PLATFORM FOR ASSESSING SHIP EMISSIONS FROM A LIFE CYCLE PERSPECTIVE

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ABSTRACT

This paper presents an original software platform that has been developed to provide assessments of air emissions produced throughout the life cycle of ocean going ships. The life cycle stages covered are shipbuilding, ship operation including major ship maintenance activities, and ship dismantling. In the platform, the ship is viewed as a series of subsystems, which are formulated by processes that themselves are essentially a series of algorithms. The MATLAB environment has been used to incorporate and handle the series of algorithms in this platform. The developed model covers the dominant ship greenhouse gas emissions and air pollutants produced during a typical life cycle of a cargo ship. Emissions inventories can be produced at process level, at subsystem level, but also per life cycle stage level, per trip, per year etc. The platform has also the capability to elaborate different ship operation scenarios in order to assess the emission impact of important parameters such as the ship speed and the use of alternative fuels. Finally, the paper presents and comments on an illustrative example with results produced from a case study of a Capesize bulk carrier ship (206,000 tonnes dwt).

Keywords: ship life cycle, emissions, shipbuilding, ship operation, dismantling

NOMENCLATURE

List of abbreviations and symbols

CH4	Methane
CO	Carbon Monoxide
CO2	Carbon Dioxide
dwt	Dead weight of the ship
ECA	Emission Control Area
EU	European Union
GHG	Greenhouse gasses
HFO	Heavy Fuel Oil
IMO	International Maritime Organisation
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LNG	Liquefied Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MDO	Marine Diesel Oil
MCR	Maximum Continuous Rating
MGO	Marine gas oil
MRV	Monitoring Reporting and Verification Regulation of EU
NMVOC	Non Methane Volatile Organic Compounds
NTUA	National Technical University of Athens
N2O	Nitrous Oxide
NOx	Nitrogen Oxides
PM	Particulate Matter
SEEMP	Ship Energy Efficiency Management Plan
SO2	Sulphur Dioxide
SOx	Sulphur Oxides
VOC	Volatile Organic Compounds
WHO	World Health Organisation

1. INTRODUCTION

Although ship air emissions represent a small part of the total anthropogenic emissions (for GHG emissions, below three percent according to the last IMO GHG study (2014)), the international shipping sector is under scrutiny since it has been very slow in adopting global rules for GHG emissions. Such rules are now in place (i.e. EEDI, SEEMP are included in Annex VI of MARPOL) and among other things they require accurate reporting of ship emissions.

Other ship emissions pose threats to the environment and human health especially in the proximity of inhabited areas around the world (Corbett, 2007). Atmospheric pollution is now considered by the WHO as the number one threat for human health (WHO, 2014) and the contribution of shipping to health impacts is not negligible in certain areas as studies reveal (Chatzinikolaou et. al, 2015c), (Tzannatos, 2010). In reaction, specific emission limits have been adopted by the IMO in the so-called ECA areas, which are gradually getting stricter.

However, transport needs are closely related to the international economic developments and since the global economy is expected to grow in the future, the need for transportation is also expected to rise which can result in increased ship emissions. The elaborated future scenarios (IMO, 2014) show an expected global sum of GHG emissions from ships between one million tonnes and 3.5 million tonnes until 2050. Therefore, it is possible that the high sea transport volumes will offset the energy efficiency advantages gained by the transport of goods by sea.

In response, the shipping industry is continuously making efforts to improve its environmental footprint with numerous technical and operational measures being launched during the recent years. The nonstop effort of sound management and improvement of ship emissions needs to be supported by accurate measurements and reporting of emissions.

This paper aims at contributing to the knowledge in this particular field, with the development of a systematic platform (software) which is capable of calculating dominant ship emissions by using inputs provided by the user and a series of algorithms and empirical equations. The software is developed in the MATLAB environment and it is based on a holistic theoretical background that can be used to expand emission results in the entire life of the ship.

2. MOTIVATION – LITERATURE REVIEW

2.1 MOTIVATION

The accurate calculation of air emissions remains a challenge for the case of maritime transport. It is generally believed that uncertainty exists even in the most cited publications with estimates and projections of emissions from international shipping. Simultaneously, the quest for precise ship emissions reported data is becoming more essential since it is also imposed by international and regional rules (such as the SEEMP of the IMO and the MRV Regulation of the EU for GHG emissions).

