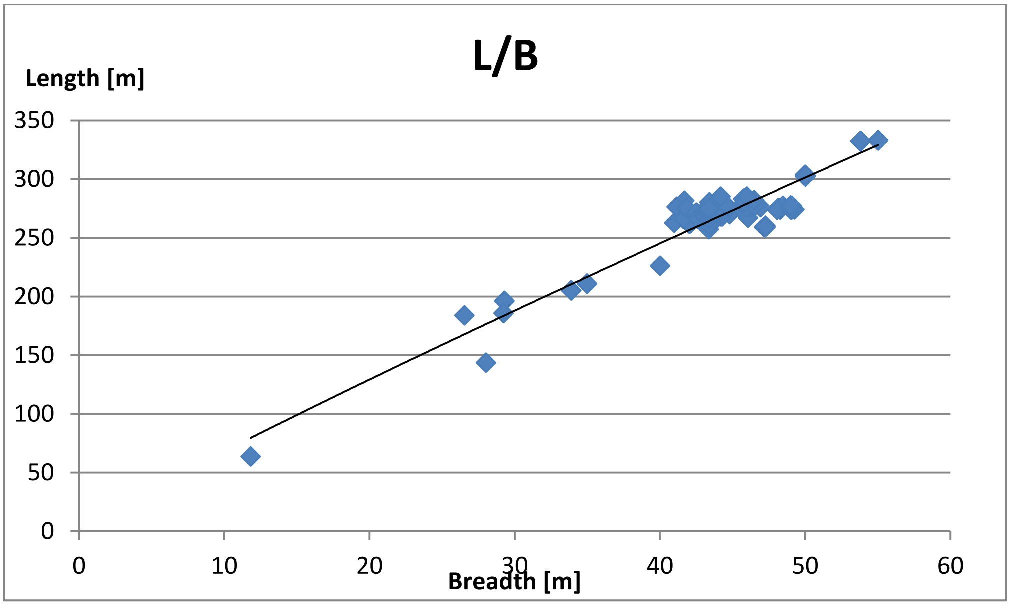


Figure 23 L/B of existing LNG fleet

Calculation of T

Next, using B, the draught (*T*) is calculated. The regression curve obtained is shown in Figure 24. T is expressed as a function of B by the equation $T = 0.9528 \cdot B^{0.6638}$ and the coefficient is $R^2 = 0.635$.

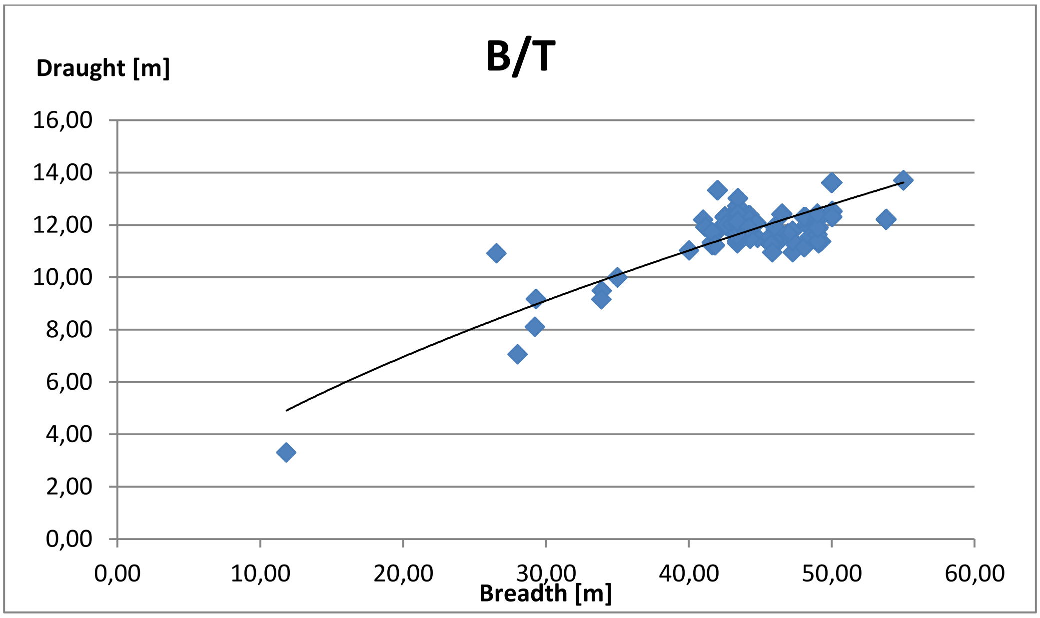


Figure 24 B/T of existing LNG fleet

Calculation of D

Finally, the Depth (D) is given as a function of T. The equation produced by the regression analysis is $D = -0.0288 \cdot T^3 + 0.6166 \cdot T^2 - 1.4284 \cdot T + 4.4189$ while the relevant coefficient is $R^2 = 0.799$. The relevant curve is shown in Figure 25

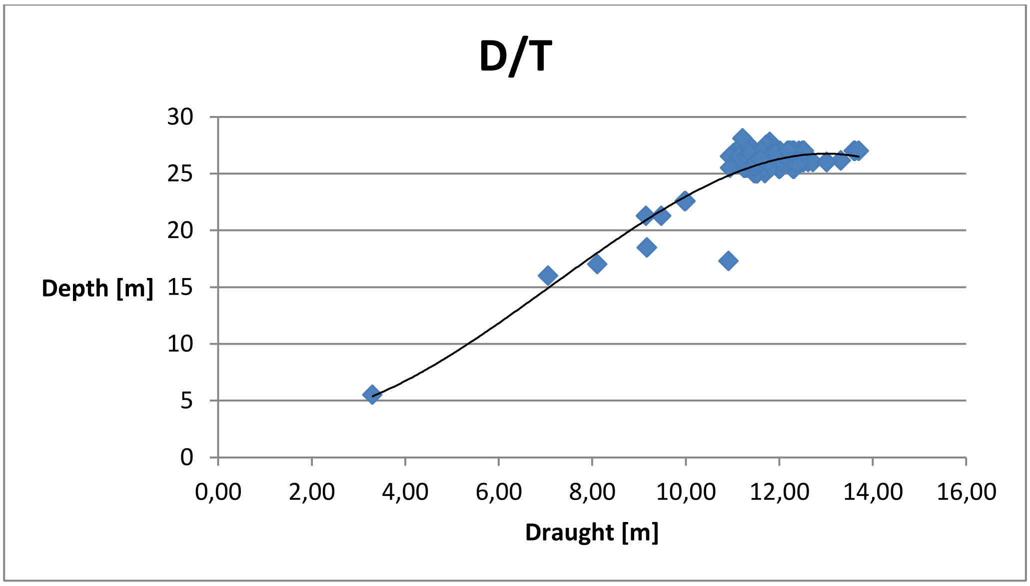


Figure 25 D/T of existing LNG fleet

IV.3 Tank Dimension Analysis

Double Hull Width

The calculation of the Double Hull Width (wdh) is based on data taken from [10]. Initially, the whd defined by Marpol is used:

$$\boxed{wdhMARPOL = \min\left(0.5 + \frac{DWT}{20000}, 2\right)}$$

Apart from this, in [10] the final wdh is assumed to be similar to that of the parent ship employed, which corresponds to

$$\boxed{wdh = 0.05 \cdot B}$$

that was initially selected as the wdh value in this thesis. However, this should not be less than the value of Marpol. Thus, if

$$wdhMARPOL > wdh,$$

then it is considered that

$$\boxed{wdh = wdhMARPOL}$$

Double Bottom Height

The following formulas for the Double Bottom Height (dbh) are borrowed from [10]:

- $ABS : hdb = (32 \cdot B + 190 \cdot T^{0.5}) / 1000 \; [mm]$
- $LR : hdb = (28 \cdot B + 205 \cdot T^{0.5}) / 1000 \; [mm]$
- $DNV : hdb = (250 + 20 \cdot B + 50 \cdot T) / 1000 \; [mm]$
- $MARPOL : hdb = max(B / 15, 2) \; [m]$

In the same source, the dbh is analogously assumed to be similar to that of the parent ship employed, corresponding to:

$$\boxed{hdb = 0.123 \cdot D}$$

As before, we start with the above equation, but if the values given by Marpol and Classification Societies are greater than the latter, then the greatest of them is chosen. Having at hand the wdh and the hdb, the length of the tanks (LTANKS) can be calculated as a function of the capacity and the number of tanks (NTANKS). To simplify the calculations, it is assumed that all vessels are equipped with 4 tanks, thus the length of the tanks of each vessel is constant but different per vessel.

$$\boxed{LTANKS = \left({C}/{0.8879 \cdot (B - 2 \cdot wdh) \cdot (D - hdb)} \right) / NTANKS}$$

A simplified estimation of the periphery (e) of the tanks is given by:

$$\boxed{e = 2 \cdot \left((B - 2 \cdot wdh) + (D - hdb) \right).}$$

The area of each tank (A) is the product of its length times the periphery.

$$\boxed{A[i] = LTANK[i] \cdot e[i]}$$

The Total Mass and the Total Weight of the Plywood insulation (TMPly and TWPly, respectively) are given as follows:

$$\boxed{TMPly = (0.23 + 0.30) \cdot \sum_{i=1}^{N_{TANKS}} A[i]}$$

The numbers above correspond to the thickness of the two layers of plywood (230mm and 300mm, respectively)

$$\boxed{TWPly = 0.55 \cdot TMPly}$$

where 0.55 is the specific weight of plywood expressed in [tn/m^3]

In the same way the Total Mass and the Total Weight of the Invar insulation (TMInvar and TWInvar, respectively) are given by

$$\boxed{TMInvar = 2 \cdot 0.7 \cdot 10^{-3} \cdot \sum_{i=1}^{N_{TANKS}} A[i]}$$

Where 2 stands for the number of layers of invar, each one of them having a thickness of 7mm

$$\boxed{TWInvar = 8.1 \cdot TMInvar}$$

where the specific weight of invar is 8.1 [tn/m^3]

Finally the total weight of the insulation (Wins) is

$$\boxed{WIns = TWPly + TWInvar}$$

IV.4 Weight Calculations

The weight of the total amount of required steel is assumed to be equal to the weight of the ship structure (W_{ST}). In order to calculate this value, a methodology similar to that of [10] is applied. According to this, at first the weight of the outfit (W_{OT}) and of the machinery (W_M) are calculated, and then are deducted from the vessel's lightship (*LS*). There are though some necessary adaptions. In the case of [10], a tanker is used as a model equipped with a two-stroke diesel engine, which nowadays has become more or less a straightforward option for meeting the propulsion demands. In the case described in the present thesis, an LNGC is selected for the implementation of the LCA method and, as seen in the previous chapters, more than one propulsion alternatives are used. Each of them induces a different W_M. One of the purposes of the thesis is the assessment of the environmental impact of a vessel that may use all the possible alternatives, thus leading to a comparative study. Hence, the calculation of the W_M would be different in each scenario. In the following section, the assumptions made are given. The calculations are performed after breaking down the W_M into its three main components: Main Machinery Weight (W_{MM}), Shaft Weight (W_{MS}), and Residual Machinery Weights (W_{MR}). The data are retrieved from [15, pp. 81-85] and [16, pp. 253]. Note that there is a conversion factor to Ps in kw, in order to ensure consistency with the remaining data of the text.

IV.4.1 Machinery Weight

In order to calculate the Machinery Weight, a series of coefficients are used. These give the weight per Kw of each type of engine selection. The coefficients are selected as a function of the examined vessel's type and displacement, and they are retrived from relevant tables in [15, pp. 81-85]. In these tables data for LNG vessels do not exist. Thus, as an approximation, the coefficients corresponding to tankers are applied. It is worthy to mention that in the afforementioned source, the large tankers which are used as reference are thought to be employing Steam Turbines (that was a common practice for Very Large Crude Carriers -VLCCs and Ultra Large Crude Carriers- ULCCs during the previous decades). This fact is useful for the examination of steam-powered LNG Carriers.

Coefficients relevant to SSD engines are taken from large Bulk Carriers

Data for DFDE are retrieved from Ro-Pax ferries which employ medium speed Four- Stroke Diesel Engines, considering that their weight is similar to that of the DFDE.

Weight Coefficients for Gas Turbines were taken from [16, pp. 253]. Note that in this case there were two examples of gas turbines with their corresponding power and weight. Hence, the relevant coefficients were calculated and then used for the vessels examined in the thesis.

The Machinery Weight for COGES configuration is taken as a combination of data from Steam Turbines weight from [15] and from Gas Turbines weight from [16].

The equations describing all the above aspects are given in the appendix for each type of engine selection.

IV.4.2 Outfit Weight

The initial outfit weight is given by [24]

- $W_{OT1} = 6.1790 \cdot (L \cdot B \cdot D)^{0.48}$

Then the insulation weight, calculated in the previous steps is added

- $W_{OT2} = W_{OT1} + W_{INS}$

IV.4.3 Steel Weight

The steel weight is given as follows:

- $W_{ST} = LS - W_M - W_{OT}$

The assessment of the W_{ST} is of paramount importance as it represents the total amount of the steel needed for the construction of the vessel and the air-emissions in the phases of construction, maintenance and dismantling are given as the product of this weight and suitable factors for each activity. The procedure is described analytically in the following chapters.

V. LCA - LCC Analysis [21]

The LCA methodology could be described as a methodology applicable to the assessment of the environmental impact of a human system throughout its whole life, thus implying the “Cradle to Grave” approach [see pictures 17 and 18]. More explicitly, in the case of the system examined here, namely a ship, four discrete phases that represent its overall life-cycle benchmarks are selected, namely: Production, operation, maintenance and dismantling. For each of these phases an inventory for energy consumption and emissions is formed [see Pictures 19 and 20].

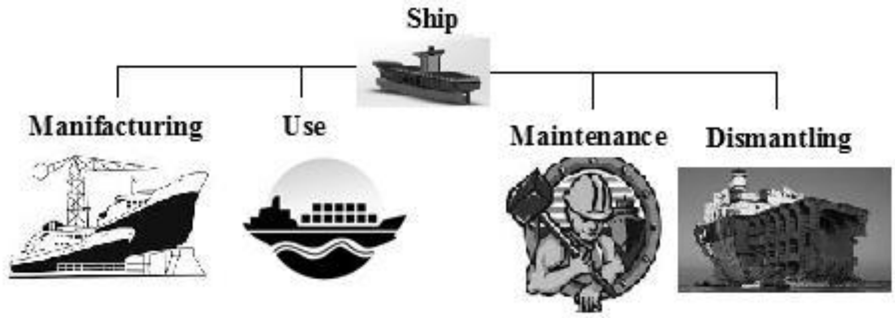


Figure 26 TheLife Cycle Assessment Method [17]

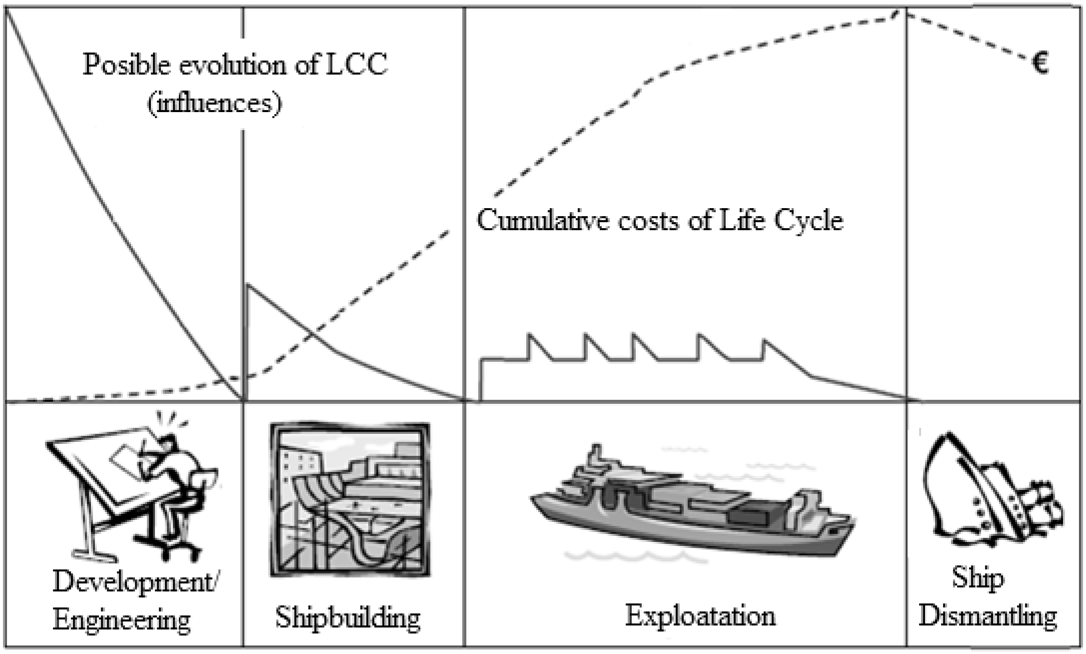


Figure 27 The Life Cycle Assessment Method [17]

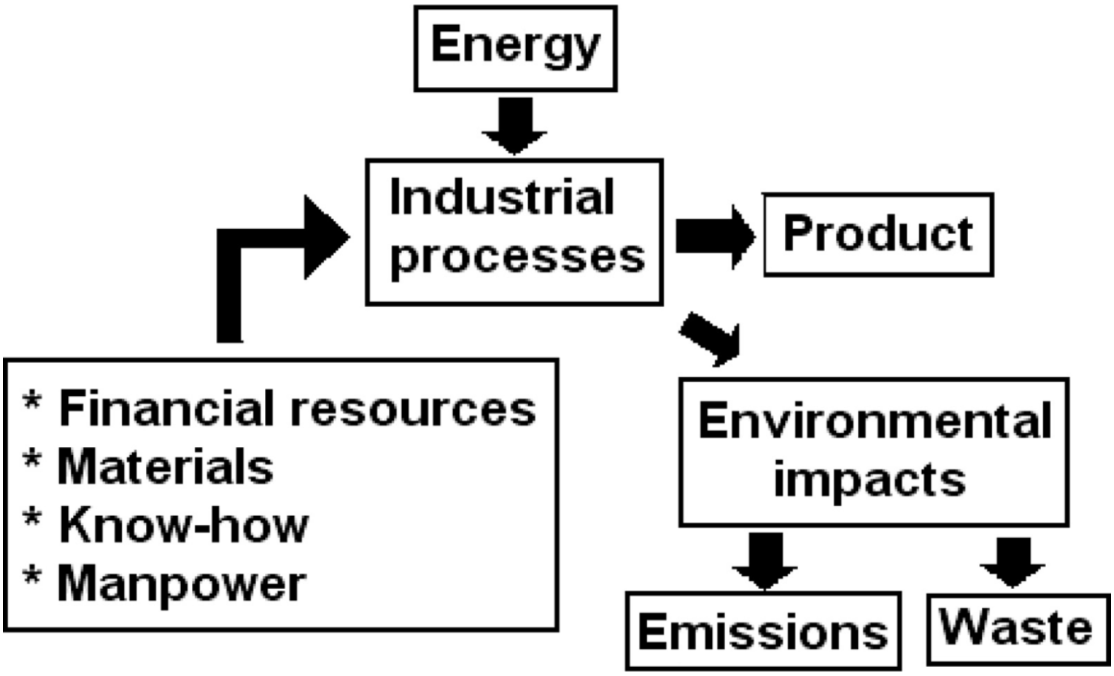


Figure 28 The Life Cycle Assessment Method [18]

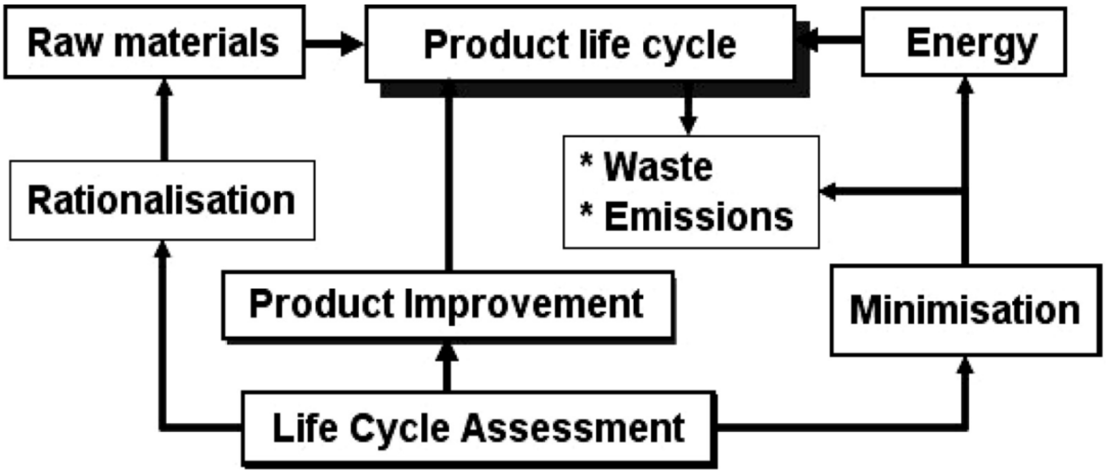


Figure 29 The Life Cycle Assessment Method [18]

The formation of the inventory is the first step to reducing the waste stream and emissions by the aforementioned phases permitting the comparison of possible modifications that may decrease both the adverse environmental impacts of the construction and the operation of the vessels, and simultaneously promote more economic solutions.

Each phase of the ship's life can be interpreted as a new subsystem, with inputs such as, energy and raw materials, and outputs pollutants and air emissions. This analysis allows the identification of possible mitigation of them with the introduction of certain improvement measures in the aforementioned phase, i.e use of lightweight materials to reduce weight [19], use of fuels with low carbon content, after-treatment methods for less harmful engine emissions or waste heat recovery methods to reduce the energy consumption on-board. Furthermore it is important to enhance the use of recyclable raw materials reducing the amount of waste produced during the final phase of the system's life – the dismantling phase [19].

Consequently this approach meets the requirement of preserving the valuable natural resources by reducing the usage of both raw materials and energy, while in the same time reducing the environmental impact of the system by producing less waste and emissions

The inventory records data for the following factors. [17]

- Carbon Footprint. It corresponds to the total amount of emissions of greenhouse gases produced by a system throughout its whole life. The sources of greenhouse gas are: Fossil Fuels burnt, the process of welding/cutting metal plates in the production/maintenance/dismantling phases, the process of fuel production and the transportation of goods necessary for the production and operation of the system.
- Air acidification. It is caused mainly by sulfur dioxide and nitrogen oxide. They both increase the acidity of rainwater and the toxicity of the air, water and soil.
- Eutrophication of water. It is caused by the overabundance of nutrients in marine ecosystems. Nitrogen is responsible for the increase of algal bloom that reduces the amount of oxygen in the water, leading to the degradation of marine life.
- Total Energy consumed. It is the total amount of energy produced by non-renewable sources. The term energy contains energy in the means of both electricity and energy produced by fossil fuels.

The LCA framework is mainly based on ISO14040 (2006). It includes four phases

- Goal and Scope definition
- The creation of an inventory that consists of the compilation of inputs and outputs of a system throughout its life cycle.
- Impact Assessment. In this phase the impacts to the environment of the examined systems are evaluated. This step also includes the classification of the inputs in categories according to their environmental impact.
- Weighting. Finally the quantification of the impact of the system inputs must be calculated.
- The results must be connected with the initial goal or scope.

The main goals of the LCA are: [18]

- Minimization of energy consumption
- Minimization of environmental impacts
- Rationalization of materials used

The main components of the LCA are: [18]

- Inventory analysis: Its purpose is to identify and quantify the energy and resources used, as well as the environmental releases to air, water and land, concerning the examined system.
- Environmental Impact Assessment: Quantitative and qualitative characterization and assessment of the consequences on the environment caused by the examined system.
- Improvement Analysis:It is dealing with the evaluation and implementation of means reducing the environmental impacts, through the alternative modifications or novel solutions

From the above it can be concluded that the LCA provides a tool for the assessment of the environmental footprint of a given system, and simultaneously, promotes improvements in processes.

Rational use of materials

The main materials used in the construction of a ship are steel plates and sections, and electrodes. The rational use of these materials should lead to reduced energy consumption, thus creating less adverse impacts. On the other hand, this effort results in a minimization of the cost of construction or operation due to the mitigation of this amount, fulfilling the aforementioned requirements of a simultaneous improvement in terms of environmental protection and economic efficiency. The same approach should also be applied in the operations phase. A vessel designed for less emissions may possibly be a vessel with lower energy demands, hence, a more economic option [18].

Life Cycle Cost Assessment

It is important though to mention that apart from the environmental issues alluded to in the preceding paragraphs, another important aspect to be assessed is the economic impact of the modifications made for the protection of the environment. This means that the effort to protect the environment must be combined with economic solutions since it is necessary not to burden the supply chain. This aspect exhibits the paradigm shift from a reactive and restrictive attitude to a modern attitude, where the measures for the environmental protection should not be perceived as restrictions, but as design variables, allowing a simultaneous improvement in both economic and environmental aspects. In order to achieve this goal a second inventory shall be conducted. In the latter, all the costs of the inputs of the system are recorded [17, 20].

VI LCC Analysis

VI.1 Construction Cost

Construction Cost comprises of two cost categories. The *Labor Cost* and the *Material Cost.* Both of them are given as a function of each weight category. The appropriate factors are given in the following tables [22].

Table 4 Conversion Factors for Labor Cost

Weight	Labor Man-Hours
Steel Weight	$C_F \cdot 177 \cdot W_{ST}{}^{0.862}$
Machinery Weight	$C_F \cdot 365 \cdot W_{MM}{}^{0.704}$
Electrical Weight	$682 \cdot W_E{}^{1.025}$
Auxiliary Weight	$C_F \cdot 34.8 \cdot W_{AUX}{}^{1.24}$
Outfit Weight	$310 \cdot W_{OUT}^{0.949}$

Table 5 Conversion Factors for Material Cost

Weight	Material Cost [$]
Steel Weight	$800 \cdot W_{ST}$
Machinery Weight	$15000 + 20000 \cdot W_{MM}$
Electrical Weight	$25000 \cdot W_E$
Auxiliary Weight	$10000 + 10000 \cdot W_{AUX}$
Outfit Weight	$5000 + 10000 \cdot W_{OUT}$

- A *Complexity Factor (CF)* is used in the calculations . It is the product of the *Type Factor (TF)* and the *Size Factor (SF).* The first is assumed to be 1.25, for *Chemical Tankers*, as long as LNG Carriers are not mentioned in that paper, and *Chemical Tankers* is thought to be the best approximation. The latter factor is estimated by the formula $SF = 32.47 \cdot \Delta^{-0.3792}$. Finally $CF = TF \cdot SF$ [22].
- In the initial calculations in this thesis the total Machinery weight was divided into three categories: W_{MM}, W_{MR}, W_{MS}. It is assumed that W_{MR} contains both W_E and W_{AUX}. Due to the lack of more specific information, it is assumed that both of them contribute to the formation of W_{MR} with 50% each.

- W_M is formed by the sum of W_{MM} and W_{MS} .
- *Total Man-hours* (*Mh*) from table IV [22] are multiplied by the *Labor Rate (LR)*, which is assumed to be [15$/Mh] [22], giving as a result the *Direct Labor Cost (DLC).*
- The *Labor Overhead Rate (LOR)* is assumed to be 100% [22], thus the *Indirect Labor Cost (ILC)=DLC.*
- *Total Labor Cost (TLC)= DLC+ILC*
- The sum of costs in table [VI] is assumed to be the *Direct Material Cost (DMC).*
- The *Material Overhead Rate (MOR)* is taken to be 2%, thus the *Indirect Material Cost (IMC)* is assumed to be: $0.02 \cdot DMC$
- *Total Material Cost (TMC)= DMC+IMC*
- A profit of 10% is assumed for both *TLC* and *TMC*
- Finally the total Price is given as follows: $P = (1 + \text{Profit}) \cdot (TLC + TMC)$

VI.2 Machinery Cost

Data for the calculation of the price of machinery equipment is extracted by [5]. However, in this thesis, vessels of different size are compared, thus variated propulsion demands are examined. Hence the prices given in the aforementioned paper are divided by the propulsive demand of the examined ship in [1], resulting in an index of specific cost per KW, [$/KW]. Extra data were retrieved from [11, 12, 13, 23] and more precisely the values of an SCR system, a Scrubber System and the value of the WHR. The same procedure is undertaken here leading again to indices [$/KW]. In the following tables these prices are given for each Propulsive Configuration. Last thing to mention is that the specific cost is also divided by the number of items. The number of items will be derived from [5] and will be set as the default value.

Table 6 Machinery Cost for ST configuration

Steam Turbine			
Item	**Number**	**Specific Cost [$/KW]**	**Source**
Steam Boiler	2	150.96	[5]
Main Propulsion Steam Turbine	1	117.42	[5]
Gear Case	1	100.64	[5]
Steam Turbine Gensets	2	30.19	[5]
Stand-by Diesel Gensets	1	30.19	[5]
Emergency Diesel Gensets	1	16.77	[5]
Propeller and Shafting	1	21.81	[5]
Rudder/Steering Gear	1	8.39	[5]
Bow Thruster	1	13.42	[5]
Installation Cost		16.77	[5]

Table 7 Machinery Cost for SSD configuration

SSD			
Item	**Number**	**Specific Cost [$/KW]**	**Source**
Two-Stroke Propulsive Engine	2	128.89	[5]
Reliquefaction Plant	2	135.59	[5]
Diesel Gensets	3	30.51	[5]
Propeller and Shafting	2	20.34	[5]
Rudder/Steering Gear	2	6.78	[5]
Emergency Diesel Generators	1	16.45	[5]
Bow Thruster	1	13.56	[5]
SCR	1	47	[11, 12, 13]
Seawater Scrubber	1	120.67	[23]
Freshwater Scrubber	1	150.83	[23]
WHR (ST&PT)	1	122	[11, 12, 13]
WHR(ST/PT)	1	183	[11, 12, 13]
Installation Cost		20.34	[5]

Table 8 Machinery Cost for DFDE configuration

DFDE			
Item	**Number**	**Specific Cost [$/KW]**	**Source**
Dual Fuel Engines	4	89.85	[5]
Electric Propulsion Motors,Transformers, Converters	2	87.51	[5]
Gear Case	1	71.88	[5]
Propeller and Shafting	1	18.75	[5]
Rudder/Steering Gear	1	15.63	[5]
Thermal Oxidiser	1	15.63	[5]
Emergency Diesel Generators	1	13.56	[5]
Bow Thruster	1	12.5	[5]
Installation Cost		14.06	[5]

Table 9 Machinery Cost for GT configuration

GT			
Item	**Number**	**Specific Cost [$/KW]**	**Source**
Main Gas Turbine	1	406.28	[5]
Auxiliary Gas Turbine	1	9.38	[5]
Electric Propulsion Motors,Transformers, Converters	2	31.25	[5]
Gear Case	1	87.51	[5]
Propeller and Shafting	1	71.88	[5]
Rudder/Steering Gear	1	18.75	[5]
Thermal Oxidiser	1	7.81	[5]
Stand-by Diesel Generators	1	15.63	[5]
Emergency Diesel Generators	1	15.63	[5]
Bow Thruster	1	28.13	[5]
Installation Cost		12.5	[5]

Table 10 Machinery Cost for COGES configuration

COGES			
Item	**Number**	**Specific Cost [$/KW]**	**Source**
Main Gas Turbine	1	406.28	[5]
Steam Turbine Gensets	1	9.38	[5]
Exhaust Gas Boiler	1	31.25	[5]
Auxiliary Boiler	1	87.51	[5]
Electric Propulsion Motors,Transformers, Converters	2	71.88	[5]
Gear Case	1	18.75	[5]
Propeller and Shafting	1	7.81	[5]
Rudder/Steering Gear	1	15.63	[5]
Thermal Oxidiser	1	15.63	[5]
Stand-by Diesel Generators	1	28.13	[5]
Emergency Diesel Generators	1	15.62	[5]
Bow Thruster	1	12.5	[5]
Installation Cost		12.5	[5]

VI.3 Total Capital Cost

The Total Capital Cost for the machinery equipment is calculated by the following formula:

$$TCPC = MCR \cdot \sum_{i=1}^{N} n_i \cdot CITEM_i + IC \ ,$$

where $TCPC$ stands for the Total Capital Cost for the machinery equipment , n_i stands for the number of each item category, $CITEM_i$ is the cost of each item, and IC stands for the *Installation Cost* [1].

VI.4 Maintenance Cost

The Maintenance Cost (*MC*) is given by the formula:

$$MC = a \cdot 10^{-3} \cdot \sum_{i=1}^{3} Pengine_i \cdot t_i + b \cdot 10^{-3} \cdot \sum_{i=1}^{6} Pauxdel_i \cdot t_i \ ,$$

where a and b are factors expressed in [$/MWh] given for each engine type in the following table [5], which are then multiplied with the total running hours for the main engine and the auxiliary engines expressed in KWh.

Table 11 Specific Maintenance Cost for all Configurations

ITEM	Specific Maintenance Cost [$/MWh]
Steam Turbine	0.4
Two Stroke Diesel+ Reliquefaction	1.3
Dual Fuel Diesel Electric	3
Gas Tyrbine	2.5
Steam Generator	0.5
Four Stroke Auxiliary Engines	3.5
Auxiliary Gas Turbine Genset	2.5

Hence for each of the selected Propulsive Configurations the MC will be as follows:

STEAM TURBINE

$$MC = 0.4 \cdot 10^{-3} \cdot \sum_{i=1}^{3} Pengine_i \cdot t_i + 0.5 \cdot 10^{-3} \cdot \sum_{i=1}^{6} Pauxdel_i \cdot t_i$$

SLOW SPEED DIESEL ENGINE

$$MC = 1.3 \cdot 10^{-3} \cdot \sum_{i=1}^{3} Pengine_i \cdot t_i + 3.5 \cdot 10^{-3} \cdot \sum_{i=1}^{6} Pauxdel_i \cdot t_i$$

DUAL FUEL DIESEL ELECTRIC

$$MC = 3.5 \cdot 10^{-3} \cdot \sum_{i=1}^{3} Pengine_i \cdot t_i + 3.5 \cdot 10^{-3} \cdot \sum_{i=1}^{6} Pauxdel_i \cdot t_i$$

GAS TURBINE

$$MC = 2.5 \cdot 10^{-3} \cdot \sum_{i=1}^{3} Pengine_i \cdot t_i + 2.5 \cdot 10^{-3} \cdot \sum_{i=1}^{6} Pauxdel_i \cdot t_i$$

COMBINED GAS AND STEAM ELECTRIC PROPULSION

$$MC = 2.5 \cdot 10^{-3} \cdot \sum_{i=1}^{3} Pengine_i \cdot t_i + 0.5 \cdot 10^{-3} \cdot \sum_{i=1}^{6} Pauxdel_i \cdot t_i$$

VI.5 Fuel Cost

Table 12 Fuel Cost

Operation Scenario	Bunkering Port	HFO	MDO	MGO	LNG
Sabine Pas -Incheon	Houston	362.5	432	620	398.5
Sabine Pass - Huelva	Houston	362.5	432	620	398.5
Bonny - Barcelona	Houston	362.5	432	620	398.5
Bonny - Dahez	Fujairah	378	423.5	617.5	415.8
Ras Laffan -Nagoya	Singapore	392	416	593	431.2
Ras Laffan - Swinousjscie	Rotterdam	367	402	571	403.7
Dampiers - Dalian	Hong -Kong	396	405.5	610	435.6

- The prices were taken from the website https://shipandbunker.com on 04/01/2018.
- The site gives prices for three fuel categories: *IFO 380, IFO 180* and *MGO* namely. Here the prices of HFO are assumed to be equal to the prices of *IFO 380,* that of MDO are equal to the prices of *IFO 180 and* finally MGO prices, undoubtedly, are equal to the prices given in the website.
- LNG prices were not found in the web, thus it was assumed that prices would be equal to $1.1 \cdot \mathrm{Price}_{HFO}$ [5]
- The prices of fuels are taken marginally with respect of geographic proximity, thus vessels involved in voyages from North America are supplied with fuel, the prices of which are equal to those of Houston. A more extreme case is the route Bonny - Barcelona, where no bunkering (according to the aforementioned website) is en route. Hence the prices of Rotterdam are considered, as marginally relevant to European Prices as a total.

VI.6 Lubricating Cost

In the following table the lub oil consumption for each Propulsive Configuration is given [5]

Table 13 Lub oil Consumption

Propulsive Coefficient	Lubricating Demand	Lub Oil Consumption	Unit
ST	Specific L.O.Consumption	0	[g/KWh]
SSD	Specific L.O. Cylinder Consumption	1.5	[g/KWh]
	System Oil Consumption	75	[kg/24h]
	Gensets Oil Consumption	1	[g/KWh]
DFDE	Specific L.O.Consumption	0.8	[g/KWh]
GT	Specific L.O.Consumption	0	[g/KWh]
COGES	Specific L.O.Consumption	0	[g/KWh]

- It is assumed that gensets are used in the case of ST, SSD, MEGI and WLPS, while in the case of DFDE and COGES the diesel –electric concept leads to electricity being produced by the main engine. When a DFDE configuration is installed, no gensets are installed (apart from Emergency Generators).The same thing occurs in the COGES case. When a GT configuration is installed, electricity is produced by turbine gensets, which do not necessitate the use of lub oil.
- Two Stroke engines usually use separate lub oil for the cylinders (*Cylinder Oil*) and the crankshaft (*System Oil*). In addition, the lubricating needs of the diesel gensets are taken into account.
- The amount of Lub oil is converted to tonnes.

