National Technical University of Athens

School of Naval Architecture and Marine Engineering

Laboratory for Maritime Transport

PROBABILISTIC ANALYSIS/ESTIMATION ON FUEL CONSUMPTION AND SHIP EMISSIONS

Diploma Thesis

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TO MY FAMILY

IOANNIS, MARIA, DIONYSSIS AND ALEXANDRA

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NOMENCLATURE

BC	Black Carbon
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
ECA	Emission Control Areas
EEDI	Energy Efficiency Design Index
EF	Emission Factor
EGR	Exhaust Gas Recirculation
EPA	United States Environmental Protection Agency
FC	Fuel Consumption
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
ICCT	The International Council on Clean Transportation
IEA	International Energy Agency
IMO	International Maritime Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LF	Loading Factor
LFO	Light Fuel Oil
M/E	Main Engine
MBM	Market-Based Measure
MC	Monte Carlo
MCR	Maximum Continuous Rating

MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MRV	Measuring, Reporting and Verification
NMVOC	Non Methane Volatile Compounds
NO_x	Nitrogen Oxide
NR	Noon Report
PDF	Probability Density Function
PM	Particulate Matter
RPM	Revolutions Per Minute
SCR	Selective Catalytic Reduction
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific Fuel Oil Consumption
SO	Sulphur Monoxide
SO_2	Sulphur Dioxide
SO_x	Sulphur Oxide
TEU	Twenty-Foot Equivalent Unit
VOC	Volatile Organic Compounds

1. ABSTRACT

Global concerns about environmental pollution, regulatory framework, the ever increasing fuel costs and the competitive container carriers industry are driving the quest for ever improved ships with higher performance efficiency, lower emissions and more attractive financially. In order to meet all these requirements, researchers make efforts on setting up methods in order to predict the effects of operational changes in vessels. The present study has analyzed fuel consumption and emissions of a Container ship's Main Engine from an operational perspective. Fuel consumption is essentially detailed in the following random variables: Loading Factor, Specific Fuel Oil Consumption and Time. The method used for this analysis is the Monte Carlo simulation, which is a well-known probabilistic methodology. The studied ship is a 2,824 TEU Sub-Panamax class Container ship and the emissions analyzed are: CO_2, NO_x, SO_x and PM. The operating condition of the specific ship is slow steaming. The study has developed probabilistic distributions for fuel consumption from two different input categories: real recordings and model constructed in this thesis. In the first occasion, data were provided by real Noon Reports of the specific Container ship, whereas a large amount of data from Noon Reports have been used in combination with data from literature for the modelling process. The software tool used in this probabilistic analysis is Oracle Crystal Ball, which works as an add-in in an Excel spreadsheet.

This study has also analyzed the impact of the three random input variables in the estimation of fuel consumption. Going further, in order to evaluate the importance of specific parameters to the results, a robustness analysis has been applied for fuel consumption.

The amount of emissions depends on the type of Main Engine (Tier I, II, III), the operation load, the type of fuel used and its sulphur percentage. Estimation of emissions is conducted with updated emission factors from literature.

A generic conclusion from this study is that the MC methodology may be applied to estimate fuel consumption and emissions in a satisfactory way, however it is very uncertain what happens in higher loads of operation. An essential feature for future research would be the creation of a probabilistic inventory based on a the whole range of load operation. This would make the probabilistic methodology more safe and easy for use in the shipping sector.

Περίληψη

Οι παγκόσμιες ανησυχίες για περιβαλλοντικά θέματα, το νομικό πλαίσιο, το ολοένα αυξανόμενο κόστος καυσίμων και ο ανταγωνισμός της βιομηχανίας μεταφοράς εμπορευματοκιβωτίων, οδηγούν στην αναζήτηση νέων βελτιωμένων πλοίων με υψηλότερη αποδοτικότητα, χαμηλότερες εκπομπές και οικονομικότερα. Προκειμένου να καλυφθούν όλες αυτές οι απαιτήσεις, οι ερευνητές προσπαθούν να εισάγουν μεθόδους με σκοπό την πρόβλεψη των επιπτώσεων των αλλαγών στη λειτουργία των πλοίων. Η παρούσα διπλωματική εργασία μελετά την κατανάλωση καυσίμου και την εκπομπή ρύπων από την Κύρια Μηχανή ενός πλοίου μεταφοράς εμπορευματοκιβωτίων, από λειτουργική άποψη. Η κατανάλωση καυσίμου αναλύεται στις παρακάτω τυχαίες μεταβλητές: Φορτίο Λειτουργίας, Ειδική Κατανάλωση Καυσίμου και Χρόνος. Η μέθοδος που χρησιμοποιήθηκε για τη μελέτη είναι η προσομοίωση Monte Carlo, η οποία είναι ευρέως γνωστή ως μια πιθανοθεωρητική μεθοδολογία. Η εφαρμογή έγινε σε πλοίο μεταφοράς εμπορευματοκιβωτίων 2,824 TEU και οι εκπομπές που αναλύθηκαν είναι: διοξείδιο του άνθρακα (CO_2), οξείδια του αζώτου (NO_x), οξείδια του θείου (SO_x) και αιωρούμενα σωματίδια (PM). Η κατάσταση λειτουργίας του υπό μελέτη πλοίου είναι το slow steaming. Η μελέτη παρήγαγε κατανομές για την κατανάλωση καυσίμου από δυο διαφορετικές εισόδους: αληθινές καταγραφές και εκείνες που παρήγαγε το μοντέλο. Στην πρώτη περίπτωση, τα δεδομένα που εισήχθησαν είναι πραγματικά και προήλθαν από τον πλοιοκτήτη. Στην άλλη περίπτωση, υπήρξε συνδυασμός δεδομένων από τον πλοιοκτήτη και τη βιβλιογραφία. Το πακέτο λογισμικού που χρησιμοποιήθηκε είναι το Oracle Crystal Ball, το οποίο λειτουργεί ως πρόσθετο του Excel.

Σε επόμενο στάδιο μελετήθηκε η επίδραση των τριών τυχαίων μεταβλητών στον υπολογισμό της κατανάλωσης καυσίμου. Επιπλέον, για να αξιολογηθεί η σημασία των συγκεκριμένων παραμέτρων, έγινε ανάλυση ευρωστίας για την κατανάλωση καυσίμου. Τα εκπεμπόμενα ποσά ρύπων εξαρτώνται από τον τύπο της Κύριας Μηχανής, το Φορτίο Λειτουργίας, τον τύπο του καυσίμου και το ποσοστό θείου στο καύσιμο. Η εκτίμηση των ποσών ρύπων γίνεται με ενημερωμένους συντελεστές ρύπων από τη βιβλιογραφία. Η προσομοίωση Monte Carlo μπορεί να εφαρμοστεί στον υπολογισμό κατανάλωσης καυσίμου και εκπομπών ρύπων, αλλά είναι πολύ αβέβαιο τι συμβαίνει σε υψηλότερα φορτία λειτουργίας. Θα ήταν πολύ χρήσιμο να δημιουργηθεί μια πιθανοθεωρητική μεθοδολογία για όλο το εύρος φορτίου λειτουργίας, κάτι το οποίο θα καθιστούσε τη μεθοδολογία πιο ασφαλή και γρήγορη για εφαρμογή σε πλοία.

2. SHIPPING AND EMISSIONS

2.1 General Description

Maritime shipping is highly fuel-efficient, but its sheer volume and rapid growth make it a major consumer of energy and source of carbon emissions. As the shipping industry and governments seek ways to reduce shipping's overall energy and carbon footprint, the answers to many questions remain elusive. Among these questions are how much variation in shipping efficiency is seen in the real-world fleet and how quickly shipping can move to embrace best technical and operational practices to increase shipping efficiency.

Government agencies, environmental stakeholders, industry representatives and consumers each struggle to find accurate, detailed information about the carbon footprint of goods that have been shipped thousands of miles around the world via various modes of transportation. International shipping, in particular, presents a major uncertainty in assessing the energy and climate impact of the global movement of goods. This data uncertainty becomes even greater when trying to quantitatively understand the carbon emissions associated with a given shipping company, route, or ship type.

With the current global trend towards a reduction of air emissions from all sectors, the shipping industry is experiencing increased pressure from stakeholders in general, and regulators in particular, to tackle its emissions and improve its energy efficiency. Emissions from shipping currently represent 3% of the world's total greenhouse gas (GHG) emissions, and the industry's share is increasing. A continued increase in international marine transport without any significant gains in energy efficiency may result in shipping being responsible for 6% of the world's GHG emissions by 2020 and 15% by 2050.

Over 90% of global trade is carried by sea. The world fleet of sea-going merchant ships of more than 100 gigatonnes (GT) comprises over 104,000 ships [1]. Like other transportation companies, shipping companies require fossil fuel to conduct their operations. The combustion of fossil fuel used by a vessel's engines produces greenhouse gases (GHG) as well as non-GHG emissions.

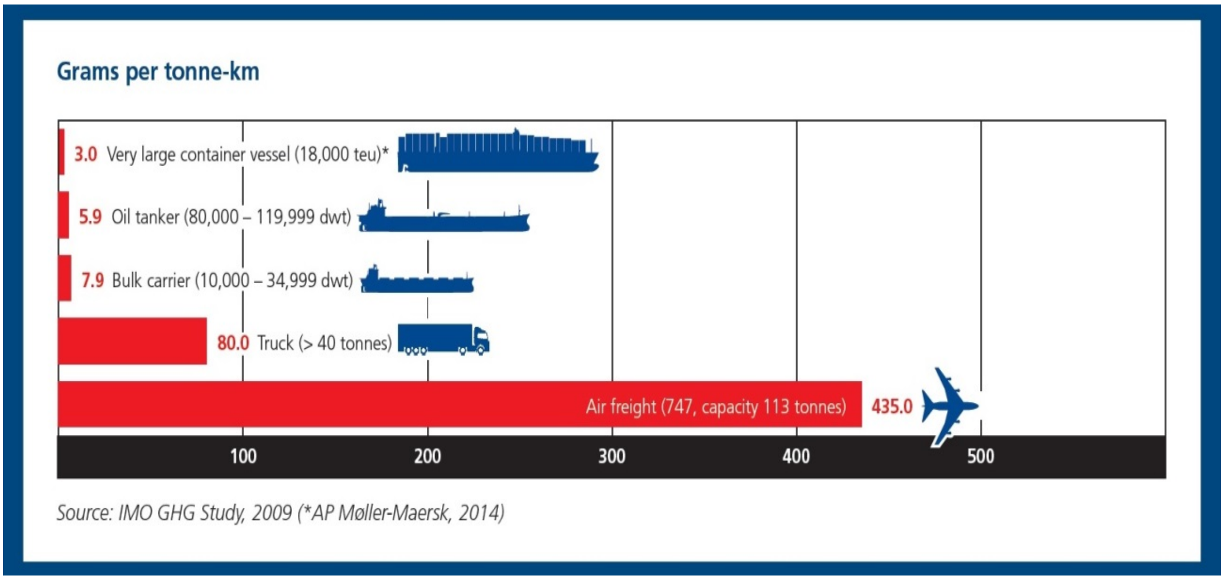


Figure 1: Comparison of typical CO_2 emissions between modes of transport (IMO, 2009)

GHG Emissions

Under the GHG Protocol, six gases are categorized as greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorooctane sulfonate (PFCs) and sulphur hexafluoride (SF_6) [2].

- Carbon dioxide (CO_2): CO_2 is the GHG most relevant to the shipping industry. Globally, 1,050 million tonnes of CO_2 were emitted by shipping in 2007, doubling 1990 levels. CO_2 emissions represent approximately 3% of the world's total CO_2 emissions.
- Other greenhouse gases: The shipping industry also emits other GHGs such as CH_4, N_2O, and HFCs. Annual aggregated emissions of these GHGs represent 21 million tonnes of CO_2 equivalent. Emissions of PFCs and SF_6 are considered negligible [1].

Non-GHG Emissions

In addition to GHGs, shipping produces other air emissions, most notably sulphur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter (PM).

- Sulphur oxides (SO_x): The shipping industry is among the top emitters of SO_x [3]. A total of 2.3 million tonnes of SO_2 (the most common sulphur oxide) was emitted by ships in the seas surrounding Europe in the year 2000 [3]. Globally, 15 million tonnes of SO_x were emitted by shipping in 2007, representing a 50% increase from 1997 levels.1 SO_x emissions from shipping represent between 5% and 8% of the world's total SO_x emissions.
- Nitrogen oxides (NO_x): Shipping also accounts for a significant portion of the world's NO_x emissions [6]. A total of 3.3 million tonnes of NO_x was emitted by ships in the seas surrounding Europe in the year 2000. Globally, 25 million tonnes of NO_x were emitted by shipping in 2007, representing a 39% increase from 1997 levels. NO_x emissions from shipping represent around 15% of the world's total NO_x emissions.
- Particulate Matter (PM): In 2000, 250,000 tonnes of PM was emitted by ships in Europe. Globally, 1.8 million tonnes of PM was released in 2007, representing a 50% increase from 1997 levels. The amount of PM released by ships is much lower than that of SO_x or NO_x emissions. It is to be noted that PM and SO_x emissions are correlated: a decrease in SO_x emissions reduces emissions of PM [1].

Shipping emissions are an important contributor to several major environmental problems. GHG emissions contribute to climate change [4] (i.e. longer term, less instantaneously visible effects), while non-GHG emissions can cause acid rain, damage to monuments, a reduction of agricultural yields, water contamination, modification of soil biology and deforestation [5] (i.e. more short term, visible effects).

Some non-GHG emissions are also linked to increases in ground-level ozone [6]. Shipping emissions can also cause negative social impacts. The effects of climate change, such as drought or rising sea levels, can lead to social conflict over resources (i.e., water, energy, agricultural products). Air pollution from non-GHG emissions can affect the heart and lungs, consequently worsening the condition of people with cardiovascular and respiratory diseases. For instance, in Hong Kong, 519 premature deaths have been linked to marine SO_2 emissions [7]. Additionally, non-GHG emissions can react chemically in the atmosphere to form particulate matter; prolonged exposure to which can affect a person's mood and cognitive abilities [8]. Another negative consequence of pollution is smog which can reduce the quality of life and inhibit the attractiveness of tourist sites.

Many efforts have helped quantify and set benchmarks for ship efficiency, to assist in understanding and decision-making regarding the carbon footprint of the goods throughout their supply chain. Parallel to these efforts in the private sector, policymakers around the world have sought to examine policies to curtail the growth of shipping carbon emissions. Two GHG reports commissioned by the International Maritime Organization (IMO) brought forth valuable information on ship speed, ship utilization, fuel consumption, and associated emission trends [9], [10]. The Second IMO GHG Study demonstrated that the CO_2 emissions growth from shipping, if unchecked, will double in the next few decades [9]. Such trends are incompatible with long-term global climate stabilization goals that will require dramatic carbon reductions from every industrial sector. The Second IMO GHG Study paved the way for an era of active policy dialogue that included the creation of the mandatory EEDI standards for new ship efficiency and the complementary Ship Energy Efficiency Management Plan (SEEMP) for in-use efficiency improvement, as well as a discussion of market-based measures.

Despite progress in understanding the state of ship efficiency, the available data remains relatively sparse compared with that of other industrial sectors and modes that have been more actively analyzed and regulated. The heterogeneity of the global shipping industry has made it difficult to characterize its general efficiency. The lack of ship-specific operational data has precluded more rigorous and detailed analysis relating the fundamental efficiency of a given ship to its in-use efficiency. Shifts in ship operation, following the drop in international trade during the global 2008–2010 economic downturn, further complicate analysis. The use of slow steaming-to address the overcapacity of ships, reduce fuel expenses, and improve the corporate bottom line may significantly change the industry landscape and alter ship operation going forward.

Speed reduction also results in substantial CO_2 savings proportional to the lower fuel use [11], [12]. These industry shifts suggest that more refined and up-to-date data are needed to characterize the carbon emissions and efficiency characteristics of the current and future shipping fleet.

Shipping tends to have the lowest carbon footprint per unit of cargo transported [9], but ships carry more than half of international goods by tonne-mile [13], [14], [15], driving up the shipping industry’s petroleum use and CO_2 emissions. Figure 2 summarizes transportation's CO_2 emissions and petroleum use by transportation mode [13]. As shown, the largest shares of transportation energy use and climate impact come from the more than 1 billion on-road passenger and commercial vehicles. However, shipping, with just tens of thousands of vessels, is the next largest energy consumer and carbon emitter. Overall, the transportation sector consumes about half of the world's petroleum supply, amounting to about 47 million barrels of oil per day. Marine shipping uses about 11% of the global transportation sector's petroleum, or about 5 million barrels per day. This energy use equates to 10 gigatonnes of CO_2 emissions annually from transportation, about 11% of which is from marine shipping.

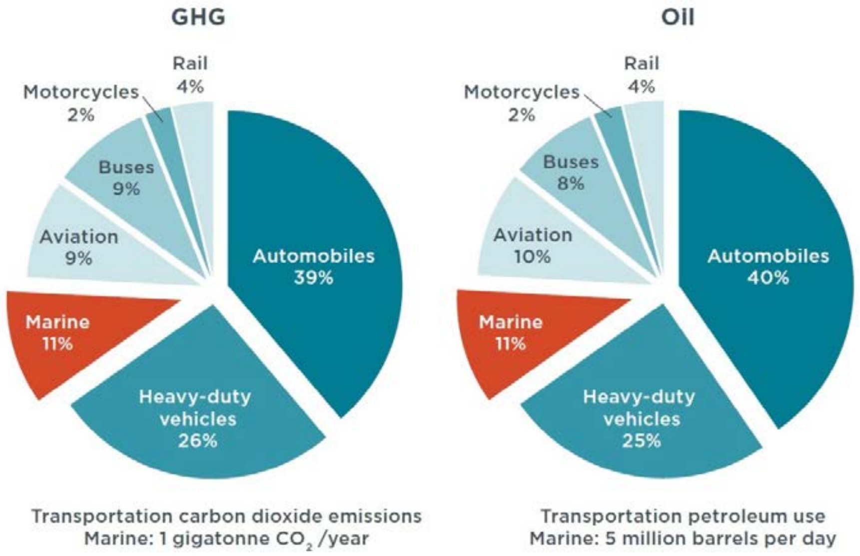


Figure 2: Marine shipping's contribution to global transportation climate emissions and petroleum consumption (ICCT, 2010)

Shipping activity, and therefore its energy and carbon emissions, is closely intertwined with broader economic factors. Business-as-usual marine CO_2 emissions are expected to grow 250–350% from 2007 to 2050 in the IMO's GHG assessment, due to the expansion of global trade [9]. Shipping activity decreased during the 2008-2010 down-turn but has now recovered to approximately pre-recession levels [14] and is widely expected to resume its previous long-term growth trend.

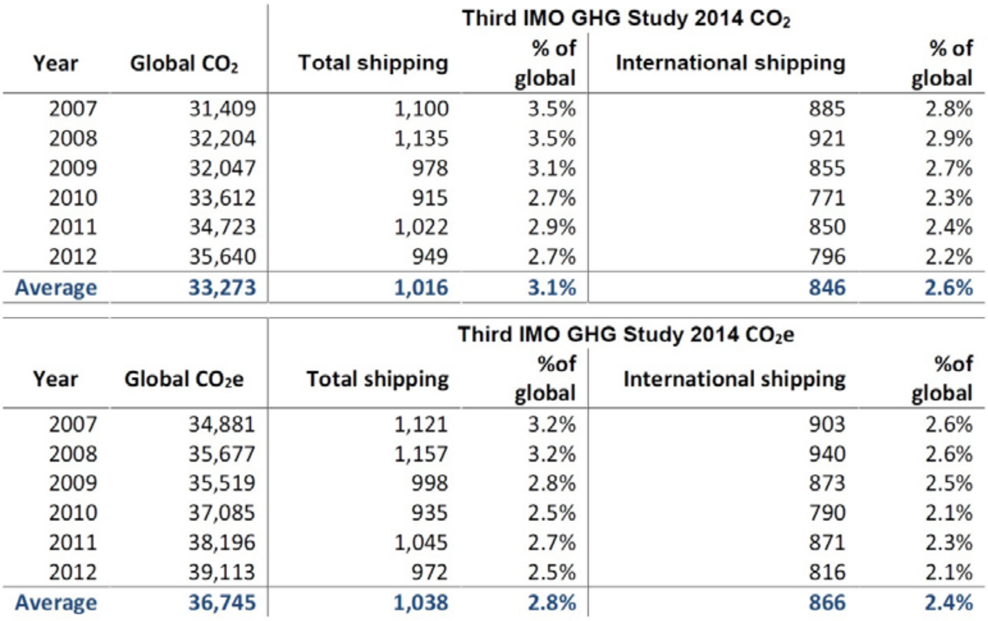
The implementation of the EEDI, although a significant first step for ship efficiency, will slow, but not bring an absolute reduction in, shipping CO_2 emissions. It will also do so only gradually over several decades as the entire fleet turns over and becomes EEDI-compliant [16], [17]. Older, less efficient ships that were built through the early 2000s, at times of lower fuel prices, higher profitability, and limited attention to efficiency and carbon emissions, will be in service well into the next decade and beyond.

The large remaining-and more near-term-opportunity for reducing CO_2 emissions in the industry therefore lies in the improvement of energy efficiency for in-use ships. Recent years have seen the emergence of highly cost-effective energy-saving technologies and maintenance routines, making such CO_2 savings a real possibility. To better reduce the risks inherent in the price of oil and its volatility, further energy-saving innovations continue to be developed in diesel engines, computerization and operational practices among the most progressive ships and shipping lines [18], [19].

Key findings from the Third IMO GHG Study 2014

- For the year 2012, total shipping emissions were approximately 949 million tonnes CO_2 and 972 million tonnes CO_2e for GHGs combining CO_2, CH_4 and N_2O. International shipping emissions for 2012 are estimated to be 796 million tonnes CO_2 and 816 million tonnes CO_2e for GHGs combining CO_2, CH_4 and N_2O. International shipping accounts for approximately 2.2% and 2.1% of global CO_2 and GHG emissions on a CO_2 equivalent (CO_2e) basis, respectively. Table 1 presents the full time series of shipping CO_2 and CO_2e emissions compared with global total CO_2 and CO_2e emissions. For the period 2007–2012, on average, shipping accounted for approximately 3.1% of annual global CO_2 and approximately 2.8% of annual GHGs on a CO_2e basis using 100-year global warming potential conversions from the AR5. A multi-year average estimate for all shipping using bottom-up totals for 2007–2012 is 1,016 million tonnes CO_2 and 1,038 million tonnes CO_2e for GHGs combining CO_2, CH_4 and N_2O. International shipping accounts for approximately 2.6% and 2.4% of CO_2 and GHGs on a CO_2e basis, respectively. A multi-year average estimate for international shipping using bottom-up totals for 2007–2012 is 846 million tonnes CO_2 and 866 million tonnes CO_2e for GHGs combining CO_2, CH_4 and N_2O. These multiyear CO_2 and CO_2e comparisons are similar to, but slightly smaller than, the 3.3% and 2.7% of global CO_2 emissions reported by the Second IMO GHG Study 2009 for total shipping and international shipping in the year 2007, respectively.

Table 1: a) Shipping CO_2 emissions compared with global CO_2 (values in million tonnes CO_2)
b) Shipping GHGs (in CO_2e) compared with global GHGs (values in million tonnes CO_2e) (IMO, 2014)



		Third IMO GHG Study 2014 CO_2			
Year	Global CO_2	Total shipping	% of global	International shipping	% of global
2007	31,409	1,100	3.5%	885	2.8%
2008	32,204	1,135	3.5%	921	2.9%
2009	32,047	978	3.1%	855	2.7%
2010	33,612	915	2.7%	771	2.3%
2011	34,723	1,022	2.9%	850	2.4%
2012	35,640	949	2.7%	796	2.2%
Average	**33,273**	**1,016**	**3.1%**	**846**	**2.6%**

		Third IMO GHG Study 2014 CO_2e			
Year	Global CO_2e	Total shipping	%of global	International shipping	%of global
2007	34,881	1,121	3.2%	903	2.6%
2008	35,677	1,157	3.2%	940	2.6%
2009	35,519	998	2.8%	873	2.5%
2010	37,085	935	2.5%	790	2.1%
2011	38,196	1,045	2.7%	871	2.3%
2012	39,113	972	2.5%	816	2.1%
Average	**36,745**	**1,038**	**2.8%**	**866**	**2.4%**

- This study estimates multi-year (2007–2012) average annual totals of 20.9 million and 11.3 million tonnes for NO_x (as NO_2) and SO_x (as SO_2) from all shipping, respectively (corresponding to 6.3 million and 5.6 million tonnes converted to elemental weights for nitrogen and sulphur, respectively). NO_x and SO_x play indirect roles in tropospheric ozone formation and indirect aerosol warming at regional scales. International shipping is estimated to produce approximately 18.6 million and 10.6 million tonnes of NO_x (as NO_2) and SO_x (as SO_2) annually; this converts to totals of 5.6 million and 5.3 million tonnes of NO_x and SO_x (as elemental nitrogen and sulphur, respectively). Global NO_x and SO_x emissions from all shipping represent about 15% and 13% of global NO_x and SO_x from anthropogenic sources reported in the latest IPCC Assessment Report (AR5), respectively; international shipping NO_x and SO_x represent approximately 13% and 12% of global NO_x and SO_x totals, respectively.

- Over the period 2007–2012, average annual fuel consumption ranged between approximately 250 million and 325 million tonnes of fuel consumed by all ships within this study, reflecting top-down and bottom-up methods, respectively. Of that total, international shipping fuel consumption ranged between approximately 200 million and 270 million tonnes per year, depending on whether consumption was defined as fuel allocated to international voyages (top-down) or fuel used by ships engaged in international shipping (bottom-up), respectively.

- Correlated with fuel consumption, CO_2 emissions from shipping are estimated to range between approximately 740 million and 795 million tonnes per year in top-down results, and to range between approximately 900 million and 1150 million tonnes per year in bottom-up results. Both the top-down and the bottom-up methods indicate limited growth in energy and CO_2 emissions from ships during 2007–2012, as suggested both by the IEA data and the bottom-up model. Nitrous oxide (N_2O) emission patterns over 2007-2012 are similar to the fuel consumption and CO_2 patterns, while methane (CH_4) emissions from ships increased due to increased activity associated with the transport of gaseous cargoes by liquefied gas tankers, particularly during 2009–2012.

- International shipping CO_2 estimates range between approximately 595 million and 650 million tonnes calculated from top-down fuel statistics, and between approximately 775 million and 950 million tonnes according to bottom-up results. International shipping is the dominant source of the total shipping emissions of other GHGs: nitrous oxide (N_2O) emissions from international shipping account for the majority (approximately 85%) of total shipping N_2O emissions, and methane (CH_4) emissions from international ships account for nearly all (approximately 99%) of total shipping emissions of CH_4.

- Refrigerant and air conditioning gas releases account for the majority of HFC (and HCFC) emissions from ships. For older vessels, HCFCs (R-22) are still in service, whereas new vessels use HCFs (R134a/R404a). Use of SF_6 and PCFs in ships is documented as rarely used in large enough quantities to be significant and is not estimated in this report.

- Refrigerant and air conditioning gas releases from shipping contribute an additional 15 million tons (range 10.8 million–19.1 million tons) in CO_2 equivalent emissions. Inclusion of reefer container refrigerant emissions yields 13.5 million tons (low) and 21.8 million tons (high) of CO_2 emissions.

- Combustion emissions of SO_x, NO_x, PM, CO and NMVOCs are also correlated with fuel consumption patterns, with some variability according to properties of combustion across engine types, fuel properties, etc., which affect emissions substances differently.

2.2 Formation of Emissions

2.2.1 In general

Maritime transport is largely dependent on Heavy Fuel Oil (HFO) which accounts for approximately 77% [20] of maritime transport fuel used and almost all fuel used by ocean-going ships. Vessels engaged in coastal trips use either HFO or lighter marine distillate oil. HFO is a viscous residual product remaining at the end of the crude oil refining chain and as such, contains an elevated share of impurities (e.g. oxides, sulphur and water). These must be removed through centrifuges/filters and the fuel's viscosity must be reduced via pre-heating to allow combustion. Nonetheless, it is an available and relatively cheap refinery by-product and well-suited for use in current large marine engines-hence its popularity.

The climate-forcing impacts from shipping are linked to the by-products of HFO, and to a lesser extent, MDO combustion. These by-products are:

Carbon Dioxide (CO_2) which has a direct, global and long-lasting climate forcing impact.

Black carbon (BC) which also has a direct but somewhat lesser and more regionally constrained impact than CO_2. Black carbon's warming impact is linked mainly to surface deposition and heat absorption in snow- and ice-covered areas (e.g. the poles and high-altitude glaciers).

Nitrogen Oxides (NO_x) is formed by high temperature combustion in ship engines and acts as a precursor to tropospheric ozone (O_3), itself a powerful greenhouse gas. In certain conditions however, NO_x emissions can lead to a rise in methane (CH_4) destruction and can thus contribute to reduced atmospheric warming.

Sulphur dioxide (SO_2) is transformed into sulphate (SO_4) in the atmosphere which is thought to have a net cooling impact on climate.

Carbon Monoxide (CO) is a precursor to both tropospheric ozone and methane.

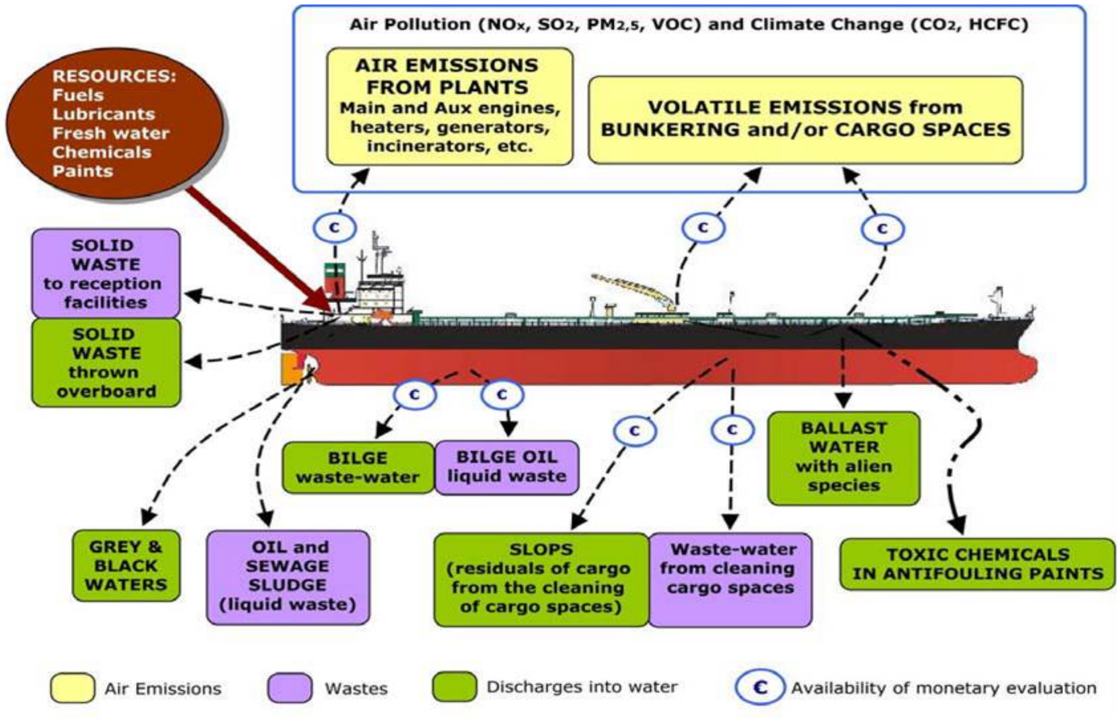


Figure 3: Ship pollution sources(The Stern Review, 2006)

Most ocean-going cargo vessels are powered by extremely large slow-speed two-stroke engines that are directly coupled to the propeller shaft (e.g. they have no clutch or reduction gears). Two-stroke marine engines have high power outputs (up to nearly 85 MW), are relatively efficient (approximately 50% of the fuel energy is delivered directly to the propeller shaft-see figure 4) and are adapted to burning heavy fuel oil via direct injection. The combined elevated power output and slow engine speed (ranging from 60 to 200 rpm) is suited for most ocean-going cargo applications. Some very large cargo carriers and most passenger ships and ferries require more acceleration power and are built with medium-speed 4-stroke MDO or HFO engines. The combination of high-temperature combustion and low quality fuels leads to very high rates of NO_x and SO_x emissions when compared to current land-based diesel engines that have already gone through several pollution reduction design cycles [21].

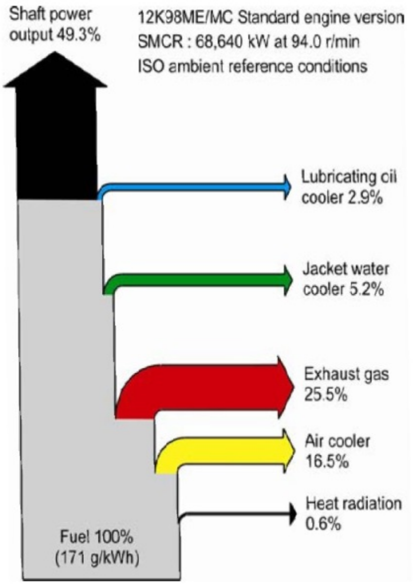


Figure 4: Marine 2-Stroke Engine Efficiency (MAN B&W, 2011)

2.2.2 Nitrogen Oxides (NO_x)

Most of the world’s nitrogen occurs naturally in the atmosphere as an inert gas contained in air, which consists of approximately 78% N_2 by volume. NO_x refers to oxides of nitrogen. These generally include nitrogen monoxide, also known as nitric oxide (NO) and nitrogen dioxide (NO_2). They may also include nitrous oxide (N_2O), also known as laughing gas, as well as other less common combinations of nitrogen and oxygen, such as nitrogen tetroxide (N_2O_4) and nitrogen pentoxide (N_2O_5). The EPA defines nitrogen oxides as “all oxides of nitrogen except nitrous oxide. In most high-temperature heating applications, the majority of the NO_x exiting the exhaust stack is in the form of nitric oxide (NO) [22].

How does NO_x form?

There are three generally accepted mechanisms for NO_x formation: thermal NO_x, prompt NO_x and fuel NO_x.

1. Thermal NO_x is formed by the high-temperature reaction (hence, the name thermal NO_x) of nitrogen with oxygen, by the well-known Zeldovich mechanism:

$N_2 + O_2 \rightarrow NO, NO_2$

Thermal NO_x increases exponentially with temperature. Above about 2,000°F (1,100°C), it is generally the predominant mechanism in combustion processes, making it important in most high-temperature heating applications. It means this mechanism becomes more important when air preheating of the combustion air is used, which normally increases the flame temperature that leads to increased NO_x.

2. Fuel NO_x is formed by the direct oxidation of organo-nitrogen compounds contained in the fuel (hence, the name fuel NO_x) and is given by the overall reaction:

$R_xN + O_2 \rightarrow NO, NO_2, CO_2, H_2O$, trace species

Fuel NO_x is not a concern for high-quality gaseous fuels like natural gas or propane, which normally have no organically-bound nitrogen. However, fuel NO_x may be important when oil (e.g., residual fuel oil), coal, or waste fuels are used, which may contain significant amounts of organically bound nitrogen.

3. Prompt NO_x is formed by the relatively fast reaction (hence, the name prompt NO_x) between nitrogen, oxygen, and hydrocarbon radicals:

$CH_4 + O_2 + N_2 \rightarrow NO, NO_2, CO_2, H_2O$, trace species

In reality, this very complicated process consists of hundreds of reactions and dozens of species. Prompt NO_x is generally an important mechanism in lower- temperature combustion processes, but is generally much less important compared to thermal NO_x formation at the higher temperatures found in many industrial combustion processes. Prompt NO_x becomes more important under fuel rich conditions.

How does NO_x affect health and environment?

Contributing to acidification, formation of ozone, nutrient enrichment and to smog formation, NO_x are deemed between the most harmful gases to the environment [23]. They can be transported over long distances and generate problems to areas not confined to areas where NO_x are emitted. Some of the most important health and environmental impacts generated by NO_x are:

Ground-level Ozone (Smog): Photochemical smog is formed when NO_x and volatile organic compound (VOC) react in the sunlight and unburned hydrocarbons. Ozone can be transported by wind currents and cause health impacts far from original sources. It generates damage to vegetation, crop and affect human health. It can compromise the immune system, generate emphysema, bronchitis and irritation of the eyes. It affects, in particular, children and people with respiratory diseases. Moreover, since particle smog is formed by PM (ultra-fine particles of soot) it can contribute to damage hearth and lungs.

Acid Rain: Acid rain is caused by NO_x and SO_x combining with water in the atmosphere and returning to the ground as mild nitric and sulfuric acid. They can deteriorate vegetation, crops, buildings and water of lakes, affecting freshwaters and terrestrial ecosystems. When acid precipitation becomes chronic in a watershed, it can exceed the buffering capacity of the soil, reducing growth of forests and leading to loss of flora and fauna.

Water Quality Deterioration: The nitrous oxide can lead to eutrophication of costal estuaries that can lead to oxygen depletion and reduce fish and shellfish population. Excess nutrient nitrogen causes species composition changes and biodiversity loss.

Global Warming: The nitrous oxide causes the formation of the ozone that is a greenhouse gas, which accumulates in the atmosphere, can cause a gradual rise in the earth’s temperature global warming leads to a rise in the sea level, biodiversity loss, ecosystems changes and risk to human health.

Toxic Chemical: A variety of toxic products, which may cause health effects and biological mutation, can be generated by reaction between NO_x, ozone and common organic chemicals.

2.2.3 **Sulphur Oxides (SO_x)**

Sulphur oxides are caused by the oxidation of the sulphur in the fuel into SO_2 and SO_3. They are formed during the combustion process through the reaction:

$S+O_2\rightarrow SO_2$

Emissions of sulphur dioxide are primarily a function of the sulphur content of the fuel. The sulphur content of petroleum-based fuels can vary from less than 0.3 percent to more than 5 percent. On average, distillate diesel fuel contains 0.3-0.5 percent sulphur and residual fuel oil around 2.3-3.0 percent. Acid rain, health effect and climate change are some of the most important effects.

Health effects: They are caused by the exposure to high levels of SO_2 and include breathing problems, respiratory illness, changes in the lung's defenses and worsening respiratory and cardiovascular disease. People with asthma or chronic lung or heart disease are the most sensitive to SO_2. Shipping emissions have been estimated to induce more than 60,000 premature deaths globally, of which about one third in Europe [23].

Acid Rain: Since SO_x is corrosive, it contributes to damages trees and crops, generates acidification of lakes and streams, accelerate corrosion of buildings and reduce visibility.

Global Warming: SO_x forms aerosol which reflects sunlight and has a direct effect on cooling. The SO_x emissions from land sources have decreased over the last years, while the SO_x ship emissions have increased.