Ship emissions can be calculated by using different methods (or software) which are typically divided in two main categories i.e. the top-down approach and the bottom-up approach, both having advantages and disadvantages.

In the top-down approach air emissions are calculated through fuel consumption with the use of marine fuel sales and do not take into account the location of emission. This fuel-based method might be not very demanding in terms of information collection, but creates reliability issues since it is widespread that the reported bunker fuels of marine sales are not exactly consistent (Psaraftis and Contovas, 2009). Moreover, with no information on the location of emissions it is not always possible to adequately address the impact of certain emissions (i.e. non GHG emissions).

The bottom-up approach considers the activity at the ship level in order to calculate air emissions. This calculation needs a large amount of information relevant to the trip characteristics (i.e. movements, ship and engine type, ship size, fuel, loading of engines). Since the collection of accurate information for the aforementioned aspects is not always possible, assumptions are frequently introduced into the calculations of the bottom-up approach. What makes the calculation even more challenging is the attempt to generalise the results at the fleet level, segment, or ship type level.

It is out of the scope of the paper to comment on the accuracy of the two aforementioned approaches. The main goal of the work reported in this paper was to develop a systematic and easy to use tool that would be able to assess ship emissions at the ship level. For that reason, in this work the preferable approach for estimating ship emissions is the bottom-up. However, this work has also utilised recorded fuel consumption data provided by a ship operator for validation purposes.

Another objective of this work was to include all phases of the ship life into these calculations. A ship's life cycle may be divided into four main phases: shipbuilding, operation, maintenance and dismantling/recycling. The great majority of emissions occur during the operational phase due to the propulsion and energy demands of the ship; however air emissions are emitted also in the other phases of the life cycle and thus need to be taken into account.

The framework was developed in the MATLAB environment, based in the series of algorithms and equations for various important processes from emissions perspective in the ship life cycle that have been developed in the Laboratory for Maritime Transport of the NTUA and reported in the work by Chatzinikolaou and Ventikos (2015a). The main GHG and non GHG emissions of significant ship processes are covered in a holistic approach which may be expanded over the entire life cycle of the ship.

2.2 LITERATURE REVIEW

Examining the environmental footprint and impact of products and systems in a life cycle approach is a concept continuously gaining acceptance due to the growing awareness of the society about the long term impacts of human activities. The most important advantage by the application of the life cycle thinking approach is the reduction or elimination of external costs. During the life cycle of system (e.g. a ship) external costs may evolve from the shifting of environmental impact from one stage of the life cycle to another, from one stakeholder of the life cycle chain to another, or altogether to other (external) systems, or even from present to the future (Chatzinikolaou and Ventikos, 2014a).

Life Cycle Assessment (LCA) is a standardised technique (by ISO 14040) that can be used for analysing the environmental impact of products and services in life cycle perspective. Yet, while LCA is being widely used in the industry, for the case of ships has so far few applications due to the complexity of the ship system (Chatzinikolaou and Ventikos, 2015b). LCA may provide an inventory analysis of environmental drivers but in a second step can also provide an impact assessment of these drivers. The impact assessment step is usually carried out with damage assessments techniques that transform emissions and wastes into categories of impacts. This step however is out of the scope of the present work.

A number of software applications have been developed for ship life cycle assessments. The National Maritime Research Institute of Japan has developed suitable software to examine the environmental impact of cargo vessels in this country (Kameyama et al., 2004). Software SSD (Sustainable Ship Design) aims at evaluating different green technologies in terms of environmental impacts from a life cycle perspective (Tincelin et al., 2010). Other ship related LCA studies are focused on the comparison of different technologies (Hou, 2011), and the evaluation of different fuel options from a life cycle perspective (Bengtsson et al., 2011).

The Laboratory for Maritime Transport of the National Technical University of Athens (NTUA) has used the life cycle approach during the past few years to conduct environmental assessments of various maritime transport scenarios. The present work has been also carried out in the context of funded and non-funded research at NTUA and it is essentially the introduction into the MATLAB environment of the series of algorithms that form the ship LCA framework of Chatzinikolaou and Ventikos (2014a, 2014b, 2015a, 2015b).

3. METHODOLOGY

The goal of this work has been to develop a software application capable of delivering air emission inventories of important ship processes per trip, year and also per life cycle perspective.