More specifically the Lub Oil consumption for each Configuration will be as follows:

STEAM TURBINE

$$LubOil_{\mathrm{PROP}} = 0 \cdot 10^{-6} \cdot \sum_{i=1}^{3} Pengine_i \cdot t_i$$

$$LubOil_{AUX} = 1 \cdot 10^{-6} \cdot \sum_{i=1}^{6} Pauxdel_i \cdot t_i$$

SLOW SPEED DIESEL ENGINE

$$CLubOil = 1.5 \cdot 10^{-6} \cdot \sum_{i=1}^{3} Pengine_i \cdot t_i$$

$$SLubOil = 75 \cdot 10^{-3} \cdot \left(t_1 + t_2 + t_3\right) / 24$$

$$LubOil_{AUX} = 1 \cdot 10^{-6} \cdot \sum_{i=1}^{6} Pauxdel_i \cdot t_i$$

$$LubOil_{PROP} = CLubOil + SLubOil$$

DUAL FUEL DIESEL ELECTRIC

$$LubOil_{\mathrm{PROP}} = 0.8 \cdot 10^{-6} \cdot \sum_{i=1}^{3} Pengine_i \cdot t_i$$

$$LubOil_{AUX} = 1 \cdot 10^{-6} \cdot \sum_{i=1}^{6} Pauxdel_i \cdot t_i$$

GAS TURBINE

$$LubOil_{\mathrm{PROP}} = 0 \cdot 10^{-6} \cdot \sum_{i=1}^{3} Pengine_i \cdot t_i \quad LubOil_{\mathrm{PROP}} = 0 \cdot 10^{-6} \cdot \sum_{i=1}^{3} Pengine_i \cdot t_i$$

$$LubOil_{AUX} = 0 \cdot 10^{-6} \cdot \sum_{i=1}^{6} Pauxdel_i \cdot t_i \quad LubOil_{AUX} = 0 \cdot 10^{-6} \cdot \sum_{i=1}^{6} Pauxdel_i \cdot t_i$$

COMBINED GAS AND STEAM ELECTRIC PROPULSION

$$LubOil_{\mathrm{PROP}} = 0 \cdot 10^{-6} \cdot \sum_{i=1}^{3} Pengine_i \cdot t_i$$

$$LubOil_{AUX} = 0 \cdot 10^{-6} \cdot \sum_{i=1}^{6} Pauxdel_i \cdot t_i$$

VI.7 Operation Expenditure *(OPEX)*

In the previous formulas $LubOil_{\mathrm{PROP}}$ stands for the lubricating demands for propulsion and $LubOil_{AUX}$ stands for the lubricating demands for auxiliary demands.

Updated data for the Lub oil value could not been found. Hence its value was calculated by a formula found in [5]. More specifically:

- Price of four – stroke diesel generators (*PLO*): $PLO = 4 \cdot \mathrm{Price}_{HFO}$
- Price of cylinder oil for two-stroke diesel engines (*PCLO*): $PCLO = 5.3 \cdot \mathrm{Price}_{HFO}$
- Price of system oil for two-stroke diesel engines (*PSLO*): $PSLO = 4 \cdot \mathrm{Price}_{HFO}$

  In this means the total cost of lub oil per year is as follows:

The number of trips per year is calculated by the following formula:

- $\mathrm{NOTY} = \dfrac{365 \cdot 24}{\sum_{i=1}^{6} t_i}$

The annual fuel cost (*TFC*) and the annual lubricating cost (*TLC*) is given as follows:

$$TFC = NOTY \cdot \left(PHFO \cdot TMHFO + PMDO \cdot TMMDO + PMGO \cdot TMMGO + PLNG \cdot EXTRAMLNG \right)$$
$$TLC = NOTY \cdot \left(PLO \cdot SLOC + PSLO \cdot SSLOC + PCLO \cdot SCLOC \right)$$

- It is mentioned here that the above formula gives the most generic expression of the *TFC* and in every case of Propulsive Configuration some fuels are not used (i.e. SSD engines do not utilize neither LNG, nor MGO, and MDO is utilized only in Seca areas, if a Scrubber is not placed).
- The term EXTRAMLNG is elaborated here and the MLNG, because as the boil-off LNG is used for propulsion the amount of extra LNG utilized and hence payed is reduced.
- In case of an SSD with an *SCR,* the *Urea* solution has to be calculated.
  At first the Urea flow is calculated with the following formula:
  $$UREAFLOW = 15 \cdot 10^{-3} \cdot (Pengine(1) \cdot t(9) + Pengine(2) \cdot t(10) + Pengine(3) \cdot t(3)) \left[tons \right]$$
  The relevant cost is expected to be: $TUC = UREAFLOW \cdot PUREA$, where TUC stands for the cost of Urea and $PUREA$ stands for the Price of Urea.
- The generic formula for the OPEX is calculated as follows: $OPEX = TFC + TLC + MC + TUC$ [11,12,13].

VI.8 Capital Expenditure (CAPEX)

The capital cost is calculated by the following formula [11, 12, 13]:

$$CAPEX = IC + R \cdot \frac{(1+R)^N}{(1+R)^N - 1}$$ where:

IC stands for the initial *Investment Cost*

R stands for the *Discount Rate.* [11,12,13]

N is the lifetime of the investment in this thesis it shall be equal to 25 years

VI.9 Net Present Value (NPV)

The following formula is exploited for the calculation of the NPV [5]

$$NPV = -IC + \sum_{t=0}^{N} \frac{AR_t - OPEX_t}{(1+i)^t} + \frac{SV_N}{(1+i)^N}$$, where:

IC stands for the initial *Investment Cost*

AR_t stands for the annual revenues [5]

i stands for the *Market Interest Rate.* In this thesis 3 rates will be used: 6% ,8%, 10%

N is the *Lifetime* of the investment, 25 years as aforementioned.

SV_N is the *Salvage Value* of the investment at the end of its' lifetime. $SV_N = 0.03 \cdot IC$

VI.10 Results of the Analysis

The aforementioned methodology is also applied to all of 6 vessels each one equipped with all possible propulsive configurations at a time. The results concerning the corresponding economic aspects are summarized in the following tables.

Cost of Hull Construction (million US$)

Employnig data from the previously shown Table 7, the cost of the Hull Constuction for each vessel examined is calculated. From the data given in the aforementioned table, the Machinery Weight is excluded. Despite this omission, the same vessel with different Propulsive Configurations implies different cost values, due to different relevant Electrical, Auxiliary and Outfitting Weight.The cost of each combination of vessel capacity and engine selection is shown in the following table.

Table 14 Cost of Hull Construction

Vessel	ST	SSD	DFDE	GT	COGES
1	82.21	97.79	126.33	126.80	126.78
2	118.84	148.02	199.85	200.64	200.62
3	124.02	155.84	214.38	215.18	215.15
4	137.15	173.66	235.00	236.07	236.03
5	150.37	190.68	264.55	265.51	265.47
6	170.64	220.18	317.53	318.47	318.44

Total Cost of Propulsive Configuration (million US$)

Since the cost of each Propulsive Configuration is of crucial importance in this thesis, it is calculated for each vessel size. As a matter of fact it is the product of the specific cost coefficients given in tables 9-13 times the relevant Power corresponding to each vessel. The results are presented in Table 18.

Table 15 Total Cost of Propulsive Configuration

Vessel	ST	SSD	With	GT	COGES
1	10.63	10.99	11.33	13.62	13.98
2	20.59	21.30	21.95	26.37	27.07
3	20.85	21.56	22.23	26.70	27.42
4	28.28	29.24	30.15	36.22	37.18
5	26.45	27.35	28.20	33.87	34.78
6	27.32	28.25	29.12	34.98	35.91

As mentioned in the previous paragraphs, SSD engines are considered to be running on HFO without the ability to utilize LNG, as all the other Propulsive Configurations examined here do. This fact causes descrepancies when vessels with the aforementioned configuration are obliged to operate in ECA areas. As a result, when this type of engine is examined, it is thought that within ECA areas MDO will be used instead of HFO, or, as an alternative option, Additional Devices may be added in order to comply with the environmental regulations in these areas without the need of fuel shift. Additionally, the use of WHR is examined in order to exploit part of the energy of the exhaust gases. As a result, fuel consumption for auxiliary use is reduced leading in favourable economic and environmental results. In the following tables the acquisition cost of various versions of SSD engines with Additional Devices are displayed. In Table 17 the acquisition cost of an SSD combined with a Scrubber device is examined in order to reduce the exhaust of SO_X. There are two options examined (Seawater Scrubber and Freshwater Scrubber) with different relevant acquisition cost. In Table 18 the selection of an SSD with the addition of a WHR is examined. Note that this option does not lead to compliance with ECA rules, but only improves the economic performance of the examined vassel. Thus this selection is necessary to be combined with another option. In Table 19 the cost of an SSD combined with a solution complying with NO_X regulations is examined. There are again two options (EGR and SCR repectively). Once more the acquisition cost of the two options is different.

Table 16 Total Cost of SSD with Seawater Scrubber and Freshwater Scrubber

Vessel	SSD+Seawater Scrubber	SSD+Freshwater Scrubber
1	12.82	13.28
2	24.83	25.72
3	25.15	26.04
4	34.11	35.32
5	31.90	33.04
6	32.94	34.11

Table 17 Total Cost of SSD with Waste Heat Recovery System

Vessel	SSD + WHR
1	12.36
2	24.32
3	24.62
4	33.39
5	31.24
6	32.26

Table 18 Total Cost of SSD with EGR and SCR systems

Vessel	SSD + EGR	SSD + SCR
1	10.99	11.71
2	21.30	22.67
3	21.56	22.96
4	29.24	31.14
5	27.35	29.12
6	28.25	30.08

In the three previous tables the cost of the acquisition of each of the aforementioned Additional Devices is recorded. In each case the selection of only one of them is not ample for the compliance with the environmental requirements, which in the present thesis are considered to be the simultaneous mitigation of both SO_X and NO_X. In the case of Scrubber there is a substantial containment in SO_X but not in NO_X. The reverse result is obtained when utilizing an SCR or EGR device. Finally in case that a WHR is used, although a reduction in fuel consumption is achieved, this is not sufficient for the compliance with the environmental rules within ECA areas.

Consequently, there are 3 options for achieving the goal of simultaneous mitigation of SO_X and NO_X. The first option is the combination of an SCR and a WHR while running on MDO in ECA areas. The shift to MDO ensures the compliance with the SO_X restrictions, the SCR with the respective NO_X while the use of the WHR reduces the fuel consumption and, as result, a further reduction of air pollutants is achieved. The second and third option constitute of the simultaneous use of a Scrubber and an EGR. In this case both Scrubber selections (Freshwater and Seawater) are examined, but at the same time only the EGR selection for dealing with the NO_X, as the combination of a Scrubber and SCR is considered to be a choice with large weight increase.

Table 19 Final selection of vessels equipped with SSD for compliance with ECA regulations

Vessel	MDO-WHR-SCR	Seawater Scrubber-EGR	Freshwater Scrubber-EGR
1	13.07	12.82	13.28
2	25.69	24.83	25.72
3	26.02	25.15	26.04
4	35.29	34.11	35.32
5	33.01	31.90	33.04
6	34.09	32.94	34.11

Total Acquisition Cost (Hull and Propulsive Configuration/million US$)

The sum of the Cost of Hull Construction, displayed in Table 17, and the Total Cost of Propulsive Configuration, displayed in Table 18, result in the Total Acquisition Cost recorded in Table 21. As mentioned previously, the selection of an SSD engine is combined with a series of Additional Devices. Following the results of the previous paragraphs, the Total Acquisition Cost of these vessels is recorded. As a result, a series of new tables is produced, where in Table 22 the Total Acquisition Cost of vessels employing SSD combined with Scrubber is given. In an analogous way, Tables 23 and 24 give the Total Acquisition Cost for vessels with SSD combined with WHR, and SSD combined with NO_X abatement devices (EGR, SCR),respectively. Finally, in Table 25 the costs of vessels complying concurrently with NO_x and SO_X regulations, in a same way as Table 20, are shown.

Table 20 Total Acquisition Cost

Vessel	ST	SSD	DFDE	GT	COGES
1	92.84	108.79	137.66	140.42	140.76
2	139.43	169.31	221.8	227.01	227.69
3	144.87	177.40	236.61	241.88	242.57
4	165.43	202.90	265.15	272.29	273.21
5	176.82	218.03	292.75	299.38	300.25
6	197.96	248.42	346.65	353.45	354.36

Table 21 Total Acquisition Cost of vessels using SSD with Seawater Scrubber and Freshwater Scrubber

Vessel	SSD+Seawater Scrubber	SSD+Freshwater Scrubber
1	110.61	111.07
2	172.85	173.74
3	180.99	181.88
4	207.77	208.98
5	222.58	223.72
6	253.12	254.29

Table 22 Total Acquisition Cost of vessels equipped with SSD with Waste Heat Recovery System

Vessel	SSD + WHR
1	110.15
2	172.34
3	180.46
4	207.05
5	221.92
6	252.44

Table 23 Total Acquisition Cost of vessels equipped with SSD with EGR and SCR Systems

Vessel	SSD + EGR	SSD + SCR
1	108.78	109.50
2	169.32	170.69
3	177.4	178.80
4	202.9	204.80
5	218.03	219.80
6	248.43	250.26

Table 24 Total Acquisition Cost of vessels equipped with SSD for compliance with ECA regulations

Vessel	MDO-WHR-SCR	Seawater Scrubber-EGR	Freshwater Scrubber-EGR
1	110.86	110.61	111.07
2	173.71	172.85	173.74
3	181.86	180.99	181.88
4	208.95	207.77	208.98
5	223.69	222.58	223.72
6	254.27	253.12	254.29

CAPEX(R=0.06) (million US$)

CAPEX is calculated as shown in paragraph VI.8. Three Discount Rates are examined, R=0.06, R=0.08 and R=0.1.Tables 26-30 display the results when R=0.06, Tables 31-35 the results when R=0.08, and 36-40 those for R=0.1. Once again the selection of SSD is analysed to more options when combined with Scrubber, SCR and WHR.

Table 25 CAPEX with R=0.06

Vessel	ST	DFDE	GT	COGES
1	7.26	10.77	10.98	11.01
2	10.91	17.35	17.76	17.81
3	11.33	18.51	18.92	18.98
4	12.94	20.74	21.30	21.37
5	13.83	22.90	23.42	23.49
6	15.49	27.12	27.65	27.72

Table 26 CAPEX with R=0.06 for vessels equipped with SSD and Seawater or Freshwater Scrubber

Vessel	SSD +Seawater Scrubber	SSD+Freshwater Scrubber
1	8.65	8.69
2	13.52	13.59
3	14.16	14.23
4	16.25	16.35
5	17.41	17.50
6	19.80	19.89

Table 27 CAPEX with R=0.06 for vessels equipped with SSD with Waste Heat Recovery System

Vessel	SSD + WHR
1	8.62
2	13.48
3	14.12
4	16.20
5	17.36
6	19.75

Table 28 CAPEX with R=0.06 for vessels equipped with SSD with EGR and SCR Systems

Vessel	SSD + EGR	SSD + SCR
1	8.51	8.57
2	13.25	13.35
3	13.88	13.99
4	15.87	16.02
5	17.06	17.19
6	19.43	19.58

Table 29 CAPEX with R=0.06 for vessels equipped with SSD for compliance with ECA regulations

Vessel	MDO-WHR-SCR	Seawater Scrubber-EGR	Freshwater Scrubber-EGR
1	8.67	8.65	8.69
2	13.59	13.52	13.59
3	14.23	14.16	14.23
4	16.35	16.25	16.35
5	17.50	17.41	17.50
6	19.89	19.80	19.89

CAPEX(R=0.08)

Table 30 CAPEX with R=0.08

Vessel	ST	DFDE	GT	COGES
1	8.70	12.90	13.15	13.19
2	13.06	20.78	21.27	21.33
3	13.57	22.17	22.66	22.72
4	15.50	24.84	25.51	25.59
5	16.56	27.42	28.05	28.13
6	18.54	32.47	33.11	33.20

Table 31 CAPEX with R=0.08 for vessels equipped with SSD and Seawater or Freshwater Scrubber

Vessel	SSD+Seawater Scrubber	SSD+Freshwater Scrubber
1	10.36	10.40
2	16.19	16.28
3	16.95	17.04
4	19.46	19.58
5	20.85	20.96
6	23.71	23.82

Table 32 CAPEX with R=0.08 for vessels equipped with SSD with Waste Heat Recovery System

Vessel	SSD + WHR
1	10.32
2	16.14
3	16.91
4	19.40
5	20.79
6	23.65

Table 33 CAPEX with R=0.08 for vessels equipped with SSD with EGR and SCR Systems

Vessel	SSD + EGR	SSD + SCR
1	10.19	10.26
2	15.86	15.99
3	16.62	16.75
4	19.01	19.19
5	20.42	20.59
6	23.27	23.44

Table 34 CAPEX with R=0.08 for vessels equipped with SSD for compliance with ECA regulations

Vessel	MDO-WHR-SCR	Seawater Scrubber-EGR	Freshwater Scrubber-EGR
1	10.39	10.36	10.40
2	16.27	16.19	16.28
3	17.04	16.95	17.04
4	19.57	19.46	19.58
5	20.96	20.85	20.96
6	23.82	23.71	23.82

CAPEX(R=0.1)

Table 35 CAPEX with R=0.1

Vessel	ST	DFDE	GT	COGES
1	10.23	15.17	15.47	15.51
2	15.36	24.44	25.01	25.08
3	15.96	26.07	26.65	26.72
4	18.23	29.21	30.00	30.10
5	19.48	32.25	32.98	33.08
6	21.81	38.19	38.94	39.04

Table 36 CAPEX with R=0.1 for vessels equipped with SSD and Seawater or Freshwater Scrubber

Vessel	SSD+Seawater Scrubber	SSD+Freshwater Scrubber
1	12.19	12.24
2	19.04	19.14
3	19.94	20.04
4	22.89	23.02
5	24.52	24.65
6	27.89	28.01

Table 37 CAPEX with R=0.1 for vessels equipped with SSD with Waste Heat Recovery System

Vessel	SSD + WHR
1	12.14
2	18.99
3	19.88
4	22.81
5	24.45
6	27.81

Table 38 CAPEX with R=0.1 for vessels equipped with SSD with EGR and SCR Systems

Vessel	SSD + EGR	SSD + SCR
1	11.98	12.06
2	18.65	18.80
3	19.54	19.70
4	22.35	22.56
5	24.02	24.21
6	27.37	27.57

Table 39 CAPEX with R=0.1 for vessels equipped with SSD for compliance with ECA regulations

Vessel	MDO-WHR-SCR	Seawater Scrubber-EGR	Freshwater Scrubber-EGR
1	12.21	12.19	12.24
2	19.14	19.04	19.14
3	20.04	19.94	20.04
4	23.02	22.89	23.02
5	24.64	24.52	24.65
6	28.01	27.89	28.01

OPEX (in million US$)

Following the analysis of paragraph VI.7, the OPEX is calculated for the first year of operation. At first the results for Propulsive Configurations apart from SSD are presented in Table 41. The OPEX for the SSD engines when combined with Scrubber are given in Table 42, in Tables 43 and 44 the results of the analysis for SSD combined with WHR and SCR, respectively. Finally in Table 45 the OPEX for the selections that comply with the ECA rules are displayed.

Table 40 OPEX

Vessel	ST	DFDE	GT	COGES
1	8.23	8.31	12.48	10.76
2	15.03	15.48	23.30	20.05
3	15.63	15.90	23.88	20.60
4	22.57	21.79	33.39	27.82
5	18.05	19.94	29.95	25.83
6	17.05	20.41	30.66	26.44

Table 41 OPEX for vessels equipped with SSD and Seawater or Freshwater Scrubber

Vessel	SSD+Seawater Scrubber	SSD+Freshwater Scrubber
1	8.41	8.41
2	15.88	15.88
3	16.10	16.10
4	21.68	21.68
5	20.13	20.13
6	20.60	20.60

Table 42 OPEX for vessels equipped with SSD with Waste Heat Recovery System

Vessel	SSD + WHR
1	8.25
2	15.77
3	15.99
4	21.52
5	19.99
6	20.46

Table 43 OPEX for vessels equipped with SSD with EGR and SCR Systems

Vessel	SSD + EGR	SSD + SCR
1	8.41	17.37
2	15.89	34.87
3	16.12	35.11
4	21.70	47.62
5	20.15	44.22
6	20.63	45.26

Table 44 OPEX for vessels equipped with SSD for compliance with ECA regulations

Vessel	MDO-WHR-SCR	Seawater Scrubber-EGR	Freshwater Scrubber-EGR
1	17.20	8.41	8.41
2	34.97	15.88	15.88
3	35.21	16.10	16.10
4	47.75	21.68	21.68
5	44.34	20.13	20.13
6	45.38	20.60	20.60

NPV (in million US$, with R=0.06)

The NPV is calculated as in paragraph VI.9. Calculations were performed for NPV with R=0.06. The results for Propulsive Configurations apart from SSD are presented in Table 46. The NPV for the SSD engines when combined with Scrubber are given in Table 47, in Tables 48 and 49 the results of the analysis for SSD combined with WHR and SCR or EGR , respectively. Finally in Table 50 the OPEX for the selections that comply with the ECA rules are displayed.

Table 45 NPV

Vessel	ST	DFDE	GT	COGES
1	409.29	366.77	338.45	350.00
2	860.84	781.55	728.68	771.20
3	863.40	775.77	721.79	743.74
4	1004.5	914.77	837.58	872.48
5	1306.3	1189.3	1122.1	1149.6
6	1636.5	1483.6	1415.6	1443.7

Table 46 NPV for vessels equipped with SSD and Seawater or Freshwater Scrubber

Vessel	SSD + Seawater Scrubber	SSD +Freshwater Scrubber
1	395.34	394.90
2	830.49	829.64
3	833.08	832.15
4	977.95	976.77
5	1259.3	1258.7
6	1574.5	1573.4

Table 47 NPV for vessels equipped with SSD with Waste Heat Recovery System

Vessel	SSD + WHR
1	396.84
2	831.51
3	834.03
4	979.36
5	1261.10
6	1575.90

Table 48 NPV for vessels equipped with SSD with EGR and SCR Systems

Vessel	SSD + EGR	SSD + SCR
1	397.17	340.85
2	834.04	714.73
3	836.60	717.18
4	982.82	819.87
5	1264.3	1113.0
6	1579.2	1424.3

Table 49 NPV for vessels equipped with SSD for compliance with ECA regulations

Vessel	MDO-WHR-SCR	Seawater Scrubber-EGR	Freshwater Scrubber-EGR
1	340.52	395.34	394.90
2	710.79	830.49	829.64
3	713.20	713.60	832.15
4	814.49	977.95	815.01
5	1108.00	1259.3	1258.7
6	1419.10	1574.5	1573.4

VII. Production Phase [24, 25, 26, 27]

VII.1 Vessel Construction

The steel processing concerning the construction of the vessel can be subdivided into three sub-processes, steel production, steel cutting and steel welding.

VII.1.1 Steel Production

The W_{ST} assessed in the previous step is multiplied by the coefficients given in the following table. The result is the amount of air pollutants emitted during the production phase expressed in gr.

Table 50 Conversion Coefficients for Steel Production during steel production

Pollutants	Coefficient	Unit
CO_2	996.00	gr/kg
CO	31.83	gr/kg
CH_4	163.17	mg/kg
NO_X	5.84	gr/kg
PM	928.96	mg/kg
SO_X	5.58372	gr/kg
VOC	12.57	mg/kg
NMVOC	10.84	mg/kg

VII.1.2 Steel Cutting

Following their production, steel plates need to be cut into pieces with the proper dimensions and form for the erection of the vessel. In this phase the amount of the air pollutants is given as a function of the power needed for this procedure and not of the W_{ST} , thus the following formula is used :

$$EM_i = EC \cdot DWT \cdot EF_i \ ,$$

where: $EC = 3.026 \frac{kW}{tn}$, is the power needed for steel cutting expressed in kW per DWT tons, while EF are conversion coefficients given in table 7.1.2

Table 51 Conversion Coefficients for Steel Production during steel cutting

Pollutants	Coefficient	Unit
CO_2	319.16	gr/kwh
CO	303.68	mg/kwh
CH_4	20.82	mg/kwh
NO_X	128.89	mg/kwh
PM	212.74	mg/kwh
SO_X	2.23	gr/kwh
NMVOC	101.97	mg/kwh

VII.1.3 Welding

For this phase both the energy demanded for the welding and the total welding meters are needed.

Longitudinal Stiffeners

$$l_{LS} = 3 \cdot \frac{B}{FS} \cdot L + 2 \cdot \frac{D}{FS} \cdot L + 2 \cdot \frac{D-2}{FS} \cdot L \ [m]$$

Transverse Stiffeners

$$l_{TS} = \frac{L}{FS} \cdot (3 \cdot B + 2 \cdot D) + 2 \cdot \frac{L}{FS} \cdot (D-2) \ [m]$$

Bulkheads

$$l_B = N_B \cdot [3 \cdot B + 2 \cdot D + 2 \cdot (D-2)] + N_B \cdot \frac{B}{FS} \cdot D \ [m]$$

Plates

$$l_P = \frac{L}{6} \cdot [3 \cdot B + 2 \cdot D + 2(D-2)] + 3\frac{B}{2} \cdot L + 2\left(\frac{D}{2} + \frac{D-2}{2}\right) \cdot L \ [m]$$

The total welding length is given as the sum of the above lengths:

$$L_{W1} = l_{LS} + l_{TS} + l_B + l_P \ [m]$$

This amount is increased by 15% in order to include extra weldings that may not be initially taken into account. Hence the total welding length is now:

$$l_W = 1.15 \cdot l_{W1}$$

$$EM_i = L_W \cdot E_W \cdot EF_i \ ,$$

where $E_W = 0.538 \frac{kW}{m}$

Table 52 Conversion Coefficients for Steel Production during steel welding

Pollutants	Coefficient	Unit
CO_2	319.16	gr/kwh
CO	303.68	mg/kwh
CH_4	20.82	mg/kwh
NO_X	128.89	mg/kwh
PM	212.74	mg/kwh
SO_X	2.23	gr/kwh
NMVOC	101.97	mg/kwh

VII.2 Maintenance

The maintenance phase includes a number of activities such as the replacement of worn steel, the cutting and the welding of replacement steel.

VII.2.1 Steel Replacement

The amount of steel due to be replaced is calculated by the following formula:

$$ARS = LS \cdot 0.0306 \cdot \exp^{0.2772 \cdot (age)} / 1000 \ ,[24]$$

where age stands for the age of the vessel.

VII.2.2 Replacement Steel Cutting

The assumption that the power needed in this phase is equal to the 10% of the equivalent energy needed in the steel cutting for the production. Hence the formula is the same but with less energy demand and as a result less air emissions [24].

VII.2.3 Replacement Steel Welding

In addition to the above, it is assumed that the total welding length for the replacement phase will be equal to the 10% of the equivalent length for the production [24].

VII.3 Dismantling

Most of the global shipbreaking activities take place in East Asia with the use of rather obsolete methods and equipment. This makes the monitoring of the air emissions to be completely non-existent. The most prominent means of assessing the emissions during this stage is to conceive the scrapping as the reverse procedure to the construction. As a result, the converting coefficients are kept the same apart from for the coefficients equivalent to the conversion of CO_2, CH_4 and NO_X , for which there have been data recorded in a shipbreaking yard of India .

Table 53 Conversion Coefficients for Steel Production during dismantling

Pollutants	Coefficient	Unit
CO_2	338.64	gr/kg
CO	31.83	gr/kg
CH_4	86.48	mg/kg
NO_X	4.38	gr/kg
PM	928.96	mg/kg
SO_X	5.58372	gr/kg
VOC	12.57	mg/kg
NMVOC	10.84	mg/kg

VII.4 Results of the Analysis

The previous methodology is applied to 6 vessels with regard to the 6 capacities mentioned in the chapters. The corresponding results are summarized in the ensuing tables and figures.

Vessel 1

Table 54 Entrance data for vessel No.1

Vessel No.1		
Variable	**Value**	**Unit**
L	210.70	m
B	35.00	m
T	9.98	m
D	22.55	m
C (Liquid Capacity)	74245	m^3
Δ	58044	tons
DWT	39520	tons
N (Number of tanks)	4	m
Lt (Length of tanks)	34.10	m
P (Periphery of tanks)	101.55	m
NB (Number of Bulkheads)	6	
FS (Frame Spacing)	2.8	m

Table 56

Table 55 Cumulative air pollutants from the hull of vessel No.1

Vessel No.1								
	Production Phase			**Maintenance Phase**				
Phase/ Pollutant	Steel Production	Steel Cutting	Steel Welding	Steel Production	Steel Cutting	Steel Welding	Dismantling	Insulation
CO2	15647	38	12	577	0	1	5320	9
CO	500.0577	0.0363	0.0110	18.4482	0.0001	0.0011	500.0577	2.5047
CH4	2.5634	0.0025	0.0008	0.0946	0	0.0001	1.3586	0.3453
NOX	91.7479	0.0154	0.0047	3.3848	0	0.0005	68.8110	2.5947
PM	14.5942	0.0254	0.0077	0.5384	0	0.0008	14.5942	0.9095
SOX	87.7162	0.2667	0.0807	3.2360	0	0.0081	87.7217	4.2310
VOC	0.1975	0	0	0.0073	0	0	0.1975	-
MVOC	0.1703	0.0122	0.0037	0.0063	0	0.0004	0.1703	-

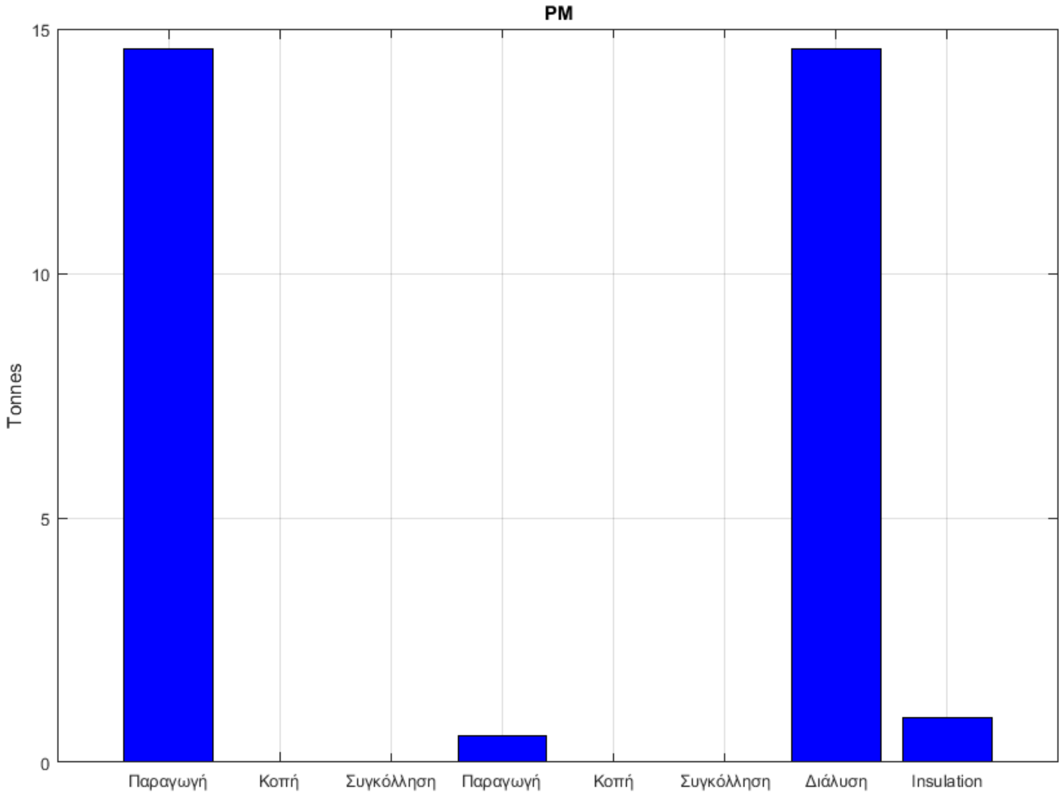


Figure 30 Cumulative PM emissions from the hull of vessel No.1

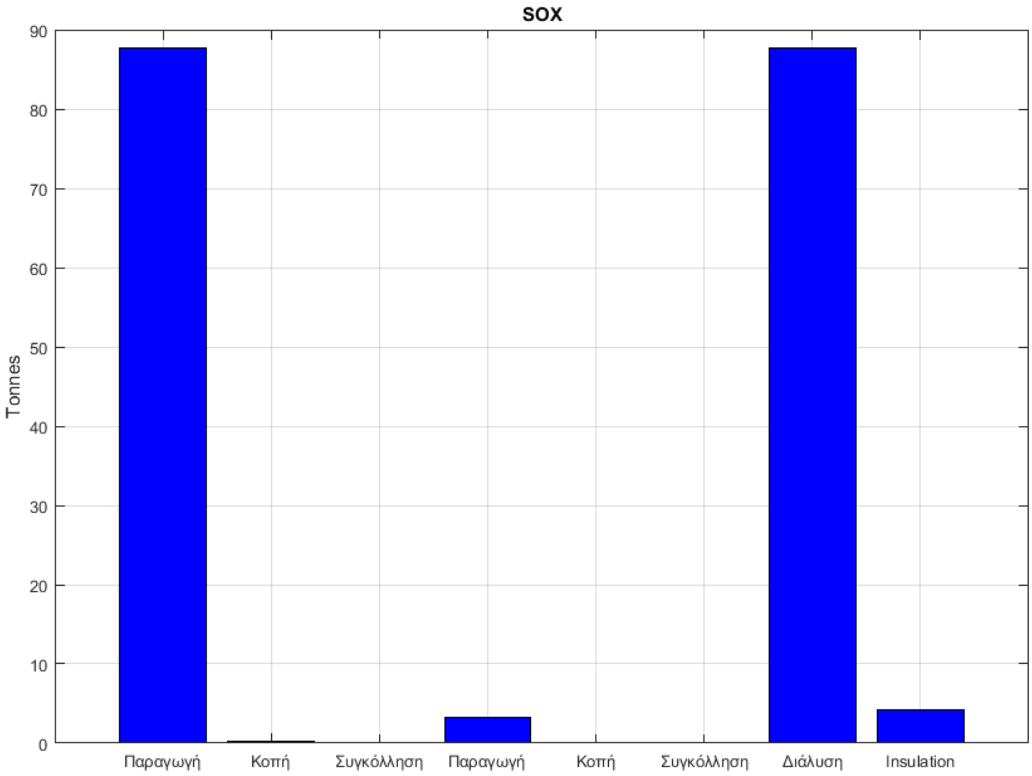


Figure 31 Cumulative SO_X emissions from the hull of vessel No.1

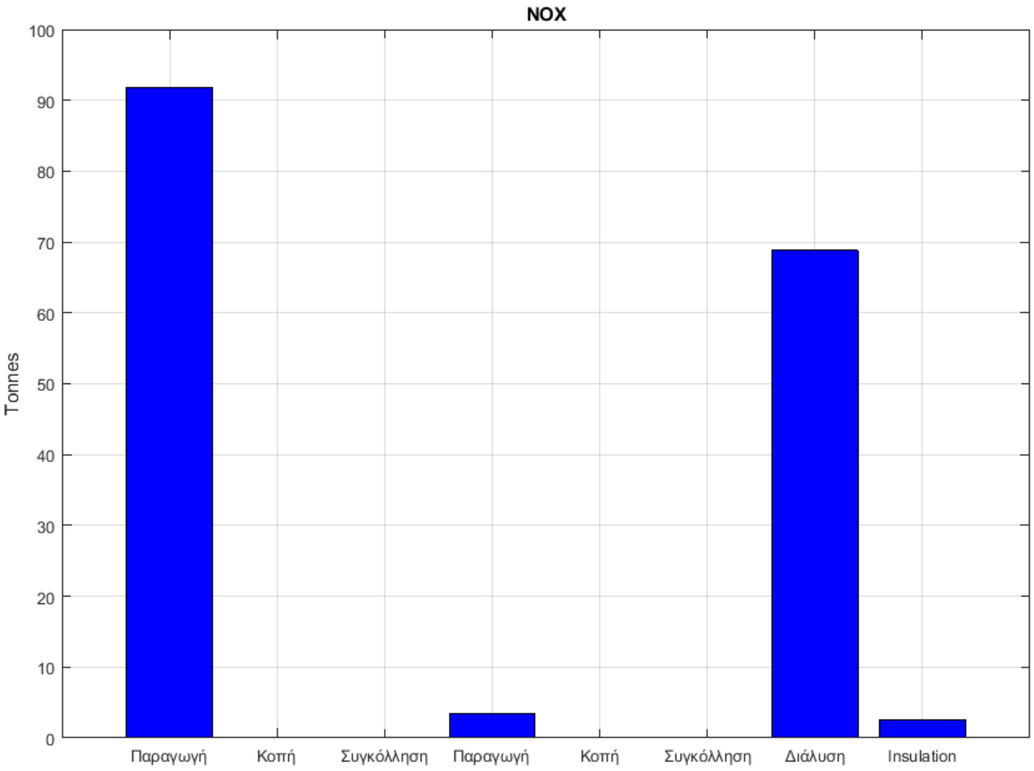


Figure 32 Cumulative NO_X emissions from the hull of vessel No.1

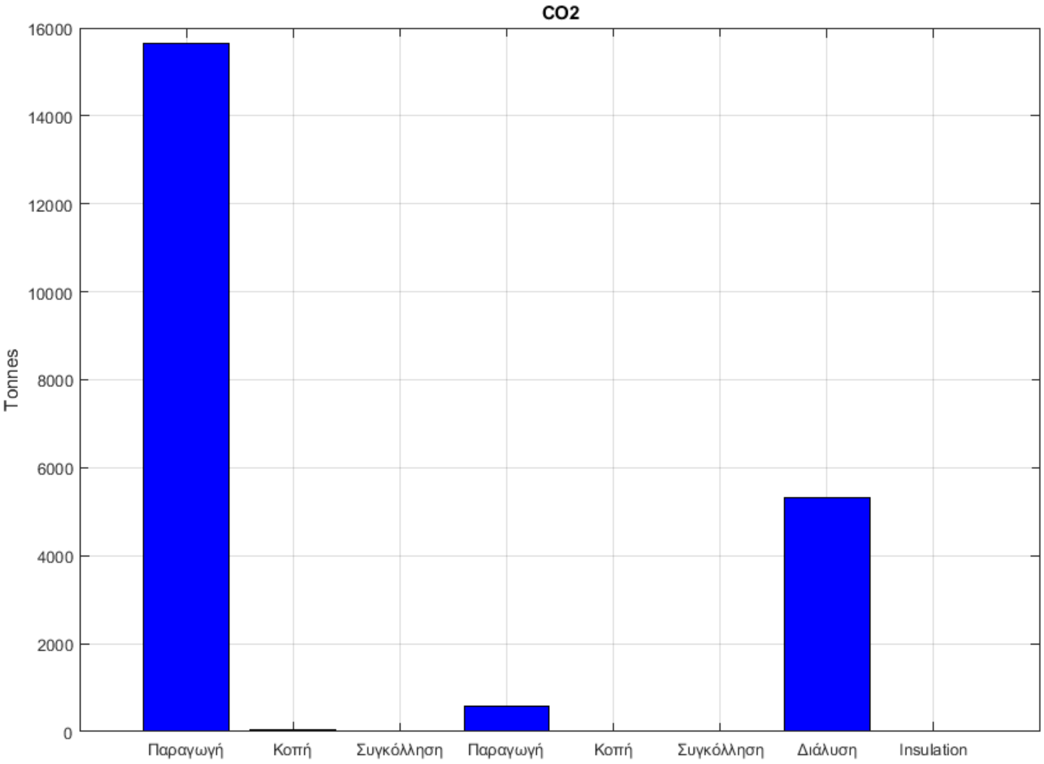


Figure 33 Cumulative CO_2 emissions from the hull of vessel No.1

Vessel 2

Table 56 Entrance data for vessel No.2

Vessel No.2		
Variable	**Value**	**Unit**
L	270	m
B	43.40	m
T	11.35	m
D	26.00	m
C (Liquid Capacity)	145000	m^3
Δ	108586	tons
DWT	79046	tons
N (Number of tanks)	4	m
Lt (Length of tanks)	45.78	m
P (Periphery of tanks)	123.82	m
NB (Number of Bulkheads)	6	
FS (Frame Spacing)	2.8	m