2.2.4 **Particulate Matter (PM)**

Particulate matter is a designation for a large variety of extremely small particles of organic and inorganic origin. They can contain carbon, metals, ash, soot (almost purely elemental carbon), acids such as sulphates and nitrates and carbonates. Some PM consist of partly combusted or non-combusted hydrocarbon material (fuel and lubrication oil) and there is an overlap between the designations of PM and HC. Ash from fuel and lube oil is only a minor component of the emitted PM and come mainly from metals (vanadium and nickel) present in those oils [24]. Particulates are a result of incomplete combustion, dirty fuel oil and imperfect lubrication of the cylinders. At low and transient loads soot can be a high contributor to the total PM emissions while at higher loads the fraction is much smaller. Because the PM emission depends on the load, the fuel oil composition, and the lubrication oil type and dosage it is difficult to establish general emission rates for PM. The sulphur content on the fuel has a large influence on the PM emissions as illustrated in figure 5.

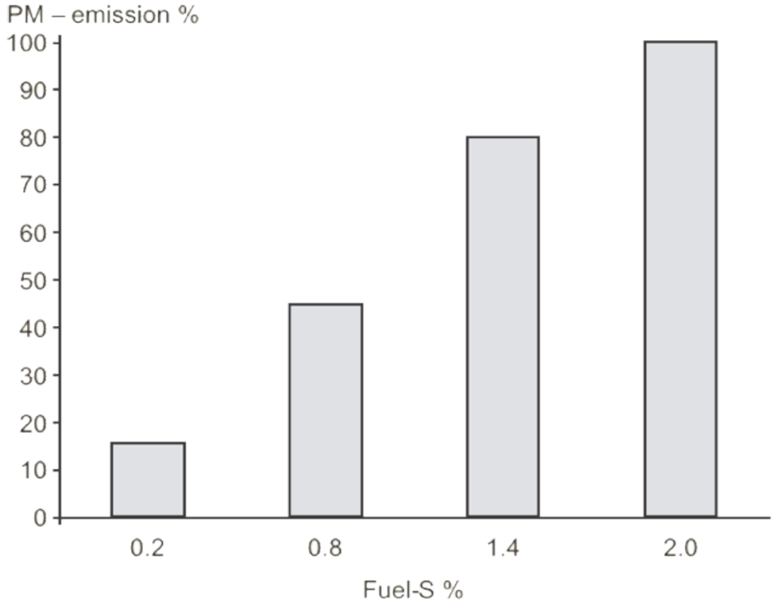


Figure 5: PM emission as function of sulphur content in the fuel oil (MAN Diesel & Turbo, 2012)

Particulate matter is categorized by the size of the particles [25]:

Table 2: Particle size (aerodynamic diameter) for particulate matter (EPA, 2013)

Fraction	Size range
PM_{10}	< 10 μm
$PM_{2.5}$	< 2.5 μm
PM_1	< 1 μm
Ultra-Fine Particles (UFP)	< 0.1 μm

Particles from marine fuel oils are normally in the small end of the size range, while deposits from the combustion chamber and exhaust system are much larger.

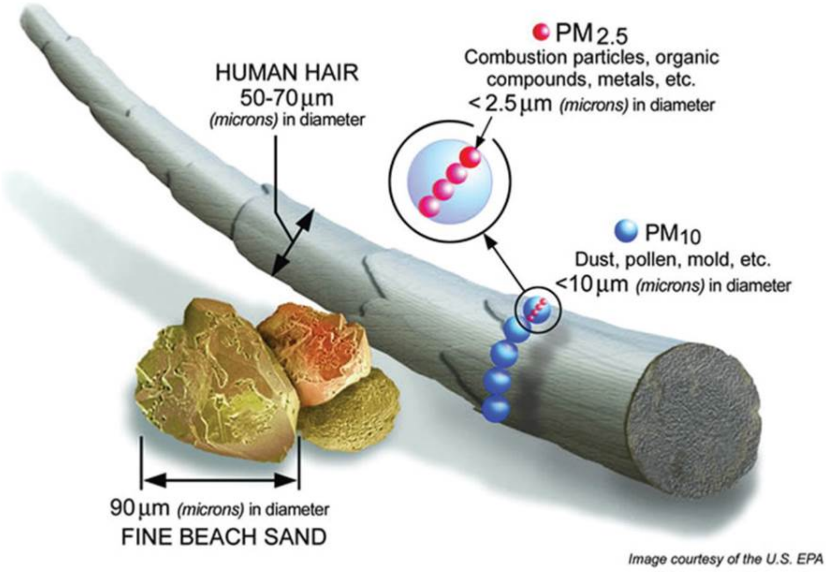


Figure 6: Particulate matter in real size (Environmental Protection Agency, 2013)

The size of the particles determines how dangerous they are to humans. The particles that are smaller than 10 μm in diameter can be inhaled by humans and the smaller the size the further the particle can penetrate into the lungs. Some may even get into the bloodstream and can cause serious health problems. Smaller particles can furthermore be carried with the wind over larger areas. Increasing concern exists with regards to PM being the cause of lung cancer and other respiratory and circulatory diseases. Studies suggest that there are many consequences of PM pollution including the following:

- Increased respiratory symptoms, such as irritation of the airways, coughing and difficulty breathing
- Decreased lung function
- Aggravated asthma
- Development of chronic bronchitis
- Irregular heartbeat
- Nonfatal heart attacks
- Premature death in people with heart or lung diseases
- Mutagenic and carcinogenic effects

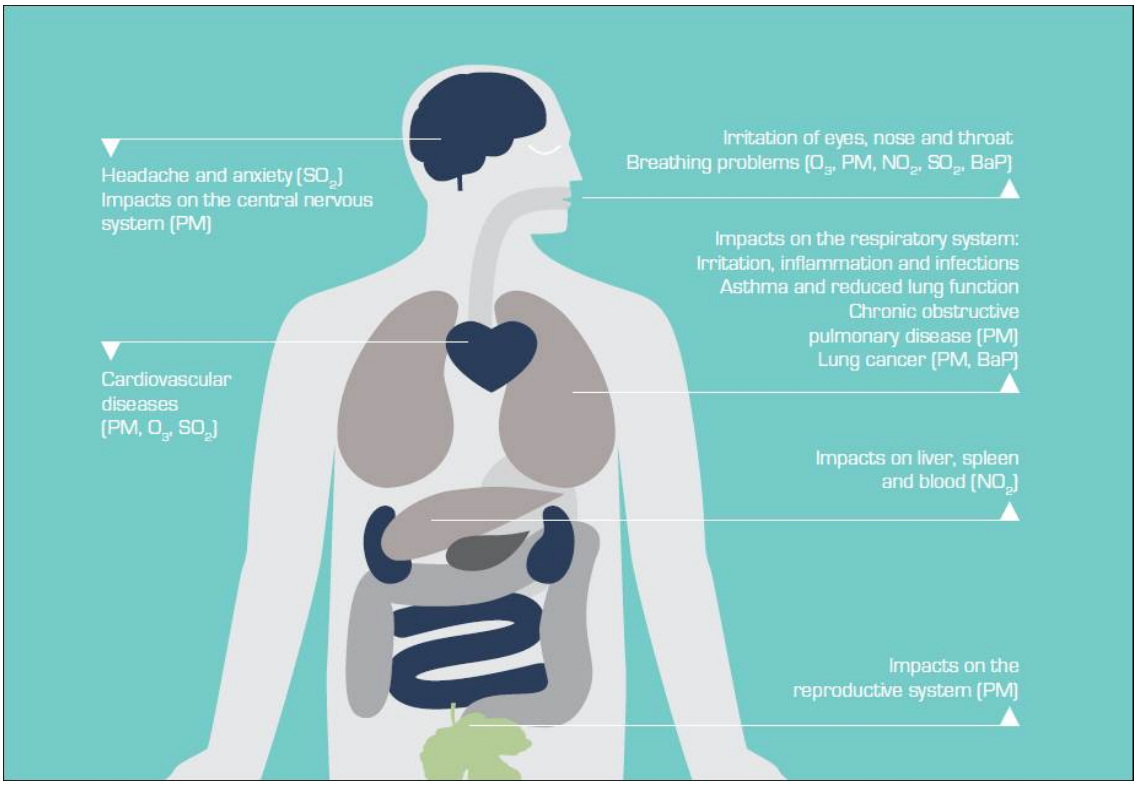


Figure 7: Air pollution health impacts(European Environmental Agency, 2013)

2.2.5 Carbon Dioxide (CO_2)

Carbon dioxide is a product of any combustion process of fossil fuels and is formed during the combustion. The amount of CO_2 from a combustion process depends on the fuel and its carbon content. . It is not toxic; however it is the main responsible of the “greenhouse effect” and global warming. Transport account for the 25% of energy-related CO_2 emissions. Shipping account for approximately 2% of global anthropogenic emissions of CO_2 but the annual grow rate was close to 2.5% during the past decade.

Carbon dioxide (CO_2) is the primary greenhouse gas emitted through human activities. In 2013, CO_2 accounted for about 82% of all U.S. greenhouse gas emissions from human activities. Carbon dioxide is naturally present in the atmosphere as part of the Earth's carbon cycle (the natural circulation of carbon among the atmosphere, oceans, soil, plants, and animals). Human activities are altering the carbon cycle—both by adding more CO_2 to the atmosphere and by influencing the ability of natural sinks, like forests, to remove CO_2 from the atmosphere. While CO_2 emissions come from a variety of natural sources, human-related emissions are responsible for the increase that has occurred in the atmosphere since the industrial revolution [1].

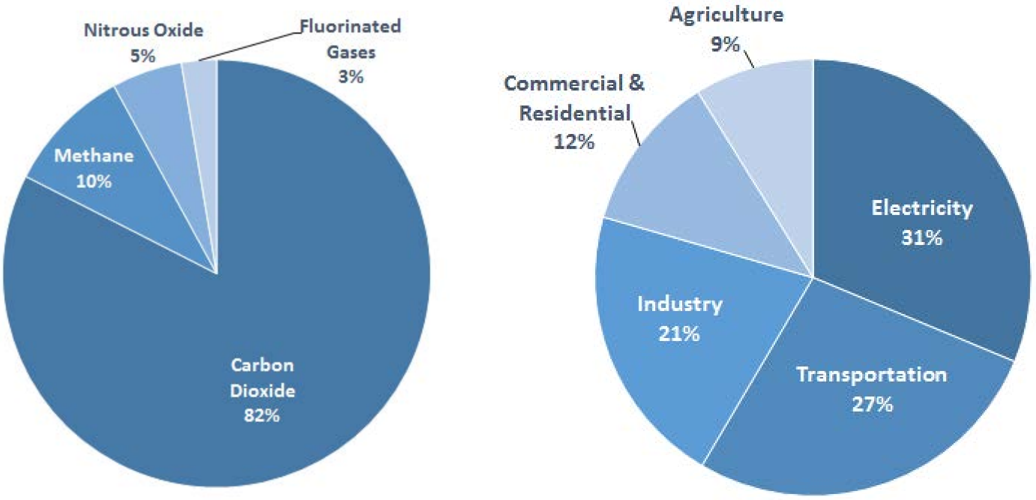


Figure 8: U.S. Carbon Dioxide Emissions in 2013 and U.S. Greenhouse Gas Emissions in 2013 (EPA, 2013)

The main worry is that the amount of radiation which escapes depends on the concentration of greenhouses gases in the atmosphere - carbon emissions add to the concentration, meaning that less radiation escapes. This means that the surface temperature of the Earth increases by 0.6°C ± 0.2°C over the last century. This may not sound like much, but the warming will increase with time, and could have disastrous consequences. These might include:

- Sea level rise - densely settled coastal plains would become uninhabitable with just a small rise in sea level, which would result from melting of the ice caps
- Impacts on agriculture - Global warming could have major effects on agricultural productivity
- Reduction of the ozone layer - Warming would result in increased high cloud cover in winter, giving chemical reactions a platform in the atmosphere, which could result in depletion of the ozone layer
- Increased extreme weather - A warmer climate could change the weather systems of the earth, meaning there would be more droughts and floods, and more frequent and stronger storms
- Spread of diseases - Diseases would be able to spread to areas which were previously too cold for them to survive in

- Ecosystem change - As with the diseases, the range of plants and animals would change, with the net effect of most organisms moving towards the North and South Poles

2.3 Regulations on Restricting Emissions in Shipping

Ship emissions are regulated worldwide. The principle of all regulations is that they shall apply to all ships regardless of flag state. Two main authorities establish the emission regulations in Europe: The International Maritime Organization (IMO) and the European Union (EU). Some countries have additionally enforced national regulations for different kinds of emissions. One country is Norway, which has introduced a NO_x-tax for ships operating between Norwegian ports. The International Maritime Organization is a specialized organization within the United Nations (UN). 168 countries are member states and three are Associate Members (Hong Kong & Macao (China) and the Faroe Islands (Denmark)). IMO works to facilitate cooperation among shipping countries, governments and the shipping industry working on improving safety and security at sea and to prevent pollution of oceans, coasts and the atmosphere.

Normally the regulations adopted in IMO also become part of the EU legislations. Independent EU regulations for ship emissions include demands to the quality of marine fuel oil, regulations on ship fuel used in inland waterways and ports in the EU and special regulations for passenger ships.

Emission Control Areas

The concept of Emission Control Areas (ECAs) is that they are areas where stricter mandatory regulations apply to all ships operating in the area regardless of flag state in order to prevent and reduce air pollution from emissions from ships. The idea is that reductions are enforced in areas where the emissions are most harmful to humans and the environment i.e. in densely populated areas and in areas with low alkalinity where acidic rain can damage crops and fresh water basins instead of reducing emission in the more open ocean where they affect relatively few people.

The Baltic Sea is one of the world’s largest seas of brackish water. Over 85 million people live in the countries around the Baltic Sea. Due to geographical, climatological, and oceanographic characteristics it is a highly sensitive ecosystem. The Baltic is almost closed off by the Danish Sound and the Belt Sea and water exchange between the Baltic and the open sea is very limited. The Baltic is very shallow with an average depth of only 53 m. Currently two ECAs have entered into force in Europe. One is the Baltic Sea and the other is the North Sea including the English Channel area. The two ECAs include coastal areas of heavy population where a unit of air emission has a much bigger impact than a unit emitted on the open ocean or in a less densely populated area. The Baltic Sea ECA went into operation on May 19th 2006 and the North Sea ECA went into operation on November 22nd 2007.

Initially the existing ECAs were proposed as SECAs (Sulphur Emission Control Areas) due to the concern sulphur emissions were causing in Northern Europe. So far the two ECAs have only been regulated with respect to sulphur emissions, but NO_x is likely to be added with time. While there are more places that will probably join the ECA down the road, there are currently four active Emission Control Areas:

1) Baltic Sea area: only for SO_x
2) North Sea area: only for SO_x
3) North American area: for SO_x, NO_x and PM
4) United States Caribbean Sea area: for SO_x, NO_x and PM

Figure 9: Geographic distribution of Emission Control Areas (IMO, 2014)

The ECA is not only for SO_x emissions, but also particulate matter and NO_x. It fully implemented on after August 2012. In September 2010 another US proposal for an ECA around Puerto Rico and the US Virgin Islands was discussed at IMO. As part of the North American ECA proposal, the US EPA presented data demonstrating that particulate matter emission rates are linked to the sulphur in fuel, which forms sulphate particles. For this reason there are no specific emissions limits for particulate matter in Annex VI. Further ECAs seem likely to be proposed for Norway, Japan and possibly the Mediterranean in the near future.

IMO Regulations

Shipping emissions are expected to double by 2050, as are the related social and environmental effects [28]. In order to mitigate environmental and social risks associated with these emissions, regulators around the world have started to act. Generally speaking, when it comes to reducing emissions and supporting energy efficiency, regulators deploy four primary policy mechanisms: emissions trading, financial incentives/taxes, emission reporting/monitoring obligations and energy efficiency/emissions standards.

GHG Emissions

The past three years have seen two new policy mechanisms set by the IMO to tackle GHG emissions: the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). The EEDI will lead to approximately 25-30% emission reductions by 2030 compared to “business as usual”.

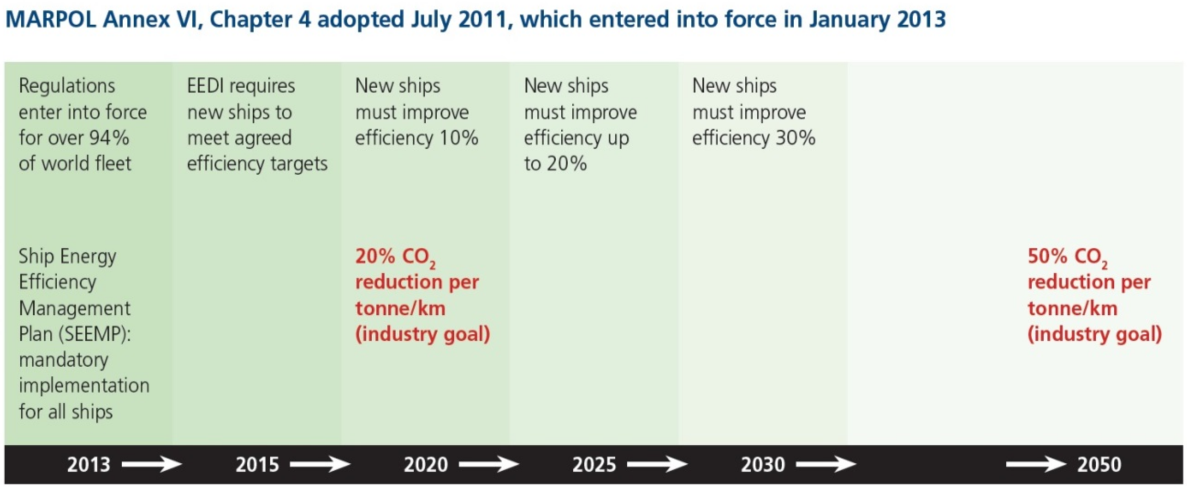


Figure 10: EEDI and SEEMP scope of view (IMO, 2013)

Both mechanisms, which fall under the category “energy efficiency/emissions standards”, are the first ever mandatory GHG regulations for the shipping industry. These mechanisms, which came into effect on 1 January 2013, apply to all ships of 400 tonnes gross tonnage and above. While the EEDI sets a minimum energy efficiency standard for new ships, the SEEMP enables ship owners to measure the fuel efficiency of existing ships and to monitor the effects of any changes in operation [29]. The EEDI, which is probably the most important measure, will allow ship designers and builders to use the solutions that they believe are the most cost-efficient to comply with the regulations. Based on the EEDI, the CO_2 reduction level (grams of CO_2 per tonne mile) for the first phase (2015-2019) is set to 10% and will be tightened every five years as outlined in the figure below. The baseline is the average efficiency for ships built between 2000 and 2010. Note that developing countries will not have to implement the standards until 2017, allowing them time to develop shipbuilding capacity.

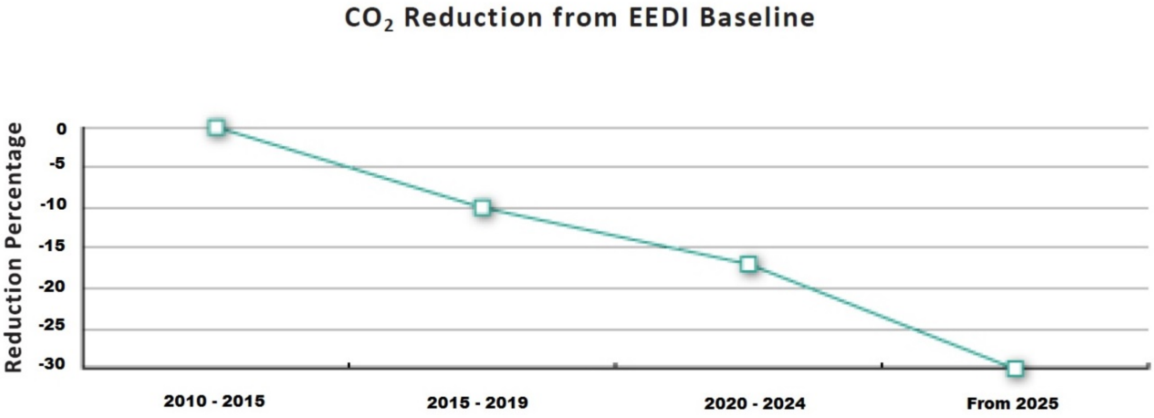


Figure 11: CO_2 reduction from EEDI Baseline (IMO, 2012)

Non-GHG Emissions

IMO MARPOL 73/78 is the International Convention for the Prevention of Pollution from Ships. It was first laid down in 1973 and subsequently modified in 1978. The MARPOL 73/78 is one of the most important environmental conventions for the ship-owners to adhere to. The convention was agreed to control pollution of the oceans including exhaust gas emissions such as SO_x, NO_x and particulates as well as Emission

Control Areas, volatile organic compounds for tankers and shipboard incineration [30]. MARPOL Annex VI is the part of the MARPOL convention concerned with air pollution. All ships over 400 GT must comply with the IMO regulations after the IMO principle about “no more favorable treatment”.

There are two main thresholds on sulphur emissions that currently apply to shipping:

- In Sulphur Emissions Control Areas (SECAs) the maximum sulphur content in marine fuels used to be under 1.00% of total mass (m/m) until 31 December 2014 and must be reduced to 0.10% m/m or less by 1 January 2015.

- In areas outside SECAs the maximum sulphur content in marine fuels used must be reduced from 3.50 % m/m to 0.50% m/m by 1 January 2020.

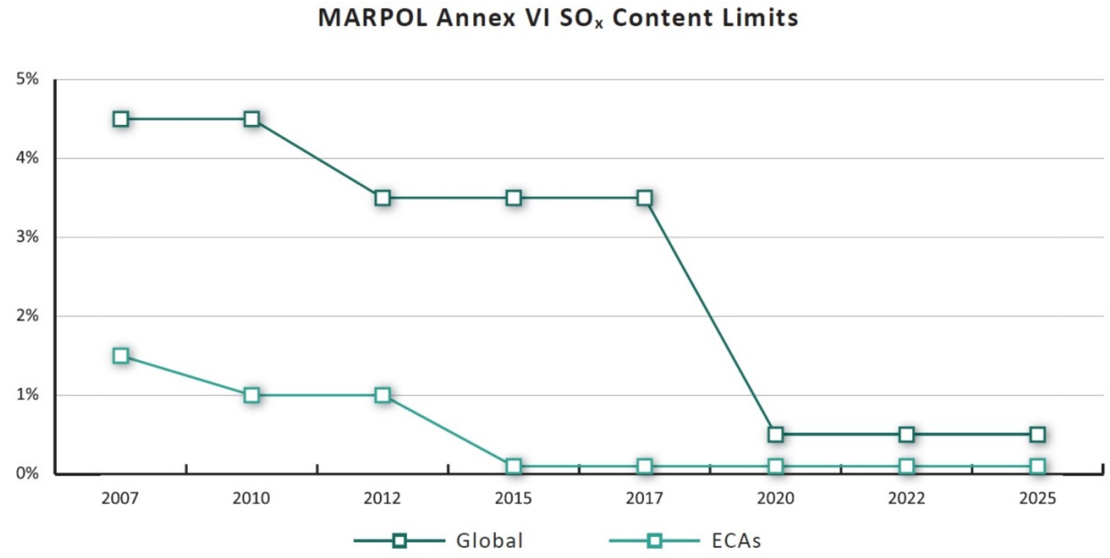
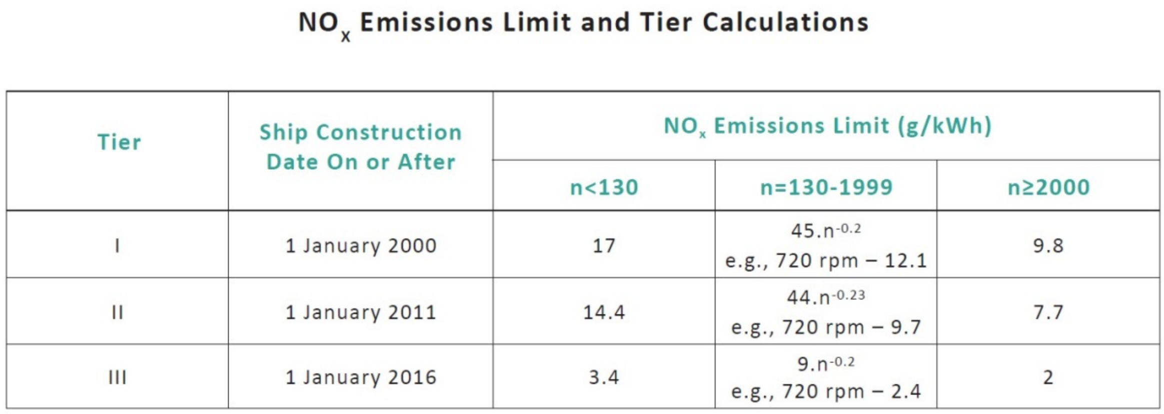


Figure 12: Marine fuel sulphur content reduction as required by Regulation 14/ MARPOL (IMO, 2012)

Regarding nitrogen oxide emissions, thresholds depend on the vessel category (Tier I, Tier II and Tier III) as highlighted in the table below. The category is determined based on the vessel’s construction date and engine speed. Ships constructed before 1 January 2000 with diesel engines above 5000 kW are required to have installed a certified Approved Method or a certification stating the compliance with Tier I standards [31].

Ships that are built after 2015 will be required to comply with Tier III standards in ECAs (outside ECAs Tier II standards can be applied). Note that NO_x regulations do not apply to vessels used for emergency operations or to marine engines that underwent major conversions before May 2005.

Table 3: NO_x emissions limit and Tier calculations (IMO, 2013)



NO_x Emissions Limit and Tier Calculations

Tier	Ship Construction Date On or After	NO_x Emissions Limit (g/kWh)		
		n<130	n=130-1999	n≥2000
I	1 January 2000	17	$45.n^{-0.2}$ e.g., 720 rpm – 12.1	9.8
II	1 January 2011	14.4	$44.n^{-0.23}$ e.g., 720 rpm – 9.7	7.7
III	1 January 2016	3.4	$9.n^{-0.2}$ e.g., 720 rpm – 2.4	2

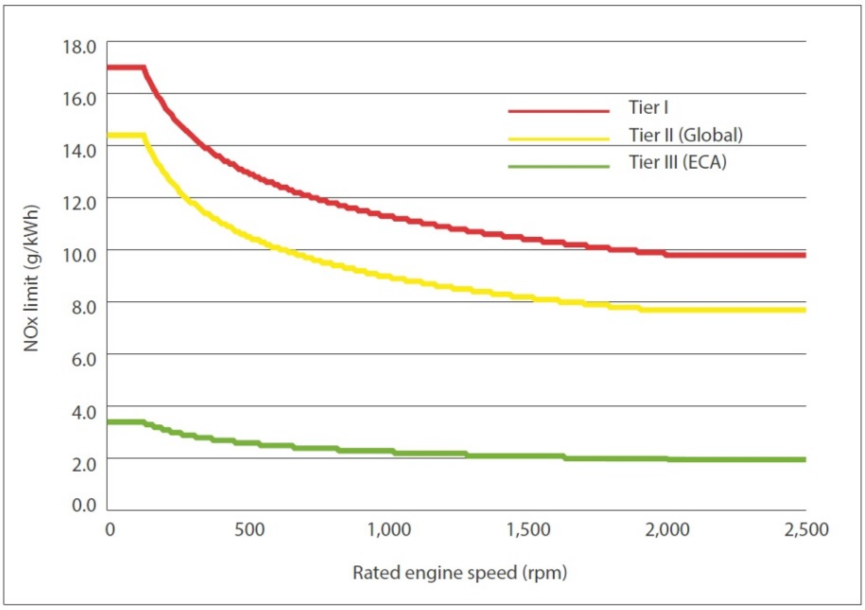


Figure 13: Regulation 13-NO_x emission limit values (IMO, 2013)

Regulations in the European Union

Regarding GHG emissions, the EU has set specific targets and is discussing various policy development mechanisms. For non-GHG emissions, the EU generally follows the standards set by the IMO.

GHG Emissions

The EU has set a target to reduce GHG emissions by 20% by the year 2020, compared to 1990 levels and is aiming to reduce shipping emissions by 40-50% by 2050.8 To achieve these targets, the EU supports the implementation of an emissions trading scheme for the shipping industry, a move similar to what occurred with the airplane industry. However, the EU will not push for a shipping inclusion too quickly given the issues that arose following the inclusion of the aviation industry into an emissions trading scheme.

In October 2012, the EU announced that it was considering the adoption of a system for the monitoring, reporting and verification (MRV) of fuel-based emissions. The EU believes an MRV is a first step towards the implementation of an emissions trading system [32]. With a policy mechanism such as an MRV in place, ship operators would be required to monitor and report their fuel consumption and CO_2 emissions and a third party would need to verify the data. The scope of the MRV is expected to cover only vessels of 5,000 gigatonnes and above, such vessels accounting for 90% of total shipping emissions [33]. The EU has yet to pass a bill that would support the creation of a pilot project for a global MRV [34]. It is likely that any market-based measures proposed by the EU will not enter into force until 2017.

2.4 Operation of 2-stroke/4-stroke engines and techniques for abatement of emissions

Marine Engines & the Combustion Process

Engines for marine use are generally compression ignited two- and four-stroke diesel engines. From an environmental and economical point of view an important factor is the

Specific Fuel Oil Consumption (SFOC, measured in gr fuel oil per kWh) of the engine. This expresses the engine’s fuel efficiency.

The fuel is injected into the cylinder at very high pressure (1,300-1,800 bar) which results in very short injection period and atomization of the injected fuel. The injection happens when the piston is near the top of the cylinder. By the time of injection the air in the cylinder is compressed to high pressure (around 200 bar) and so hot that the fuel ignites when injected. Mixing of the fuel and the air in the cylinder is essential. Good mixing means that more fuel is exposed to the air needed for combustion. The high injection velocity created turbulence which serves to mix the fuel and the air. The time elapsed from the fuel is injected to it ignites is called the ignition delay. This is because it takes time for the flame to appear and for the pressure to build up in the cylinder. Delayed ignition can result in high peak temperatures which play an important role for NO_x formation.

The fuel injection takes place just before the piston reaches Top Dead Center (TDC) and is stated in ° before TDC. The timing of the fuel injection is another important engine parameter for controlling the formation of different emission species. For complete combustion of an amount of fuel a certain amount of air is required (two oxygen atoms for one carbon atom and one oxygen atom for two hydrogen atom). If the fuel-air mixture is contains exactly the amount of oxygen required to burn all the fuel it is called stoichiometric (excess air ratio $\lambda = 1$). If there is an excess of air the mixture is lean ($\lambda > 1$) and if there is too little air to fully combust all the fuel the mixture is rich. Generally there is always an excess of air in diesel engines to ensure proper combustion of all fuel, but in the combustion chamber the mix can be locally lean or rich.

Main Propulsion Engines

The propulsion engines(s) on the ship propel the ship. On most cargo ships they are coupled to the propeller shaft directly or through reduction gears. Generally low speed engines are two-stroke engines and medium speed engines and high speed are four-stroke engines. The average specific fuel consumptions of the three engine groups (and gas turbines) are listed below:

Engine Type: SFOC [g/kWh]

Low Speed: 170

Medium Speed: 190

High Speed: 200

Gas turbines: 240

It must be kept in mind that the SFOC given by the engine manufacturer originates from the test bed where all conditions are ideal and therefore the actual SFOC in real operation may be considerably higher.

Auxiliary Engines

The auxiliary engines supply all the systems on board needed for running and operating the ship: Cooling pumps for the main engine, general service pumps, ballast pumps, bilge pumps, compressors for starting air, fuel oil treatment systems, electricity on board for lights, navigation etc, thrusters and cargo gear such as ramps and cranes.

In most ships the auxiliary engine are medium or high speed four-stroke engines. Normally each auxiliary engine is coupled to a generator which generates electricity and this couple is called a generator set or genset. The same engine type can be a propulsion engine on smaller ships and an auxiliary engine on a larger ship. Only difference is that it is coupled to a generator instead of a propulsion system. On ships with diesel-electric propulsion a number of gensets produce electricity for both propulsion and the auxiliary system.

Power-Take-Off

Some ships are equipped with shaft generators. The system is also called Power- Take-Off (PTO) because electric power is generated off the main shaft. PTO is generally installed on ships operation on longer trips with little speed variation [35]. The electrical efficiency of a shaft generator is typically 90-95%. There are several advantages of using PTO. The power generating takes place directly off the main engine and thus one, some or all auxiliary engines can be turned off when the ship is under way. The large main engine sometimes run on cheaper oil than the auxiliary engines and have lower SFOC, and thus the electricity produced by PTO will be cheaper than running the auxiliary engines.

Auxiliary Boilers

Exhaust gas boilers are used for producing heat on board for e.g. hot water, air conditioning and heating of cargo and fuel oil. When the ship is under way the exhaust gas boilers are used to utilize the excess heat in the exhaust gas for heating purposes. When the ship is at berth and the main engines are not running the heating is produced from auxiliary boilers (figure below) by burning various kinds of fuel oil. The use of auxiliary boilers thus adds to the total fuel consumption of the ship.

Figure 14: View of auxiliary boiler (Aalborg Industries, 2013)

Conventional Ship Engines

Although electronically controlled engine types have been introduced to the market the recent years many engines are of the mechanically controlled type. Larger ships typically use two-stroke engines as main propulsion, while smaller ships, e.g. Ro-Ro ships use four-stroke medium speed engines. Auxiliary engines are typically four-stroke engines.

Low Speed, Two-Stroke Engines

The definition of low speed is a widely used engine term but not exact. Generally engines operating with a speed lower than 200 revolutions per minute are designated low speed engines. Low speed type today always incorporate two-stroke operation and crosshead type design which makes the engine narrow and rather tall.

Low speed two-stroke engines are the most energy efficient engines on the market and the dominating engine type on large vessel types such as tankers, bulk carriers and Container ships. Some two-stroke engines are very large and can deliver up to 85 MW. At the same time the low speed two-stroke design is one of the simplest and most reliable engine designs. For very large bore engines the SFOC can be as low as 154 g/kWh [36] and have an overall thermal efficiency of up to 55%. If no other data is available the SFOC of low speed engines is estimated to 170 g/kWh. Two-stroke engines are typically insensitive to fuel oil quality and are normally operated on cheap residual oils. The engine is coupled directly to the propeller without the use of a gearbox and thus the propeller turns with the same number of revolutions as the main engine. If the ship is to move in reverse the main engine must be stopped and started again turning in the opposite direction.

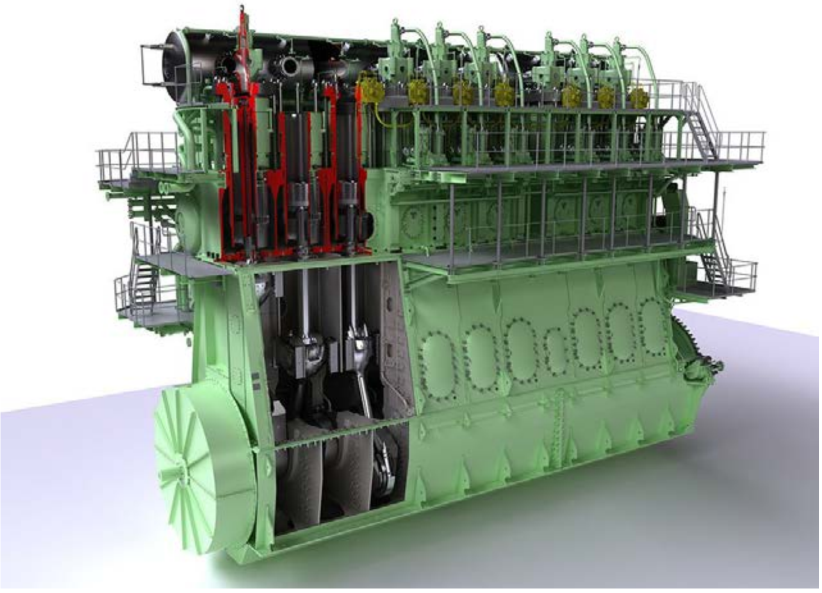


Figure 15: 2-stroke slow-speed Main Engine G95ME-C9.2 (MAN Diesel & Turbo, 2014)

Medium Speed, Four-Stroke Engines

Medium speed engines are primarily used for propulsion of smaller vessels, but also in some ship types such as large cruise ships and Ro-Ro ships. Marine applications range from one-engine/one-propeller configurations to multiple engines/two propellers mechanical or diesel/electric transmission systems. The speed range is from 200 –

1,000 rpm. Four-stroke engines are found in in-line and V-configurations. One advantage of medium speed four-stroke engines is the lower weight-to-power ratio compared to low speed two-stroke engines and the compactness.

Engine output for four-strokes can be up to 20,000 kW and the engine type is found in configurations varying from 4 in-line cylinders to V20-configurations. Four-stroke engines are normally coupled to the propeller via reduction gears and more than one engine can be coupled to one propeller shaft. NO_x emissions are generally lower for four-stroke engines than for two-strokes and thus four-strokes meet IMO NO_x regulations more easily. Depending on the engine they can run on HFO or distillates. If no other data is available the SFOC of medium speed engines can be estimated to 190 g/kWh.

Figure 16: Medium-speed engine (Wärtsilä, 2014)

Techniques for reduction of emissions

CO_2

A number of measures to reduce CO_2 emissions are available to the shipping industry. The emission reduction measures can be divided into four main categories:

- Technical measures generally aim at either reducing the power requirement to the engines or improving fuel efficiency. These measures are linked to the design and building of ships (e.g. hull design), to optimization of the propulsion system, to the control and efficient operation of the main and auxiliary engines and to retrofits on existing ships. These measures generally have a substantial investment cost and potentially very significant emission reduction effects. Many technical measures are limited to application on new ships, due to the difficulties or high costs of retrofitting existing ships.

- Alternative fuels and power sources form another set of technical measures. The alternatives range from supplementary measures (e.g. wind, solar) to a complete switch of fuel (e.g. to gas, bio-diesel, or nuclear), and generally require significant investments upfront, both onboard and in new infrastructure.

- Operational measures relate to the way in which the ship is maintained and operated and include measures such as optimized trim and ballasting, hull and propeller cleaning, better engine maintenance and optimized weather routing and scheduling. Operational measures do not require significant investment in hardware and equipment. The measures generally have low investment needs and moderate operating costs. Implementation of many of these measures requires execution of programs involving changes in management and training. Many of these measures are attractive for purely economic reasons.

As shown in the figure below, many technologies are available to reduce the loads on, and losses within, each vessel to reduce fuel consumption and CO_2 emissions [37].

Engine, propeller, hydrodynamic, aerodynamic, and auxiliary power technologies offer the ability to reduce ships’ energy requirements, but there are also many maintenance and operational practices within these areas that can optimize the existing physical ship components. For example, regularly removing growths on propellers or enhancing the smoothness of the hull reduce power requirements. Vessel speed reduction is the single largest fuel use and CO_2 reduction opportunity because it can simultaneously optimize engine efficiency and reduce hydrodynamic and aerodynamic loads.