This work uses a theoretical ship LCA framework which is already reported elsewhere, therefore only its basic features are going to be briefly explained here. Initially, the ship is viewed as a system that can be divided in two important (with respect to air emissions) subsystems; namely the ship hull and the ship machinery.

The hull subsystem corresponds to the metal structure of the ship and includes all fixed metal parts of the ship's hull and superstructure. Processes related to the life cycle of metal parts of the ship are mainly: steel welding, steel cutting, steel replacements, steel surface preparation, blasting, and surface protection and coatings. The life cycle of this subsystem is broken down into three different stages: construction, maintenance and dismantling/recycling. During the operational life cycle stage of a ship, the hull subsystem contributes with minimum amounts of emissions and therefore this stage is excluded from the analysis.

The machinery subsystem includes processes such as the construction of engines, shop tests, engines installation on the ship, sea trials, maintenance of main components and fuel consumption. The latter is the dominant process in terms of emissions. The fuels that can be handled by the software are Heavy Fuel Oil (HFO), Marine Diesel Oil (MDO) and Liquefied Natural Gas (LNG). Three different sulphur contents are considered for the HFO (2.5%, 0.5%, and 0.1%). Emission factors for the fuels examined are taken from official IMO documentation (IMO, 2014). In Figure 1, the ship - LCA framework is shown.

The software is built in the Matlab numerical computing environment which corresponds to a fourth-generation programming language. The software is interactive in the sense that it uses dialog boxes to ask from the user to insert the required input. Dialog boxes are also used to record user's preferences. For example, the user has the option to analyse separately the subsystems, to make decisions about the mix of fuels used in the ship engines, and to extract specific results per voyage, per year, per process etc.

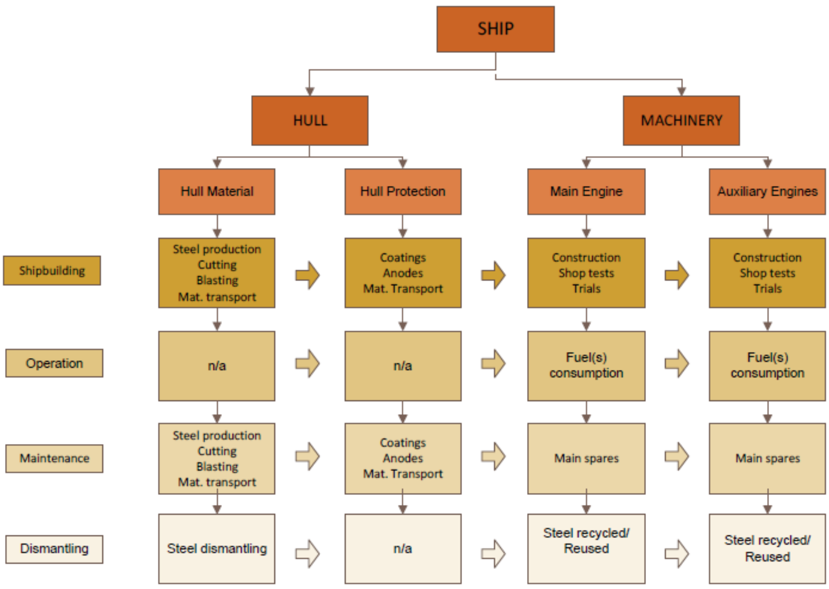

Figure 1: Ship – LCA. The Theoretical Framework of a ship's life cycle (Chatzinikolaou and Ventikos, 2015b)

4. CASE STUDY

4.1 THE SHIP OF THE CASE STUDY

The case study ship is a Capesize bulk carrier (206,104 tonnes dwt) built in 2012. The ship is owned and operated by a Greek shipping company. The details of this ship are provided in Table 1.

Table 1: Main particulars and characteristics of the case study ship

Case study ship	
TYPE	Bulk-Carrier
NAME	Test ship 2
Year of Built	2012
Length between perp, L_{BP} [m]	294
Breadth, B [m]	50
Depth, D [m]	24.9
Draught, T [m]	18.466
C_B	0.8483
Deadweight, dwt [tn]	206104
Lightship [tn]	30383
Displacement [tn]	236487
Payload [tn]	198558
Number of bulkheads	9 C/H + FP + AP B/H
Service Speed [knots]	15
Main Engine (Number)	Two stroke (1)
Auxiliary Engines (Number)	3
Main Engine [kW]	18660 @ 91 RPM
Auxiliary Engines [kW]	900

Information for the operation of the ship was provided by the shipping company. The information covers the trips of the ship between Australia and China ports for a period of almost one year (2013 – 2014). The common pattern of these ships is to sail in two legs, the fully laden leg and the ballast leg. Overall, data for twenty one single trips (in ballast and laden legs) have been collected. An example of the information used as inputs in the case study that is presented in this paper, is given in the following Table 2, (it concerns the first three trips of the case study ship).