Table 57 Cumulative air pollutants from the hull of vessel No.2

Vessel No.2								
	Production Phase			**Maintenance Phase**				
Phase/ Pollutant	**Steel Production**	**Steel Cutting**	**Steel Welding**	**Steel Production**	**Steel Cutting**	**Steel Welding**	**Dismantling**	**Insulation**
CO2	25176	76	18	921	0	2	8560	11
CO	804.5820	0.0726	0.0168	29.4191	0.0001	0.0017	804.5820	3.0540
CH4	4.1245	0.0005	0.0012	0.1508	0	0.0001	2.1860	0.4210
NOX	147.6204	0.0308	0.0071	5.3977	0	0.0007	110.7153	3.1637
PM	23.4818	0.0509	0.0118	0.8586	0.0001	0.0012	23.4818	1.1090
SOX	141.1335	0.5334	0.1237	5.1605	0	0.0124	141.1335	5.1589
VOC	0.3177	0	0	0.0116	0	0	0.3177	-
MVOC	0.2740	0.0244	0.0057	0.0100	0	0.0006	0.2740	-

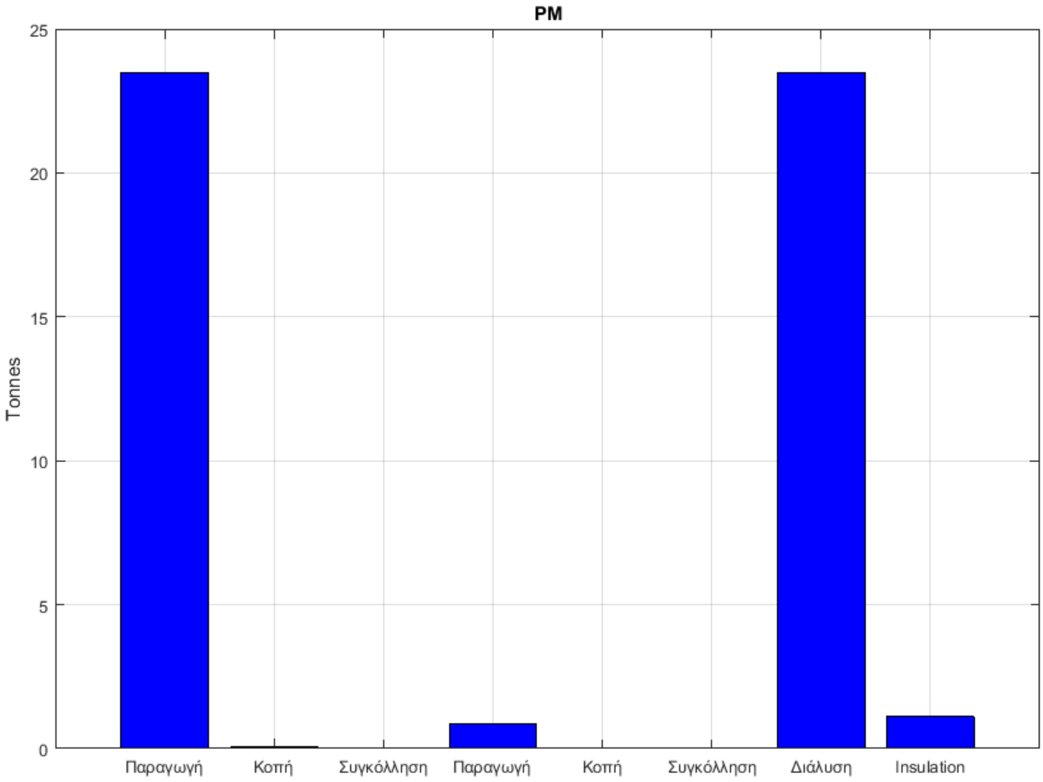


Figure 34 Cumulative PM emissions from the hull of vessel No.2

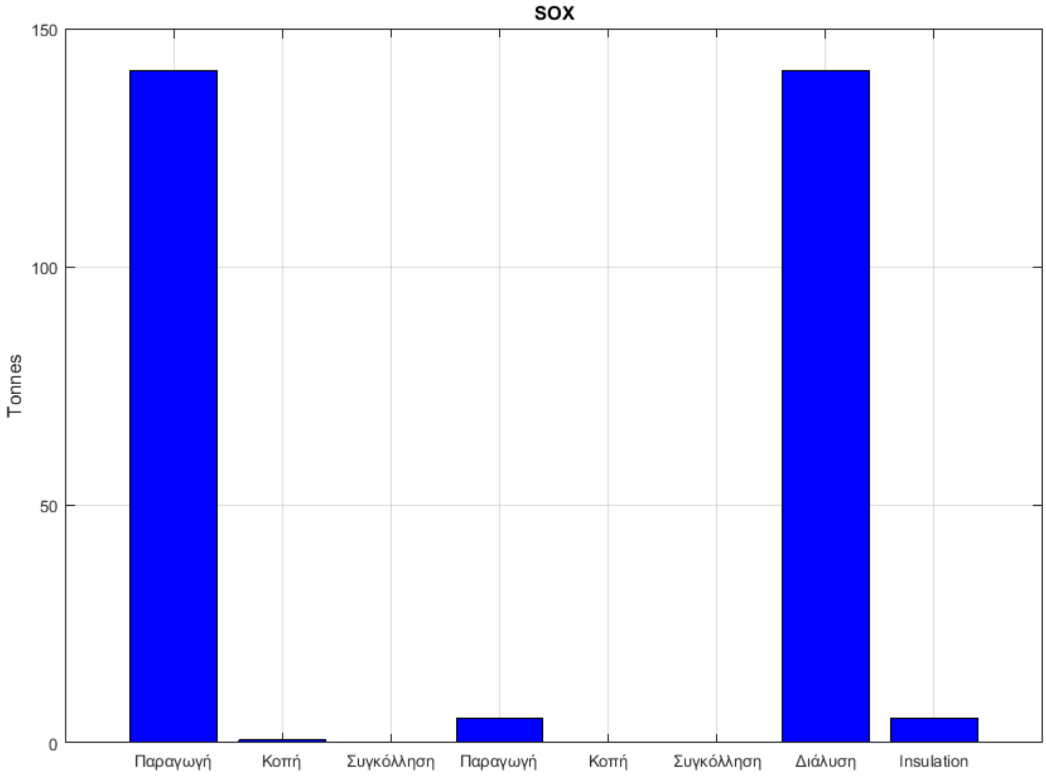


Figure 35 Cumulative SO_X emissions from the hull of vessel No.2

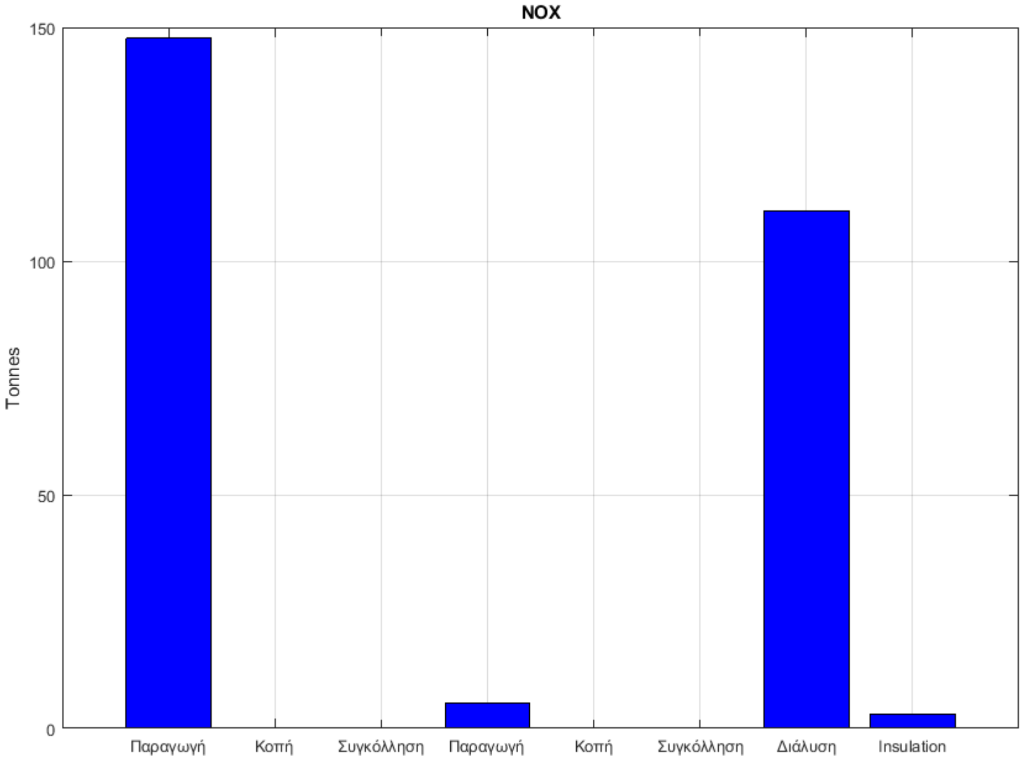


Figure 36 Cumulative NO_X emissions from the hull of vessel No.2

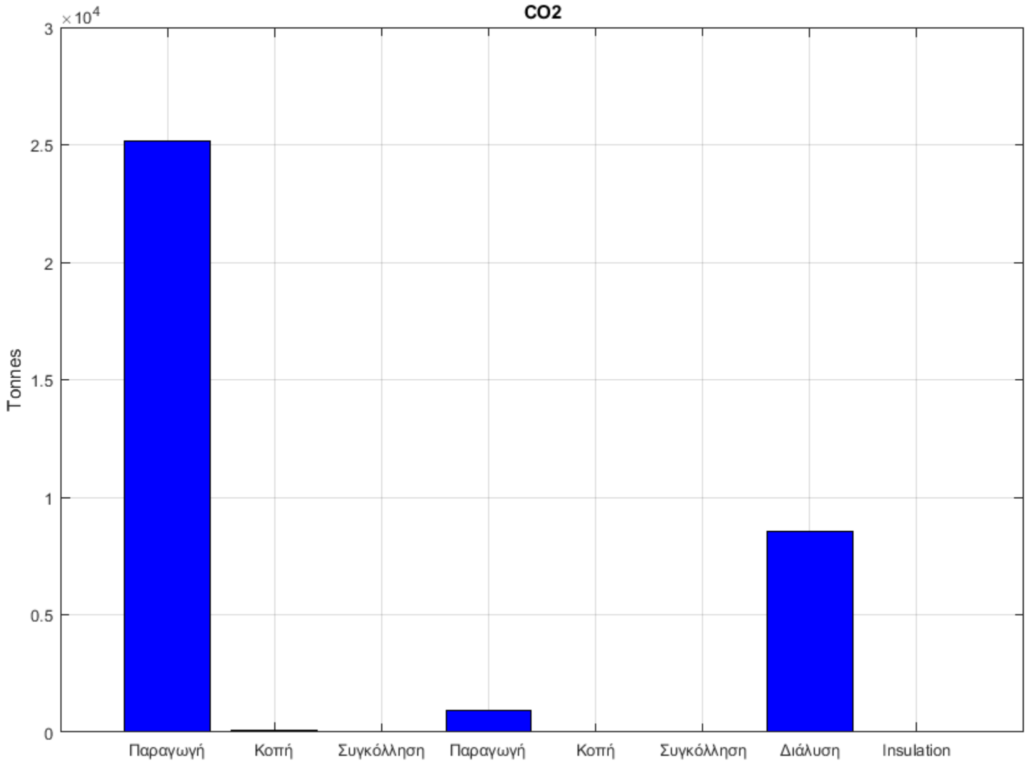


Figure 37 Cumulative CO_2 emissions from the hull of vessel No.2

Vessel 3

Table 58 Entrance data for vessel No.3

Vessel No.3		
Variable	**Value**	**Unit**
L	275	m
B	44.24	m
T	12.37	m
D	26.00	m
C (Liquid Capacity)	146791	m^3
Δ	116325	tons
DWT	85214	tons
N (Number of tanks)	4	m
Lt (Length of tanks)	45.52	m
P (Periphery of tanks)	125.44	m
NB (Number of Bulkheads)	6	
FS (Frame Spacing)	2.8	m

Table 59 Cumulative air pollutants from the hull of vessel No.3

Vessel No.3								
	Production Phase			**Maintenance Phase**				
Phase/ Pollutant	**Steel Production**	**Steel Cutting**	**Steel Welding**	**Steel Production**	**Steel Cutting**	**Steel Welding**	**Dismantling**	**Insulation**
CO2	26570	82	18	970	0	2	9034	12
CO	849.1096	0.0783	0.0173	30.9837	0.0001	0.0017	849.1096	3.0939
CH4	4.3528	0.0054	0.0012	0.1588	0	0.0001	2.3070	0.4265
NOX	155.7901	0.0332	0.0074	5.6848	0	0.0007	116.8426	3.2051
PM	24.7813	0.0549	0.0121	0.9043	0.0001	0.0012	24.7813	1.1235
SOX	148.9442	0.5750	0.1273	5.4341	0	0.0127	148.9442	5.2264
VOC	0.3353	0	0	0.0122	0	0	0.3353	-
MVOC	0.2892	0.0263	0.0058	0.0106	0	0.0006	0.2892	-

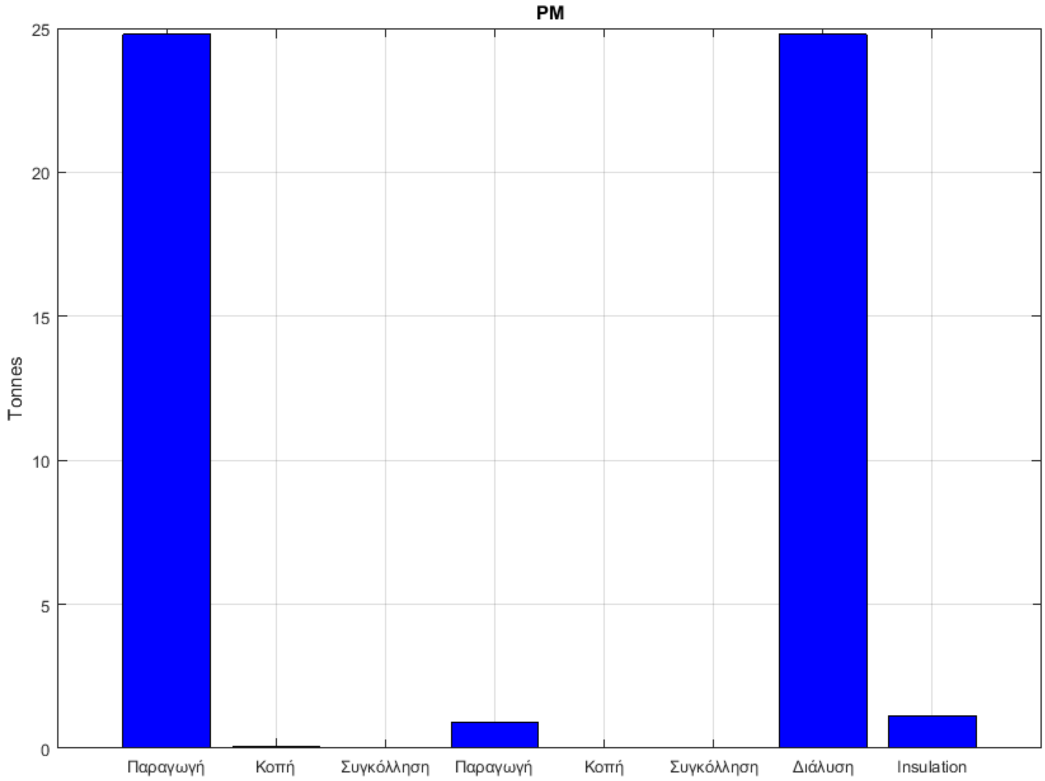


Figure 38 Cumulative PM emissions from the hull of vessel No.3

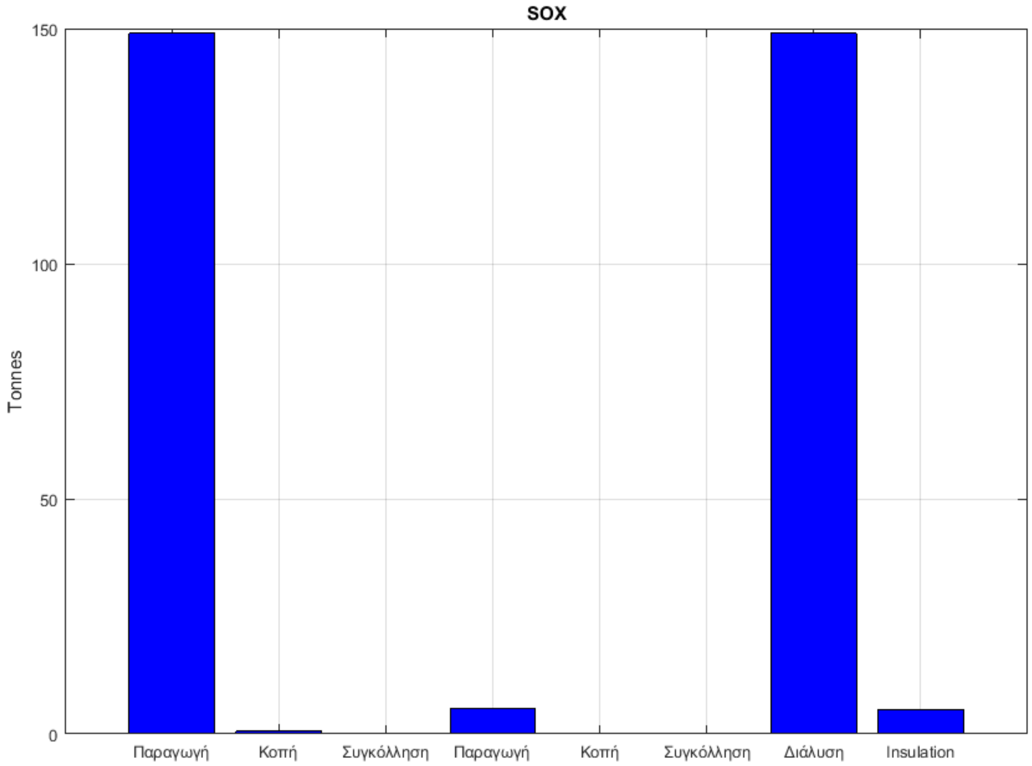


Figure 39 Cumulative SO_X emissions from the hull of vessel No.3

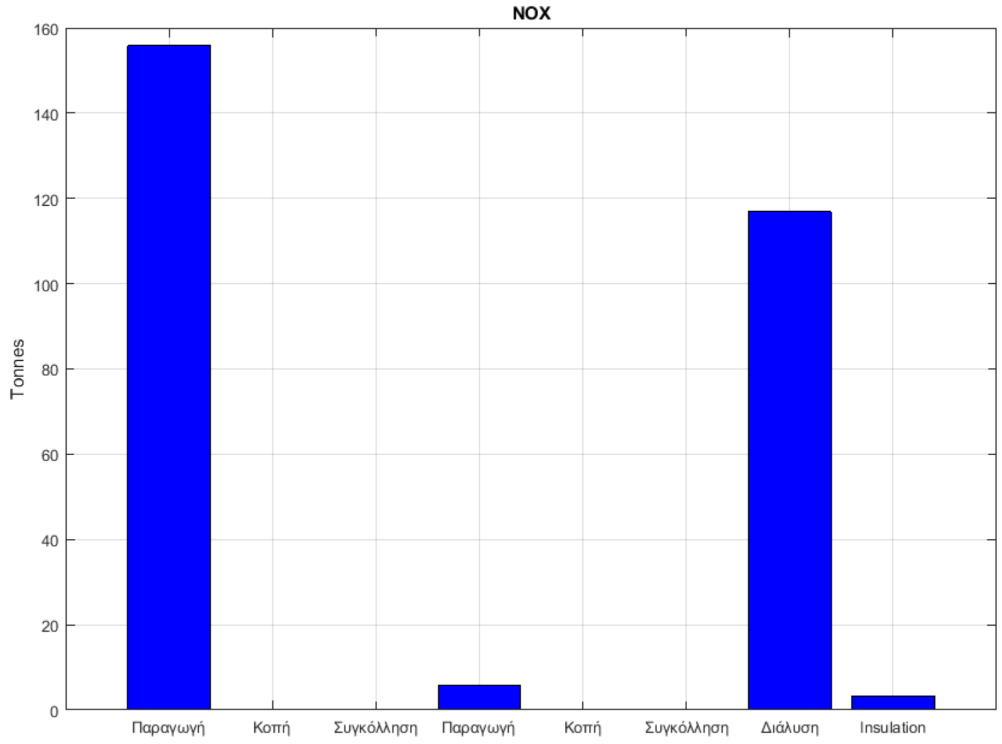


Figure 40 Cumulative NO_X emissions from the hull of vessel No.3

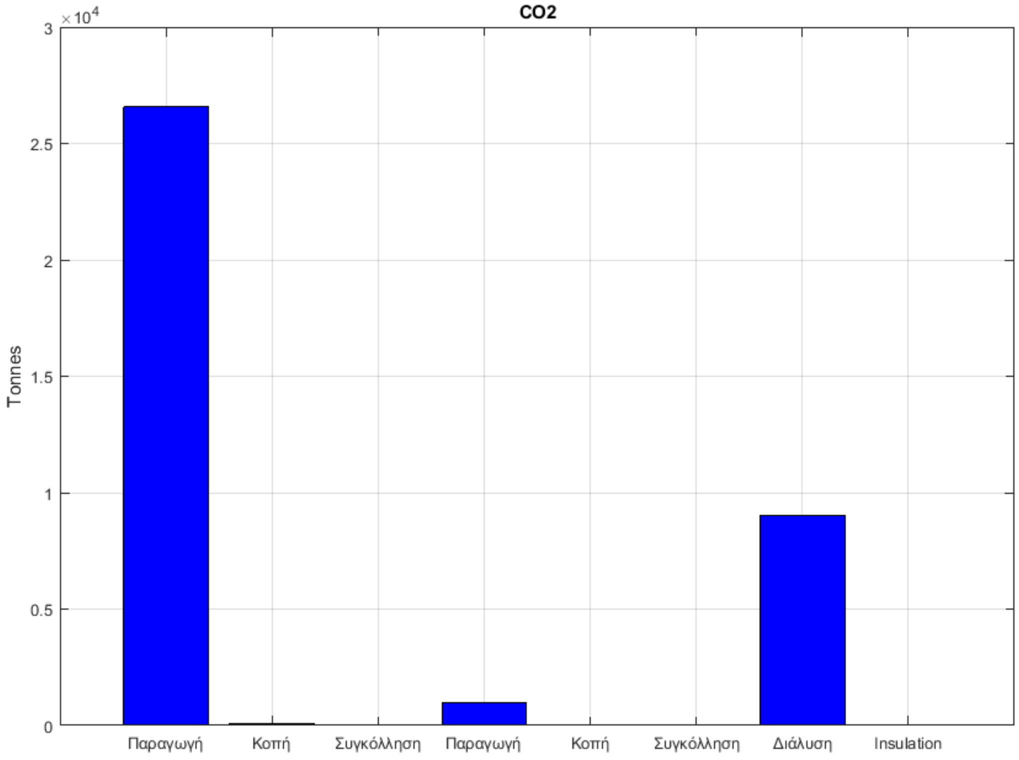


Figure 41 Cumulative CO_2 emissions from the hull of vessel No.3

Vessel 4

Table 60 Entrance data for vessel No.4

Vessel No.4		
Variable	**Value**	**Unit**
L	285	m
B	46	m
T	11.93	m
D	26.80	m
C (Liquid Capacity)	173870	m^3
Δ	125563	tons
DWT	91306	tons
N (Number of tanks)	4	m
Lt (Length of tanks)	50.31	m
P (Periphery of tanks)	129.81	m
NB (Number of Bulkheads)	6	
FS (Frame Spacing)	2.8	m

Table 61 Cumulative air pollutants from the hull of vessel No.4

Vessel No.4								
	Production Phase			**Maintenance Phase**				
Phase/ Pollutant	**Steel Production**	**Steel Cutting**	**Steel Welding**	**Steel Production**	**Steel Cutting**	**Steel Welding**	**Dismantling**	**Insulation**
CO2	29054	88	20	1068	0	2	0.9878	12
CO	928.5109	0.0839	0.0186	34.1168	0.0001	0.0019	928.5109	3.2017
CH4	4.7598	0.0058	0.0013	0.1749	0	0.0001	2.5227	0.4414
NOX	170.3583	0.0356	0.0079	6.2596	0	0.0008	127.7687	3.3168
PM	27.0986	0.0588	0.0130	0.9957	0.0001	0.0013	27.0986	1.1626
SOX	162.8722	0.6161	0.1366	5.9845	0	0.0137	162.8823	5.4085
VOC	0.3667	0	0	0.0135	0	0	0.3667	0.3667
MVOC	0.3162	0.0282	0.0062	0.0116	0	0.006	0.3162	0.3162

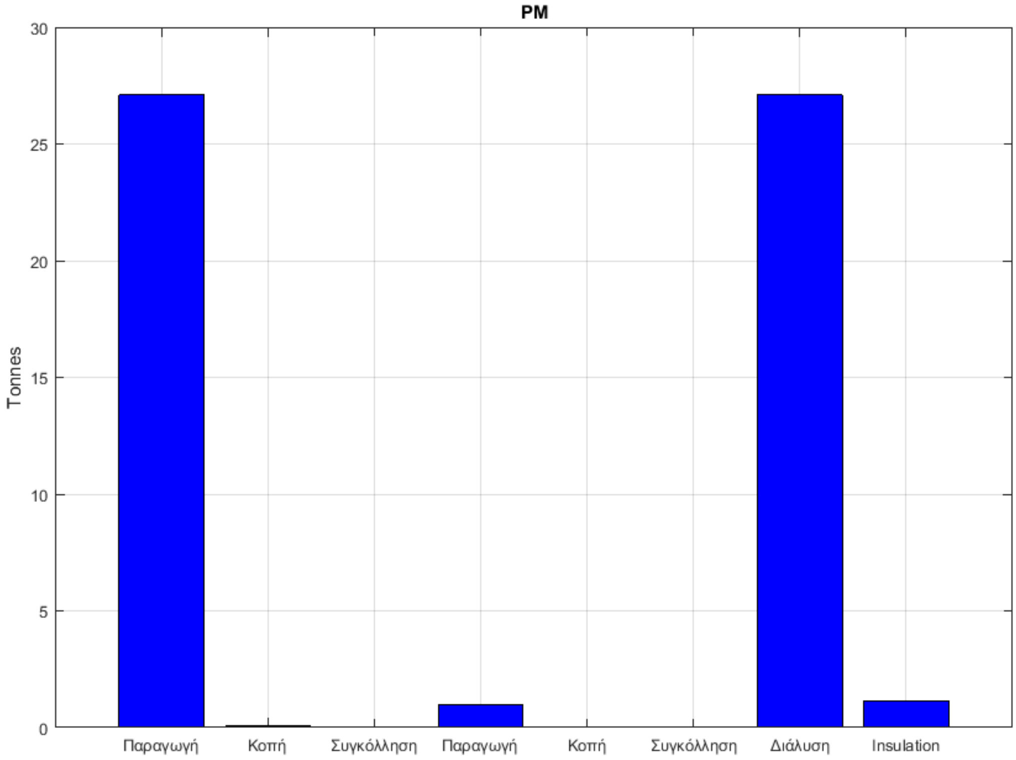


Figure 42 Cumulative PM emissions from the hull of vessel No.4

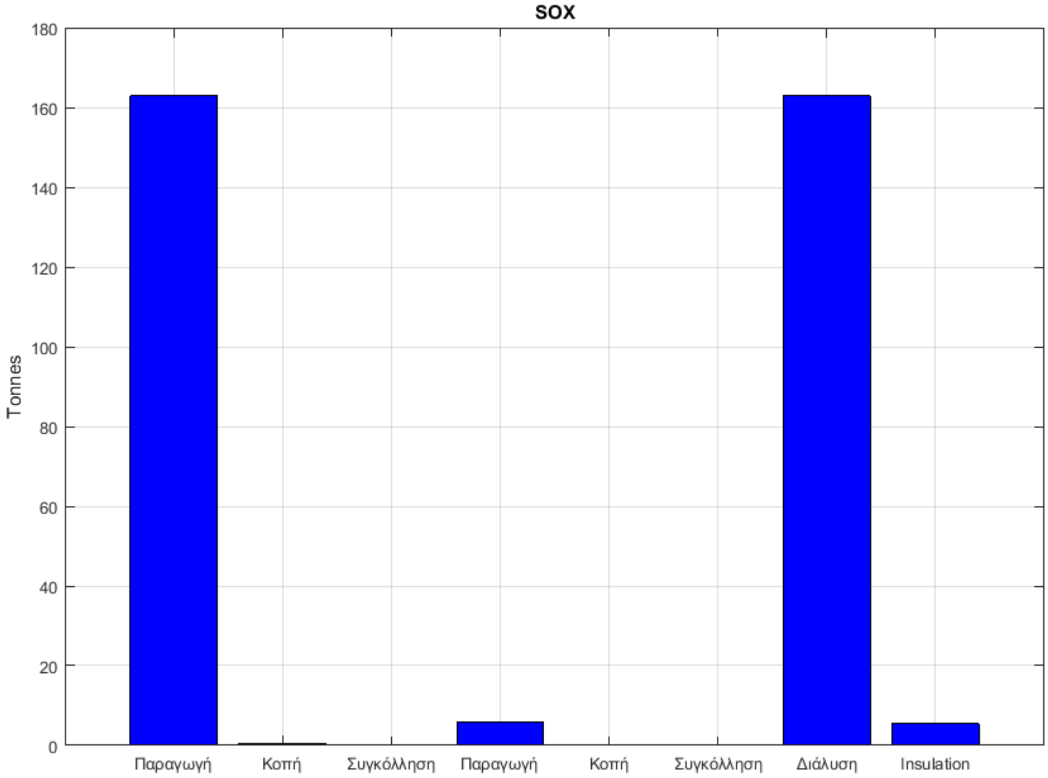


Figure 43 Cumulative SO_X emissions from the hull of vessel No.4

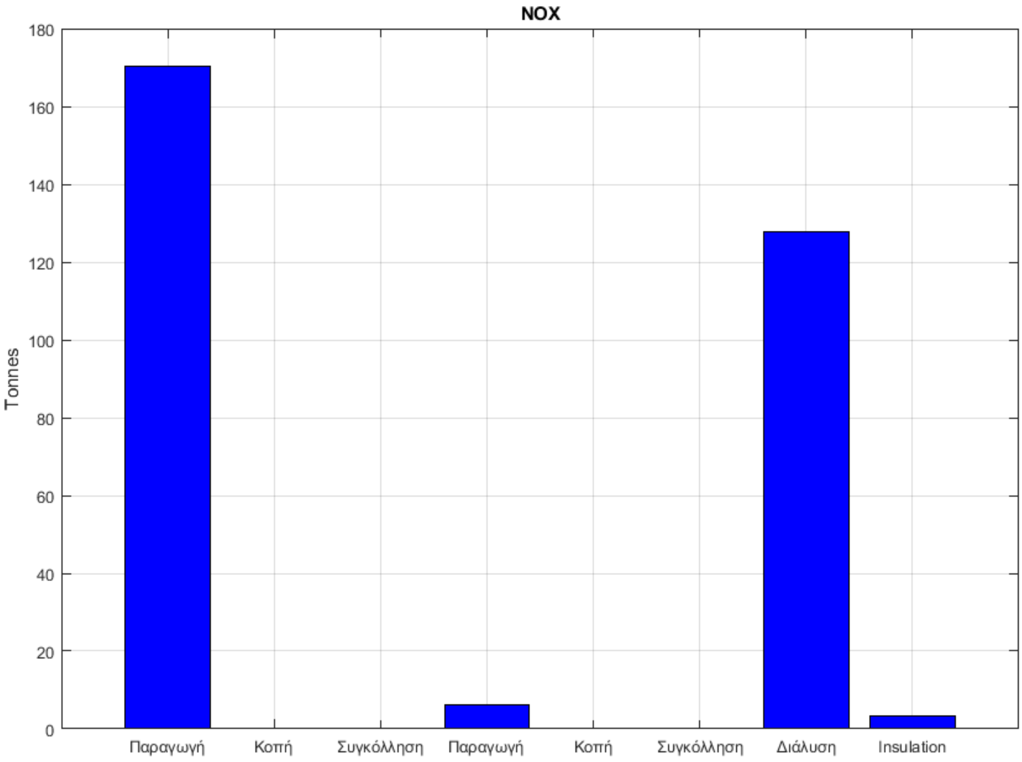


Figure 44 Cumulative NO_X emissions from the hull of vessel No.4

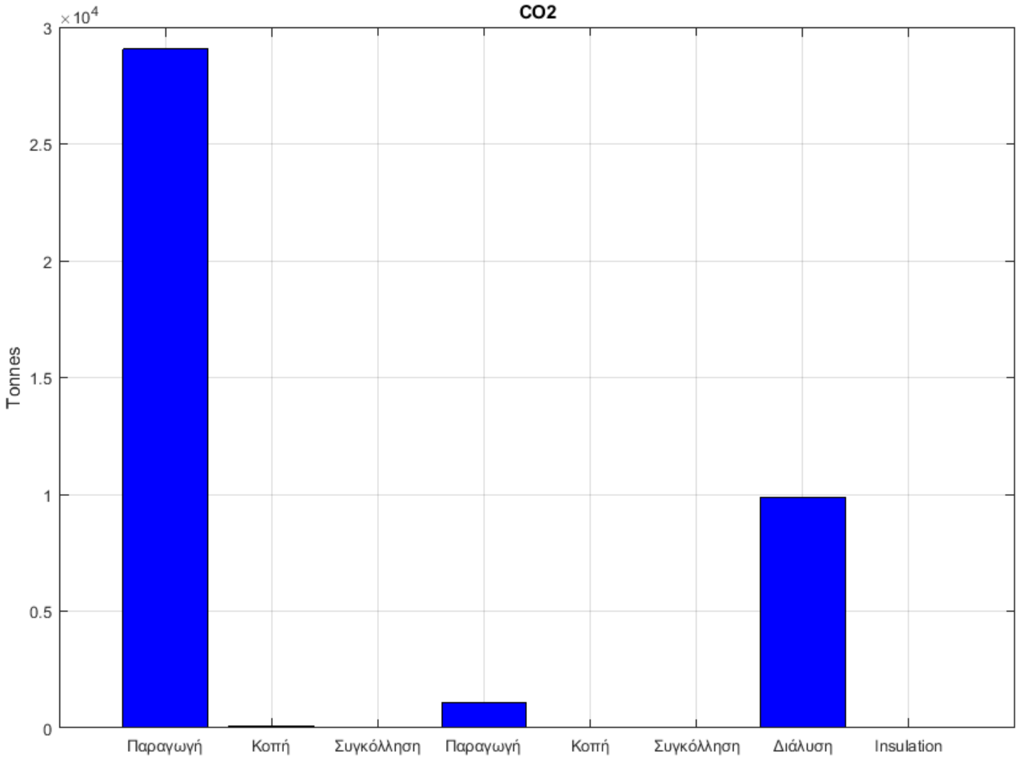


Figure 45 Cumulative CO_2 emissions from the hull of vessel No.4

Vessel 5

Table 62 Entrance data for vessel No.5

Vessel No.5		
Variable	**Value**	**Unit**
L	303	m
B	50.05	m
T	12.5	m
D	27	m
C (Liquid Capacity)	211862	m^3
Δ	149214	tons
DWT	107514	tons
N (Number of tanks)	4	m
Lt (Length of tanks)	56.18	m
P (Periphery of tanks)	137.46	m
NB (Number of Bulkheads)	6	
FS (Frame Spacing)	2.8	m