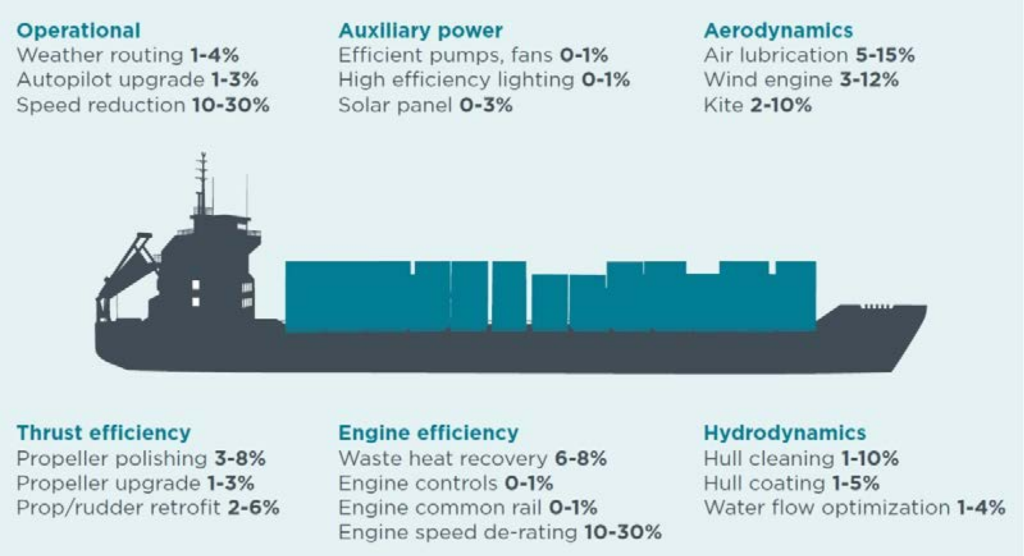


Figure 17: Potential fuel use and CO_2 reductions from various efficiency approaches for vessels (ICCT, 2013)

Examination of the Actual EEDI defining equation suggests a number of ways that compliance with the requirements might be achieved as well as options for reducing the value of the Index for a given ship. Typically these are:

- The installation of engines, subject to certain minima, in a ship with less power and, thereby, the adoption of a lower ship speed.

- To incorporate a range of energy-efficient technologies in order to minimize the fuel consumption for a given power absorption.

- The use of renewable or innovative energy reduction technologies so as to minimize the CO_2 production.

- To employ low-carbon fuels and in so doing produce less CO_2 than would otherwise have been the case with conventional fuels.

- To increase the ship’s deadweight by changes to or enhancements in the design.

If the option to install engines into the ship of a lower power rating were adopted, this would be a relatively simple and effective way to reduce the value of EEDI. Such an option, however, begs the question as to whether the ship would then have sufficient power to navigate safely in poor weather conditions. Another potentially dangerous situation is to be found in maneuvering satisfactorily in restricted channels or harbors under a range of adverse tidal and weather conditions. However, in the latter context, tugs might normally be employed.

There is a considerable range of energy-saving technologies available for ships. These broadly relate to primary propulsion and hydrodynamic options. However, there is also an emerging class of devices which are dependent on aerodynamic principles. The deployment of these technologies in specific instances is dependent on the ship's type, size and operational profile, with in some cases sociopolitical considerations, as well as on the ship's hull form. This is further complicated for some existing ship designs in relation to any other energy-saving devices that have been previously fitted: some being incompatible with each other. In all cases, however, a total systems engineering approach should be undertaken to avoid disappointing results.

SO_x, NO_x, PM

The industry has at its disposal a wide range of options and techniques to cut pollution, most of which are already available on a large scale and easily implementable. These include:

- Using low sulphur fuels: it's the easiest way of reducing pollutants from ships. Shipping fuels currently have almost 3,000 times the sulphur content of fuels used in road transport in Europe. Also, low sulphur fuels make the ship's engine run smoother and with less operating problems and maintenance costs. Last, but not least, using low sulphur fuel reduces other pollutant emissions.

- Scrubbers: a possible alternative to low sulphur fuels, they would cut emissions of SO_2 by 99% and considerably reduce emissions of other polluting particles A scrubber is a system that uses sea water and chemicals to remove sulphur from engine exhaust gas [38]. The scrubber uses a chemical reaction to neutralize the SO_x present in the exhaust gas. This reaction generates sulphates, which are then discharged into the sea. There are still some concerns about the by-products they produce in the cleaning process.

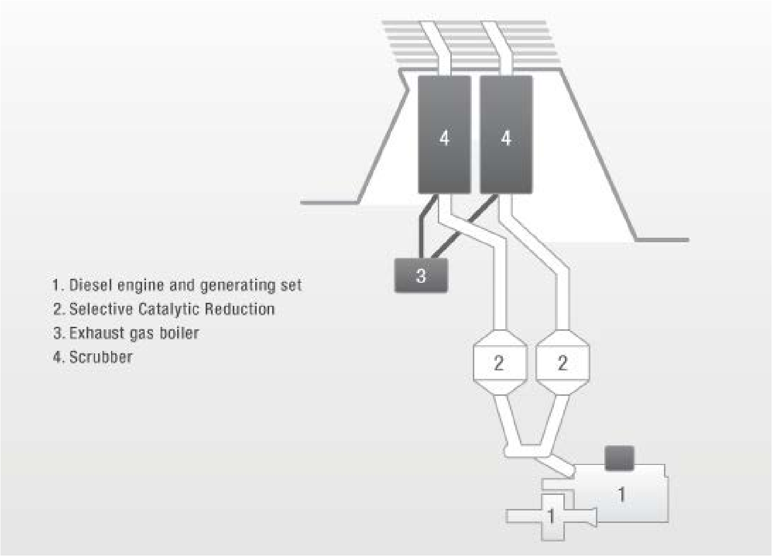


Figure 18: A Standard SO_x Scrubber (Wärtsilä, 2013)

- Internal engine modifications - such as water injection and exhaust gas recirculation: these are techniques to prevent NO_x production during the combustion process, and can abate NO_x emissions by 30 to 50%.

- Humid air motor: by adding water vapor to the combustion air, NO_x emissions could be cut by 70 to 85%.

- Exhaust gas recirculation (EGR): it is a mature technology, used in automotive engines for several decades. Exhaust gas is fed back into the cylinder air intake, lowering oxygen and increasing CO_2, which has a higher specific heat capacity than air. This slows combustion and reduces temperature, lowering NO_x. The EGR fan can adjust the amount of exhaust gas that is recirculated (the EGR ratio). EGR systems can cause higher CO and PM emissions. CO emissions can be controlled by adding water to the fuel. However, adding water can reduce fuel efficiency and increase PM. Increasing turbocharger and fuel injection pressure can help to reduce the PM emissions [39].

- Selective catalytic reduction (SCR): a system to treat exhaust gases after their production but before they are actually emitted. SCR can cut NO_x by up to 95%.

It's already used in some 500 ships worldwide and works better with low sulphur fuels [39].

Figure 19: Two-way approach for Tier III engine - EGR and SCR solutions (MAN Diesel & Turbo, 2015)

- Gas engines: ship engines can work with liquefied natural gas (LNG) which doesn't contain sulphur and therefore has SO_2 emissions close to zero. Gas engines also dramatically reduce other PM emissions. Although it's easier to fit new ships with such engines, conversions have already taken place.

- Shore-side electricity: can be used while ships are at the port and could cut SO_2, NO_x and other PM emissions by up to 90% (known as cold ironing)

- Alternative energy sources: experiments with wind and solar power, biofuels and fuel cells are ongoing and could be useful in the future.

More recommendations for the EU and its member states:

- Transposing the international standards for NO_x emissions into EU law and adopt regulation in Europe to address the NO_x emissions of the existing fleet.

- Extending the SO_x Emission Control Areas in the EU (e.g. in the Mediterranean, in the Black Sea, in the Irish Sea and the North East Atlantic) and designate NO_x Emission Control Areas as soon as possible.

- Monitoring that proper enforcement procedures are adopted in Europe in order to ensure compliance with the standards.

- Adopting market-based measures to make polluters pay a fair price for the emissions the shipping sector is responsible for. Among the proposals for a market-based measure (MBM) submitted to MEPC by the Parties, a proposal, originally by Denmark, on a levy on bunker fuel has gained growing support from other countries and the shipping industry. The revenues would be allocated to a Fund and used for buying emission credits in the international market to offset any emissions above a baseline or cap that would be gradually lowered over the years. The remaining part of the money would be used for other purposes related to greenhouse gas (GHG) abatement and adaptation [40].

3. PROBLEM DESCRIPTION

3.1 Monitoring fuel consumption and emissions

From different perspectives the need for reliable information on the consumption and combustion of bunker fuel and resulting emissions of air pollutants and GHGs is essential. Firstly, ship owners need to know the amount of fuel bunkered and consumed because fuel cost forms a large fraction of ship operating costs (up to 50 %). Secondly, in order to understand the present-day and potential future environmental impact of ships, the amount, type and location of the release of air pollutants and GHGs into the atmosphere need to be quantified. Thirdly, in order to propose environmental policies or to monitor progress or compliance with existing policies and legislation, the release of emissions from the sector over time periods (e.g. emissions inventories) or from individual ships (e.g. air emission limits, fuel quality requirements) needs to be known.

Monitoring of fuel consumption and GHG emissions from international shipping is currently under discussion at the EU level as well as at the IMO. The European Commission supports an internationally agreed global solution to decrease GHG emissions from ships. In October 2012, the European Commission announced it was preparing a proposal on a monitoring, reporting and verification (MRV) system for ship emissions based on fuel consumption as a necessary starting point to further mitigation strategies such as the development of market-based instruments or ship efficiency measures. At its sixty-third session the Marine Environment Protection Committee agreed that the development of an IMO performance standard for fuel consumption measurement for ships could be a useful tool, that the standard should be considered at future sessions, and invited further submissions on specific aspects of such a standard. (MEPC 63/23, 14 March 2012)

There are several approaches to monitoring, each with different characteristics. Important differences exist with regards to the costs of the equipment, operational costs, the accuracy of the measurements and the potential to monitor emissions of gases other than CO_2. Moreover, some approaches offer more opportunities to improve the operational fuel-efficiency of ships and fit better to possible future policies than others.

Monitoring of ship movements and fuel consumption

There is a large variety of different monitoring activities in use to establish information on ship movements and fuel consumption. The most important ones are presented here in alphabetical order: Automatic Identification System (AIS), Automated Mutual-Assistance Vessel Rescue System (AMVER), fuel sale statistics, information on board ships, International Comprehensive Ocean‑Atmosphere Data Set (ICOADS), Long Range Identification and Tracking (LRIT) and port statistics.

Automatic Identification System (AIS)

The highest level of detail on ship movements can be obtained with AIS data. The AIS was developed to avoid collisions and to assist port authorities to control marine traffic. IMO adopted a regulation (footnote on Regulation 19 of SOLAS Chapter V) requiring AIS to be installed on all ships larger than 300 GT engaged in international voyages, cargo ships over 500 GT engaged in national voyages and all passenger ships. An AIS transponder as installed on vessels includes a GPS (Global Positioning Receiver), which collects position, speed and course. It also includes VHF transmitters, which periodically transmit GPS information and information on the ship (such as vessel name, IMO number, flag, length, draught, destination and expected time of arrival). Currently, approximately 72,000 vessels are equipped with AIS. With position data, speed can be instantaneously calculated, providing a good estimate of delivered engine power, which can be further processed in emissions calculations. In coastal areas, AIS messages are captured by ground stations, while messages sent on the oceans are captured by satellite.

Information onboard ships

Under IMO regulation, specific information on fuel sales and fuel consumption is recorded by individual ships and their owner companies. Under regulation 18 of MARPOL Annex VI, the preparing and making available of bunker fuel delivery notes (BDNs) is compulsory for ships over 400 GT. This means in practice, for example, that the sulphur content of bunkered fuel is specified in the BDN by the fuel supplier and that, for example, a so-called MARPOL sample of the delivered fuel is kept on the ship. Furthermore, under SOLAS Chapter V regulation 28, ships over 500 GT on international voyages longer than 48 hours have to provide a daily report to the owner company including information on ship position, course and speed. Recently, several ship companies have started using flow meter information and frequent bunker tank readings to establish a monitoring system providing close to real-time information and through the use of software tools the actual and prognosed fuel consumption during the voyage can be used to optimize shipping operations, resulting in the reduction of fuel consumption.

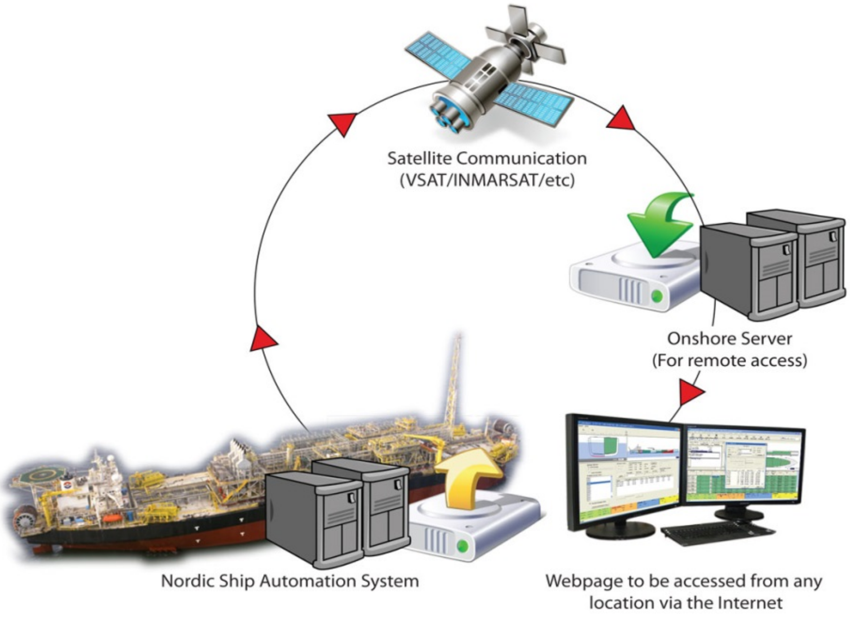


Figure 20: VRAS (Nordic, 2014)

Monitoring of ship emissions

There are different methods for monitoring emissions from shipping and the applied/required technique and frequency depends on the objective of the emissions monitoring. In the case of an emissions trading scheme, a continuous monitoring system or a system that is able to calculate the emissions budget is necessary. This can be achieved through emissions modelling using detailed activity data such as those provided by the AIS, continuous on-board measurements or a combination of both. In the case of CO_2 emissions only, verified fuel consumption data can be combined with certified fuel-specific emissions factors. In the case of control and enforcement of sulphur and NO_x regulations, once-only measurements such as on-board inspection or fuel sampling are sufficient to determine compliance.

In order to control more ships at a higher frequency, remote sensing techniques might be more practical or continuous emissions measurement on board ships could be implemented.

Onboard emissions measurements

Monitoring equipment could be installed onboard every ship to transmit measurements on a regular basis. There are different possible configurations. When only fuel consumption is measured, emission factors have to be applied for NO_x and SO_2. As mentioned above, there is uncertainty about the fuel quality and the effective use of after-treatment equipment. The latter problem can be solved with a direct measurement of CO_2, SO_2 and NO_x in the stack. This is the most accurate way to monitor the emissions of a ship. It allows controlling emissions anywhere and anytime. The drawback of this solution is its elevated cost. The advantage is that a continuous measurement, anywhere and anytime, is possible. This is necessary for the implementation of an emission trading system or the control of a SECA or NECA.

Continuous emissions monitoring systems (CEMS) were historically used as a tool to monitor flue gas for oxygen, carbon monoxide and carbon dioxide to provide information for combustion control in industrial settings but are now also applied in the shipping industry to continuously collect, record and report the required emissions data. However, the technology is not widely applied in the maritime transport sector yet.

The standard CEM system consists of a sample probe, filter, sample line (umbilical), gas conditioning system, calibration gas system, and a series of gas analyzers which reflect the parameters being monitored. Typical monitored emissions include: sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), diluent gases (CO_2 or oxygen O2), flue gas velocity and opacity (EPA, 1994). Direct monitoring thus permits the combining of CO_2 measurement with the measurement of other air pollutants.

Accuracy

There is little information on the accuracy of direct emissions monitoring systems on-board ships. According to the Center for Tankship Excellence (2011), CO_2 stack emissions can be monitored to an accuracy of +/-2%.

Completeness

If all stacks are equipped with an emissions monitoring device, all emissions of the ship can be captured with the emissions monitoring approach.

Consistency

Since the location of the measurement cannot vary, the consistency of the results between ships seems to be ensured for emissions meters. Measurement will always be automatic and there is no need for converting the fuel consumption data into emissions. However, differences in equipment as well as the care with which these are applied, calibrated and maintained can lead to inconsistencies between ships.

The cost of an emission monitoring system is roughly estimated at USD 100,000 for equipment (MariNO$_x$, Martek-Marine) while installation costs would add up to another USD 25,000 for a single main engine system.

Since the data is reported automatically, the burden for the crew is minimized. It is therefore relieving crew, company staff and regulatory authorities of paperwork and prevents administrative disputes [41]. However, it would be harder for the crew to detect whether a certain engine or boiler is running inefficiently and needs maintenance, since it would not be possible to immediately see where the emissions are created.

Figure 21: MariNO$_x$ (Martek-Marine, 2012)

Satellite monitoring

With satellite measurements, it is possible to determine NO_2 and SO_2 concentrations in the atmosphere. However, it is complicated to determine emissions from these concentrations. It seems that NO_2 emissions can be determined well in large areas but it is uncertain if this technique will allow monitoring of individual ships. One of the problems is background pollution from sources other than shipping in areas like the North Sea and the Baltic Sea.

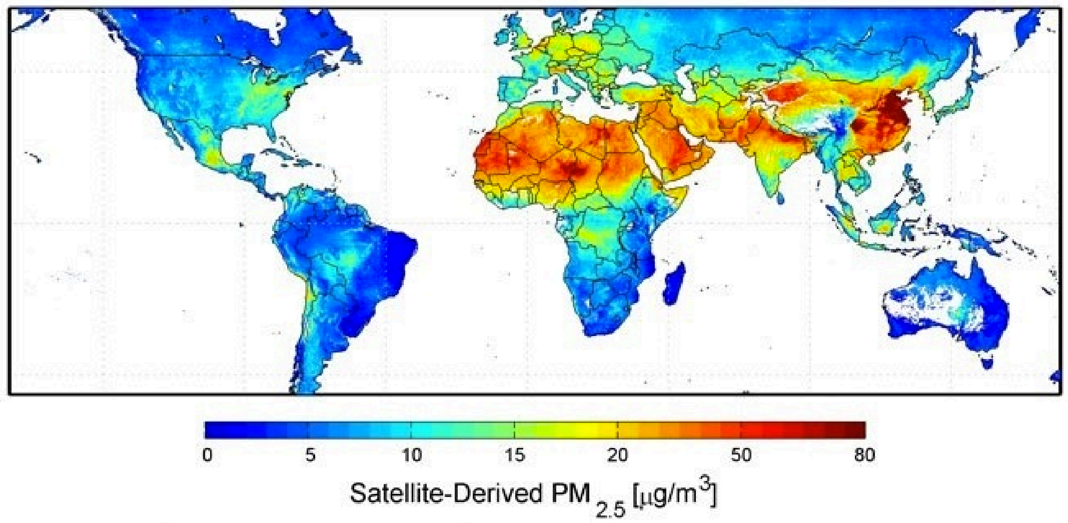


Figure 22: Geographic distribution of PM (Dalhousie University, 2006)

Sniffers

With an airplane, helicopter or unmanned aerial vehicle (UAV) it is possible to measure the concentrations of CO_2, NO_x and SO_2 in the plume behind a ship. The ratio of SO_2 and CO_2 is proportional to the sulphur content in the fuel. The ratio between NO_x and CO_2 can be used to check if the ship complies with NO_x regulations. An assumption has to be made about the specific fuel consumption (SFOC) of the engine. This technique is considered to be the most reliable, with an accuracy of 15% regarding sulphur content [42].

Figure 23: Photoshoot of unmanned aerial vehicle (Explicit, 2014)

3.2 Bottom-up and top-down inventories

Significant progress in estimating international ship emissions has been made in the past decade and several global, regional and local inventories have been performed. In general, the level of detail achieved and achievable within a certain study depends on the approach followed (“bottom-up” or “top down”) and the specific purpose of the analysis itself.

For example, emissions of CO_2 may be analyzed at a global scale, whereas NO_x and SO_x emissions should be analyzed at a more local scale since their greatest effects are produced on the environment in which they are released. In a bottom-up approach, each single element involved in a certain phenomenon is modelled and then the global impact is evaluated by aggregating the impacts of the different elements. The “bottom-up” approach estimates emissions for individual vessels combining ship type specific engine emission modeling, global distribution methods and ship operation data. It multiplies the energy consumption of the ships with a certain emission factor and aggregates the value to estimate the total emissions [43]. The “top-down” approach estimates emissions dividing the aggregate numbers for the total EU over the different countries, ships or locations. For the evaluation of emissions arising from maritime transport, two dimensions have to be considered: the quantity of emissions produced and where they are emitted. For both dimensions we can use a bottom-up or a top-down approach, or a mixture of the two:

- Full bottom-up approach: the pollution that a single ship emits in a specific location is evaluated. By integrating the evaluation over time and over the fleet it is possible to evaluate total emissions and their geographic distribution. This approach can be considered much more reliable, but the data required for such an approach have only recently come available, so for the moment there is a limited amount of studies using this approach. As a result, a considerable amount of studies take approaches that are more hybrid.

- Bottom-up approach in the evaluation of total emissions, but top-down in the geographical characterization: a single vessel is considered in the analysis, but nothing is known about its position. By making assumptions, it is possible to provide an estimate of the total emissions which are later geographically characterized using different criteria.

- Top-down approach in the evaluation of total emissions, but bottom-up in the geographical characterization: this analysis starts by considering a single maritime route or a particular geographic cell and evaluating the global activity which is carried out on it, no matter which vessel carries out the activity. Emissions from the individual cells are then aggregated to calculate total emissions and assumptions are made in order to assign total emissions to the different ships (or at least to the different categories).

- Full top-down approach: total emissions are calculated without considering the characteristics of the individual vessels and are later spatially assigned. The first studies on ship emissions took this approach and used international marine fuel usage statistics to estimate ship emissions, but results from this approach were later considered to be unreliable.

In regional inventories, the bottom-up approach is applied. In a bottom-up approach the individual base elements of the system are first specified in great detail. These elements are then linked together to form the main system. Thus, the emissions are calculated based on information from individual vessels and its movements.

One of the main advantages of the global inventories is their global coverage. Furthermore, the top-down approach used for global inventories allows a much faster emission calculation than the more detailed hence time consuming bottom-up approach used by the regional inventories. On the other hand, the resolution of the regional inventories is usually finer and their spatial distribution much more accurate. Since international fuel statistics do not include the fuel consumed for domestic ship traffic - from harbor to harbor within the same country – it has not been represented by the global inventories. The domestic ship traffic can be significant for the inland seas like the Mediterranean, which is surrounded by 22 countries. Applying bottom-up approach on a global scale would not only be much too costly, but would also be limited by the global unavailability of detailed ship movement data.

In terms of data quality, bottom-up apportionment methods (including apportioning based on the flag of a ship, location and between importer and exporter) are considered to be more comprehensive and accurate for the individual nations concerned. This is because the emissions are based on the movements and characteristics of individual vessels and their port callings. However, the data required is costly and requires annual updates. If data cost is a pivotal issue for policymakers, then top-down proxies could be favored for methods using a bottom-up models, or a top-down method could be used instead.

The most important sources of uncertainty in the bottom-up method results are the number of days a ship spends at sea per year (attributable to incomplete AIS coverage of a ship's activity) and the number of ships that are active (in-service) in a given year (attributable to the discrepancy between the difference between the number of ships observed in the AIS data and the number of ships described as in-service in the IHSF database). The top-down estimates are also uncertain, including observed discrepancies between global imports and exports of fuel oil and distillate oil, observed transfer discrepancies among fuel products that can be blended into marine fuels and potential for misallocation of fuels between sectors of shipping (international, domestic and fishing). Neither the top-down nor the bottom-up uncertainties are symmetric, showing that uncertainty in the top-down best estimate is more likely to increase the estimate of fuel consumption from the best estimate and that uncertainty in bottom-up best-estimate value is more likely to lower estimated values from the best estimate.

Uncertainties are associated with the accuracy of top-down fuel statistics and with the emissions calculations derived from marine fuel sales statistics. Uncertainties also exist in the bottom-up calculations of energy use and emissions from the world fleet of ships.

These uncertainties can affect the totals, the distributions among vessel categories and the allocation of emissions between international and domestic shipping.

Although bottom-up approaches can be more precise, large-scale bottom-up inventories are also uncertain because they estimate engine workload, ship speed, and most importantly, the locations of the routes determining the spatial distribution of emissions. The quality of regional annual inventories in bottom-up approaches is also limited when selected periods within a calendar year studied are extrapolated to represent annual totals. Bottom-up approaches to date have been limited to smaller scale or regional emissions inventories due to the significant efforts associated with routing. Moreover, because they often use straight lines as routes between ports, they may overestimate ship emissions, as straight lines on a map usually are not the shortest path between two points on the globe. As such, locations of emissions may not be assigned correctly at larger scales.

The scope and design of the Third IMO GHG Study 2014 responds directly to specific directives from the IMO Secretariat that derived from the IMO Expert Workshop (2013) recommendations with regard to activity-based (bottom-up) ship emissions estimation. These recommendations were:

- to consider direct vessel observations to the greatest extent possible
- to use vessel-specific activity and technical details in a bottom-up inventory model
- to use "to the best extent possible" actual vessel speed to obtain engine loads.

The IMO Expert Workshop recognized that "bottom-up estimates are far more detailed and are generally based on ship activity levels by calculating the fuel consumption and emissions from individual ship movements" and that "a more sophisticated bottom-up approach to develop emission estimates on a ship-by-ship basis" would "require significant data to be inputted and may require additional time […] to complete".

3.3 Presentation of bottom-up and top-down estimates in shipping

3.3.1 Full bottom-up approach

The data required for this approach have only recently become available. Different papers have produced different types of full bottom-up analyses that can be classified into three main groups. In the first group, Entec (2005) [44], Faber et al. (2009) [45] and Paxian et al. (2010) [46] calculate the emissions per ship on each maritime route, based on Lloyd’s MIU ships’ movement data. Both Entec (2005) [44] and Faber et al. (2009) [45] consider the European area only. However, aware of the limitations of LMIU movement data, Faber et al. (2009) [45] evaluate global emissions and compare them with the “consensus” estimates provided in IMO (2009) [4]. They then apply the ratio between IMO estimates and their own estimates to correct results in a more limited context (in this case in the European context).

A second group is composed of Georgakaki et al. (2005) [47], Wang et al. (2007) [48] and Schrooten et al. (2009) [50]. All of these studies focus on smaller contexts. Wang et al. (2007) [47] focus on U.S. trade routes, while the other two focus on the European context. They all analyzed a waterway network composed of the routes actually used by ships. They evaluate the traffic (for different ships’ categories) on each link of the network by using information on the trade activities to calculate the traffic demand between different pairs of ports. They evaluate fuel consumption, emissions and their spatial distribution based on assumptions on the average travel time for each link of the network. This approach is also used in Wang et al. (2007, 2010) [48], [49] and Corbett et al. (2009) [51]. Thirdly, Jalkanen et al. (2009) [52] provide a full bottom-up approach which includes two new features. Shipping activities are collected in real time using AIS data, and the approach considers the effect of waves on fuel consumption and therefore on emissions. A similar but less sophisticated approach has also been used by the Danish National Environmental Research Institute to estimate emissions from the maritime sector around Denmark (Olesen et al., 2009) [53].

3.3.2 Bottom-up for total emissions evaluation plus top-down for geographic characterization

This approach was proposed by Endresen et al. (2003, 2004, 2007) [43], [54], [55], Corbett and Koehler (2003, 2004) [56], [57] and Eyring et al. (2005) [58]. These studies apply similar methodologies (all explicitly using ships' activities). Starting from the world's fleet statistics provided by the Lloyd's Register of Shipping, the fuel consumption (and thus the emissions) is calculated for each ship category (i.e. given the average engine power) by making some assumptions on the average engine load and the average number of annual operating hours. The two groups in the literature differ in their estimation of annual operating hours. Endresen et al. (2003, 2004, 2007) [43], [54], [55] base their calculations on total fuel consumption as extrapolated from fuel sales statistics, while Corbett and Koehler (2003, 2004) [56], [57] and Eyring et al. (2005) [58] assign set values. As a result, emission estimates provided by the first group were considerably lower than those of the second group. Eyring et al. (2009) [59] try to explain this ambiguity. They attribute the discrepancy to the uncertainties in the estimation of worldwide bunker fuel sales, which are due to two main factors. First, most energy inventories try to reflect the International Energy Agency's energy allocation criteria (Thomas et al., 2002) [60]. Second, not all statistical sources for marine fuels define international marine fuels in the same way (Olivier and Peters, 1999) [61].

Dalsoren et al. (2009) [62] and IMO (2009) [4] propose a greatly improved methodology. In these studies, ship activities are estimated rather than hypothesized. Dalsoren et al. (2009) [62] use the data on ships' movements provided by the Lloyd's MIU, while IMO (2009) [4] uses information from the AISLive network (http://www.aislive.com) for the whole of 2007. Results of Dalsoren et al. (2009) [62] are lower than those reported in IMO (2009) [4], which are now considered to be "consensus estimates" of the global emissions resulting from the maritime transport sector. This is probably due to the use of somewhat inaccurate movement data. However, Dalsoren et al. (2009) [62] were the first to show that emissions due to ships' activities around ports account for 5% of the total emissions from navigation activities. All of these works geographically characterize total emissions using the ICOADS or the AMVER traffic intensity information. More detailed approaches such as direct measurements of emissions (Miola et al., 2009) [63] or detailed ship activities

(Tzannatos, 2010) [64] can be used to evaluate emissions on a smaller scale, for example from a single port.

3.3.3 Top-down for total emissions plus bottom-up for geographic characterization

A complementary approach is proposed in Wang and Corbett (2005) [65] and in Wang et al. (2008) [66]. These studies divide the world into 0.1° x 0.1° cells. For each cell, the intensity of ship traffic is defined on the basis of the AMVER and the ICOADS datasets on ships activities. The emissions are directly calculated as emitted from the cells, making some assumptions on the type of ships travelling within each of them. Errors introduced by the weak coverage of both the ICOADS and the AMVER datasets should, however, be taken into consideration in any use of these data. This can be seen in figure 24, where main maritime routes are identified by red and yellow points. The dots represent global emissions produced by ships in each 0.1° x 0.1° geographic cell. The two buffers Europe_Buffer_12 and Europe_Buffer_200 give an indication of the amount of emissions produced within 12 miles (Territorial Sea) and 200 miles (Exclusive Economic Zone) (Miola et al. 2010) [67]. The figure illustrates how some local ship activities are underestimated. For example, there are few points in the Black Sea and low impact of traffic to and from the Portuguese ports and from the ports of Rotterdam and Hamburg (which should attract and generate much more traffic than the ports of Marseille, Genova and Ajaccio). This because the penetration of AMVER and ICOADS in Europe is quite low.

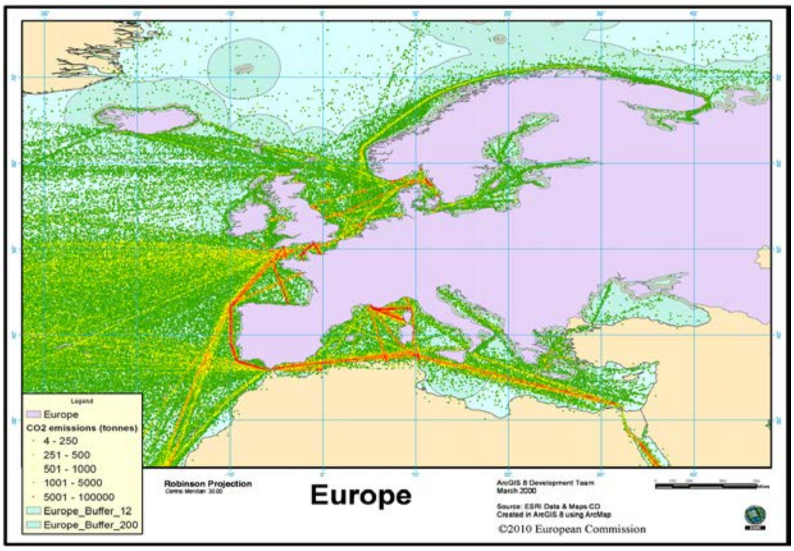


Figure 24: CO_2 emissions geographical characterization via improved traffic proxy (Wang et al., 2008)

3.3.4 Full top-down approach

In a full top-down approach, total emissions are calculated without considering the vessels' characteristics. This approach, applied in Corbett and Fischbeck (1997) [68], Corbett et al. (1999) [69], Skjølsvik et al. (2000) [10] and Endresen et al. (2007) [55], uses the international marine fuel usage statistics reported by the Energy Information Administration (EIA). Applying different emission factors to different fuel types and different engine types, these studies derive an estimation of global emissions based on the total fuel used. Results deriving from this approach were later considered unreliable, but these first studies did illustrate the magnitude of the maritime transport sector's impact on the atmosphere. They also highlighted the problem of the uncertainty in estimation: a problem that subsequently attracted scientific attention over the following ten years.

3.3.5 Comparison of the results from the different approaches

Several inventories have been established over the past two decades. The works are grouped on the basis of the classification provided in the preceding paragraph and ordered more or less chronologically. The debate on the evaluation of maritime emissions is still open and has resulted in several different estimations being made over the past decade. These are not all that easy to compare, since different contexts are analyzed and different assumptions are made. In IMO (2009) [4] an attempt is made to homogenize the results of different studies. Figure 25 shows the estimates of the IMO expert group which confirm the results from Corbett and Koelher (2003) [56] rather than those from Endresen et al. (2003) [43] (the works opening the debate). In addition, the graph clearly highlights the high level of uncertainty introduced by the different methodologies used to estimate emissions.

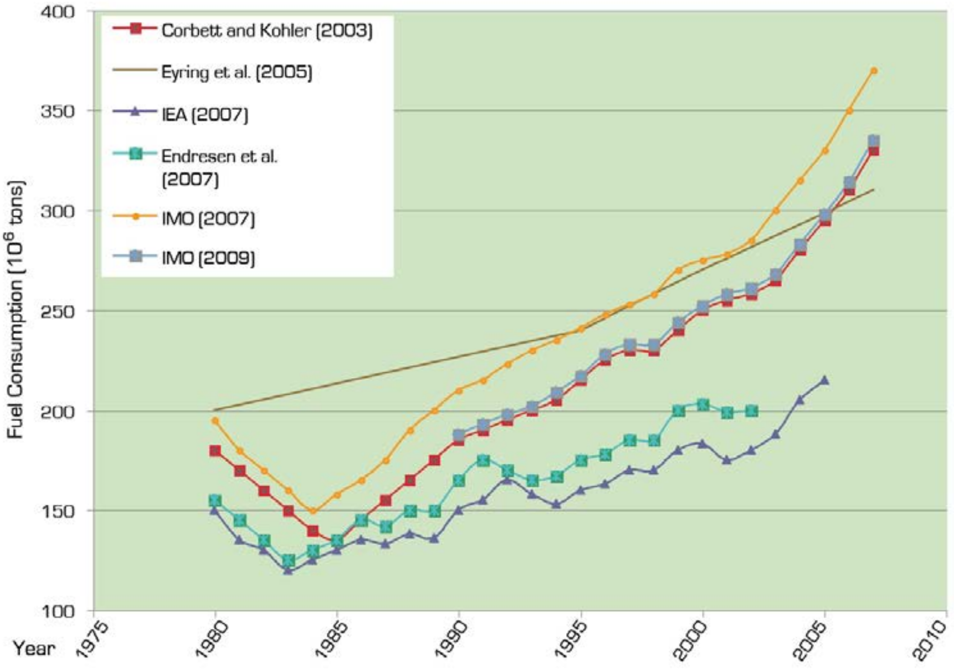


Figure 25: Fuel consumption estimation and evolution from different sources-elaborations on IMO data (IMO, 2009)

This further confirms the need for different approaches to the problem (improvements are expected in the coming years as a result of the application of more sophisticated full bottom-up approaches).

3.4 Scope of work

Reading the title of this thesis: “Probabilistic analysis/estimation on fuel consumption and ship emissions”, the two main objectives are clarified straight forward. The first leg deals mainly with the construction of a probabilistic model and its analysis that will be capable to estimate daily fuel consumption for a single vessel. This approach is based on bottom-up inventories for estimating fuel consumption, as we are interested in the operational profile of the ship. Estimation of fuel consumption varies according to the ship speed. This parameter is very important and we need to focus on slow steaming which is very common nowadays. As a result, the model will focus on low load profile of the ship examined. Once the model is completed, it can be used to produce estimations for ship emissions, like CO_2, NO_x, SO_x and PM.

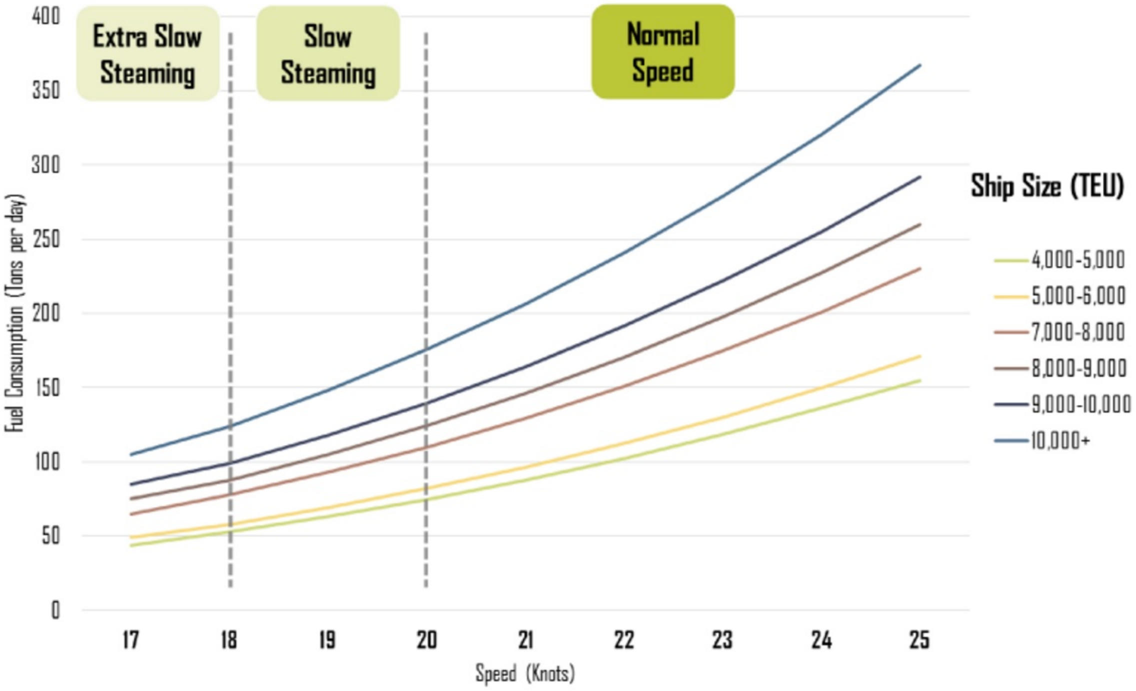


Figure 26: Fuel consumption rise with ship speed (P. Cariou, 2009)

4. PROBABILISTIC MODELLING

4.1 Case study: 2,824 TEU Container ship

The study conducted in the scope of this thesis is focused on the case of a 2,824 TEU Container ship employed on the spot market globally. In the following table, there are the ship's main particulars. Noon report (NR) for a period of 5 years has been provided by the ship-owner. NR datasets are coarse but convenient and cheap to compile. They are currently in widespread use across the global fleet. The frequency of recording is once every 24h (time zone changes allowing) and the fields reported are limited, generally included as a minimum are ship speed and position, fuel consumption, shaft rotational speed, wind speed derived Beaufort number, date/time and draught.