Table 2: Example of available ship operation data

	Trip No1	*Trip No2*	*Trip No3*
Distance [nm]	3652	3570	3551
Speed [knots]	12.093	10.818	12.460
Loading factor of AE in Operation	0.5 (x2)	0.5 (x2)	0.5 (x2)
Loading factor of AE in Port	0.2 (x2)	0.2 (x2)	0.2 (x2)
Sailing days [days]	12.708	14.875	13.000
Port time [in hours]	192	144	96
Loading condition	Ballast	Laden	Ballast
Payload [tonnes]	-	198558	-

It is noted that the loading factors of auxiliary engines (in port and at sea) were not available in the collected data; hence their values are logical assumptions which illustrate the common practice.

Fuel consumption data per trip were also provided by the shipping company. In Figure 2, a comparison is displayed between the reported data and the data calculated by the software. The comparison reveals some small reasonable differences which are attributed to the fact that the software calculations do not consider some parameters that can affect fuel consumption (such as weather conditions, sea state, sea currents etc.).

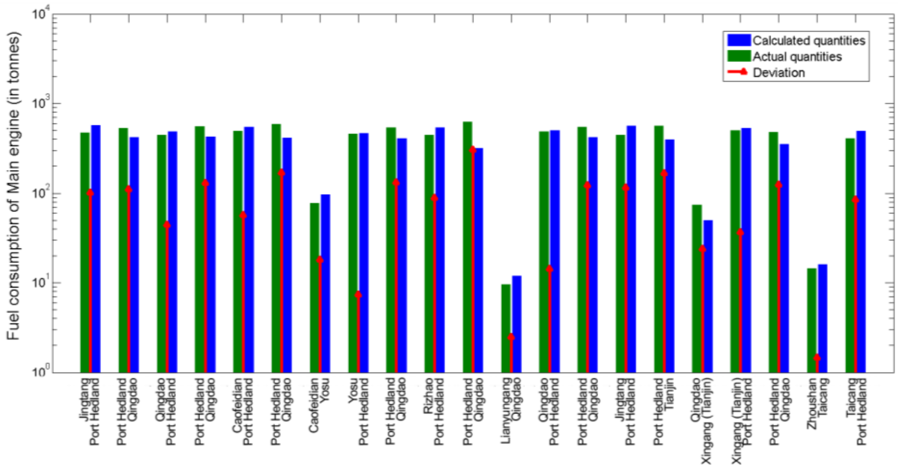

Figure 2: Calculated vs. reported fuel consumption data

4.2 MACHINERY SUBSYSTEM RESULTS

The ship in the period covered by the data has travelled in total 3,326 n. miles with an average speed of 11.66 knots (the average sailing speed of twenty one trips). The ship spent 230 days sailing at sea and 116 days at port (exact port hours were reported). According to the calculations from the model, the total fuel consumption was 8,033 tonnes in the main engine, and 1,199 tonnes in the auxiliary engines. The overall emission results for the period with the aforementioned characteristics are given in Table 3. The model provides emissions results for different fuels. In Table 3 the HFO (with 2.5% sulphur content) is the actual fuel used by the ship. Results of two alternative fuels are also available. The emission results are shown on a year basis. The usual life cycle of this type of ship is twenty years or more. The platform has the capability to project the life cycle emissions of the machinery subsystem however since the data available illustrate that the ship was practicing slow steaming the authors decide not to make life cycle emissions projections for this case study, based only on this information.