Table 63 Cumulative air pollutants from the hull of vessel No.5

	Vessel No.5							
	Production Phase			**Maintenance Phase**				
Phase/ Pollutant	**Steel Production**	**Steel Cutting**	**Steel Welding**	**Steel Production**	**Steel Cutting**	**Steel Welding**	**Dismantling**	**Insulation**
CO2	36322	104	22	1300	0	2	1.2350	13
CO	1160.8	0.1	0	41.5	0	0	1160.8	3.4
CH4	5.9505	0.0068	0.0014	0.2129	0	0.0001	3.1538	0.4674
NOX	212.9737	0.0419	0.0088	7.6196	0.0001	0.0009	159.7303	3.5123
PM	33.8774	0.0692	0.0146	1.2120	0.0001	0.0015	33.8774	1.2311
SOX	203.6150	0.7255	0.1528	7.2848	0	0.0153	203.6277	5.7272
VOC	0.4584	0	0	0.0164	0	0	0.4584	-
MVOC	0.3953	0.0332	0.0070	0.0141	0	0.0007	0.3953	-

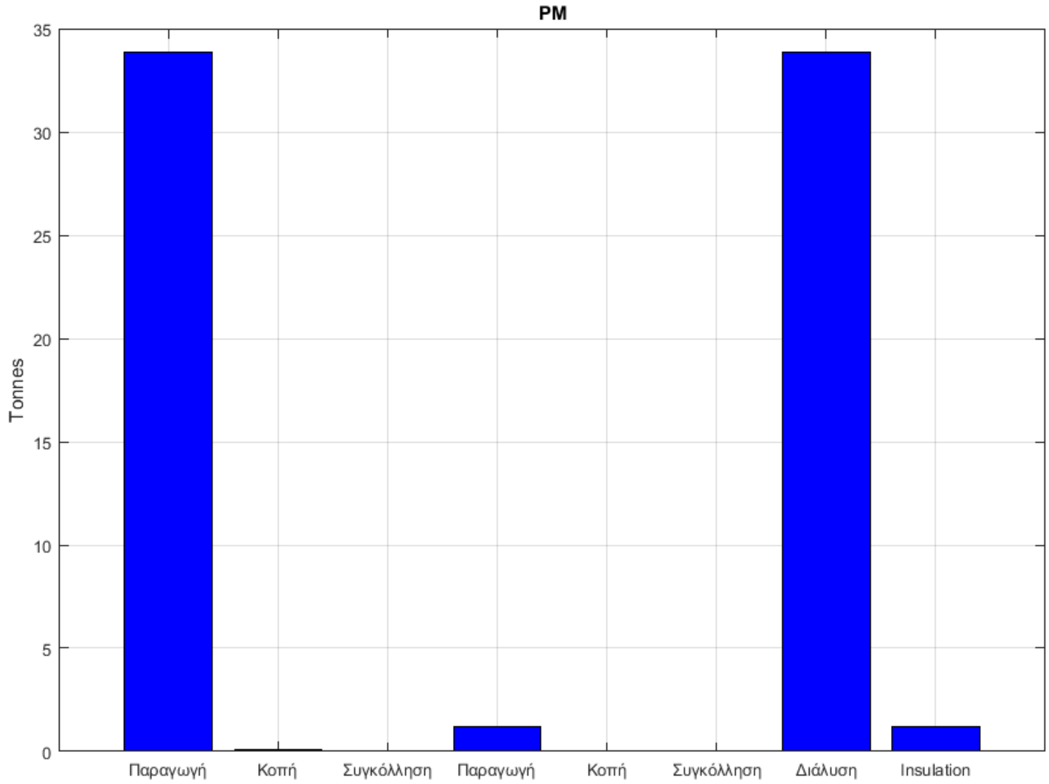


Figure 46 Cumulative PM emissions from the hull of vessel No.5

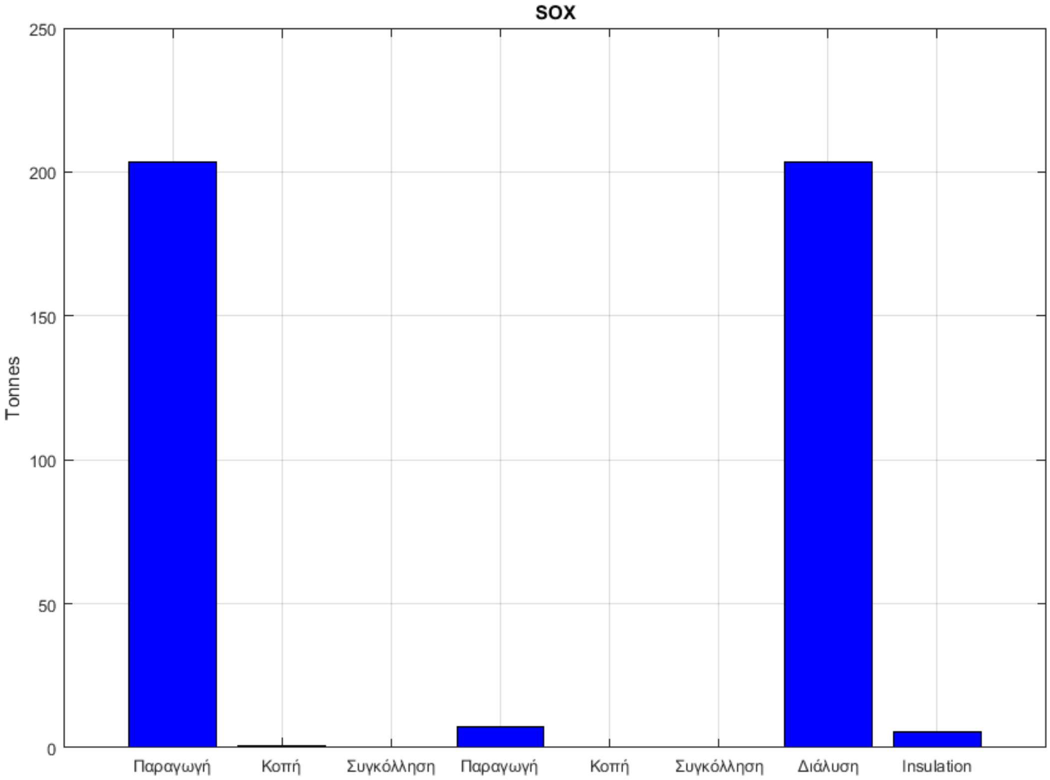


Figure 47 Cumulative SO_X emissions from the hull of vessel No.5

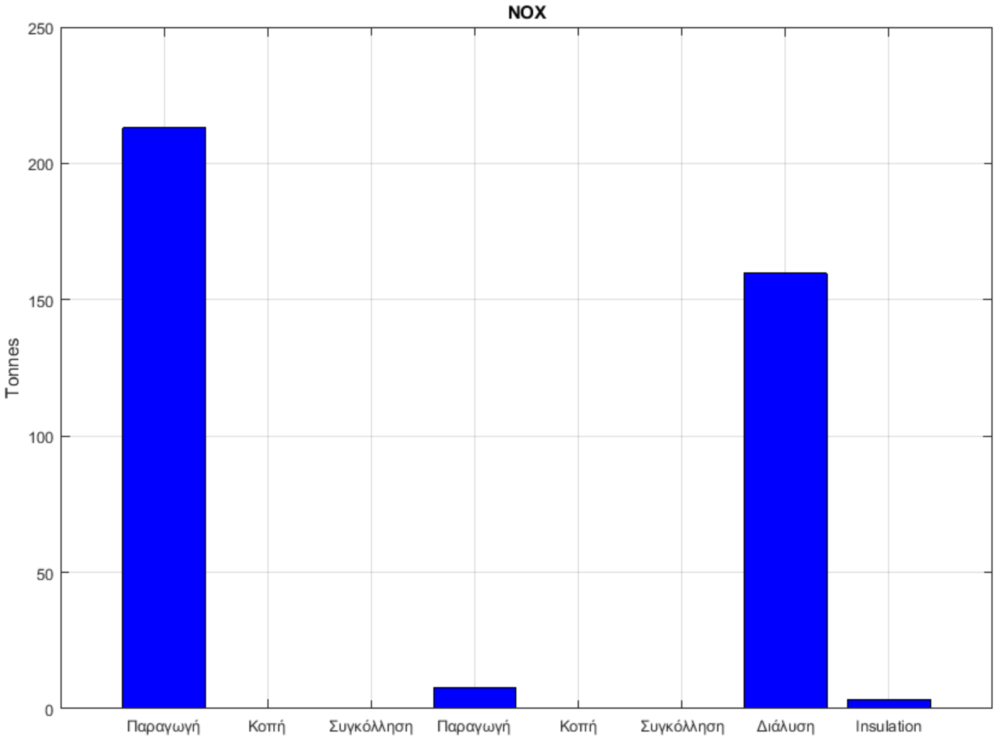


Figure 48 Cumulative NO_X emissions from the hull of vessel No.5

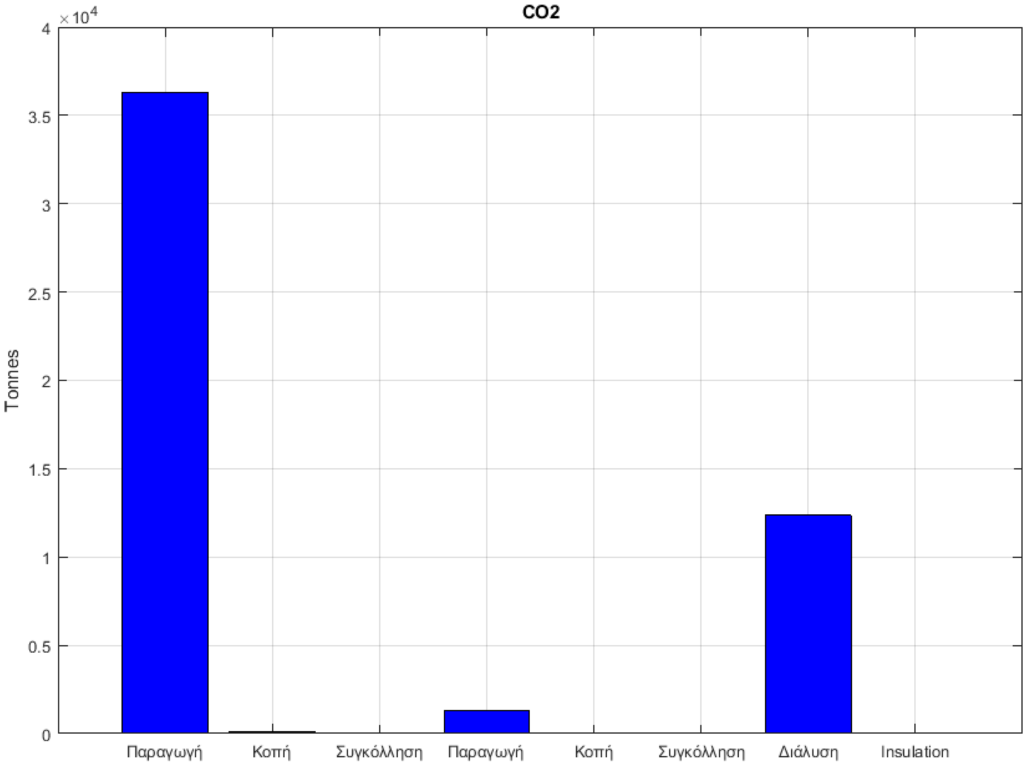


Figure 49 Cumulative CO_2 emissions from the hull of vessel No.5

Vessel 6

Table 64 Entrance data for vessel No.6

Vessel No.6		
Variable	**Value**	**Unit**
L	333	m
B	55.03	m
T	13.7	m
D	27	m
C (Liquid Capacity)	258054	m^3
Δ	205706	tons
DWT	154900	tons
N (Number of tanks)	4	m
Lt (Length of tanks)	61.95	m
P (Periphery of tanks)	146.42	m
NB (Number of Bulkheads)	6	
FS (Frame Spacing)	2.8	m

Table 65 Cumulative air pollutants from the hull of vessel No.6

Vessel No.6								
	Production Phase			Maintenance Phase				
Phase/ Pollutant	Steel Production	Steel Cutting	Steel Welding	Steel Production	Steel Cutting	Steel Welding	Dismantling	Insulation
CO2	44855	150	25	1583	0	3	1.5251	13
CO	1433.5	0.1	0	50.6	0	0	1433.5	3.6
CH4	7.3484	0.0098	0.0017	0.2594	0	0.0002	3.8946	0.4979
NOX	263.0058	0.0604	0.0103	9.2835	0.0001	0.0010	197.2544	3.7412
PM	41.8359	0.0997	0.0169	1.4767	0.0001	0.0017	41.8359	1.3114
SOX	251.4485	1.0453	0.1773	8.8755	0	0.0017	251.4485	6.1005
VOC	0.5661	0	0	0.2000	0	0	0.5661	-
MVOC	0.4882	0.0478	0.0081	0.0172	0	0.0008	0.4882	-

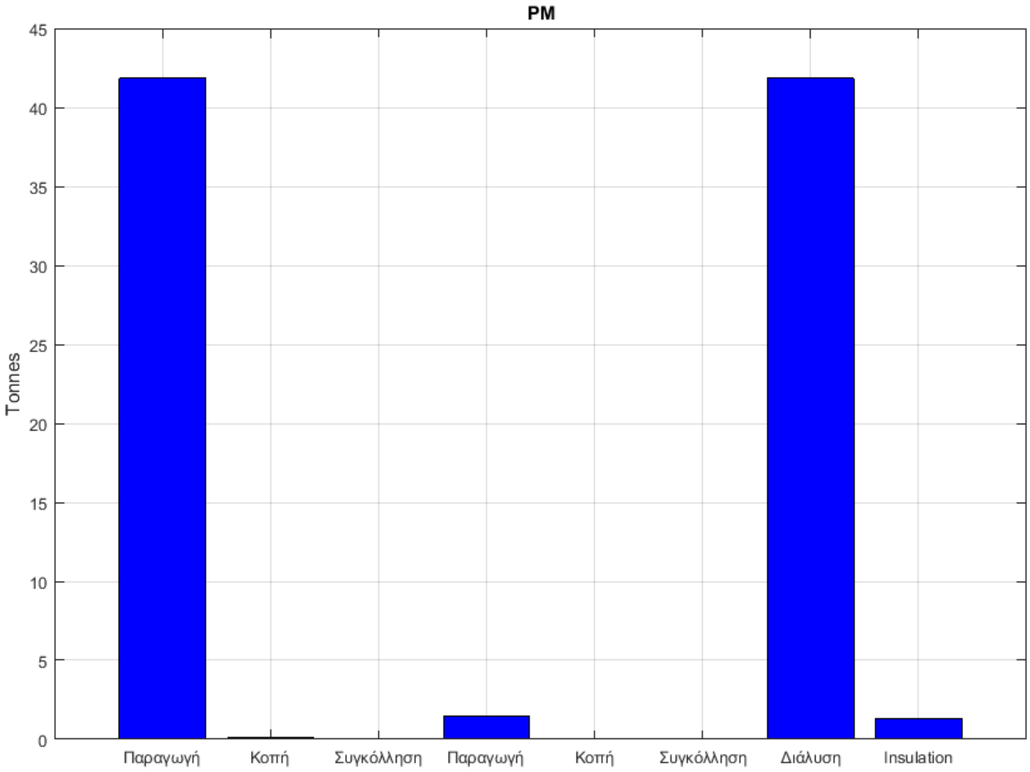


Figure 50 Cumulative PM emissions from the hull of vessel No.6

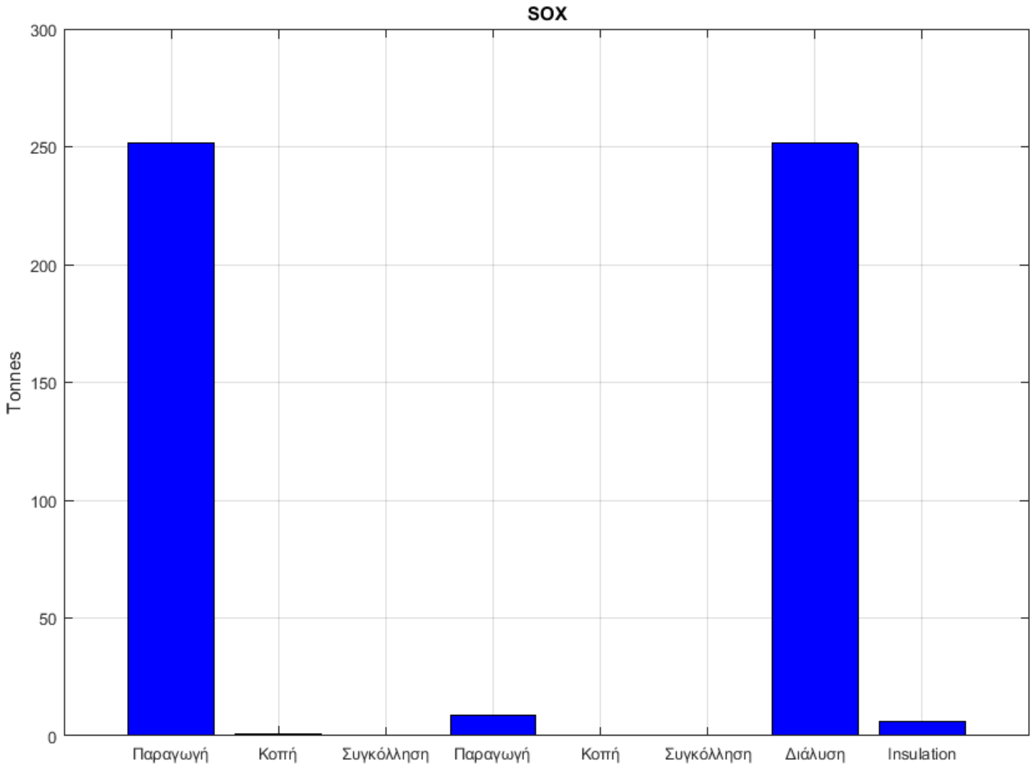


Figure 51 Cumulative SO_X emissions from the hull of vessel No.6

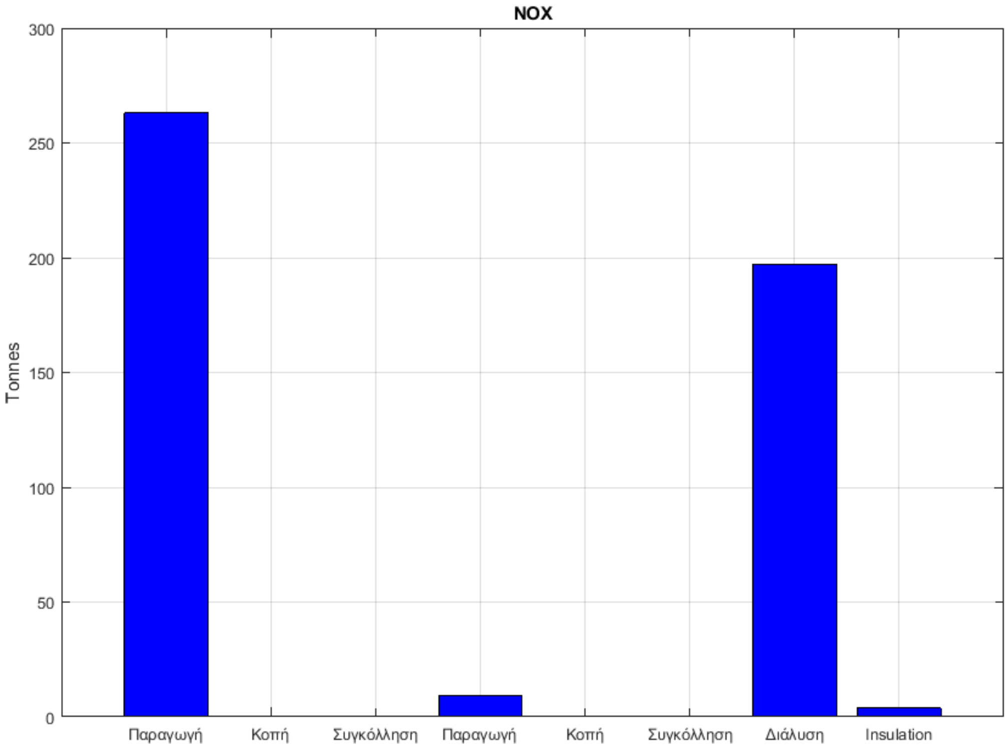


Figure 52 Cumulative NO_X emissions from the hull of vessel No.6

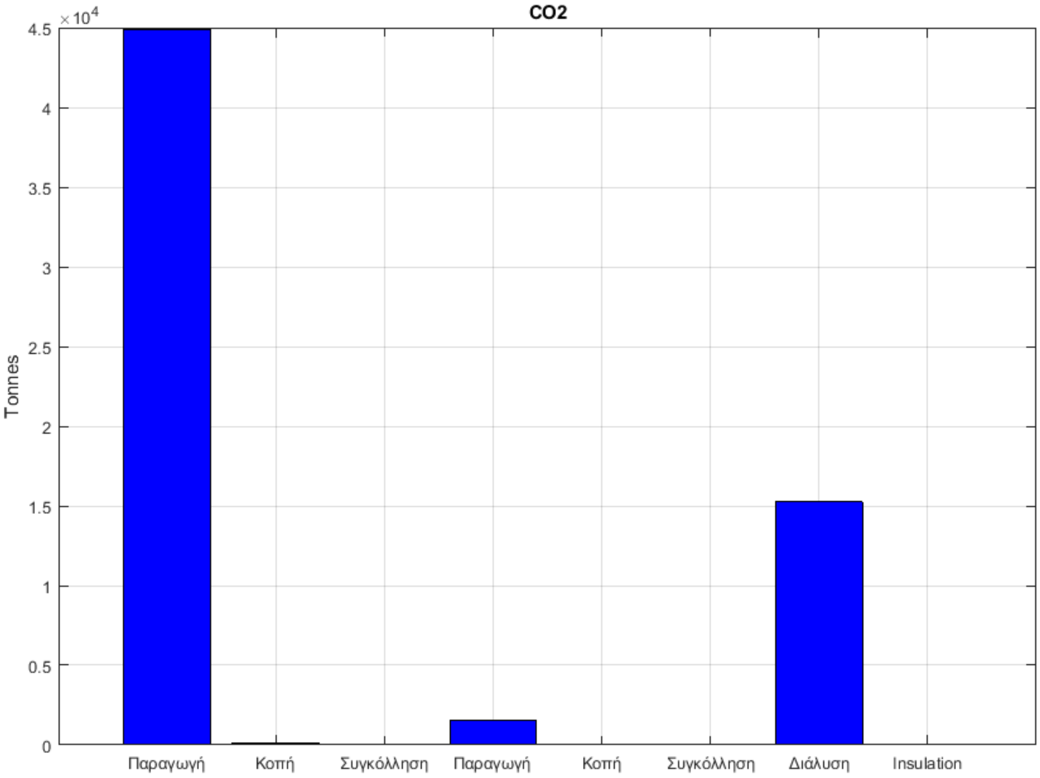


Figure 53 Cumulative CO_2 emissions from the hull of vessel No.6

VIII. Operational Phase

In this paragraph calculations relevant to the pollutants produced during the operational phase of the vessels are calculated. Furthermore, the amount of fuels and lubricants consumed are also calculated. The results will be used in the next chapter, where the operational costs will be assessed.

At first, a certain round trip shall be divided into discrete times. This is necessary since, during different operational phases, the amount of fuel consumed (and thus the pollutants) are different, for instance, when the vessels are docked, the main engines are thought to be out of service and fuel consumption is caused only by the auxiliary engines. The aforementioned discrete times are shown in the following table.

VIII.1 Time Calculation

Table 66 Time calculations for the discrete operational phases

Phase	Formula
Loaded	$t_1 = \frac{Distance}{U_1}$
Ballast	$t_2 = \frac{Distance}{U_2}$
Manoeuvring	$t_3 = 1$ (By Default)
Loading	$t_4 = 24$ (By Default)
Unloading	$t_5 = 24$ (By Default)
Residual Time	$t_6 = 48$ (By Default)
Loaded in Seca	$t_7 = \frac{D_{SECA}}{U_1}$
Unloaded in Seca	$t_8 = \frac{D_{SECA}}{U_2}$
Loaded in Neca	$t_9 = \frac{D_{NECA}}{U_1}$
Unloaded in Neca	$t_{10} = \frac{D_{NECA}}{U_2}$
Loaded with use of WHR	$t_{11} = \frac{D_{WHR}}{U_1}$

Unloaded with use of WHR	$t_{12} = \frac{D_{WHR}}{U_2}$

- Residual time is the time between two round trips in which the vessel might remain idle, either for bunkering, inspection or waiting for orders.
- t_7 and t_9 are fragments of t_1. They are taken into account separately because SECA and NECA zones may require a different equipment. In this thesis, the examined ECA will be considered as both SECA and NECA.

VIII.2 Boil-off Gas Calculations

- The tanks are assumed to be filled up to 98.5% (*Filling Ratio)* of their capacity.
- The *Boil- Off Rate* is differentiated during various operational phases as follows [5] :

Table 67 Boil –Off during discrete operational phases

Phase	**Boil-Off Rate (% per day)**
Loaded	0.12%
Baliast	0.06%
Manoeuvring	0.10%
Loading	0.08%
Unloading	0%
Residual Time	0.1%

- The *Boil-off Gas Volume* (*VBOG*) for each phase is calculated with the following formula:

$$VBOG_i = BOR_i \cdot FillingRatio \cdot C / 24 \left[m^3 / h \right]$$

- The aforementioned quantity is converted to tons, using the *Average Density of BOG* (*ADBOG*) which is assumed to be equal to 465 $\left[kg / m^3 \right]$ [5] , thus

$$MBOG_i = VBOG_i \cdot ADBOG \ \left[kg / \mathrm{h} \right]$$

- Furthermore, considering that the *Lower Heating Value* of *BOG* is 49700$\left[KJ / kg \right]$ [1], the energy content of the *BOG* (*EBOG*) in each phase shall be :

$$EBOG_i = MBOG_i \cdot LHVBOG \ \left[KJ / h \right]$$

- Multiplying the latter two quantities by the relevant times allows us to calculate the mass of BOG and it's energy for each phase in $\left[kg \right]$ and $\left[KJ \right]$ respectively.

VIII.3 Plant Efficiencies

During the power transmission from engine to propeller there are losses of power. These losses are summed up in the following lines, [5]

STEAM TURBINE

$$n_{ST} = n_{GEAR} \cdot n_{SHAFT}$$

SLOW SPEED DIESEL ENGINE

$$n_{SSD} = n_{SHAFT}$$

DUAL FUEL DIESEL ELECTRIC

$$n_{DFDE} = n_{GEAR} \cdot n_{SHAFT} \cdot n_{ELMOT} \cdot n_{TRANSF} \cdot n_{ALT}$$

GAS TURBINE

$$n_{GT} = n_{GEAR} \cdot n_{SHAFT} \cdot n_{ELMOT} \cdot n_{TRANSF} \cdot n_{ALT}$$

COMBINED GAS AND STEAM ELECTRIC PROPULSION

$$n_{COGES} = n_{GEAR} \cdot n_{SHAFT} \cdot n_{ELMOT} \cdot n_{TRANSF} \cdot n_{ALT}$$

Where:

n_{ST} stands for the propulsion transmission losses when a Steam Turbine is used

n_{SSD} stands for the propulsion transmission losses when an SSD is used

n_{DFDE} stands for the propulsion transmission losses when a DFDE is used

n_{GT} stands for the propulsion transmission losses when a Gas Turbine is used

n_{COGES} stands for the propulsion transmission losses when a COGES is used

n_{GEAR} stands for the losses due to a gearbox

n_{SHAFT} stands for the losses at shaft

n_{ELMOT} stands for the losses due to electric motors

n_{TRANSF} stands for the losses due to transfere and conversion

n_{ALT} stands for the losses due to the alternators

Finally the delivered power for propulsion is given as a function of the above relevant coefficients and the power demand of the propeller.

$$P_{ENGi} = P_{PROPi} / n$$

In a similar way the delivered power for electric generation is given as a function of the electric power demand and the relevant coefficients.

$$P_{GENi} = P_{ELi} / n$$

VIII.4 Environmental Impact

Table 68 Estimated Emissions Comparison [3]

Propulsion Configuration	NO_X	SO_X	CO_2	PM	Unit
Steam Turbine	1	11	950	2.5	gr/kwh
SSD	17	7.7	580	0.5	gr/kwh
DFDE	1.3	0.05	445	0.05	gr/kwh
GT	2.5	0	480	0.01	gr/kwh
COGES	2.5	0	480	0.01	gr/kwh

Table 69 Conversion factors of fuel to CO_2 [28]

Type of Fuel	Reference	Carbon Content	C_F (t-CO_2/t-Fuel)
1. Diesel/Gas Oil	ISO 8217 Grades DMX through DMB	0.8744	3.206
2. Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.8594	3.151
3. Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.8493	3.114
4.Liquefied Petroleum Gas (LPG)	Propane	0.8182	3.000
	Butane	0.8264	3.030
5. Liquefied Natural Gas (LNG)		0.7500	2.750
6. Methanol		0.3750	1.375
7. Ethanol		0.5217	1.913

VIII.5 Additional Installations [23,29, 30]

Table 70 Performance of Additional Installations

Scrubber	Seawater Scrubber	FreshWater Scrubber	
SO_X Reduction	90%	90%	
NO_X Reduction	9%	9%	-
PM Reduction	75%	75%	-
Additional Fuel Consumption	0.015 [kg/kg HFO]	0.01 [kg/kg HFO]	-
Tier III Technologies	**EGR**	**SCR**	
NO_X Reduction	80%	95%	
Additional Fuel Consumption	0.6 [g/KWh]	1.2 [g/KWh]	
WHR	**Power Turbine**	**Steam Turbine**	**Steam Turbine & Power Turbine**
Energy Recovered	3-5%	5-8%	8-11%
Additional Fuel Consumption	0.012 * Pengine [Kw]	0.012 * Pengine [Kw]	0.012 * Pengine [Kw]
Variant Selection	Pengine<15000[Kw]	Pengine<25000[Kw]	Pengine>25000[Kw]
Lowest Power for starting WHR	40% of MCR	35% of MCR	ST starts at 30-35% of MCR and PT at 40-50% of MCR

VIII.6 Methane Slip

A significant demerit of the DFDE engines is the *Methane Slip*. The term is refering to an amount of unburned methane emitted into the atmosphere through the exhaust ports of the engine. Methane is a highly potent greenhouse gas and has 20-25 times the global warming potential of CO_2 in a period of 100 years or an equivalent of 72 times the warming potential of CO_2 in a period of 20 years. Therefore, in an LCA the impact of the methane slip must be taken into account. This is theoretically achieved by transforming the methane slip to its CO_2 equivalent, which is the measure of the global warming potential. The equivalent amount of CO_2 is calculated as follows [31]:

Assume that the amount of methane slip is 8 [g/KWh]. An average Specific Fuel Consumption of the DFDE engines is taken to be 175 [g/KWh]. As a result, the methane equivalent is $\frac{8}{175} = 4.57\%$. Thus, in the 20 years scenario, the equivalent amount of CO_2 is $72 \cdot 0.457$ [tons].

However, in another paper [2], the same authors give values of methane slip between 4 [g/KWh] and 8 [g/KWh]. Due to the fact that 8% seems to be very high, the lowest value of 4 [g/KWh] is selected. Concurrently, in order to maintain the values of SFC for DFDE given in [2], we assume that the methane equivalent is $\frac{4}{190} = 2.3\%$, significantly lower than that in [31]. Finally, note that in this thesis the coversion factor of LNG to CO_2 is 2.75, as in [28], while the paper [31] presumes a factor equal to 2.624.

VIII.7 Operational Scenario

In order to produce results, an indicative journey is selected. In this thesis the journey involves a gas shipment from a typical producing country, e.g. Qatar to a port of Northern Europe, e.g. in Poland. Such a journey was selected in order to take into account the restriction of an ECA zone, thus enabling different results to be produced for different propulsive configurations. The data for this trip are summarized in the following table.

Table 71 Selected journey details

Scenario 6	**Ras Laffan (Qatar) – Swinoujscie (Poland)**	
Distance	6431	miles
Distance in SECA	381	miles

VIII.8 Results of the Analysis

The methodology described in sections 7.1 – 7.5 is applied to all of the 6 vessels each one equipped with all possible propulsive configurations at a time. The following tables summarize the extracted data corresponding to the fuel consumption and air-emissions.

First, data concerning the duration of each single trip are presented (namely the speed, the cargo capacity, the pump capacity and the power demands for propulsion and auxiliary use, see Tables 73, 82, 91, 100, 109 and 118).

Next the times for each discrete voyage phase are given (Tables 74, 83, 92, 101, 110 and 119).

The VBOG rates are given for each of the aforementioned phases (Tables 75, 84, 93, 102, 111 and 120).

With these data available, computations for the pollutants are performed. The environmental footprint of the main propulsive engines, which are considered to be operating only when the vessel is at sea (Loaded, Ballast, Manoeuvring), are presented in Tables 76, 85, 94, 103, 112 and 121. On the other hand, the environmental footprint of the auxiliary engines, which are considered to be operating in all phases (that is, the afforementioned phases including also Loading, Unloading and Residual times) is shown in Tables 77, 86, 95, 104, 113, 122.

The total amount of pollutants (both from propulsion and auxiliary) are given in Tables 78, 87, 96, 105, 114 and 123.

Working as in the cost analysis of the previous chapter, there will be a separate analysis for the SSD configuration relative to the other configurations (ST, DFDE, GT and COGES).This analysis is necessary, as the SSD configuration is supposed to be combined with additional installations in order to comply to the environmental regulations. In this case the propulsion and auxiliary demands are not separated. Therefore:

Firstly, the total fuel consumption and air pollutants from main propulsion and auxiliary engines, equipped with SSD with Seawater Scrubber, Freshwater Scrubber and WHR, are presented in Tables 79, 80, 97, 106, 115 and 124.

Secondly, analysis of the environmental impact when NO_X abatement systems are involved (EGR and SCR with a concurrent use of MDO in SECA areas), is presented in Tables 80, 89, 98, 107, 116 and 125.

Finally, the environmental footprint of the three final solutions (SSD equipped with WHR and SCR, SSD equipped with a Seawater Scrubber and an EGR and SSD equipped with Freshwater Scrubber and an EGR) is shown in Tables 81, 90, 99, 108, 117 and 126.

The above data will be summarized for each vessel in the appendix

IX. Case Study (Vessel No.4)

To make the results more comparable, an indicative vessel is selected to present the results in bar diagrams. The vessel selected is the **No. 4** figuring in the previous tables, which is of an average capacity.

For space reasons, the Propulsive Configurations are expressed by a number. Thus **1** is the configuration corresponding to **ST**, **2** to **DFDE**, **3** to **GT**, **4** to **COGES**, **5** to **SSD** combined with a **Seawater Scrubber**, **6** to **SSD** combined with a **Freshwater Scrubber**, **7** to **SSD** combined with a **WHR**, **8** to **SSD** combined with **EGR**, **9** to **SSD** combined with **SCR**, and finally **10** corresponds to an **SSD** equipped with a **WHR** and burning **MDO** in SECA areas.