Table 4: Ship particulars of the 2,824 TEU Container ship

Ship Particulars	
Ship Type	Container carrier
Completion Year	04 / 2006
Country of Build	Republic of Korea
Gross Tonnage	28592
Net Tonnage	14769
Deadweight	39,241.0 t
Overall Length	222.17 m
Lpp	212.2 m
Breadth	30.0 m
Draught	12.02 m
Service Speed	23.0 knots
TEU Capacity	2,824
Fuel Type	Diesel
MCR at Sea	25599 kW (104 rpm)
Propelling Machinery	1 MAN B&W 7K80MC-C

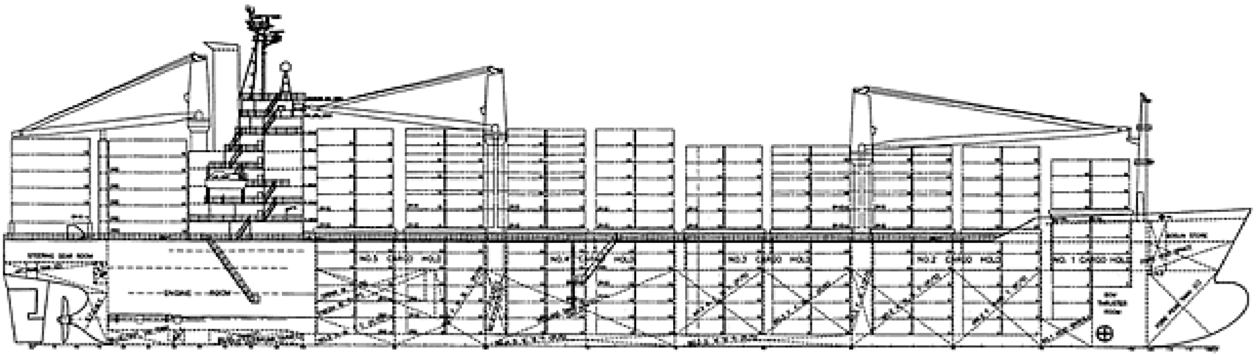
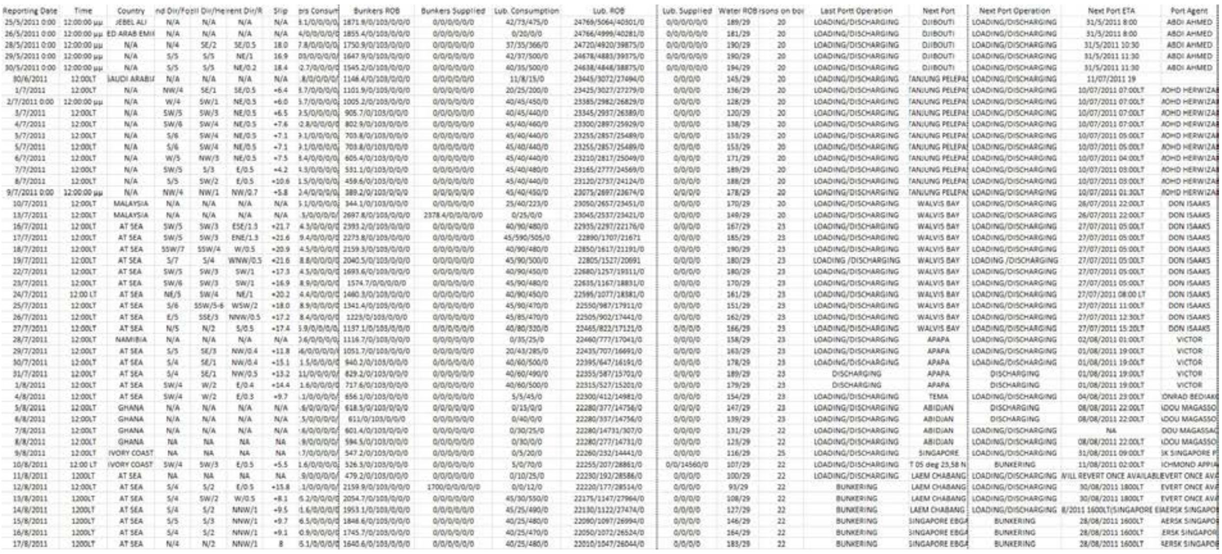


Figure 27: General Arrangement of a Sub-Panamax Container ship



Reporting Date	Time	Country	nd Dir/Fo	ell Dir/He	rent Dir/R	Slip	ers Consum	Bunkers ROB	Bunkers Supplied	Lub. Consumption	Lub. ROB	Lub. Supplied	Water ROB	rsons on boa	Last Portt Operation	Next Port	Next Port Operation	Next Port ETA	Port Agent
25/5/2011 0:00	12:00:00 μμ	JEBEL ALI	N/A	N/A	N/A	N/A	3.1/0/0/0/0,	1871.9/0/103/0/0/0	0/0/0/0/0/0	42/73/475/0	24769/5064/40301/0	0/0/0/0/0/0	189/29	20	LOADING/DISCHARGING	DJIBOUTI	LOADING/DISCHARGING	31/5/2011 8:00	ABDI AHMED
26/5/2011 0:00	12:00:00 μμ	ED ARAB EMIR	N/A	N/A	N/A	N/A	4/0/0/0/0/0	1855.4/0/103/0/0/0	0/0/0/0/0/0	0/20/0/0	24766/4999/40281/0	0/0/0/0/0/0	181/29	20	LOADING/DISCHARGING	DJIBOUTI	LOADING/DISCHARGING	31/5/2011 8:00	ABDI AHMED
28/5/2011 0:00	12:00:00 μμ	N/A	N/4	SE/2	SE/0.5	18.0	7.8/0/0/0/0,	1750.9/0/103/0/0/0	0/0/0/0/0/0	37/35/366/0	24720/4920/39875/0	0/0/0/0/0/0	190/29	20	LOADING/DISCHARGING	DJIBOUTI	LOADING/DISCHARGING	31/5/2011 10:30	ABDI AHMED
29/5/2011 0:00	12:00:00 μμ	N/A	S/5	S/5	NE/1	16.9	03/0/0/0/0/	1647.9/0/103/0/0/0	0/0/0/0/0/0	42/37/500/0	24678/4883/39375/0	0/0/0/0/0/0	190/29	20	LOADING/DISCHARGING	DJIBOUTI	LOADING/DISCHARGING	31/5/2011 11:30	ABDI AHMED
30/5/2011 0:00	12:00:00 μμ	N/A	S/5	S/5	NE/0.2	18.4	2.7/0/0/0/0	1545.2/0/103/0/0/0	0/0/0/0/0/0	40/35/500/0	24638/4848/38875/0	0/0/0/0/0/0	194/29	20	LOADING/DISCHARGING	DJIBOUTI	LOADING/DISCHARGING	31/5/2011 11:30	ABDI AHMED
30/6/2011	12:00LT	AUDI ARABI	N/A	N/A	N/A	N/A	.8/0/0/0/0/	1146.4/0/103/0/0/0	0/0/0/0/0/0	11/8/15/0	23445/3072/27494/0	0/0/0/0	145/29	20	LOADING/DISCHARGING	TANJUNG PELEPA	LOADING/DISCHARGING	11/07/2011 19	
1/7/2011	12:00LT	N/A	NW/4	SE/1	SE/0.5	+6.4	3.7/0/0/0/0,	1101.9/0/103/0/0/0	0/0/0/0/0/0	20/25/200/0	23425/3027/27279/0	0/0/0/0	136/29	20	LOADING/DISCHARGING	TANJUNG PELEPA	LOADING/DISCHARGING	10/07/2011 07:00LT	IOHD HERWIZA
2/7/2011 0:00	12:00:00 μμ	N/A	W/4	SW/1	NE/0.5	+6.0	5.7/0/0/0/0,	1005.2/0/103/0/0/0	0/0/0/0/0/0	40/45/450/0	23385/2982/26829/0	0/0/0/0	128/29	20	LOADING/DISCHARGING	TANJUNG PELEPA	LOADING/DISCHARGING	10/07/2011 07:00LT	IOHD HERWIZA
3/7/2011	12:00LT	N/A	SW/5	SW/3	NE/0.5	+6.5	3.5/0/0/0/0,	905.7/0/103/0/0/0	0/0/0/0/0/0	40/45/440/0	23345/2937/26389/0	0/0/0/0	120/29	20	LOADING/DISCHARGING	TANJUNG PELEPA	LOADING/DISCHARGING	10/07/2011 07:00LT	IOHD HERWIZA
4/7/2011	12:00LT	N/A	SW/6	SW/4	NE/0.5	+7.6	2.8/0/0/0/0	802.9/0/103/0/0/0	0/0/0/0/0/0	45/40/460/0	23300/2897/25929/0	0/0/0/0	138/29	20	LOADING/DISCHARGING	TANJUNG PELEPA	LOADING/DISCHARGING	10/07/2011 07:00LT	IOHD HERWIZA
5/7/2011	12:00LT	N/A	S/6	SW/4	NE/0.5	+7.1	3.1/0/0/0/0,	703.8/0/103/0/0/0	0/0/0/0/0/0	45/40/440/0	23255/2857/25489/0	0/0/0/0	153/29	20	LOADING/DISCHARGING	TANJUNG PELEPA	LOADING/DISCHARGING	10/07/2011 05:00LT	IOHD HERWIZA
5/7/2011	12:00LT	N/A	S/6	SW/4	NE/0.5	+7.1	3.1/0/0/0/0,	703.8/0/103/0/0/0	0/0/0/0/0/0	45/40/440/0	23255/2857/25489/0	0/0/0/0	153/29	20	LOADING/DISCHARGING	TANJUNG PELEPA	LOADING/DISCHARGING	10/07/2011 05:00LT	IOHD HERWIZA
6/7/2011	12:00LT	N/A	W/5	NW/3	NE/0.5	+7.5	3.4/0/0/0/0,	605.4/0/103/0/0/0	0/0/0/0/0/0	45/40/440/0	23210/2817/25049/0	0/0/0/0	171/29	20	LOADING/DISCHARGING	TANJUNG PELEPA	LOADING/DISCHARGING	10/07/2011 04:00LT	IOHD HERWIZA
7/7/2011	12:00LT	N/A	SW/5	S/3	E/0.5	+4.2	3.3/0/0/0/0,	531.1/0/103/0/0/0	0/0/0/0/0/0	45/40/480/0	23165/2777/24569/0	0/0/0/0	189/29	20	LOADING/DISCHARGING	TANJUNG PELEPA	LOADING/DISCHARGING	10/07/2011 03:00LT	IOHD HERWIZA
8/7/2011	12:00LT	N/A	S/5	SW/2	E/0.5	+10.6	1.5/0/0/0/0,	459.6/0/103/0/0/0	0/0/0/0/0/0	45/40/440/0	23120/2737/24124/0	0/0/0/0	188/29	20	LOADING/DISCHARGING	TANJUNG PELEPA	LOADING/DISCHARGING	10/07/2011 03:00LT	IOHD HERWIZA
9/7/2011 0:00	12:00:00 μμ	N/A	NW/4	NW/1	NW/0.7	+5.8	2.4/0/0/0/0,	389.2/0/103/0/0/0	0/0/0/0/0/0	45/40/450/0	23075/2697/23674/0	0/0/0/0	178/29	20	LOADING/DISCHARGING	TANJUNG PELEPA	LOADING/DISCHARGING	10/07/2011 01:30LT	IOHD HERWIZA
10/7/2011	12:00LT	MALAYSIA	N/A	N/A	N/A	N/A	5.1/0/0/0/0,	344.1/0/103/0/0/0	0/0/0/0/0/0	25/40/223/0	23050/2657/23451/0	0/0/0/0	170/29	20	LOADING/DISCHARGING	WALVIS BAY	LOADING/DISCHARGING	26/07/2011 22:00LT	DON ISAAKS
13/7/2011	12:00LT	MALAYSIA	N/A	N/A	N/A	N/A	.5/0/0/0/0/	2697.8/0/103/0/0/0	2378.4/0/0/0/0/0	0/25/0/0	23045/2537/23421/0	0/0/0/0	149/29	20	LOADING/DISCHARGING	WALVIS BAY	LOADING/DISCHARGING	26/07/2011 22:00LT	DON ISAAKS
16/7/2011	12:00LT	AT SEA	SW/5	SW/3	ESE/1.3	+21.7	4.3/0/0/0/0	2393.2/0/103/0/0/0	0/0/0/0/0/0	40/90/480/0	22935/2297/22176/0	0/0/0/0	167/29	23	LOADING/DISCHARGING	WALVIS BAY	LOADING/DISCHARGING	27/07/2011 05:00LT	DON ISAAKS
17/7/2011	12:00LT	AT SEA	SW/5	SW/3	ENE/1.3	+21.6	9.4/0/0/0/0	2273.8/0/103/0/0/0	0/0/0/0/0/0	45/590/505/0	22890/1707/21671	0/0/0/0	185/29	23	LOADING/DISCHARGING	WALVIS BAY	LOADING/DISCHARGING	27/07/2011 05:00LT	DON ISAAKS
18/7/2011	12:00LT	AT SEA	SSW/7	SSW/4	W/0.5	+20.9	4.5/0/0/0/0	2159.3/0/103/0/0/0	0/0/0/0/0/0	40/90/480/0	22850/1617/21191/0	0/0/0/0	190/29	23	LOADING/DISCHARGING	WALVIS BAY	LOADING/DISCHARGING	27/07/2011 05:00LT	DON ISAAKS
19/7/2011	12:00LT	AT SEA	S/7	S/4	WNW/0.5	+21.6	8.8/0/0/0/0	2040.5/0/103/0/0/0	0/0/0/0/0/0	45/90/500/0	22805/1527/20691	0/0/0/0	180/29	23	LOADING /DISCHARGING	WALVIS BAY	LOADING /DISCHARGING	27/07/2011 05:00LT	DON ISAAKS
22/7/2011	12:00LT	AT SEA	SW/5	SW/3	SW/1	+17.3	4.5/0/0/0/0	1693.6/0/103/0/0/0	0/0/0/0/0/0	40/90/450/0	22680/1257/19311/0	0/0/0/0	180/29	23	LOADING/DISCHARGING	WALVIS BAY	LOADING/DISCHARGING	27/07/2011 05:00LT	DON ISAAKS
23/7/2011	12:00LT	AT SEA	SW/6	SW/3	SW/1	+16.9	8.9/0/0/0/0	1574.7/0/0/0/0/0	0/0/0/0/0/0	45/90/480/0	22635/1167/18831/0	0/0/0/0	170/29	23	LOADING/DISCHARGING	WALVIS BAY	LOADING/DISCHARGING	27/07/2011 05:00LT	DON ISAAKS
24/7/2011	12:00 LT	AT SEA	NE/5	SW/4	NE/1	+20.2	4.4/0/0/0/0	1460.3/0/103/0/0/0	0/0/0/0/0/0	40/90/450/0	22595/1077/18381/0	0/0/0/0	161/29	23	LOADING/DISCHARGING	WALVIS BAY	LOADING/DISCHARGING	27/07/2011 08:00 LT	DON ISAAKS
25/7/2011	12:00LT	AT SEA	S/6	SSW/5-6	WSW/2	+18.0	8.9/0/0/0/0	1341.4/0/103/0/0/0	0/0/0/0/0/0	45/90/470/0	22550/987/17911/0	0/0/0/0	151/29	23	LOADING/DISCHARGING	WALVIS BAY	LOADING/DISCHARGING	27/07/2011 11:00LT	DON ISAAKS
26/7/2011	12:00LT	AT SEA	E/5	SSE/3	NNW/0.5	+17.2	8.4/0/0/0/0	1223/0/103/0/0/0	0/0/0/0/0/0	45/85/470/0	22505/902/17441/0	0/0/0/0	162/29	23	LOADING/DISCHARGING	WALVIS BAY	LOADING/DISCHARGING	27/07/2011 12:30LT	DON ISAAKS
27/7/2011	12:00LT	AT SEA	N/5	N/2	S/0.5	+17.4	5.9/0/0/0/0,	1137.1/0/103/0/0/0	0/0/0/0/0/0	40/80/320/0	22465/822/17121/0	0/0/0/0	166/29	23	LOADING/DISCHARGING	WALVIS BAY	LOADING/DISCHARGING	27/07/2011 15:20LT	DON ISAAKS
28/7/2011	12:00LT	NAMIBIA	N/A	N/A	N/A	N/A	3.6/0/0/0/0,	1116.7/0/103/0/0/0	0/0/0/0/0/0	0/35/25/0	22460/777/17041/0	0/0/0/0	158/29	23	LOADING/DISCHARGING	APAPA	LOADING/DISCHARGING	02/08/2011 01:00LT	VICTOR
29/7/2011	12:00LT	AT SEA	S/5	SE/3	NW/0.4	+11.8	6/0/0/0/0/	1051.7/0/103/0/0/0	0/0/0/0/0/0	20/43/285/0	22435/707/16691/0	0/0/0/0	163/29	23	LOADING/DISCHARGING	APAPA	LOADING/DISCHARGING	01/08/2011 19:00LT	VICTOR
30/7/2011	12:00LT	AT SEA	S/4	SE/1	NW/0.4	+15.1	1.5/0/0/0/0	940.2/0/103/0/0/0	0/0/0/0/0/0	40/60/500/0	22395/647/16191/0	0/0/0/0	178/29	23	LOADING/DISCHARGING	APAPA	LOADING/DISCHARGING	01/08/2011 19:00LT	VICTOR
31/7/2011	12:00LT	AT SEA	S/4	SE/1	NW/0.5	+13.2	11/0/0/0/0/	829.2/0/103/0/0/0	0/0/0/0/0/0	40/60/490/0	22355/587/15701/0	0/0/0/0	189/29	23	DISCHARGING	APAPA	DISCHARGING	01/08/2011 19:00LT	VICTOR
1/8/2011	12:00LT	AT SEA	SW/4	W/2	E/0.4	+14.4	1.6/0/0/0/0	717.6/0/103/0/0/0	0/0/0/0/0/0	40/60/500/0	22315/527/15201/0	0/0/0/0	179/29	23	DISCHARGING	APAPA	DISCHARGING	01/08/2011 19:00LT	VICTOR
4/8/2011	12:00LT	AT SEA	SW/4	W/2	E/0.3	+9.7	.1/0/0/0/0/	656.1/0/103/0/0/0	0/0/0/0/0/0	5/5/45/0	22300/412/14981/0	0/0/0/0	154/29	23	LOADING/DISCHARGING	TEMA	LOADING/DISCHARGING	04/08/2011 23:00LT	ONRAD BEDIAK
5/8/2011	12:00LT	GHANA	N/A	N/A	N/A	N/A	.6/0/0/0/0/	618.5/0/103/0/0/0	0/0/0/0/0/0	0/15/0/0	22280/377/14756/0	0/0/0/0	147/29	23	LOADING/DISCHARGING	ABIDJAN	DISCHARGING	08/08/2011 22:00LT	ADOU MAGASSO
6/8/2011	12:00LT	GHANA	N/A	N/A	N/A	N/A	.5/0/0/0/0/	611/0/103/0/0/0	0/0/0/0/0/0	0/40/0/0	22280/337/14756/0	0/0/0/0	139/29	23	LOADING/DISCHARGING	ABIDJAN	DISCHARGING	08/08/2011 22:00LT	ADOU MAGASSO
7/8/2011	12:00LT	GHANA	N/A	N/A	N/A	N/A	.6/0/0/0/0/	601.4/0/103/0/0/0	0/0/0/0/0/0	0/30/25/0	22280/14731/307/0	0/0/0/0	131/29	22	LOADING/DISCHARGING	ABIDJAN	LOADING/DISCHARGING	NA	DOU MAGASSAC
8/8/2011	12:00LT	GHANA	NA	NA	NA	NA	.9/0/0/0/0/	594.5/0/103/0/0/0	0/0/0/0/0/0	0/30/0/0	22280/277/14731/0	0/0/0/0	123/29	22	LOADING/DISCHARGING	ABIDJAN	LOADING/DISCHARGING	08/08/2011 22:00LT	ADOU MAGASSO
9/8/2011	12:00LT	IVORY COAST	NA	NA	NA	NA	.7/0/0/0/0/	547.2/0/103/0/0/0	0/0/0/0/0/0	0/5/20/0	22260/232/14441/0	0/0/0/0	116/29	25	LOADING/DISCHARGING	SINGAPORE	LOADING/DISCHARGING	31/08/2011 09:00LT	SK SINGAPORE P
10/8/2011	12:00 LT	IVORY COAST	SW/4	SW/3	E/0.5	+5.5	1.6/0/0/0/0,	526.3/0/103/0/0/0	0/0/0/0/0/0	5/0/70/0	22255/207/28861/0	0/0/14560/0	107/29	22	LOADING/DISCHARGING	T 05 deg 23,58 N	BUNKERING	11/08/2011 02:00LT	ICHMOND APPIA
11/8/2011	1200LT	AT SEA	NA	NA	NA	NA	.9/0/0/0/0/	479.2/0/103/0/0/0	0/0/0/0/0/0	0/10/25/0	22230/192/28586/0	0/0/0/0	100/29	22	LOADING/DISCHARGING	LAEM CHABANG	LOADING/DISCHARGING	VILL REVERT ONCE AVAILABL	EVERT ONCE AVA
12/8/2011	12:00LT	AT SEA	S/4	S/2	E/0.5	+15.8	.1/0/0/0/0/	2159.9/0/103/0/0/0	1700/0/0/0/0/0	0/0/12/0	22220/177/28514/0	0/0/0/0	93/29	22	BUNKERING	LAEM CHABANG	LOADING/DISCHARGING	30/08/2011 1800LT	EVERT ONCE AVA
13/8/2011	1200LT	AT SEA	S/4	SW/2	W/0.5	+8.1	6.2/0/0/0/0	2054.7/0/103/0/0/0	0/0/0/0/0/0	45/30/550/0	22175/1147/27964/0	0/0/0/0	108/29	22	BUNKERING	LAEM CHABANG	LOADING/DISCHARGING	30/08/2011 1800LT	EVERT ONCE AVA
14/8/2011	1200LT	AT SEA	S/4	S/2	NNW/1	+9.5	1.6/0/0/0/0	1953.1/0/103/0/0/0	0/0/0/0/0/0	45/25/490/0	22130/1122/27474/0	0/0/0/0	127/29	22	BUNKERING	LAEM CHABANG	LOADING/DISCHARGING	8/2011 1600LT(SINGAPORE E	AERSK SINGAPO
15/8/2011	1200LT	AT SEA	S/5	S/3	NNW/1	+9.7	6.5/0/0/0/0	1846.6/0/103/0/0/0	0/0/0/0/0/0	40/25/480/0	22090/1097/26994/0	0/0/0/0	146/29	22	BUNKERING	SINGAPORE EBGA	BUNKERING	28/08/2011 1600LT	AERSK SINGAPO
16/8/2011	1200LT	AT SEA	S/4	S/2	NNW/1	+9.1	0.9/0/0/0/0	1745.7/0/103/0/0/0	0/0/0/0/0/0	40/25/470/0	22050/1072/26524/0	0/0/0/0	164/29	22	BUNKERING	SINGAPORE EBGA	BUNKERING	28/08/2011 1600LT	ERSK SINGAPO
17/8/2011	1200LT	AT SEA	N/4	N/2	NNW/1	8	5.1/0/0/0/0	1640.6/0/103/0/0/0	0/0/0/0/0/0	40/25/480/0	22010/1047/26044/0	0/0/0/0	183/29	22	BUNKERING	SINGAPORE EBGA	BUNKERING	28/08/2011 1600LT	AERSK SINGAPO

Figure 28: Example of Noon Report

The most important observation linked to energy efficiency from NR is that the average operational profile of this ship refers to slow steaming. The basic idea of slow steaming is not new as it is well known, that the fuel consumption of cargo vessels is rising exponentially with a vessel’s velocity. Due to this fact, ships were operated with a lower speed in former times as well. Even nowadays, as the crisis in the transport sector is nearly over, slow steaming remains a common operating mode for Container ships. As a second slow steaming benefit, reduced fuel consumption directly corresponds with lower levels of GHG emissions, namely CO_2. By consuming 265 million tons of fuel annually, ocean shipping produces 840 million tons of CO_2, which represents 3 per cent of all global GHG emissions. As a result, ocean transport is equivalent to the sixth largest polluting country in the world and the annual GHG emissions of Germany. Container ships specifically emit more GHGs than most other ocean vessel classes, generating 270 million tons per year.

4.2 Mathematic approach of the model

The environmental conditions (sea state, wind speed, sea/air temperature etc.) are dynamic, largely unpredictable and complicated to quantify, due in part to the characteristics of the chaotic and turbulent flow fields by which they are determined. These environmental conditions exert an influence on the ship's resistance and therefore the ship power requirements in differing relative quantities.

The rate of deterioration in ship performance (engine, hull and propeller) is dependent on a large array of variables; including the quality and type of hull coating and the frequency of hull and propeller cleaning which are also dependent on the ocean currents, temperature and salinity in which the ship operates. Further, the shipping industry operates in an economic sphere in which the global consumption of goods and global energy demand, and conditions in the various shipping markets determine operating profiles, costs and prices (e.g. slow steaming). In addition, technological investment, fuel efficiency and savings are complicated by the interactions between ship owner-charterer-manager.

Data collection, either through daily noon reporting procedures or high frequency, automatic data acquisition systems, and data processing techniques such as filtering and/or modelling have so far proven to be useful tools in capturing and quantifying some of the intricacies and nuances of these interactions to better understand the consequences of operational decisions. However, there are uncertainties in the data that introduce a potentially significant bias in the results and this need to be understood and evaluated. A study of the sensitivities of the uncertainty in the ship performance measurement is pertinent to inform where resources can be invested most effectively in order to reduce the overall uncertainty to the desired level.

Uncertainty analysis methodology

The aim of an uncertainty analysis is to describe the range of potential outputs of the system at some probability level, or to estimate the probability that the output will exceed a specific threshold or performance measure target value. The main aim in the uncertainty analysis deployed in the quantification of performance trends is to estimate the parameters of the output distribution and to conduct a sensitivity analysis to estimate the relative impact of input uncertainties.

The most commonly-used method to propagate probability distributions is the Monte Carlo analysis. This method is implemented in many calculation tools and consists in randomly sampling values in the probability distributions of input parameters, to obtain the frequency distribution of the calculated results. Monte Carlo simulation is a widely used approach to evaluate the influence that rises from the uncertainty within a specific variable/set of variables on the outcome of the model. For this study, applying Monte Carlo simulation to the model will generate a range of results based on different input values of the parameters, which helps to understand the impact from uncertainties in those key parameters.

The uncertainty stems from partial ignorance or lack of perfect knowledge. Based on the experiences regarding uncertainty in LCA/LCI studies, it seems that our inventory must be performed from a probabilistic point of view, rather than by considering deterministic aspects. Among the probabilistic tools, in order to include the above aspects the use of MC analysis has been increasing in recent years and is one of the most widespread stochastic model uncertainty analyses.

MC simulation uses these distributions, referred to as "assumptions", to automate the complex "what-if" process and generate realistic random values. The benefits of a simulation modeling approach are: (1) an understanding of the probability of specific outcomes, (2) the ability to pinpoint and test the driving variables within a model, (3) a far more flexible model; and (4) clear summary charts and reports. One of the problems associated with traditional spreadsheet models is that for variables that are uncertain. Without the aid of simulation, a spreadsheet model would only reveal a single outcome. Spreadsheet uncertainty analysis uses a spreadsheet model and simulation to analyze the effect of varying inputs or outputs of the modeled system automatically.

Simulation involves a large number of drawings (typically hundreds of thousands) from the distribution of the input parameters in the model that are combined to obtain values for the output parameters (which will be a function of the input parameters). As many values are available for the output parameters a probability distribution can be evaluated. The outputs from each run of the model are saved and a probability distribution for the output values is generated. The output can be in the form of a probability density function or more often as a cumulative probability distribution, which is the integrated PDF. Figure 29 illustrates this process. This allows the probability of the occurrence of any particular value or range of values for the output to be calculated. Based on the distribution of the output, the desired levels of probability could be identified, including the high and low end (e.g., 95th and 5th percentile), the central tendency (e.g., mean and median), or any other level of probability.

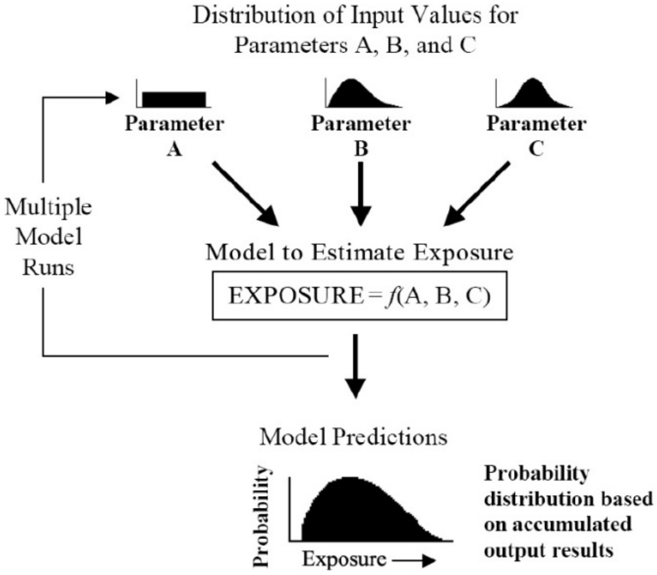


Figure 29: Diagrammatic representation of the application of Monte Carlo analysis to a model

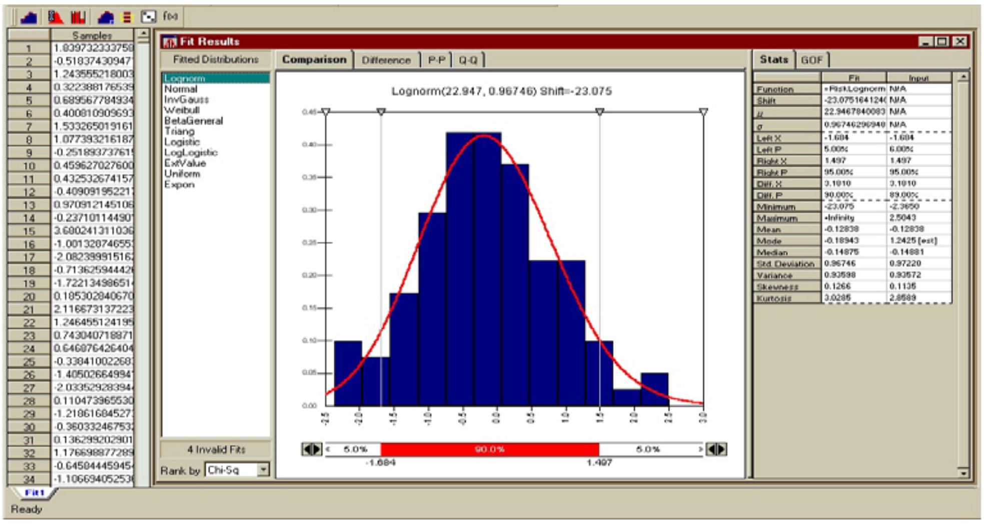
It should be noted that Monte Carlo analysis does not require that probability distribution function are defined for all input parameters. Where there is no basis for assigning a probability distribution function to particular parameters in multiple-parameter models, it is acceptable to keep a fixed value for those parameters while assigning probability density functions to parameters where sufficient information is available. Well known probability density functions are: Normal, Triangular, Uniform and Lognormal. For discrete variables (i.e. a variable that can only assume certain isolated or fixed values), the probability mass function expresses the probability that a randomly selected discrete variable will be a specific value.

4.3 BestFit and Oracle Crystal Ball

BestFit was used to find the distribution that best fit in our input data and Crystal Ball software was used to develop scenarios for uncertainty inputs.

BestFit does not produce an absolute answer; it identifies a distribution that most likely produced our data. For a given distribution, BestFit looks for the parameters of the function that optimize the goodness of fit, a measurement of the probability that the input data was produced by the given distribution. BestFit goes through the following steps when finding the best fit for our input data:

- For input sample data, parameters are estimated using **maximum-likelihood estimators.** For density and cumulative data, the **method of least squares** is used to minimize the distance between the input curve points and the theoretical function.
- Fitted distributions are ranked using one or more fit statistics, including Chi-square, Anderson-Darling, and Kolmogorov-Smirnov.



	Samples
1	1.839732333758
2	-0.51837430947
3	1.243555218003
4	0.322388176539
5	0.689567784934
6	0.400810909693
7	1.533265019161
8	1.077393216187
9	-0.25189373761
10	0.459627027600
11	0.432532674157
12	-0.40909195221
13	0.970912145106
14	-0.23710114490
15	3.680241311036
16	-1.00132874655
17	-2.08239991516
18	-0.71362594442
19	-1.72213498651
20	0.185302840670
21	2.116673137223
22	1.246455124195
23	0.743040718871
24	0.646876426404
25	-0.33841002268
26	-1.40502664994
27	-2.03352928394
28	0.110473965530
29	-1.21861684527
30	-0.36033246753
31	0.136299202901
32	1.176698877289
33	-0.64504445945
34	-1.10669405253

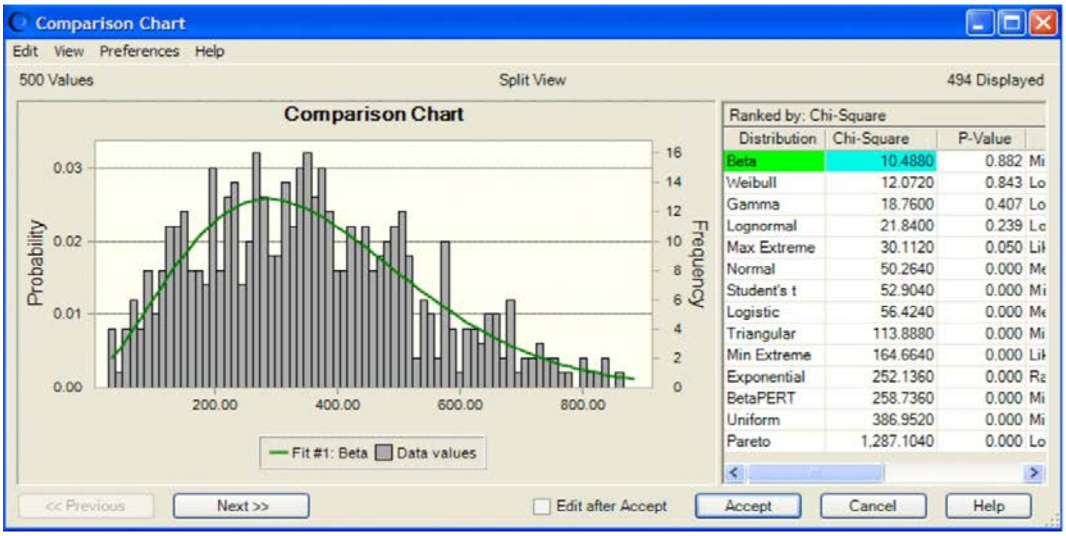
	Fit	Input
Function	=RiskLognorm	N/A
Shift	-23.0751641246	N/A
μ	22.9467840083	N/A
σ	0.967462969940	N/A
Left X	-1.684	-1.684
Left P	5.00%	6.00%
Right X	1.497	1.497
Right P	95.00%	95.00%
Diff. X	3.1810	3.1810
Diff. P	90.00%	89.00%
Minimum	-23.075	-2.3650
Maximum	+Infinity	2.5043
Mean	-0.12838	-0.12838
Mode	-0.18943	1.2425 [est]
Median	-0.14875	-0.14881
Std. Deviation	0.96746	0.97220
Variance	0.93598	0.93572
Skewness	0.1266	0.1135
Kurtosis	3.0285	2.8589

Figure 30: Snapshot of software tool kit "BestFit"

With Crystal Ball, we have the ability to replace each uncertain variable with a probability distribution, a function that represents a range of values and the likelihood of occurrence over that the range. The MC sampling is done using an Excel spreadsheet modified to develop scenarios for inputs given the probability distributions, means values, etc. and Crystal Ball, a software package offered by Decisionnering, generates random numbers for a probability distribution over the entire range of possible values, based on the assumption variables. For this reason, a large number of trials are required to obtain accurate results for the true shape of the distribution results and probabilities for those results. Crystal Ball eliminates the need to run, test, and present multiple spreadsheets. With Crystal Ball analysis we can handle dozen assumptions simultaneously and establish correlation coefficients among variables.

Once a probability distribution is incorporated into a spreadsheet cell, each time the spreadsheet is recalculated a new value of the random variable is selected from the distribution and used for calculations. The key to the method is to run the entire simulation at least 100,000 times in order to have a sufficient high number of trials. Each time new values of the random variables are selected and a new estimate of the final scenario is foreseen. The results of the calculations are summarized in a single histogram of scenario values. With the support of special software MC simulation is quite simple.

By means of a sensitivity analysis it is possible to show which parameters have most importance for the final result. If small modifications of one parameter characterized by a probability distribution strongly influence the final result, it could be concluded that the sensitivity of the considered variable was elevated for the relation between parameter and final result. This information is crucial for decision-makers in order to understand which the variables to act on are, and moreover it could be very important to know the parameters that might be neglected, especially if it is hard to get detailed information about them. The sensitivity could be analyzed by an approach that displayed the sensitivity as a percentage of the contribution from each parameter to the variance of the final result. The software Crystal Ball Version approximates this approach by lifting to square the correlation coefficients of ranks and normalizes them to 100%.