Table 3: Machinery subsystem – Emissions per year

Emissions		***HFO (2.5%S)***	***MDO***	***LNG***
CO2	tonnes	28747.749	29597.072	25387.382
NOx	tonnes	724.325	680.843	72.285
SOx	tonnes	453.096	24.372	0.185
PM	tonnes	64.530	9.416	1.662
CO	tonnes	25.572	25.572	72.285
CH4	tonnes	0.554	0.554	472.667
N2O	tonnes	1.477	1.385	1.015
NMVOC	tonnes	28.434	28.434	27.788

4.3 EMISSIONS PER TRIP

Monitoring emissions per trip is important for ship energy management and also foreseen in new regulations. In this paragraph, emissions are provided per trip and comparisons with existing regulations are made. As shown in Figure 3, CO_2 emissions are expressed per cargo transported over mile. Only laden trips are taken into account (eleven trips in total). This CO_2 index is calculated for three different fuels (i.e. HFO, MDO, and LNG). Higher CO_2 index derives with the use of HFO, and lower with the use of LNG.

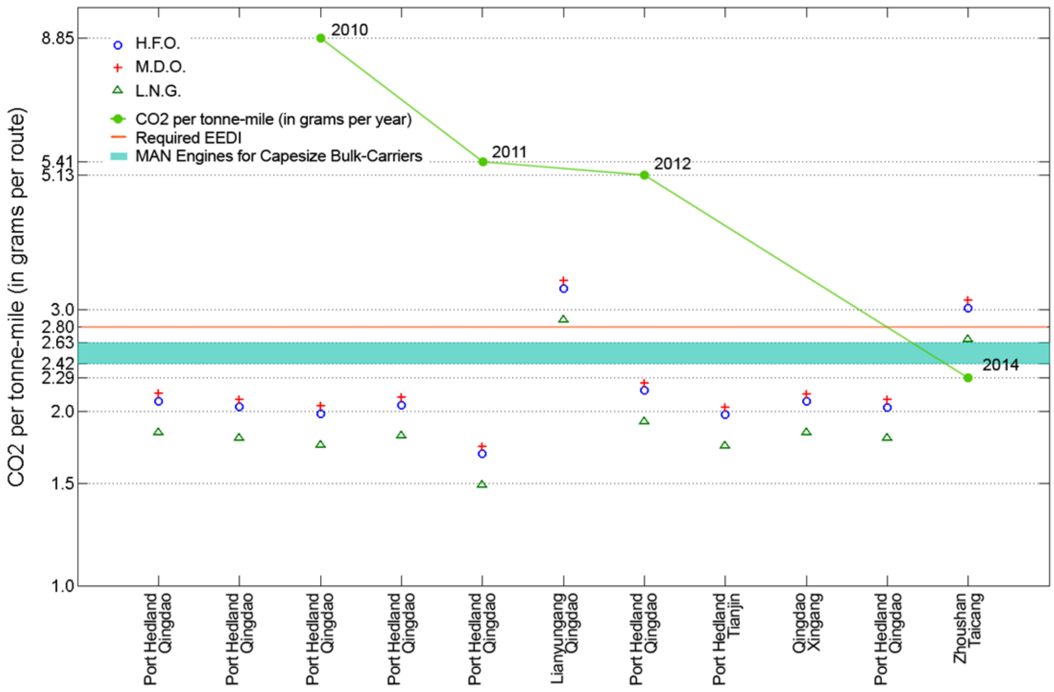

Figure 3: gr CO_2 emissions per tonne-mile for the laden trips of the bulk carrier ship

The green line in Figure 3 depicts the average CO_2 per tonne-mile for Capesize bulk carriers for the period 2010 -2014 (IMO, 2015). The red line is the EEDI threshold for (new-built) bulk carriers of this size, and the cyan area is the range of this index in MAN engines for Capesize bulk carriers. The case study ship manages to satisfy all the above limits in all but two trips (Trip No6 and Trip No 11). It is noted though that the average sailing speed of the ship in these trips is significantly below the service speed which depicts a slow steaming practice.