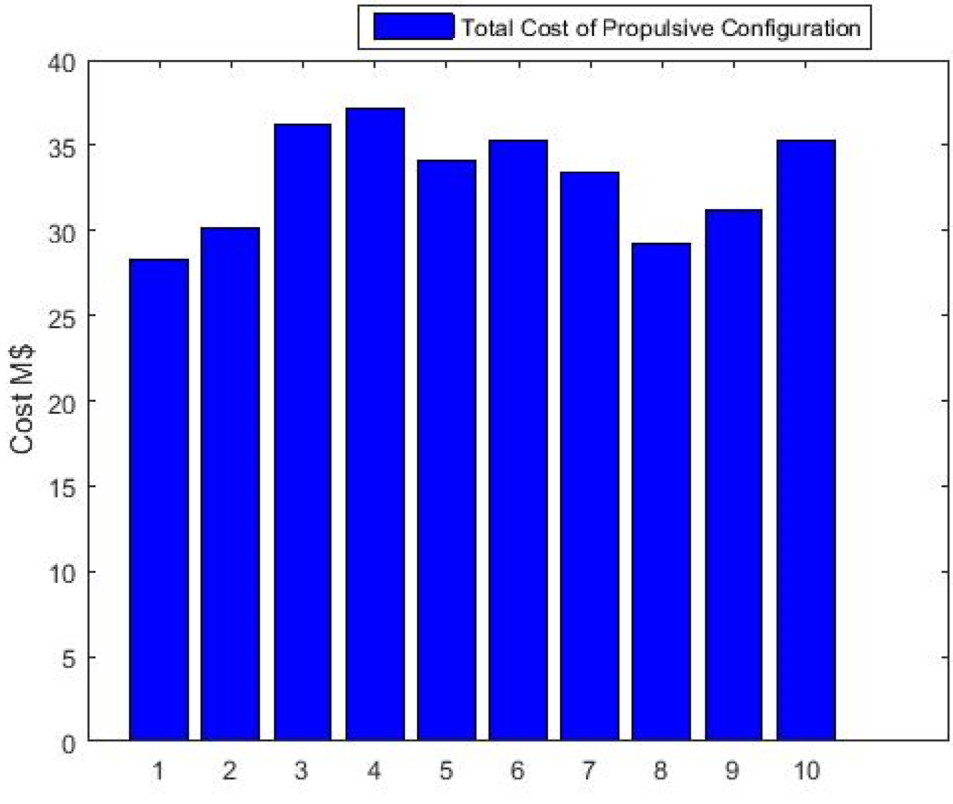


Figure 54 Comparative total Cost of Propulsive Configurations for vessel No. 4

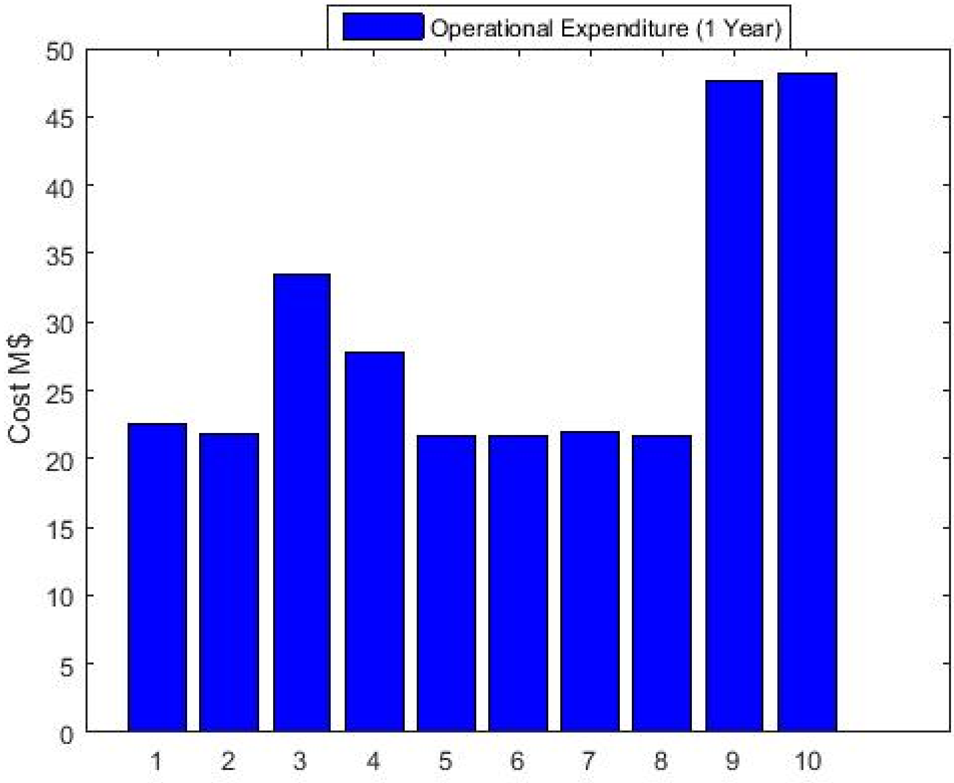


Figure 55 Comparative OPEX of Propulsive Configurations for vessel No.4.

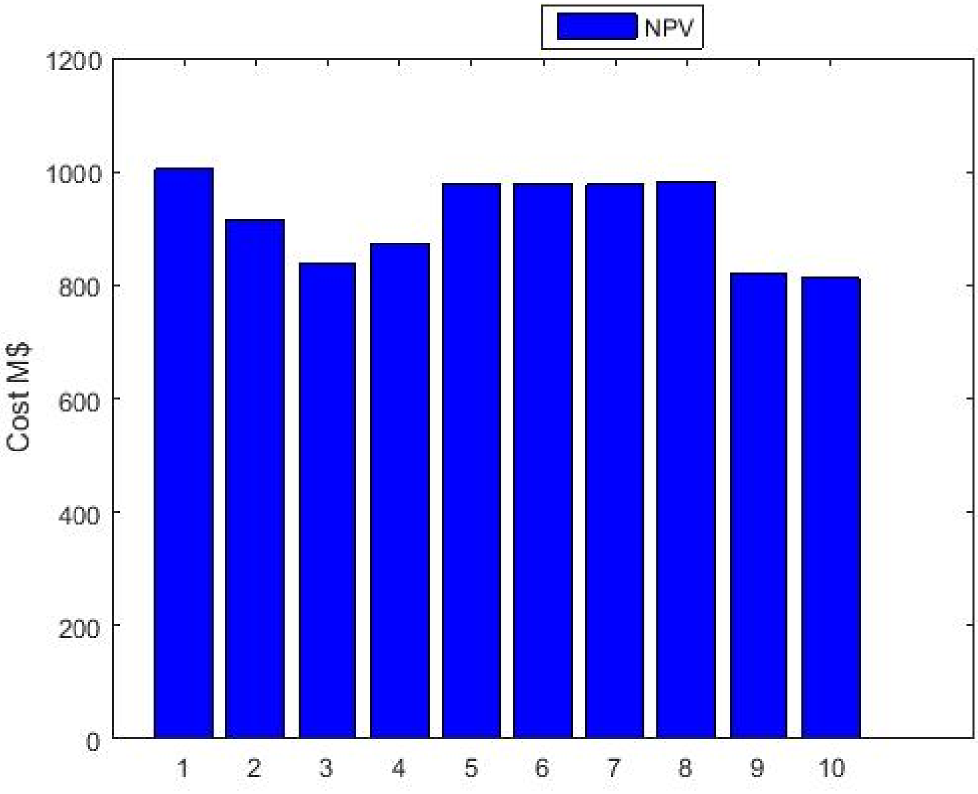


Figure 56 Comparative NPV of Propulsive Configurations for vessel No.4.

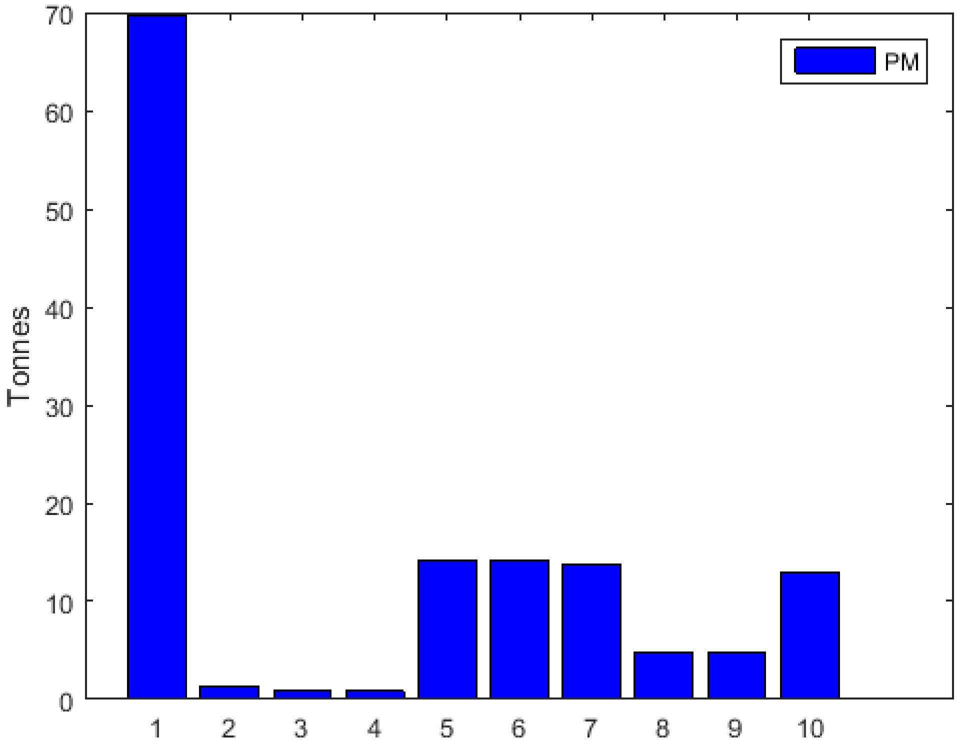


Figure 57 Cumulative PM emissions during the operation phase for all Propulsive Configurations for vessel No.4.

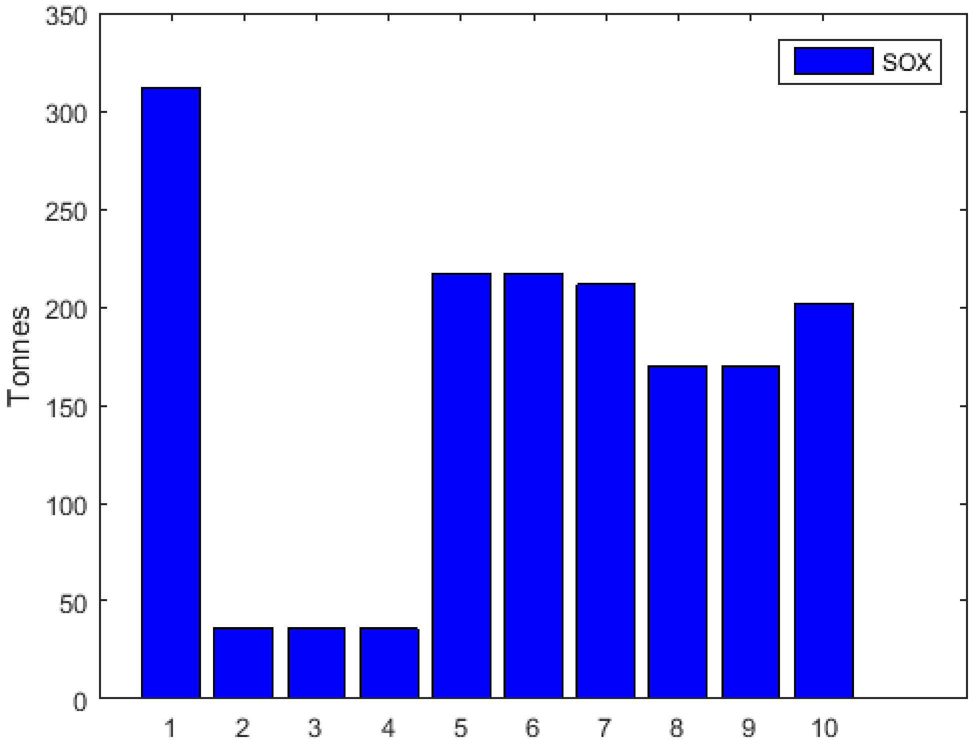


Figure 58 Cumulative SO_X emissions during the operation phase for all Propulsive Configurations for vessel No.4.

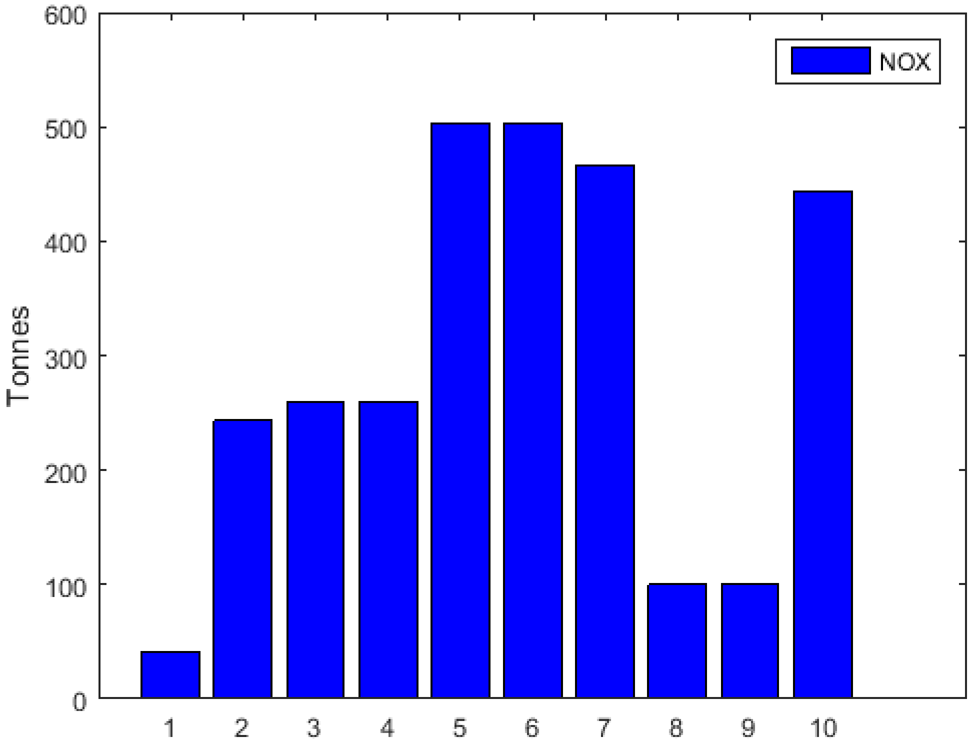


Figure 59 Cumulative NO_X emissions during the operation phase for all Propulsive Configurations for vessel No.4.

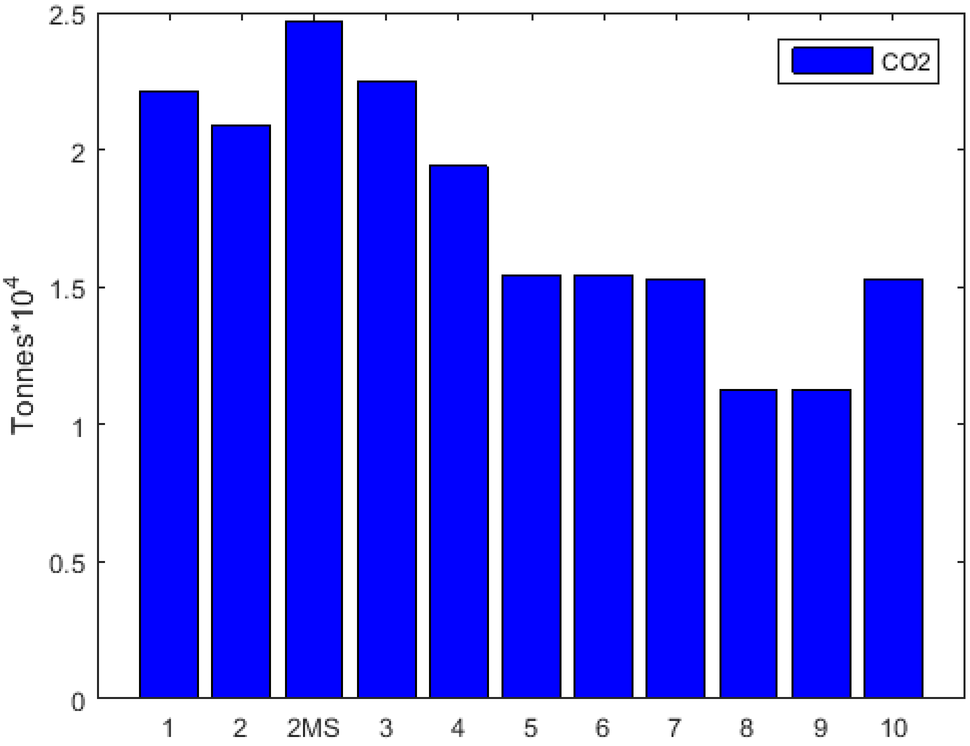


Figure 60 Cumulative CO_2 emissions during the operation phase for all Propulsive Configurations for vessel No.4.

Note. In the preceding figure the additional entry 2MS corresponds to DFDE when methane slip is taken into account.

Conclusions

As shown in the statistical analysis presented in Chapter 3, during the recent years, vast changes have happened concerning the capacity and the propulsive configuration of the LNG fleet. More specifically, the totality of the vessels under construction is precisely divided into two categories: 145000-170000 and 170000-200000 cm, virtually leading to the disappearance of both the smaller and bigger categories from the orderbook.

Regarding the propulsive configuration, the majority of the existing vessels even today continues to be equipped with steam turbines, in addition to a rather small number of vessels under construction, still employing this type of engine. There is though a clear turn to the use of diesel engines, with SSD being the big losers, as they are selected mostly for the Q-flex and Q-max series, whose production has been completed. A similar downgrade concerns the DFDE engines in favor of the more flexible TFDE. In the last two years there is a significant expansion of the use of MEGI engines, suggesting a possible dominance of this engine type in the following years. Finally XDF engine have equipped only a few vessels, so its success remains to be seen.

The results presented in Chapter 7 show a straightforward correlation of the amount of air pollutants, produced during the construction, maintenance and dismantling phases, with the vessels' size. As can be easily observed, the most harsh environmental impact due to CO_2, NO_X, SO_X and PM is connected with the construction and the dismantling phases, whereas the contribution of the other phases seems to be of minor importance.

In Chapter 7 the results of the economic evaluation are presented. As expected, the lowest Capital Cost is obtained when using the ST whereas the highest cost is that of the COGES. Furthermore, all versions of SSD engines also have a significant acquisition cost. In terms of operational cost the worst performance is that of an SSD configuration with an SCR. This is explained by the high cost of the urea solution used in this case. Apart from the GT and COGES, all the other configurations show an even performance. Finally, regarding NPV, the GT and the COGES have low values where the other engines show similar results.

In Chapter 8 the results of the operation phase are presented. In terms of PM, the ST configuration, when using HFO and LNG in equal quantities, have a vast contribution to the formation of PM. Clearly, a better performance is obtained with the use of DFDE, GT and COGES running on MDO and switching to LNG at certain parts of the journey. Worse performance than the latter configurations is obtained with the use of SSD, still better than the one of the ST. In the latter case the best performance is obtained when an SCR system is implemented in combination with the use of MDO within SECA areas.

Similar results can be seen when examining the performance of the selected configuration regarding their SO_X emissions. Again the ST has the worst performance, while DFDE, GT and COGES have better, almost mutually equivalent performances. The performance of the SSD is definitely worse but better than the one of the ST, and again the best performance is obtained when employing SCR systems combined with MDO fuel.

A significant reverse of the the aforementioned performances can be seen for NO_X emissions. Now, the best performance is obtained by the ST. The second best performance is obtained from the SSD when employing SCR systems and MDO. It is worth noticing that in this case, DFDE, GT and COGES cannot achieve the satisfactory results of the previous cases of PM and NO_X.

Concerning CO_2 emissions the results seem to be more balanced, with the SSD gaining the best results, especially when using the SCR systems and MDO (perhaps MDO's higher *Lower Heating Value*, results finally in less quantities of fuel and thus less emissions). It should be mentioned that the worse performance is obtained by the DFDE when the *methane slip* is examined.

Further Work

This thesis presents a first attempt to apply the LCA methodology on a series of LNG vessels. However, various aspects remain to be examined.

Further research involving the air pollutants of the production of metal alloys, such as invar and aluminium alloys, should be conducted. In fact, there are only a few references, since the majority of the metal structure of the vessels is constructed of steel. Nevertheless, the insulation of the LNG tanks is constructed from such alloys, thus making a precise LCA analysis of the metal structure of a modern LNG Carrier insufficient. The same problem appears when examining composite materials such as plywood, used again for insulation. However, the need for more lightweight materials, aiming to the reduction of the structure’s weight and that of the fuel consumption, could direct the relevant scientific research to the quest of the necessary data.

More data must be found for the emissions of the propulsive configurations, when power demands are different from those at the nominal point. Analogous data should be found when these engines use different fuels from those mentioned in the papers mentioned here.

Similarly, more data are needed for novel engine concepts, such as two-stroke engines elaborating the use of LNG along with HFO, that is MEGI engines produced by MAN, and XDF engines produced by Wartsila. Because of the lack of data concerning fuel demands and emissions, these engines were not included here. Nevertheless, as seen in the statistical analysis given in previous chapters, these engine types will gain an important fragment of the machinery selection in the future.

The installation of WHR, SCR and Scrubbers has been applied only to a few vessels. This is a significant drawback for the calculation of their performance. More precise data will be necessary to obtain more specific results.

Finally, it is crucial to conduct a more thorough study of the real operational patterns under which vessels perform, in order to determine the percentage of the voyage using each fuel. This will allow more realistic assumptions concerning fuel consumption and emissions.

The wide range of both capacity and propulsive configurations might provide data for a multiple criteria decision analysis, in which the combination of the vessel’s size and propulsive configuration will give the best results both in ecological and economical terms.

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Appendix

Description of the Computational Code

In order to perform the necessary calculations, a code in MATLAB was constructed. The code consists of 8 m-files. One of them is the main program m-file (*Main*), while the remaining 7 are the function files.

From the 7 function files, the first one (*Input*) permits the calculation of basic design parameters that may be unknown to the user of the program, and the results originate from the statistical analysis of the LNG fleet conducted in Chapter 3.

The 3 following files (*Insulation, Prokatarktika, Kataskeui*) carry out the calculations dealing with the construction of the hull of the LNG vessels examined here. The *Insulation* file performs calculations related to the weight of the tanks' insulation, while the *Prokatarktika* file gives the values of the main weight categories of the vessels (Steel Weight W_{ST}, Machinery Weight W_M and Outfitting Weight –W_{OT}). The results of both the above files are presented in Chapter 4. Finally the *Kataskeui* file employs the data provided by the preceding 2 files to give results relevant to the environmental impact caused by the construction, the maintenance, and the dismantling of the ships' hulls . The relevant results are presented in Chapter 7.

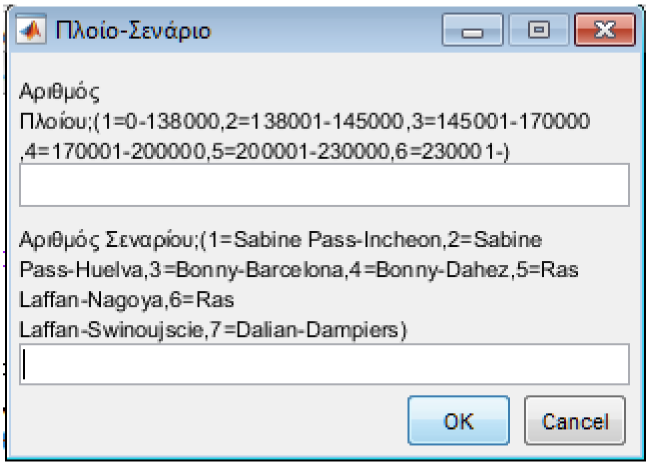
The *Operation* file conducts calculations concerning the fuel consumption for propulsion and auxiliary use, for a variety of propulsive configurations. Following that, the environmental impact during the operation of a vessel is given in terms of air pollutants. Special analysis is undertaken when an SSD propulsive configuration burning HFO is selected. There is a number of additional devices that can be combined with the aforementioned engine selection in order to make possible the operation of a vessel employing the aforementioned type in Emission Control Areas or to reduce energy consumption. The results and the relevant figures are presented in Chapter 8.

The last 2 files (*Constructioncost* and *Machinecost)* present results concerning the acquisition and operational cost of the vessels examined. In the file *Constructioncost*, the cost of the vessels' hull construction is calculated while the file *Machinecost* performs calculations relevant to the operational costs. Again a special analysis concerning the additional devices of the SSD type are examined in order to compare their economic performance, especially in accordance with the corresponding environmental impact.

User - Program Interface

In this thesis, a wide range of data is supposed to be provided by the user, in order to enhance his ability to perform calculations for a large amount of combinations of different hulls, propulsive configurations, operational scenarios and economic data, while only a small number of data are taken by default in the codes, usually those extracted from statistical analysis.

In an effort to provide a user's friendly interface, several dialog-boxes are created, so that the user can insert the selected data. The dialog-boxes used are shown in the following pages.

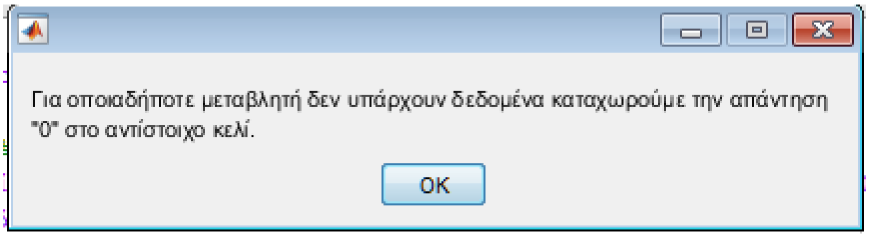


Πλοίο-Σενάριο

Αριθμός Πλοίου;(1=0-138000,2=138001-145000,3=145001-170000 ,4=170001-200000,5=200001-230000,6=230001-)

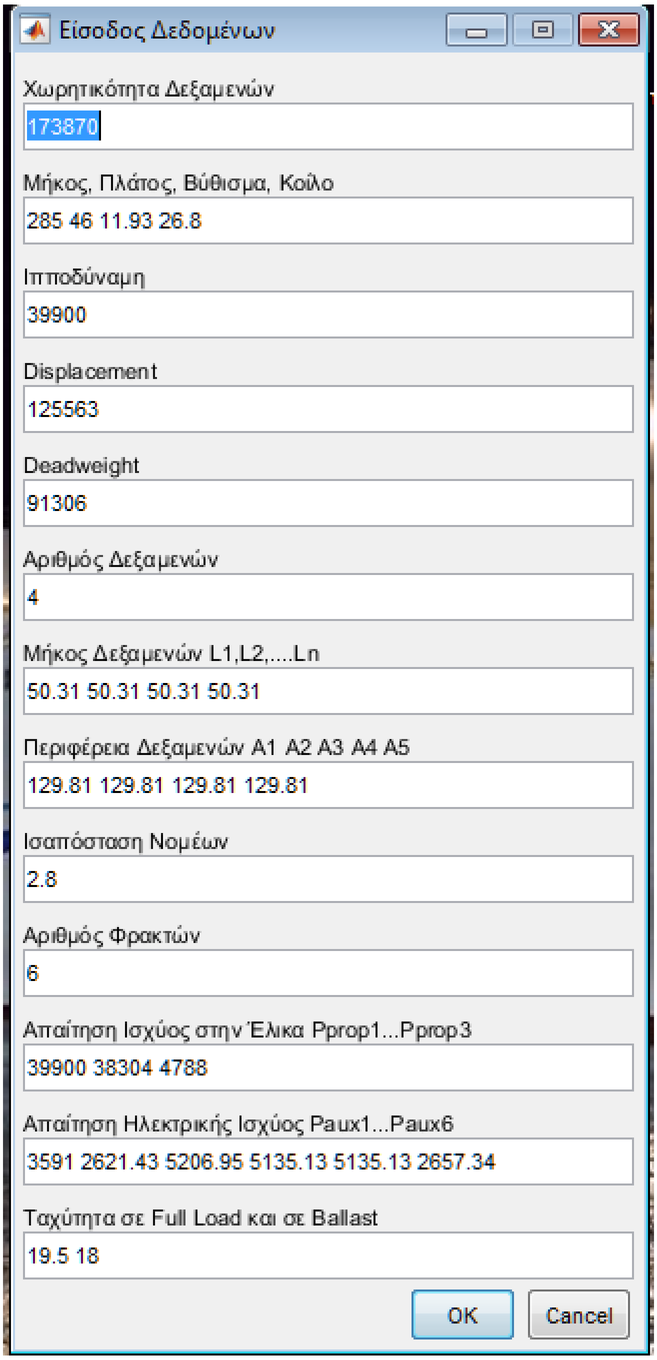
Αριθμός Σεναρίου;(1=Sabine Pass-Incheon,2=Sabine Pass-Huelva,3=Bonny-Barcelona,4=Bonny-Dahez,5=Ras Laffan-Nagoya,6=Ras Laffan-Swinoujscie,7=Dalian-Dampiers)

Picture 1. Dialog – box 1. Selection between preselected vessels and scenarios.



Για οποιαδήποτε μεταβλητή δεν υπάρχουν δεδομένα καταχωρούμε την απάντηση "0" στο αντίστοιχο κελί.

Picture 2. Dialog – box 2. Instructions to the user when data are missing.



Χωρητικότητα Δεξαμενών
173870

Μήκος, Πλάτος, Βύθισμα, Κοίλο
285 46 11.93 26.8

Ιπποδύναμη
39900

Displacement
125563

Deadweight
91306

Αριθμός Δεξαμενών
4

Μήκος Δεξαμενών L1,L2,....Ln
50.31 50.31 50.31 50.31

Περιφέρεια Δεξαμενών A1 A2 A3 A4 A5
129.81 129.81 129.81 129.81

Ισαπόσταση Νομέων
2.8

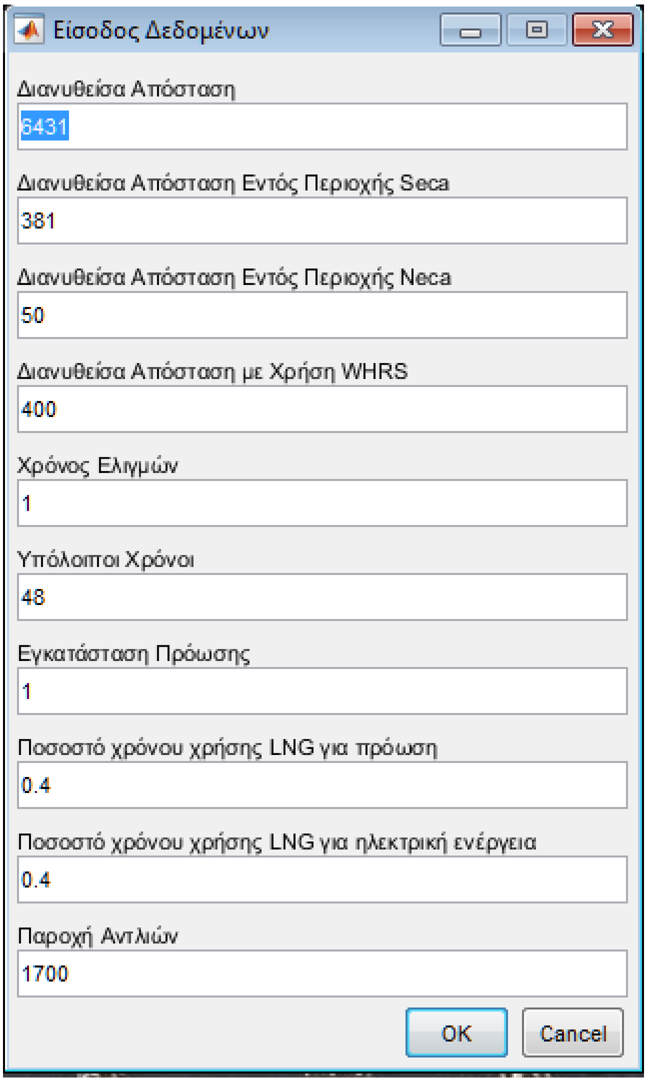
Αριθμός Φρακτών
6

Απαίτηση Ισχύος στην Έλικα Pprop1...Pprop3
39900 38304 4788

Απαίτηση Ηλεκτρικής Ισχύος Paux1...Paux6
3591 2621.43 5206.95 5135.13 5135.13 2657.34

Ταχύτητα σε Full Load και σε Ballast
19.5 18

Picture 3. Dialog – box 3. Selection of vessel's main dimensions and characteristics.



Διανυθείσα Απόσταση
6431

Διανυθείσα Απόσταση Εντός Περιοχής Seca
381

Διανυθείσα Απόσταση Εντός Περιοχής Neca
50

Διανυθείσα Απόσταση με Χρήση WHRS
400

Χρόνος Ελιγμών
1

Υπόλοιποι Χρόνοι
48

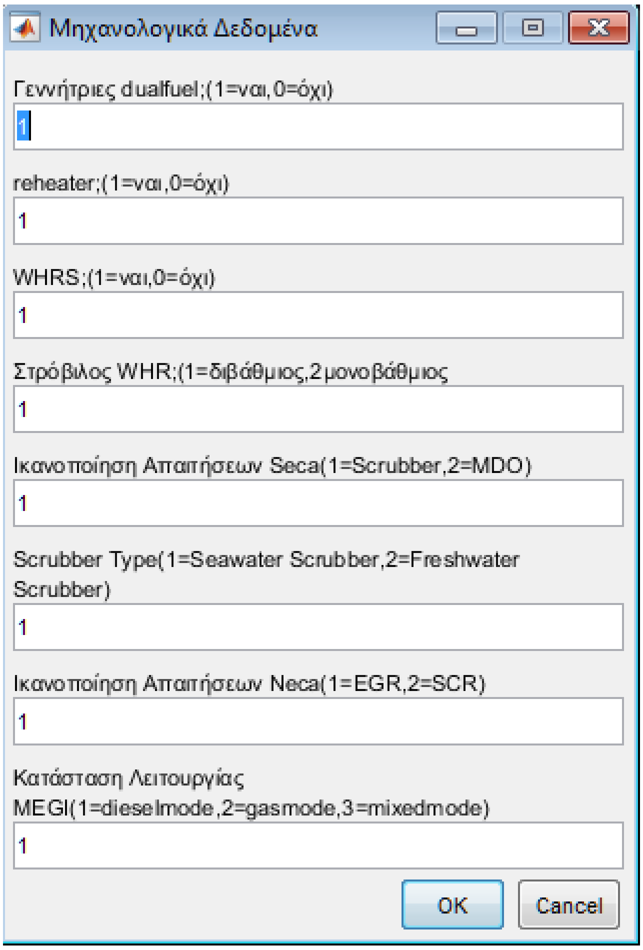
Εγκατάσταση Πρόωσης
1

Ποσοστό χρόνου χρήσης LNG για πρόωση
0.4

Ποσοστό χρόνου χρήσης LNG για ηλεκτρική ενέργεια
0.4

Παροχή Αντλιών
1700

Picture 4. Dialog – box 1. Selection of voyage data.



Γεννήτριες dualfuel;(1=ναι,0=όχι)
1

reheater;(1=ναι,0=όχι)
1

WHRS;(1=ναι,0=όχι)
1

Στρόβιλος WHR;(1=διβάθμιος,2μονοβάθμιος
1

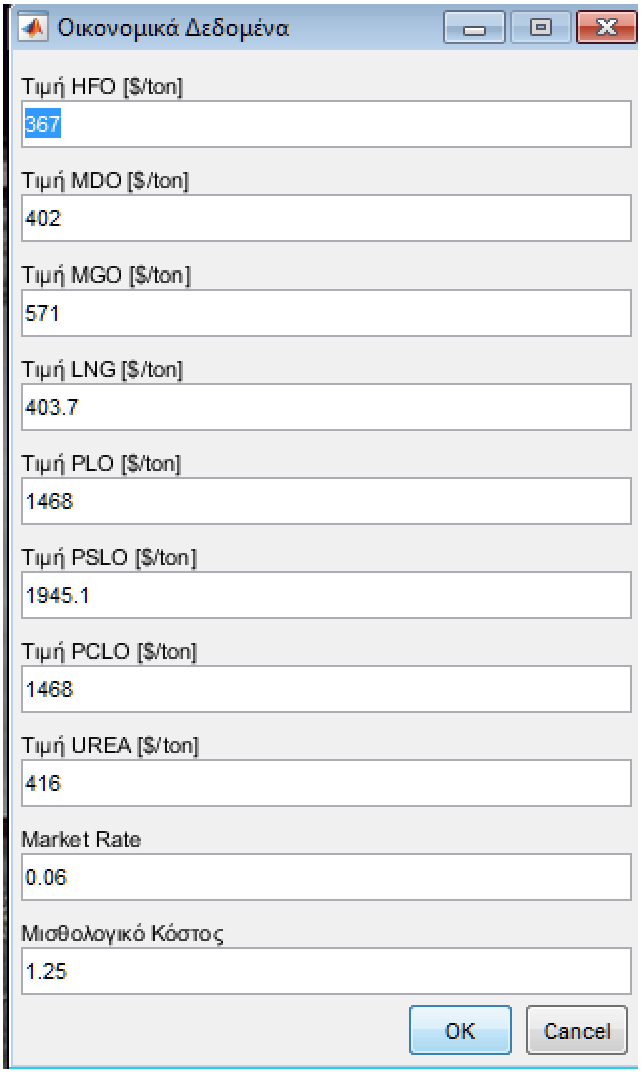
Ικανοποίηση Απαιτήσεων Seca(1=Scrubber,2=MDO)
1

Scrubber Type(1=Seawater Scrubber,2=Freshwater Scrubber)
1

Ικανοποίηση Απαιτήσεων Neca(1=EGR,2=SCR)
1

Κατάσταση Λειτουργίας MEGI(1=dieselmode,2=gasmode,3=mixedmode)
1

Picture 5. Dialog – box 5. Selection of additional equipment.