Ranked by: Chi-Square

Distribution	Chi-Square	P-Value	
Beta	10.4880	0.882	Mi
Weibull	12.0720	0.843	Lo
Gamma	18.7600	0.407	Lo
Lognormal	21.8400	0.239	Lo
Max Extreme	30.1120	0.050	Li
Normal	50.2640	0.000	Me
Student's t	52.9040	0.000	Mi
Logistic	56.4240	0.000	Me
Triangular	113.8880	0.000	Mi
Min Extreme	164.6640	0.000	Li
Exponential	252.1360	0.000	Ra
BetaPERT	258.7360	0.000	Mi
Uniform	386.9520	0.000	Mi
Pareto	1,287.1040	0.000	Lo

Figure 31: Snapshot of software tool kit "Oracle Crystal Ball"

4.4 Equations' analysis of fuel consumption and emissions

The current practice obtains engine power directly for our vessel studied and applies vessel activity data to document and compute power, energy and fuel consumption. Updated emission factors are then applied to this "bottom-up" information to estimate emissions. This methodology (for Main Engine and operation at sea) can be summarized in the following equations.

$$Fuel\ Consumption_{metric\ tonnes\ per\ day} = \sum_{i=1}^{n} P_{KW} \cdot LF_{\%MCR} \cdot t_{\frac{hrs}{day}} \cdot SFOC_{\frac{gr}{kWh}} \cdot \frac{1}{10^6}$$

$$Emissions_{metric\ tonnes\ per\ day} = \sum_{i=1}^{n} P_{KW} \cdot LF_{\%MCR} \cdot t_{\frac{hrs}{day}} \cdot EF_{\frac{gr}{kWh}} \cdot \frac{1}{10^6}$$

where

$\boldsymbol{P_{KW}}$ is accumulated installed engine power for each subgroup

$\boldsymbol{LF_{\%MCR}}$ is engine load factor based on duty cycle profile

$\boldsymbol{t}_{\frac{hrs}{day}}$ is average engine running hours for each subgroup

$\boldsymbol{SFOC}_{\frac{gr}{kWh}}$ is the power-based specific fuel oil consumption

$\boldsymbol{EF}_{\frac{gr}{kWh}}$ is the power-based emissions factor for each pollutant

Essentially, any vessel emissions calculation requires, in some format, that engine power, load factor, emissions or fuel rate, and time in service be estimated; in a fuel-based inventory, power, load, and time inputs are essentially combined. This data is needed for both main and auxiliary engines to be representative of total vessel activity. Due to incomplete data for auxiliary engines' activity, this thesis evaluates the ability of modeling to characterize main engine emissions. However, the insights are applicable to auxiliary engine activity-based modelling as well.

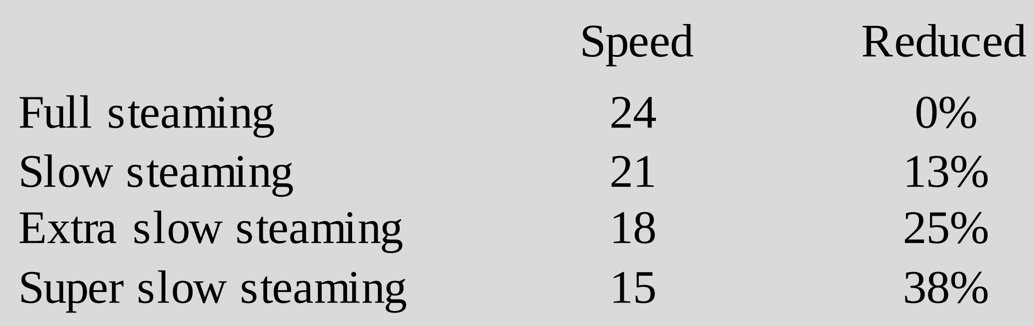
Main Engine installed power

For small container carriers around 2,000-4,000 TEU, the SMCR power varies from 17,700 kW to 35,500 kW in a 2-stroke diesel engine [70].

Loading Factor

From the following table, it is obvious that reduction in speed because of slow steaming results in lower loading factors (average 25-35% of MCR) [70].

Table 5: Degrees of slow steaming in container shipping (Meyer et al., 2012)



	Speed	Reduced
Full steaming	24	0%
Slow steaming	21	13%
Extra slow steaming	18	25%
Super slow steaming	15	38%

Specific Fuel Oil Consumption

For a typical small Container ship, the SFOC in 100% of power is around 175.3 gr/kWh whereas in 80% of power it is around 172.3 gr/kWh. In part load (50% of power), SFOC is approximately 175.9 gr/kWh [71].

The following figure represents a typical example of SFOC-Loading Factor diagram for a 2-stroke slow-speed Main Engine.

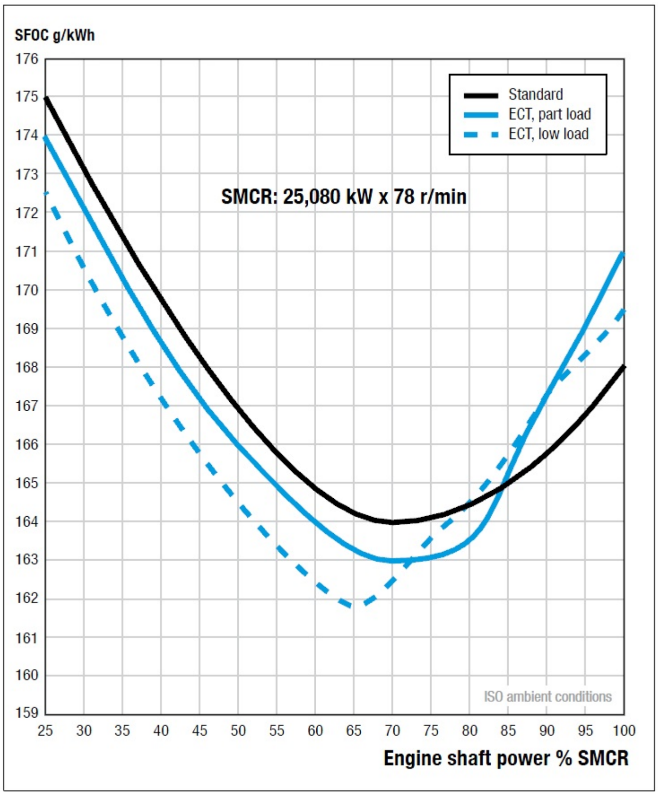


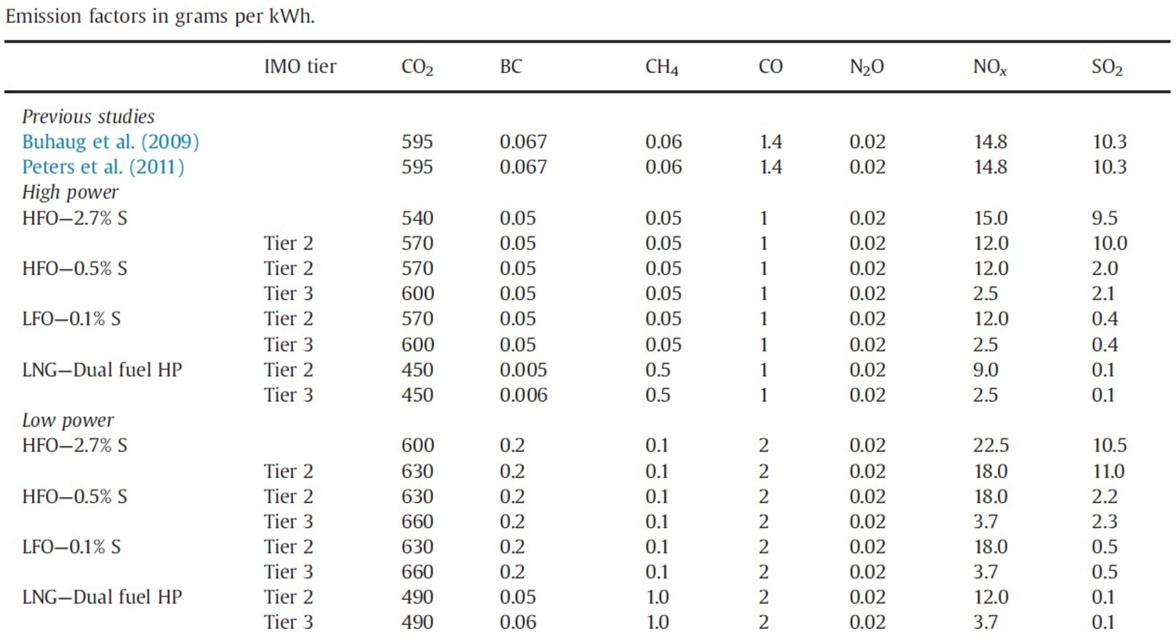
Figure 32: Example of SFOC reductions for 6S80ME-C8.2 with ECT (MAN B&W, 2013)

Emission Factors

Table 6 presents the updated emission factors in grams per kWh used for each of the fuels and the values used by previous studies of shipping emissions. “Tier 2” NO_x regulations are the established global requirements for vessels built after 2011, while “Tier 3” regulates NO_x emissions for vessels built 2016 onwards that operate fully or partly in the North American ECA. “Tier 1” are for vessels built between 2001 and

2011. The fuels to be compared are heavy fuel oil (HFO-2.7%) with maximum sulphur content up to 3.5%, heavy fuel oil where the sulphur content has been reduced to 0.5% (HFO-0.5%) or marine diesel oil (MDO) with a sulphur content of 0.5%, light fuel oil (LFO) or marine gas oil (MGO) with sulphur content up to 0.1% and liquefied natural gas (LNG). HFO and LFO are used in traditional diesel engines, while LNG is used in diesel dual-fuel engines. Dual- fuel engines can operate on traditional fuels such as HFO, LFO, MGO or on LNG, where the LNG is injected at either high or low pressure. For each fuel, "high" indicates emissions at medium to high engine loads, i.e., 50–90% of maximum power (MCR) and "low" indicates emissions at low engine loads, i.e., 15–35% MCR.

Table 6: Emission factors for Main Engine in grams per kWh (Lindstad et al., 2015)



Emission factors in grams per kWh.

	IMO tier	CO_2	BC	CH_4	CO	N_2O	NO_x	SO_2
Previous studies								
Buhaug et al. (2009)		595	0.067	0.06	1.4	0.02	14.8	10.3
Peters et al. (2011)		595	0.067	0.06	1.4	0.02	14.8	10.3
High power								
HFO–2.7% S		540	0.05	0.05	1	0.02	15.0	9.5
	Tier 2	570	0.05	0.05	1	0.02	12.0	10.0
HFO–0.5% S	Tier 2	570	0.05	0.05	1	0.02	12.0	2.0
	Tier 3	600	0.05	0.05	1	0.02	2.5	2.1
LFO–0.1% S	Tier 2	570	0.05	0.05	1	0.02	12.0	0.4
	Tier 3	600	0.05	0.05	1	0.02	2.5	0.4
LNG–Dual fuel HP	Tier 2	450	0.005	0.5	1	0.02	9.0	0.1
	Tier 3	450	0.006	0.5	1	0.02	2.5	0.1
Low power								
HFO–2.7% S		600	0.2	0.1	2	0.02	22.5	10.5
	Tier 2	630	0.2	0.1	2	0.02	18.0	11.0
HFO–0.5% S	Tier 2	630	0.2	0.1	2	0.02	18.0	2.2
	Tier 3	660	0.2	0.1	2	0.02	3.7	2.3
LFO–0.1% S	Tier 2	630	0.2	0.1	2	0.02	18.0	0.5
	Tier 3	660	0.2	0.1	2	0.02	3.7	0.5
LNG–Dual fuel HP	Tier 2	490	0.05	1.0	2	0.02	12.0	0.1
	Tier 3	490	0.06	1.0	2	0.02	3.7	0.1

Table 6 shows that CO_2 and SO_x emissions per kWh at low loads are approximately 10% higher than at high loads. Furthermore, CH_4 emissions are doubled at low power for the fuel oils and increases by a factor of five in the LNG option, NO_x emissions increase by 50% at low power and the ratio of BC emissions at low power to BC emissions at high power increases more drastically than for any other emissions species.

5. PROBABILISTIC ANALYSIS AND RESULTS

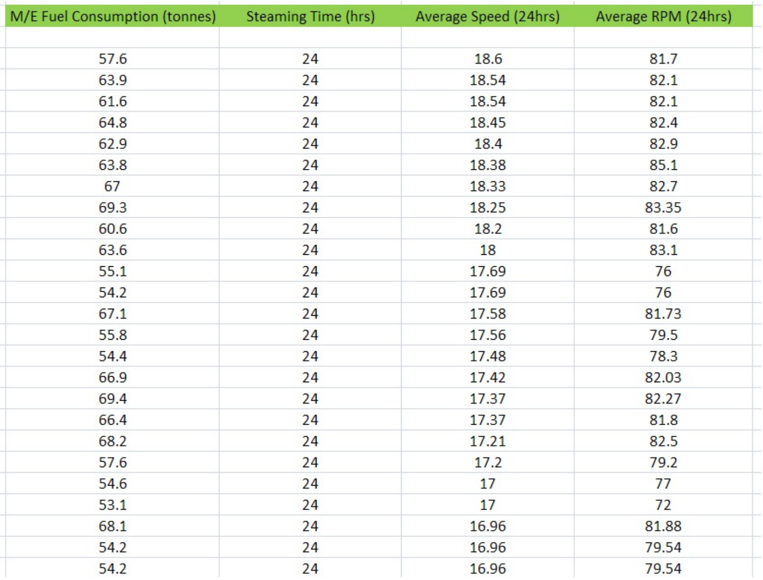
All calculations were made in Microsoft Office Excel and forecasts were produced by the Oracle Crystal Ball. All fitted distributions were ranked using three fit statistics: Chi-square, Anderson-Darling and Kolmogorov-Smirnov.

5.1 Model presentation

This model was built to examine three main topics:

- estimate and compare probabilistic distributions of fuel consumption (tons per day) coming from noon reports of our ship and from our approach described in paragraph 4.4
- apply robustness analysis of the equation assumed for fuel consumption
- estimate ship emissions for the above findings

The sample of the NR contains 1,470 recordings with a lot of data (in columns) for every day. The final sample data contains 570 recordings due to incomplete register. The appropriate columns for our model are: “M/E Fuel Consumption (tonnes)”, “Average Speed (24 hrs)”, “Average RPM (24 hrs)” and “Steaming Time (24 hrs)”.



M/E Fuel Consumption (tonnes)	Steaming Time (hrs)	Average Speed (24hrs)	Average RPM (24hrs)
57.6	24	18.6	81.7
63.9	24	18.54	82.1
61.6	24	18.54	82.1
64.8	24	18.45	82.4
62.9	24	18.4	82.9
63.8	24	18.38	85.1
67	24	18.33	82.7
69.3	24	18.25	83.35
60.6	24	18.2	81.6
63.6	24	18	83.1
55.1	24	17.69	76
54.2	24	17.69	76
67.1	24	17.58	81.73
55.8	24	17.56	79.5
54.4	24	17.48	78.3
66.9	24	17.42	82.03
69.4	24	17.37	82.27
66.4	24	17.37	81.8
68.2	24	17.21	82.5
57.6	24	17.2	79.2
54.6	24	17	77
53.1	24	17	72
68.1	24	16.96	81.88
54.2	24	16.96	79.54
54.2	24	16.96	79.54

Figure 33: Part of Noon Report used in the study

5.1.1 Estimation of probabilistic distributions of FC

In this part, the model for the first topic is described in detail.

5.1.1.1 Probabilistic distribution of FC from data

Model assumptions

There is no assumption made here. This distribution is fitted in the data coming from the column "M/E Fuel Consumption" of the NR.

Input data

Input data consists of a column given by the NR.

5.1.1.2 Probabilistic distribution of FC from our approach

In this case, we provide our random variables ($\boldsymbol{LF}_{\%\boldsymbol{MCR}}$, $\boldsymbol{t}_{\frac{\boldsymbol{hrs}}{\boldsymbol{day}}}$ and $\boldsymbol{SFOC}_{\frac{\boldsymbol{gr}}{\boldsymbol{kWh}}}$) with suitable distributions in order to estimate Fuel Consumption as a forecast. It is highly noted that in our study, total installed power $\boldsymbol{P}_{\boldsymbol{KW}}$ is not a random variable, because our scope aims to a single, known vessel.

Model assumptions

- From the column "Average RPM (24hrs)" of the NR, we can estimate the average daily power needed for the ship to sail, via the propeller curve.
- Loading factor values come out from the following equation: $\boldsymbol{LF}_{\%\boldsymbol{MCR}} = \frac{P_{average}}{P_{MCR}}$
- Distribution for $\boldsymbol{t}_{\frac{\boldsymbol{hrs}}{\boldsymbol{day}}}$ is fitted in the data coming from the column "Steaming Time (24 hrs)" of the NR.
- Distribution for $\boldsymbol{SFOC}_{\frac{\boldsymbol{gr}}{\boldsymbol{kWh}}}$ is provided by the user, due to lack of information (neither on NR nor on Project Guide of Main Engine). From the examination of the sample data, the vast majority of recordings refer to super slow steaming as operational condition of the ship. As a result, the distribution comprises great values of SFOC.

- There is a correlation between SFOC-Loading Factor which can be seen below.

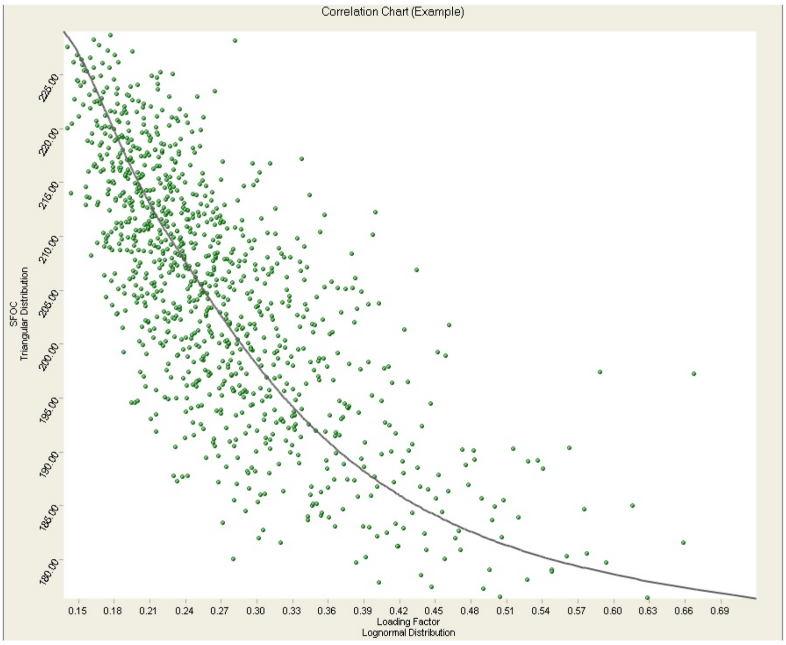


Figure 34: Correlation Chart of SFOC and LF in low load

- We are given the P_{KW}-n_{rpm} diagram (propeller curve) and we plot the curve in an Excel spreadsheet.

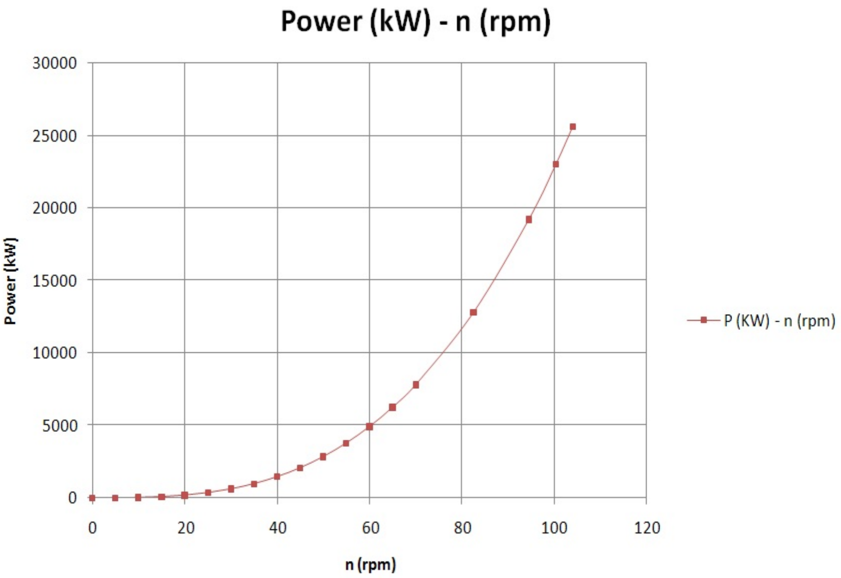


Figure 35: Propeller Curve for the 2,824 TEU Container ship

Input data

Input data consists of three probabilistic distributions and a single value for P_{MCR}, multiplied together via MC simulation. The forecast that comes out is a new distribution for FC (tonnes per day).

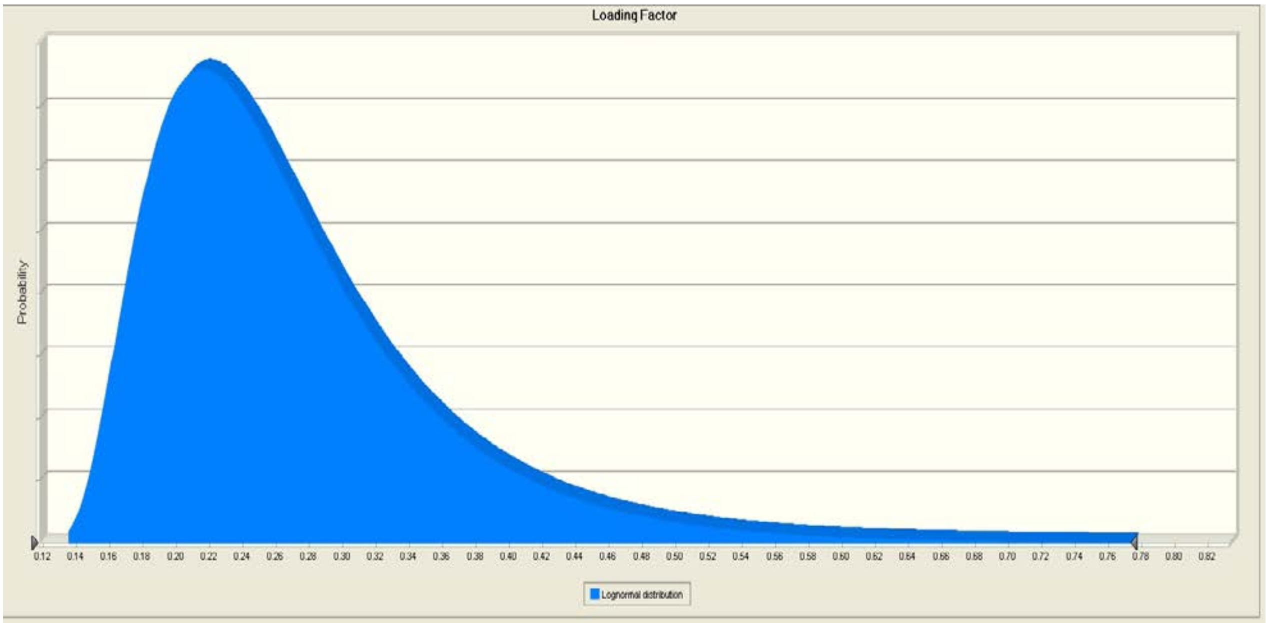


Figure 36: Lognormal distribution of Loading Factor for the model

Lognormal description

The lognormal distribution is widely used in situations where values are positively skewed (where most of the values occur near the minimum value). This means that the random variable can increase without bound, but is confined to a finite value at the lower limit. It is a continuous probability distribution of a random variable whose logarithm is normally distributed. The random variable must take only positive real values.

For example, financial analysts have observed that the stock prices are usually positively skewed, rather than normally (symmetrically) distributed. Stock prices exhibit this trend because the stock price cannot fall below the lower limit of zero but may increase to any price without limit. Similarly, real estate prices illustrate positive skewness since property values cannot become negative.

The parameters for lognormal distribution are mean and standard deviation.

Lognormal distribution in figure 36 is formed in such way due to slow steaming and the low values of Loading Factor for this condition.

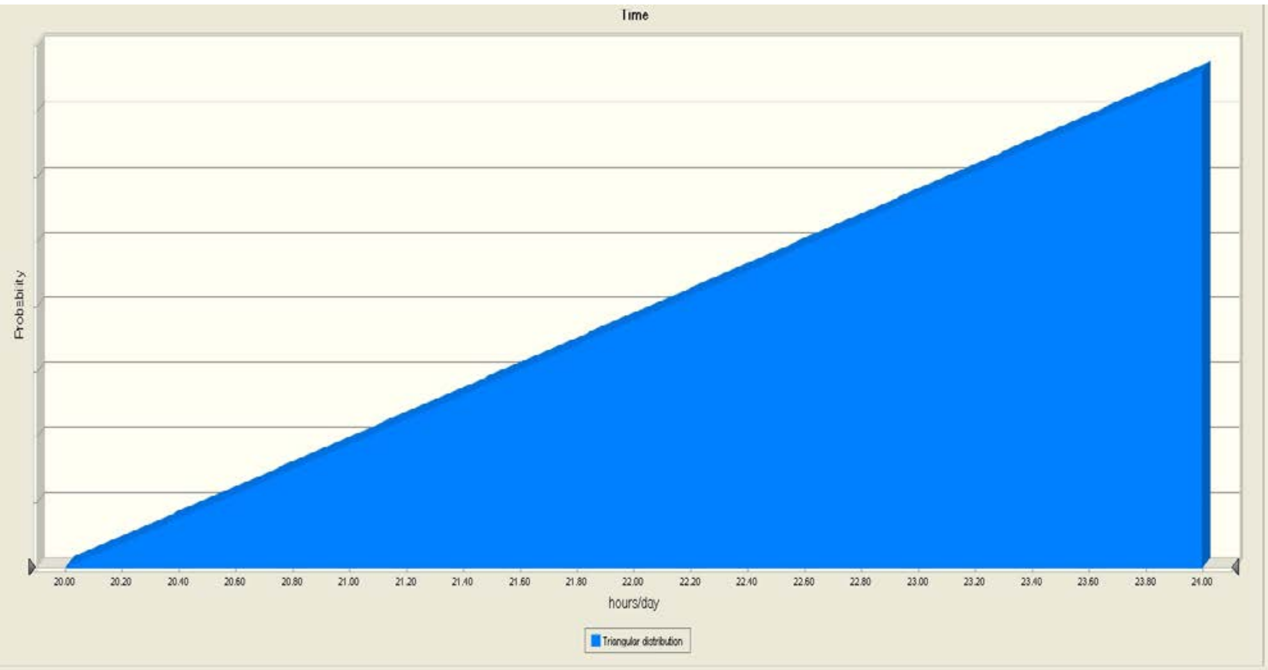


Figure 37: Triangular distribution of Time for the model

Triangular description

The triangular distribution is commonly used when you know the minimum, maximum and most likely values. The triangular distribution is typically used as a subjective description of a population for which there is only limited sample data and especially in cases where the relationship between variables is known but data is scarce (possibly because of the high cost of collection). It is based on a knowledge of the minimum and maximum and an "inspired guess" as to the modal value. For these reasons, the triangular distribution has been called a "lack of knowledge" distribution. It is a continuous probability distribution, whose the most likely value falls at a point between the minimum and maximum values, forming a triangular shaped distribution. This shows that values near the minimum and maximum are less likely to occur than those near the most likely value.

For example, we could describe the number of cars sold per week when past sales show the minimum, maximum and most likely number of cars sold.

The parameters for the triangular distribution are minimum, likeliest and maximum.

Triangular distribution in figure 37 is formed in such way because our data indicates that for at sea operation, the ship sails mostly 24 hours per day and the mostly minimum steaming time is 20 hours per day.

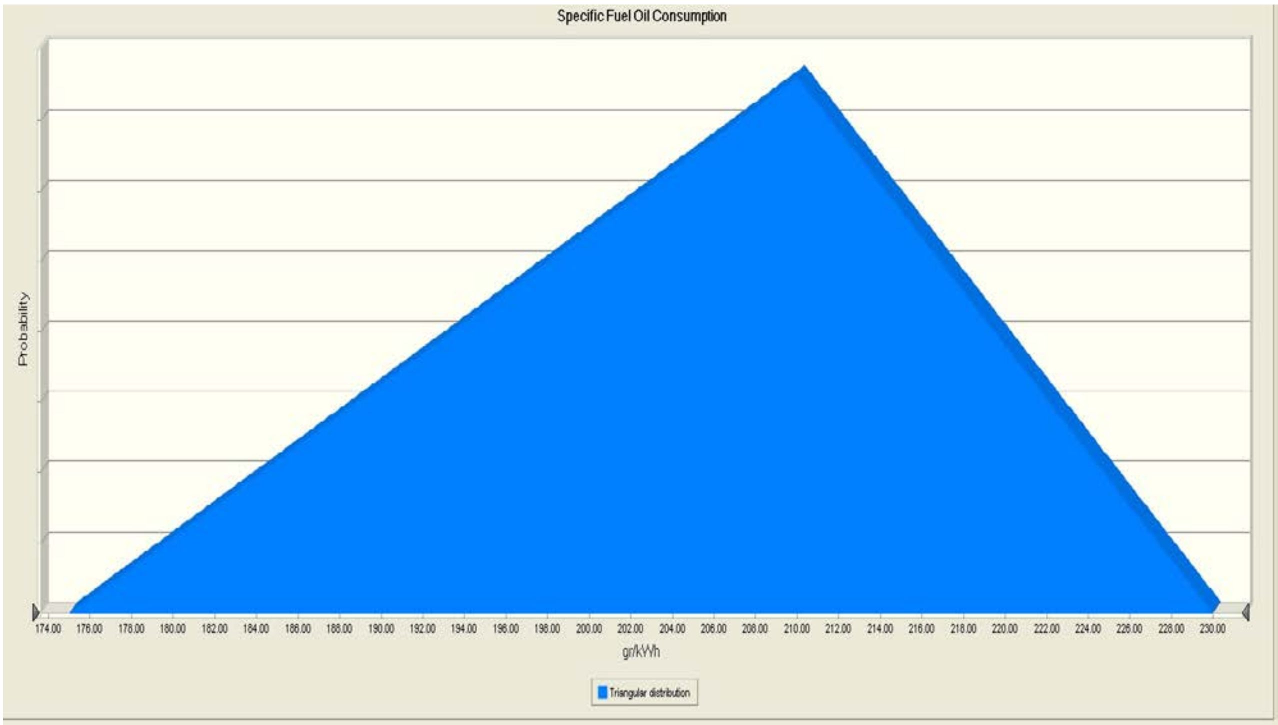


Figure 38: Triangular distribution of Specific Fuel Oil Consumption for the model

Triangular distribution in figure 38 is formed in such way due to slow steaming. The Main Engine is 10 years old and has an elevated specific fuel oil consumption in low load compared with a Tier II slow-speed engine.

Table 7: Input data for estimation of Fuel Consumption for the model

Input Data			
Model	**Loading Factor**	**Time (hours)**	**Specific Fuel Oil Consumption (gr/kWh)**
	Range: 0.12-0.77 Lognormal distribution Location= 0.11 Mean= 0.256 Std Dev= 0.09	Range: 20-24 Triangular distribution Minimum= 20 Likeliest= 24 Maximum= 24	Range: 175-230 Triangular distribution Minimum= 175 Likeliest= 210 Maximum= 230

Table 8: Comparison of input data for estimation of Fuel Consumption for the model

Input Data			
Model	**Loading Factor**	**Time (hours)**	**Specific Fuel Oil Consumption (gr/kWh)**
	Mean= 0.256 Median= 0.24 P80= 0.33	Mean= 22.67 Median= 22.83 P80= 23.58	Mean= 205 Median= 206.02 P80= 215.17

5.1.2 Robustness analysis

This term of analysis considers the influence of input variability on output variability of a model. The question is "how sensitive does a small input change effect on the system output". For consistent input variability, the output variances have to be computed to determine the robustness of the model. The equation of fuel consumption (model) is robust and insensitive to changing environment if the output variance is small.

Otherwise, the model is not robust and sensitive if the output variance caused by the same input distribution is great.

Robustness analysis for our probabilistic model is conducted as follows: two of our random variables, $\boldsymbol{LF}_{\%\boldsymbol{MCR}}$ and $\boldsymbol{SFOC}_{\frac{\boldsymbol{gr}}{\boldsymbol{kWh}}}$, will slightly change, whereas the remain variable ($\boldsymbol{t}_{\frac{\boldsymbol{hrs}}{\boldsymbol{day}}}$) will stay fixed. The well-known correlation between the two variables is shown before. From the correlation chart (figure 34), we estimate that at the range of values 0.25-0.35 for Loading Factor, SFOC follows the following function:

$$y = 48.43x^2 - 70.38x + 189.8$$

This range of values is knowingly selected because our ship operates in slow steaming condition for most of the time. From the above function, it is estimated that since Loading Factor rises of 8% in the specific range of values, SFOC decreases about 0.5%. Robustness analysis in this model contains three case studies which are coming after the initial estimation of the probabilistic distribution of FC from our approach:

1. Increase of LF by 8%, decrease of SFOC by 0.5%
2. Increase of LF by 16%, decrease of SFOC by 1.0%
3. Increase of LF by 24%, decrease of SFOC by 1.5%

Input data

For each case study, input data consists of the same probabilistic distributions like the initial for our model and the variables changing are multiplied with the appropriate coefficient, resulting in the final distribution for FC (tonnes per day)

Case Study No.1:

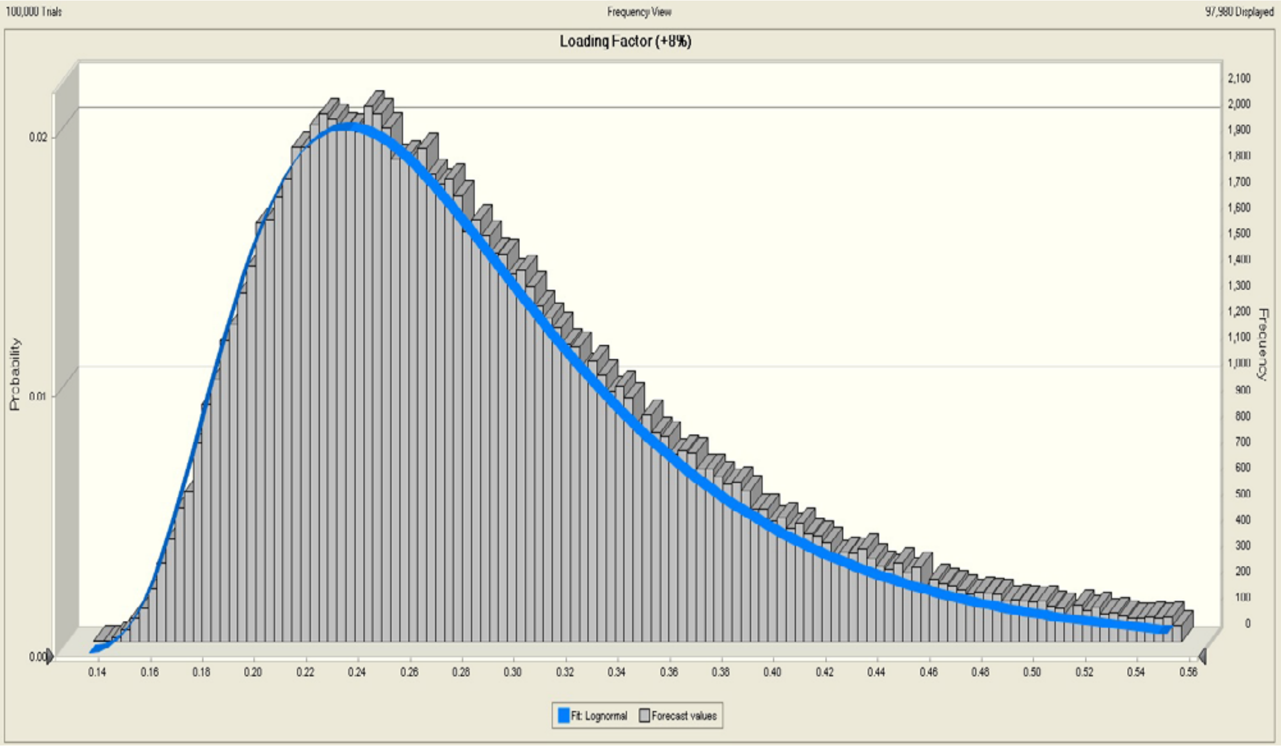


Figure 39: Lognormal distribution of Loading Factor for Case Study No. 1

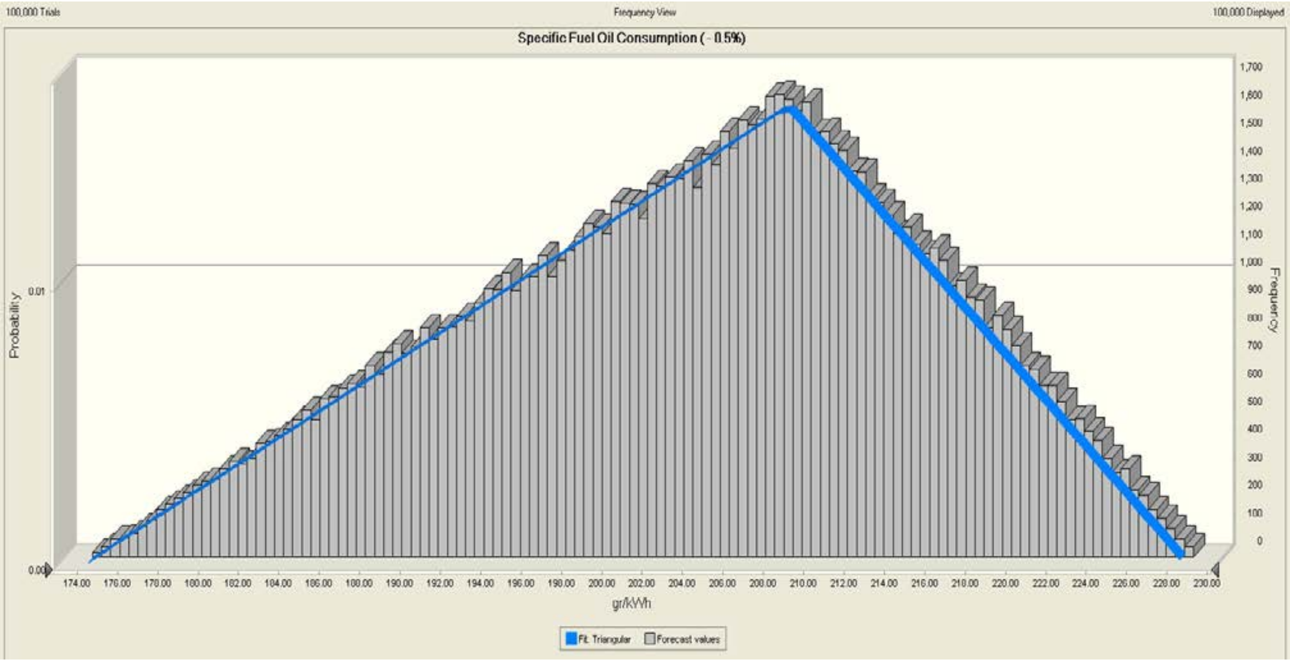


Figure 40: Triangular distribution of Specific Fuel Oil Consumption for Case Study No. 1

Case Study No. 2:

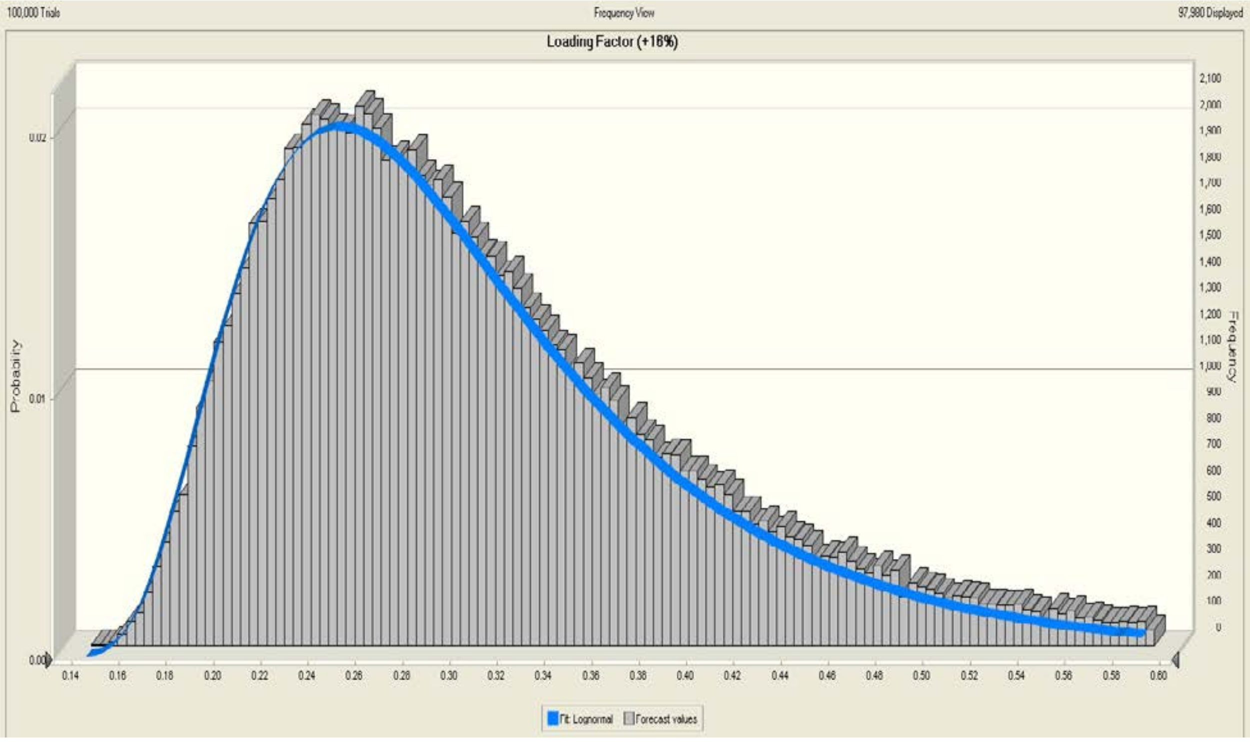


Figure 41: Lognormal distribution of Loading Factor for Case Study No. 2

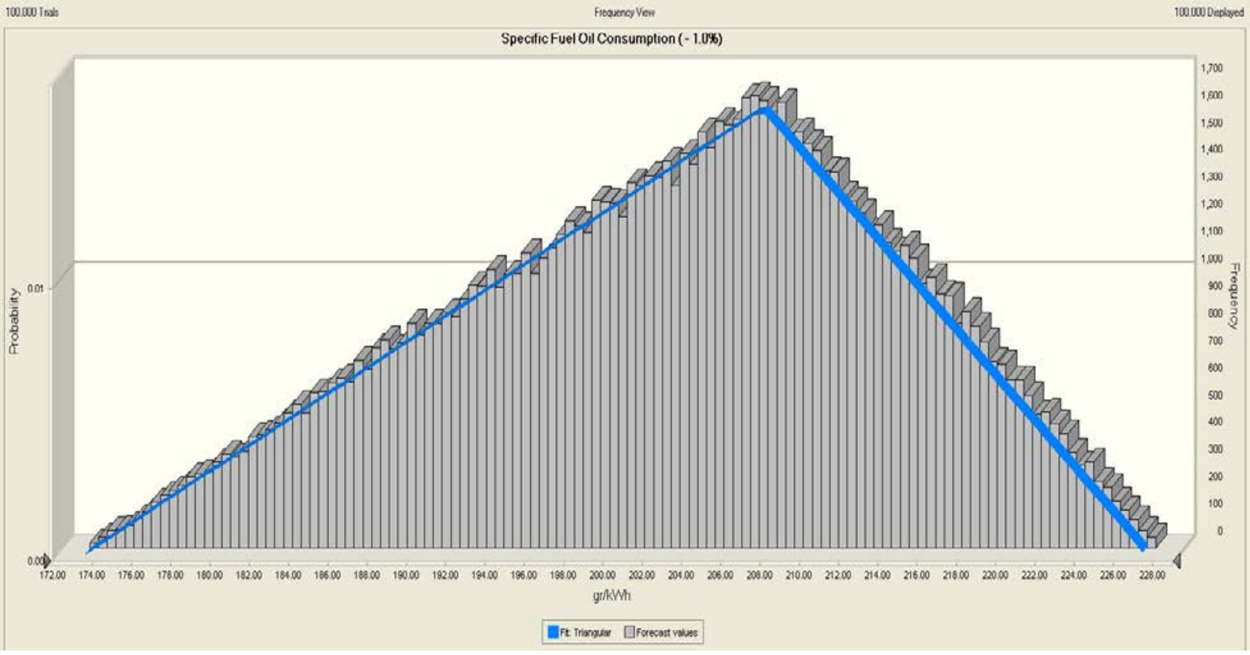


Figure 42: Triangular distribution of Specific Fuel Oil Consumption for Case Study No. 2

Case Study No. 3:

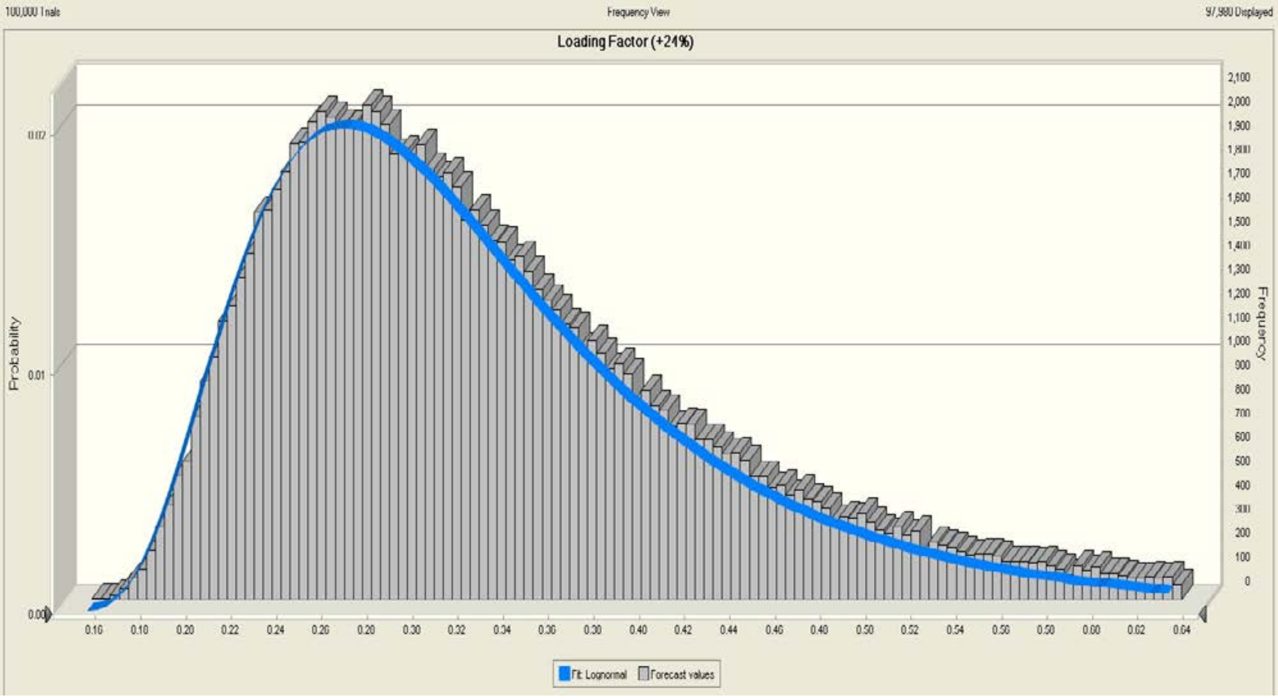


Figure 43: Lognormal distribution of Loading Factor for Case Study No. 3

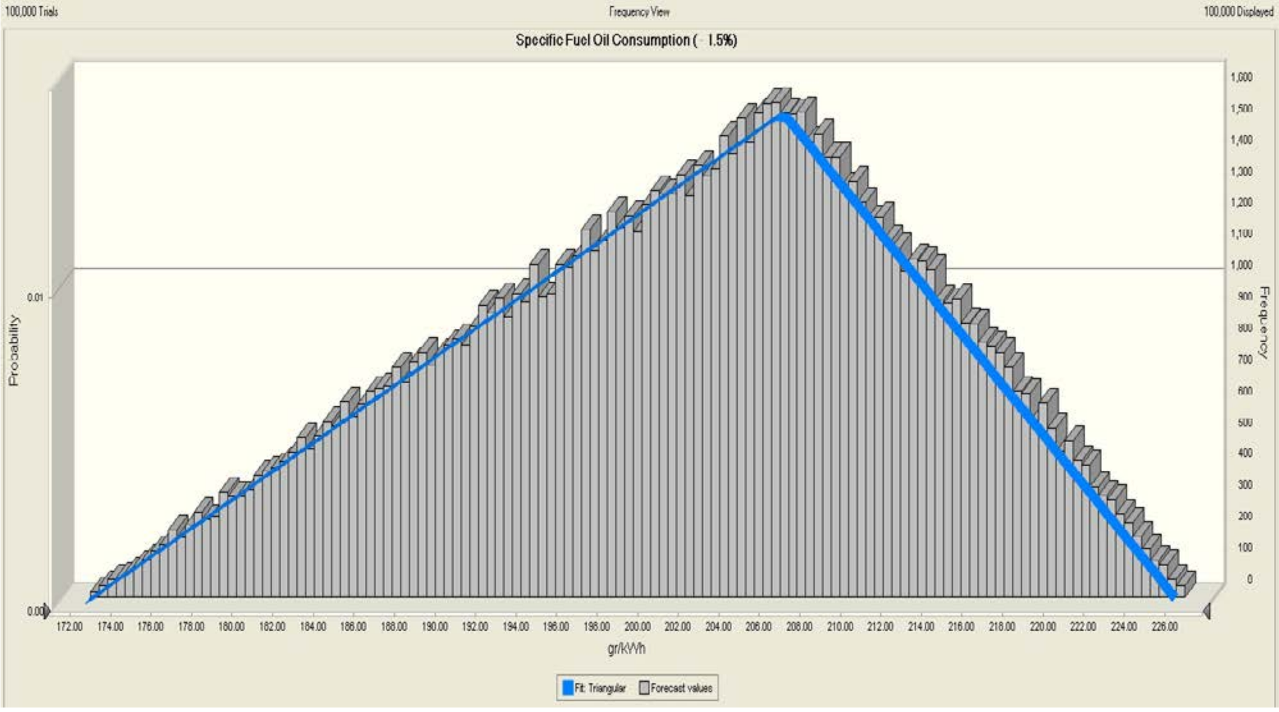


Figure 44: Triangular distribution of Specific Fuel Oil Consumption for Case Study No. 3

Table 9: Input data for estimation of Fuel Consumption for the three Case Studies

Input Data			
	Loading Factor	**Time (hours)**	**Specific Fuel Oil Consumption (gr/kWh)**
Case Study No. 1	Range: 0.14-0.55 Lognormal distribution Location= 0.12 Mean= 0.281 Std Dev= 0.10	Range: 20-24 Triangular distribution Minimum= 20 Likeliest= 24 Maximum= 24	Range: 174.16-228.89 Triangular distribution Minimum= 174.16 Likeliest= 208.82 Maximum= 228.89
Case Study No. 2	Range: 0.14-0.59 Lognormal distribution Location= 0.13 Mean= 0.303 Std Dev= 0.10	Range: 20-24 Triangular distribution Minimum= 20 Likeliest= 24 Maximum= 24	Range: 173.29-227.74 Triangular distribution Minimum= 173.29 Likeliest= 207.77 Maximum= 227.74
Case Study No. 3	Range: 0.15-0.64 Lognormal distribution Location= 0.13 Mean= 0.324 Std Dev= 0.11	Range: 20-24 Triangular distribution Minimum= 20 Likeliest= 24 Maximum= 24	Range: 172.41-226.59 Triangular distribution Minimum= 172.41 Likeliest= 226.59 Maximum= 226.59

Table 10: Comparison of input data for estimation of Fuel Consumption for the three Case Studies

Input Data			
	Loading Factor	**Time (hours)**	**Specific Fuel Oil Consumption (gr/kWh)**
Case Study No. 1	Mean= 0.281 Median= 0.27 P80= 0.35	Mean= 22.67 Median= 22.83 P80= 23.58	Mean= 203.96 Median= 204.96 P80= 214.07
Case Study No. 2	Mean= 0.303 Median= 0.29 P80= 0.38	Mean= 22.67 Median= 22.83 P80= 23.58	Mean= 202.93 Median= 203.93 P80= 212.99
Case Study No. 3	Mean= 0.324 Median= 0.31 P80= 0.40	Mean= 22.67 Median= 22.83 P80= 23.58	Mean= 201.91 Median= 202.90 P80= 211.92

5.1.3 Estimation of ship emissions

Model assumptions

It is not clear from the NR what type of HFO is used in the ship's trips. By examining the NR more precisely, it is obvious that the ship did not sail in the ECA's during the past five years. We examine the operational profile at sea, which means that the fuel mostly used contains upon 0.5% sulphur. As a result, it is assumed in all forecasts that the average fuel used is HFO-2.7% S.

The equation for estimating emissions is written previously. Emission factors (in grams per kWh) are taken from table 6 and for low power due to slow steaming. Emission factor for Particulate Matter is taken from [72] for the same fuel used in this model (1.46 gr/kWh).

$$\mathrm{EF_{CO_2}} = 600\ \mathrm{gr/kWh}$$

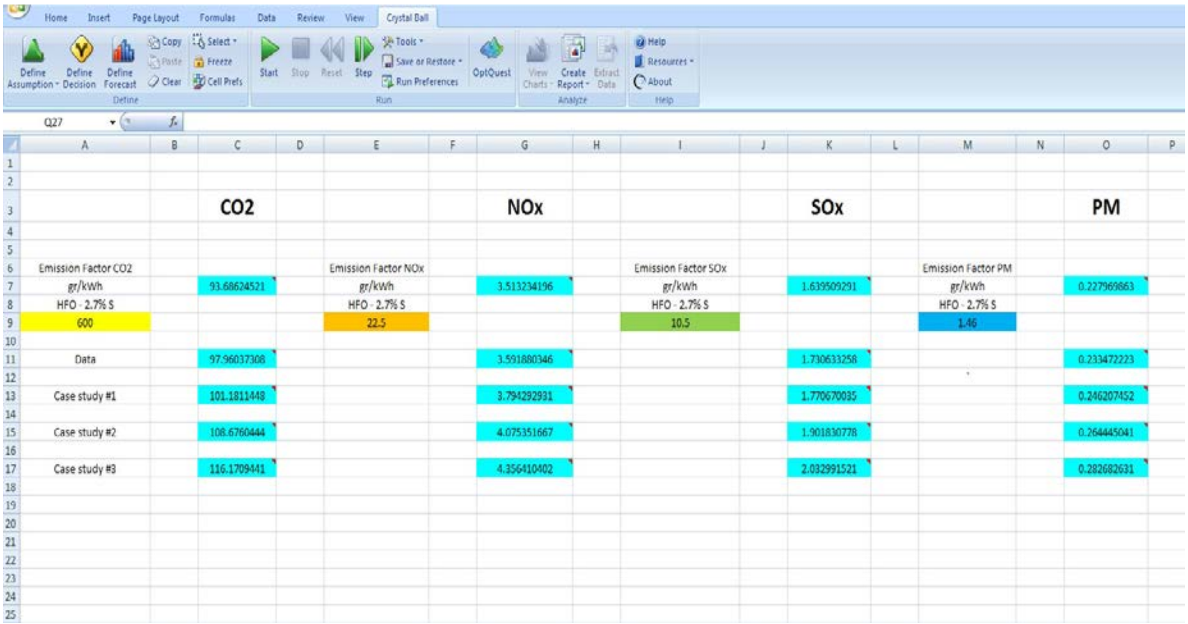
$$\mathrm{EF_{NO_x}} = 22.5\ \mathrm{gr/kWh}$$

$$\mathrm{EF_{SO_x}} = 10.5\ \mathrm{gr/kWh}$$

$$\mathrm{EF_{PM}} = 1.46\ \mathrm{gr/kWh}$$

Input data

Input data consists of two probabilistic distributions ($\boldsymbol{LF_{\%MCR}}$, $\boldsymbol{t_{\frac{hrs}{day}}}$) and two single values for $\mathrm{P_{MCR}}$ and $\mathrm{EF_{\frac{gr}{kWh}}}$, multiplied together via MC simulation. The forecast that comes out is a new distribution for each pollutant (tonnes of pollutant per day).



	A	C	E	G	I	K	M	O
3		CO2		NOx		SOx		PM
6	Emission Factor CO2		Emission Factor NOx		Emission Factor SOx		Emission Factor PM	
7	gr/kWh	93.68624521	gr/kWh	3.513234196	gr/kWh	1.639509291	gr/kWh	0.227969863
8	HFO - 2.7% S		HFO - 2.7% S		HFO - 2.7% S		HFO - 2.7% S	
9	600		22.5		10.5		1.46	
11	Data	97.96037308		3.591880346		1.730633258		0.233472223
13	Case study #1	101.1811448		3.794292931		1.770670035		0.246207452
15	Case study #2	108.6760444		4.075351667		1.901830778		0.264445041
17	Case study #3	116.1709441		4.356410402		2.032991521		0.282682631

Figure 45: Spreadsheet from Excel for estimating emissions

5.2 Presentation of results

All results of the probabilistic approach for all random variables are subsequently presented in detail. All forecasts are compared with three statistics' measures: mean, median and P80.

Mean refers to a measure of the central tendency either of a probability distribution or of the random variable characterized by that distribution.

Median is the number separating the higher half of a data sample, a population, or a probability distribution, from the lower half.

A percentile is a measure used in statistics indicating the value below which a given percentage of observations in a group of observations fall. For example, the 80th percentile (P80) is the value below which 80 percent of the observations may be found.

5.2.1 Fuel Consumption from NR and our approach

Figures for fuel consumption coming out from NR and our model are below.

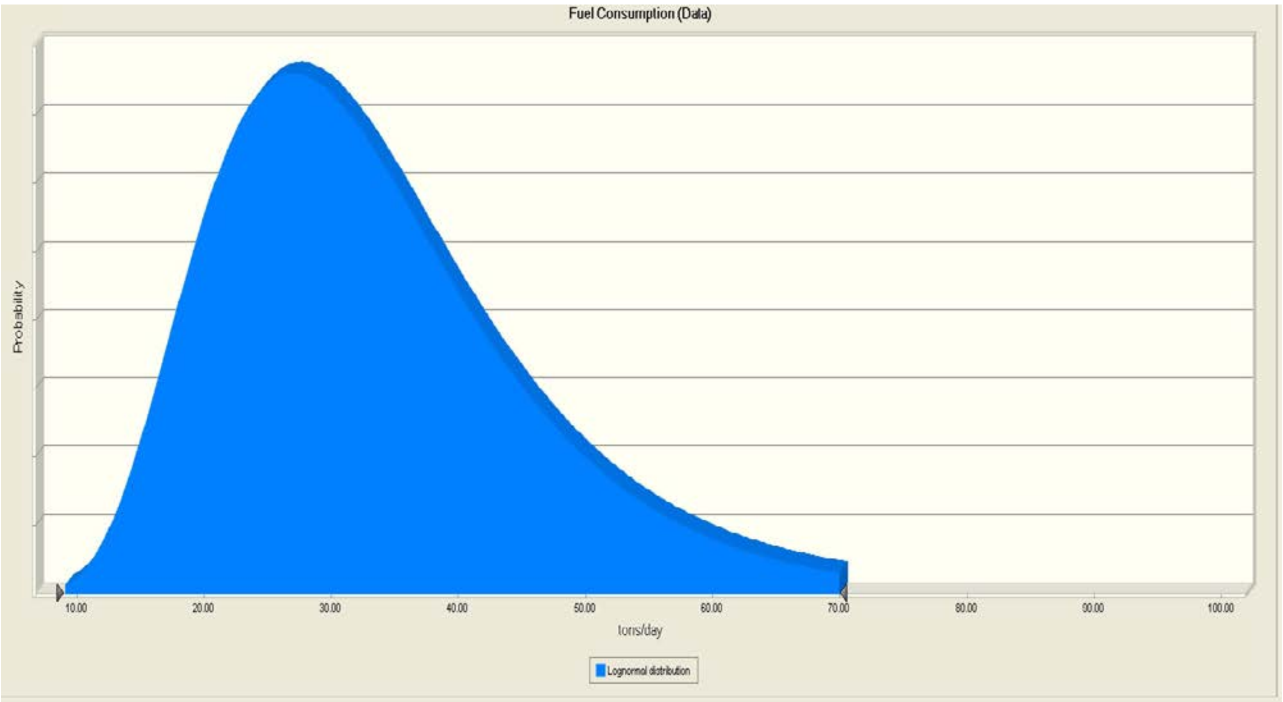
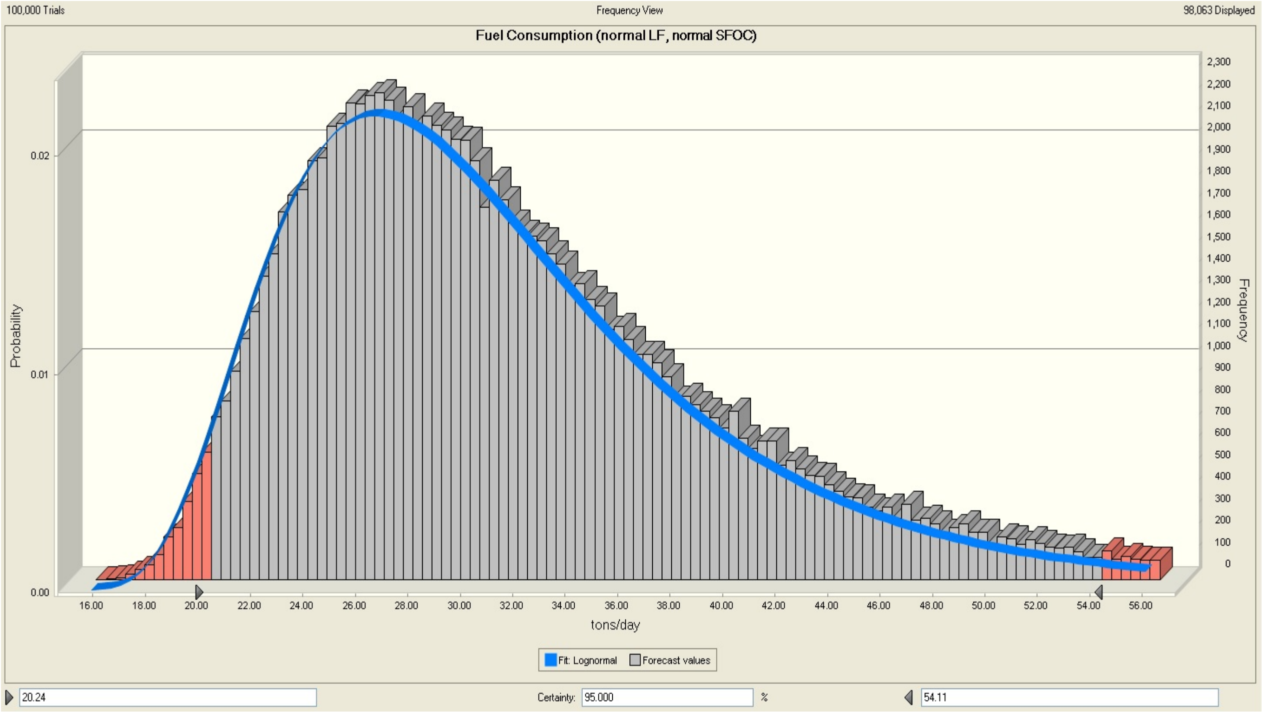


Figure 46: Lognormal distribution of Fuel Consumption for the NR



20.24 Certainty: 95.000 % 54.11

Figure 47: Lognormal distribution of Fuel Consumption for the model

Figure 45 shows the distribution that outlines Fuel Consumption for data taken from NR of the known ship. Respectively, figure 46 shows the distribution that outlines Fuel Consumption for the probabilistic model. In this figure, we can see up left the number of total trials of Monte Carlo simulation (100,000 trials). Up right, there is the total number of trials used for the extraction of the distribution (98,063 trials). Difference between these values is due to the fact that some results produced by Monte Carlo simulation did not meet requirements and restrictions of the model.

Table 11: Output data for estimation of Fuel Consumption for NR and model

Output Data	
	Fuel Consumption (tons/day)
Noon Report	Range: 0-70 Lognormal distribution Location= 0 Mean= 32.65 Std Dev= 11.60
Model	Range: 20.24-54.11 Lognormal distribution Location= 13.78 Mean= 31.72 Std Dev= 8.86

Table 12: Comparison of output data for estimation of Fuel Consumption for the NR and model

Output Data	
	Fuel Consumption (tons/day)
Noon Report	Mean= 32.65 Median= 30.89 P80= 42.02
Model	Mean= 31.72 Median= 29.87 P80= 37.62

Results are satisfactory in comparison with fuel consumption for Container ships in figure 26.

In a probabilistic view, it is easily seen that our model approaches in a good way data from NR. Differences are small, about a ton per day divergence in terms of mean and median.

Afterwards, figure 48 presents sensitivity among random variables used for the estimation of Fuel Consumption for the model:

- Loading Factor: 66.9%
- Specific Fuel Oil Consumption: 31.1%
- Time: 1.9%

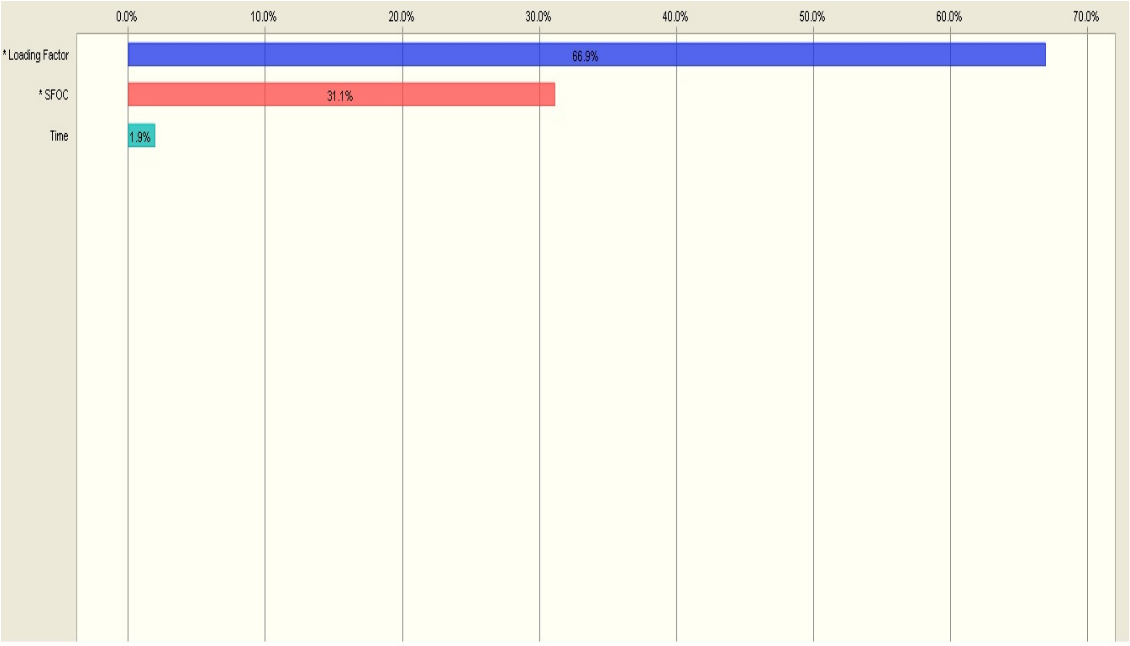
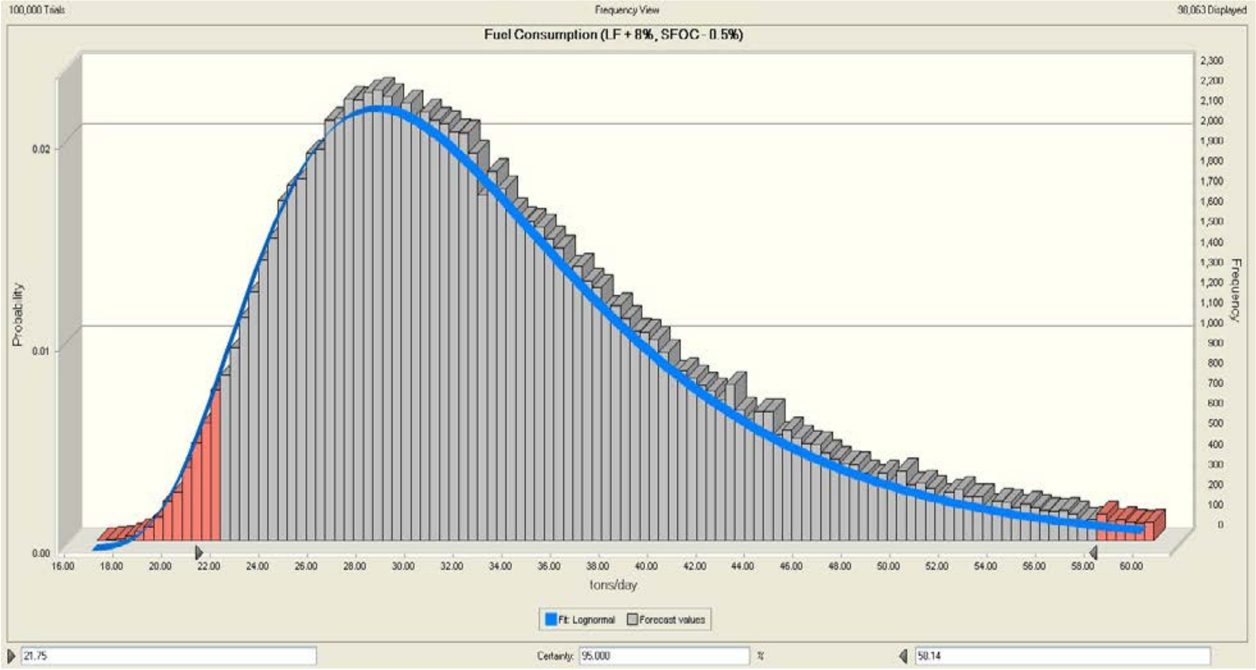


Figure 48: Sensitivity Chart of Fuel Consumption for the model

5.2.2 **Robustness Analysis**

Figures for fuel consumption coming out from Case Studies are below.

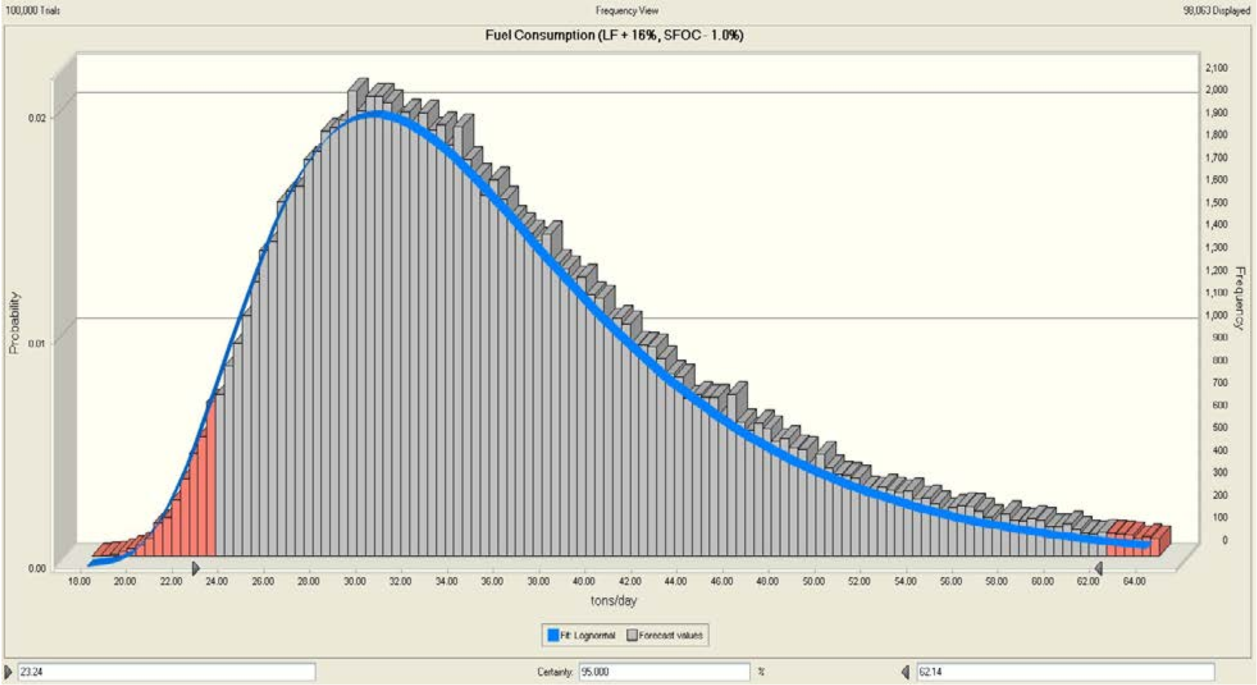


21.75

Certainty: 95.000 %

58.14

Figure 49: Lognormal distribution of Fuel Consumption for Case Study No. 1

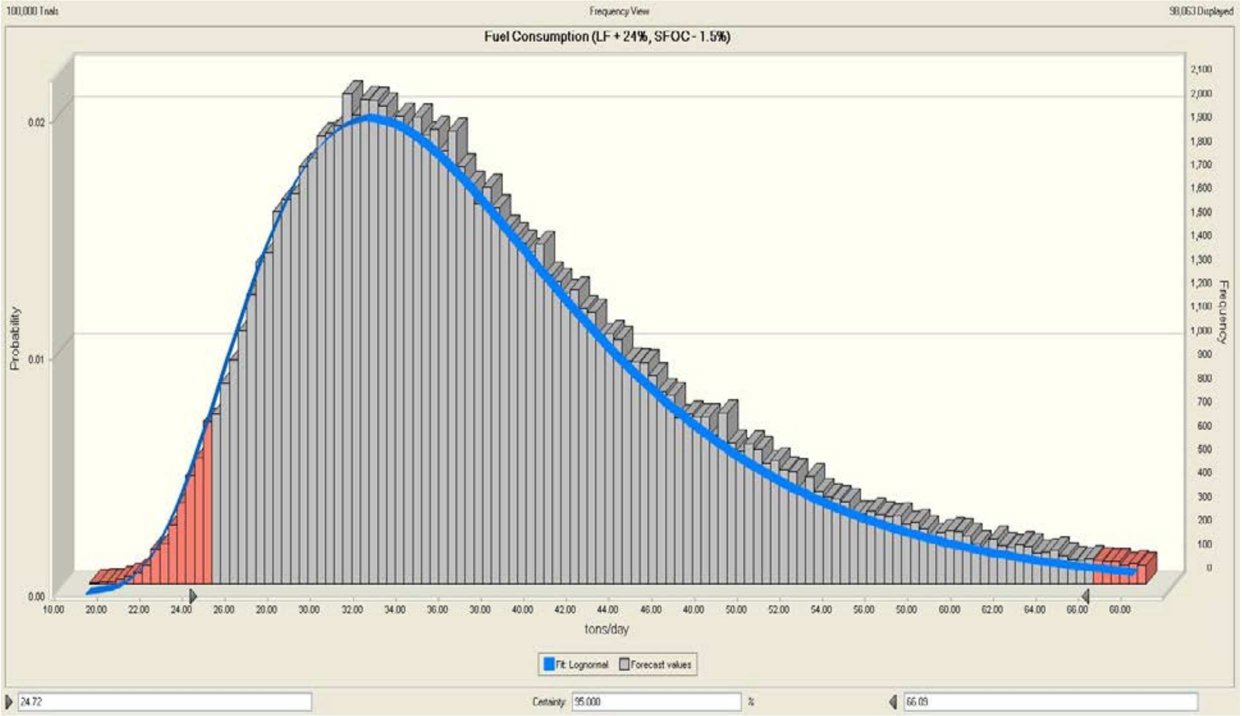


23.24

Certainty: 95.000 %

62.14

Figure 50: Lognormal distribution of Fuel Consumption for Case Study No. 2



24.72

Certainty: 95.000 %

66.09

Figure 51: Lognormal distribution of Fuel Consumption for Case Study No. 3

In figures 49-51, the x-axis refers to Fuel Consumption per day (tons/day). On the left, y-axis shows the probability for any value of Fuel Consumption, while on the right, there are frequencies for the respective values. In figure 49, probability of burning 30 tons/day for the specific operational conditions is approximately 0.02. In the same figure, Fuel Consumption belongs to a lognormal distribution at a range of 21.75 to 58.14 tons/day in a certainty interval of 95%.

Table 13: Output data for estimation of Fuel Consumption for model and three Case Studies

Output Data	
	Fuel Consumption (tons/day)
Model	Range: 20.24-54.11 Lognormal distribution Location= 13.78 Mean= 31.72 Std Dev= 8.86
Case Study No. 1	Range: 21.75-58.14 Lognormal distribution Location= 14.81 Mean= 34.09 Std Dev= 9.52
Case Study No. 2	Range: 23.24-62.14 Lognormal distribution Location= 15.82 Mean= 36.43 Std Dev= 10.18
Case Study No. 3	Range: 24.72-66.09 Lognormal distribution Location= 16.83 Mean= 38.75 Std Dev= 10.82

Table 14: Comparison of output data for estimation of Fuel Consumption for the model and three Case Studies

Output Data	
	Fuel Consumption (tons/day)
Model	Mean= 31.72 Median= 29.87 P80= 37.62
Case Study No. 1	Mean= 34.09 Median= 32.10 P80= 40.42
Case Study No. 2	Mean= 36.43 Median= 34.30 P80= 43.20
Case Study No. 3	Mean= 38.75 Median= 36.48 P80= 45.95

From figure 48, it is obvious that the random variable which mostly affects fuel consumption is Loading Factor. Under this consideration, a slight rise of fuel consumption occurs by a progressive rise of Loading which is visible in figure 52.