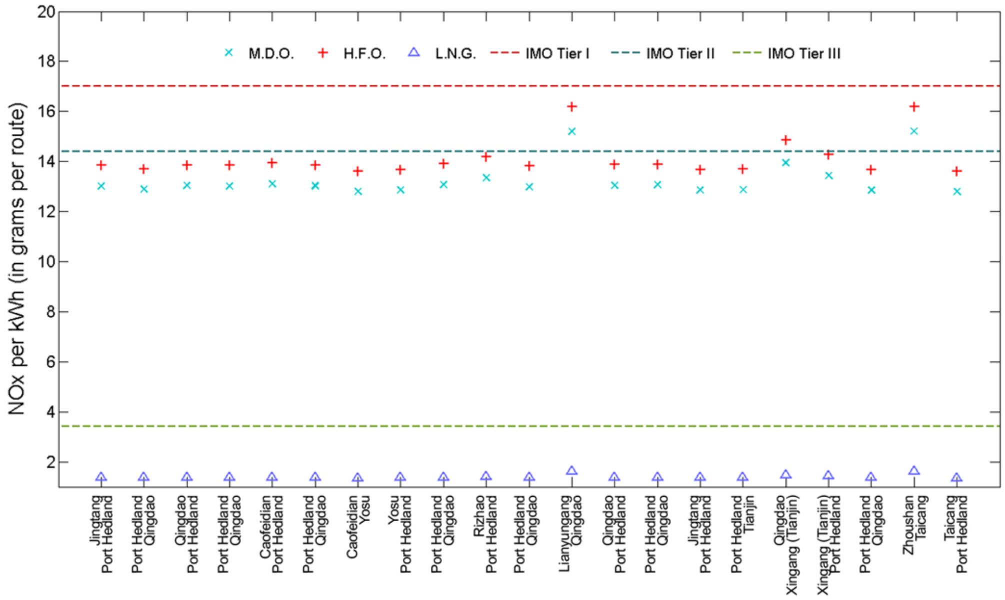

Figure 4: NOx emissions per kilowatt-hour – Bulk carrier case study

In Figure 4, the NOx emissions per kilowatt-hour are shown. The NOx emissions limits are regulated by IMO in Tiers that are gradually getting stricter (IMO, 2014). The three tiers are shown in Figure 4: Tier I (red line), Tier II (blue line), and Tier III (green line). The results of the NOx index are presented per trip. The resulted ship NOx index is way below Tier I and with current operating practice the ship is right below the limits of Tier II limits (except for three trips). However, only with the use of LNG as fuel it is possible for this ship to have NOx index below the limits of Tier III.

4.3 HULL SUBSYSTEM PROCESSES

The hull subsystem results are provided in this paragraph per process during the life cycle of the ship. Specific algorithms per process have been introduced in the software originated from previous work at NTUA (Chatzinikolaou and Ventikos, 2015a). The results of the hull subsystem illustrate that considerable CO_2 emissions derive from the processes of steel production, steel replacement, and steel cutting. In Figure 5, emissions from all steel related processes of the hull subsystem are projected for a period of twenty years.

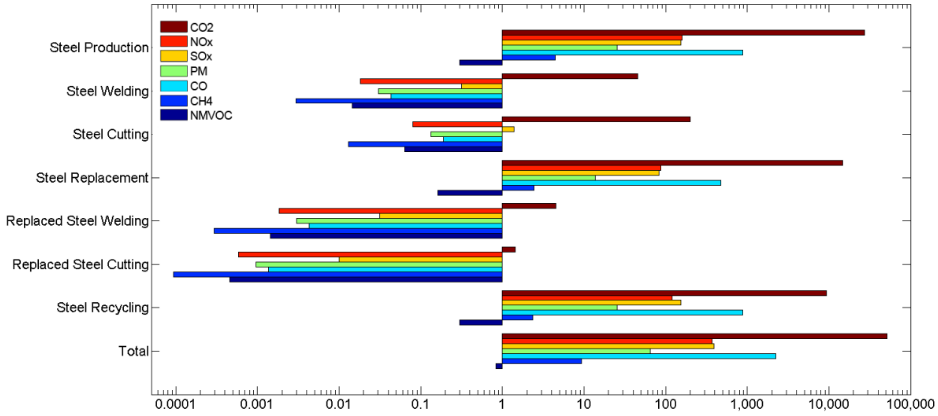

Figure 5: Hull subsystem of Bull Carrier. Emissions during the life cycle (in tonnes)

Overall the emissions Inventory of the hull subsystem for this ship is provided in Table 4.The dominant emissions are CO_2 (51,747 tonnes) followed by CO emissions (2,223 tonnes) throughout the ship life cycle. It is noted that these concern projected emission quantities deriving from a typical scenario of operation and maintenance activities of the ship. Five year intervals of dry-docks are considered and information for steel replacement is taken from previous studies on the subject (Touran et al, 2006). The emissions from coating processes are not included in this paper; however it should be noted that they are not negligible, especially with respect to NMVOC, as has been demonstrated in other studies (Chatzinikolaou and Ventikos, 2014b), (Celebi and Vardar, 2008).