Οικονομικά Δεδομένα

Τιμή HFO [$/ton]
367

Τιμή MDO [$/ton]
402

Τιμή MGO [$/ton]
571

Τιμή LNG [$/ton]
403.7

Τιμή PLO [$/ton]
1468

Τιμή PSLO [$/ton]
1945.1

Τιμή PCLO [$/ton]
1468

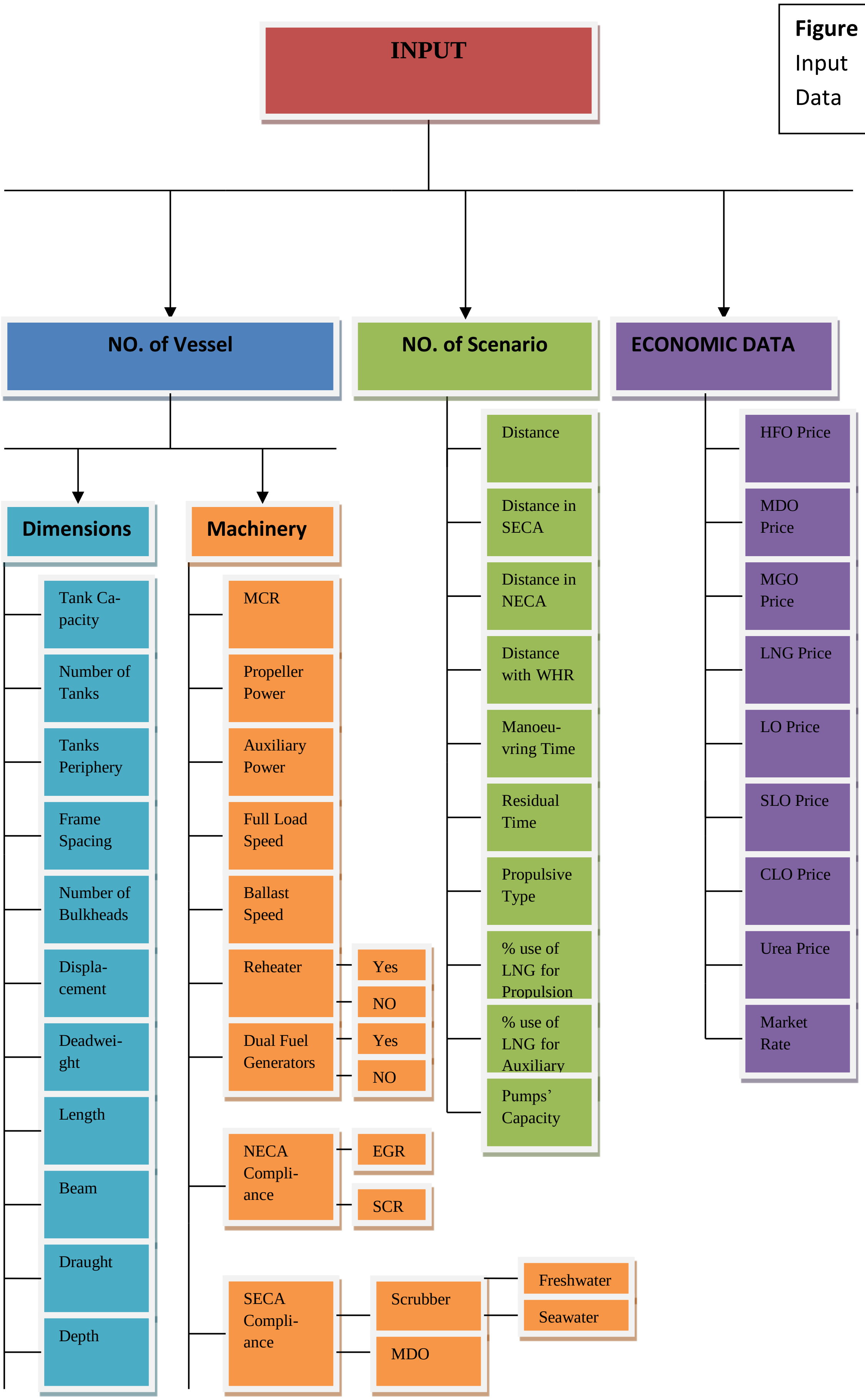
Τιμή UREA [$/ton]
416

Market Rate
0.06

Μισθολογικό Κόστος
1.25

Picture 6. Dialog – box 6. Selection of economic data.

Figure 1. Input Data



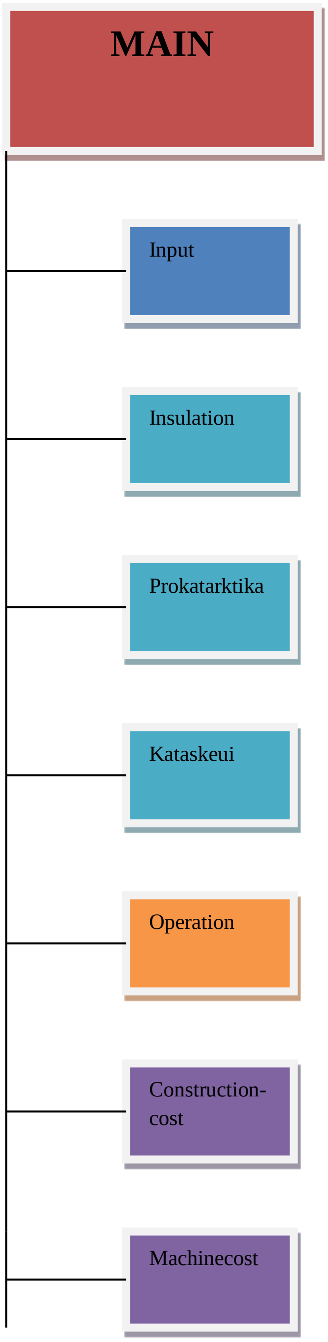


Figure 2. Structure Matlab Code

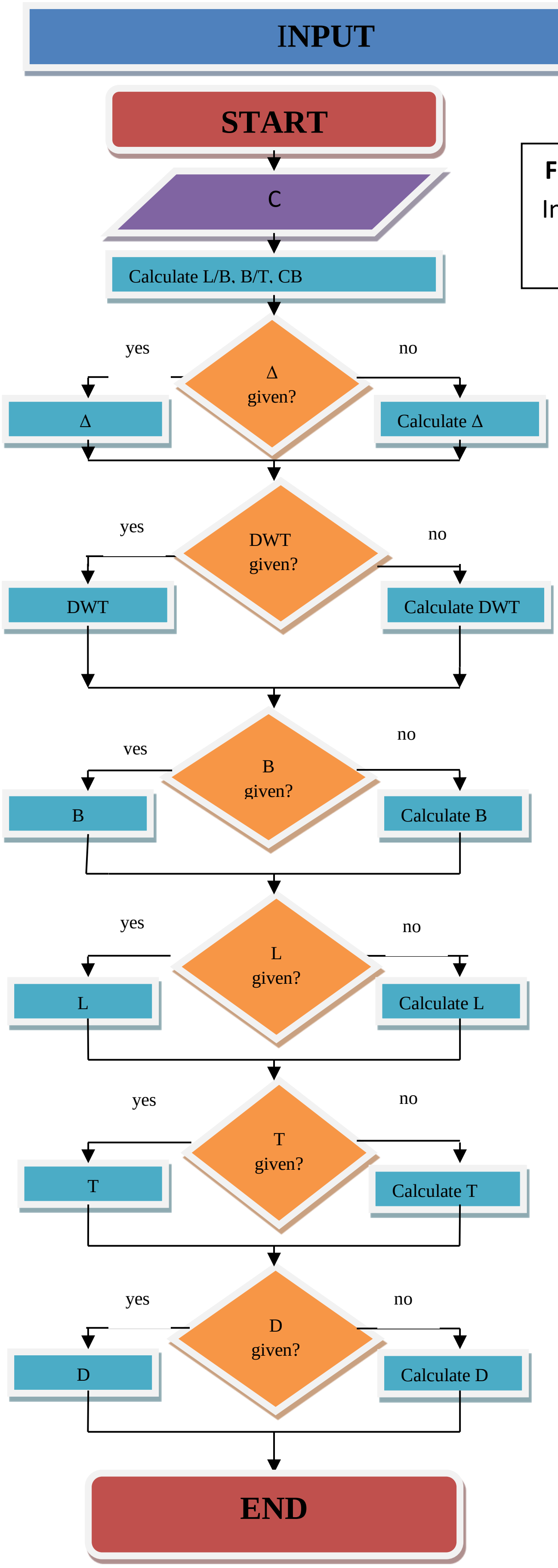


Figure 3.
Input File

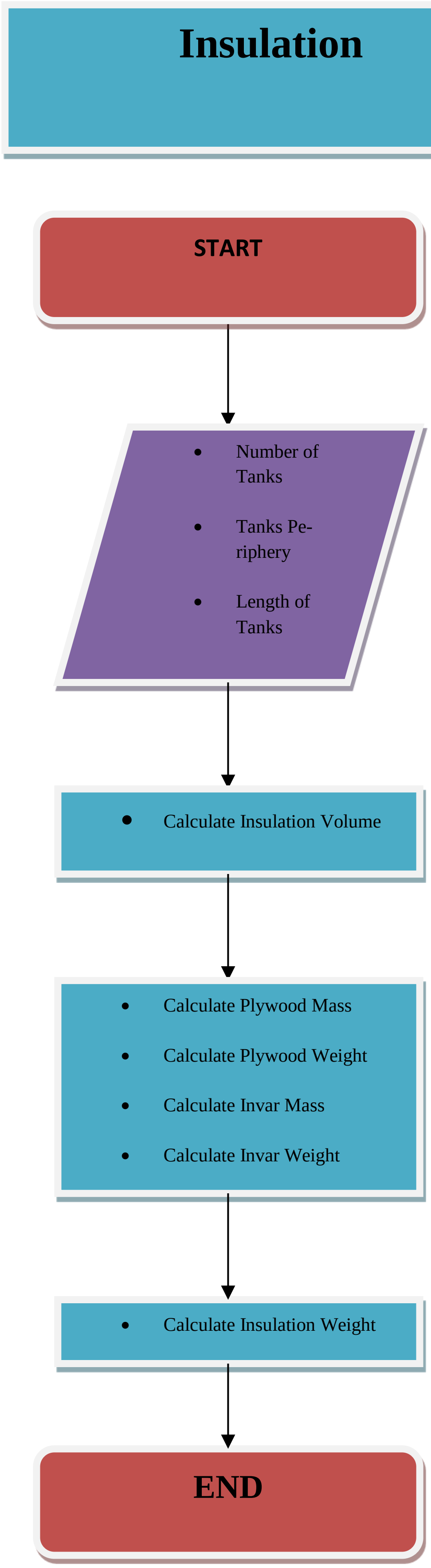


Figure 4. Insulation File

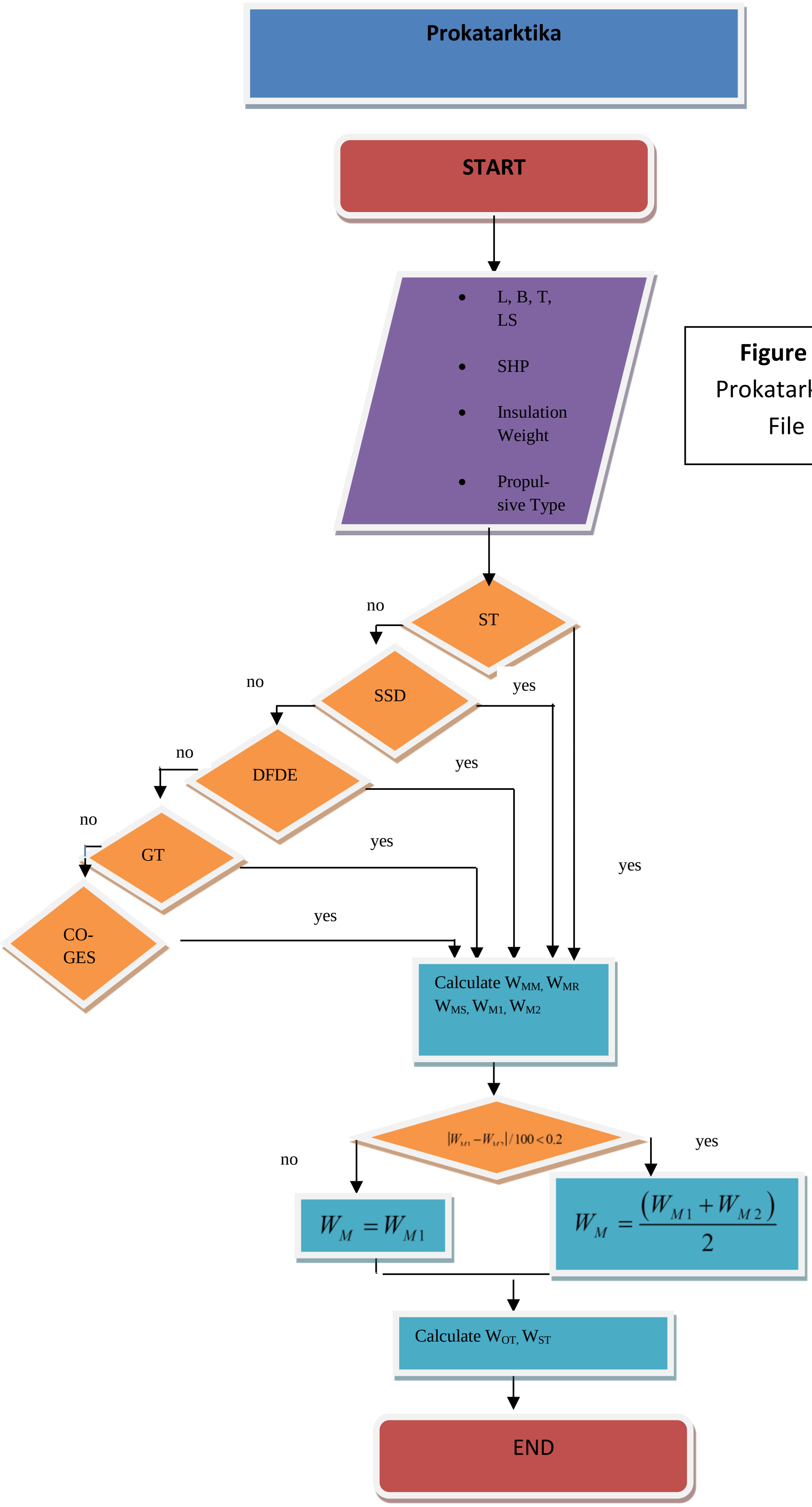


Figure 5. Prokatarktika File

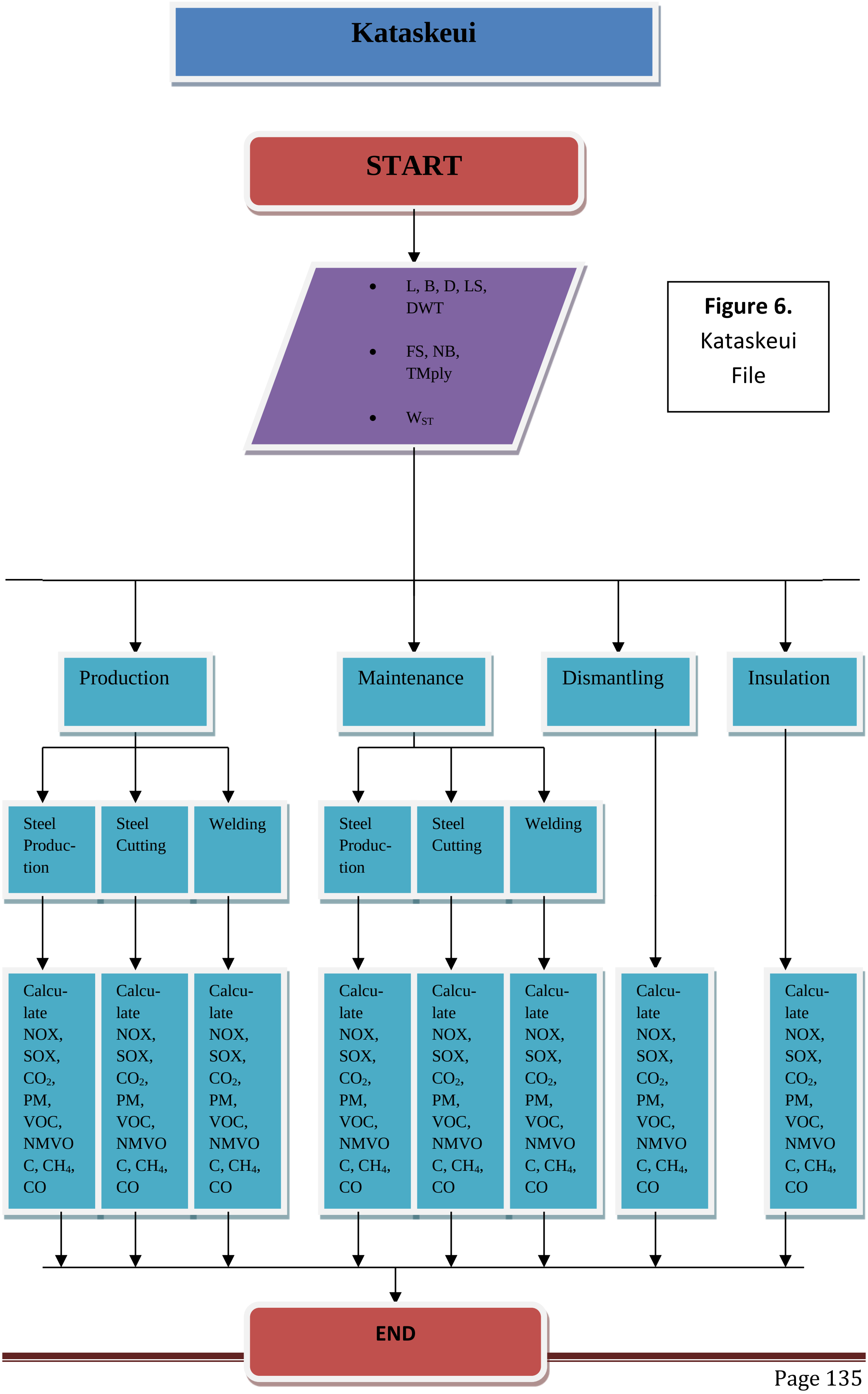


Figure 6.
Kataskeui
File

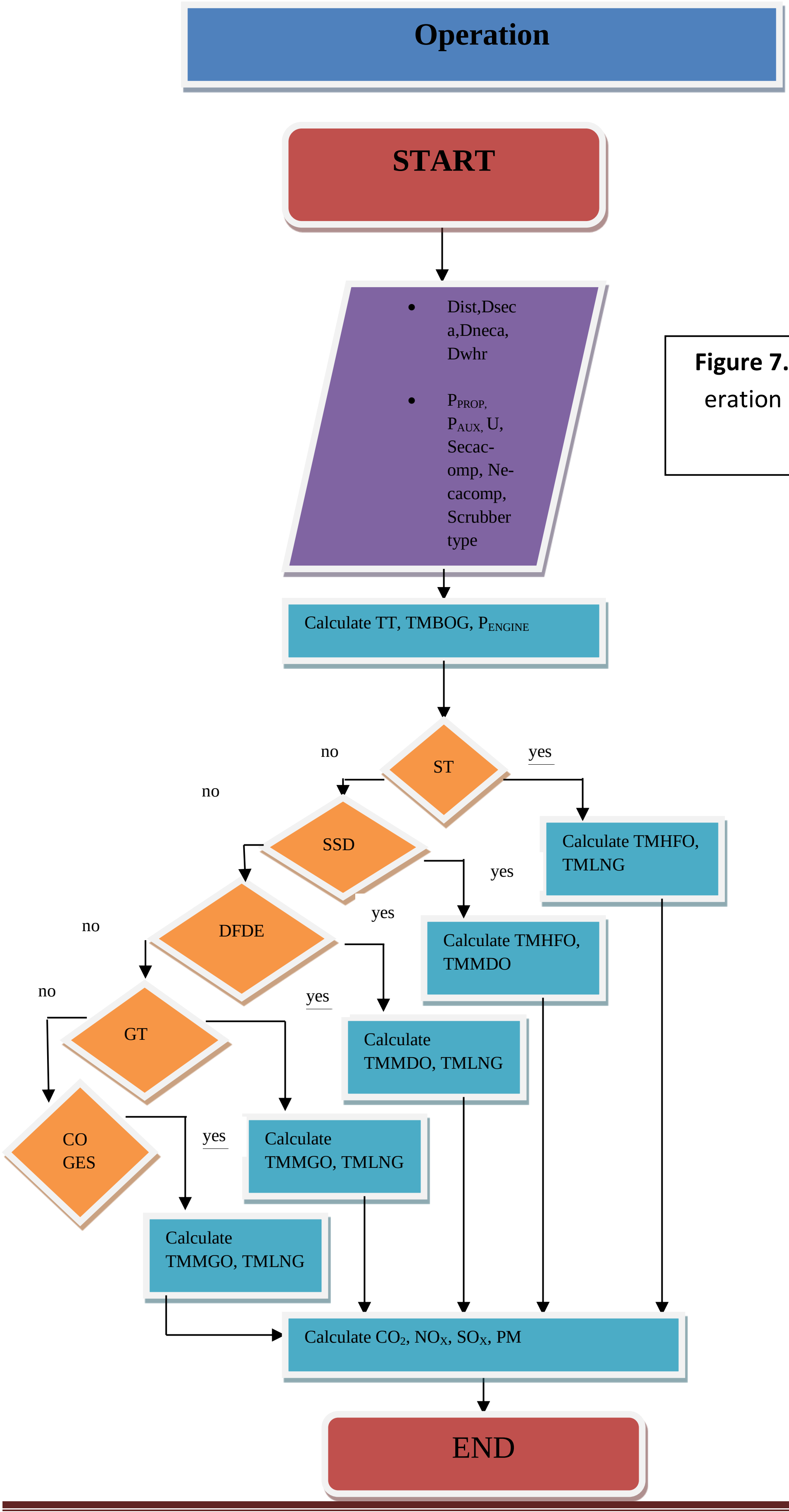


Figure 7. Operation File

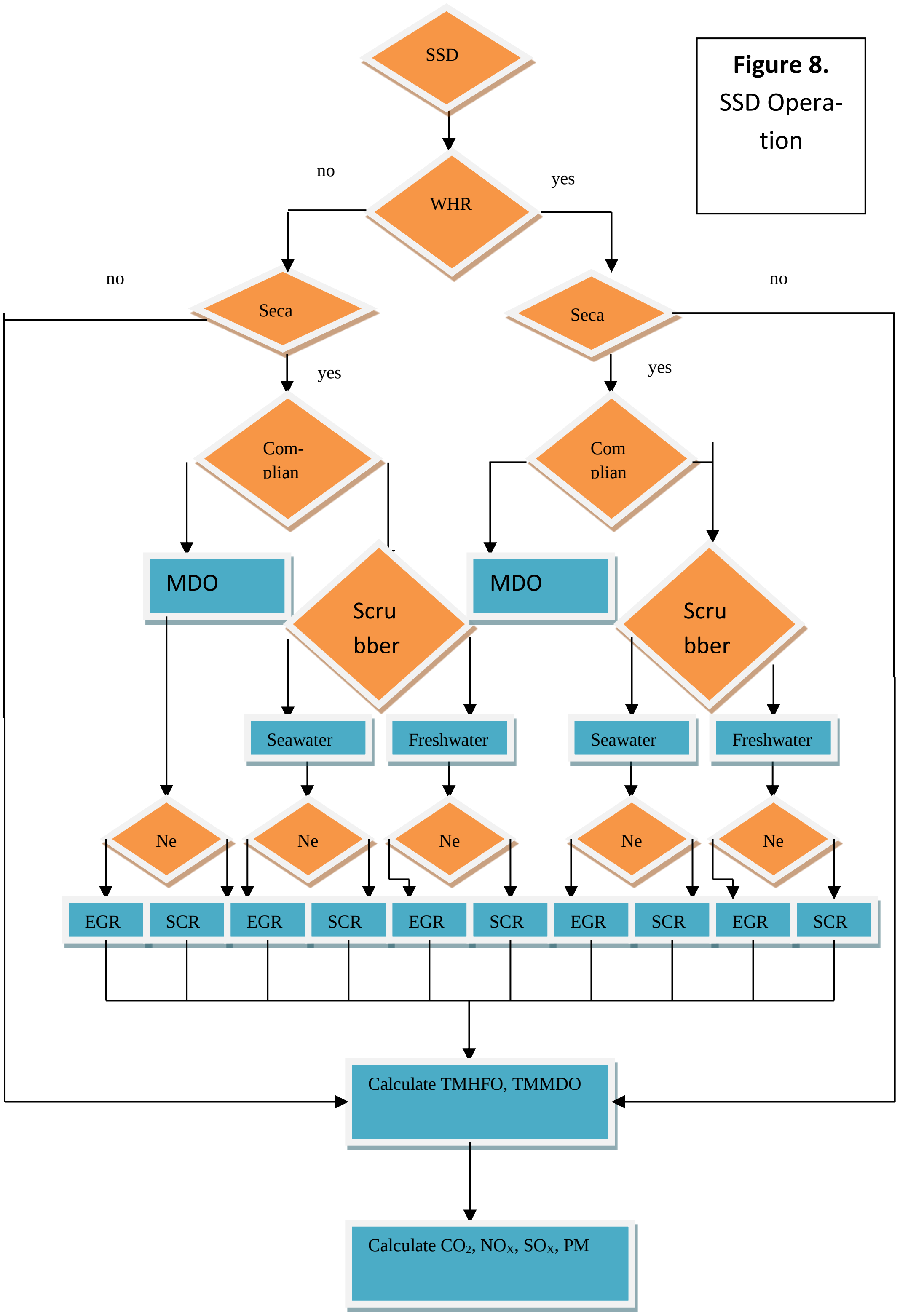


Figure 8. SSD Operation

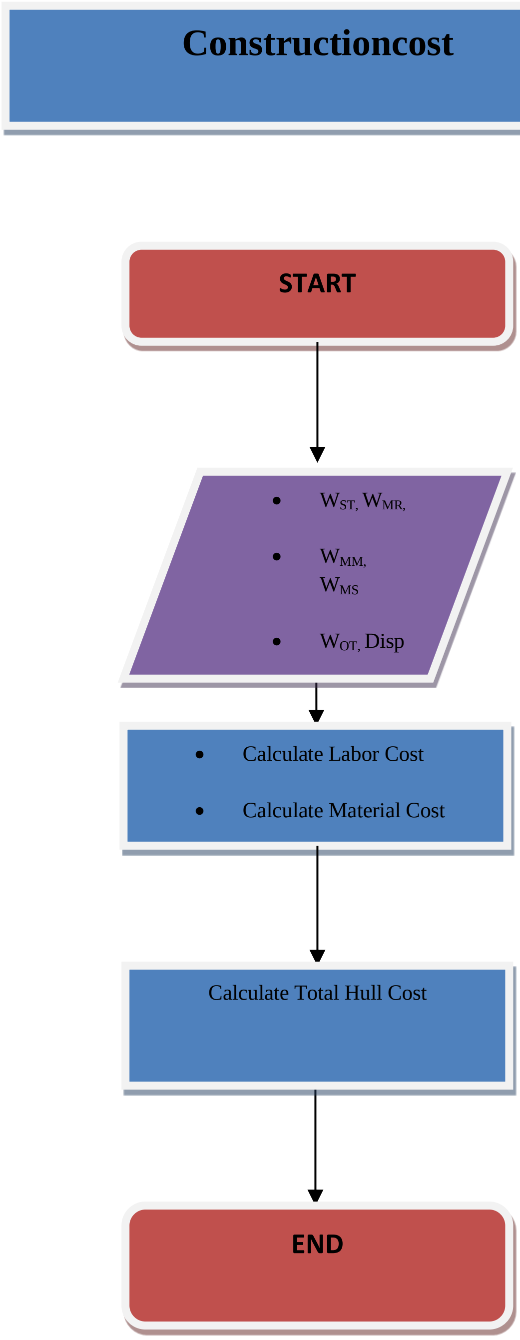


Figure 9. Constructioncost File

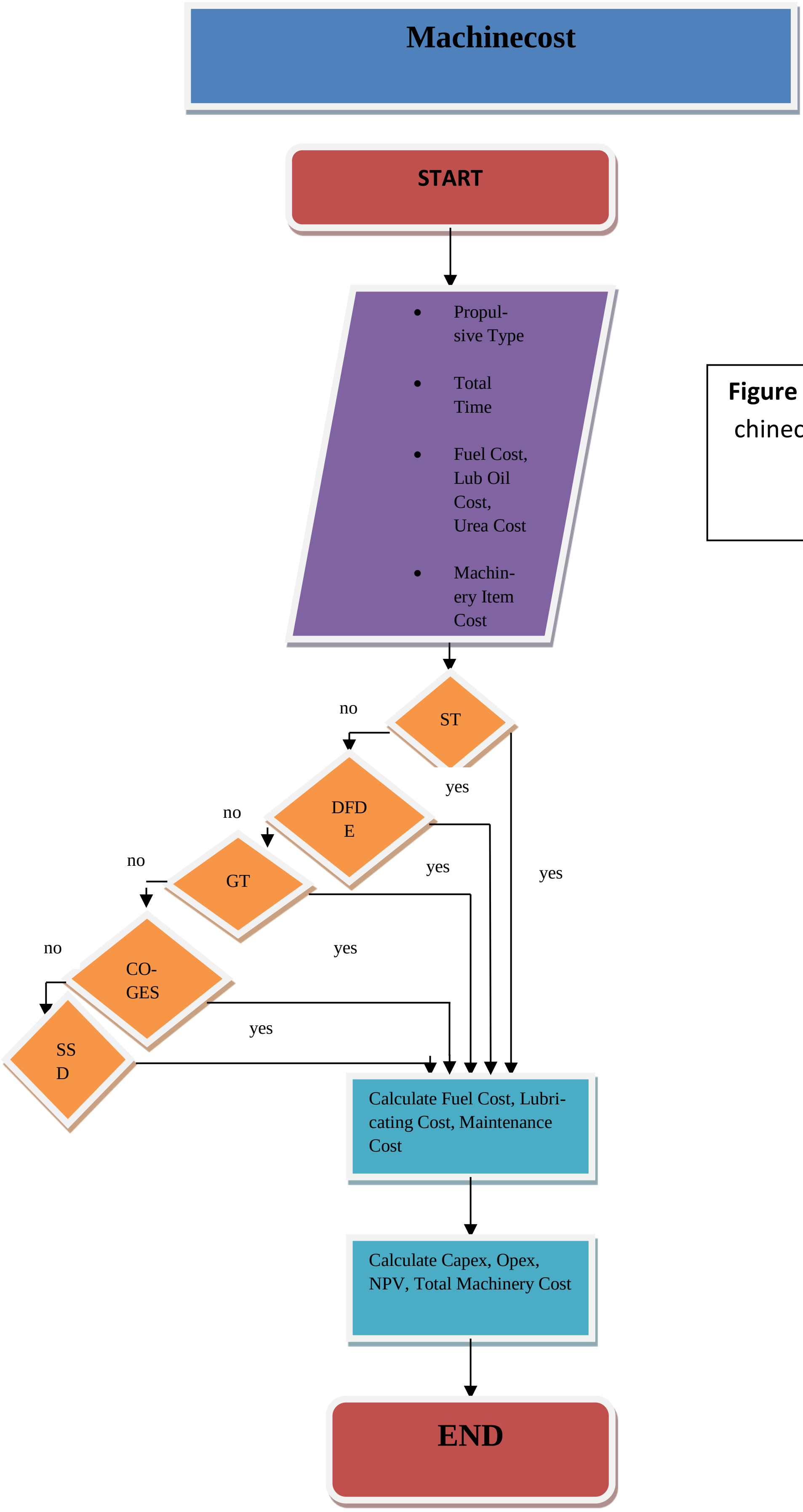
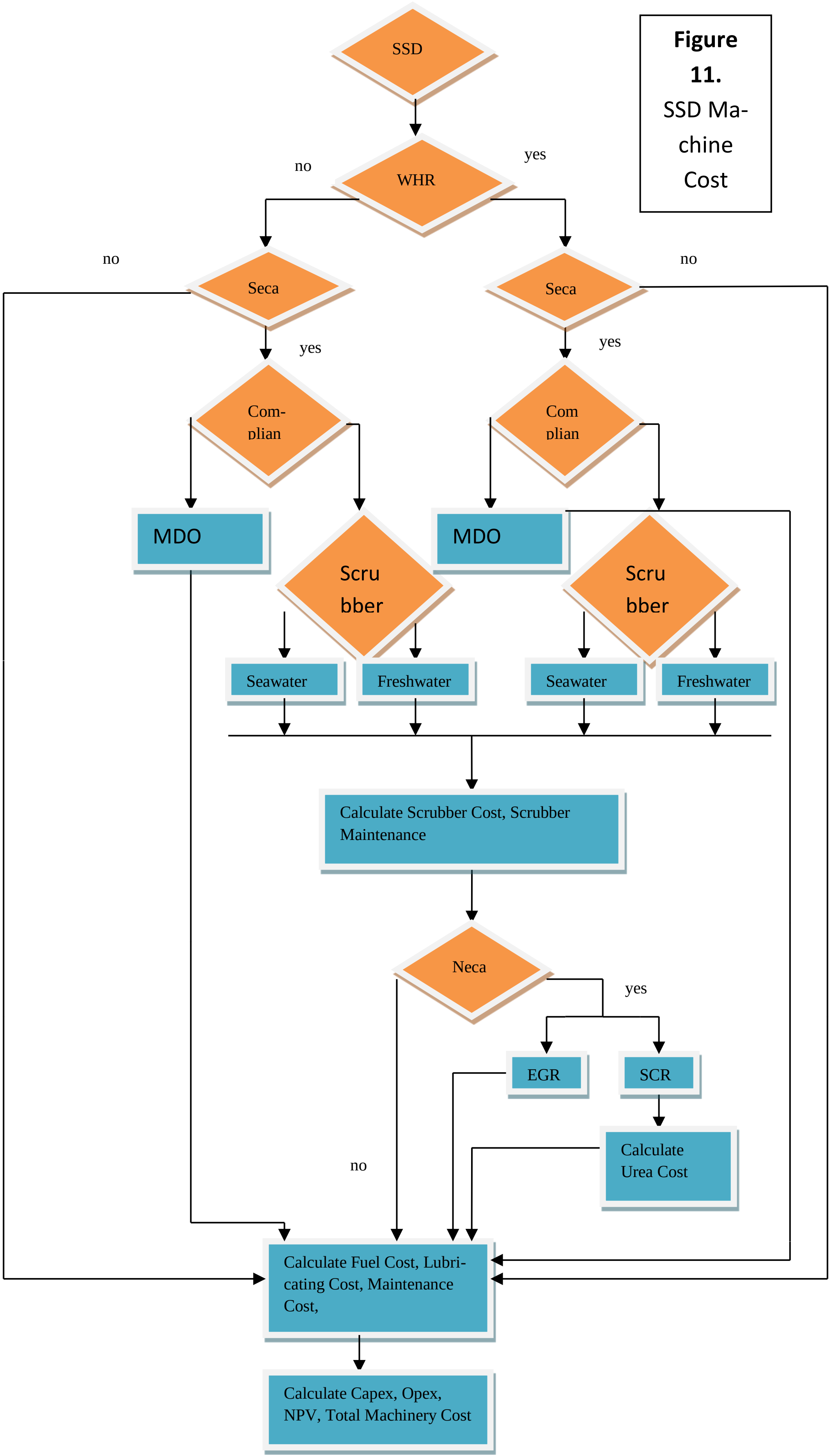


Figure 10. Machinecost File

Figure 11. SSD Machine Cost



Weight Calculations for each type of Propulsive Configuration

STEAM TURBINE

- $W_{MM} = 22.5 \cdot SHP \cdot 1.341 \cdot 10^{-3}$
- $W_{MR1} = 4 \cdot L \cdot B \cdot T \cdot 1.341 \cdot 10^{-3}$
- $W_{MR2} = 30 \cdot SHP \cdot 1.341 \cdot 10^{-3}$
- $W_{MR} = \dfrac{\left(W_{MR1} + W_{MR2}\right)}{2}$
- $W_{MS} = 4 \cdot SHP \cdot 1.34 \cdot 10^{-3}$
- $WM_1 = W_{MM} + W_{MR} + W_{MS}$
- $WM_2 = 57.5 \cdot SHP \cdot 1.34 \cdot 10^{-3}$
- $W_M = \dfrac{\left(W_{M1} + W_{M2}\right)}{2}$

SLOW SPEED DIESEL ENGINE

- $W_{MM} = 35 \cdot SHP \cdot 1.341 \cdot 10^{-3}$
- $W_{MR1} = 12.5 \cdot L \cdot B \cdot T \cdot 10^{-3}$
- $W_{MR1} = 42.5 \cdot SHP \cdot 1.341 \cdot 10^{-3}$
- $W_{MR} = \dfrac{\left(W_{MR1} + W_{MR2}\right)}{2}$
- $W_{MS} = 7.5 \cdot SHP \cdot 1.341 \cdot 10^{-3}$
- $WM_1 = W_{MM} + W_{MR} + W_{MS}$
- $WM_2 = 87.5 \cdot SHP \cdot 1.341 \cdot 10^{-3}$
- $W_M = \dfrac{\left(W_{M1} + W_{M2}\right)}{2}$

DUAL FUEL DIESEL ELECTRIC

- $W_{MM} = 14.5 \cdot SHP \cdot 1.341 \cdot 10^{-3}$
- $W_{MR1} = 35 \cdot L \cdot B \cdot T \cdot 10^{-3}$
- $W_{MR1} = 42.5 \cdot SHP \cdot 1.341 \cdot 10^{-3}$

- $W_{MR} = \frac{(W_{MR1} + W_{MR2})}{2}$
- $W_{MS} = 7.5 \cdot SHP \cdot 1.341 \cdot 10^{-3}$
- $WM_1 = W_{MM} + W_{MR} + W_{MS}$
- $WM_2 = 75 \cdot SHP \cdot 1.341 \cdot 10^{-3}$
- $W_M = \frac{(W_{M1} + W_{M2})}{2}$

GAS TURBINE

- $W_{MM} = 1.4 \cdot SHP \cdot 1.341 \cdot 10^{-3}$
- $W_{MR1} = 35 \cdot L \cdot B \cdot T \cdot 10^{-3}$
- $W_{MR1} = 42.5 \cdot SHP \cdot 1.341 \cdot 10^{-3}$
- $W_{MR} = \frac{(W_{MR1} + W_{MR2})}{2}$
- $W_{MS} = 7.5 \cdot SHP \cdot 1.341 \cdot 10^{-3}$
- $WM_1 = W_{MM} + W_{MR} + W_{MS}$
- $WM_2 = 75 \cdot SHP \cdot 1.341 \cdot 10^{-3}$
- $W_M = \frac{(W_{M1} + W_{M2})}{2}$

COMBINED GAS AND STEAM ELECTRIC PROPULSION

- $W_{MM} = (1.4 \cdot 0.7 + 3.515 \cdot 0.3) \cdot SHP \cdot 1.34 \cdot 10^{-3}$
- $W_{MR1} = 35 \cdot L \cdot B \cdot T \cdot 10^{-3}$
- $W_{MR1} = 42.5 \cdot SHP \cdot 1.341 \cdot 10^{-3}$
- $W_{MR} = \frac{(W_{MR1} + W_{MR2})}{2}$
- $W_{MS} = 7.5 \cdot SHP \cdot 1.341 \cdot 10^{-3}$
- $WM_1 = W_{MM} + W_{MR} + W_{MS}$
- $WM_2 = 75 \cdot SHP \cdot 1.341 \cdot 10^{-3}$
- $W_M = \frac{(W_{M1} + W_{M2})}{2}$

Note. It is an intention to give emphasis to W_{M1} rather than to W_{M2} as it is thought to be more compatible with the scope of the thesis where different vessel dimensions are taken as the basis of all changes including Power Demands. Thus, as seen in Figure 5, the mean average of W_{M1} and W_{M2} is taken only when the absolute diference of the two values is less than 2%.