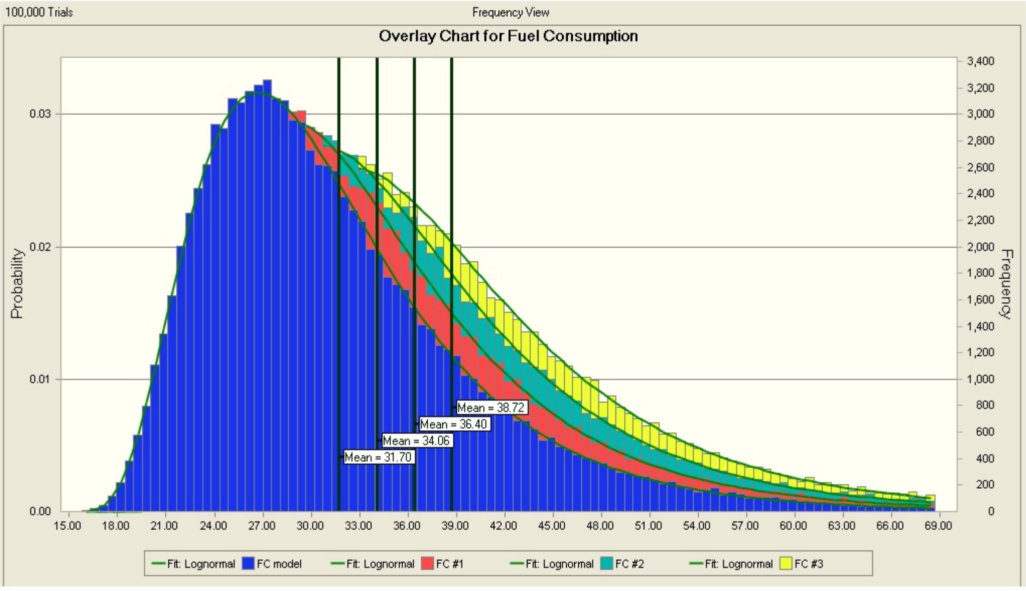
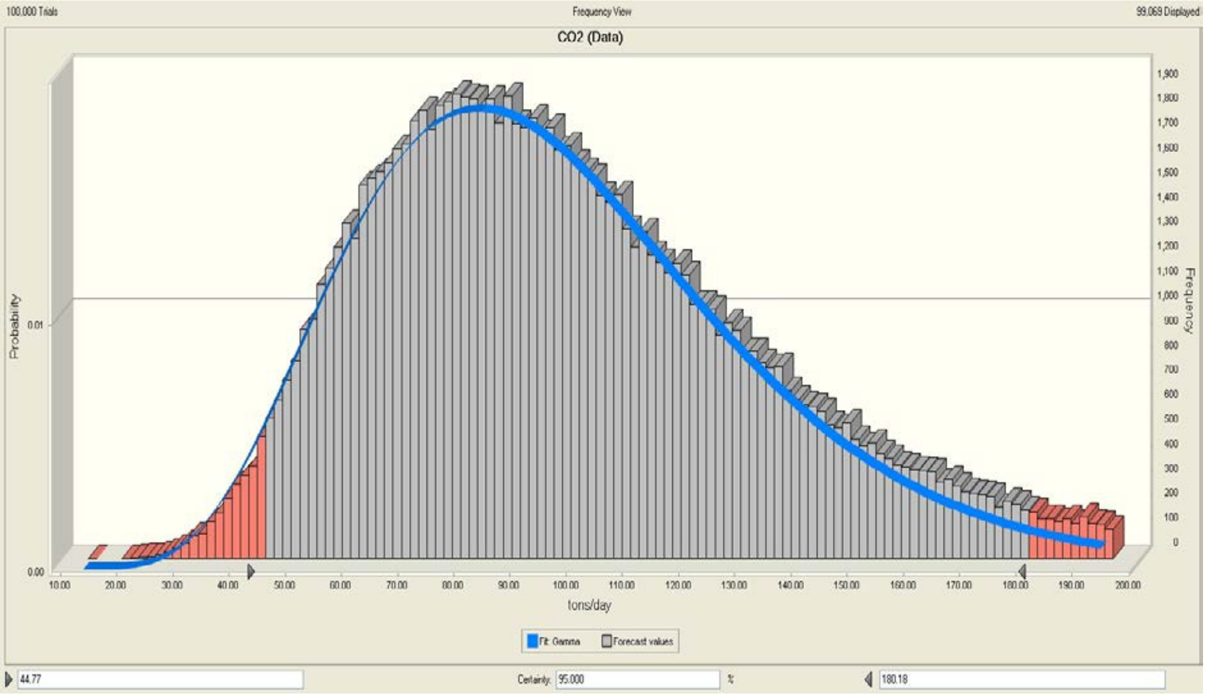


Figure 52: Overlay Chart for Fuel Consumption

5.2.3 Ship emissions

Figures for ship emissions coming out from NR, model and all Case Studies are below.

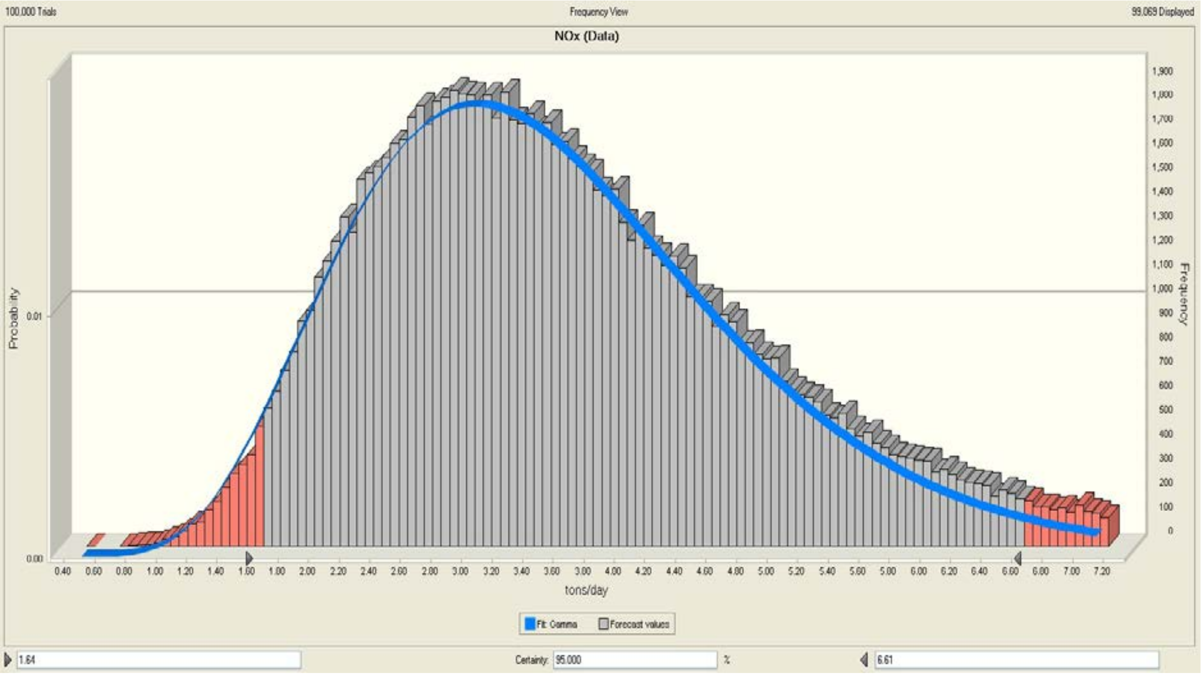


44.77

Certainty: 95.000 %

180.18

Figure 53: Gamma distribution of CO_2 for the NR



1.64

Certainty: 95.000 %

6.61

Figure 54: Gamma distribution of NO_x for the NR

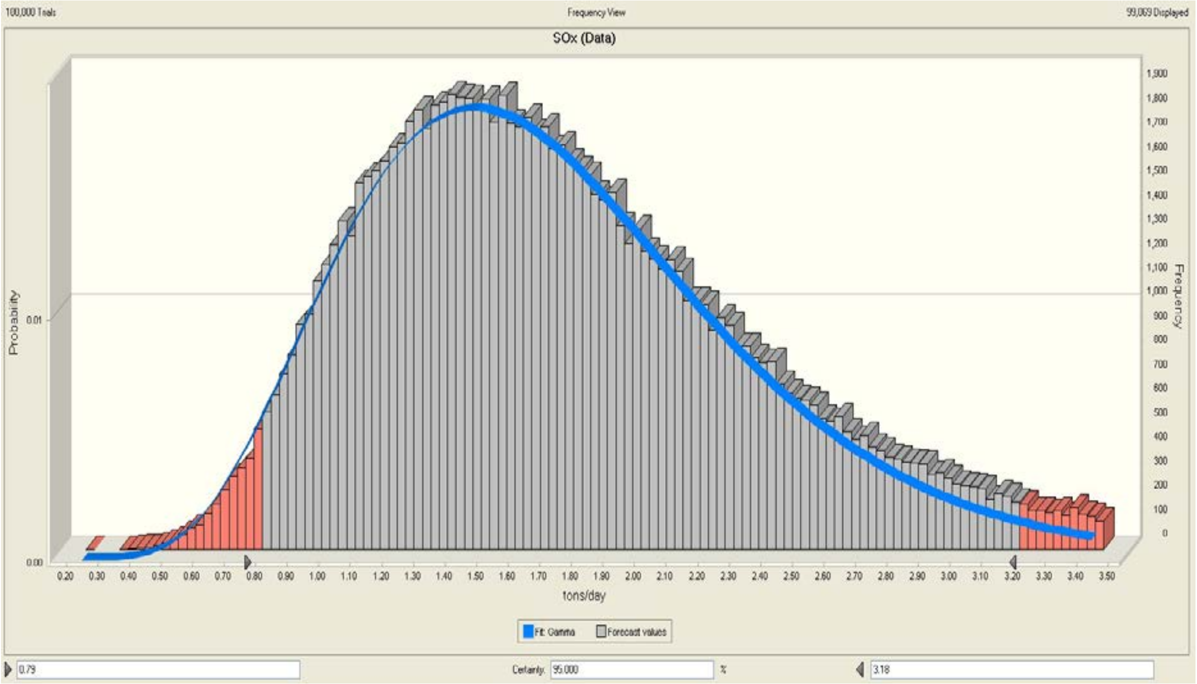


Figure 55: Gamma distribution of SO_x for the NR

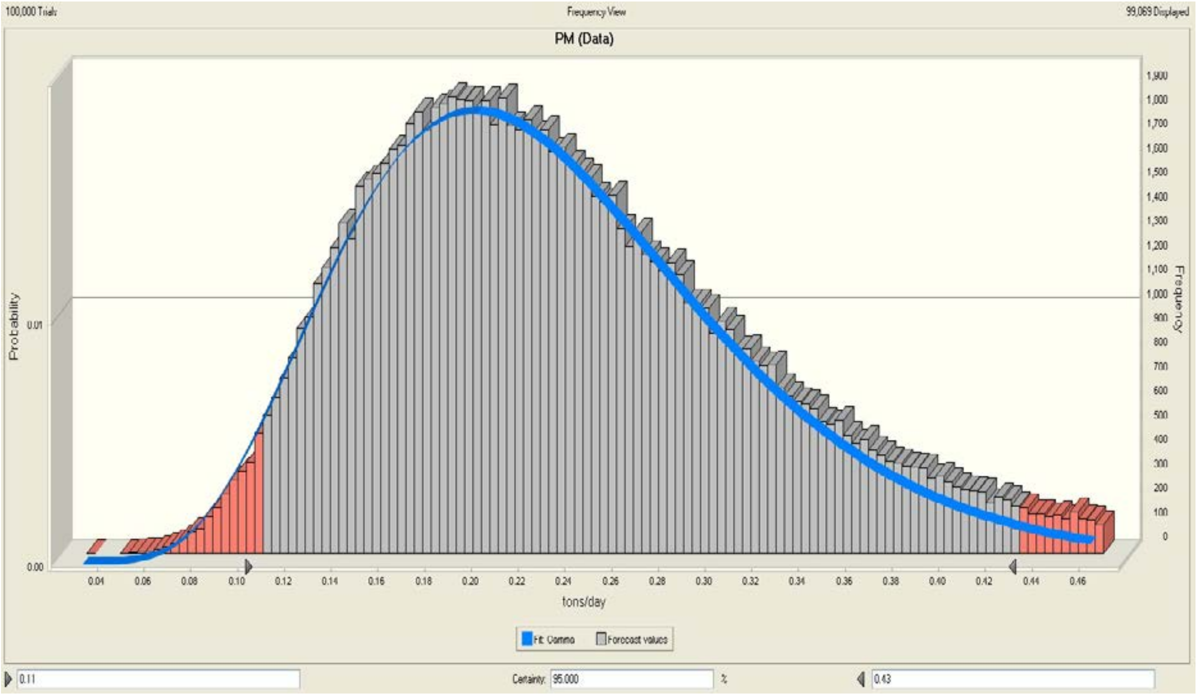
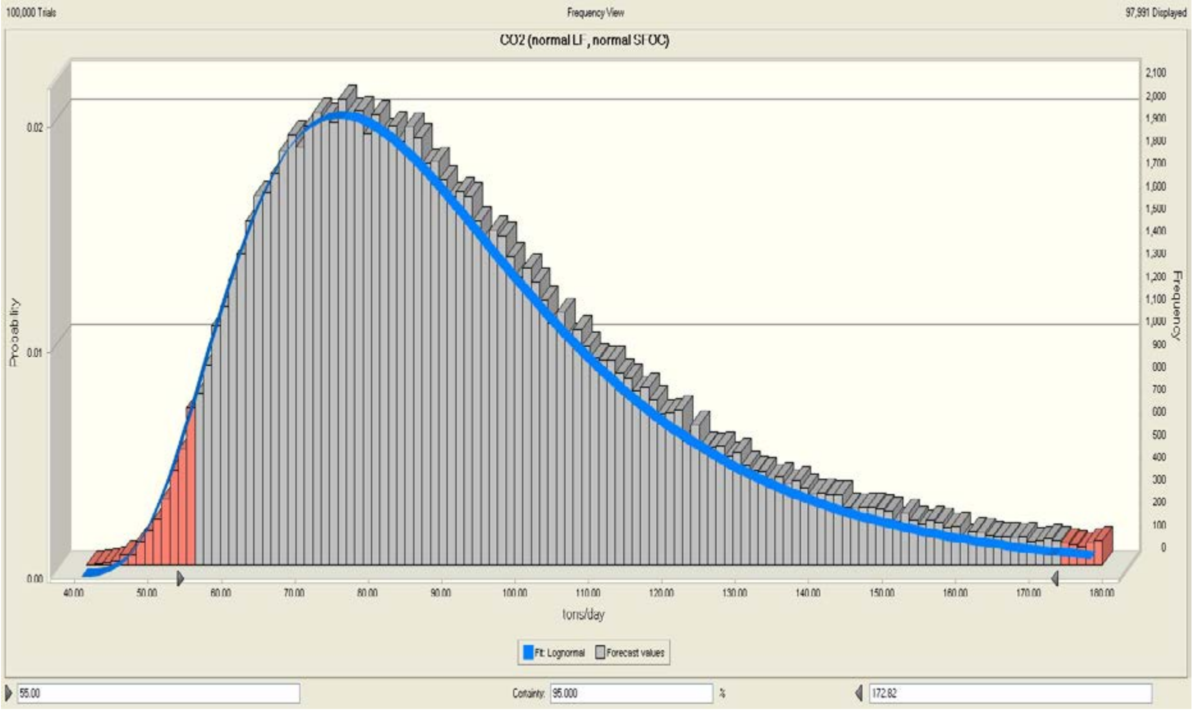
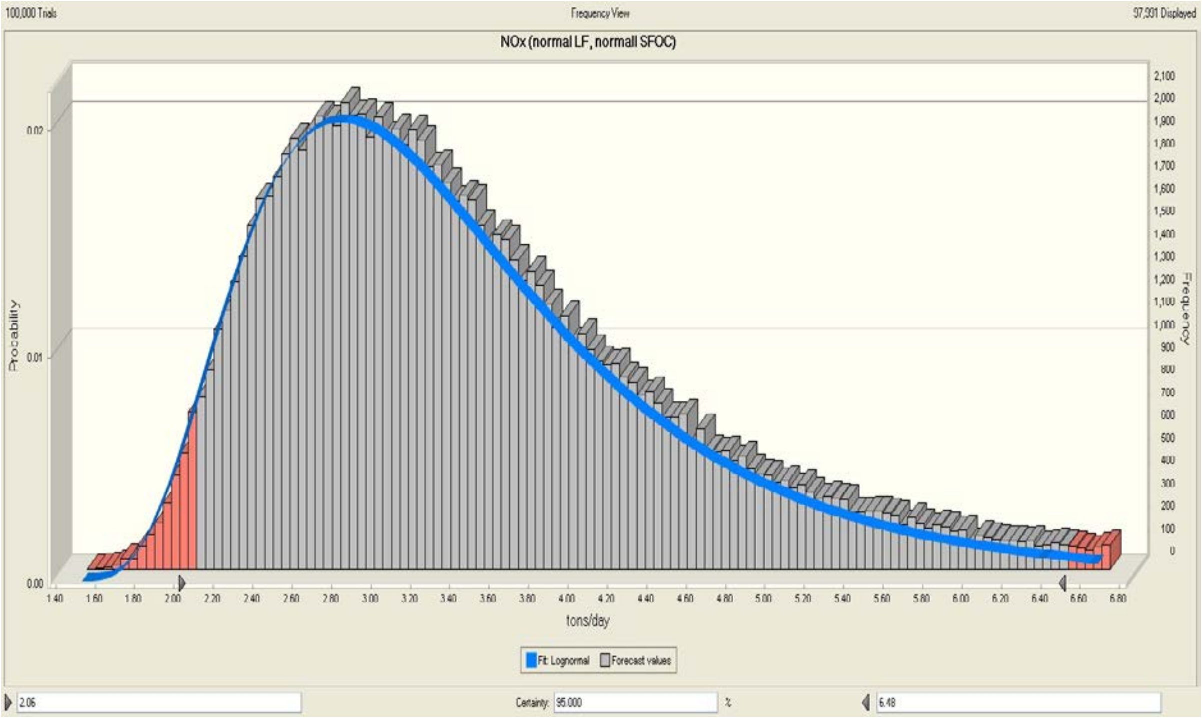


Figure 56: Gamma distribution of Particulate Matter for the NR



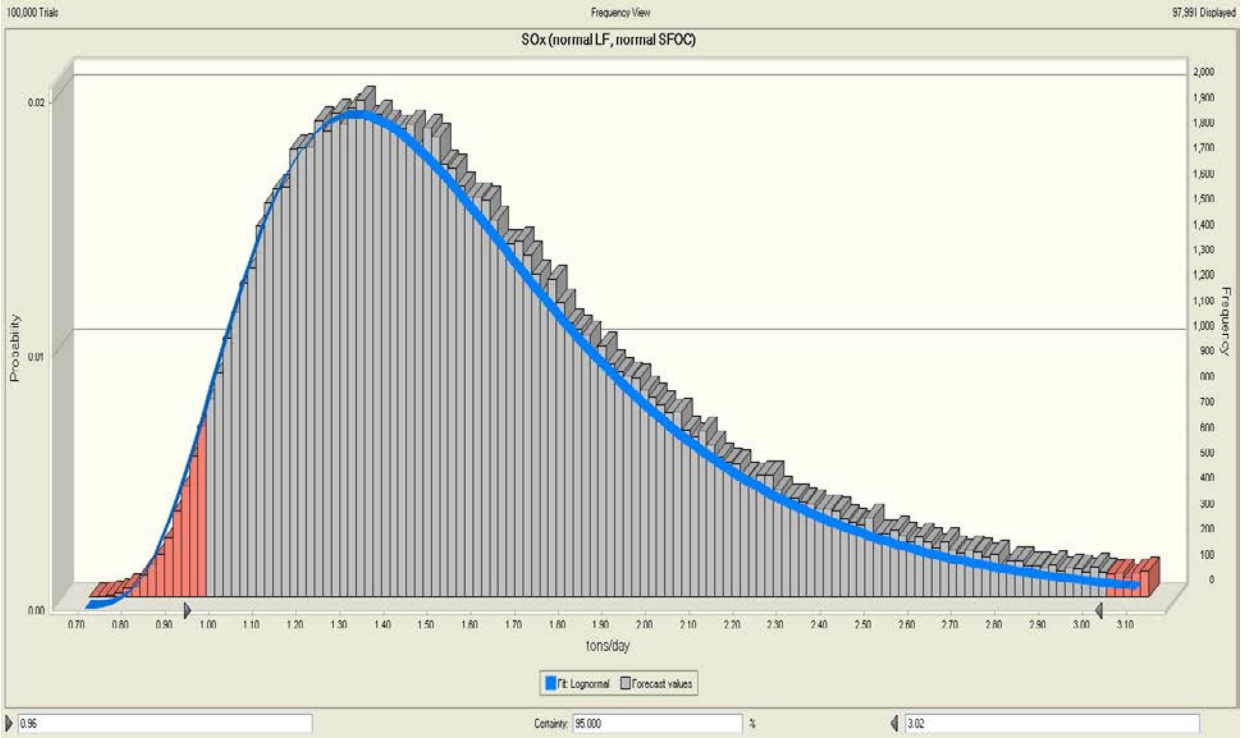
55.00 Certainty: 95.000 % 172.82

Figure 57: Lognormal distribution of CO_2 for the model



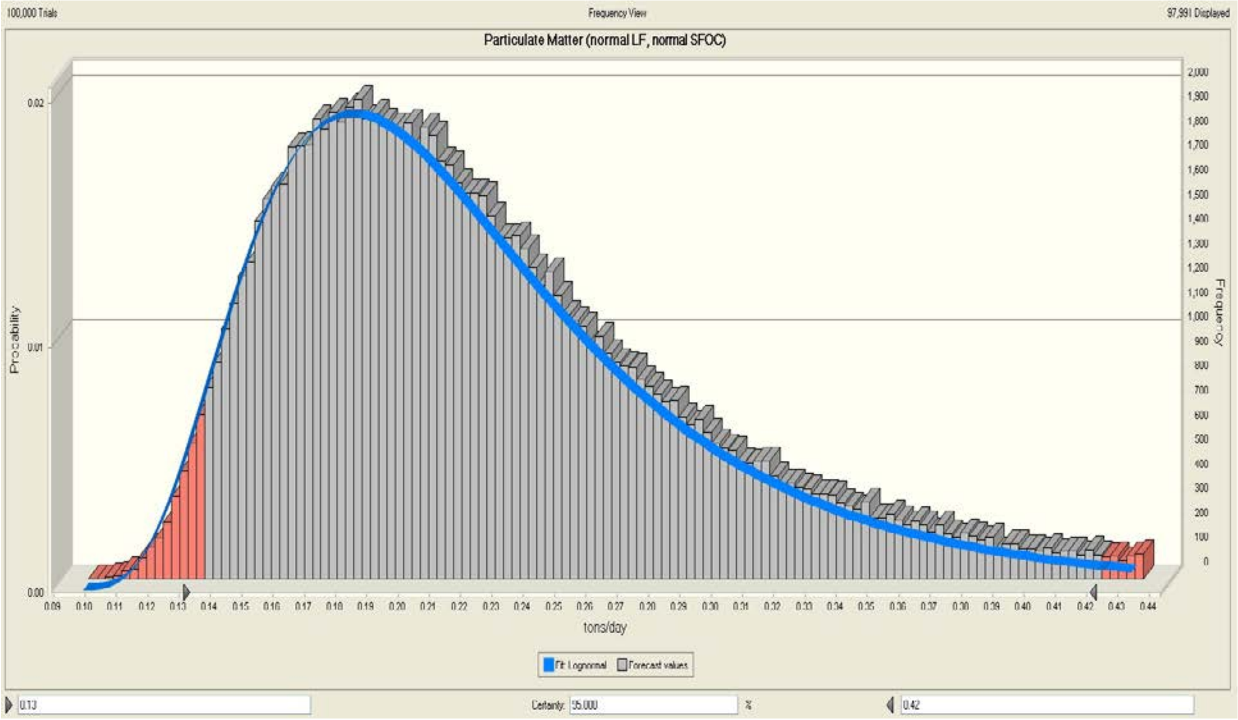
2.06 Certainty: 95.000 % 6.48

Figure 58: Lognormal distribution of NO_x for the model



0.96 Certainty: 95.000 % 3.02

Figure 59: Lognormal distribution of SO_x for the model



0.13 Certainty: 95.000 % 0.42

Figure 60: Lognormal distribution of Particulate Matter for the model

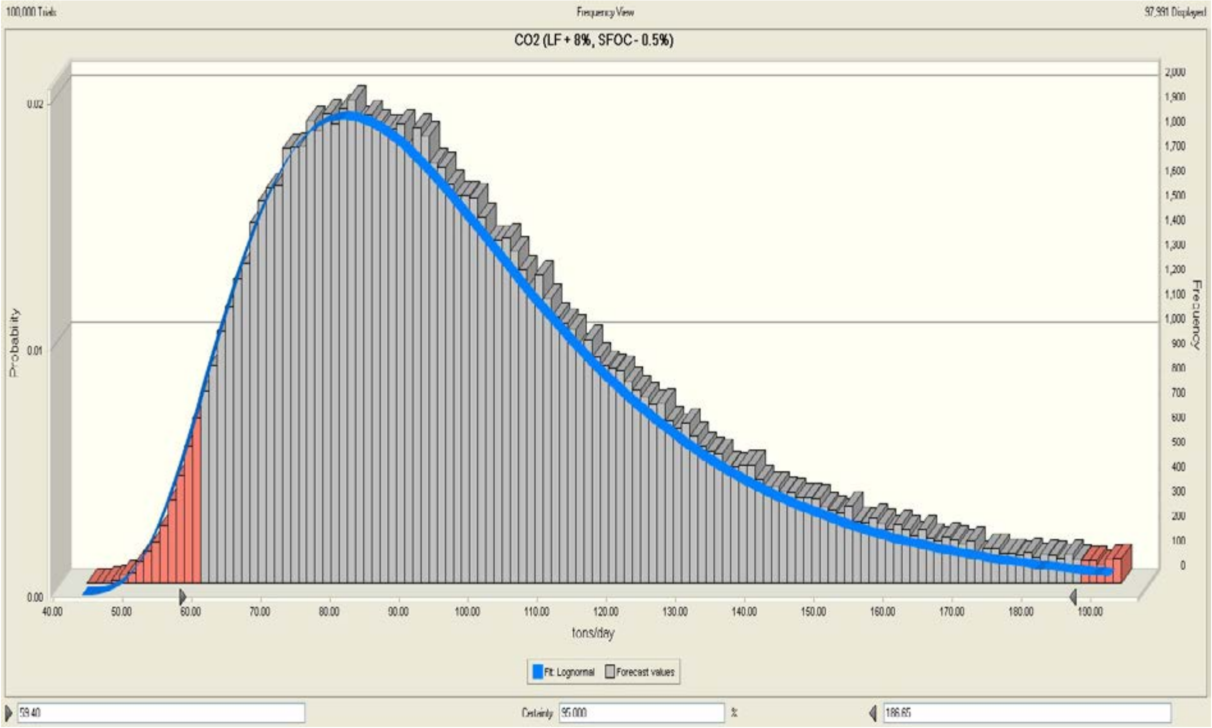


Figure 61: Lognormal distribution of CO_2 for Case Study No. 1

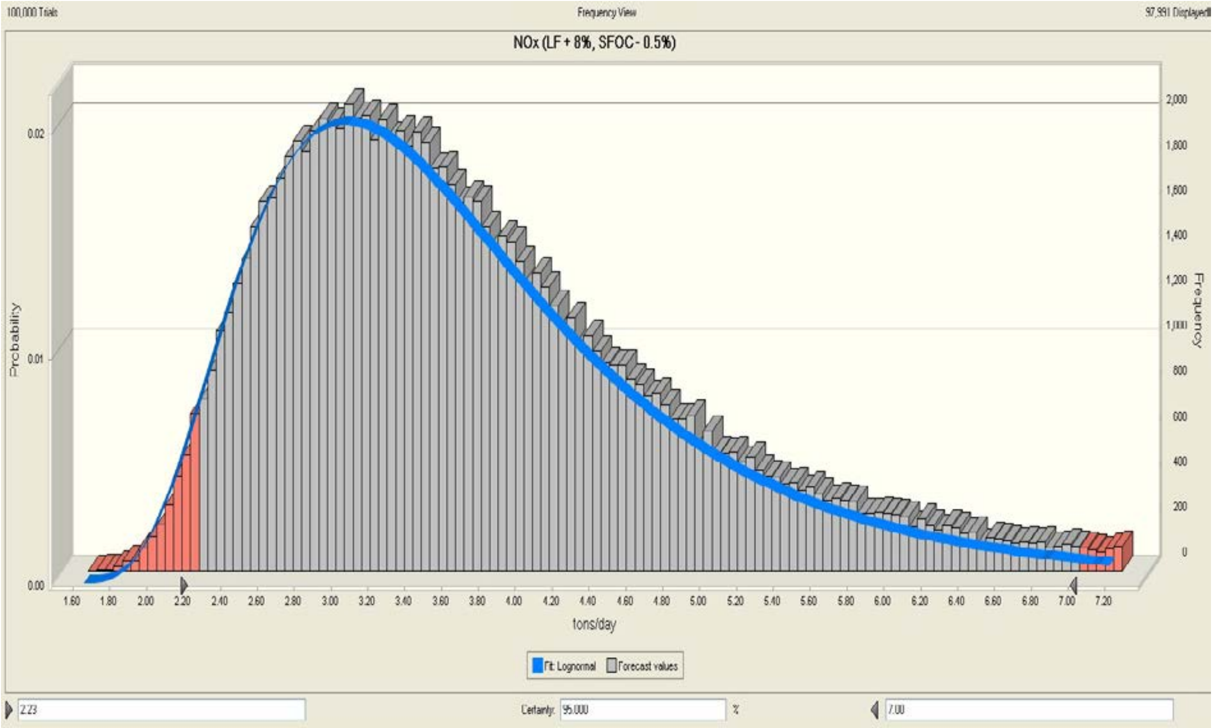
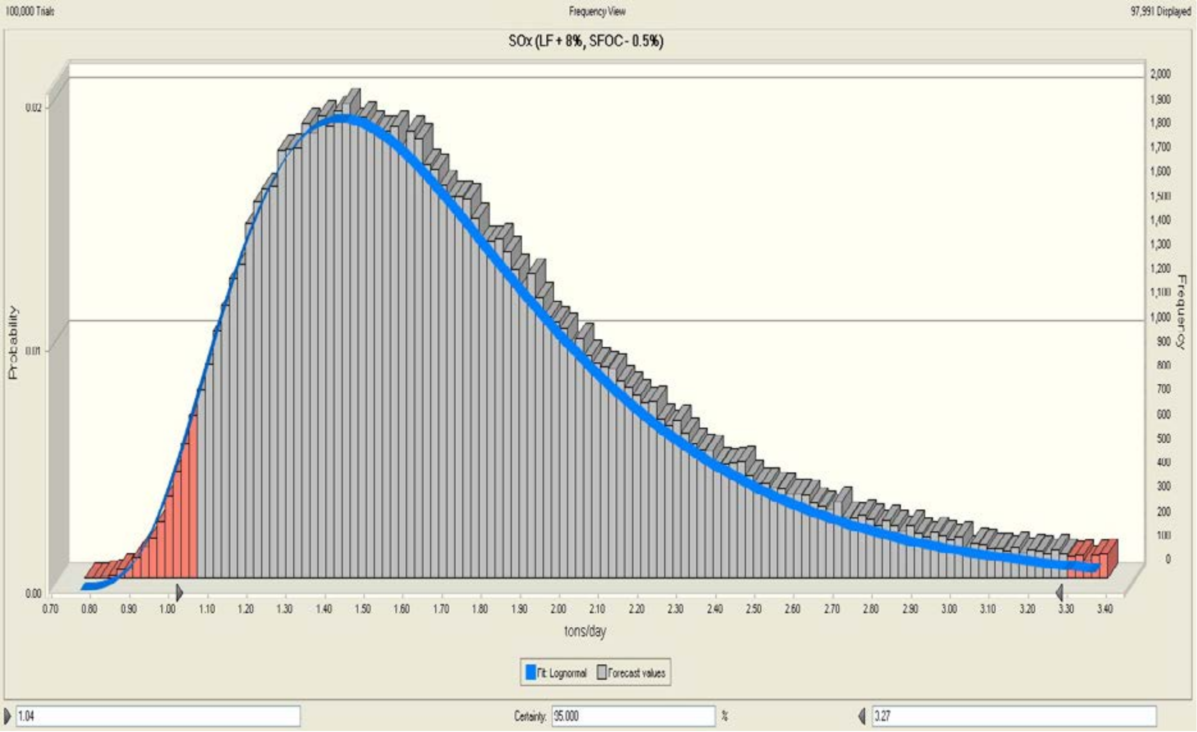