Table 4: Hull subsystem – Emissions in life cycle (20 years)

Emission	*units*	*Quantity*
CO2	tn	51746.872
NOx	tn	367.863
SOx	tn	391.742
PM	tn	65.049
CO	tn	2223.391
CH4	tn	9.305
NMVOC	tn	0.837

4.4 MACHINERY SUBSYSTEM PROCESSES

The operation of main and auxiliary engines is the most important processes being responsible for most of the GHG and air pollutants emitted over the life cycle of a ship.

The operation of a ship may include a number of different functions such as normal operation, manoeuvring movements, staying in port, loading and unloading, and towing. In this sense, the total time, in days, of a round trip can be calculated as the sum of the time of individual functions that occur during the operation. There might be also days that the ship remains off hire for market reasons or for repairs. In the data collected for the case study ship the operational time is divided in sailing time that includes also the time spent in manoeuvring, and port time. Days off hire have been also reported by the company.

Figure 6, depicts the CO2 emissions of machinery in one year which reveal the dominance of emissions from operation of engines. Other possible emission sources are from the construction stage, shop tests, and sea trials. Life cycle results of the operation of engines are not provided in this paper for reasons explained previously. Finally, the exact faith of the engines at the final ship dismantling/recycling phase is not known.

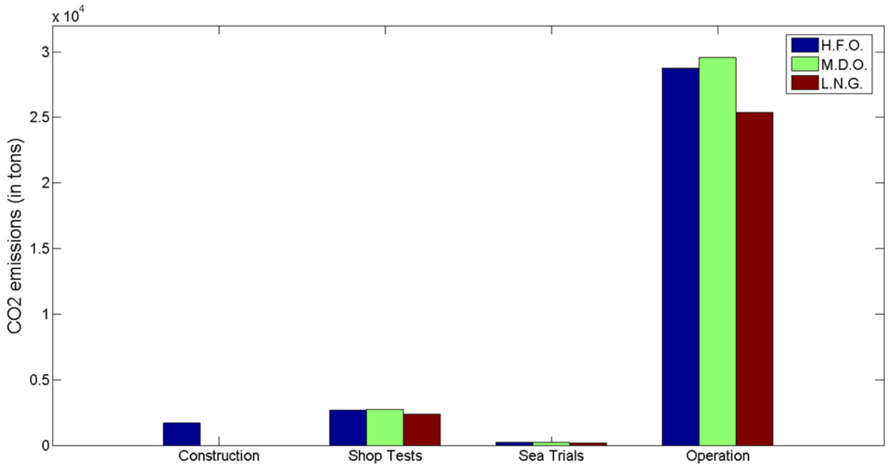

Figure 6: Bulk carrier Case Study. Machinery subsystem processes. Emissions during one year of operation (in tonnes)

5. CONCLUSIONS

This paper presents a software application which can be used to assess ship air emissions for cargo ships. This assessment is carried out in two levels which correspond to two important ship subsystems: the ship hull and the ship machinery. Each of these two subsystems comprises of a series of processes which are modeled with algorithms, empirical equations, and input data. Algorithms and empirical equations are provided from the theoretical ship-LCA framework of previous work (Chatzinikolaou and Ventikos, 2015a).

The paper presents the results of a case study (Capesize bulk carrier; 200,000 tonnes dwt) in which the software has been tested. In the hull subsystem the case study has been conducted with a hypothetical life cycle of twenty years and for the machinery subsystem case study, real data have been available which cover the operation of the ship during an entire year. The results obviously illustrate that the dominant stage of ship life with respect to emissions is the operational stage although emissions in other life cycle stages are not negligible. It is therefore important to collect adequate information and data for this stage in order to arrive to reliable emissions results. The accuracy of calculations in the software has been evaluated using real data provided by the ship operator and results show acceptable differences.

Finally, this software aims at contributing in the particular field of reporting and monitoring of ship air emissions and proposes a systematic way of collecting and elaborating data for various ship processes that play an important role in the production of these emissions. The software can be used also for supporting decisions in the long term since it can estimate emissions results per year or even project emissions during the life cycle of the ship.

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