Results of the Operation Scenario

Vessel 1

Table 72 Speed and propulsion specifications of Vessel 1

Vessel No.1		
Variable	**Value**	**Unit**
U_{LOAD}	17.5	kn
U_{UNLOAD}	17.5	kn
C	74245	m^3
Pumping Capacity	1700	m^3/h
P_{PROP}	[15000 14400 1800]	kW
P_{AUX}	[1350 985.5 1957.5 1930.5 1930.5 999]	kWe

Table 73 Times of the discrete operational phases of Vessel 1

t_1	367.4857
t_2	401.9375
t_3	1
t_4	5.4592
t_5	5.4592
t_6	48
t_7	21.7714
t_8	23.8125

Table 74 VBOG rates of the discrete operational phases of Vessel 1 [m^3/h]

Loaded	3.66
Baliast	1.83
Manoeuvring	3.05
Loading	2.44
Unloading	0
Residual Time	3.05

Table 75 Fuel consumption and air pollutants from main propulsion engines for Vessel 1

ST	nst	0.9702
	Pengine [KW]	[15461 14842 1855]
	EDP(withreheater)*10^8(kJ/h)	[1.665 1.5990 0.2157]
	$TMHFO_{OP}$*10^3 (tons)	1.6795
	$TMLNG_{OP}$*10^3 (tons)	1.1846
	SOX_{OP} (tons)	[128.1404]
	NOX_{OP}	[11.6491]
	PM_{OP}	[29.1228]
DFDE	nDFDE	0.9038
	Pengine (KW)	[1.6596 1.5932 0.1992]
	EDP*10^8(kJ/h)	[1.3464 1.2926 0.1743]
	$TMMDO_{OP}$*10^3 (tons)	1.7619
	$TMLNG_{OP}$ (tons)	880.3764
	SOX_{OP} (tons)	14.3866
	NOX_{OP} (tons)	95.2959
	PM_{OP} (tons)	0.5547
GT	nGT	0.9038
	Pengine (KW)	[1.6596 1.5932 0.1992]
	EDP*10^8 (kJ/h)	[1.4669 1.4082 0.1899]
	$TMMGO_{OP}$*10^3(tons)	1.9195
	$TMLNG_{OP}$ (tons)	959.1469
	SOX_{OP} (tons)	14.1143
	NOX_{OP} (tons)	101.8329
	PM_{OP} (tons)	0.3368
COGES	nCOGES	0.9038
	Pengine (KW)	[16596 15932 1992]
	EDP*10^8(kJ/h)	[1.2469 1.1970 0.1614]
	$TMMGO_{OP}$*10^3 (tons)	1.6316
	$TMLNG_{OP}$*10^3 (tons)	815.2749
	SOX_{OP} (tons)	14.1143
	NOX_{OP} (tons)	101.8329
	PM_{OP} (tons)	0.3368

Table 76 Fuel consumption and air pollutants from auxiliary engines for Vessel 1

ST	naux	0.96
	Pauxdel (KWe)	[1406.3 1026.6 2039.1 2010.9 2010.9 1040.6]
	EDA*10^7(kJ/h)	[1.6476 1.2027 2.3890 2.3560 2.3560 1.2192]
	$TMHFO_{AUX}$*10^3 (tons)	152.1334
	$TMLNG_{AUX}$*10^3 (tons)	118.0470
	SOX_{AUX} (tons)	3.1204
	NOX_{AUX} (tons)	5.5986
	PM_{AUX} (tons)	0.1906
DFDE	naux	0.97
	Pauxdel (KWe)	[1391.8 1016.0 2018.0 1990.2 1990.2 1029.9]
	EDA*10^7 (kJ/h)	[1.1291 0.8243 1.6372 1.6147 1.6147 0.8356]
	$TMMDO_{AUX}$*10^3 (tons)	158.4913
	$TMLNG_{AUX}$*10^3 (tons)	76.6893
	SOX_{AUX} (tons)	1.0621
	NOX_{AUX} (tons)	7.1058
	PM_{AUX} (tons)	0.0445
GT	naux	0.97
	Pauxdel (KWe)	[13918 10160 20180 19902 19902 10299]
	EDA*10^7(kJ/h)	[1.0683 0.7799 1.5490 1.5277 1.5277 0.7905]
	$TMMGO_{AUX}$ (tons)	149.9543
	$TMLNG_{AUX}$ (tons)	72.5585
	SOX_{AUX} (tons)	1.0384
	NOX_{AUX} (tons)	7.6743
	PM_{AUX} (tons)	0.0255
COGES	naux	0.97
	Pauxdel (KWe)	[1391.8 1016.0 2018.0 1990.2 1990.2 1029.9]
	EDA*10^7(kJ/h)	[1.0683 0.7799 1.5490 1.5277 1.5277 0.7905]
	$TMMGO_{AUX}$ (tons)	149.9543
	$TMLNG_{AUX}$ (tons)	72.5585
	SOX_{AUX} (tons)	1.0384
	NOX_{AUX} (tons)	7.6743
	PM_{AUX} (tons)	0.0255

Table 77 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 1.

ST	$TMHFO_{TOT}$*10^3 (tons)	1.8317
	$TMLNG_{TOT}$*10^3 (tons)	1.3027
	CO_2*10^3 (tons)	9.2862
	SOX_{TOT} (tons)	131.2608
	NOX_{TOT} (tons)	17.2477
	PM_{TOT} (tons)	29.3135
DFDE	$TMMDO_{TOT}$*10^3 (tons)	1.9204
	$TMLNG_{TOT}$*10^3 (tons)	957.0657
	CO_2*10^3 (tons)	8.7886
	(Methane slip)CO_2*10^3 (tons)	10.373
	SOX_{TOT} *10^3 (tons)	15.4487
	NOX_{TOT} *10^3 (tons)	102.4017
	PM_{TOT} *10^3 (tons)	0.5991
GT	$TMMGO_{TOT}$*10^3 (tons)	2.0695
	$TMLNG_{TOT}$*10^3 (tons)	1.0317
	CO_2 *10^3 (tons)	9.4719
	SOX_{TOT} (tons)	15.1527
	NOX_{TOT} (tons)	109.5072
	PM_{TOT} (tons)	0.3623
COGES	$TMHFO_{TOT}$*10^3 (tons)	1.7815
	$TMLNG_{TOT}$ (tons)	887.8334
	CO_2 *10^3 (tons)	8.1531
	SOX_{TOT} (tons)	15.1527
	NOX_{TOT} (tons)	109.5072
	PM_{TOT} (tons)	0.3623

Table 78 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 1, equipped with SSD with Seawater Scrubber, Freshwater Scrubber and WHR.

	Seawater Scrubber	Freshwater Scrubber	WHR
nssd	0.99	0.99	0.99
Pengine (KW)	[1515.2 1454.5 181.8]	[1515.2 1454.5 181.8]	-
EDP*10^8(kJ/h)	[1.0934 1.0496 0.1416]	[1.0934 1.0496 0.1416]	-
$TMHFO_{OP}$*10^3 (tons)	2.0846	2.0839	-
$TMMDO_{OP}$ (tons)	0	0	-
SOX_{OP} (tons)	83.2054	83.2054	-
NOX_{OP} (tons)	194.0745	194.0745	-
PM_{OP} (tons)	5.4538	5.4538	-
naux	0.96	0.96	0.96
Pauxdel (KWe)	[1406.3 1026.6 2039.1 2010.9 2010.9 1040.6]	[1406.3 1026.6 2039.1 2010.9 2010.9 1040.6]	-
EDA*10^7(kJ/h)	[1.1409 0.8329 1.6543 1.6315 1.6315 0.8443]	[1.1409 0.8329 1.6543 1.6315 1.6315 0.8443]	-
$TMMDO_{AUX}$ (tons)	1.8115	1.8115	-
SOX_{AUX} (tons)	7.7257	7.7257	-
NOX_{AUX} (tons)	17.0567	17.0567	-
PM_{AUX} (tons)	0.5017	0.5017	-
CO_2 *10^3 (tons)	6.4971	6.4952	-
SOX_{TOT} (tons)	90.9311	90.9311	-
NOX_{TOT} (tons)	211.1312	211.1312	-
PM_{TOT} (tons)	5.9555	5.9555	-

Table 79 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 1, equipped with SSD with EGR and SCR systems burning MDO when operating in SECA.

	EGR	**SCR**
nssd	0.99	0.99
Pengine (KW)	[1515.2 1454.5 181.8]	[1515.2 1454.5 181.8]
EDP*10^8(kJ/h)	[1.0934 1.0496 0.1416]	[1.0934 1.0496 0.1416]
$TMHFO_{OP}$*10^3 (tons)	1.9181	1.9181
$TMMDO_{OP}$ (tons)	114.6151	114.6151
SOX_{OP} (tons)	87.9043	87.9043
NOX_{OP} (tons)	38.8149	38.8149
PM_{OP} (tons)	5.7081	5.7081
naux	0.96	0.96
Pauxdel (KWe)	[1406.3 1026.6 2039.1 2010.9 2010.9 1040.6]	[1406.3 1026.6 2039.1 2010.9 2010.9 1040.6]
EDA*10^7(kJ/h)	[1.1409 0.8329 1.6543 1.6315 1.6315 0.8443]	[1.1409 0.8329 1.6543 1.6315 1.6315 0.8443]
$TMMDO_{AUX}$*10^3 (tons)	1.8115	1.8115
SOX_{AUX} (tons)	7.7257	7.7257
NOX_{AUX} (tons)	17.0567	17.0567
PM_{AUX} (tons)	0.5017	0.5017
$TMHFO_{TOT}$*10^3 (tons)	1.9181	1.9181
$TMMDO_{TOT}$*10^3 (tons)	116.4266	116.4266
CO_2 *10^3 (tons)	6.3461	6.3461
SOX_{TOT} (tons)	95.6300	95.6300
NOX_{TOT} (tons)	55.8716	55.8716
PM_{TOT} (tons)	6.2097	6.2097

Table 80 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 1, for the three selected means for complying with the ECA regulations.

	MDO-WHR-SCR	Seawater Scrubber-EGR	Freshwater Scrubber-EGR
nssd	0.99	0.99	0.99
Pengine (KW)	-	[15152 14545 1818]	[15152 14545 1818]
EDP*10^8(kJ/h)	-	[1.0934 1.0496 0.1416]	[1.0934 1.0496 0.1416]
$TMHFO_{OP}$*10^3 (tons)	-	2.0846	2.0839
$TMMDO_{OP}$(tons)	-	0	0
SOXOP (tons)	-	83.2054	83.2054
NOXOP (tons)	-	184.8530	184.8530
PMOP (tons)	-	5.4538	5.4538
naux	0.96	0.96	0.96
Pauxdel (KWe)	-	[1406.3 1.026.6 2039.1 2010.9 2010.9 1040.6]	[1406.3 1.026.6 2039.1 2010.9 2010.9 1040.6]
EDA*10^7(kJ/h)	-	[1.1409 0.8329 1.6543 1.6315 1.6315 0.8443]	[1.1409 0.8329 1.6543 1.6315 1.6315 0.8443]
$TMHFO_{AUX}$*10^3 (tons)	-	0	0
$TMMDO_{AUX}$ (tons)	-	1.8115	1.8115
SOX_{AUX} (tons)	-	7.7257	7.7257
NOX_{AUX} (tons)	-	17.0567	17.0567
PM_{AUX} (tons)	-	0.5017	0.5017
$TMHFO_{TOT}$*10^3 (tons)	-	2.0846	2.0839
$TMMDO_{TOT}$ (tons)	-	1.8115	1.8115
CO_2 *10^4 (tons)	-	6.4971	6.4952
SOX_{TOT} (tons)	-	90.9311	90.9311
NOX_{TOT} (tons)	-	201.9097	201.9097
PM_{TOT} (tons)	-	5.9555	5.9555

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Note. In vessel 1 a WHR system is not applied due to its rather low power

Vessel 2

Table 81 Speed and propulsion specifications of Vessel 2

Vessel No.2		
Variable	**Value**	**Unit**
U_{LOAD}	19.5	kn
U_{UNLOAD}	19.5	kn
C	145000	m^3
Pumping Capacity	1700	m^3/h
P_{PROP}	[29052 27889.92 3486.24]	kW
P_{AUX}	[2124 1550.52 3079.8 3037.32 3037.32 1571.76]	kWe

Table 82 Times of the discrete operational phases of Vessel 2

t_1	329.79
t_2	357.28
t_3	1
t_4	10.66
t_5	10.66
t_6	48
t_7	19.54
t_8	21.17

Table 83 VBOG rates of the discrete operational phases of Vessel 2 [m^3/h]

Loaded	7.14
Baliast	3.57
Manoeuvring	5.95
Loading	4.76
Unloading	0
Residual Time	5.95

Table 84 Fuel consumption and air pollutants from main propulsion engines for Vessel 2

ST	nst	0.9702
	Pengine (KW)	[29944 28747 3593]
	EDP*10^8(kJ/h)	[3.2260 3.0969 0.4177]
	$TMHFO_{OP}$*10^3 (tons)	2.9051
	$TMLNG_{OP}$*10^3 (tons)	2.0489
	SOX_{OP} (tons)	221.6455
	NOX_{OP} (tons)	20.1496
	PM_{OP} (tons)	50.3740
DFDE	nDFDE	0.9038
	Pengine (KW)	[32143 30858 3857]
	EDP*10^8(kJ/h)	[2.6078 2.5035 0.3377]
	$TMMDO_{OP}$*10^3 (tons)	3.0441
	$TMLNG_{OP}$*10^3 (tons)	1.5228
	SOX_{OP} (tons)	24.8842
	NOX_{OP} (tons)	164.8315
	PM_{OP} (tons)	0.9594
GT	nGT	0.9038
	Pengine (KW)	[3.2143 3.0858 0.3857]
	EDP*10^8(kJ/h)	[2.8411 2.7275 0.3679]
	$TMMGO_{OP}$*10^3 (tons)	3.3165
	$TMLNG_{OP}$*10^3 (tons)	1.6591
	SOX_{OP} (tons)	24.4131
	NOX_{OP} (tons)	176.1388
	PM_{OP} (tons)	0.5825
COGES	nCOGES	0.9038
	Pengine (KW)	[32143 30858 3857]
	EDP*10^8(kJ/h)	[2.4149 2.3184 0.3127]
	$TMMGO_{OP}$*10^3 (tons)	2.8190
	$TMLNG_{OP}$*10^3 (tons)	1.4102
	SOX_{OP} (tons)	24.4131
	NOX_{OP} (tons)	176.1388
	PM_{OP} (tons)	0.5825

Table 85 Fuel consumption and air pollutants from auxiliary engines for Vessel 2

ST	naux	0.96
	Pauxdel (KWe)	[2.2125 1.6151 3.2081 3.1639 3.1639 1.6373]
	EDA*10^7(kJ/h)	[2.5922 1.8923 3.7586 3.7068 3.7068 1.9182]
	$TMHFO_{AUX}$ (tons)	213.8989
	$TMLNG_{AUX}$ (tons)	176.6510
	SOX_{AUX} (tons)	4.5281
	NOX_{AUX} (tons)	8.1244
	PM_{AUX} (tons)	0.2766
DFDE	naux	0.97
	Pauxdel (KWe)	[2.1897 1.5985 3.1751 3.1313 3.1313 1.6204]
	EDA*10^7(kJ/h)	[1.7765 1.2968 2.5759 2.5404 2.5404 1.3146]
	$TMMDO_{AUX}$ (tons)	222.8380
	$TMLNG_{AUX}$ (tons)	115.1425
	SOX_{AUX} (tons)	1.4955
	NOX_{AUX} (tons)	10.0499
	PM_{AUX} (tons)	0.0647
GT	naux	0.97
	Pauxdel (KWe)	[2.1897 1.5985 3.1751 3.1313 3.1313 1.6204]
	EDA*10^7(kJ/h)	[1.6808 1.2270 2.4372 2.4036 2.4036 1.243]
	$TMMGO_{AUX}$ (tons)	210.8351
	$TMLNG_{AUX}$ (tons)	108.9404
	SOX_{AUX} (tons)	1.4600
	NOX_{AUX} (tons)	10.9039
	PM_{AUX} (tons)	0.0363
COGES	naux	0.97
	Pauxdel (KWe)	[2189.7 1598.5 3175.1 3131.3 3131.3 1620.4]
	EDA*10^7(kJ/h)	[1.6808 1.2270 2.4372 2.4036 2.4036 1.2438]
	$TMMGO_{AUX}$ (tons)	210.8351
	$TMLNG_{AUX}$ (tons)	108.9404
	SOX_{AUX} (tons)	1.4600
	NOX_{AUX} (tons)	10.9039
	PM_{AUX} (tons)	0.0363

Table 86 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 2.

ST	$TMHFO_{TOT}$*10^3 (tons)	3.1189
	$TMLNG_{TOT}$*10^3 (tons)	2.2256
	CO_2*10^4 (tons)	1.5833
	SOX_{TOT} (tons)	226.1736
	NOX_{TOT} (tons)	28.2740
	PM_{TOT} (tons)	50.6506
DFDE	$TMMDO_{TOT}$*10^3 (tons)	3.2670
	$TMLNG_{TOT}$*10^3 (tons)	1.6380
	CO_2*10^4 (tons)	1.4978
	(Methane slip)CO_2*10^3 (tons)	1.7691
	SOX_{TOT} (tons)	26.3798
	NOX_{TOT} (tons)	174.8814
	PM_{TOT} (tons)	1.0241
GT	$TMMGO_{TOT}$*10^3 (tons)	3.5273
	$TMLNG_{TOT}$*10^3 (tons)	1.7680
	CO_2 *10^4(tons)	1.6171
	SOX_{TOT} (tons)	25.8731
	NOX_{TOT} (tons)	187.0427
	PM_{TOT} (tons)	0.6188
COGES	$TMMGO_{TOT}$*10^3 (tons)	3.0299
	$TMLNG_{TOT}$*10^3 (tons)	1.5192
	CO_2 *10^4 (tons)	1.3891
	SOX_{TOT} (tons)	25.8731
	NOX_{TOT} (tons)	187.0427
	PM_{TOT} (tons)	0.6188

Table 87 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 2, equipped with SSD with Seawater Scrubber, Freshwater Scrubber and WHR.

	Seawater	**Freshwater**	**WHR**
nssd	0.99	0.99	0.99
Pengine (KW)	[29345 28172 3521]	[29345 28172 3521]	[29698 28510 3521]
EDP*10^8(kJ/h)	[2.1177 2.0329 0.2742]	[2.1177 2.0329 0.2742]	[2.1431 2.0573 0.2742]
WHRE (kW)	0	0	[2641.1 2535.4 0]
TMHFO$_{OP}$*10^3 (tons)	3.6053	3.6043	3.5714
TMMDO$_{OP}$ (tons)	0	0	0
SOX$_{OP}$ (tons)	143.9187	143.9187	149.8500
NOX$_{OP}$ (tons)	335.6922	335.6922	339.7198
PM$_{OP}$ (tons)	9.4334	9.4334	9.9918
naux	0.96	0.96	0.96
Pauxdel (KWe)	[2212.5 1615.1 3208.1 3163.9 3163.9 1637.3]	[2212.5 1615.1 3208.1 3163.9 3163.9 1637.3]	0
EDA*10^7(kJ/h)	[1.7950 1.3104 2.6028 2.5669 2.5669 1.3283]	[1.7950 1.3104 2.6028 2.5669 2.5669 1.3283]	[1.7950 1.3104 2.6028 2.5669 2.5669 1.3283]
TMMDO$_{AUX}$*(tons)	2.8500	2.8500	0
SOX$_{AUX}$ (tons)	11.2111	11.2111	0
NOX$_{AUX}$ (tons)	24.7517	24.7517	0
PM$_{AUX}$ (tons)	0.7280	0.7280	0
TMHFO$_{TOT}$ *10^3 (tons)	3.6053	3.6043	3.5714
TMMDO$_{TOT}$(tons)	2.8500	2.8500	0
CO$_2$ *10^4 (tons)	1.1236	1.1233	1.1121
SOX$_{TOT}$ (tons)	155.1297	155.1297	149.8500
NOX$_{TOT}$ (tons)	360.4439	360.4439	339.7198
PM$_{TOT}$ (tons)	10.1613	10.1613	9.9918

Table 88 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 2, equipped with SSD with EGR and SCR systems burning MDO when operating in SECA.

	EGR	SCR
nssd	0.99	0.99
Pengine (KW)	[29345 28172 3521]	[2.934.5 2817.2 3521]
EDP*10^8(kJ/h)	[2.1177 2.0329 0.2742]	[2.1177 2.0329 0.2742]
TMHFO$_{OP}$*10^3 (tons)	3.3176	3.3176
TMMDO$_{OP}$ (tons)	198.3155	198.3155
SOX$_{OP}$ (tons)	152.0488	152.0488
NOX$_{OP}$ (tons)	67.1384	67.1384
PM$_{OP}$ (tons)	9.8733	9.8733
naux	0.96	0.96
Pauxdel (KWe)	[2212.5 1615.1 3208.1 3163.9 3163.9 1637.3]	[2212.5 1615.1 3208.1 3163.9 3163.9 1637.3]
EDA*10^7(kJ/h)	[1.7950 1.3104 2.6028 2.5669 2.5669 1.3283]	[1.7950 1.3104 2.6028 2.5669 2.5669 1.3283]
TMMDO$_{AUX}$*10^3 (tons)	2.8500	2.8500
SOX$_{AUX}$ (tons)	11.2111	11.2111
NOX$_{AUX}$ (tons)	24.7517	24.7517
PM$_{AUX}$ (tons)	0.7280	0.7280
TMHFO$_{TOT}$*10^3 (tons)	3.3176	3.3176
TMMDO$_{TOT}$*10^3 (tons)	201.1656	201.1656
CO$_2$ *10^4 (tons)	1.0976	1.0976
SOX$_{TOT}$ (tons)	163.2599	163.2599
NOX$_{TOT}$ (tons)	91.8901	91.8901
PM$_{TOT}$ (tons)	10.6013	10.6013

Table 89 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 2, for the three selected means for complying with the ECA regulations.

	MDO-WHR-SCR	Seawater Scrubber-EGR	Freshwater Scrubber-EGR
nssd	0.99	0.99	0.99
Pengine (KW)	[29698 28510 3521]	[29345 28172 3521]	[29345 28172 3521]
EDP*10^8(kJ/h)	[2.1431 2.0573 0.2742]	[2.1177 2.0329 0.2742]	[2.1177 2.0329 0.2742]
$TMHFO_{OP}$*10^3 (tons)	3.3574	3.6053	3.6043
$TMMDO_{OP}$ (tons)	200.6876	0	0
SOX_{OP} (tons)	147.1059	143.9187	143.9187
NOX_{OP} (tons)	324.0049	319.7369	319.7369
PM_{OP} (tons)	9.4456	9.4334	9.4334
naux	0.96	0.96	0.96
Pauxdel (KWe)	0	[2212.5 1615.1 3208.1 3163.9 3163.9 1637.3]	[2212.5 1615.1 3208.1 3163.9 3163.9 1637.3]
EDA*10^7(kJ/h)	[1.7950 1.3104 2.6028 2.5669 2.5669 1.3283]	[1.7950 1.3104 2.6028 2.5669 2.5669 1.3283]	[1.7950 1.3104 2.6028 2.5669 2.5669 1.3283]
$TMHFO_{AUX}$ (tons)	0	0	0
$TMMDO_{AUX}$ (tons)	0	2.8501	2.8501
SOX_{AUX} (tons)	0	11.2111	11.2111
NOX_{AUX} (tons)	0	24.7517	24.7517
PM_{AUX} (tons)	0	0.7280	0.7280
$TMHFO_{TOT}$*10^3 (tons)	3.3574	3.6053	3.6043
$TMMDO_{TOT}$ (tons)	200.6876	2.8501	2.8501
CO_2 *10^4 (tons)	1.1107	1.1236	1.1233
SOX_{TOT} (tons)	147.1059	155.1297	155.1297
NOX_{TOT} (tons)	324.0049	344.4886	344.4886
PM_{TOT} (tons)	9.4456	10.1613	10.1613

Vessel 3

Table 90 Speed and propulsion specifications of Vessel 3

Vessel No.3		
Variable	**Value**	**Unit**
U_{LOAD}	19	kn
U_{UNLOAD}	19	kn
C	146791	m^3
Pumping Capacity	1700	m^3/h
P_{PROP}	[29420 28243.2 3530.4]	kW
P_{AUX}	[2647.8 1932.84 3839.31 3786.35 3786.35 1959.37]	kWe

Table 91 Times of the discrete operational phases of Vessel 3

t_1	338.47
t_2	357.28
t_3	1
t_4	10.79
t_5	10.79
t_6	48
t_7	20.05
t_8	21.17

Table 92 VBOG rates of the discrete operational phases of Vessel 3 [m^3/h]

Loaded	7.23
Baliast	3.62
Manoeuvring	6.03
Loading	4.82
Unloading	0
Residual Time	6.03

Table 93 Fuel consumption and air pollutants from main propulsion engines for Vessel 3

ST	nst	0.9702
	Pengine (KW)	[30324 29111 3639]
	EDP(with reheater)*10^8(kJ/h)	[3.2668 3.1362 0.4230]
	TMHFO$_{OP}$*10^3 (tons)	2.9798
	TMLNG$_{OP}$*10^3 (tons)	2.1011
	SOX$_{OP}$ (tons)	227.3480
	NOX$_{OP}$ (tons)	20.6680
	PM$_{OP}$ (tons)	51.6700
DFDE	nDFDE	0.9038
	Pengine (KW)	[32550 31248 3906]
	EDP*10^8(kJ/h)	[2.6408 2.5352 0.3419]
	TMMDO$_{OP}$*10^3 (tons)	3.1132
	TMLNG$_{OP}$*10^3 (tons)	1.5620
	SOX$_{OP}$ (tons)	25.5245
	NOX$_{OP}$ (tons)	169.0726
	PM$_{OP}$ (tons)	0.9841
GT	nGT	0.9038
	Pengine (KW)	[32550 31248 3906]
	EDP*10^8(kJ/h)	[2.8771 2.7620 0.3725]
	TMMGO$_{OP}$*10^3 (tons)	3.3917
	TMLNG$_{OP}$*10^3 (tons)	1.7018
	SOX$_{OP}$ (tons)	25.0413
	NOX$_{OP}$ (tons)	180.6707
	PM$_{OP}$ (tons)	0.5975
COGES	nCOGES	0.9038
	Pengine (KW)	[3.2550 3.1248 0.3906]
	EDP*10^8(kJ/h)	[2.4455 2.3477 0.3166]
	TMHFO$_{OP}$*10^3 (tons)	2.8830
	TMLNG$_{OP}$*10^3 (tons)	1.4465
	SOX$_{OP}$ (tons)	25.0413
	NOX$_{OP}$ (tons)	180.6707
	PM$_{OP}$ (tons)	0.5975

Table 94 Fuel consumption and air pollutants from auxiliary engines for Vessel 3

ST	naux	0.96
	Pauxdel (KWe)	[2758.1 2013.4 3999.3 3944.1 3944.1 2041.0]
	EDA*10^7(kJ/h)	[3.2314 2.3589 4.6856 4.6209 4.6209 2.3912]
	$TMHFO_{AUX}$ (tons)	270.5635
	$TMLNG_{AUX}$ (tons)	223.0490
	SOX_{AUX} (tons)	5.7224
	NOX_{AUX} (tons)	10.2672
	PM_{AUX} (tons)	0.3496
DFDE	naux	0.97
	Pauxdel (KWe)	[2729.7 1992.6 3958.1 3903.5 3903.5 2020.0]
	EDA*10^7(kJ/h)	[2.2146 1.6166 3.2112 3.1669 3.1669 1.6388]
	$TMMDO_{AUX}$ (tons)	281.8708
	$TMLNG_{AUX}$ (tons)	145.3717
	SOX_{AUX} (tons)	1.8916
	NOX_{AUX} (tons)	12.7089
	PM_{AUX} (tons)	0.0818
GT	naux	0.97
	Pauxdel (KWe)	[2729.7 1992.6 3958.1 3903.5 3903.5 2020.0]
	EDA*10^8(kJ/h)	[2.0953 1.5295 3.0382 2.9963 2.9963 1.5505]
	$TMMGO_{AUX}$ (tons)	266.6881
	$TMLNG_{AUX}$ (tons)	137.5414
	SOX_{AUX} (tons)	1.8467
	NOX_{AUX} (tons)	13.7860
	PM_{AUX} (tons)	0.0459
COGES	naux	0.97
	Pauxdel (KWe)	[2729.7 1992.6 3958.1 3903.5 3903.5 2020.0]
	EDA*10^8(kJ/h)	[2.0953 1.5295 3.0382 2.9963 2.9963 1.5505]
	$TMMGO_{AUX}$ (tons)	266.6881
	$TMLNG_{AUX}$ (tons)	137.5414
	SOX_{AUX} (tons)	1.8467
	NOX_{AUX} (tons)	13.7860
	PM_{AUX} (tons)	0.0459

Table 95 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 3.

ST	TMHFO$_{TOT}$*10^3 (tons)	3.2504
	TMLNG$_{TOT}$*10^3 (tons)	2.3241
	CO_2 *10^4 (tons)	1.6513
	SOX$_{TOT}$ (tons)	233.0704
	NOX$_{TOT}$ (tons)	30.9352
	PM$_{TOT}$ (tons)	52.0196
DFDE	TMMDO$_{TOT}$*10^3 (tons)	3.3951
	TMLNG$_{TOT}$*10^3 (tons)	1.7074
	CO_2 *10^4 (tons)	1.5580
	(Methane Slip)CO_2 *10^4 (tons)	1.8407
	SOX$_{TOT}$ (tons)	27.4161
	NOX$_{TOT}$ (tons)	181.7815
	PM$_{TOT}$ (tons)	1.0659
GT	TMMGO$_{OT}$*10^3 (tons)	3.6584
	TMLNG$_{TOT}$*10^3 (tons)	1.8393
	CO_2 *10^4 (tons)	1.6787
	SOX$_{TOT}$ (tons)	26.8880
	NOX$_{TOT}$ (tons)	194.4568
	PM$_{TOT}$ (tons)	0.6434
COGES	TMMGO$_{TOT}$*10^3 (tons)	3.1497
	TMLNG$_{TOT}$*10^3 (tons)	1.5840
	CO_2 *10^4 (tons)	1.4454
	SOX$_{TOT}$ (tons)	26.8880
	NOX$_{TOT}$ (tons)	194.4568
	PM$_{TOT}$ (tons)	0.6434

Table 96 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 3, equipped with SSD with Seawater Scrubber, Freshwater Scrubber and WHR

	Seawater	**Freshwater**	**WHR**
nssd	0.99	0.99	0.99
Pengine	[29717 28528 3566]	[29717 28528 3566]	[30074 28871 3566]
EDP*10^8(kJ/h)	[2.1445 2.0587 0.2777]	[2.1445 2.0587 0.2777]	[2.1702 2.0834 0.2777]
WHRE *10^3(kJ/h)	0	0	[2.6745 2.5676 0]
$TMHFO_{OP}$*10^3 (tons)	3.6971	3.6960	3.6613
$TMMDO_{OP}$ (tons)	0	0	0
SOX_{OP} (tons)	147.6217	147.6217	153.75
NOX_{OP} (tons)	344.3289	344.3289	348.5
PM_{OP} (tons)	9.6761	9.6761	10.2488
naux	0.96	0.96	0.96
Pauxdel (KWe)	[2758.1 2013.4 3999.3 3944.1 3944.1 2041.0]	[2758.1 2013.4 3999.3 3944.1 3944.1 2041.0]	0
EDA*10^7(kJ/h)	[2.2377 1.6335 3.2446 3.1999 3.1999 1.6559]	[2.2377 1.6335 3.2446 3.1999 3.1999 1.6559]	[2.2374 1.6332 3.2446 3.1999 3.1999 1.6559]
$TMMDO_{AUX}$ (tons)	3.5530	3.5530	0
SOX_{AUX} (tons)	14.1680	14.1680	0
NOX_{AUX} (tons)	31.2799	31.2799	0
PM_{AUX} (tons)	0.9200	0.9200	0
$TMHFO_{TOT}$ (tons)	3.6971	3.6960	3.6613
$TMMDO_{TOT}$(tons)	3.5530	3.5530	0
CO_2 *10^4 (tons)	1.1524	1.1521	1.1401
SOX_{TOT} (tons)	161.7896	161.7896	157.8319
NOX_{TOT} (tons)	375.6088	375.6088	348.4601
PM_{TOT} (tons)	10.5961	10.5961	10.2488

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Table 97 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 3, equipped with SSD with EGR and SCR systems burning MDO when operating in SECA.

	EGR	SCR
nssd	0.99	0.99
Pengine (KW)	[2971.7 2852.8 3566]	[2971.7 2852.8 3566]
EDP*10^8(kJ/h)	[2.1445 2.0587 0.2777]	[2.1445 2.0587 0.2777]
$TMHFO_{OP}$*10^3 (tons)	3.4030	3.4030
$TMMDO_{OP}$ (tons)	203.4098	203.4098
SOX_{OP} (tons)	155.9607	155.9607
NOX_{OP} (tons)	68.8658	68.8658
PM_{OP} (tons)	10.1273	10.1273
naux	0.96	0.96
Pauxdel (KWe)	[2758.1 2013.4 3999.3 3944.1 3944.1 2041.0]	[2758.1 2013.4 3999.3 3944.1 3944.1 2041.0]
EDA*10^7(kJ/h)	[2.2377 1.6335 3.2446 3.1999 3.1999 1.6559]	[2.2377 1.6335 3.2446 3.1999 3.1999 1.6559]
$TMMDO_{AUX}$*10^3 (tons)	3.5530	3.5530
SOX_{AUX} (tons)	14.1680	14.1680
NOX_{AUX} (tons)	31.2799	31.2799
PM_{AUX} (tons)	0.9200	0.9200
$TMHFO_{TOT}$*10^3 (tons)	3.4030	3.4030
$TMMDO_{TOT}$*10^3 (tons)	206.9628	206.9628
CO_2 *10^4 (tons)	1.1260	1.1260
SOX_{TOT} (tons)	170.1287	170.1287
NOX_{TOT} (tons)	100.1457	100.1457
PM_{TOT} (tons)	11.0473	11.0473

Table 98 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 3, for the three selected means for complying with the ECA regulations.