Figure 62: Lognormal distribution of NO_x for Case Study No. 1

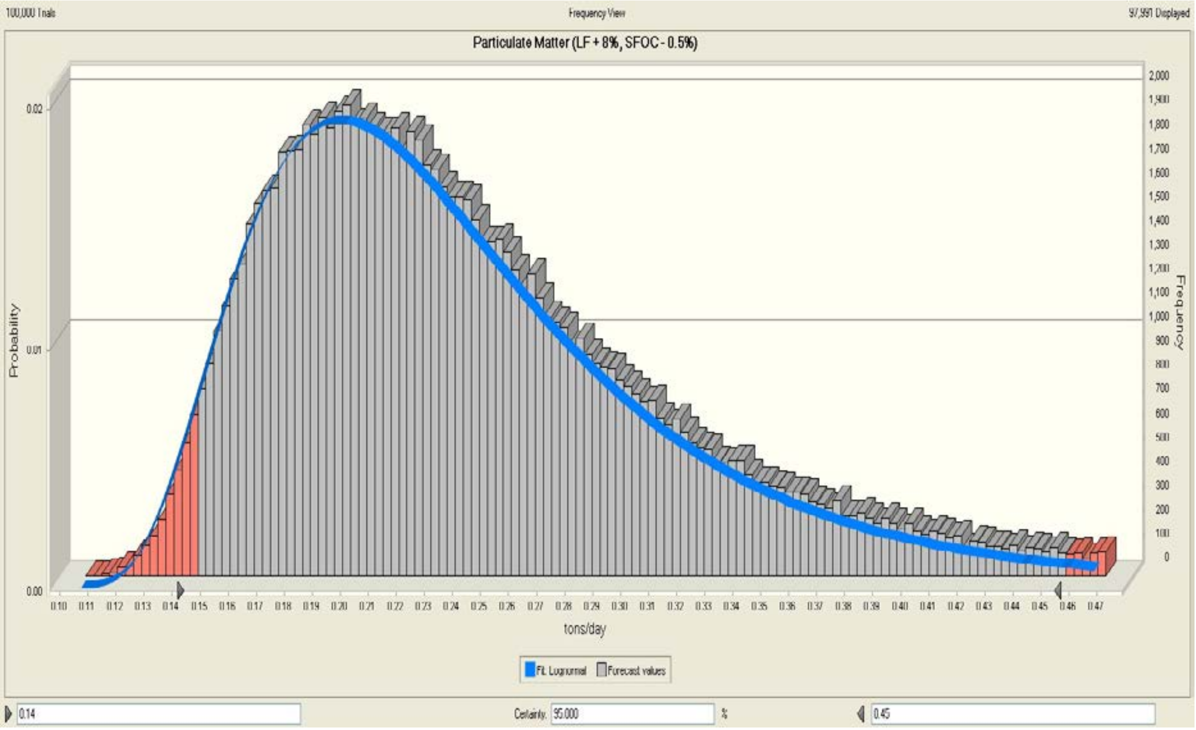


1.04

Certainty: 95.000 %

3.27

Figure 63: Lognormal distribution of SO_x for Case Study No. 1

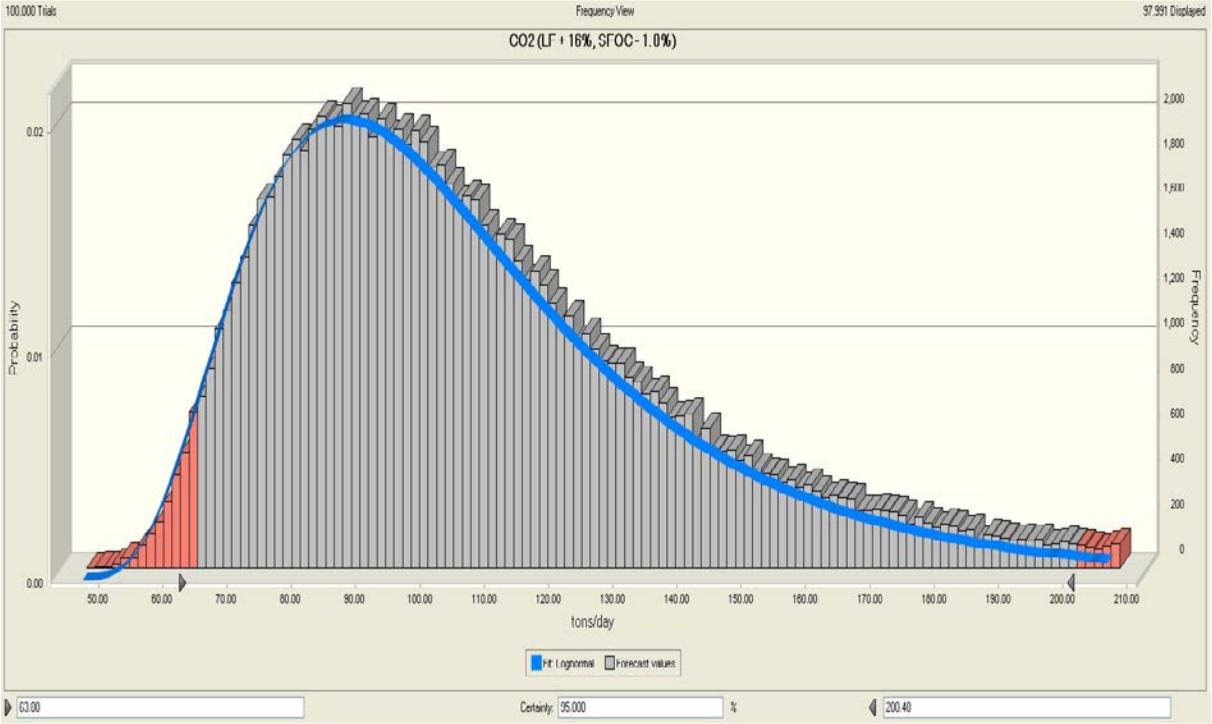


0.14

Certainty: 95.000 %

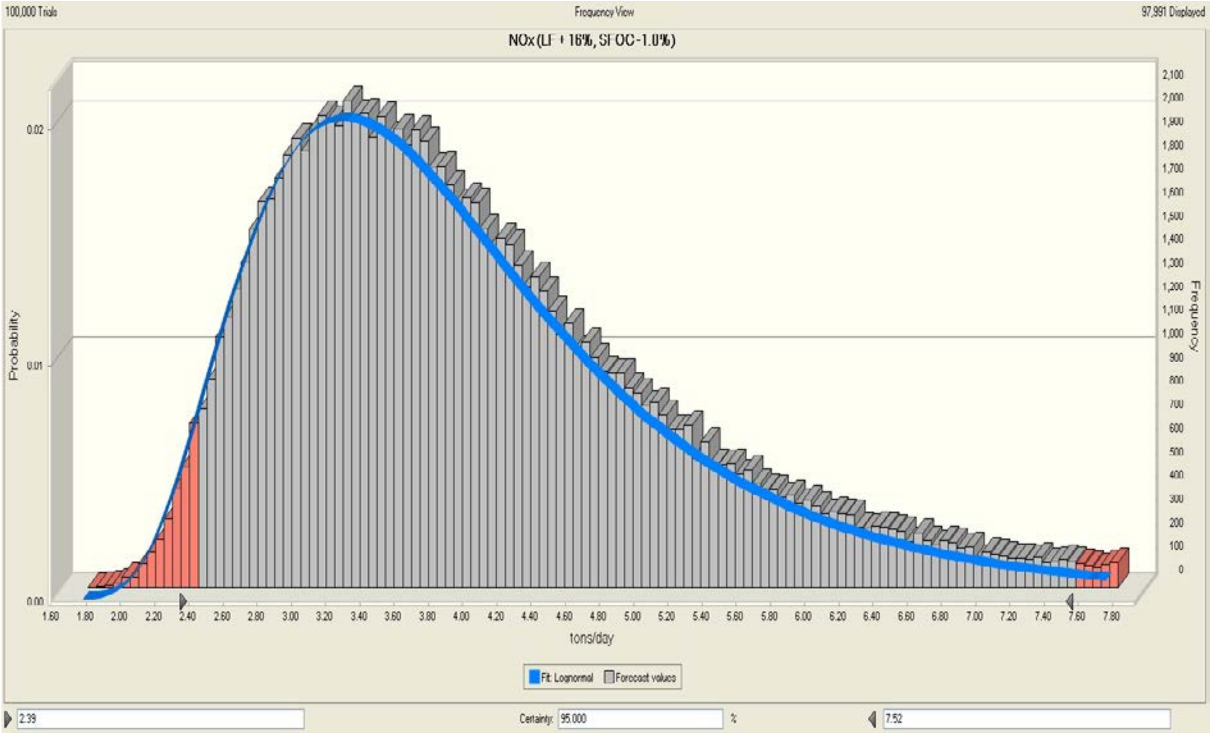
0.45

Figure 64: Lognormal distribution of Particulate Matter for Case Study No. 1



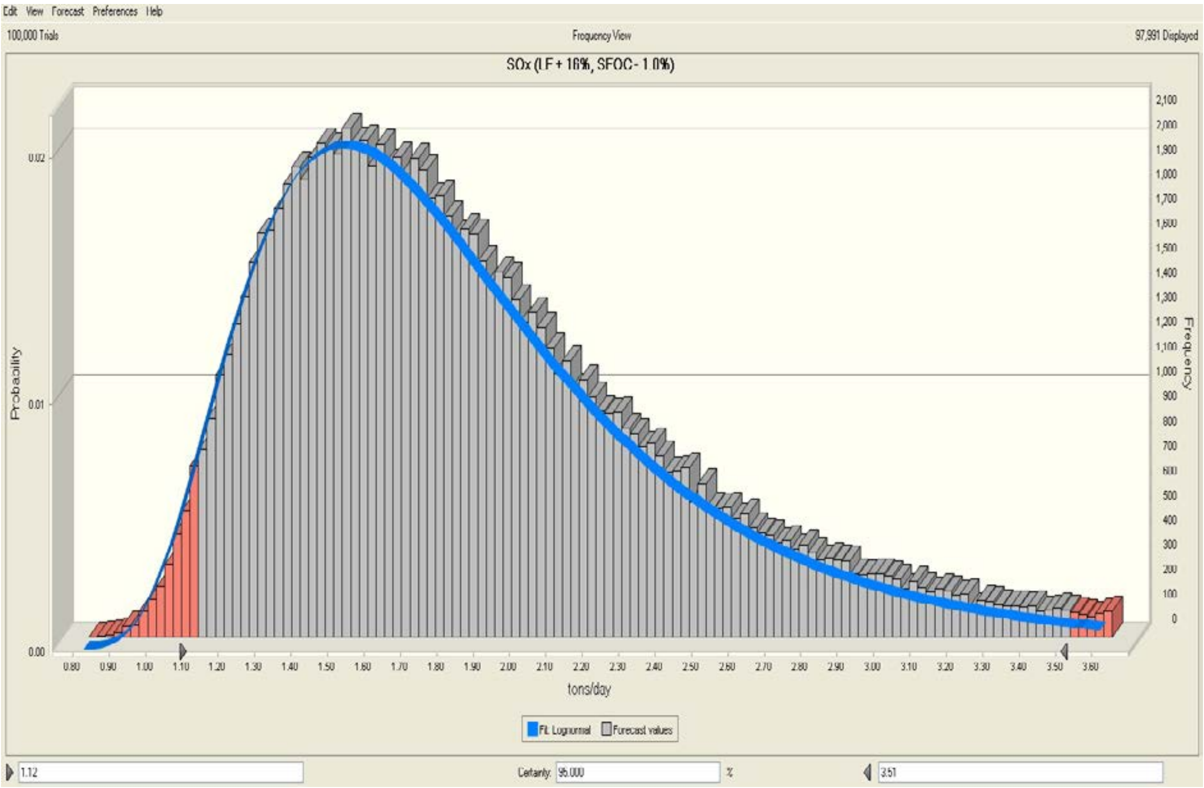
63.00 Certainty: 95.000 % 200.40

Figure 65: Lognormal distribution of CO_2 for Case Study No. 2



2.39 Certainty: 95.000 % 7.52

Figure 66: Lognormal distribution of NO_x for Case Study No. 2

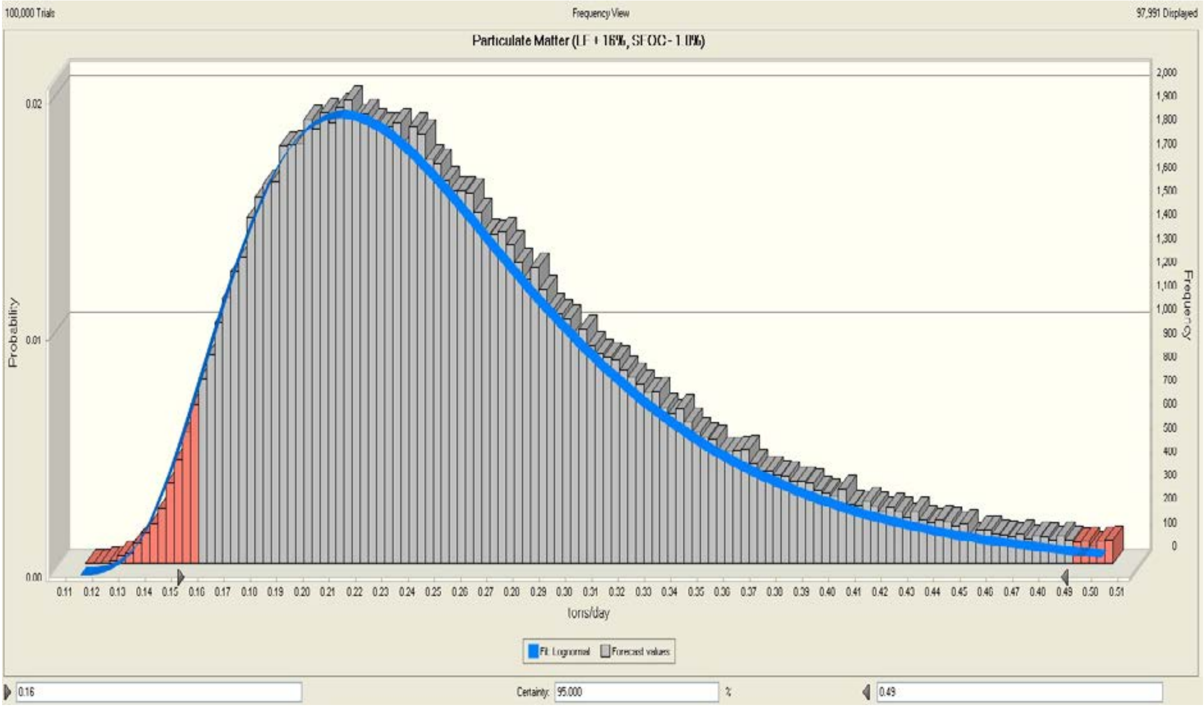


1.12

Certainty: 95.000 %

3.51

Figure 67: Lognormal distribution of SO_x for Case Study No. 2



0.16

Certainty: 95.000 %

0.49

Figure 68: Lognormal distribution of Particulate Matter for Case Study No. 2

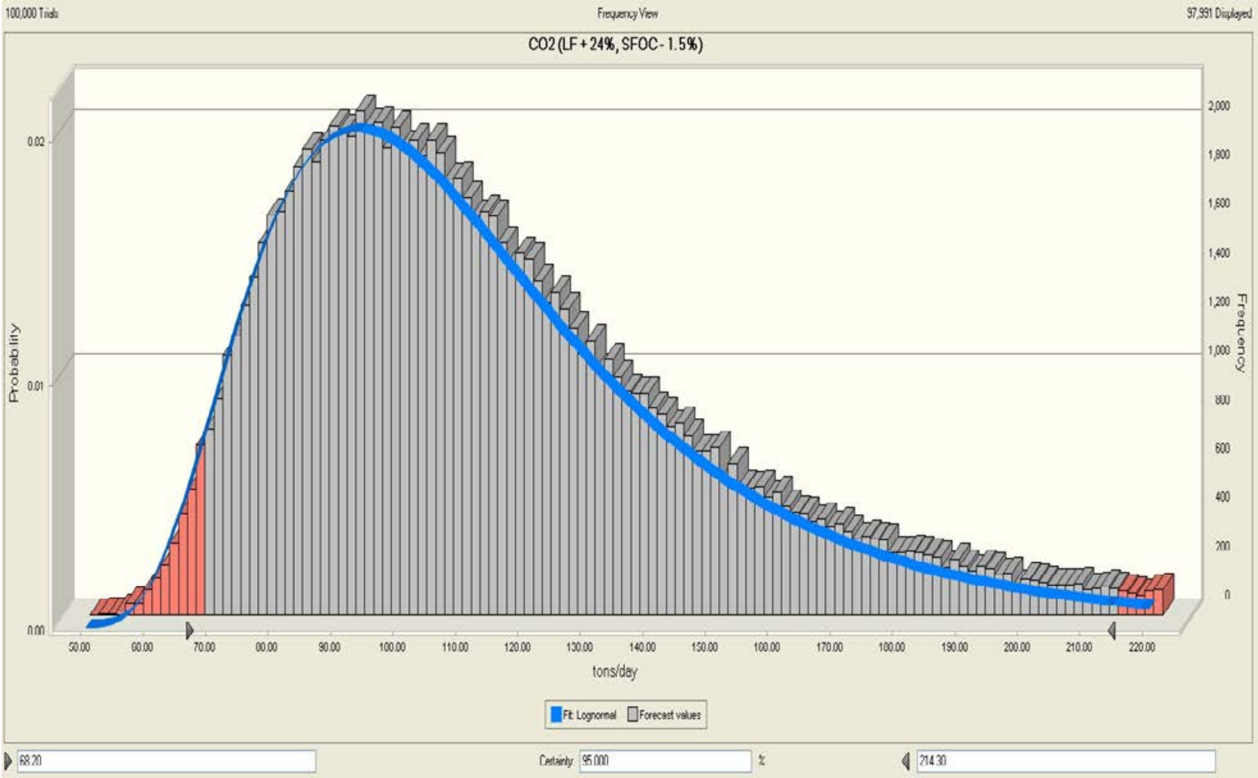


Figure 69: Lognormal distribution of CO_2 for Case Study No. 3

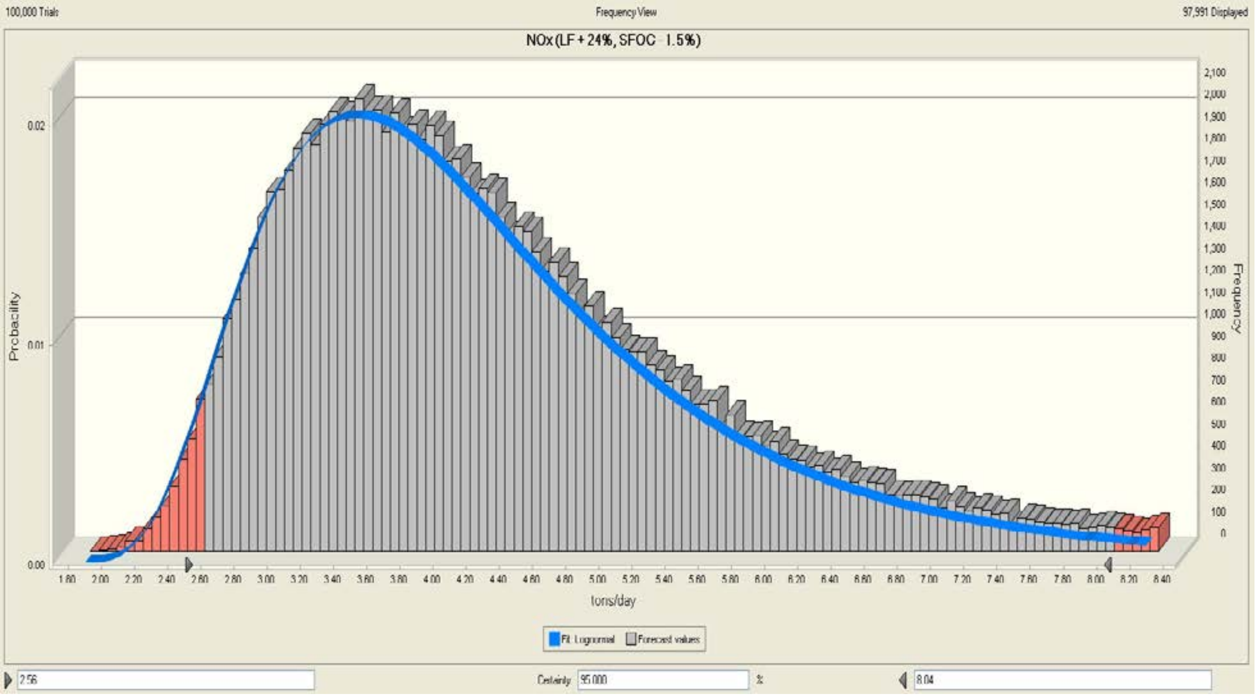


Figure 70: Lognormal distribution of NO_x for Case Study No. 3

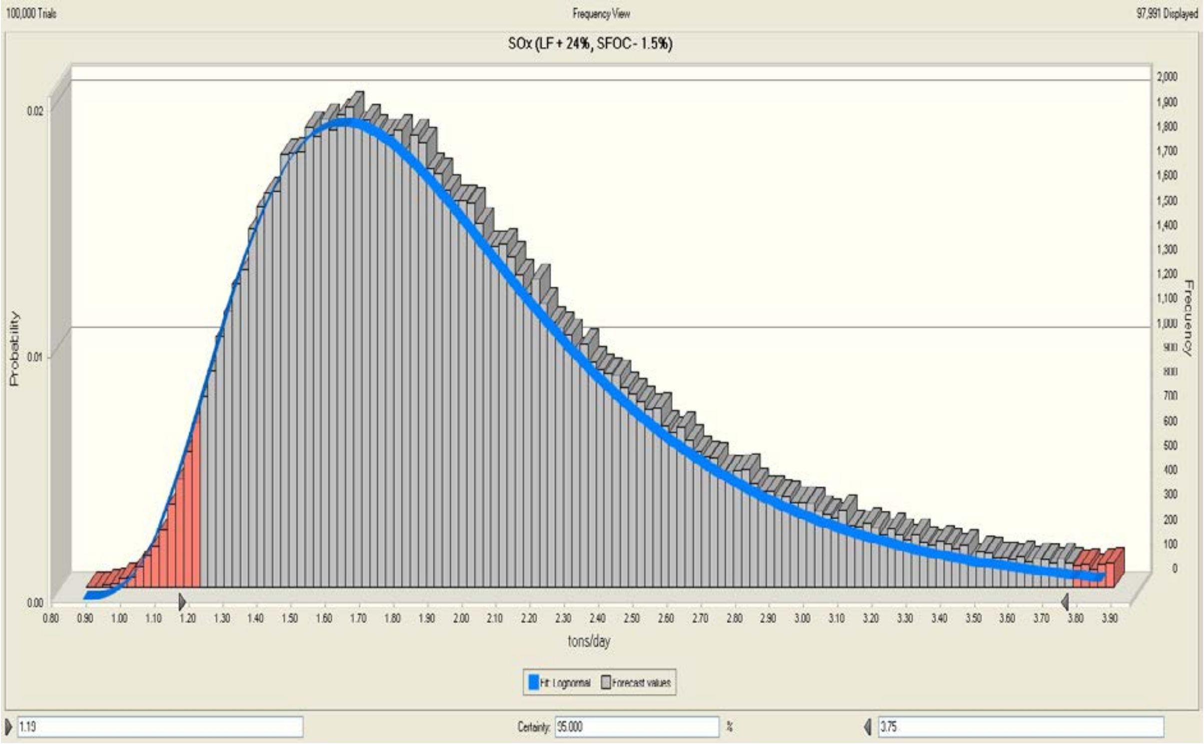


Figure 71: Lognormal distribution of SO_x for Case Study No. 3

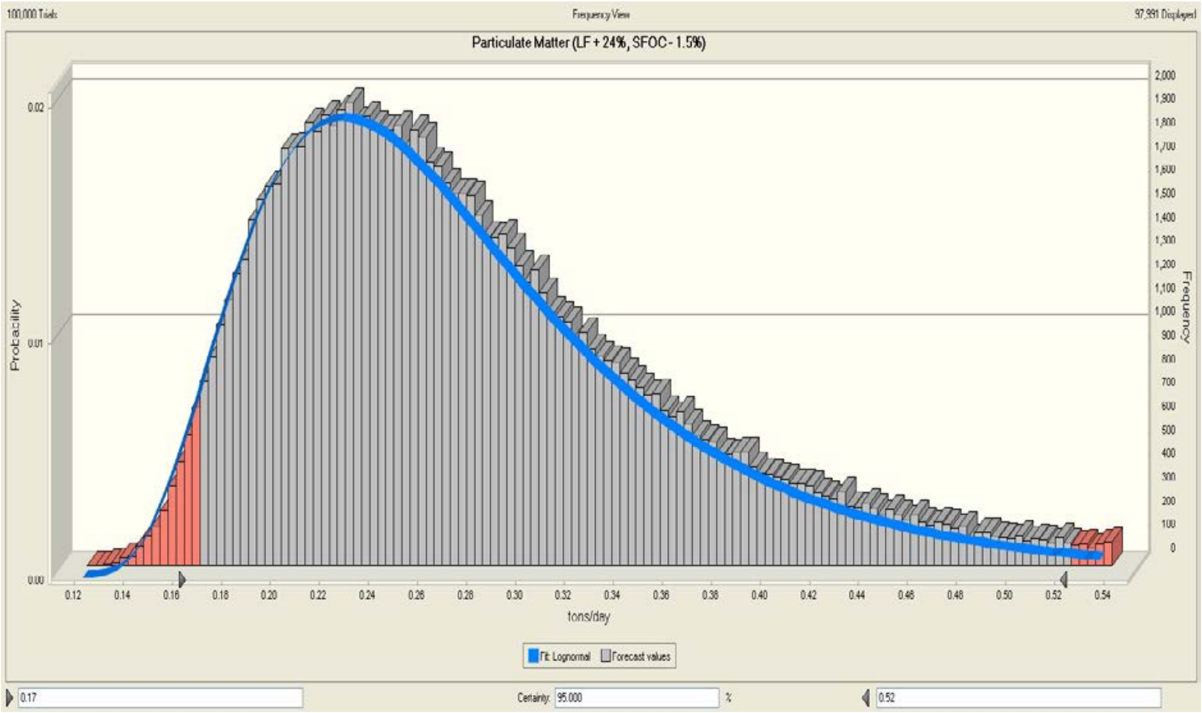


Figure 72: Lognormal distribution of Particulate Matter for Case Study No. 3

Figure 53 shows the Gamma distribution that outlines CO_2 emissions (tons/day) for data taken from NR of the known ship. Gamma distribution applies to a wide range of physical quantities and is similar to lognormal. It is a continuous probability distribution and is used in meteorological processes to represent pollutant concentrations.

The tables following bring together all information about ship emissions estimation and comparison of the respective probability distributions.

Table 15: Output data for estimation of emissions for NR, model and three Case Studies

Output Data				
	CO_2 (tons/day)	**NO_x (tons/day)**	**SO_x (tons/day)**	**PM (tons/day)**
Noon Report	Range: 44.77-180.18 Gamma distrib. Location= 14.68 Scale= 14.74 Shape= 5.656	Range: 1.64-6.61 Gamma distrib. Location= 0.54 Scale= 0.54 Shape= 5.656	Range: 0.79-3.18 Gamma distrib. Location= 0.26 Scale= 0.26 Shape= 5.656	Range: 0.11-0.43 Gamma distrib. Location= 0.03 Scale= 0.04 Shape= 5.656
Model	Range: 55-172.82 Lognormal distrib. Location= 35.89 Mean= 93.76 Std Dev= 30.86	Range: 2.06-6.48 Lognormal distrib. Location= 1.35 Mean= 3.52 Std Dev= 1.16	Range: 0.96-3.02 Lognormal distrib. Location= 0.63 Mean= 1.64 Std Dev= 0.54	Range: 0.13-0.42 Lognormal distrib. Location= 0.09 Mean= 0.23 Std Dev= 0.08
Case Study No. 1	Range: 59.4-186.65 Lognormal distrib. Location= 38.76 Mean= 101.26 Std Dev= 33.33	Range: 2.23-7 Lognormal distrib. Location= 1.45 Mean= 3.80 Std Dev= 1.25	Range: 1.04-3.27 Lognormal distrib. Location= 0.68 Mean= 1.77 Std Dev= 0.58	Range: 0.14-0.45 Lognormal distrib. Location= 0.09 Mean= 0.25 Std Dev= 0.08
Case Study No. 2	Range: 63.8-200.48 Lognormal distrib. Location= 41.63 Mean= 108.76 Std Dev= 35.80	Range: 2.39-7.52 Lognormal distrib. Location= 1.56 Mean= 4.08 Std Dev= 1.34	Range: 1.12-3.51 Lognormal distrib. Location= 0.73 Mean= 1.90 Std Dev= 0.63	Range: 0.16-0.49 Lognormal distrib. Location= 0.10 Mean= 0.26 Std Dev= 0.09
Case Study No. 3	Range: 68.2-214.3 Lognormal distrib. Location= 44.50 Mean= 116.26 Std Dev= 38.27	Range: 2.56-8.04 Lognormal distrib. Location= 1.67 Mean= 4.36 Std Dev= 1.44	Range: 1.19-3.75 Lognormal distrib. Location= 0.78 Mean= 2.03 Std Dev= 0.67	Range: 0.17-0.52 Lognormal distrib. Location= 0.11 Mean= 0.28 Std Dev= 0.09

Table 16: Comparison of output data for estimation of emissions for NR, model and three Case Studies

Output Data				
	CO_2 (tons/day)	NO_x (tons/day)	SO_x (tons/day)	PM (tons/day)
Noon Report	Mean= 98.06 Median= 93.20 P80= 125.25	Mean= 3.60 Median= 3.42 P80= 4.59	Mean= 1.73 Median= 1.65 P80= 2.21	Mean= 0.23 Median= 0.22 P80= 0.30
Model	Mean= 93.76 Median= 86.95 P80= 113.69	Mean= 3.52 Median= 3.26 P80= 4.26	Mean= 1.64 Median= 1.52 P80= 1.99	Mean= 0.23 Median= 0.21 P80= 0.28
Case Study No. 1	Mean= 101.26 Median= 93.91 P80= 122.78	Mean= 3.80 Median= 3.52 P80= 4.60	Mean= 1.77 Median= 1.64 P80= 2.15	Mean= 0.25 Median= 0.23 P80= 0.30
Case Study No. 2	Mean= 108.76 Median= 100.86 P80= 131.88	Mean= 4.08 Median= 3.78 P80= 4.95	Mean= 1.90 Median= 1.77 P80= 2.31	Mean= 0.26 Median= 0.25 P80= 0.32
Case Study No. 3	Mean= 116.26 Median= 107.82 P80= 140.97	Mean= 4.36 Median= 4.04 P80= 5.29	Mean= 2.03 Median= 1.89 P80= 2.47	Mean= 0.28 Median= 0.26 P80= 0.34

6. CONCLUSIONS AND FUTURE WORK

6.1 General conclusions

This diploma thesis led to an outcome of many conclusions.

That model provides the distributions of all random input variables for a specific Container ship operating in slow steaming. Furthermore, any directly involved user can extract distributions for daily fuel consumption of the Main Engine. This is important because user can easily study the behavior of the ship and estimate future fuel consumption in similar operational profile.

The main conclusion is that our probabilistic model approaches reality in a very representative extent. We succeeded in confronting the large amount of uncertainties that take place in estimation of fuel consumption and ship emissions. This happened by testing, in a probabilistic approach, fuel consumption coming from Noon Report and from the model; there is about a ton per day divergence in terms of mean and median.

From the equation of random variables used in the model, it is presumed via the sensitivity chart which random variables play an important role to the final result. Loading Factor comes first with 66.9%, while Specific Fuel Oil Consumption comes second with 31.1%. Investigation between Loading Factor and Specific Fuel Oil Consumption indicates that in low load, when Loading Factor rises about 8% of its value, Specific Fuel Oil Consumption decreases by 0.5% of its value.

Robustness analysis shows that with slight raise of Loading Factor, fuel consumption and subsequently ship emissions accordingly increase.

Finally, estimation of ship emissions is also available for all findings concerning fuel consumption. User can change emission factors if studying behavior of another Main Engine (Tier II, Tier III) or fuel used (HFO, LFO, LNG) and find the respective amount of ship emissions, including CO_2, NO_x, SO_x and Particulate Matter.

6.2 Future work

The main problem of this diploma thesis was finding data. Since our data were specific, the approach of fuel consumption and ship emissions was based on three random input variables. However, there are a lot more variables that play a key role in fuel consumption and should be examined. Some of them are: weather conditions, slip, condition of the hull etc. Moreover, it is interesting to examine fuel consumption for all engines, including Auxiliary Engines. An area that seems really promising in terms of operation is what happens in the whole range of Loading Factor as far as fuel consumption and emissions are concerned.

Another idea of further analysis would be to conduct a probabilistic bottom-up model in order to examine what goes on a specific vessel fleet, e.g. Panamax Container ships and compare with deterministic bottom-up inventories. Finally, this idea can be conducted in different areas, like ECAs-non-ECAs or globally.

7. BIBLIOGRAPHY

[1] International Maritime Organization, 2012. International Shipping Facts and Figures-Information Resources on Trade, Safety, Security, Environment. 6 March 2012.

[2] Greenhouse Gas Protocol website, www.ghgprotocol.org, accessed October 2015.

[3] European Policy Center, 2012. Reducing CO emissions from shipping-rethinking European policies. 18 September 2012.

[4] International Maritime Organization, 2009. Second IMO GHG Study 2009.

[5] Sustainalytics, 2011. Sustainable Mobility: 100 Investment Ideas. 5 October 2011.

[6] Air Clim, 2011. Air pollution from ships. November 2011.

[7] Civic Exchange, 2012. A Price Worth Paying: The Case for Controlling Marine Emissions in the Pearl River Delta. September 2012.

[8] Environmental Science & Technology, 2007. Mortality from Ship Emissions: A global assessment. October 2007.

[9] Buhaug, Ø., Corbett, J.J., Endresen, Ø, Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lindstad, H., Markowska, H., Mjelde, A., Nelissen, A., J Pålsson, Winebrake, J.J., Wanquing, W., Yoshida, K., 2009. Second IMO GHG study 2009 update of the 2000 GHG study: Final report covering phase 1 and phase 2. London: International Maritime Organization.

[10] Skjølsvik, K., Andersen, A., Corbett, J. J., Skjelvik, J., 2000. Study of greenhouse gas emissions from ships. International Maritime Organization.

[11] Cariou, P., 2012. Is slow steaming a sustainable means of reducing CO_2 emissions from container shipping? Transportation Research Part D: Transport and Environment.

[12] Faber, J., Nelissen, D., Hon, G., Wang, H., Tsimplis, M., 2012. Regulated slow-steaming in maritime transport. Washington: International Council on Clean Transportation. Retrieved from http://www.theicct.org/regulated-slow-steaming-maritime-transport.

[13] Façanha, C., Blumberg, K., Miller, J., 2012. Global transportation energy and climate roadmap. International Council on Clean Transportation. Retrieved from http://www.theicct.org/global-transportation-energy-and-climate-roadmap.

[14] United Nations Conference on Trade and Development, 2012. Review of maritime transport. New York: UNCTAD.

[15] Boeing, 2012. World Air Cargo Freight Forecast: 2012-2013

[16] International Council on Clean Transportation (ICCT), 2011. The energy efficiency design index for new ships. Washington: ICCT. Retrieved from http://www.theicct.org/eedi-new-ships.

[17] International Maritime Organization, 2012. Estimated CO_2 emissions reduction from introduction of mandatory technical and operational energy efficiency measures for ships. London: Marine Environmental Protection Committee.

[18] Kat, J. O., Cerup-Simonsen, B., Jakobsen, O. G., Pedersen, L. R., Petersen, J. B., Posborg, T., 2009. An integrated approach towards cost-effective operation of ships with reduced GHG emissions. SNAME Annual Meeting, Providence, R.I.

[19] Eide, Magnus, S. B. Dalsoeren, Ø Endresen, B Samset, Gunnar Myhre, JS Fuglestvedt, and T Bernstein., 2013. Reducing CO_2 from shipping-do non-CO_2 effects matter? Atmospheric Chemistry and Physics 13:4183-4201.

[20] Philip Crist, 2011. Greenhouse gas emissions reduction potential from international shipping.

[21] MAN Diesel & Turbo SE. Retrieved from http://dieselturbo.man.eu/.

[22] EPA, 2009. Proposal to Designate an Emission Control Area for Nitrogen Oxides, Sulfur Oxides and Particulate Matter.

[23] V. Andreoni, A. Miola, A. Perujo, 2008. Cost Effectiveness Analysis of the Emission Abatement in the Shipping Sector Emissions.

[24] Jana Moldanova, Erik Fridell, Olga Popovicheva, Benjamin Demirdjian, Victoria Tishkova, Alessandro Faccinetto, Cristian Focsa, 2009. Characterization of particulate matter and gaseous emissions from a large ship diesel engine.

[25] J. Moldanova, E. Fridell1, H. Winnes, S. Holmin-Fridell, J. Boman, A. Jedynska, V. Tishkova, B. Demirdjian, S. Joulie, H. Bladt, N. P. Ivleva and R. Niessner, 2013. Physical and chemical characterization of PM emissions from two ships operating in European Emission Control Areas.

[26] NRC, 2010. Advancing the Science of Climate Change. National Research Council. The National Academies Press, Washington, DC, USA.

[27] U.S. Department of State, 2007. Fourth Climate Action Report to the UN Framework Convention on Climate Change: Projected Greenhouse Gas Emissions. U.S. Department of State, Washington, DC, USA.

[28] International Maritime Organization. Breakthrough at IMO, accessed October 2015.

[29] International Maritime Organization website, www.imo.org, accessed October 2015.

[30] UK Parliament, 2013. Sulphur emissions by ships - Transport Committee Contents. April 2013.

[31] International Maritime Organization, 2008. RESOLUTION MEPC.176 (58). 10 October 2008.

[32] Environmental Science & Technology, 2007. Mortality from Ship Emissions: A global assessment. October 2007.

[33] European Union, 2012. Stakeholder meeting on monitoring, reporting and verification (MRV) of greenhouse gas emissions from ships – Background document. 5 December 2012.

[34] European Union, 2012. Stakeholder meeting on monitoring, reporting and verification (MRV) of greenhouse gas emissions from ships - Main conclusions from the meeting. 5 December 2012.

[35] Allan M. Friis, Poul Andersen & Jørgen Juncher Jensen, 2002. Ship Design. Department of Mechanical Engineering, Section of Costal, Maritime and Structural Engineering, Technical University of Denmark, 2002.

[36] Doug Woodyard, 2004. Pounder's Marine Diesel Engines and Gas Turbines. 8th edition, Elsevier, 2004.

[37] International Council on Clean Transportation (ICCT). Reducing greenhouse gas emissions from ships: Cost effectiveness of available options. Washington: ICCT. Retrieved from http://www.theicct.org/reducing-ghg-emissions-ships.

[38] Nippon Yusen Kaisha Line, 2012. Carbon Disclosure Project – 2012 Investors response.

[39] Emission Project Guide for MAN B&W Two-stroke Marine Engines, 4th Edition March 2015, MAN Diesel & Turbo.

[40] Per Kageson, 2011. The financial implications of a Levy & GHG Fund.

[41] Neef, 2009. The Development of a Global Maritime Emissions Inventory Using Electronic Monitoring and Reporting Techniques.

[42] Balzany Lööv, J.M., Alfoldy, B., Lagler, F. et al., 2011. Why and how to measure remotely ship emissions. Climate Change and Air Quality Unit Seminars-Ispra 2011, Ispra, Italy.

[43] Endresen, Ø., Sørgård, E., Sundet, J.K., Dalsøren, S.B., Isaksen, I.S.A., Berglen, T.F., Gravir, G., 2003. Emission from international sea transportation and environmental impact. Journal of Geophysical Research, 108, 4560.

[44] Entec UK Limited, 2005. Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments. European Commission Directorate General Environment.

[45] Faber, J., Markowska, A., Nelissen, D., Davidson, M., Eyring, V., Cionni, I., Selstad, E., Kageson, P, Lee, D., Buhaug, O., Lindtsad, H., Roche, P., Humpries, E., Graichen, J., Cames, M, Schwarz, W., 2009. Technical support to European actions to reducing GHG from ships. Delft: CE Delft.

[46] Paxian, A., Eyring, V., Beer, W., Sausen, R., and Wright, C., 2010. Present-Day and Future Global Bottom-Up Ship Emission Inventories Including Polar Routes.

[47] Aliki Georgakaki, Robert A. Coffey, Graham Lock, Spencer C. Sorenson, 2004. Transport and Environment Database System (TRENDS): Maritime air pollutant emission modelling.

[48] Wang, C., Corbett, J.J., Firestone, J., 2007. Improving spatial representation of global ship emissions inventories.

[49] Wang, H., Faber, J., Nelissen, D., Russell, B., and St Amand, D., 2010. Reduction of GHG Emissions from ships – Marginal abatement costs and cost effectiveness of energy efficiency measure, Document MEPC 61/INF.18, London UK: International Maritime Organization.

[50] L. Schrooten, I. De Vlieger, L. Int Panis, C. Chiffi and E. Pastori, 2009. Emissions of maritime transport: a reference system.

[51] James J. Corbett, Haifeng Wang, James J. Winebrake, 2009. The effectiveness and costs of speed reductions on emissions from international shipping.

[52] J.-P. Jalkanen, A. Brink, J. Kalli, H. Pettersson, J. Kukkonen and T. Stipa, 2009. A modelling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area.

[53] Helge Rørdam Olesen, Morten Winther, Thomas Ellermann, Jesper Christensen og Marlene Plejdrup, 2009. Ship emissions and air pollution in Denmark-Present situation and future scenarios. National Environmental Research Institute Aarhus University.

[54] Endresen, Ø., E. Sørgard, J. Bakke, I. S. A. Isaksen, 2004. Substantiation of a lower estimate for the bunker inventory.

[55] Endresen, Ø., Sørgard, E., Behrens, H.L., Brett, P.O., Isaksen, I.S.A., 2007. A historical reconstruction of ships fuel consumption and emissions.

[56] Corbett, J. J., H. W. Köhler, 2003. Updated emissions from ocean shipping.

[57] Corbett, J. J., and H. W. Köhler, 2004. Considering alternative input parameters in an activity-based ship fuel consumption and emissions model.

[58] Eyring, V., H. W. Köhler, A. Lauer, and B. Lemper, 2005. Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050.

[59] Eyring, V., I. S. A. Isaksen, T. Berntsen, W. J. Collins, J. J. Corbett, O. Endresen, R. G. Grainger, J. Moldanova, H. Schlager, and D. S. Stevenson, 2009. Transport impacts on atmosphere and climate.

[60] Thomas, R., Lauretis, R.D., Fontelle, J.P., Hill, N., Kilde, N., Rypdal, K., 2002. Shipping activities, Chapter B842. In: Lavender, K., Reynolds, G., Webster, A., Rypdal, K. (Eds.), EMEP/CORINAIR Emission Inventory Guidebook – October 2002 UPDATE. European Environment Agency, Copenhagen, Denmark.

[61] Olivier, J.G.J., Peters, J.A.H.W., 1999. International Marine and Aviation Bunker Fuel: Trends, Ranking of Countries and Comparison with National CO_2 Emissions. RIVM.

[62] S. B. Dalsøren, M. S. Eide, Ø. Endresen, A. Mjelde, G. Gravir, I. S. A. Isaksen, 2009. Update on emissions and environmental impacts from the international fleet of ships: the contribution from major ship types and ports.

[63] Miola et al., 2009. External costs of transportation Case study: Maritime transport.

[64] Tzannatos, E., 2010. Ship emissions and their externalities for the port of Piraeus – Greece.

[65] Chengfeng Wang, James J. Corbett, Jeremy Firestone, 2005. Modeling Energy Use and Emissions from North American Shipping: Application of the Ship Traffic, Energy, and Environment Model.

[66] Wang, C., Corbett, J.J., Firestone, J., 2008. Modeling energy use and emissions from north American shipping: application of ship traffic, energy and environment model.

[67] Miola , A., Ciuffo, B., Marra, M., Giovine, E., 2010. Analytical framework to regulate air emissions from maritime transport.

[68] Corbett, J.J., Fischbeck, P.S., 1997. Emissions from ships.

[69] Corbett, J. J., P. S. Fischbeck, S. N. Pandis, 1999. Global nitrogen and sulfur inventories for oceangoing ships.

[70] MAN Diesel & Turbo, 2013. Propulsion Trends in Container Vessels, Two-stroke Engines.

[71] MAN Diesel & Turbo, 2012. SFOC Optimization Methods For MAN B&W Two-stroke IMO Tier II Engines.

[72] Juan Moreno-Gutierrez, Fátima Calderay, Nieves Saborido, Cristina Vanesa Durán Grados, 2015. Methodologies for estimating shipping emissions and energy consumption: A comparative analysis of current methods.