	MDO-WHR-SCR	Seawater Scrubber-EGR	Freshwater Scrubber-EGR
nssd	0.99	0.99	0.99
Pengine (KW)	[3.0074 2.8871 0.3566]	[29717 28528 3566]	[29717 28528 3566]
EDP*10^8(kJ/h)	[2.1702 2.0834 0.2777]	[2.1445 2.0587 0.2777]	[2.1445 2.0587 0.2777]
TMHFO$_{OP}$*10^3 (tons)	3.4438	3.6971	3.6960
TMMDO$_{OP}$ (tons)	205.8429	0	0
SOX$_{OP}$ (tons)	150.8909	147.6217	147.6217
NOX$_{OP}$ (tons)	332.3219	327.9636	327.9636
PM$_{OP}$ (tons)	9.6887	9.6761	9.6761
naux	0.96	0.96	0.96
Pauxdel (KWe)	0	[2758.1 2013.4 3999.3 3944.1 3944.1 2041.0]	[2758.1 2013.4 3999.3 3944.1 3944.1 2041.0]
EDA*10^7(kJ/h)	[2.2377 1.6335 3.2446 3.1999 3.1999 1.6559]	[2.2377 1.6335 3.2446 3.1999 3.1999 1.6559]	[2.2377 1.6335 3.2446 3.1999 3.1999 1.6559]
TMHFO$_{AUX}$*10^3 (tons)	0	0	0
TMMDO$_{AUX}$(tons)	0	3.5530	3.5530
SOX$_{AUX}$ (tons)	0	14.1680	14.1680
NOX$_{AUX}$ (tons)	0	31.2799	31.2799
PM$_{AUX}$ (tons)	0	0.9200	0.9200
TMHFO$_{TOT}$*10^3 (tons)	3.4438	3.6971	3.6960
TMMDO$_{TOT}$ (tons)	205.8429	3.5530	3.5530
CO$_2$ *10^4 (tons)	1.1395	1.1524	1.1521
SOX$_{TOT}$ (tons)	150.8909	161.7896	161.7896
NOX$_{TOT}$ (tons)	332.3219	359.2436	359.2436
PM$_{TOT}$ (tons)	9.6887	10.5961	10.5961

Vessel 4

Table 99 Speed and propulsion specifications of Vessel 4

Vessel No.4		
Variable	**Value**	**Unit**
U_{LOAD}	19.5	kn
U_{UNLOAD}	19.5	kn
C	173870	m^3
Pumping Capacity	1700	m^3/h
P_{PROP}	[39900 38304 4788]	kW
P_{AUX}	[3591 2621.43 5206.95 5135.13 5135.13 2657.34]	kWe

Table 100 Times of the discrete operational phases of Vessel 4

t_1	329.79
t_2	357.28
t_3	1
t_4	12.78
t_5	12.78
t_6	48
t_7	19.54
t_8	21.17

Table 101 VBOG rates of the discrete operational phases of Vessel 4 [m^3/h]

Loaded	8.56
Baliast	4.28
Manoeuvring	7.14
Loading	5.71
Unloading	0
Residual Time	7.14

Table 102 Fuel consumption and air pollutants from main propulsion engines for Vessel 4

ST	nst	0.9702
	Pengine (KW)	[41126 39481 4935]
	EDP(withreheater)*10^8(kJ/h)	[4.4305 4.2533 0.5737]
	$TMHFO_{OP}$*10^3 (tons)	3.9898
	$TMLNG_{OP}$*10^3 (tons)	2.8140
	SOX_{OP} (tons)	304.4078
	NOX_{OP} (tons)	27.6734
	PM_{OP} (tons)	69.1836
DFDE	nDFDE	0.9038
	Pengine (KW)	[44146 42380 5297]
	EDP*10^8(kJ/h)	[3.5815 3.4383 0.4637]
	$TMMDO_{OP}$*10^3 (tons)	4.1808
	$TMLNG_{OP}$*10^3 (tons)	2.0915
	SOX_{OP} (tons)	34.1760
	NOX_{OP} (tons)	226.3795
	PM_{OP} (tons)	1.3176
GT	nGT	0.9038
	Pengine (KW)	[44146 42380 5297]
	EDP*10^8(kJ/h)	[3.9020 3.7459 0.5052]
	$TMMGO_{OP}$*10^3 (tons)	4.5549
	$TMLNG_{OP}$*10^3 (tons)	2.2786
	SOX_{OP} (tons)	33.5289
	NOX_{OP} (tons)	241.9089
	PM_{OP} (tons)	0.8000
COGES	nCOGES	0.9038
	Pengine (KW)	[44146 42380 5297]
	EDP*10^8(kJ/h)	[3.3167 3.1840 0.4294]
	$TMMGO_{OP}$*10^3 (tons)	3.8716
	$TMLNG_{OP}$*10^3 (tons)	1.9368
	SOX_{OP} (tons)	33.5289
	NOX_{OP} (tons)	241.9089
	PM_{OP} (tons)	0.8000

Table 103 Fuel consumption and air pollutants from auxiliary engines for Vessel 4

ST	naux	0.96
	Pauxdel (KWe)	[3740.6 2730.7 5423.9 5349.1 5349.1 2768.1]
	EDA*10^7(kJ/h)	[4.3825 3.1992 6.3546 6.2670 6.2670 3.2431]
	$\text{TMHFO}_{\text{AUX}}$ (tons)	361.6341
	$\text{TMLNG}_{\text{AUX}}$ (tons)	304.0135
	SOX_{AUX} (tons)	7.7262
	NOX_{AUX} (tons)	13.8624
	PM_{AUX} (tons)	0.4720
DFDE	naux	0.97
	Pauxdel (KWe)	[3702.1 2702.5 5368.0 5293.9 5293.9 2739.5]
	EDA*10^7(kJ/h)	[3.0035 2.1925 4.3551 4.2950 4.2950 2.2226]
	$\text{TMMDO}_{\text{AUX}}$ (tons)	376.7474
	$\text{TMLNG}_{\text{AUX}}$ (tons)	198.3378
	SOX_{AUX} (tons)	2.5295
	NOX_{AUX} (tons)	17.0188
	PM_{AUX} (tons)	0.1106
GT	naux	0.97
	Pauxdel (KWe)	[3702.1 2702.5 5368.0 5293.9 5293.9 2739.5]
	EDA*10^7(kJ/h)	[2.8417 2.0744 4.1205 4.0636 4.0636 2.1029]
	$\text{TMMGO}_{\text{AUX}}$ (tons)	356.4542
	$\text{TMLNG}_{\text{AUX}}$ (tons)	187.6545
	SOX_{AUX} (tons)	2.4683
	NOX_{AUX} (tons)	18.4881
	PM_{AUX} (tons)	0.0616
COGES	naux	0.97
	Pauxdel (KWe)	[3.7021 2.7025 5.3680 5.2939 5.2939 2.7395]
	EDA*10^7(kJ/h)	[2.8417 2.0744 4.1205 4.0636 4.0636 2.1029]
	$\text{TMMGO}_{\text{AUX}}$ (tons)	356.4542
	$\text{TMLNG}_{\text{AUX}}$ (tons)	187.6545
	SOX_{AUX} (tons)	2.4683
	NOX_{AUX} (tons)	18.4881
	PM_{AUX} (tons)	0.0616

Table 104 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 4.

ST	$TMHFO_{TOT}$*10^3 (tons)	4.3514
	$TMLNG_{TOT}$ *10^3 (tons)	3.1180
	CO_2 *10^4 (tons)	2.2125
	SOX_{TOT} (tons)	312.1340
	NOX_{TOT} (tons)	41.5359
	PM_{TOT} (tons)	69.6556
DFDE	$TMMDO_{TOT}$*10^3 (tons)	4.5575
	$TMLNG_{TOT}$*10^3 (tons)	2.2898
	CO_2 *10^4 (tons)	2.0908
	(Methane Slip)CO_2 *10^4 (tons	2.4700
	SOX_{TOT} (tons)	36.7055
	NOX_{TOT} (tons)	243.3982
	PM_{TOT} (tons)	1.4282
GT	$TMMGO_{TOT}$*10^3 tons	4.9113
	$TMLNG_{TOT}$*10^3 tons	2.4662
	CO_2 *10^4 tons	2.2528
	SOX_{TOT} (tons)	35.9973
	NOX_{TOT} (tons)	260.3970
	PM_{TOT} (tons)	0.8616
COGES	$TMMGO_{TOT}$*10^3 (tons)	4.2281
	$TMLNG_{TOT}$*10^3 (tons)	2.1245
	CO_2*10^4 (tons)	1.9398
	SOX_{TOT} (tons)	35.9973
	NOX_{TOT} (tons)	260.3970
	PM_{TOT} (tons)	0.8616

Table 105 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 4, equipped with SSD with Seawater Scrubber, Freshwater Scrubber and WHR.

	Seawater	Freshwater	WHR
nssd	0.99	0.99	0.99
Pengine	[40303 38691 4836]	[40303 38691 4836]	[40787 39155 4836]
EDP*10^8(kJ/h)	[2.9084 2.7921 0.3766]	[2.9084 2.7921 0.3766]	[2.9433 2.8256 0.3766]
WHRE *10^3(kJ/h)	0	0	[3.6273 3.4822 0]
$TMHFO_{OP}$*10^3 (tons)	4.9516	4.9501	4.9024
$TMMDO_{OP}$ (tons)	0	0	275.6242
SOX_{OP} (tons)	197.6578	197.6578	211.3292
NOX_{OP} (tons)	461.0395	461.0395	466.5710
PM_{OP} (tons)	12.9558	12.9558	13.7227
naux	0.96	0.96	0.96
Pauxdel (KWe)	[3740.6 2730.7 5423.9 5349.1 5349.1 2768.1]	[3740.6 2730.7 5423.9 5349.1 5349.1 2768.1]	0
EDA*10^7(kJ/h)	[3.0348 2.2154 4.4004 4.3397 4.3397 2.2457]	[3.0348 2.2154 4.4004 4.3397 4.3397 2.2457]	[3.0348 2.2154 4.4004 4.3397 4.3397 2.2457]
$TMMDO_{AUX}$ (tons)	4.8187	4.8187	0
SOX_{AUX} (tons)	19.1291	19.1291	0
NOX_{AUX} (tons)	42.2332	42.2332	0
PM_{AUX} (tons)	1.2422	1.2422	0
$TMHFO_{TOT}$ (tons)	4.9516	4.9501	4.9024
$TMMDO_{TOT}$(tons)	4.8187	4.8187	0
CO_2 *10^4 (tons)	1.5435	1.5430	1.5266
SOX_{TOT} (tons)	216.7869	216.7869	211.3292
NOX_{TOT} (tons)	503.2727	503.2727	466.5710
PM_{TOT} (tons)	14.1979	14.1979	13.7227

Table 106 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 4, equipped with SSD with EGR and SCR systems burning MDO when operating in SECA.

	EGR	SCR
nssd	0.99	0.99
Pengine	[40303 38691 4836]	[40303 38691 4836]
EDP*10^8(kJ/h)	[2.9084 2.7921 0.3766]	[2.9084 2.7921 0.3766]
$TMHFO_{OP}$*10^3 (tons)	4.9501	4.9501
$TMLNG_{OP}$ (tons)	0	0
SOX_{OP} (tons)	208.8238	208.8238
NOX_{OP} (tons)	441.8945	441.8945
PM_{OP} (tons)	13.5600	13.5600
naux	0.96	0.96
Pauxdel (KWe)	[3740.6 2730.7 5423.9 5349.1 5349.1 2.768.1]	[3740.6 2730.7 5423.9 5349.1 5349.1 2.768.1]
EDA*10^7(kJ/h)	3.0348 2.2154 4.4004 4.3397 4.3397 2.2457	3.0348 2.2154 4.4004 4.3397 4.3397 2.2457
$TMHFO_{AUX}$ (tons)	0	0
$TMMDO_{AUX}$ (tons)	4.8187	4.8187
SOX_{AUX} (tons)	19.1291	19.1291
NOX_{AUX} (tons)	42.2332	42.2332
PM_{AUX} (tons)	1.2422	1.2422
$TMHFO_{TOT}$*10^4 (tons)	4.9501	4.9501
$TMMDO_{TOT}$ (tons)	4.8187	4.8187
CO_2 *10^3 (tons)	1.5416	1.5416
SOX_{TOT} (tons)	227.9529	227.9529
NOX_{TOT} (tons)	484.1277	484.1277
PM_{TOT} (tons)	14.8022	14.8022

Table 107 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 4, for the three selected means for complying with the ECA regulations.

	MDO-WHR-SCR	**Seawater Scrubber-EGR**	**Freshwater Scrubber-EGR**
nssd	0.99	0.99	0.99
Pengine (KW)	[4.0787 3.9155 0.4836]	[40303 38691 4836]	[40303 38691 4836]
EDP*10^8(kJ/h)	[2.9433 2.8256 0.3766]	[2.9084 2.7921 0.3766]	[2.9084 2.7921 0.3766]
$TMHFO_{OP}$*10^3 (tons)	4.6111	4.9516	4.9501
$TMMDO_{OP}$(tons)	275.6242	0	0
SOX_{OP} (tons)	202.0352	197.6578	203.40
NOX_{OP} (tons)	444.9882	439.1265	461.04
PM_{OP} (tons)	12.9726	12.9558	13.56
naux	0.96	0.96	0.96
Pauxdel (KWe)	0	[3740.6 2730.7 5423.9 5349.1 5349.1 2768.1]	[3740.6 2730.7 5423.9 5349.1 5349.1 2768.1]
EDA*10^7(kJ/h)	[3.0348 2.2154 4.4004 4.3397 4.3397 2.2457]	[3.0348 2.2154 4.4004 4.3397 4.3397 2.2457]	[3.0348 2.2154 4.4004 4.3397 4.3397 2.2457]
$TMHFO_{AUX}$ (tons)	0	0	0
$TMMDO_{AUX}$ (tons)	0	4.8187	4.8187
SOX_{AUX} (tons)	0	19.1291	19.1291
NOX_{AUX} (tons)	0	42.2332	42.2332
PM_{AUX} (tons)	0	1.2422	1.2422
$TMHFO_{TOT}$*10^3 (tons)	4.6111	4.9516	4.9516
$TMMDO_{TOT}$ (tons)	275.6242	4.8187	4.8187
CO_2 *10^4 (tons)	1.5258	1.5435	1.5430
SOX_{TOT} (tons)	202.0352	216.7869	203.40
NOX_{TOT} (tons)	444.9882	481.3596	461.04
PM_{TOT} (tons)	12.9726	14.1979	13.56

Vessel 5

Table 108 Speed and propulsion specifications of Vessel 5

Vessel No.5		
Variable	**Value**	**Unit**
U_{LOAD}	19.5	kn
U_{UNLOAD}	19.5	kn
C	211862	m^3
Pumping Capacity	1700	m^3/h
P_{PROP}	[37320 35827.2 4478.4]	kW
P_{AUX}	[3358.8 2451.42 4870.26 4803.08 4803.08 2485.51]	kWe

Table 109 Times of the discrete operational phases of Vessel 5

t_1	329.79
t_2	357.28
t_3	1
t_4	12.78
t_5	12.78
t_6	48
t_7	19.54
t_8	21.17

Table 110 VBOG rates of the discrete operational phases of Vessel 5 [m^3/h]

Loaded	10.43
Baliast	5.22
Manoeuvring	8.70
Loading	6.96
Unloading	0
Residual Time	8.70

Table 111 Fuel consumption and air pollutants from main propulsion engines for Vessel 5

ST	nst	0.9702
	Pengine (KW)	[38466 36928 4616]
	EDP(withreheat)*10^8(kJ/h)	[4.1441 3.9783 0.5366]
	$TMHFO_{OP}$*10^3 (tons)	3.7318
	$TMLNG_{OP}$*10^3 (tons)	2.6320
	SOX_{OP} (tons)	284.7243
	NOX_{OP} (tons)	25.8840
	PM_{OP} (tons)	64.7101
DFDE	nDFDE	0.9038
	Pengine (KW)	[41291 39639 4955]
	EDP*10^8(kJ/h)	[3.3499 3.2159 0.4338]
	$TMMDO_{OP}$*10^3 (tons)	3.9105
	$TMLNG_{OP}$*10^3 (tons)	1.9562
	SOX_{OP} (tons)	31.9661
	NOX_{OP} (tons)	211.7414
	PM_{OP} (tons)	1.2324
GT	nGT	0.9038
	Pengine (KW)	[41291 39639 4955]
	EDP*10^8(kJ/h)	[3.6497 3.5037 0.4726]
	$TMMGO_{OP}$*10^3 (tons)	4.2603
	$TMLNG_{OP}$*10^3 (tons)	2.1313
	SOX_{OP} (tons)	31.3609
	NOX_{OP} (tons)	226.2667
	PM_{OP} (tons)	0.7483
COGES	nCOGES	0.9038
	Pengine (KW)	[41291 39639 4955]
	EDP*10^8(kJ/h)	[3.1022 2.9781 0.4017]
	$TMMGO_{OP}$*10^3 (tons)	3.6213
	$TMLNG_{OP}$*10^3 (tons)	1.8116
	SOX_{OP} (tons)	31.3609
	NOX_{OP} (tons)	226.2667
	PM_{OP} (tons)	0.7483

Table 112 Fuel consumption and air pollutants from auxiliary engines for Vessel 5

ST	naux	0.96
	Pauxdel (KWe)	[3.4988 2.5536 5.0732 5.0032 5.0032 2.5891]
	EDA*10^7(kJ/h)	[4.0991 2.9918 5.9437 5.8618 5.8618 3.0334]
	TMHFO$_{AUX}$ (tons)	338.2195
	TMLNGAUX (tons)	290.9247
	SOX$_{AUX}$ (tons)	7.3129
	NOX$_{AUX}$ (tons)	13.1210
	PM$_{AUX}$ (tons)	0.4468
DFDE	naux	0.97
	Pauxdel (KWe)	[3462.7 2527.2 5020.9 4951.6 4951.6 2562.4]
	EDA*10^7(kJ/h)	[2.8093 2.0503 4.0734 4.0173 4.0173 2.0789]
	TMMDO$_{AUX}$ (tons)	352.3543
	TMLNG$_{AUX}$ (tons)	190.0159
	SOX$_{AUX}$ (tons)	2.3671
	NOX$_{AUX}$ (tons)	15.9529
	PM$_{AUX}$ (tons)	0.1048
GT	naux	0.97
	Pauxdel (KWe)	[3462.7 2527.2 5020.9 4951.6 4951.6 2562.4]
	EDA*10^8(kJ/h)	[2.6580 1.9399 3.8540 3.8009 3.8009 1.9669]
	TMMGO$_{AUX}$ (tons)	333.3750
	TMLNG$_{AUX}$ (tons)	179.7808
	SOX$_{AUX}$ (tons)	2.3085
	NOX$_{AUX}$ (tons)	17.3603
	PM$_{AUX}$ (tons)	0.0579
COGES	naux	0.97
	Pauxdel	[3462.7 2527.2 5020.9 4951.6 4951.6 2562.4]
	EDA*10^7(kJ/h)	[2.6580 1.9399 3.8540 3.8009 3.8009 1.9669]
	TMMGO$_{AUX}$ (tons)	333.3750
	TMLNG$_{AUX}$ (tons)	179.7808
	SOX$_{AUX}$ (tons)	2.3085
	NOX$_{AUX}$ (tons)	17.3603
	PM$_{AUX}$ (tons)	0.0579

Table 113 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 5.

ST	$TMHFO_{TOT}$*10^3 (tons)	4.0700
	$TMLNG_{TOT}$*10^3 (tons)	2.9230
	CO_2 *10^4 (tons)	2.0712
	SOX_{TOT} (tons)	292.0373
	NOX_{TOT} (tons)	39.0050
	PM_{TOT} (tons)	65.1568
DFDE	$TMMDO_{TOT}$*10^3 tons	4.2628
	$TMLNG_{TOT}$*10^3 tons	2.1462
	CO_2 *10^4 tons	1.9569
	(Methane Slip)CO_2 *10^4 tons	2.3123
	SOX_{TOT} (tons)	34.3333
	NOX_{TOT} (tons)	227.6943
	PM_{TOT} (tons)	1.3373
GT	$TMMGO_{TOT}$*10^3 (tons)	4.5937
	$TMLNG_{TOT}$*10^3 (tons)	2.3110
	CO_2 *10^4 (tons)	2.1083
	SOX_{TOT} (tons)	33.6694
	NOX_{TOT} (tons)	243.6270
	PM_{TOT} (tons)	0.8062
COGES	$TMMGO_{TOT}$*10^3 (tons)	3.9547
	$TMLNG_{TOT}$*10^3 (tons)	1.9913
	CO_2 *10^3 (tons)	1.8155
	SOX_{TOT} (tons)	33.6694
	NOX_{TOT} (tons)	243.6270
	PM_{TOT} (tons)	0.8062

Table 114 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 5, equipped with SSD with Seawater Scrubber, Freshwater Scrubber and WHR.

	Seawater	**Freshwater**	**WHR**
nssd	0.99	0.99	0.99
Pengine	[3769.7 3618.9 4524]	[3769.7 3618.9 4524]	[38149 36623 4524]
EDP*10^8(kJ/h)	[2.7203 2.6115 0.3522]	[2.7203 2.6115 0.3522]	[2.7530 2.6429 0.3522]
WHRE *10^3(kJ/h)	0	0	[3.3927 3.2570 0]
$TMHFO_{OP}$*10^3 (tons)	4.6314	4.6300	4.5854
$TMMDO_{OP}$ (tons)	0	0	0
SOX_{OP} (tons)	184.8769	184.8769	192.53
NOX_{OP} (tons)	431.2279	431.2279	436.39
PM_{OP} (tons)	12.1180	12.1180	12.84
naux	0.96	0.96	0.96
Pauxdel (KWe)	[3498.8 2553.6 5073.2 5003.2 5003.2 2589.1]	[3498.8 2553.6 5073.2 5003.2 5003.2 2589.1]	0
EDA*10^7(kJ/h)	[2.8385 2.0717 4.1159 4.0591 4.0591 2.1005]	[2.8385 2.0717 4.1159 4.0591 4.0591 2.1005]	[2.8385 2.0717 4.1159 4.0591 4.0591 2.1005]
$TMMDO_{AUX}$ (tons)	4.5070	4.5070	0
SOX_{AUX} (tons)	18.1060	18.1060	0
NOX_{AUX} (tons)	39.9743	39.9743	0
PM_{AUX} (tons)	1.1757	1.1757	0
$TMHFO_{TOT}$ (tons)	4.6314	4.6300	4.5854
$TMMDO_{TOT}$(tons)	4.5070	4.5070	0
CO_2 *10^4 (tons)	1.4437	1.4432	1.4279
SOX_{TOT} (tons)	202.9829	202.9829	192.53
NOX_{TOT} (tons)	471.2022	471.2022	436.39
PM_{TOT} (tons)	13.2937	13.2937	12.84

Table 115 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 5, equipped with SSD with EGR and SCR systems burning MDO when operating in SECA.

	EGR	**SCR**
nssd	0.99	0.99
Pengine	[37697 36189 4524]	[37697 36189 4524]
EDP*10^8(kJ/h)	[2.7203 2.6115 0.3522]	[2.7203 2.6115 0.3522]
$TMHFO_{OP}$*10^3 (tons)	4.6300	4.6300
$TMMDO_{OP}$ (tons)	0	0
SOX_{OP} (tons)	195.3209	195.3209
NOX_{OP} (tons)	413.3209	413.3209
PM_{OP} (tons)	12.6832	12.6832
naux	0.96	0.96
Pauxdel (KWe)	[3498.8 2553.6 5073.2 5003.2 5003.2 2589.1]	[3498.8 2553.6 5073.2 5003.2 5003.2 2589.1]
EDA*10^7(kJ/h)	[2.8385 2.0717 4.1159]	[2.8385 2.0717 4.1159]
$TMHFO_{AUX}$*10^3 (tons)	0	0
$TMMDO_{AUX}$*10^3 (tons)	4.5070	4.5070
SOX_{AUX} (tons)	18.1060	18.1060
NOX_{AUX} (tons)	39.9743	39.9743
PM_{AUX} (tons)	1.1757	1.1757
$TMMGO_{TOT}$*10^3 (tons)	4.6300	4.6300
$TMLNG_{TOT}$*10^3 (tons)	4.5070	4.5070
CO_2 *10^3 (tons)	1.4432	1.4432
SOX_{TOT} (tons)	202.9829	202.9829
NOX_{TOT} (tons)	471.2022	471.2022
PM_{TOT} (tons)	13.2937	13.2937

Table 116 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 5, for the three selected means for complying with the ECA regulations.

	MDO-WHR-SCR	Seawater Scrubber-EGR	Freshwater Scrubber-EGR
nssd	0.99	0.99	0.99
Pengine (KW)	[3.8149 3.6623 0.4524]	[3769.7 3618.9 4524]	[3769.7 3618.9 4524]
EDP*10^8(kJ/h)	[2.7530 2.6429 0.3522]	[2.7203 2.6115 0.3522]	[2.7203 2.6115 0.3522]
TMHFO$_{OP}$*10^3 (tons)	4.3129	4.6314	4.6300
TMMDO$_{OP}$(tons)	257.8019	0	0
SOX$_{OP}$ (tons)	188.9713	184.8769	184.8769
NOX$_{OP}$ (tons)	416.2145	410.7318	410.7318
PM$_{OP}$ (tons)	12.1338	12.1180	12.1180
naux	0.96	0.96	0.96
Pauxdel (KWe)	0	[3498.8 2553.6 5073.2 5003.2 5003.2 2589.1]	[3498.8 2553.6 5073.2 5003.2 5003.2 2589.1]
EDA*10^7(kJ/h)	[2.8385 2.0717 4.1159 4.0591 4.0591 2.1005]	[2.8385 2.0717 4.1159 4.0591 4.0591 2.1005]	[2.8385 2.0717 4.1159 4.0591 4.0591 2.1005]
TMHFO$_{AUX}$*10^3 (tons)	0	0	0
TMMDO$_{AUX}$ (tons)	0	4.5070	4.5070
SOX$_{AUX}$(tons)	0	18.1060	18.1060
NOX$_{AUX}$ (tons)	0	39.9743	39.9743
PM$_{AUX}$ (tons)	0	1.1757	1.1757
TMHFO$_{TOT}$*10^3 (tons)	4.3129	4.6314	4.6300
TMMDO$_{TOT}$ (tons)	257.8019	4.5070	4.5070
CO$_2$ *10^4 (tons)	1.4271	1.4437	1.4432
SOX$_{TOT}$ (tons)	188.9713	202.9829	202.9829
NOX$_{TOT}$ (tons)	416.2145	450.7061	450.7061
PM$_{TOT}$ (tons)	12.1338	13.2937	13.2937

Vessel 6

Table 117 Speed and propulsion specifications of Vessel 6

Vessel No.6		
Variable	**Value**	**Unit**
U_{LOAD}	19.5	kn
U_{UNLOAD}	19.5	kn
C	74245	m^3
Pumping Capacity	1700	m^3/h
P_{PROP}	[38540 36998.4 4624.8]	kW
P_{AUX}	[3468.6 2532.08 5029.47 4960.10 4960.10 2566.76]	kWe

Table 118 Times of the discrete operational phases of Vessel 6

t_1	329.79
t_2	357.28
t_3	1
t_4	12.78
t_5	12.78
t_6	48
t_7	19.54
t_8	21.17

Table 119 VBOG rates of the discrete operational phases of Vessel 6 [m^3/h]

Loaded	12.71
Baliast	6.35
Manoeuvring	10.59
Loading	8.47
Unloading	0
Residual Time	10.59

Table 120 Fuel consumption and air pollutants from main propulsion engines for Vessel 6

ST	nst	0.9702
	Pengine (KW)	[39724 38135 4767]
	EDP(me reheat)*10^8(kJ/h)	[4.2795 4.1083 0.5541]
	$TMHFO_{OP}$*10^3 (tons)	3.8538
	$TMLNG_{OP}$*10^3 (tons)	2.7181
	SOX_{OP} (tons)	294.0320
	NOX_{OP} (tons)	26.7302
	PM_{OP} (tons)	66.8255
DFDE	nDFDE	0.9038
	Pengine (KW)	[42641 40935 5117]
	EDP*10^8(kJ/h)	[3.4595 3.3211 0.4479]
	$TMMDO_{OP}$*10^3 (tons)	4.0383
	$TMLNG_{OP}$*10^3 (tons)	2.0202
	SOX_{OP} (tons)	33.0111
	NOX_{OP} (tons)	218.6633
	PM_{OP} (tons)	1.2727
GT	nGT	0.9038
	Pengine (KW)	[42641 40935 5117]
	EDP*10^8(kJ/h)	[3.7690 3.6182 0.488]
	$TMMGO_{OP}$*10^3 (tons)	4.3996
	$TMLNG_{OP}$*10^3 (tons)	2.2009
	SOX_{OP} (tons)	32.3861
	NOX_{OP} (tons)	233.6634
	PM_{OP} (tons)	0.7727
COGES	nCOGES	0.9038
	Pengine (KW)	[42641 40935 5117]
	EDP*10^8(kJ/h)	[3.2036 3.0755 0.4148]
	$TMMGO_{OP}$*10^3 (tons)	3.7397
	$TMLNG_{OP}$*10^3 (tons)	1.8708
	SOX_{OP} (tons)	32.3861
	NOX_{OP}(tons)	233.6634
	PM_{OP} (tons)	0.7727

Table 121 Fuel consumption and air pollutants from auxiliary engines for Vessel 6

ST	naux	0.96
	Pauxdel (KWe)	[3613.1 2637.6 5239.0 5166.8 5166.8 2673.7]
	EDA*10^7(kJ/h)	[4.2331 3.0902 6.1380 6.0534 6.0534 3.1325]
	$TMHFO_{AUX}$ (tons)	349.3078
	$TMLNG_{AUX}$ (tons)	308.7298
	SOX_{AUX} (tons)	7.6618
	NOX_{AUX} (tons)	13.7468
	PM_{AUX} (tons)	0.4681
DFDE	naux	0.97
	Pauxdel (KWe)	[3575.9 2610.4 5185.0 5113.5 5113.5 2646.1]
	EDA*10^7(kJ/h)	[2.9011 2.1178 4.2066 4.1486 4.1486 2.1468]
	$TMMDO_{AUX}$ (tons)	363.9060
	$TMLNG_{AUX}$ (tons)	201.9113
	SOX_{AUX} (tons)	2.4465
	NOX_{AUX} (tons)	16.5210
	PM_{AUX} (tons)	0.1100
GT	naux	0.97
	Pauxdel (KWe)	[3575.9 2610.4 5185.0 5113.5 5113.5 2646.1]
	EDA*10^8(kJ/h)	[2.7448 2.0037 3.9800 3.9251 3.9251 2.0312]
	$TMMGO_{AUX}$ (tons)	344.3045
	$TMLNG_{AUX}$ (tons)	191.0356
	SOX_{AUX} (tons)	2.3842
	NOX_{AUX} (tons)	18.0162
	PM_{AUX} (tons)	0.0601
COGES	naux	0.97
	Pauxdel (KWe)	[3575.9 2610.4 5185.0 5113.5 5113.5 2646.1]
	EDA*10^7(kJ/h)	[2.7448 2.0037 3.9800 3.9251 3.9251 2.0312]
	$TMMGO_{AUX}$ (tons)	344.3045
	$TMLNG_{AUX}$ (tons)	191.0356
	SOX_{AUX} (tons)	2.3842
	NOX_{AUX} (tons)	18.0162
	PM_{AUX} (tons)	0.0601

Table 122 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 6.

ST	$TMHFO_{TOT}$*10^3 (tons)	4.2031
	$TMLNG_{TOT}$*10^3 (tons)	3.0268
	CO_2 *10^4 (tons)	2.1412
	SOX_{TOT} (tons)	301.6938
	NOX_{TOT} (tons)	40.4770
	PM_{TOT} (tons)	67.2935
DFDE	$TMMDO_{TOT}$*10^3 (tons)	4.4022
	$TMLNG_{TOT}$*10^3 (tons)	2.2221
	CO_2 *10^4 (tons)	2.0224
	(MethaneSlip)CO_2 *10^4 (tons)	2.3904
	SOX_{TOT} (tons)	35.4576
	NOX_{TOT} (tons)	235.1843
	PM_{TOT} (tons)	1.3827
GT	$TMMGO_{TOT}$*10^3 (tons)	4.7439
	$TMLNG_{TOT}$*10^3 (tons)	2.3920
	CO_2 *10^4 (tons)	2.1787
	SOX_{TOT} (tons)	34.7703
	NOX_{TOT} (tons)	251.6796
	PM_{TOT} (tons)	0.8329
COGES	$TMMGO_{TOT}$*10^3 (tons)	4.0840
	$TMLNG_{TOT}$*10^3 (tons)	2.0618
	CO_2 *10^4 (tons)	1.8763
	SOX_{TOT} (tons)	34.7703
	NOX_{TOT} (tons)	251.6796
	PM_{TOT} (tons)	0.8329

Table 123 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 6, equipped with SSD with Seawater Scrubber, Freshwater Scrubber and WHR.

	Seawater	Freshwater	WHR
nssd	0.99	0.99	0.99
Pengine (KW)	[38929 37372 4672]	[38929 37372 4672]	[39396 37821 4672]
EDP*10^8(kJ/h)	[2.8093 2.6969 0.3637]	[2.8093 2.6969 0.3637]	[2.8430 2.7292 0.3637]
WHRE *10^3(kJ/h)	0	0	[3.5036 3.3635 0]
$TMHF_{OP}$*10^3 (tons)	4.7828	4.7814	4.7353
$TMMD_{OP}$ (tons)	0	0	0
SOX_{OP} (tons)	190.9206	190.9206	198.83
NOX_{OP} (tons)	445.3249	445.3249	450.67
PM_{OP} (tons)	12.5142	12.5142	13.26
naux	0.96	0.96	0.96
Pauxdel (KWe)	[3613.1 2637.6 5239.0 5166.8 5166.8 2673.7]	[3613.1 2637.6 5239.0 5166.8 5166.8 2673.7]	0
EDA*10^7(kJ/h)	[2.9313 2.1399 4.2504 4.1918 4.1918 2.1692]	[2.9313 2.1399 4.2504 4.1918 4.1918 2.1692]	[2.9313 2.1399 4.2504 4.1918 4.1918 2.1692]
TMMDOA (tons)	4.6544	4.6544	0
SOX_{AUX} (tons)	18.9697	18.9697	0
NOX_{AUX} (tons)	41.8811	41.8811	0
PM_{AUX} (tons)	1.2318	1.2318	0
$TMHFO_{TOT}$ (tons)	4.7828	4.7814	4.7353
$TMMDO_{TOT}$(tons)	4.6544	4.6544	0
CO_2 *10^4 (tons)	1.4909	1.4904	1.4746
SOX_{TOT} (tons)	209.8902	209.8902	198.83
NOX_{TOT} (tons)	487.2059	487.2059	450.67
PM_{TOT} (tons)	13.7460	13.7460	13.26

Table 124 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 6, equipped with SSD with EGR and SCR systems burning MDO when operating in SECA.

	EGR	**SCR**
nssd	0.99	0.99
Pengine (KW)	[38929 37372 0.4672]	[38929 37372 0.4672]
EDP*10^8(kJ/h)	[2.8093 2.6969 0.3637]	[2.8093 2.6969 0.3637]
TMHF$_{OP}$*10^3 (tons)	4.7814	4.7814
TMMD$_{OP}$ (tons)	0	0
SOX$_{OP}$ (tons)	201.7060	201.7060
NOX$_{OP}$ (tons)	426.8324	426.8324
PM$_{OP}$ (tons)	13.0978	13.0978
naux	0.96	0.96
Pauxdel (KWe)	[3613.1 2637.6 5239.0 5166.8 5166.8 2673.7]	[3613.1 2637.6 5239.0 5166.8 5166.8 2673.7]
EDA*10^7(kJ/h)	[2.9313 2.1399 4.2504 4.1918 4.1918 2.1692]	[2.9313 2.1399 4.2504 4.1918 4.1918 2.1692]
TMHFO$_{AUX}$ (tons)	0	0
TMMDO$_{AUX}$ (tons)	4.6544	4.6544
SOX$_{AUX}$ (tons)	18.9697	18.9697
NOX$_{AUX}$ (tons)	41.8811	41.8811
PM$_{AUX}$ (tons)	1.2318	1.2318
TMHFO$_{TOT}$*10^3 (tons)	4.7814	4.7814
TMMDO$_{TOT}$*10^3 (tons)	4.6544	4.6544
CO_2 *10^4 (tons)	1.4904	1.4904
SOX$_{TOT}$ (tons)	209.8902	209.8902
NOX$_{TOT}$ (tons)	487.2059	487.2059
PM$_{TOT}$ (tons)	13.7460	13.7460

Table 125 Total fuel consumption and air pollutants from main propulsion and auxiliary engines for Vessel 6, for the three selected means for complying with the ECA regulations.

	MDO-WHR-SCR	Seawater Scrubber-EGR	Freshwater Scrubber-EGR
nssd	0.99	0.99	0.99
Pengine (KW)	[39396 37821 4672]	[38929 37372 4672]	[38929 37372 4672]
EDP*10^8(kJ/h)	[2.8430 2.7292 0.3637]	[2.8093 2.6969 0.3637]	[2.8093 2.6969 0.3637]
TMHF$_{OP}$*10^3 (tons)	4.4539	4.7828	4.7814
TMMD$_{OP}$(tons)	266.2295	0	0
SOX$_{OP}$ (tons)	195.1488	190.9206	190.9206
NOX$_{OP}$ (tons)	429.8207	424.1587	424.1587
PM$_{OP}$ (tons)	12.5305	12.5142	12.5142
naux	0.96	0.96	0.96
Pauxdel (KWe)	0	[3.6131 2.6376 5.2390 5.1668 5.1668 2.6737]	[3.6131 2.6376 5.2390 5.1668 5.1668 2.6737]
EDA*10^7(kJ/h)	[2.9313 2.1399 4.2504 4.1918 4.1918 2.1692]	[2.9313 2.1399 4.2504 4.1918 4.1918 2.1692]	[2.9313 2.1399 4.2504 4.1918 4.1918 2.1692]
TMHFO$_{AUX}$*10^3 (tons)	0	0	0
TMMDO$_{AUX}$ (tons)	0	4.6544	4.6544
SOX$_{AUX}$ (tons)	0	18.9697	18.9697
NOX$_{AUX}$ (tons)	0	41.8811	41.8811
PM$_{AUX}$ (tons)	0	1.2318	1.2318
TMHFO$_{TOT}$*10^3 (tons)	4.4539	4.7828	4.7814
TMMDO$_{TOT}$ (tons)	266.2295	4.6544	4.6544
CO$_2$ *10^4 (tons)	1.4738	1.4909	1.4904
SOX$_{TOT}$ (tons)	195.1488	209.8902	209.8902
NOX$_{TOT}$ (tons)	429.8207	466.0398	466.0398
PM$_{TOT}$ (tons)	12.5305	13.7460	13.7460

Where:

U_{LOAD}: Speed in Loaded Condition

U_{UNLOAD}: Speed in Laden Condition

C: Cargo Capacity

P_{PROP}: Power at Propeller

P_{AUX}: Auxilliary Power

EDP: Energy Demand for Propulsion

EDA: Energy Demand for Auxiliary

SOX_{OP}: SOX produced for Propulsion needs

SOX_{AUX}: SOX produced for Auxiliary needs

SOX_{TOT}: Total SOX emissions

NOX_{OP}: SOX produced for Propulsion needs

NOX_{AUX}: SOX produced for Auxiliary needs

NOX_{TOT}: Total SOX emissions

PM_{OP}: SOX produced for Propulsion needs

PM_{AUX}: SOX produced for Auxiliary needs

PM_{TOT}: Total SOX emissions

CO_2: Total SOX emissions

$TMHFO_{OP}$: Total Mass of HFO consumed for Propulsion needs

$TMHFO_{AUX}$: Total Mass of HFO consumed for Auxiliary needs

$TMHFO_{TOT}$: Total Mass of HFO consumed

$TMMDO_{OP}$: Total Mass of MDO consumed for Propulsion needs

$TMMDO_{AUX}$: Total Mass of MDO consumed for Auxiliary needs

$TMMDO_{TOT}$: Total Mass of MDO consumed

$TMLNG_{OP}$: Total Mass of LNG consumed for Propulsion needs

$TMLNG_{AUX}$: Total Mass of LNG consumed for Auxiliary needs

$TMLNG_{TOT}$: Total Mass of LNG consumed

$TMMG_{OP}$: Total Mass of MGO consumed for Propulsion needs

$TMMGO_{AUX}$: Total Mass of MGO consumed for Auxiliary needs

$TMMGO_{TOT}$: Total Mass of MGO consumed